Sap flow and responses to meteorological about the Larix principis-rupprechtii plantation in Gansu Xinlong mountain, northwestern China

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ABSTRACT

The transpiration of trees plays a decisive role in the water balance of forest stands and in water yields from forested catchments, especially an artificial forest planted for the purpose of soil and water conservation in semiarid mountain ecosystem regions. For proper management of watershed ecosystems, quantification of water use, sensitivity and adaptation for artificial forest is needed. This study were monitored the sap flow for Larix principis-rupprechtii plantation by thermal dissipation probes (TDP), analyzed the correlation between the sap flow and the meteorological factors on daily and seasonal scale, and upscaled stand transpiration from individual sap flow measurements. Within a daily timescale, the net radiation (Ra), air temperature (AT), air humidity (AH), vapor pressure deficit (VPD) and wind speed (WS) showed a significantly positive correlation with sap flow velocity in day-time, but in the night-time sap flow had no significant correlation. Within a monthly timescale, the Ra, AT, WS, and VPD showed a significantly positive correlation with stand water use, whereas precipitation (Pp) showed a significantly negative correlation with stand water use. Our results also showed that the daily transpiration of L. principis-rupprechtii continued to increase with the increase of net radiation (Ra), until the late stages of growth season (except rainy and cloudy days), and the sap flow velocity showed an obvious hysteresis response to meteorological factors to alleviate plant water stress from June to October, while there was no significant correlation between day-time and night-time water use during the stage of germination and rapid growth in May. Besides, due to the relatively low temperature, the water consumption of forest stands was only about 151.05 mm during the whole growing season, and there was no obvious ‘noon break’ phenomenon in the whole growing season. These results indicated that L. principis-rupprechtii could manage the water consumption conservatively, and were appropriate for afforestation in the mountains ecosystem with high altitude and low temperature.

1. Introduction

It is well know that the arid and semi-arid area of the world is more than 1/3 of the global land area, where soil water shortage is a major factor influencing the ecology and hydrology of vegetation (Okin et al., 2006). Such environments are harsh, vegetation coverage is low and soil erosion extensive, restricting local economic development. Meanwhile, global climate change has also exacerbated the situation. In the past several decades, Chinese afforestation projects have contributed to progress towards ecological restoration in China (Chen et al., 2019; Zhu et al., 2019). As a result of these nationwide afforestation projects, the forest fraction coverage in China has increased from 12% in the 1970s to 22% in 2013 (Wang et al., 2019). These strategies aim to increase the carbon sink, reduce water loss and improve control of soil erosion (Moran et al., 2009; Deng et al., 2014). However, recent studies have shown that because of a high rate of water use (Jackson et al., 2005; Cao et al., 2010), particularly in semi-arid regions where water resources are scarce, large-scale afforestation can strongly affect water consumption of the whole ecosystem by changing evapotranspiration, infiltration and surface runoff (Jian et al., 2015). Therefore, inappropriate afforestation can lead to soil water shortage and even imbalance the whole ecosystem, different vegetation restoration strategies should be adopted in different climatic region. For instance, due to high water consumption, water yields have dropped by 30 to 50% in the semi-arid Loess Plateau (Deng et al., 2016). Therefore, it is vitally important to understand relationships between tree sap flow and...
characteristics, meteorological factors and soil-water availability. The results are expected to determine whether a given area is suitable for developing a stable forest ecosystem, and to promote land degradation mitigation and vegetation for other countries in the arid and semi-arid areas.

The transpiration of trees plays a decisive role in the water balance of forest stands and in water yields from forested catchments (Buckley et al., 2012), especially an artificial forest planted for the purpose of soil and water conservation in semiarid mountain ecosystem regions (Chang et al., 2014a). In northwest of China, Larix principis-rupprechtii have been widely planted for soil conservation and afforestation in mountain ecosystem since past three decades. It is not only being a valuable forest resource, but also performs the ecological function for water resource management. Studies have shown that transpiration is influenced not only by the hydraulic structure of the trees (Tyree, 1988) but also by meteorological factors (Cinniarella et al., 2002), soil moisture (Sperry et al., 2002; Nan et al., 2019), radial variations (Kumagai et al., 2007; Shinohara et al., 2013), height differences (Zhang et al., 2018), vegetation structure (Plautsch et al., 2010) and many other factors. However, considerable uncertainty in the estimates of transpiration in these systems, because of the complex terrain and the spatial heterogeneity of the mountain environment. Thus, accurate quantification of water consumption, sensitivity and adaptation is important when devising strategies for maintaining healthy and sustainable development of local forests. Such knowledge is vital for predicting the effects of possible land use and climate changes on water resources in the region.

The night-time sap flow is an important water use strategy to adapt to the environment, but few studies have focused on its ecological significance (Marks and Lechowicz, 2007; Phillips et al., 2014). Daley and Phillips (2006) showed that the night-time water use of Betula papyrifera accounted for 10% of the total sap flow. They proposed that the strategy may provide an ecological advantage, enabling the trees to maximize photosynthesis during the following morning and supporting rapid growth. Wang et al. (2018a) studied the night-time water use characteristics of Schima superba, Castanopsis hystrix and Michelia macclurei using thermal dissipation probe (TDP) sensors and found that the sap flow was mainly used for water recharge at night. Other studies have shown that night-time sap flow might play an important role in sustaining carbohydrate transport (Marks and Lechowicz, 2007) and delivering oxygen (Daley and Phillips, 2006). Such studies would help improve understanding the water-use strategies and mechanisms for L. principis-rupprechtii in semi-arid mountain ecosystem.

The responses of sap flow to soil moisture and meteorological factors have been widely used to characterize water use (Du et al., 2011; Chang et al., 2014b). The thermal dissipation probe method (TDP), which utilizes sap flow sensors originally designed by Granier (1987) based on the heat flux exchange principle, is currently the most convenient method for measuring the characteristics of tree transpiration (Meinzer et al., 2004). This technique, which is not limited by the spatial and temporal heterogeneity (Link et al., 2014), can be used to examine the relationship between transpiration and water consumption of a whole tree dynamically, and reveal its ecological and physiological mechanism (Berry et al., 2017). It has become a reliable method for monitoring individual tree sap flow in the field and has been widely used in forest water use research (Wilson et al., 2001; Kumagai et al., 2007; Miniti et al., 2007). In many forests, estimates of transpiration from the TDP method agree favorably with estimates of transpiration from the Bowen ratio and eddy covariance (Chang et al., 2014b). The technique, which expands the time-space scale of studies on the water consumption process of forest transpiration, provides a reliable method for analyzing differences between individual and forest stand transpiration (Mackay et al., 2002; Ewers et al., 2005; Mitchell et al., 2009) by measuring individual sap flow (Berdanier et al., 2016).

The main objectives of this study were as follows: (1) Investigate and identify relationships between the sap flow features and environmental drivers (e.g., air humidity (AH), air temperature (AT), vapor pressure deficit (VPD), net radiation (Rn), soil humidity (SH), soil temperature (ST), wind speed (WS) and precipitation (Pp)) for L. principis-rupprechtii plantation in the mountains ecosystem on different timescales; (2) Compare transpiration rates during the day-time and night-time to clarify the driving mechanism of diurnal water use; (3) Investigate the relationship between individual tree use and to estimate the stand water use for L. principis-rupprechtii plantation during a whole growing season. The overall aims were to understand the sap flow of L. principis-rupprechtii and analyze the correlation between sap flow and meteorological factors. The results were expected to provide comprehensive empirical data for afforestation, management of water resources, carrying out proper forestation practices in semi-arid mountains ecosystem.

2. Materials and methods

2.1. Study site

The study was conducted in the Gansu Xinlongshan National Nature Reserve, (35°44′20.12″N, 104°1′3.07″E, H. 2778 m) located in Lanzhou City, Gansu Province, China, which lies at the intersection of the Qinghai-Tibet Plateau, Loess Plateau and Neimenggu Plateau, belonging to the eastern extension of the Qilian Mountains. The study area has a semi-arid continental monsoon climate. The annual mean air temperature and annual precipitation at the site were 5 °C and 498.8 mm, respectively, and the frequency of precipitation was uneven, mostly concentrated in July, August and September. There was a large amount of herbaceous and shrub vegetation growing on the forest floor. The landform was characterized by intermountain valleys of the small watershed.

2.2. Forest structure

A large number of L. principis-rupprechtii were planted in the 1980s to aid land restoration, soil erosion control and water conservation. The trees have grown to form a tree canopy of dense mature forest with a high content of soil organic matter. We established three sample plots (25 m × 25 m) containing about 38 trees (i.e., 608 trees·ha⁻¹). All trees in the plots were identified and tagged, and the height and DBH of each were measured. The mean DBH of the sampled L. principis-rupprechtii trees was 17.85 cm, ranging from 10.19 to 25.47 cm, and the mean height was 15.8 m, ranging from 13 to 18.5 m. A litter layer 5 cm to 15 cm deep covered more than 95% of the forest floor. The shrub vegetation mainly comprised Sorbus koehneana, Berberis kansuensis, Rosa sweiginskii Koehne, Rosa omeiensis Rolfe, Cotoneaster multiflorus Bge., Spiraea alpina Pall. and Lonicera hispida. The herbaceous vegetation mainly consisted of Carex rigescens, Fragaria orientalis Losinsk, Acoutium sinomontanum Nakai and Potentilla bifurca.

2.3. Sap flow measurements

In this study, six trees were monitored for sap flow velocity (Fv) at a depth of 15 mm below the cambium in stems at DBH by the thermal dissipation probe (TDP) (Dynamax SapIP, USA) from November 2017 to October 2018, the measurement information of each tree selected for sap flow measurements is summarized in Table 1. The data from the sap flow sensors were measured every 30 min and mean values were recorded by a data logger (Dynamax SapIP, USA), providing 48 data points for each sensor daily. Considering the influence of azimuthal variations on the sap flow, the probes were placed on the eastern side (Shinohara et al., 2013). Before installing the sensor, bark was removed from the trunk at the height of DBH and drill holes were made perpendicular to the trunk face. The sensors were covered with a reflective aluminum sheet and wrapped with a plastic tarpaulin to protect them from sunlight and precipitation damage. In this study, we found that the sap flow of L. principis-rupprechtii obviously rose starting on 29 April.
and declined starting on 3 October 2018 (negative values or zero were seen before 29 April and after 15 October 2018), and this rule is consistent with the phenology of *L. principis-rupprechtii* in this research site. Therefore, this research used for analysis was started from 29 April and ended on 15 October.

### 2.4. Meteorological and soil water measurements

Meteorological measurements were conducted throughout the study and all the meteorological instruments were installed on a 24 m tower over the stands. Air temperature and relative humidity were measured at 16 m using a thermo recorder (HMP155A, Vaisala, Finland). Soil temperature and relative humidity were measured at 10 cm, 20 cm and 40 cm depths by reflectometry probes (GS3, Decagon, USA). Wind speed and direction (ATMOS 22, Decagon, USA) were measured at 16 m, as well as photosynthetically active radiation (LI-190R, LI-COR, USA) were measured continuously at 24 m in the forest. All meteorological data were sampled every 1 min, averaged every 10 min and recorded using a CR6 datalogger (Campbell Scientific Inc., Logan, Utah, USA). The vapor pressure deficit (VPD, kPa) was calculated from the average air temperature (\(T_a\), °C) and air relative humidity (RH, %) per hour according to the following formula (Yang et al., 2015):

\[
\text{VPD} = 0.611 \times \text{Exp}(\frac{17.502 - 240.97}{T_a}) \times (1 - \text{RH})
\]  

(1)

#### 2.5. Sapwood area determination and sap flow estimation methods

Data for the six monitored trees, and another six unmonitored trees distributed across the study area were used to calculate sapwood area (SA). Assuming that the stem cross-sections were circular, individual values of SA were obtained by distinguishing between the heartwood area and stem cross-sectional area beneath the bark. For each tree, the sapwood thickness was extracted with a 0.5 cm increment borer at DBH fixed in an annual ring groove made of wood and measured with a caliper to the nearest 0.01 mm. As *L. principis-rupprechtii* sapwood is easily distinguished in cross section, color differences were used to identify the boundary between sapwood and heartwood. The DBH and SA of *L. principis-rupprechtii* did not conform to a linear relationship owing to variations in the tree age and individual growth characteristics (Liu et al., 2017; Zhang et al., 2015). Based on measurements from 12 trees, an exponential relationship between DBH and SA was established (Fig. 1):

\[
\text{SA} = a \times \text{DBH}^b
\]  

(2)

The temperature differences (\(\Delta T\)) between the heated and reference probes was used to calculate the sap flux velocity (\(Fv\)) according to a previously published empirical calibration equation (Granier, 1985, 1987):

\[
Fv = 0.0199 \times \left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231}
\]  

(3)

where \(Fv\) is the sap flux velocity (cm·s\(^{-1}\)) and \(\Delta T_m\) is the maximal temperature difference between the heated and reference probes when the xylem sap flux velocity is near zero. When xylem sap flow occurs, some of the heat produced by the heated probe is dissipated by convection. Therefore, \(\Delta T\) decreases with increasing \(Fv\). It is reasonable to assume that sometime during the night, sap flow ceases and \(\Delta T\) reaches \(\Delta T_m\) (Peng et al., 2015). Miscalculation of the zero sap flow, needed for the calibration process, may lead to under- or over-estimation of transpiration.

We assumed that the sap flow velocity was consistent across the sapwood. Thus, SA (cm\(^2\)) and \(Fv\) (cm·s\(^{-1}\)) could be used to calculate the sap flow density (\(F_{sd}\) (g·h\(^{-1}\)) (Granier 1985, 1987):

\[
F_{sd} = \text{SA} \times F_v \times 3600
\]  

(4)

The individual tree transpiration (\(E_T\) (kg·day\(^{-1}\) or kg·hour\(^{-1}\)) was calculated directly by summing \(F_d\) and time (\(T\)) as follows:

\[
E_T = \sum (F_d \times SA \times T)
\]  

(5)

The whole-tree water use per year (\(Q\)) was calculated by summing the \(E_T\):

\[
Q = \sum_{i=1}^{n} E_{Ti}
\]  

(6)

where \(i\) represents days in all growing season (e.g., \(i = 1\) corresponds to the first day), \(Q\) is the total water use (kg·year\(^{-1}\)), the day-time and night-time lengths are determined by the local time of sunrise and sunset, respectively.

Sap flow data were scaled up from individual tree measurements to the whole tree, from 30 min values to season values. The stand water use (SWU) was calculated by means of regression models based on cumulated SA and DBH as predictors, these could be determined as follows (Krauss et al., 2015):

\[
\text{SWU} = \frac{\sum_{i=1}^{n} Q_i}{A} \times \frac{1}{\rho}
\]  

(7)

where \(i\) represents individual trees in the stand (e.g., \(i = 1\) corresponds to the first tree), \(Q\) is determined by \(E_T\), (Eq. (5)), \(\rho\) is the density of water (\(\rho = 998\) kg·m\(^{-3}\)), \(n\) means tree numbers in sample plots and \(A\) is the ground area of the stand. For the forest, structural data were collected over a known ground area (in m\(^2\)) and SWU was reported as kg H\(_2\)O per m\(^2\) ground area, which is equivalent to the same value in millimeters (mm).

#### 2.6. Data analysis and statistics

Exponential curve regression was used to identify the relationship between SA and DBH. Due to the weather and the failure of
experimental instruments, a small amount of data were lost in this research (25 July to August). To estimate the whole-tree water use per year, a multiple linear regression model was established by stepwise regression analysis based on the collected data and used to interpolate the missing data (Liu et al., 2017a). Relationships between meteorological factors, soil moisture and sap flux were analyzed by Pearson’s correlation analysis. The correlation analysis was used to compare the daytime water use and night-time water use. All statistical analyses were performed using SPSS, version 22.0 (SPSS Inc. an IBM Company, Chicago, IL, USA), and all curve fittings and figures were prepared with Origin Version 2018 software (Origin Lab Inc., Northampton, MA, USA).

3. Results

3.1. Relationship between DBH and sapwood area

The results showed that DBH and SA of L. principis-rupprechtii did not follow a linear trend, probably due to variations in the individual growth characteristics. Instead, SA scaled exponentially with DBH ($SA = 0.2159 \times DBH^{2.1197}$), highlighting that SA generally increased with increasing DBH for the range of sizes sampled ($R^2 = 0.9556$).

3.2. Daily variation between sap flow velocity and meteorological variables

In this study, there are differences in the time when the sap flow begins to rise in different months, but the shape of the sap flow curves versus time in different month is similar. Thus, we select July as a typical example research the diurnal variation of sap flow for L. principis-rupprechtii on three different days, one rainy day (10 July) and the following two days with typical environmental conditions (11 and 12 July) (Fig. 2). It can be seen that the diurnal variation of sap flow of L. principis-rupprechtii displayed an obvious circadian rhythm, and the sap flow changed considerably between sunny and rainy days, which was greatly affected by the environmental factors, e.g., $Ra$, VPD and $Pr$. The diurnal variation of sap flow exhibited a typical single-peaked curve on sunny days, the sap flow was started to increase with the increase of net radiation in the morning (around at 8:00), reaching peak values at 12:00 to 14:00, then it started to decrease, and went back to minimum values until 23:00 in the evening. Therefore, there are obviously that the sap flow of L. principis-rupprechtii started synchronously with the net radiation, but there was an obvious delay phenomenon in comparison with net radiation after midday (delay 2–4 h). On rainy days, the $Ra$ shows multi-peak curve variation rule due to the instantaneous change of meteorological factors, but the sap flow velocity showed a weak variation. The meteorological variables also showed clear diurnal variations. Net radiation reached its highest values at 12:00 to 14:00 but fell to zero during the night, and the air temperature ($AT$) showed a similar trend to VPD. The soil humidity increased after precipitation and then decreased gradually.

Considering the integrated impact of environmental variables, individual characteristics of trees and different sap flow velocity during the day-time and night-time, we were able to exploit the underlying structure of co-varying weather data to predict whole-tree sap flux responses (Chang et al., 2014b). Thus, separate multiple linear regression relationships were established by stepwise regression for the 6 sample trees between tree transpiration per hour ($ET_h$) and $Ra$, VPD, $SH$, $ST$, $WS$ and $Pr$ during the day-time and night-time (Table 2). The results showed that the main factors influencing $ET_h$ varied among the 6 trees. $Ra$, $WS$, $ST$, VPD, $SH$, $Pr$ were the main influencing factors during the day-time, whereas $WS$, $ST$, VPD, $SH$, $Pr$ were the main factors during the night-time.

3.3. Relationship between day-time and night-time water use

The day-time water use, night-time water use and the percentage of night-time transpiration to daily transpiration during different months in sunny days are shown in Fig. 3. Our research demonstrated that the day-time water use of L. principis-rupprechtii was different in different months, but no difference in night-time water consumption (Fig. 3A). The percentage of night-time transpiration to daily transpiration of L. principis-rupprechtii is about 2%-13% (highest in September and October, followed by May and lowest in June to August) (Fig. 3B).

To evaluate the water use strategy of L. principis-rupprechtii plantation, optimal regression models were identified for day-time and night-time water use during different months in sunny days (Fig. 4). It was found that the day-time water use had a significant correlation with the night-time water use during June to October ($P < 0.05$), but no clear correlation during May ($P > 0.05$). In addition, there was an obvious seasonal change in water consumption, which increased from May to July and gradually decreased from August onwards.

3.4. Seasonal variation between transpiration and meteorological variables

During the whole growing season, the seasonal variation between daily transpiration ($ET_{d}$) and metrological factors of L. principis-
to a similar seasonal pattern to *L. principis-rupprechtii*. The daily transpiration (*E*<sub>d</sub>) increased from 29 April, reached the highest values of over 10 °C on 12 Aug, and then decreased until the end of the study period. Furthermore, the low canopy density led to dramatic changes of VPD. The *E*<sub>d</sub> reached the highest value of over 14.5 °C on 18 May. VPD decreased from 28 May from 1.36 kPa on 13 May and then decreased rapidly until 28 May.

To better reveal influence the correlation between daily transpiration (*E*<sub>d</sub>) and meteorological factors on different timescale, a correlation analysis was performed to evaluate the impact of the *Ra*, VPD, AT, ST, SH, WS, Pr and *E*<sub>d</sub> on different timescales (Table 3). Within a daily scale, the *E*<sub>d</sub> was significantly positively correlated with *Ra*, AT, AH, WS and VPD for *L. principis-rupprechtii* during the day-time (*P* < 0.05), but there was no significant correlation (*P* > 0.05) during the night-time. It is worth noting that the sap flow velocity was negatively significantly correlated with SH (*P* < 0.05) during the day-time in July and August. Within a monthly scale, the *E*<sub>d</sub> was significantly positively correlated with *Ra*, VPD, AT and WS with correlation coefficients of *R* = 0.74, 0.39, 0.56 and 0.54 (*P* < 0.01), respectively, insignificantly correlated with AH, ST and SH (*P* > 0.05) and significantly negatively correlated with Pr with *R* = −0.31 (*P* < 0.01). The results indicated that the primary factors affecting of *E*<sub>d</sub> are different on different timescales.

3.5. Stand water use (SWU) characteristics

In this study, the annual water consumption of individuals was accurately estimated by combining DBH information of three samples of *L. principis-rupprechtii* and the exponential curve relationship between DBH and SA, and expanded to forest stand water use. The results indicated that SWU was about 151.05 mm, accounting for 24.84% of growing season precipitation.

### 4. Discussion

#### 4.1. Relationships between sap flow and meteorological factors

Changing the sap flow is a mechanism by which trees meet demands for transpiration. Thus, sap flow velocity is directly related to tree water consumption by transpiration (Peng et al., 2015). Previous studies have reported that the major environmental factors affecting sap flow velocity during the day have been shown to be *Ra*, AT and VPD (Du et al., 2011; Chang et al., 2014b; Wieser et al., 2015; Tian et al., 2018), whereas the major factors at night are VPD, wind speed and tree features (Zeppel et al., 2010; Rosado et al., 2012). Our results showed that the *Ra*, AT, AH, WS, VPD were the most significant environmental factors affecting the sap flow during the day-time, whereas on the night-time sap flow were no significant correlation (Table 3). The main reason for this was that VPD, AH and AT increased with increasing *Ra* from the morning, which results in an increase in the leaf-to-air boundary water potential difference and onset of transpiration and sap flow (Lei et al., 2010). In addition, the wind alters the air status within and above the canopy and VPD changes accordingly, which in turn induces variation of leaf transpiration (Wang et al., 2018a). Several studies have shown that sap flow positively correlates with air temperature (Chang et al., 2014; Liu et al., 2017; Walter et al., 2015), which is consistent with our results. Our results are also in agreement...
with previous findings for *Caragana korshinskii* (Xia et al., 2008) and *Salix matsudana* (Yin et al., 2014). Besides, our data showed that the sap flow on sunny days was greater than that on rainy days, and the precipitation events had the greatest influence on sap flow in our study site (Fig. 2). The most likely reason is that the precipitation events not only affect transpiration by greatly reducing *Ra* and VPD, but also increase *AH* significantly (Devine and Harrington, 2011; King et al., 2013), result in reducing the water stress of trees.

We also observed that *ET* had a significant positive correlation with *Ra*, *ATd*, VPD, and WS, and negative correlation with *Pr* during the whole growing season. The order of importance of the main meteorological factors affecting the sap flow rate was *Ra* > *ATd* > WS > VPD, and there was a significantly negative correlation between *Pr* and sap flow. At the start of the growing season, most of the water is used for rapidly growth and synthesis of other organic compounds. Therefore, the reason for the lack of significant correlation between day-time and night-time water use in May was likely rapidly growth. Phillips et al. (2014) demonstrated that higher night-time water transport correlated with a higher proportion of young foliage, suggesting that night-time transpiration might be beneficial during periods of rapidly growth. This phenomenon has previously been observed in *Pinus* (Grulke et al., 2004) and *Eucalyptus* (Phillips et al., 2014). However, there was no obvious 'noon break' phenomenon, sap flow showed an obvious hysteresis phenomenon to alleviate plant water stress from June to October. The frequently precipitation is the reason for the negative correlation between *SH* and *ET* in July and

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**Fig. 3.** The day-time water use, night-time water use and the percentage of night-time transpiration to daily transpiration in different months. The different lowercase letters represent significance at the 0.05 level (*P* < 0.05).

**Fig. 4.** Relationships between day-time water use (D) and night-time water use (N) of *L. principis-rupprechti* in different months during the growth season.
August. We also detected an obvious monthly change in water consumption, which increased from May to July and gradually decreased from August. Due to the influence of phenology, the results of this study are similar to those for *Quercus acutissima* and *Cunninghamia lanceolata* (Liu et al., 2017a), *Schima superba*, *Castanopsis hystrix* and *Michelia macclurei* (Wang et al., 2018a).

### 4.2. Ecological significance of night-time water use

Previous studies have reported that factors affecting plant sap flow differ between day-time and night-time. Although night-time water use may amount to only 5–7% of daily water use (Phillips et al., 2010), plant water use during night-time enables adaptation to the environment (Wang et al., 2018a). Time hysteresis may be closely related to stem water storage (Köcher et al., 2013). A time lag in the trunk may indicate that stem water storage is used for transpiration early in the morning (Scholz et al., 2008). Alternatively, it might indicate a water deficit produced by the previous day’s transpiration (Wang et al., 2018a). Our results showed that the sap flow velocity had an obvious delay (Fig. 2) and that the night-time water use was significantly affected by day-time water use (Fig. 4), except in May. There was a significant correlation between day-time water use and night-time water use from June to October. Based on the principle of water balance, the water deficit increases as a result of day-time transpiration and tree roots absorb the abundant water for transpiration to alleviate plant water stress (Tian et al., 2018). Besides, if VPD and WS cannot explain the variation in night-time water use, the water use is considered to be the primary cause of recharge (Benyon, 1999; Daley and Phillips, 2006). Thus, by analyzing the correlation between the sap flow velocity and VPD and WS, it is possible to identify whether the night-time water use is mainly used for transpiration or recharge. Our results showed that there are no correlation between VPD and night-time water use, and no correlation between WS and night-time water use (except in June and July) (Table 3). These supports the idea that the night-time sap flow is mainly used to alleviate the tree water stress induced by transpiration. Therefore, the night-time water use was mainly used for

![Fig. 5. Seasonal variation between daily transpiration ($E_T$) and environmental factors (Ra, VPD, AT, Pr, ST, SH) during experimental period (29 Apr-15 October 2018).](image)

#### Table 3

<table>
<thead>
<tr>
<th>Timescale</th>
<th>AH</th>
<th>AT</th>
<th>VPD</th>
<th>Ra</th>
<th>SH</th>
<th>ST</th>
<th>WS</th>
<th>Pr</th>
</tr>
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<td>May Day-time</td>
<td>−0.27</td>
<td>0.44*</td>
<td>0.27</td>
<td>0.52**</td>
<td>0.42</td>
<td>−0.23</td>
<td>0.54**</td>
<td>−0.43*</td>
</tr>
<tr>
<td>Night-time</td>
<td>−0.36</td>
<td>0.01</td>
<td>0.29</td>
<td>0.08</td>
<td>−0.02</td>
<td>0.05</td>
<td>0.27</td>
<td>−0.36*</td>
</tr>
<tr>
<td>Jun Day-time</td>
<td>0.57**</td>
<td>0.57**</td>
<td>0.57**</td>
<td>0.86**</td>
<td>0.12</td>
<td>−0.21</td>
<td>0.68**</td>
<td>−0.60**</td>
</tr>
<tr>
<td>Night-time</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.36</td>
<td>0.02</td>
<td>0.22</td>
<td>0.40*</td>
<td>−0.50**</td>
</tr>
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<td>0.88**</td>
<td>0.68*</td>
<td>0.92**</td>
<td>−0.58**</td>
<td>0.28</td>
<td>0.66**</td>
<td>−0.38*</td>
</tr>
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<td>0.12</td>
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<td>0.12</td>
<td>0.03</td>
<td>−0.22</td>
<td>0.28</td>
<td>0.43*</td>
<td>−0.05</td>
</tr>
<tr>
<td>Aug Day-time</td>
<td>0.67**</td>
<td>0.67**</td>
<td>0.68*</td>
<td>0.92**</td>
<td>−0.40**</td>
<td>0.04</td>
<td>0.51**</td>
<td>−0.32</td>
</tr>
<tr>
<td>Night-time</td>
<td>−0.02</td>
<td>−0.02</td>
<td>−0.02</td>
<td>0.26</td>
<td>0.23</td>
<td>−0.01</td>
<td>−0.14</td>
<td>−0.04</td>
</tr>
<tr>
<td>Sep Day-time</td>
<td>0.81**</td>
<td>0.81**</td>
<td>0.82*</td>
<td>0.73**</td>
<td>−0.24</td>
<td>0.28</td>
<td>0.61**</td>
<td>−0.14</td>
</tr>
<tr>
<td>Night-time</td>
<td>−0.12</td>
<td>−0.12</td>
<td>−0.13</td>
<td>−0.21</td>
<td>−0.09</td>
<td>0.36</td>
<td>0.09</td>
<td>−0.04</td>
</tr>
<tr>
<td>Oct Day-time</td>
<td>0.70**</td>
<td>0.70**</td>
<td>0.71**</td>
<td>0.91**</td>
<td>0.22</td>
<td>0.01</td>
<td>0.74**</td>
<td>−0.35</td>
</tr>
<tr>
<td>Night-time</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.12</td>
<td>0.16</td>
<td>0.10</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>Whole growth season</td>
<td>0.14</td>
<td>0.56**</td>
<td>0.39**</td>
<td>0.74**</td>
<td>−0.10</td>
<td>−0.11</td>
<td>0.54**</td>
<td>−0.31**</td>
</tr>
</tbody>
</table>

** indicates $P < 0.01$, * indicates $P < 0.05$. 
either transpiration or replenishment of the water deficit. In addition, our results suggest that the night-time water use of *L. principis-rupprechtii* accounted for 8.66% of the daily transpiration in May (Fig. 3B), and there was no correlation between night-time and day-time water use (Fig. 4A). These results supported the view that plants consumed more water at night-time when in the stage of germination and rapid growth (Daley and Phillips, 2006; Wang et al., 2018).

4.3. Estimation of stand forest water use from individual tree transpiration

The method of scaling up sap flow to individual tree transpiration has been widely used to estimate forest stand water use in planted forests (Peng et al., 2015; Zhang et al., 2015; Pfäutch et al., 2010), coniferous forests (Noormets et al., 2010; Moon et al., 2015), bamboo forests (Yang et al., 2015) and broadleaved deciduous forests (Krauss et al., 2015; Jiao et al., 2016). To estimate SWU from an individual tree scale, the relationship between Q and SA has been suggested to be an important scalar for converting values for individual plants to stand water consumption (Zeppe et al., 2010; Zhang et al., 2015). Finally, our results showed that the daily average transpiration consumption of *L. principis-rupprechtii* plantation was about 0.89 mm per day and stand consumption was 151.05 mm in the whole growing season. Our results are lower than in previous studies showing that water use through transpiration in deciduous forests is 300–522 mm during a complete growing season (Wullschleger et al., 2001; Schiller et al., 2007; Ouyang et al., 2018). Ren et al. (2018) reported that the water consumption of *L. principis-rupprechtii* was about 2145 ± 54.60 kg·y⁻¹ for individual trees during the growing season, which is significantly higher than our study. By comparing the meteorological factors and tree features which affect the water consumption of *L. principis-rupprechtii*, we found that although the tree morphological features were similar, there were relatively lower temperature for our research site than that of Ren et al. (2018) studies (e.g., in July, the average temperature of our research site was only 16.6 °C, while it was 22.1 °C in the study site of Ren et al. (2018)). Thus, it supported the view that the relatively low temperature is the main reason for the lower stand water use in the whole growing season for studied here, and one of the reasons for no obvious ‘noon break’ phenomenon during the growing season. Besides, ignoring the azimuthal and radial variation across the entire sapwood cross-section could lead to some discrepancies when estimating the water use of trees (Zhao et al., 2018). Thus, a better understanding of water fluxes in *L. principis-rupprechtii* plantation in the mountains ecosystem, it is necessary by coupling sap flow measurements with eddy flux towers to evaluate the contribution of SWU to evapotranspiration. Such studies would greatly aid species selection and vegetation management in the region.

5. Conclusion

For proper management of watershed ecosystems, quantification of water use characteristics and meteorological responses of *L. principis-rupprechtii* plantation were studied in mountains ecosystem of northwest, China. The results suggested that the factors Ra, AT, AH, VPD and WS showed a significant positive correlation with tree transpiration during the day-time, but there was no significant correlation during the night-time on a daily timescale. The Ra, AT, WS and VPD showed a significant positive correlation with stand transpiration, whereas Pr showed a significant negative correlation with ET on a monthly timescale. The sap flow was a significant correlation between daily water use and night-time water use in order to alleviate plant water stress from June to October, and there had an obvious hysteresis response to meteorological factors. While there was no significant correlation between day-time and night-time water use during the rapidly growth stage in May. Besides, due to the relatively low temperature and high altitude, the water consumption of forest stands was only about 151.05 mm, and there was no obvious ‘noon break’ phenomenon until late into the growing season. Overall, the results provided information on transpiration of *L. principis-rupprechtii* in semi-arid regions of northwest China, which should be useful for water balance estimation and ecological vegetation construction and management.

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Appendix A. Supplementary material

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References


