RESEARCH ARTICLE

Evaluating canopy transpiration and water use of two typical planted tree species in the dryland Loess Plateau of China

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Abstract

Large-scale vegetation restoration has been conducted in China's Loess Plateau over the past several decades to control soil and water loss. However, these efforts have not followed any specific guidelines to select plant species that balance the twin goals of vegetation restoration and water demand. In the present study, we measured canopy transpiration characteristics of oriental arborvitae (*Platycladus orientalis*) and Chinese pine (*Pinus tabulaeformis*), two species that are commonly planted in restoration efforts, and recorded water input and output for these two species during the growing season. *P. tabulaeformis* had a higher tolerance than *P. orientalis* to warmer and drier environments and used water over a wider time span. Canopy transpiration significantly increased when rainfall exceeded 15 mm and was negatively correlated with net change of soil water content. Meanwhile, rainless intervals also affected canopy transpiration recovery. Canopy transpiration of *P. tabulaeformis* was 25.4% higher than that of *P. orientalis*. Soil water content under *P. orientalis* declined by 28.4% after the growing season, while it slightly increased under *P. tabulaeformis* (0.7%). Our results suggested that although *P. tabulaeformis* plantation had higher canopy transpiration, this water use did not drastically reduce soil water content, mainly due to the lower evaporation caused by the dense canopy cover. However, the low soil water content also implied that a better management, such as a mixed plantation of these two species and other supplemental water-conservation techniques, should be considered to better use water in this semiarid region.

KEYWORDS

canopy transpiration, Loess Plateau, sap flow, soil water, water budget

1 | INTRODUCTION

Tree transpiration plays an important role in the water balance of forests and has significant influence on water yields (Chang, et al., 2014a). It can be regulated by a series of ecological factors, such as competition for water among different species and the ability of plants to “bioengineer” the soils that they occupy, and physiological factors that affect the delivery of water to the leaf surface (Mitchell, Veneklaas, Lambers, & Burgess, 2009). Understanding water use by trees is crucial for sustainable ecological restoration, especially in arid and semiarid regions where water availability is the primary limiting factor for tree survival and stand development (Chen et al., 2014a).

Previous studies indicate that precipitation and soil water condition have an integrated influence on plant water use (Chen et al., 2014a; Chen et al., 2014b; Zhao & Liu, 2010), and climate conditions influence transpiration demands (Caldeira et al., 2015;

Zhang, He, Burnham, & Zhang, 2016; Zheng & Wang, 2014). The conceptual “threshold-delay” model, proposed by Ogle and Reynolds (2004), has been used to determine the threshold of rainfall pulses that initiate sap flow (*SF*) responses in shrubs (Zhao & Liu, 2010) and woodlands (Zeppel, Macinnis-Ng, Ford, & Eamus, 2008). Generally, the threshold differs by species and areas, mainly due to the differences in climate conditions and edaphic properties (Chen et al., 2014a; Du et al., 2011). Under dry conditions, soils usually experience a water deficit, and the rainfall pulses remain below some critical thresholds. Lower thresholds may just meet the need for surface moistening or evaporation, without affecting the *SF*. If the pulse is greater than the lowest threshold, it triggers the plant's response (Ogle & Reynolds, 2004). The balance of soil water between replenishment (e.g., precipitation) and extraction (e.g., evaporation and transpiration) affects the influence of rainfall over subsequent transpiration during the later rainless intervals (Chen et al., 2014a; Chen et al., 2014b).

For Qinhai spruce, Chang, Zhao, and He (2014b) established a logistic function between *SF* and soil moisture content that explained 84% of the variations in *SF* velocity. Shen, Gao, Fu, and Lü (2015) showed that sufficient recharge of soil water can significantly accelerate stand transpiration. At an annual temporal scale, stand transpiration showed a positive relationship with soil water content (SWC; Zhang, Guan, Shi, Yamanaka, & Du, 2015).

Meanwhile, the response of plant water use to precipitation and soil water conditions is associated with stomatal control (Chen et al., 2015; de Dios et al., 2014). Stomatal closure is the main mechanism that regulates transpiration, avoiding irreversible damage to plant hydraulic systems (Gotsch et al., 2014). Hysteresis is one of the most obvious phenomena related to plant transpiration that has been examined as a function of micrometeorological variables (Rodríguez-Dominguez et al., 2012; Zheng & Wang, 2014). The hysteresis between *SF* and vapor pressure deficit occurred in a clockwise manner, while the hysteresis between *SF* and photosynthetic photon flux density changed from counterclockwise (after precipitation) to clockwise (under dry conditions; Zheng & Wang, 2014). Besides, plant transpiration shows species-specific responses to variation in microclimatic and soil water conditions (Chirino, Bellot, & Sanchez, 2011; Du et al., 2011). For example, in drought-prone regions, intermittent water availability threatens the survival rates of woodland trees (Chen et al., 2014a). In the semiarid Mediterranean region, *Pinus halepensis*, *Pistacia lentiscus*, and *Erica multiflora* show water-saving mechanisms to cope with drought, while *Quercus coccifera* and *Stipa tenacissima* show water-spending mechanisms (Chirino et al., 2011). In the semiarid Loess Plateau of China, the exotic *Robinia pseudoacacia* was defined as a drought-sensitive type, and the naturally dominant *Quercus liaotungensis* and the indigenous concomitant species, *Armeniaca sibirica*, were defined as drought-insensitive types (Du et al., 2011). Compared with *Eucalyptus melliodora* and *Eucalyptus polybractea*, *Eucalyptus cladocalyx* could better tolerate saline soils, hot weather, and periods of drought, and it was determined to be the best-suited species to meet the goals of a phytoremediation project at a mine site (Doronila & Forster, 2015). Obviously, monitoring tree transpiration characteristics is essential in phytoremediation and can have key implications for plant species selection and management.

The semiarid Loess Plateau in China has experienced severe soil erosion, vegetation degradation, and desertification for centuries (Fu et al., 2006). Since the 1970s, vegetation restoration practices (i.e., planting trees and perennial shrubs) have been carried out to improve the environmental quality and to reduce water and soil losses (Chen, Wang, Wei, Fu, & Wu, 2010). However, several researchers have reported that soils become extremely dry in both deep and shallow layers after large-scale vegetation restoration (Yang, Wei, Chen, Chen, & Wang, 2014). Because it causes soil desiccation, the initially promoted afforestation has not had the positive effect on the landscape that it was intended to have (Liu et al., 2010; Rodríguez-Caballero, Cantón, Chamizo, Afana, & Solé-Benet, 2012); indeed, it has resulted in vegetation deterioration and difficulties in natural regeneration (Chen, Shao, & Li, 2008; Yang et al., 2014), fluctuations in agricultural crop production (Wang, Muhammad, Hao, & Li, 2011a), and unfavorable provision of ecosystem services (Yang, Chen, & Wei, 2015; Zhang, He, et al., 2016). Consequently, a better understanding of the water

use characteristics of different planted species is necessary for sustainable ecological restoration in the dryland Loess Plateau and other water-limited regions.

This study focused on a small catchment in the western Chinese Loess Plateau, where we compared the transpiration characteristics of two typical tree species that are commonly planted in the area, *Pinus tabulaeformis* and *Platycladus orientalis*, and evaluated their water budgets during the growing season. Specifically, we examined the soil water changes of both sites during the growing season. The results are expected to provide insights into plant water use strategies, species selection, and sustainable forest managements.

2 | MATERIALS AND METHODS

2.1 | Site description

The study area was located in Longtan watershed in Gansu Province, in the western part of the Loess Plateau in China (35°43'–35°46' N and 104°27'–104°31' E). The study site is a typical hilly region with gullies and elevations ranging from 1,937 to 2,151 m. The area is located in a semiarid temperate zone with an annual mean temperature of 6.8 °C and annual mean precipitation of 386 mm. Most rainfall occurs during the summer months, from July to September, in the form of thunderstorms. The mean annual potential evapotranspiration is about 1,649 mm. These annual averages were derived from meteorological data provided by a meteorological station located 0.6 km from the watershed and represent the averages of 45 years (1961–2006; Yang et al., 2015).

Soil types in the study area are mainly composed of loess soil with low fertility and are vulnerable to soil erosion. Soil thickness varies from 40 to 60 m. The texture is composed of a loose structure, with a high silt content (ca. 81%), a soil moisture field capacity of 0.180–0.240 g/g, a saturated moisture content of about 0.470 g/g, and little organic matter (ca. 0.2–2.9%).

With the implementation of the “Grain for Green” project, Chinese pine (*P. tabulaeformis* Carr.), oriental arborvitae (*P. orientalis*), purple alfalfa (*Medicago sativa*), and korshinsk peashrub (*Caragana korshinskii*) were widely planted. Land-cover patterns in the study area can be classified into abandoned cropland, arable land, native grassland, artificial grassland, shrubland, and tree plantations.

2.2 | Experimental design and data collection

2.2.1 | Experimental design

Two experimental plots (10 m length × 10 m width), in the middle of east-facing slopes, were selected for comparison, one planted with *P. orientalis* in 1984 and the other planted with *P. tabulaeformis* in 1972 (Figure 1). Each plot was bordered with a steel fence about 20 cm high and an outer fence about 1.5 m high surrounded the plot in order to prevent anthropogenic disturbances. Through tree, surveys were conducted before the growing season. For each plot, eight individual trees with different diameters at breast height (DBH, cm) were selected for the *SF* measurement. Detailed information regarding tree samples is shown in Table 1. *SF*, SWC, and meteorological data were monitored from April 27 to October 1, 2015.

FIGURE 1 Sketch map and information of the *Platycladus orientalis* plantation (left) and *Pinus tabulaeformis* plantation (right)

2.2.2 | SF measurement

SF was measured at 10-s intervals with constant heat flow gauges using the Granier type thermal dissipation sensor (TDP5, TDP10, Rain Root Scientific Limited Company, Beijing, China). An average value for the SF measurements spanning 10 min was recorded. SF density was calculated according to standard calibration for the TDP method based on temperature differences between two probes (Granier, 1987):

$$J_s = 0.0119 * [(\Delta T_{\max} - \Delta T) / \Delta T]^{1.231} \quad (1)$$

where J_s is SF density ($\text{g m}^{-2} \text{s}^{-1}$), $\Delta T_{\max}$ is the maximum temperature difference with zero SF assumed ($^{\circ}\text{C}$), and ΔT is the temperature difference between sensors at any given time ($^{\circ}\text{C}$).

SF (kg day^{-1}) was derived from the product of the SF density by the sapwood area (A_s , cm^2), based on the assumption of a uniform radial SF profile (Chang et al., 2014a). It was calculated as

$$SF = 86.4 J_s A_s / 10,000 \quad (2)$$

Canopy transpiration (T_c , mm day^{-1}) was obtained from the SF and crown projected area (A_c , m^2) (Shen et al., 2015) as

$$T_c = SF / A_c \quad (3)$$

2.2.3 | Environmental variables

Meteorological data, including solar radiation (R_a), air temperature (T), relative humidity (RH), wind speed (W_s), atmospheric pressure (P_a), and precipitation (P), were measured continuously with an automatic weather station Vantage Pro2 (Davis Company, USA). All measurements were taken at 10-s intervals and averaged every hour. Vapor pressure deficit (VPD) was calculated from T and RH data.

SWC was monitored continuously using HOBO U30 (Onset Computer Corporation, Bourne, USA). Each instrument included seven probes set to depths of 10, 20, 30, 40, 60, 80, and 100 cm, respectively. The net change in SWC (ΔSWC) was given as $\Delta\text{SWC} = \text{SWC}_2 - \text{SWC}_1$, where SWC_1 was the antecedent SWC and SWC_2 was the SWC at a certain time. The SWC monitored in late April was considered the antecedent SWC.

2.3 | Data analysis

T_c data were converted to an average value per hour to analyze the trend with meteorological factors, and the daily maximum and the corresponding R_a , VPD, and T were selected to calculate the optimal values. Student t test was used to determine significant differences between species regarding the daily maximum and daily average. Linear regression analysis was used to assess the trends of daily transpiration versus ΔSWC , with significance set at $p < .05$. To evaluate the water budget variation for both sites, we assessed monthly precipitation, transpiration, evaporation, and net changes of SWC. Statistical analyses were run using the SPSS version 17.0 software (SPSS Inc., Chicago, IL, USA). Plotting and curve fitting were performed using the OriginPro Version 8.0 software (OriginLab Corporation, USA).

3 | RESULTS

3.1 | Daily variation in T_c

The diurnal variations of T_c of *P. orientalis* and *P. tabulaeformis* followed a similar trend, with higher values in daytime and lower values at night, but they did not reach zero (Figure 2). Both species showed an obvious night SF. The diurnal course of T_c was closely related to changes in

TABLE 1 Characteristics of sample trees (mean $\pm$ standard deviation)

Species	DBH (m)	Sapwood area (A_s , cm^2)	Crown area (m^2)	Height (m)
<i>Platycladus orientalis</i>	5.05 ^a $\pm$ 1.28	18.13 ^a $\pm$ 8.28	3.51 ^a $\pm$ 0.47	3.33 ^a $\pm$ 0.82
<i>Pinus tabulaeformis</i>	9.44 ^b $\pm$ 1.29	52.96 ^b $\pm$ 13.64	5.89 ^b $\pm$ 0.89	7.54 ^b $\pm$ 0.65

Note. DBH = diameter at breast height. Significant differences between species are indicated by superscript letters.

solar radiation and vapor pressure deficit. The maximum value of T_c of *P. orientalis* occurred earlier (10:00–11:00 hr) than the maximum values of R_a (13:00–14:00 hr) and VPD (14:00–16:00 hr), and the maximum value of T_c of *P. tabulaeformis* was observed concurrently with the maximum value of R_a but occurred slightly earlier than the maximum value of VPD.

During the growing period, *P. orientalis* had a significantly higher maximum SF density ($J_{s, \max}$) than did *P. tabulaeformis* (Table 2). The optimal meteorological variations for both species are presented in Table 2. For *P. orientalis*, J_s reached the maximum under a relatively mild climate, with R_a of $517.6 \pm 205.1 \text{ W m}^{-2}$, VPD of $0.9 \pm 0.4 \text{ kPa}$, and T of $18.2 \pm 3.8 \text{ }^\circ\text{C}$, and the corresponding climate for *P. tabulaeformis* to reach $J_{s, \max}$ was much higher, with R_a of $649.0 \pm 259.5 \text{ W m}^{-2}$, VPD of $1.6 \pm 0.7 \text{ kPa}$, and T of $21.3 \pm 4.6 \text{ }^\circ\text{C}$. Student t test showed that these differences between the two tree species were significant.

3.2 | Influence of rainfall on transpiration

During the experimental period, 60 rainfall events were recorded, ranging from 0.2 to 38.4 mm, with a total rainfall depth of 295.6 mm. Most of the rainfall events were small, and the majority (73.4%) were less than 5 mm (Table 3). As rainfall amounts increased, rainfall

frequency decreased. However, the larger events ($>15 \text{ mm}$) accounted for 52.0% of the total precipitation amount.

Figure 3 shows the T_c between pre- and post-rainfall periods in different rainfall sizes. Post-rainfall T_c was slightly higher than pre-rainfall transpiration, and was significantly different when rainfall depths exceeded 15 mm. For each pre- and post-rainfall T_c value, no significant differences were observed among rainfall sizes. *P. orientalis* and *P. tabulaeformis* showed different time lags in their responses to rainfall pulses. *P. orientalis* reached the maximum T_c the second day after rainfall, and the maximum T_c of *P. tabulaeformis* occurred about 2 days later (Figure 4).

3.3 | Correlation between T_c and net change in SWC

We examined the relationship between T_c and ΔSWC . T_c of *P. orientalis* and *P. tabulaeformis* were negatively correlated with a wide range of ΔSWC (Figure 5). During the study period, 77.5% and 64.3% of the T_c of *P. orientalis* and *P. tabulaeformis*, respectively, occurred in a water deficit ($\Delta\text{SWC} < 0$; Figure 5). This observation is supported by Figure 6, which shows that mean SWC of *P. orientalis* site declined from 11.86% to 8.49%. In contrast, SWC of *P. tabulaeformis* showed a slight increase, from 5.77% to 5.81% (Figure 6).

FIGURE 2 Diurnal courses of solar variation (R_a), vapor pressure deficit (VPD), and canopy transpiration (T_c) of two tree species. Data are means $\pm$ standard deviation ($n = 8$)

TABLE 2 Diurnal maximum sap flow density ($J_{s, \max}$) and key meteorological variables

Species	$J_{s, \max}$ ($\text{g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	R_a ($\text{W}\cdot\text{m}^{-2}$)	VPD (kPa)	RH (%)	T ($^\circ\text{C}$)
<i>Platycladus orientalis</i>	$0.005^a \pm 0.002$	$517.6^a \pm 205.1$	$0.9^a \pm 0.4$	$57.5^a \pm 15.1$	$18.2^a \pm 3.8$
<i>Pinus tabulaeformis</i>	$0.003^b \pm 0.001$	$649.0^b \pm 259.5$	$1.6^b \pm 0.7$	$41.2^b \pm 18.2$	$21.3^b \pm 4.6$

Note. Mean values without common letters in the same column are significantly different. $J_{s, \max}$, R_a , VPD, RH, and T represent diurnal maximum sap flow density, solar radiation, vapor pressure deficit, relative humidity, and air temperature, respectively.

TABLE 3 Distribution of rainfall and rainfall events during the study period

Rainfall class (mm)	Frequency (%)	Rainfall (mm)	Proportion (%)
<1	31.7	9.6	3.2
1–5	41.7	59	20.0
5–10	16.6	73.2	24.8
>15	10	153.8	52.0
Total	100	295.6	100

3.4 | Water budget

The monthly P , T_c , evaporation (E), and net change in ΔSWC during the growing season were calculated and the results are presented in Table 4. The total T_c of *P. tabulaeformis* was 25.4% higher than that of *P. orientalis*, and E was 34.0% higher in *P. orientalis*. The ΔSWC was negative in most months from May to September, especially in *P. orientalis*. Water loss exceeded precipitation during these months,

a notable situation in this semiarid climate (Jian, Zhao, Fang, & Yu, 2015a; Yaseef, Yakir, Rotenberg, Schiller, & Cohen, 2010). *P. tabulaeformis* had a soil water surplus in May, June, and July, while *P. orientalis* had a surplus only in May. During the growing season, E/P accounted for 76.8% and 57.3% of *P. orientalis* and *P. tabulaeformis*, respectively.

4 | DISCUSSION

4.1 | The effect of plant species on T_c

Results showed that there was a pronounced diurnal hysteresis between T_c and R_a , and between T_c and VPD , and it differed in species (Figure 2). Hysteresis may be viewed as a self-protection strategy for plants that helps them avoid extremely high transpiration rates, thus preventing excessive extraction of water from the stem (Roddy & Dawson, 2013; Zheng & Wang, 2014). Species-specific effects,

FIGURE 3 Comparison of average daily canopy transpiration between pre- and post-rainfall periods in different rainfall size classes. The error bars indicate standard deviation. Means without common letters are significantly different at $p < .05$ according to t test **FIGURE 4** Relationship between T_c and corresponding duration of rainless intervals

FIGURE 5 Correlation between daily T_c and the net change in soil water content (Δ SWC)

FIGURE 6 Vertical distribution of soil water content in two plots measured on April 27 and September 30, representing soil water content at the beginning and end of the growing season

TABLE 4 Monthly values of water budget calculated by observed components (mm)

Species	Month	P	T_c	Δ SWC	E
<i>Platycladus orientalis</i>	May	71.8	17.97	4.6	49.03
	June	51.6	17.88	-3.09	36.61
	July	105.2	23.26	-11.02	92.63
	August	26.0	20.29	-19.11	24.73
	September	41.0	18.55	-1.81	24.11
	Total	295.6	97.95	-30.43	227.11
<i>Pinus tabulaeformis</i>	May	71.8	27.24	11.78	32.31
	June	51.6	21.72	0.48	29.21
	July	105.2	28.76	8.21	67.61
	August	26.0	25.61	-14.33	14.6
	September	41.0	19.52	-4.37	25.75
	Total	295.6	122.85	1.77	169.48

Note. P = precipitation; T_c = canopy transpiration; Δ SWC = net change in soil water content; E = evaporation.

primarily variation in the stomatal regulation of transpiration, played an important role in such physiological processes. For example, Wang et al. (2009) indicated that SF responses differed significantly among *Robinia pseudoacacia*, *P. tabulaeformis*, and *Cedrus deodara*. In addition, stomatal sensitivity to R_a , VPD, leaf water potential, and SWC vary with time (Wang et al., 2009; Zheng & Wang, 2014). SF of *R. pseudoacacia*, *P. tabulaeformis*, and *C. deodara* showed a rapid response to R_a in the morning but began to follow the pattern of VPD in the afternoon (Wang et al., 2009). Zheng and Wang (2014) found that *Haloxylon ammodendron* presented a clockwise rotation between SF and VPD.

Meanwhile, plant morphology (i.e., DBH, height, and crown projected area) was another factor causing hysteresis (Wang et al., 2009). Under similar climate conditions, the longer the distance between canopy and trunk, the lower SF density was observed,

indicating a delayed *SF* response (Liu, Li, & Ma, 2008; Wang, Ma, & Sun, 2002). Granier, Biron, and Lemoine (2000) suggested that the different *SF* response was probably due to the different amount of exchangeable water in tissues, and the capacitance phenomenon has been observed in coniferous species. In the present study, both *P. orientalis* and *P. tabulaeformis* clearly show nighttime *SF*, suggesting that stored water may also contribute to hysteresis (Figure 2). Furthermore, the nighttime flow reflects the adaptation strategy of plants to severe drought (Yin et al., 2013). As reported by Doronila and Forster (2015), the ability of a plant to maintain transpiration (*SF*) under high temperature and high VPD conditions allows a plant to uptake additional CO_2 for a given amount of water lost, thereby enabling higher growth rates. *P. tabulaeformis* was observed to have a greater tolerance to a warmer and drier climate (Table 2), suggesting that it can effectively consume much more water. Yang, Chen, Zhu, and Bi (2008) indicated that in the semiarid Loess Plateau, *P. tabulaeformis* uses water more efficiently than *R. pseudoacacia*, and *Malus pumila*. Similar results were also found in mixed forests of different ages (Chang, Wang, Wu, Cui, & Liu, 2013) and different species (Chen et al., 2014a; Nie, Li, & Zhai, 2005). However, other studies reported that the same strategy appeared to be a disadvantage in some water-limited environments (Doronila & Forster, 2015). The phenomenon can be expressed as a species-specific response to water supplementation. For example, *R. pseudoacacia* tends to transpire water actively as long as it is supplied (Du et al., 2011), while *Quercus coccoifera* maintains a high daily *SF* rate regardless of the decline in water potential (Chirino et al., 2011), and *Larix decidua* maintains high transpiration rates under severe soil drought stress (Leo et al., 2014).

4.2 | The relationship between transpiration and rainfall

Previous studies have demonstrated a relationship between the size of rainfall events and plant responses (Chen et al., 2014a; Du et al., 2011; Zeppel et al., 2008; Zhao & Liu, 2010). For example, the increase and persistence of *SF* density and the time constant of the decay in transpiration after rainfall are positively correlated with the amount of precipitation (Zeppel et al., 2008). For *Eucalyptus crebra* and *Callitris glaucophylla* in eastern Australia, 20 mm rainfall was needed to elicit a significant increase in T_c (Zeppel et al., 2008). The maximum *SF* density of *R. pseudoacacia*, *Quercus liaotungensis*, and *Armeniaca sibirica* generally showed an increasing trend in response to the rainfall events, and it differed in months and plant species (Du et al., 2011).

In contrast, Chen et al. (2014b) indicated that rainfall amount did not affect T_c recovery on the event scale. T_c recovery was significantly related to the difference between post- and pre-rainfall VPD values. Moreover, the time interval between consecutive rain events significantly affected the recovery of T_c (i.e., T_c declined as the interval extended). Zeppel et al. (2008) found that when antecedent soil moisture was ample or when potential evapotranspiration was low after rain, the percentage increase of post-rainfall T_c was always small, and vice versa.

SWC and potential evapotranspiration affected the ability of roots to supply water to the canopy and that of the atmosphere to drive evaporation from the canopy (Bosch, Marshall, & Teskey, 2014; Ungar

et al., 2013; Zhang et al., 2015). Similarly, a general increase in T_c was observed for *P. tabulaeformis* and *P. orientalis* after rainfall, but it only increased significantly when the rainfall exceeded 15 mm (Figure 3). Small rainfall events were not able to replenish the deep soil moisture effectively due to their ineffective infiltration and high evaporation rate. Time lags of plant response to rainfall pulses always occurred (Ogle & Reynolds, 2004). For example, *Nitraria sphaerocarpa* and *Elaeagnus angustifolia* in the desert-oasis ecotone of China reached the maximum sap velocity about 4.17 and 5.13 days, respectively, after rainfall (Zhao & Liu, 2010), while the hemi-parasitic species *Nuytsia floribunda* in southern Australia required more than 2 weeks to fully respond to rainfall events (Burgess, 2006).

In the present study, the maximum T_c of *P. tabulaeformis* occurred about 4 days after rainfall, and that of *P. orientalis* occurred after 2 days (Figure 4). *P. orientalis* had a much more rapid response to rainfall events than did *P. tabulaeformis*. One important factor that contributes to species-specific responses to rainfall is the root distribution, which varies among species and affects the depth to which roots can reach and absorb soil water (Chen et al., 2014a). Shallow-rooted plants had higher sensitivity to SWC and respond faster to precipitation than deep-rooted ones (Fang, Zhao, & Jian, 2016; Meinzer, James, & Goldstein, 2004). According to our previous studies, the fine roots of *P. tabulaeformis* and *P. orientalis* are concentrated within the 0–1 m soil profile, and *P. orientalis* had a relatively more robust shallow root system than *P. tabulaeformis* (Yang et al., 2012a). Moreover, Chen et al. (2014a) indicated that the timing of the rainfall events is another important factor affecting the total amount of transpiration. Generally, large rainfall events lead to large pulses, and small events may only be able to wet the uppermost soil layers, and a large fraction of the soil water is lost by direct evaporation (Cavanaugh, Kurc, & Scott, 2011). In semiarid areas, small rainfall accounts for a large proportion of total rainfall events and the large cumulative effect of consecutive small rainfalls were proved to be higher than the corresponding changes caused by a single large rainfall (Zhao & Liu, 2010).

4.3 | Effects of plant species on water budget

The plantation of woody species and shrubs is one of the main measures to restore fragile ecosystems. It has been encouraged worldwide because of its benefits, such as soil erosion control (Chen, Huang, Gong, Fu, & Huang, 2007; Yu et al., 2015), sediment reduction (Yang et al., 2012b; Zhang, Deng, Yan, & Shangguan, 2016), hydrological regime regulation (Jian et al., 2015a), and carbon sequestration (Jin et al., 2014). Previous studies indicated that land cover types had different effects on soil water dynamics. Wang, Ma, Zhu, and Liu (2011) found that native species are associated with higher soil moisture than exotic species, and vegetation restoration efforts that use non-native species may result in soil desiccation in the dryland Loess Plateau. Introduced vegetation decreased deep soil moisture drastically compared with farmland and native grassland (Yang et al., 2012a; Yang et al., 2014). Jian et al. (2015a) reported that in the Loess Plateau of China, *P. tabulaeformis* exhibited a more severe decline in SWC than did *C. korshinskii*, *Hippophae rhamnoides*, or *R. pseudoacacia*. As mentioned, SWC is mainly affected by rainfall amount, T_c , soil evaporation, and surface runoff. In water-limited environments, the ability of tree species to exploit soil water has a

crucial effect on their survival. An isotopic study also found that the water proportions of different soil layers for plant uptake vary across seasons and plant species (Chen et al., 2014b).

In the present study, the annual rainfall was almost entirely consumed by evapotranspiration, and only a small amount remained for soil water recharge. SWC under *P. orientalis* clearly declined (by 28.4% during the growing season) because of the high evaporation and transpiration rates (Figure 6). The small crown area of *P. orientalis* (Table 1) allowed much more light to penetrate into the ground, increasing soil temperature and thus enhancing soil evaporation, although the shade from the overstory canopy cover reduced energy input. A comparison of water budget showed that *P. tabulaeformis* plantations had a higher T_c/P ratio (41.6% for *P. tabulaeformis*, compared with 33.1% for *P. orientalis*) and lower E/P ratio (57.3% for *P. tabulaeformis*, compared with 76.8% for *P. orientalis*).

Much more water, however, was lost by evaporation than transpiration (Table 3). Raz-Yaseef, Rotenberg, and Yakir (2010) reported that mean soil evaporation measured in sun-exposed areas was double than that of shaded areas. Greater canopy coverage also increased intercepted water loss. Canopy interception can account for 10–40% of annual evapotranspiration (Chang et al., 2013; Raz-Yaseef et al., 2010), an amount that varied with canopy density (Kumagai et al., 2014), rainfall intensity (Fang, Zhao, Jian, & Kai, 2013), and precipitation type (Li, Cai, Man, Sheng, & Ju, 2015). Large evapotranspiration values, combined with low levels of soil water infiltration, could cause severe soil desiccation. Wei, Zhu, Zhang, Hua-Xing, and Zhu (2007) found that SWC is higher at the early stage of tree plantation than at the late stage. The soil water in a *C. korshinskii* plantation was nearly balanced at the beginning of the growing season and gradually turned to be in a deficit (Jian, Zhao, Fang, & Yu, 2015b).

Stand age and density are important factors affecting T_c . T_c declined with stand age in Norway spruce (*Picea abies*) from 40 to 140 years (Alsheimer, Köstner, Falge, & Tenhunen, 1998), boreal black spruce (*Picea mariana*) from 71 to 151 years (Ewers, Gower, Bond-Lamberty, & Wang, 2005), and ponderosa pine (*Pinus ponderosa*) from 25 to 250 years (Irvine et al., 2004). Moreover, stand density decreased with increasing stand age due to the decline in SWC (Alsheimer et al., 1998). However, Chang et al. (2013) indicated that there was no significant difference in total evapotranspiration and total water output between middle-aged (average 22 years) and mature (average 58 years) *P. tabulaeformis* forests. This result can be explained by the long-term cumulative effects of T_c and the plants' physiological regulation, which result in nonsignificant differences over a short term. In the present study, *P. orientalis* and *P. tabulaeformis* were planted in 1984 and 1972, respectively, and were aged around 40 years. *P. tabulaeformis* showed better growth (higher plant height, larger DBH, and greater crown area) than *P. orientalis* (Table 1), with a relatively lower SWC (Figure 6). Under specific climate conditions, evapotranspiration was a conservative process (Caldeira et al., 2015; Kumagai et al., 2014). Differences in stand status and plant composition mainly affect the aspects of evapotranspiration (e.g., soil evaporation, T_c , canopy interception), but not its magnitude (Chang et al., 2013; Granier et al., 2000; Kumagai et al., 2014). Therefore, in the semiarid Loess Plateau, it is critical to increase productive water loss and reduce unproductive water loss (Wang et al., 2012).

5 | CONCLUSIONS

In the present study, we mainly examined the characteristics of T_c of *P. orientalis* and *P. tabulaeformis* with regard to water balance during the growing season in China's dryland Loess Plateau. SF of the two species showed a similar diurnal variation, but the flow varied explicitly in peak time and the corresponding optimal climate variations. Compared with *P. orientalis*, *P. tabulaeformis* showed a greater tolerance to warmer and drier climates. Both *P. orientalis* and *P. tabulaeformis* increased T_c after rainfall due to the alleviation of water stress, although the responses were species-specific. After rainfall, *P. orientalis* showed a rapid response and reached the maximum transpiration in 2 days, while *P. tabulaeformis* reached the maximum about 2 days later. During the growing season, much more attenuation of SWC occurred in the *P. orientalis* site. Compared with the *P. tabulaeformis* plantation, 20.3% lower T_c was observed at the *P. orientalis* plantation, and 34.0% more water loss caused by evaporation was observed at the *P. orientalis* plantation. These findings indicated that *P. tabulaeformis* had a relatively higher productive water loss; however, this amount was still much lower than the unproductive water loss.

Our study suggests that a combined plantation of *P. orientalis* and *P. tabulaeformis* is an optimal approach. The higher and denser canopy of *P. tabulaeformis* can reduce the soil evaporation, while the lower and smaller canopy of *P. orientalis* can compensate for water loss caused by interception, thus promoting more sustainable use of water.

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