Estimating the transpiration of *Pinus sylvestris* trees: from an individual to a stand scale

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**Abstract:** Mongolian pine (*Pinus sylvestris* L.) is an important tree afforestation species in China. Plants of this species have died on large areas since the early 1990’s. Although this decline has been largely attributed to drought stress, how the water balance (i.e., precipitation – stand transpiration) might limit the survival of Mongolian pines has not been fully addressed. We developed a stand-monthly model to (1) estimate the transpiration capacity of Mongolian pine trees, (2) examine the water balance between precipitation and stand transpiration, and (3) explore the extent to which water supply might limit the survival of Mongolian pines. This model was developed including (1) a sap flow velocity model, (2) the distribution of diameter at breast height (DBH) at an individual scale, and (3) the relationship between sapwood area and DBH. The number of months, where monthly stand transpiration was greater than monthly precipitation, was nearly 39.3% of the total number of months in the early 1990’s, suggesting that water supply might have indeed limited the survival of Mongolian pines. Also, we suggest that the inter-monthly variations in stand transpiration and precipitation may have been a key factor in producing death of large areas of Mongolian pine in the early 1990’s.

**Key words:** Horqin Sandy Land; sap flow; scale; time series analysis; water balance

**Introduction**

Mongolian pine (*Pinus sylvestris* var. *mongolica*) is an important tree species of afforestation in China, especially in sandy areas (Jiao, 1989; Zhu et al., 2003). The area of Mongolian pine plantations used to reach more than 30,000 ha in sandy lands (Kang et al., 2004). However, there has been a decline in the plantations because of several shortcomings (Chang and Zhao, 1990; Jiao, 2001; Liu et al., 2002; Zeng et al., 2002a; Zhu et al., 2003a). They have been attributed to (1) withering of the upper plant parts, (2) low growth rates, and (3) no regeneration from saplings (Chang and Zhao, 1990; Jiao, 2001; Liu et al., 2002; Zeng et al., 2002a; Zhu et al., 2003a). Drought might have been a major cause of these problems, and of producing the death of Mongolian pine on large areas in the early 1990’s (Jiao, 2001; Zhu et al., 2005; Zhu et al., 2006). However, how water balance (i.e., precipitation–stand transpiration) might have limited the survival of Mongolian pine in the early of 1990’s has not been fully studied.

Transpiration is essential to estimate the water requirements of a forest woody plant. This is because 90% of this requirement is needed to satisfy the transpiration process, 99.8% of which is via sap flow (Chen et al., 2009). Knowledge of the water requirements of Mongolian pine forests is also essential for exploring the suitable density of Mongolian pine plantations that will make use of that water in northeastern China, especially in sandy lands (Zhang et al., 2005).

There has been reports on the transpiration strength (Meng et al., 2012) and response to extreme drought (Song et al., 2012) at an individual scale, and water balance at a population scale in Mongolian pine forests (Zeng and Jiang 1995; Han et al., 2012). However, estimates of transpiration in these forests have not been fully explored. This has been
mainly due to: (1) a spatial scaling-up obstacle: transpiration can be measured accurately on individual plants; however, scaling up to a Mongolian pine forest is very difficult as it is not possible to measure each individual in the whole Mongolian pine forest, and (2) a temporal scaling-up obstacle: transpiration data can be accurately obtained with sap flow measurements (Granier et al., 2006). However, these data directly reflect the current but not the past or future status. Therefore, information on sap flow is not accurately known in the past time, when it was not measured.

Quantitative models are expected to be an appropriate method to estimate transpiration capacity. A series of quantitative models have been developed recently. For example, Ford et al. (2004) predicted the total stem flow in Pinus taeda trees using a sap flow model. However, obstacles for scaling-up in this subject have not been completely overcome. To do this, the distribution of individuals has to be included. Also, the connection between sap flow velocity and various variables (which is accumulated in historical data) has to be established to overcome obstacles for scaling-up in a temporal scale. Therefore, a quantitative model to estimate a Mongolian pine forest transpiration has to include the distribution of individuals according to its diameter in breast height (DBH), and a relationship between sap flow velocity and environmental variables.

We developed a quantitative model including (1) a sap flow velocity model, (2) the distribution of DBH at an individual scale, and (3) the relationship between sapwood area and DBH to estimate the transpiration capacity of Mongolian pine trees on a sandy land soil. The objectives of this study were to (1) estimate the transpiration capacity of Mongolian pine trees at a stand scale, (2) examine the water balance between precipitation and stand transpiration, and (3) explore the extent to which water supply might limit survival of Mongolian pines.

**Materials and Methods**

**Model development**

Our model was based on four assumptions: (1) the Mongolian pine forest has individuals with different DBH; (2) the sapwood area is equal on individuals that have the same DBH, (3) individuals with the same sapwood area have the same sap flow velocity, and (4) the transpiration capacity is the definite integrals of the products between sap flow velocity and sapwood area.

**Development of a sap flow velocity (SFV) model**

Photosynthetically active radiation (PAR), and vapor pressure deficit (VPD) are closely related to sap flow velocity (Hinckley et al., 1994; O’Brien et al., 2004; Wu et al., 2010). Thereafter, we constructed a sap flow velocity model using PAR and VPD as independent variables.

We found that SFV, PAR and VPD did not correlate in a perfect linear manner after carefully investigating their relationships. To improve a linear relationship between them, we took their natural logarithm values, which is a common practice. Since there were many zeroes in the SFV data, we added 1 to those data and thereafter took their natural logarithm. This procedure did not change the essential mathematical structure among these variables. Hence, the SFV model was expressed as:

$$\ln \text{SFV}_t = \alpha_0 + \alpha_1 \ln \text{SFV}_{t-1} + \alpha_2 \ln \text{VPD}_t + \alpha_3 \ln \text{VPD}_{t-1} + \alpha_4 \ln \text{PAR}_t + \alpha_5 \ln \text{PAR}_{t-1} + \varepsilon_t$$

where $\alpha_i = 0, \ldots, 5$ are constants, and $\varepsilon_t$ is the random noise at time $t$. Here we included lag times for SFV, VPD and PAR, which can partially contribute to explain the underlying dynamic structure of sap flow velocities.

Photosynthetically active radiation (PAR) was calculated following (Zhou et al., 1984) as

$$\text{PAR} = \eta \cdot \frac{Q}{\eta}$$

where $Q$ is total radiation, and $\eta$ is the ratio of PAR and Q.

Vapor pressure deficit (VPD) was calculated following (Cao et al., 2013):

$$\text{VPD} = a_1 \cdot \exp \left( \frac{a_2}{T} \right) \cdot (1 - RH)$$

where $a_1$, $a_2$, and $a_3$ are constants; $T$ is air temperature (°C), and RH is the canopy air relative humidity (i.e., %).
Distribution of DBH at an individual scale

The distribution of individual DBH can be described with the inverse-Weibull distribution function (Zeng and Jiang, 1997). We have,

\[
f(x) = \frac{c}{b} \left(\frac{a-x}{b}\right)^{c-1} \cdot \exp\left(-\left(\frac{a-x}{b}\right)^c\right) \quad (a \geq 0, b > 0, c > 0)
\]

According to a previous study of Zeng and Jiang (1997), \(a, b, c\) are as follows:

\[
a = 4.011 + 0.5063 \cdot A + \frac{2391.3130}{N}
\]

\[
b = -14.9199 + 0.1967 \cdot A + 2.3162 \cdot \ln(N)
\]

\[
c = 3.3137 + 0.0176 \cdot A - \frac{1114.1640}{N}
\]

where \(A\) is age of any Mongolian pine, and \(N\) is population density of Mongolian pines.

The relationship between sapwood area and DBH

The relationship between the sapwood area \((A_{si})\) and the DBH was described following the allometric equation of Vertessy et al. (1995):

\[
A_{si} = B_0 \cdot DBH^{B_1}
\]

where \(B_0\) and \(B_1\) are species-specific coefficients determined by nonlinear regression techniques. The total sapwood area \((TAs)\) in the whole stand was the sum of the sapwood area of all individuals, which were divided into a series of classes according to their DBH. Within each DBH-class, the sapwood area was determined taking into account the number of individuals \((D_i)\) in that class; we had assumed that the sapwood area was similar among individuals pertaining to the same DBH class. Thereafter,

\[
TAs = \sum_{i=1}^{n} D_i \cdot A_{si}
\]

where \(n\) is the number of DBH classes.

Calculation of stand transpiration

Stand transpiration \((E_s)\) is the sum of transpiration occurred within each month of the growing season \((E_{si})\). \(E_{si}\) is approximately equal to the product between the sap flow velocity and the total sapwood area for any given month. We have,

\[
E_s = \int_{d=0}^{D} \int_{h=0}^{H} E_{si} \, dh \, dd = \int_{d=0}^{D} \int_{h=0}^{H} SFV_i \cdot TAs_i \, dh \, dd
\]

where \(D\) is the number of days per month during the growing season, and \(H\) is the number of hours per day when sap flow occurred.

Model parameters and calibration

The data used to estimate the parameters and thereafter calibrate the model were obtained in the Zhanggutai region \((42^\circ35'-42^\circ47'N, 122^\circ23'-122^\circ40'E, \text{altitude} 226.5 \text{m})\), in the southern part of the Horqin Sandy Land, where Mongolian pine was planted in the 1950’s (Jiao, 2001). This region has a typical semi-arid climate with a mean annual (1) precipitation of 475.7 mm; more than 60% of this precipitation falls

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tr>
<td><strong>Value, unit and description of the model parameters</strong></td>
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<tr>
<td><strong>Parameters</strong></td>
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<tr>
<td>a1</td>
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<td>a2</td>
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<tr>
<td>A</td>
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<tr>
<td>D</td>
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</table>
during summer (from June to August); (2) pan evaporation of 1400 mm, and (3) temperature of 5.7 °C (Zheng et al., 2012). The mean annual wind speed ranges from 4.5 to 5.0 m/s (Yu et al., 2008). The soil develops from sandy parent material, and its pH is about 6.7. The nutrient content (N and P) of the surface soil is very low (Hu et al., 2008).

The meteorological and radiation data to develop the sap flow velocity model were obtained from the China Meteorological Data Sharing Service System in 2010 and 2011. During these years, flow velocity was also measured using the thermal dissipation method (Han et al., 2013). We calibrated our sap flow velocity model using transpiration data from a Mongolian pine stand in 1984 (Jiao, 1985); Mongolian pines at this stand were 25-year-old, and their density was 1250 individuals per hectare.

Values used for our parameters are listed in Table 1. Mongolian pines were initially planted in 1955. In this study, the density of Mongolian pines was considered as 1250 individuals per hectare.

In 2010 and 2011, we obtained 24 monthly data of sap flow velocity. Within each year, it was positive from April through October (Fig. 1). However, values in the other months were very small (Fig. 1). The fact that data in 2010 were quite different from those in 2011 (Fig. 1) would introduce some difficulties in our model fitting, and the fitted model will lack predicting ability. It is obvious that (1) sample size was small, and (2) we preferred a simple model to depict the relation among SFV, VPD and PAR. Estimates of the intercepts and slopes are provided for the relationships which follow. We found that the ln SFV was significantly linearly related to ln SFV (ln SFV = -6.556 + 0.620 ln SFV + ε; r² = 0.4226; P = 0.012) (Fig. 2). However, there was no clear relationship between the natural logarithms of SFV and VPD (ln SFV = 1.4831 + 0.0876 ln VPD + ε; r² = 0.0067;

### Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Estimates</th>
<th>Standard Errors</th>
<th>t values</th>
<th>P value</th>
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</thead>
<tbody>
<tr>
<td>α0</td>
<td>-6.556</td>
<td>1.359</td>
<td>-4.82</td>
<td>0.0009</td>
</tr>
<tr>
<td>α1</td>
<td>0.620</td>
<td>0.086</td>
<td>7.24</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>α2</td>
<td>-0.444</td>
<td>0.130</td>
<td>-3.43</td>
<td>0.0076</td>
</tr>
<tr>
<td>α3</td>
<td>1.032</td>
<td>0.194</td>
<td>5.30</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
Nevertheless, relationships between (1) the ln SFVt versus the ln VPD_{t-1} (ln SFV_t = 1.3897 - 0.1073 \ln VPD_{t-1} + \varepsilon_t) and (2) the ln SFVt versus the ln PARt (ln SFV_t = -2.4470 + 0.5792 \ln PAR_t + \varepsilon_t) were significant (p<0.05) when all independent variables were included in the linear model with stepwise regression (Fig. 2). The relationship between ln SFVt and ln PAR_{t-1} was also not significant at p<0.05 (data not shown).

Hence, the model we used to depict the data in years 2010 and 2011 was

\[ \ln SFV_t = \alpha_0 + \alpha_1 \ln SFV_{t-1} + \alpha_2 \ln VPD_{t-1} + \alpha_3 \ln PAR_t + \varepsilon_t \]

The data were analyzed with SAS to fit the model above. The estimation results are shown in Table 2. The parameter estimates were all significant at P<0.05. The r^2 and the adjusted r^2 were 0.8781 and 0.8374, respectively. Since the data were quite different between 2010 and 2011, an adjusted r^2 of 0.8374 is very satisfying. It means, our model can explain 83% of the relationship among SFV, VPD and PAR.

Since the SFV were quite different in 2010 and 2011 (Fig. 1), it means that if we applied our fitted model to predict SFV, results would be unsatisfying. However, it was not the case. We predicted SFV from transpiration data of a Mongolian pine stand (Jiao, 1985) during May to September in 1984, and compared these predictions with our observations (Table 3). The prediction in May can be regarded as an outlier. For the other predictions, 66.4% could be explained from the measured data, with a standard deviation of 8.95%. These results can be considered relatively good since we were able to predict SFV with a very simple model at a low cost, because of the expenses for measuring VPD and PAR were relatively cheap.

### TABLE 3

**Prediction of SFV from transpiration data of a Mongolian pine stand during May to September in 1984. Model results are compared with measured data during those months in that year**

<table>
<thead>
<tr>
<th>Month</th>
<th>Measured data</th>
<th>Model result</th>
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<tbody>
<tr>
<td>May</td>
<td>0.666159</td>
<td>1.380602</td>
</tr>
<tr>
<td>June</td>
<td>1.467649</td>
<td>1.164329</td>
</tr>
<tr>
<td>July</td>
<td>2.176912</td>
<td>1.283780</td>
</tr>
<tr>
<td>August</td>
<td>1.879198</td>
<td>1.174473</td>
</tr>
<tr>
<td>September</td>
<td>1.977714</td>
<td>1.280388</td>
</tr>
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Results

Estimate of the distribution of pine individuals on DBH classes and total sapwood area in the early 1990's

Individuals of *P. sylvestris* distributed from 4-5 cm to 21-22 cm in DBH in the early 1990's (Table 4). The greatest number of individuals (196, 195, 191 and 186 from 1990 to
1993, respectively) pertained to a DBH of 13-14 cm (Table 4). The total sapwood area within the study population of Mongolian pine increased as the population age also increased (Table 4).

**Estimate of the sap flow velocity and stand transpiration in the early 1990's**

Both study variables changed monthly during the growing season in 1991, 1992, 1993 and 1994 (Table 5). Maximum values of sap flow velocity and stand transpiration occurred in August 1990, while minimum values for these parameters were found in October 1991 (Table 5). Total stand transpiration values were 366.6 mm (1990), 115.1 mm (1991), 254.8 mm (1992) and 255.5 mm (1993) (Table 5).

**Precipitation during the growing seasons of the early 1990's**

Total precipitation during the growing season was 527.7 mm, 609.3 mm, 454.5 mm, and 373.0 mm in 1990, 1991, 1992 and 1993, respectively (Table 5). Precipitation changed monthly during the whole study growing seasons (i.e., 1990-1993, Table 5). Most precipitation occurred from June to August during each of the study years (Table 5). The ratio of highest/lowest values for precipitation was 34.6 in 1990, 134.0 in 1991, 27.6 in 1992, and 32.0 in 1993 (Table 5).

**Comparison between precipitation and stand transpiration**

The difference between precipitation and stand transpiration within each study month during 1990-1993 represents the water balance in those months at the study site. Negative water balances were obtained in May and October 1990; April and May 1991; April, August and October 1992, and April, May, September and October 1993 (Table 5, Fig. 3). The number of negative values occurred in more than 39% of the total number of water balance comparisons during the study periods from 1990 to 1993 (Table 5, Fig. 3). However, total precipitation was always greater than total stand transpiration in all four years of study (Table 5).

**Discussion**

In this study, we constructed a model of stand transpiration of Mongolian pine for estimating its water requirements using micrometeorological data (e.g., PAR and VPD) and

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<tbody>
<tr>
<td>Sapwood area (cm²)</td>
<td>Sapwood area (cm²)</td>
<td>Sapwood area (cm²)</td>
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<td>Sapwood area (cm²)</td>
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<tr>
<td>The number of individuals</td>
<td>The number of individuals</td>
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<tr>
<td>5-6</td>
<td>2</td>
<td>49</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>6-7</td>
<td>6</td>
<td>202</td>
<td>5</td>
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<td>4901</td>
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<td>20147</td>
</tr>
<tr>
<td>17-18</td>
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<td>10275</td>
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<td>961</td>
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<tr>
<td>21-22</td>
<td>-</td>
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**Total** | - | 170437 | - | 178292 | - | 185841 | - | 192954
experimental data of sap flow velocity. Firstly, a time lag model was constructed to predict sap flow velocity at a month scale. Secondly, sapwood area was estimated using the spatial distribution of individuals in various DBH classes within the whole pine population. The relationship between sapwood area and DBH had been fully studied in various tree species (Vertessy et al., 1995). Finally, stand transpiration was estimated per month during the study growing seasons using the integral of the product between the sap flow velocity and the total sapwood area at the time of appearance of sap flow.

The model presented in this paper offers advantages for scaling-up obstacles in previous knowledge of spatial and temporal aspects. Theoretically, individual transpiration can be accurately measured with the thermal probe technique (Granier et al., 2006). In fact, the thermal probe technique is only used on typical individuals, which represent a small proportion of the whole population. Therefore, it is difficult to evaluate transpiration at a population scale directly, which is a spatial obstacle for assessing transpiration. We provided an individual distribution of DBH and sapwood area within a Mongolian pine population to connect typical individuals which transpiration was accurately known with other individuals in the same population, being the key factor to overcome the spatial obstacle. More importantly, our model is suitable for circumstances where sap flow is vital for research objectives, and past sap flow data have not been measured. In our model, past data of sap flow velocity were calculated from micrometeorological data, and recent experimental data of sap flow velocity. Even more, future data of sap flow velocity can be predicted from our model, which is essential for evaluating the water requirements of plants in the future, and for assessing effects of climate change on plant populations.

Our model is in a spatial-temporal scale, which is different from previous studies. To date, daytime models and stand-level models had been developed. For example, Ford et al. (2004) reported a daytime model to predict the total stem flow in Pinus taeda trees. Wang et al. (2010) developed a stand-level model to estimate water use of black locust plantations. However, models scaling up both in spatial-temporal aspects, i.e. from individuals to a stand scale (spatial scale), and from a daily- to a month-scale (temporal scale) are lacking. Monthly micrometeorological data (i.e., PAR, VPD) were used in this study, determining that our model was a month-level model in a temporal scale. We suggest that our model can be expanded from a daytime to an annual-scale, because of micrometeorological data (i.e., PAR, VPD) can be provided from a daily to an annual basis.

According to our model, photosynthetically active radiation and vapor pressure deficit showed a great influence on sap flow velocity. There was a strong negative correlation between sap flow velocity and vapor pressure deficit (Table 2), which is consistent with the results of Pataki et al. (2000). These authors reported that Pinus species maintained high transpiration at low vapor pressure deficit. Meanwhile, sap flow velocity showed a positive relationship with photosynthetically active radiation, which agrees with results of O’Brien et al. (2004) and Zhu et al. (2010).

Soil water content was not included in our model because of two reasons. Firstly, soil water content changes rapidly during a day in sand dune ecosystems (Zhang et al., 2004)
al., 2005). As a result, it is difficult to obtain a value that represents a soil water content during a month. Secondly, soil water content has been reported to be relatively a minor factor influencing sap flow velocity in Pinus trees (Ford et al., 2004).

In this study, photosynthetically active radiation was calculated as a constant proportion of total radiation. This constant value could simplify the model as total radiation is relatively easy to obtain from micrometeorological stations. Recently, it was reported that the proportion of photosynthetically active radiation from total radiation was not always a constant, but a variable controlled by astronomical and meteorological factors (Dong et al., 2011). For example, the ratio of photosynthetically active radiation to total radiation was considered to be a function of the atmospheric integral transparency coefficient and the sine of solar height (Mottus et al., 2001). A more accurate method to estimate this ratio should be explored in the future.

During the growing seasons of the early 1990’s, nearly 39.3% of the total number of months in 1990-1993 showed that monthly stand transpiration was greater than monthly precipitation. This suggests that periods when there was a negative water balance might have contributed to limit the survival of Mongolian pines. Zhao (1992) reported that Mongolian pine showed a lower stem water content in the upper, windward slopes than in the sand dunes, where water supply was richer. Drought is considered as a major factor in the development of forest decline (Freer-Smith, 1998).

In conclusion, and in agreement with the results of Kang et al. (2005) in Mongolian pine, we suggest that the inter-monthly variations in stand transpiration and precipitation, but not water supply from annual precipitation, were the key factors in producing death of large areas of Mongolian pine in the early 1990’s. Therefore, regulating allocation of water supply among months is vital for the sustainable development of Mongolian pine populations. Furthermore, the stand-monthly model that we provided could be useful to estimate stand transpiration of Mongolian pines in the past and to predict stand transpiration of Mongolian pines in the future. In addition, this model might be applied to other tree and shrub species.

Acknowledgements

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