Combining sap flow measurements and modelling to assess water needs in an oasis farmland shelterbelt of *Populus simonii* Carr in Northwest China

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ABSTRACT

Farmland shelterbelts provide an ecological protection screen for an oasis but exhibit high mortality in the face of water shortage. It is necessary to understand farmland shelterbelt tree transpiration under different levels of water stress and stand ages for proper management. Sap flux measurement techniques and models are among the most useful method to detect water stress and to evaluate plant water consumption. The usefulness of both methods decreases, however, when applied to species, such as *Populus simonii* Carr, that have an outstanding tolerance to drought and a remarkable capacity to take up water from drying soils. Our hypothesis is that analysis using simultaneous measurements of sap flow and models in the same trees is useful for assessing the irrigation needs in farmland shelterbelts. To test our hypothesis, we analysed the relationships between canopy transpiration, canopy conductance, relative extractable water and atmospheric factors in a farmland shelterbelt and evaluated the effectiveness of the model. Measurements were made during one growing season. The time courses of sap flow measured and modelled on days of contrasting weather and soil water conditions were analysed to evaluate the usefulness of the method to assess the crop water needs. We calculated the daily tree water consumption from sap flow measurements and the parameterized modified Jarvis-Stewart model, and we evaluated the model's usefulness to assess the final water needs under water stress and stand ages for farmland shelterbelt irrigation. The transpiration decreased as the soil drought increased, and it increased as the atmospheric drought increased. The time course of the water needs showed that the occurrence of water stress in the farmland shelterbelt trees had a large impact on their water consumption, which increased as the water stress decreased, following the equation $y = 1/[1 + e^{-60.67 \times (REW_x - 0.402)}]$. The simultaneous use of modelling and tree structural data increased the reliability of assessing water needs from youth to maturity. A similar analysis with the water consumption values, from which stand age values were derived, showed that water needs increased with the tree age following the equation $y = 847 - 844/[1 + (x/87.9)^{1.9}]$. We conclude that compared to the use of sap flow records alone, the simultaneous use of sap flow records and model values provides more detailed information to assess water needs in a farmland shelterbelt, which has an important significance for farmland shelterbelt protection.

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1. Introduction

Water is becoming an increasingly scarce resource, and its shortage has become a growing threat to the growth of artificial forests in semi-arid land (Chen et al., 2008). As an important form of artificial forest, farmland shelterbelts provide an ecological protection screen for agriculture (Fan et al., 2002; Ryszkowski and Kedziora, 2007), and these shelterbelts decline with water shortage. Water-saving agricultural technology is widely used in semi-arid

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regions (Shan et al., 2002). Low-pressure pipeline technology, micro-irrigation techniques and sprinkler-irrigation techniques are often carried out in semi-arid agriculture (Xinli, 2006), and these techniques either prevent water side supplying or deep percolation (Kang et al., 2012; Xinli, 2003), causing the farmland shelterbelt to decline. Infant farmland shelterbelt trees and even mature trees exhibit high mortality from water shortages. Moreover, only a few woodland or agro-forestry areas were established after two decades (Xiubin et al., 2003). In recent decades, a large amount of cultivated land had to be discarded because of the lack of farmland shelterbelt protection (Chen et al., 2007). To encourage the protection of the agro-forestry system, water use strategies for farmland shelterbelt trees must be investigated. It has become increasingly necessary to understand farmland shelter tree transpiration under water stress and growth periods (Anderegg et al., 2012, 2013).

Sap flow techniques are routinely used to estimate the transpiration from canopies of woody plants, typically without any local calibration. However, it cannot explain the response of soil water and meteorological factors. Coupled with a model, this issue could be resolved. Canopy transpiration (E_c) is the main factor in the evaluation of tree transpiration (Cermak et al., 2004; Chang et al., 2006; Zeppel et al., 2008). E_c depends on a number of site-specific parameters that relate to the physical properties of the soil, the vegetation and the ambient meteorological conditions (Bonan, 2008; Chen et al., 2012; Jung et al., 2014; Li et al., 2013, 2010; She et al., 2013; Whitley et al., 2013). Solar radiation, VPD, and soil moisture are the primary determinants of transpiration (Jung et al., 2014; She et al., 2013). Numerous modelling methods are available to estimate transpiration from these driving parameters. Some

methods used semi-empirical relationships between the water and soil fluxes and vegetation and atmospheric conditions, such as the Penman–Monteith (PM) equation (Monteith, 1965), whereas others used empirical relationships between canopy water fluxes and meteorological drivers, such as Jarvis-type models (Jarvis and McNaughton, 1986; Lagergren and Lindroth, 2002; Whitley et al., 2013). Because of the semi-mechanistic basis of the PM equation, there is a wide appeal in using it to estimate rates of tree water use. However, its implementation is often limited by the need for aerodynamic and canopy conductance (g_c) data. Aerodynamic conductance often exerts a negligible effect on transpiration and could be calculated from wind speed (She et al., 2013; Sommer et al., 2002; Whitley et al., 2009). However, the response of g_c to the influencing factors has been incorporated into land surface models for transpiration estimation (Wang et al., 2014). g_c is a key parameter in controlling energy and water exchanges between the canopy and atmosphere (Han et al., 2011) and depends mainly on soil moisture, air temperature and relative humidity (Gharun et al., 2013). Canopy conductance models have been widely constructed following the Jarvis–Stewart approach (Jarvis, 1976; Stewart, 1988), which calculates the canopy conductance from the maximum stomatal conductance by applying different stress functions related to the influencing factors (Jonard et al., 2011; Naithani et al., 2012; She et al., 2013). Transpiration can be estimated by coupling with meteorological factors and the canopy conductance (She et al., 2013; Yunusa et al., 2000).

The purpose of this research was to evaluate the usefulness of simultaneous sap flow measurements and modelling for detecting the water consumption during water stress in farmland shelterbelts

Fig. 1. The location of the Manas Oasis.

Table 1
Basic physical and chemical property of soil.

Depth (cm)	Soil textures	Bulk density (g cm ⁻³)	Saturated water content (cm ³ cm ⁻³)	Field capacity (cm ³ cm ⁻³)	PH	Soil salt (g kg ⁻¹)
0–20	Medium Loam	1.48	0.42	0.30	8.15	0.72
20–40	Medium Loam	1.51	0.46	0.33	8.17	0.74
40–60	Medium Loam	1.57	0.47	0.33	8.23	0.65
60–80	Medium Loam	1.53	0.43	0.31	8.41	0.85
80–100	Medium Loam	1.59	0.38	0.28	8.37	1.03
100–120	Sandy Loam	1.67	0.32	0.25	8.29	0.96
120–150	Sandy Loam	1.77	0.32	0.25	8.46	1.10

Fig. 2. Soil moisture characteristics curve of different depth.

and the effect of the tree water stress on its water consumption. A second goal is to assess water needs under different levels of water stress and at different stand ages. We analysed the relationships among the canopy conductance and transpiration with the soil water content and climatic factors in a farmland shelterbelt comprising *Populus simonii* Carr trees with different stand ages.

2. Materials and methods

2.1. Study site

The study was conducted in Manas Oasis, located southwest of the Zhungaer Basin in Xinjiang, with geographical coordinates of E85°01'–86°32', N43°27'–45°21' (Fig. 1). Manas Oasis is in the north of Xinjiang, and it is known as the “Western Gate” of Urumqi. It is located between the middle range of the northern Tianshan Mountains and the southern border of the Zhungaer Basin. South of it are the famous TianShan mountains, and west of Manas Oasis is the edge of the Zhungaer Basin. Mountains and plains equally share the area. Manas basin covers 5156 km², with an average altitude is 302.2 m, and a glacier covers 608.25 km². The main sources of runoff are rain and melt water, of which 34.5% is melt water. The climate is a temperate continental dry and semi-dry climate, with an annual radiation of 1280 Mcal m⁻² (Dong et al., 2011). The annual precipitation is 190.3 mm, concentrated in the April–October period, and the annual evaporation is 1713.4 mm. The soil texture of the plot is generally medium loam (Table 1); and under the depth of 1 m, there was sand loam. Because of the different textural soil types between depths, their abilities of suction were various. Table 1 and Fig. 2 showed that the upper soil (1.0 m) had higher field capacity and stronger water absorption capacity. On average, there are 172 frost-free days, and the annual average air temperature is 6.9 °C. The aspect of this region slopes downwards from the south toward the north and tilts from the southeast to the northwest. The geomorphological sectors include mountains, flat plains, and deserts. The 1.176 × 10⁹ m² central alluvial plain

is the major agricultural crop growing area. Farmland shelterbelts were installed to protect the agro-forestry system in the oasis in the 1960s (Zhao et al., 2009). The surface soil is grey desert soil and is sandy loam from the depth of 90 cm (Table 1).

2.2. Sap flow and meteorological factor measurements

During the 2014 growing season, sap-flow gauges were installed at breast height in the stems (Granier, 1987) of *Populus simonii* Carr at the Mosowan experiment stations (Xinjiang Institute of Ecology and Geography, Chinese Academy of Science). The installation and maintenance routine followed the protocol prescribed by the manufacturer. The sap flow (SFD, cm m⁻² s⁻¹) of individual trees was measured with Granier-type heat pulse sensors (TDP80 Dynamax, USA) every 30 s, and 20-min averages were recorded with a data logger (DTKDT80-AL with a multiplexer AM 5/15, Thermo, USA) (Granier, 1987).

Soil water sensors (SM300) were installed at a 10–150 cm depth, and the counts were logged every 20 min from 20 April 2014 to 10 October 2014. Soil samples were collected by a soil auger (5 cm in diameter) and a ring-knife in the experimental plots at 10-cm intervals down the soil profile until 200 cm. The soil moisture data used in the subsequent section are based on this calibration. A growth cone was used to measure the sapwood radius and heartwood radius by tape. The diameter at breast height (DBH) was measured by a vernier calliper, the crown radius by tape, and the tree height by a hypsometer. These investigations were conducted on young *Populus simonii* Carr prior to maturity. Meteorological data were collected from Mosuowan meteorological stations with proximity to the experimental plot.

2.3. Canopy transpiration and canopy conductance

A standard calibration is widely used for the heat pulse method (Granier, 1987), relating the sap flow density (SFD, cm s⁻¹) to the difference in temperature between a pair of probes (ΔT °C)

$$SFD = 0.0119K^{1.23} \quad (1)$$

where K (dimensionless) is a parameter calculated as

$$K = \frac{\Delta T_{\max} - \Delta T}{\Delta T} \quad (2)$$

where $\Delta T_{\max}$ is the value of ΔT when there is no sap flux, which corresponds to the nocturnal ΔT maximum over a 24 h period.

$$E_c = SFD \times \frac{A_{sw}}{A_{canopy}} \quad (3)$$

where E_c (cm s⁻¹) is the canopy transpiration rate, A_{sw} (m²) is the sapwood area, and A_{canopy} (m²) is the canopy area. According to the description (Kumagai et al., 2005), the transpiration is calculated by summing the products of SFD and A_s . The rates (E , cm h⁻¹ ground area) are then normalized by the ground area and converted to units of cm d⁻¹ to compare with the rainfall (Chen et al., 2012). Canopy

transpiration is calculated from the transpiration divided by A_{canopy} (Eq. (3)).

The qualitative response of the canopy conductance (g_c , m s^{-1}) to the climate driving force is estimated from the time-averaged transpiration (T_r , mm) per unit canopy area and mean vapour pressure deficit (VPD, kPa) for the *Populus simonii* Carr trees. The actual g_c was calculated from the simple inverted Penman–Monteith equation as (Granier and Loustau, 1994; Han et al., 2012)

$$g_c = \frac{1}{\Delta R_n r_a / (\lambda E \gamma) + \rho C_p \text{VPD} / (\lambda E \gamma) - \Delta r_a / \gamma - r_a} \quad (4)$$

where λ is the latent heat of vaporization of water (2465 kJ/kg), γ is the psychrometric constant (65.5 Pa/K), ρ is the density of the air (1.25 kg m^{-3}), r_a (s m^{-1}) is the aerodynamic resistance calculated from the logarithmic wind profile for the neutral condition per (She et al., 2013; Sommer et al., 2002; Whitley et al., 2009), C_p is the specific heat of air (1010 $\text{J kg}^{-1} \text{K}^{-1}$), and VPD is the vapour pressure deficit of the canopy air (Chang et al., 2006), calculated by the Campbell equation (Campbell and Norman, 1998; Li et al., 2013, 2010):

$$\text{VPD}_i = (1 - RH_i) \times 0.6108 \times \exp\left(\frac{17.27T}{T + 237.3}\right) \quad (5)$$

where RH is the relative humidity (%), and T is the air temperature ($^{\circ}\text{C}$).

2.4. Modelling

2.4.1. Canopy transpiration

The Penman–Monteith equation was used to estimate the *Populus simonii* Carr canopy transpiration (E_c^{pred} , mm s^{-1}) (Han et al., 2011; She et al., 2013; Yunusa et al., 2000).

$$E_c^{\text{pred}} = \frac{\Delta (R_n - G) + \rho C_p \text{VPD} g_a}{\lambda \left[\Delta + \gamma \left(1 + g_a / g_c^{\text{pred}} \right) \right]} \quad (6)$$

where Δ (Pa K^{-1}) is the slope of the relationship between the saturation vapour pressure and temperature (Zeppel et al., 2008), G is the heat flux to the soil (W m^{-2}), R_n is the solar radiation above the forest canopy (W m^{-2}), g_a is the aerodynamic conductance (m s^{-1}) (She et al., 2013; Sommer et al., 2002; Whitley et al., 2009), and g_c^{pred} is the predicted canopy conductance (m s^{-1}).

2.4.2. Canopy conductance

The modelling approach is based on the work of Jarvis (Jarvis and McNaughton, 1986), wherein the canopy conductance is separable and parameterized as a multiple response of the leaf stomatal resistance to environmental factors (Sommer et al., 2002). The canopy conductance (g_c , m s^{-1}) is modelled by response functions (f , $0 \leq f \leq 1$). In the study, g_c is assumed to be determined by VPD, R_n and the soil moisture (θ) (Jarvis and McNaughton, 1986), which is modified as

$$g_c^{\text{pred}} = g_{c\text{Max}} LA f(R_n) f(\text{VPD}) f(\theta) \quad (7)$$

where $g_{c\text{Max}}$ is the maximum canopy conductance and $f(R_n)$, $f(\text{VPD})$ and $f(\theta)$ are the limiting functions of R_n , VPD and the soil moisture (θ), respectively,

$$f(R_n) = \frac{R_n \times (R_{nH} + k_1)}{R_{nH} \times (k_1 + R_n)} \quad (8)$$

$$f(\text{VPD}) = k_2 \ln(\text{VPD}) + k_3 \quad (9)$$

$$f(\theta) = \frac{1}{1 + (\theta_r / \theta_0)^{-k_4}} \quad (10)$$

$$\theta_r = (\theta - \theta_w) / (\theta_{fd} - \theta_w) \quad (11)$$

in which R_{nH} is the approximate maximum solar radiation, assumed to be 400 (W m^{-2}) for daily step calculations according to the measurements; k_1 is a fitted parameter (Wang et al., 2014; Whitley et al., 2013); θ_r is the relative extractable water (REW) in the soil; θ_w is the wilting point; θ_{fd} is the soil water field capacity; $\theta_0 = 0.38$ when $f(\theta) = 0.5$; and k_1 , k_2 , k_3 and k_4 are parameters identified by data measurements.

2.5. Calibration and verification

The predicted g_c and E_c values were graphically compared with the measured values and determined to be robust and consistent (Lu et al., 2003). The root mean square error (RMSE) was used to weight the deviation between the i th experimental value (y_i) and the i th predicted value ($\hat{y}_i$) of $g_c(E_c)$, where we express the RMSE as

$$\text{RMSE} = \left[\frac{1}{n} \sum (y_i - \hat{y}_i)^2 \right]^{1/2} \quad (12)$$

In addition to the aforementioned data processing procedure, statistical analyses were conducted using the SPSS software package (version 19.0 for Windows, SPSS Inc., USA) to determine the model that links the canopy conductance to VPD, R_n , and θ_r . All statistical analyses were performed using SPSS software with $\alpha = 0.05$ as the threshold for statistical significance.

3. Results and discussion

3.1. Microclimate and soil moisture

Variations in the weather during the tree-growing season in 2014 are shown in Figs. 3 and 4. The monthly temperatures from May to August during the experiment year increased, but they decreased from September to October. During the experimental period, the total rainfall was 75.5 mm. The relative humidity was higher in June than in August or September, and the VPD was inverted. The mean daily temperature was $19.6 (\pm 5)^{\circ}\text{C}$, with a minimum of 1°C and a maximum of 32°C . The mean daily VPD was 1.7 (± 0.3) kPa, with a maximum of 3.5 kPa. The variations of the soil

Fig. 3. Environmental conditions during the 2014 growing season. Mean daily air temperature (line, $^{\circ}\text{C}$) and daily precipitation (mm).

Fig. 4. Environmental conditions from May 2014 to September 2014 (VPD, R_n).

water content 1.5 m underneath the surface are shown in Fig. 5. The relative extractable water was $0.53 (\pm 0.06)$ at 20 cm, $0.29 (\pm 0.05)$ at 40 cm, $0.49 (\pm 0.05)$ at 90 cm, and $0.72 (\pm 0.05)$ at 150 cm soil depth throughout the experimental period. The soil moisture experienced its largest variations in the upper 90 cm, especially during low rainfall periods (Fig. 5). It decreased as the depth increases from 0 to 40 cm and increased as the depth increased from 50 to 150 cm. The surface soil water content sharply decreased in June and was stable from August to September (Fig. 5). The decline in the soil moisture content during this period was reflected by the water uptake by trees. However, the cause of this result was not only soil water evaporation but also tree transpiration. Two periods of irrigation were carried out in the study plot (Fig. 5), and the soil water content greatly changed in the upper 90 cm.

3.2. Stand structural characters

According to measured sapwood radius (SR) and heartwood radius (HR), the sapwood area (A_{SW}) could be calculated by $A_{SW} = \pi \times [(SR + HR)^2 - HR^2]$. The individual A_{SW} was determined from the increment cores, and then the stand sapwood area was obtained by the regression of the DBH– A_{SW} relationship (Eq. (13)). Based on this relationship and the tree distribution per ha with respect to the DBH, the daily Tr was calculated by integrating the actual E_c for each day over all the DBH classes (Brito et al., 2014).

$$A_{SW} = 6.6308 \times e^{0.1566 \times DBH}, \quad R^2 = 0.9774, \quad n = 8 \quad (A_{SW} : m^2, DBH : cm) \quad (13)$$

The canopy areas were calculated by conical surfaces, and a regression was obtained between the canopy area and the DBH. Based on this relation and the tree age with respect to the DBH, the tree canopy areas of different stand ages could be calculated.

$$A_{canopy} = 8.0143 \times \ln(DBH) + 1.5828, \quad R^2 = 0.8776, \quad (A_{canopy} : m^2, DBH : cm) \quad (14)$$

The measured DBH values for different stand ages were used to obtain the regression function from the sample trees:

$$DBH = 8.489 \times \ln(x) - 8.84 \quad R^2 = 0.928, \quad (DBH : cm, X : stand age) \quad (15)$$

From the above equations, the tree sapwood area and canopy area increased with the DBH, which increases with the stand age. The canopy area peaked at $25 m^2$ and then stabilized during the mature period. The DBH continued to grow, quickly in the young period, slowly in the immature period, and reaching a peak in the mature period. Using these equations, the tree sapwood area, canopy area and DBH from young trees to mature trees could be estimated.

3.3. Canopy transpiration and canopy conductance

The canopy transpiration and canopy conductance varied considerably on a seasonal cycle (Fig. 6). The canopy transpiration

varied between $0.5 mm day^{-1}$ during cloudless days, with a high evaporative demand and ample soil water availability, and it was close to 0.1 during the hot and dry summer (Fig. 6a). The total annual canopy transpiration was 31.5 mm, with 75% occurring during the cold and wet period, when the soil water was not limited.

A similar seasonal trend was observed for g_c (Fig. 6b), with maximum values up to $0.6 mm s^{-1}$ (May 12, 2014), when the soil water availability was not limited, and it reached minimum values close to $0.1 mm s^{-1}$ under conditions of soil drought (Fig. 4).

3.4. Model calibration and verification

A careful check suggests that this result is because some extreme large conductance values were accidentally allocated to the training data set. The period from May to June was applied for model calibration and later for model verification, parameters were showed in Table 2. The results showed a consistent overestimation of the measured canopy conductance at night for these two periods (Fig. 7, a: calibration; b: verification). In the model, g_c is a hyperbolic curve with R_n , and the value of R_n at night is zero; therefore, the modelled value at night is zero. However, in fact, there was still sap flow at night; thus, the conductance was above zero (Zweifel and Häslar, 2001).

The canopy transpiration rate is shown in Fig. 6, and the daily stand transpiration could be calculated from $E_{day} = E_c \times A_{canopy} / A_{stand}$. The measured hourly (dashed regression line) stand transpiration of the *Populus simonii* Carr shelterbelt was compared to the estimated values (solid regression line) (Fig. 8). From May to June, the hourly measured transpiration was larger than the modelled transpiration (Fig. 8a) at noon, but the daily transpiration stayed the same (Fig. 8). In July, the modelled hourly transpiration at noon was higher than the measured hourly transpiration at noon, and the modelled daily transpiration was also higher than the measured daily transpiration (Fig. 8b). There was little deviation between the measured and modelled daily transpirations. The daily transpiration was fit by a regression to $y = 1.0513x - 0.0021$, and the R^2 was 0.81 (y is the measured transpiration and x is the modelled transpiration).

The correlation coefficient (r), root-mean-square error (RMSE), and slope of the linear regression were determined to evaluate the

Fig. 6. Seasonal course of daily canopy transpiration and the mean daily canopy conductance between May 1, 2014 and October 20, 2014.

Fig. 5. Relative extractable water at different depths.

Table 2
Parameters of the model.

	k1	k2	k3	k4
Parameter Values	0.025	−0.13	0.27	−15.23

effectiveness of the model (Table 3). For the canopy conductance, the slope was 0.976, and $R^2 = 0.79$, which indicates that the model was well fit in the study. As verified from the transpiration, the model generally fit the measured data well, with a slope of 1.05 and an R^2 of 0.81.

Although the model performed well in this study area, there was some deviation. Most of the deviation occurred at night, probably because intense transpiration results in a water deficit in living organisms during the daytime. To recover the water balance, soil water enters via root pressure during the night. For example, the nightly contribution of the sapwood to soil water exceeds 1 mm per day of transpiration (Zweifel and Häslar, 2001). In May, the modelled transpiration was slightly lower than the measured stand sap flow, possibly because young leaves, even if fully expanded, had not yet reached physiological maturity and were thus severely affected by soil water stress (Kume et al., 2007). However, in July, the modelled transpiration was larger than the actual measurements, which can be attributed to the non-involvement of the temperature response function in the model. High temperatures coupled with strong solar radiation and low air humidity can limit the plants' physiological activity and transpiration (Zhou et al., 2004).

A higher atmospheric evaporative demand and lower soil moisture influences the trees' sap flow and canopy conductance (Kume et al., 2007). The REW and VPD were usually used as indexes to identify soil water stress and atmospheric drought. The effect of soil water stress on vegetation has been a significant research topic in recent years. The REW varies between 0 and 1, and the soil moisture conditions are defined as stressed when the REW is below 0.4 (Breda et al., 2006; Chen et al., 2014). The soil was considered to be under a more severe drought when the values of REW were

less. The summer was particularly dry (precipitation of 74.5 mm during the study period) and hot (mean $T > 23^\circ\text{C}$ each month) in 2014. While the soil was progressively drying during the vegetation period, the REW quickly decreased from the surface to a depth 90 cm and dropped below the threshold of 0.4 in early July. Below this threshold, trees are known to suffer from water stress (Bernier et al., 2002; Granier et al., 1999). In the farmland shelterbelt, the REW was below 0.4 for a long time during the growing season. By contrast, the tree conductance logistic increased from the wilt point to the field capacity. The tree conductance changed little with no water stress, and when the relative extractable water exceeds 0.4 (She et al., 2013), changing in a similar manner to the transpiration. *Populus simonii* Carr trees close their leaf stoma to cut water loss when suffering water stress; therefore, the g_c and transpiration decreased as the water stress increased. Both the daytime and night-time transpiration decreased as the soil drought increased, but they increased as the atmospheric drought increased.

In contrast to the relatively simple relationship linking REW and E_c and g_c , the relationship between E_c , g_c and VPD was more complex. The function relating E_c , g_c and VPD was determined by both the direct response of the stoma to VPD and the response of diffusion to VPD (Whitley et al., 2009). VPD is an atmospheric drought index (Naithani et al., 2012). When the VPD decreases, the atmosphere drought increases, and vice versa. The threshold of 2–3 kPa for declining transpiration with increasing VPD observed in the present study is larger than that observed by Komatsu et al. (2006). This difference is probably because the site used in the present study is much drier and thus experiences a much larger range of VPD. The response of the stomata to VPD is strongly influenced by the soil moisture content (Whitley et al., 2009), and therefore, the long-term drought experienced at the present site was likely to have influenced the response we observed. Hence, soil drought and atmospheric drought had a synergistic effect on farmland shelterbelt transpiration. Both the tree growing character and meteorological factors were considered in the model. We conclude that compared to using sap flow records alone, the simultaneous

Fig. 7. Comparison of the measured hourly canopy conductance (dashed regression line) to the estimated during the growing period (a: calibration b: verification).

Fig. 8. Comparison of the measured hourly stand transpiration in the *Populus simonii* Carr shelterbelt (dashed regression line) to the estimated hourly transpiration using the submodel calibrated in the Mosuowan experimental plot (solid regression line).

Table 3

Regression statistics for the model that were applied at the site. The slope (m) and intercept (c) of the regression line, the explained variance (R^2), and the root mean-square error (RMSE) are listed.

	$g_c(\text{m s}^{-1})$	Canopy transpiration (cm/day)
m	0.976	1.0513
c	0.0002	0.0021
R^2	0.79	0.81
RMSE	9.45×10^{-4}	6.39×10^{-3}
N	1520	140

use of sap flow and model values provides more detailed information to assess water needs in farmland shelterbelts.

3.5. Assessment of water needs

3.5.1. Response of water needs to water stress

The model performed well in the canopy conductance and transpiration estimations. The stand transpiration under different water stresses was needed to calculate the required irrigation. The SFD occurred during the day and the night, and it increased in absolute magnitude with the increasing atmospheric drought and declined as the soil drought increased. When the drought was at its worst, no sap flow could be detected in the trees. On average, transpiration stopped when 80% of the relative extractable water in the rooting zone had been depleted (Lagergren and Lindroth, 2002). Under different soil water contents, the transpiration of the *Populus simonii* Carr tree was different. The soil moisture influences the LAI and the whole tree transpiration. We assumed

that the REW was maintained at one level during the growing season and estimated the tree transpiration under different soil moisture levels. Fig. 9 shows that there was micro transpiration when the REW was 0.2, and the transpiration was 0.06 cm/day at REW=0.3. This result agrees with recent research (Lagergren and Lindroth, 2002) showing that no sap flow was detected when 80% of the relative extractable water in the rooting zone had been depleted. The transpiration significantly changed when the REW ranged from 0.3 to 0.4. The soil moisture conditions were defined as stressed when the REW ranged below 0.4 (Breda et al., 2006; Chen et al., 2014). The transpiration increased as the REW rose (Fernandez et al., 2011) and followed a S logistic equation: $y = 1/[1 + e^{-60.67 \times (\text{REW} - 0.402)}]$ ($R^2 = 0.98$) showed in Fig. 10. With no water stress, the transpiration may reach 170 mm, 333 mm, 307 mm, 263 mm and 65 mm/month from May to September. And stand transpiration was 98.5 mm, 172 mm, 170 mm, 106 mm and 30 mm from May to September under REW = 0.4, respectively. To keep the farmland shelterbelt away from water stress in 2014, 67 mm, 133 mm, 141 mm, 79 mm and 15 mm of irrigation were needed for each month from May to September, respectively.

In 2014, the transpiration was close to the sum of the precipitation, and changes in the soil water storage were only shown in May. The total precipitation (mm) and runoff (mm) in May were 11.4 mm, the irrigation was 0 mm, the change in soil water storage was 50.78 mm, and the transpiration was 66 mm. The gap between the transpiration and the precipitation became larger in the later months. We ignored bare soil evaporation in the analysis; thus, the shelterbelt transpiration must come from a deep supply. In addition to these factors, groundwater is also an important cause of

Fig. 9. Comparison of the estimated daily stand transpiration in the *Populus simonii* Carr shelterbelt under different soil moisture levels.

Fig. 10. Relationship between the transpiration and the REW (Tr/Tr_0 : the rate of Tr to Tr_0 ; Tr : transpiration at various REW; Tr_0 : transpiration at REW = 1; REW: relative extractable water in the soil).

tree transpiration. In the present study, free water released from the groundwater decline (release) is calculated by the equation $ET = \mu \Delta h$. When μ is 0.05, the Δh of groundwater declines (Shen et al., 1999). In the study area, drip irrigation was most often used, and the groundwater quickly declined in the growing season (April to September). Hence, the transpiration supply by groundwater needs further research.

3.5.2. Response of water needs to stand age

The threshold of tree transpiration in different stand ages is necessary to protect farmland shelterbelts. The transpiration at the water stress point (REW=0.4) was calculated for young trees to mature trees. The farmland shelterbelt considered was built in 1980 with three-year-old *Populus simonii* Carr trees. We defined three periods based on the stand ages: young (0–10 years), immature (10–20 years) and mature (above 20 years). The transpiration results are shown in Figs. 11 and 12. In the young period, the transpiration was 2.77 ± 1.31 , 4.31 ± 1.53 , 4.3 ± 2.3 , 3.01 ± 1.46 and 0.75 ± 0.42 cm for each month from May to September, respectively, and the values were 10.67 ± 1.36 , 16.32 ± 1.55 , 15.94 ± 3.30 , 11.46 ± 2.50 and 2.87 ± 0.75 cm for each month in the immature period. In the mature period, the transpiration was higher than in the other phases: 21.33 ± 3 , 31.98 ± 4.5 , 31.87 ± 4.92 , 22.22 ± 3.46 and 5.78 ± 0.61 cm for each month from May to September. The stand transpiration of the whole growing season was 16.69 ± 5.1 cm/year in the young period, 62.5 ± 8.2 cm/year in the immature period, and 116.7 ± 16 cm/year in the mature. The values were near those experimentally determined in the plot (Shi et al., 2011). When the trees were young, the stand transpiration was small and slowly increased. In the immature trees, it quickly increased as the stand ages rose, and it rarely increased in the mature period. The changes followed a logistic equation increasing with the tree age, $y = 847 - 844/[1 + (x/87.9)^{1.9}]$ ($R^2 = 0.98$, y :

cm/year, x : tree ages). These results can help managers determine the farmland shelterbelt stand transpiration under different levels of water stress and provide details for the transpiration of different stand age farmland shelterbelts.

4. Conclusions

For a farmland shelterbelt of *Populus simonii* Carr trees with high water consumption in a soil with a medium to high water holding capacity, the signal intensity approach for sap flow shows poor reliability for detecting water stress in deficit-irrigated trees. Knowledge of the physiological behaviour of the species must be taken into account for interpreting transpiration records, especially when the atmospheric and soil moisture changes, when recovery irrigations are applied. The model was useful to indicate the water needs, and the severity, the water stress and the species physiology are taken into account. The time course of the water needs showed that the occurrence of water stress in the farmland shelterbelt trees had a large impact on its water consumption because the water consumption increased as the water stress decreased, following

Fig. 11. Monthly transpiration of young, immature and mature growth periods.

Fig. 12. Stand transpiration of growing season from 1980 to 2014.

the equation $y = 1/[1 + e^{-60.67 \times (\text{REW} - 0.402)}]$. The simultaneous use of the model and the tree structure increases the reliability of the assessment of water needs from young to mature. Improving the recognition of plant water consumption has important significance for farmland shelterbelt protection. Future research is needed to confirm these results and analyse the influence of groundwater and the atmosphere.

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