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CANOPY TRANSPIRATION RESPONSE TO ENVIRONMENTAL VARIATIONS IN *PLATYCLADUS ORIENTALIS*: PROPERTIES AND MODELLING

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Abstract

Regrowth of tall, dense forests consumes more water, with the result that catchment yield may decline and even soil desiccation occurred especially in the semi-arid Loess Plateau of China. In this study, meteorological measurements combined with sap flow techniques provided a low-cost option to study the rates of water uptake by individual trees of *Platycladus orientalis* response to environmental factors on a continuous basis. A series of environmental control functions: vapour pressure deficit, solar radiation and air temperature were used to characterize canopy transpiration (E_c). A Jarvis-type model, modified to directly estimate the E_c rather than canopy conductance, explained 89% of the variation observed in E_c. Cross validation shows that this model provided good predictions of canopy transpiration for *P. orientalis*. Such a methodology offers a reasonable estimation of water use in the determination of water balance for land water resources planning, vegetation management and impact assessments of rehabilitation.

Introduction

Tree planting and afforestation has been a key project of soil and water conservations for ecological environment managements on the Loess Plateau of China. Some researchers have reported that regrowth of tall, dense forests consumes more water, with the result that catchment yield may decline and even soil desiccation occurred (Cornish & Vertessy, 2001; Roberts *et al.*, 2001; Vertessy *et al.*, 2001; Li *et al.*, 2008; Macfarlane *et al.*, 2010). So how to evaluate water use and requirements as well as the effects of increasing artificial forest cultivation on the hydrological cycle becomes a key issue for research. As is an important component of the water balance in forests, transpiration of whole forests canopies has been experimentally measured in a wide range of environments, from boreal to tropical, using different methodologies. Sap flow technique based on thermal dissipation probe (TDP) method has been commonly used to estimate transpiration from different species or a single component of mixed vegetation (Granier, 1996; Lu *et al.*, 2003; Rana *et al.*, 2005; Oguntunde *et al.*, 2007).

Theoretically, for a well-coupled forest, where transpiration is controlled by stomatal aperture in response to meteorological changes, E_c can be calculated from g_c and vapour pressure deficit (VPD) since $E_c=g_cVPD$ (Whitehead, 1998; Whitley *et al.*, 2008). If we assume a negligible effect of aerodynamic conductance on transpiration (that is, aerodynamic conductance is much greater than g_c), then we can express g_c as a function of its driving environmental variables (Jarvis, 1976; Stewart,1988; Wright *et al.*, 1995; Han *et al.,* 2011): $g_c=k_1\ f(VPD)\ f(R_s)\ f(T_a)$, where k_1 represent maximum stomatal conductance.

This Jarvis-type model for g_c requires only three environmental variables and short-term measurements of sap flow and is much simpler to fit (Harris *et al.*, 2004; Bernier *et al.*, 2006). In this study, we used a modified Jarvis-type model combined with sap flow method to directly model tree canopy transpiration (E_c) specifically rather than inverting the Penman-Monteith (P-M) equation to derive measurements of canopy conductance (g_c) and then using P-M again to estimate E_c from g_c as has been applied in the past (Lu *et al.*, 2003; Oguntunde *et al.*, 2007). The aim of this study is to (1) investigated how variations in the driving variables impact E_c, (2) develop a model in E_c for *P. orientalis* which has been widely planted in China, and (3) compare the predicted E_c values (modelled E_c) using the modified Jarvis-type model (see below), with the observed sap flow data (observed E_c).

Materials and Methods

Study site: The study was conducted in a *P. orientalis* plantation at Tuqiaogou watershed of Fangshan County in Shanxi province of China (37°36′ N, 110°02′ E, elevation 1200 m). The plot is characterized by continental monsoon climate, and mean annual temperature (1975–1992) was 7.3°C and annual rainfall averaged 416mm, concentrated in the June–September period with the soil texture within the plot as generally medium loam. The *P. orientalis* trees (spacing of 1.5 m×4 m giving a density of 1666 trees ha^{-1}) established in 1993 from four–year–old bare root seedling has an average height of 6.5m and average trunk diameter of 6.2 cm. Basal area and diameter at breast height (DBH) of all trees were measured in five replicate 20 m×20 m plots.

Environmental variables: Solar radiation (R_s), air temperature (T_a), relative humidity (RH), wind speed (u) and rainfall were recorded as 15 minutes averages with an automatic weather station installed about 200 m away from the plot. Volumetric soil water content (%) was regularly measured by oven drying method by 10 cm depth intervals down to 100cm.

Water use by individual trees: The water transpired by individual trees was measured by sap flow technique with the TDP method of Granier (1987). Five representative trees were selected to cover the range size distribution at the stand (mean tree height 6.5±0.2 m and sapwood area

44.1±6.17 cm^2). Two cylindrical sensor probes about 2 mm in diameter, each containing a copper-constantan thermocouple, were inserted in the sapwood of the tree trunks with one probe about 10 cm above the other. The probes were installed in the trunk at a point halfway between the soil surface and the lowest actively growing branch, then the trunk was shielded with aluminium foil, to minimize the effect of thermal fluctuation on the measurements (Lu *et al.*, 2004). Transpiration (E_c, mm h^{-1}) of an individual tree was calculated as:

$$E_c = J_s \frac{A_{sw}}{A_c}$$

where J_s is the whole tree sap flux density (cm s^{-1}), A_{sw} is the sapwood area (cm^2) and A_c is the projected canopy area (cm^2). Sap flow measurements, sampled at 15-min intervals in step with the weather data, were made between 30 June [Day of Year (DOY) 181] and 16 (DOY 228) August 2009.

Modeling: Canopy transpiration was modeled directly (E_c^{mod}, mm h^{-1}) from functions of vapour pressure deficit (*VPD*, kPa), R_s and T_a (Jarvis, 1976; Stewart, 1988; Whitley *et al.*, 2009):

$$E_c^{\mathrm{mod}} = E_{c\max} f(VPD) f(T_a) f(R_s) \qquad \text{............(1)}$$

$$f(VPD) = k_1 VPD \exp(-k_2 VPD) \qquad \text{............(2)}$$

$$f(T_a) = \exp\{-k_3 (T_a - T_{opt})^2\} \qquad \text{............(3)}$$

$$f(R_s) = \frac{R_s}{1000} \frac{1000 + k_4}{R_s + k_4} \qquad \text{............(4)}$$

where $E_{c\max}$ is a theoretical maximum canopy transpiration under optimal environmental and leaf conditions. T_{opt} is the optimum temperature limit to transpiration. The function forms (f, $0 \le f \le 1$) for this study were based on those of Stewart (1988), Wright *et al.*, (1995) and Niu *et al.*, (2005). Parameters k_1–k_4 were optimized using the Levenberg-Marquart algorithm (Marquardt, 1963).

Root mean square error (*RMSE*) was used to weighted the deviation between the *i*th experimental value (y_i) and the *i*th predicted value ($\hat{y}_i$) of E_c. Where we express the *RMSE* as:

$$RMSE = \left[\frac{1}{n} \sum (y_i - \hat{y}_i)^2 \right]^{1/2} \qquad \text{............(5)}$$

Daily measurements of sap flow were filtered to exclude hours when solar radiation was zero (night) within Days with rainfall events were also excluded to eliminate wet-canopy conditions. To avoid circularity and to validate the selected model, the whole data was divided into two groups, covering the odd days (Database A) and even days (Database B) of measurement respectively. The selected model was then fitted separately to each of the two groups and cross-validated on each other. This type of validation procedure has been described as robust and consistent (Stewart, 1988; Lu *et al.*, 2003).

Results and Discussion

Soil moisture: As was shown in Fig. 1, average volumetric soil moisture in the trial during the sap flow measurements ranged from of 8.35% to 21.56%, and the SWC in root zone averaged 16.98% (the soil depth from 40cm to 80cm). Drought stress studies conducted by He *et al.* (2003) and Tian *et al.*, (2005) showed that the suitable soil moisture for *P. orientalis* growing ranged from 9.88% to 13.21%, while the soil moisture to maintain the maximum of leaf transpiration was between 16% and 19%. This suggests that tree water use during this period was not limited by soil water content. Bauerle *et al.*, (2002) noted that when soil water was extractable, measured and modelled transpiration was mainly controlled by atmospheric demand.

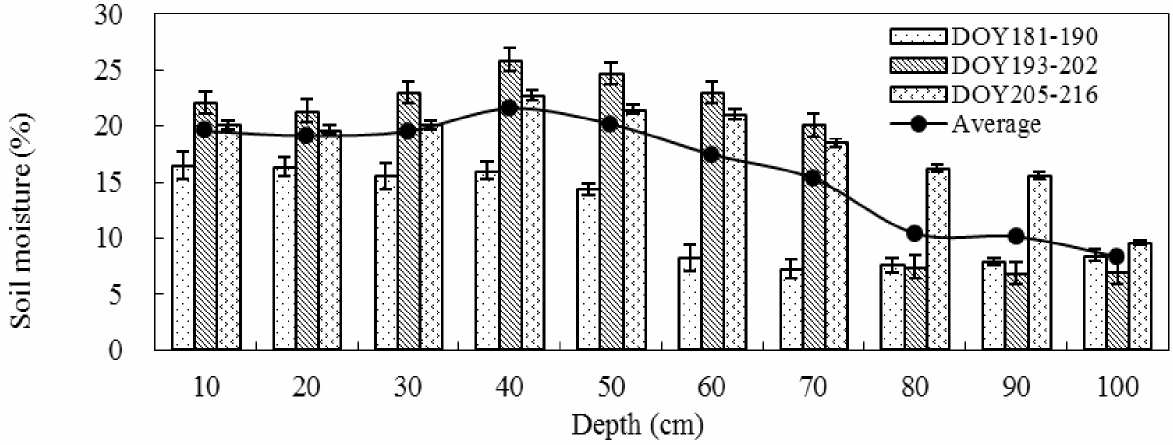

Fig. 1. Variation of the volumetric soil moisture in trial

Canopy transpiration: Normalized canopy transpiration (E_c / E_{cmax}) was plotted against the functions of R_s, *VPD* and T_a in Fig. 2. The functional forms of the curves described by Eqs.2~4 fitted to the experimental data respectively. The boundary curves showed a hyperbolic increase from zero to a maximum in E_c with increasing R_s

(Fig. 2A). At low levels of radiation, energy supply limits evaporation, but further increase in R_s, leaf stoma closed to avoid excessive water loss and prevent leaf water potential from falling to a dangerous level (Tyree & Sperry, 1988). Similar forms to these response were noted by Oguntunde & van de Giesen (2005), Morris *et al.*, (2006) and Whitley *et al.*, (2008). Canopy transpiration also exhibits a linear increase response to the increasing vapour pressure deficit (*VPD*) at lower values (*VPD* < 1.2 kPa) (Fig. 2B). For the higher values of *VPD* (1.2-3.0kPa), water transpired by individual trees showed a minimal decline as *VPD* increased. This follows from the argument that stomatal closure would more than offset the increased evaporative demand (Jarvis, 1980; Pataki & Oren, 2000; Zahid *et al.*, 2010). As results shown in Fig. 2C, air temperature seemed to be reached near the threshold value of 25~27°C so that further increase in T_a led to corresponding decrease in canopy transpiration. These trends may further confirm that high sensitivity of *P. orientalis* leaves to changing atmospheric variations and hence the regulation of its transpiration at the canopy level.

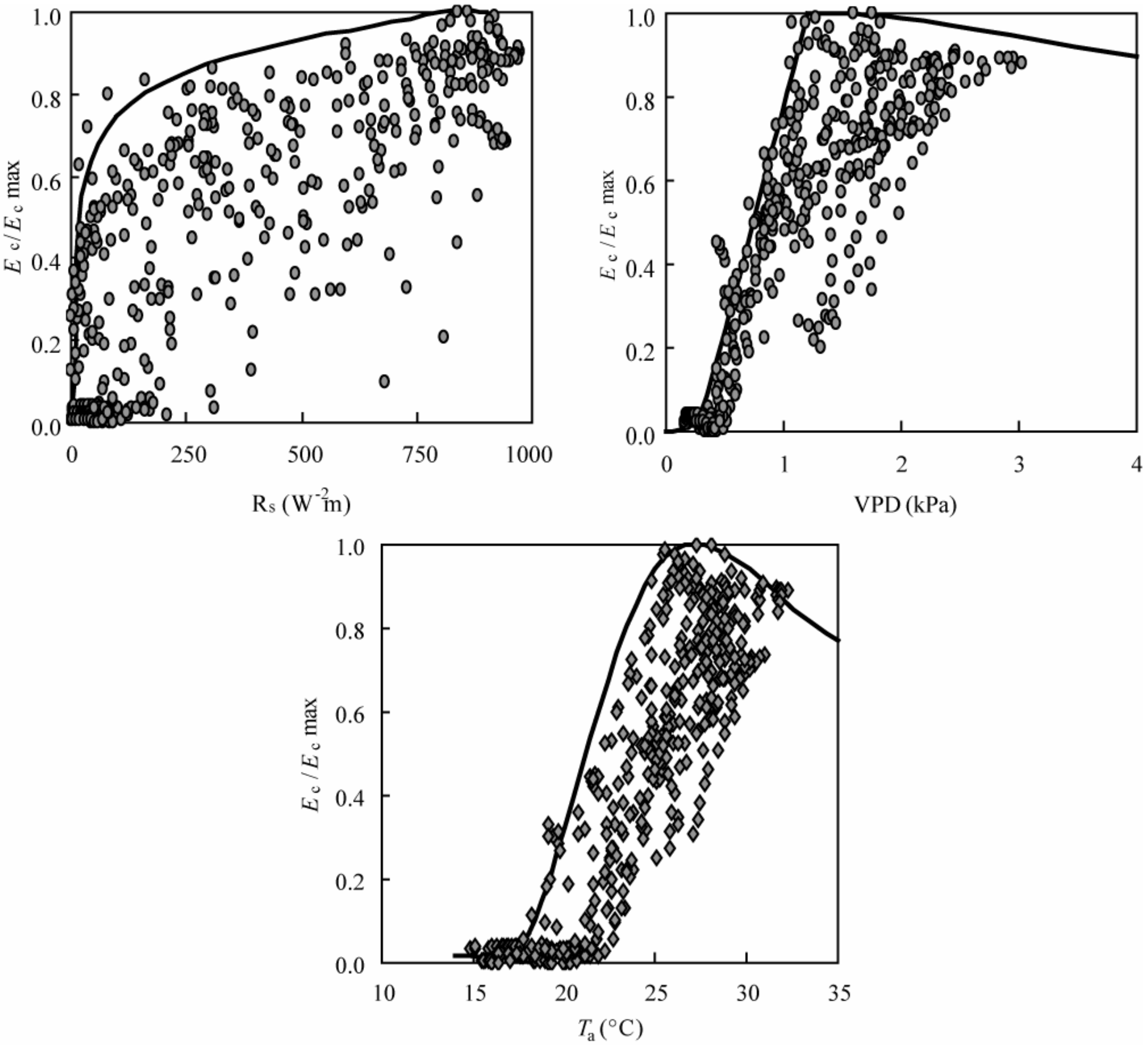

Fig. 2. Normalised canopy transpiration response to (A) solar radiation (R_s), (B) vapour pressure deficit (*VPD*) and (C) air temperature (T_a).

Modelled canopy transpiration: Table 1 shows the optimised parameters and their standard errors for the modified Jarvis-type model. The three stamatal control functions of R_s, *VPD* and T_a explained above 89% of variation in E_c. The predicted maximal value for E_c ranging from 0.074 mm h^{-1} to 0.097 mm h^{-1} is very close to but under the observed maximal value of 0.11 mm h^{-1}. These values were found to be low compared to 0.24 mm h^{-1} in citrus (Oguntunde *et al.*, 2007) and 0.13 mm h^{-1} in *Eucommia ulmoides* (Li *et al.*, 2008). The optimum temperature for *P. orientalis* transpiration was about 26.9~28.8°C compared to 28.5 °C (Wright *et al.*, 1995), and 25.5°C (Oguntunde *et al.*, 2007). Predicted E_c followed closely those measured on rainless days though the model may either slightly under-predict or over-estimate midday rates of transpiration (Fig. 3). This could be considered acceptable, as the predicted values were also within the threshold of standard error in observed E_c. The weighted mean for modelled water use by individual trees was 0.76mm d^{-1} and for measured one it was 0.78mm d^{-1}. This may be connected to the fact that *P. orientalis* presents a very high resistance to flow compared to several other species.

Table 1. Parameters from the optimization of the modified Jarvis model predicting canopy transpiration for *P. orientalis* for a weighted nonlinear least squares regime.

Parameter		R^2	*RMSE*	E_{cmax}	k_1	k_2	k_3	k_4	T_{opt}
Database A	value	0.920	0.010	0.097	1.037	0.342	0.017	36.133	26.324
(n=229)	S.E.			0.000	0.000	0.032	0.002	4.685	0.268
Database B	value	0.889	0.012	0.074	1.592	0.442	0.009	23.100	28.759
(n=219)	S.E.			0.000	0.000	0.060	0.002	4.026	0.867
All data	value	0.898	0.011	0.092	1.065	0.340	0.011	28.874	26.948
(n=448)	S.E.			0.000	0.000	0.050	0.001	3.114	0.347

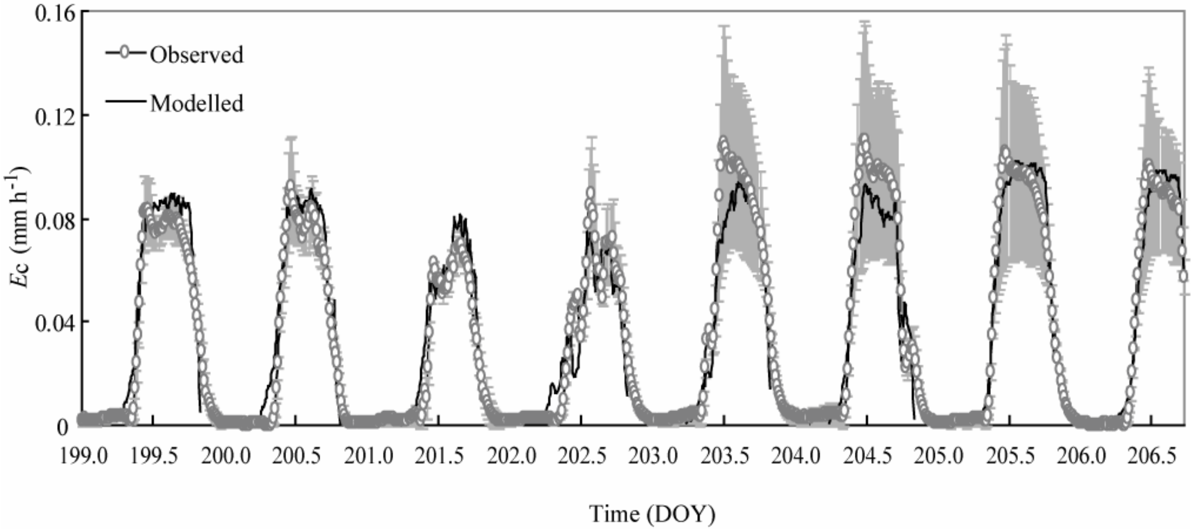

Fig. 3. Diurnal courses of modelled canopy transpiration compared with observed data (vertical bars are ±S.E. of the mean).

Database A and B were analyzed by cross-validation which has been verified to be a more stringent test of the model than selecting random subsets (Lu *et al.*, 2003; Han *et al.,* 2011). The regression in Fig. 4 showed good agreements (R^2>0.86, P<0.001) between predicted and observed E_c for the two subsets. Comparing with the trend line of each dataset, some scatted points were mostly on one side of the line but not noticeable further away from it. This because the *VPD* and R_s fluctuated dramatically especially when clouds increased suddenly in certain time of day.

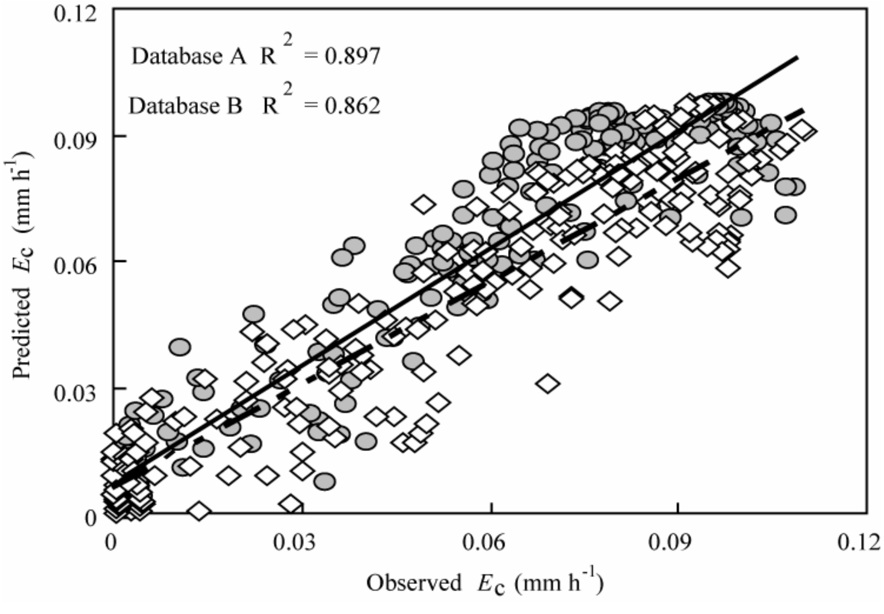

Fig. 4. Cross validation between predicted and observed canopy transpiration in Database A (solid line and closed grey symbols) and B (dotted line with open symbols).

Conclusion

This study characterizes the impacts of main environmental variables on canopy water flux of *P. orientalis* and a modified Jarvis-type model based on a series functions of meterological factors has been used to directly estimate water transpired by individual trees. Functional forms of the modified Jarvis-type model is found suitable for predicting the canopy transpiration to variation in vapour pressure deficit, solar radiation and air temperature. Though there are some uncertainty present in the measurements, this parameterized model explains about 89% of the variation observed in E_c. Cross validation shows that this model works well with an acceptable level of error between observed and modeled values.

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