Capacity of Stem Water Conductivity for Two Eucalyptus (*Eucalyptus urophylla*) Plantations in South China

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ABSTRACT The sap flux density (*SFD*) was used as a measure of water capacity through stems of eucalyptus in this paper. It was found that daily *SFD* increased with daily vapor pressure deficit (*VPD*) in nonlinear regression $Y = AX^3 + BX^2 + CX + D$ ($R^2 = 0.702\,1$, $n = 135$, $p = 0.01$) at both sites (Hetou and Jijia) in the Leizhou Peninsula, Guangdong Province, China, where Y was daily *SFD*, X was mean daily *VPD*, A, B, C, D were constants. But extremely high *VPD* might limit stem water conductivity. The environmental factors, such as air vapor pressure deficit (*VPD*), solar radiation (*RAD*), etc., were the main determinants of *SFD* for *E. urophylla* plantations. The upper threshold of diurnal *SFD* was 51.55–55.65 $mL \cdot cm^{-2} \cdot h^{-1}$ under the selected extremely high environmental conditions.

KEY WORDS south China, sap flux density (*SFD*), eucalyptus plantation, water conductivity

1 Introduction

Eucalyptus is one of the most important commercial plantation and pioneer tree species in successful ecological restoration of degraded lands in south China (Yu 1994, 1995, Zhou *et al.* 2001). But concerns over excessive water consumption by eucalyptus plantations in China and elsewhere also arose (Kallarackal 1992).

Systematic attention has long been devoted to the study of transpiration in many scientific disciplines: plant physiology, hydrology, ecology, meteorology, and so on (Pražák *et al.* 1994, Daudet *et al.* 1999, Granier *et al.* 2000, Montero *et al.* 2001, Fredrik and Anders 2002). Tree transpiration is a major pathway for both water and energy leaving the forest ecosystem (Fredrik and Anders 2002). The capacity of transferring water from the soil to the leaves is regarded as a limiting factor, and the plant is considered to be capable of regulating the water output by transpiration depending on the water content in the plant body (Pražák *et al.* 1994). Estimation of stand transpiration requires the analysis of among-tree variation of sap flow (Köstner 1996), which is commonly scaled up to stand level and is considered to represent transpiration (Fredrik and Anders 2002). The use of sap flow measurements allows the analysis of the variability in tree transpiration, and to quantify the contribution of different crown status to the total water flux (Granier *et al.* 2000).

Recent findings suggested that sap flow or transpiration of trees might be closely linked to plant hydraulic variables and environmental factors, especially soil types (Du and Yang 1995, Cienciala *et al.* 1997). There is growing evidence of a higher frequency of climatic extremes as a result of global climatic change (Karl *et al.* 1995). Even in the regions without climatic extremes, South China for example, the annual variability of precipitation may be high and the rainfall distribution during the growing season very uneven. This may affect both growth and stability of a forest ecosystem.

It indicated that the climatic factors had great impact on water fluxes (Devitt *et al.* 1997, Lan 1997, Tenhunen *et al.* 1998, Granier *et al.* 2000, Welander and Ottosson 2000, Oltchev *et al.* 2002). The sap flow fluctuates acutely with a large variability of environmental factors. It is very theoretically important to study the upper and lower thresholds of sap flow, which are mainly determined by the characteristics and ages of species, under the extreme environmental stresses. While in the field experiments, the extreme environments are often time-limited, i.e. the extreme conditions only occur in occasion during a certain time interval. Except for the climatic environments, the sap flow is also controlled by the soil moisture (Pražák *et al.* 1994, Dye 1996, Fredrik and Anders 2002). The aim of this paper is to discuss the responses of sap flow to the extreme climatic conditions and to analyze the potential capacity of stem water conductivity scaled from the sap flow measurements, in the case of abundant soil moisture from September 14, 1999 to September 22, 2000. We assumed that the plant's capacity of

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regulating water output by transpiration was related to the available soil moisture. Our hypothesis was that there existed an upper and lower diurnal *SFD* threshold under extremely high and low environmental conditions within a period of time when the soil moisture was sufficient. This threshold may of course attain different values for different plant species.

2 Materials and methods

2.1 Site description

A field study to quantify stem water conductivity of two eucalyptus plantations (*E. urophylla*) from September 14, 1999 to September 22, 2000 was conducted at two sites (Hetou and Jijia) in the Nandu River catchment in Leizhou Peninsula, Guangdong Province, China. The Hetou site (21°05 N, 109°54 E) is on a sandy soil of sedimentary origin, while Jijia (20°54 N, 109°52 E) is on a basalt-derived clay soil, approximately 40 km away. The climate is tropical, with long-term annual air temperature of 23.5 ℃, monthly mean air temperature of around 28 ℃ in July and 16 ℃ in January. Annual rainfall varies from 1 300 mm in the south to 2 500 mm in the north of the peninsular with a high annual variation. Over 80% of the rain falls between April and September, up to half is typhoons, which occur up to seven times per year. At the study sites, the monitored plantations were *E. urophylla* planted in the middle of 1996. A 40 m × 40 m plot was taken at each site in September 1999, and based on investigation, a set of standing trees within the plot were selected according to the diameter distribution of the stand to make a monitoring.

2.2 Sap flow measurements

The term sap flux density (*SFD*) is used to denote the volume of water moving through the stem vessels per square sapwood area per unit time, expressed in unit of $mL \cdot cm^{-2} \cdot h^{-1}$. During the observation period, heat-pulse sensors were cycled through a representative sample of trees (20 at Hetou and 18 at Jijia) for 4–6 weeks per tree at both sites. Four heat-pulse probes were positioned in each tree in four different directions (north, south, east and west) and sapwood depths according to the diameter of cambium and heartwood. The controlled module/data logger was programmed to provide a heat pulse, and measurements were recorded every 30 min. The details of sampling regime and analysis were given by Zhou *et al.* (2002).

2.3 Environmental measurements

An automatic weather station was installed at each site near the plot in September 1999. Instruments for observation of meteorological factors, including air temperature (*T*), relative humidity (*RH*), solar radiation (*RAD*), and wind speed (*WS*) were installed. A data logger was used to collect data every 30 min. Precipitation (*P*) was measured above the canopy with a tipping bucket rain gauge. Soil moisture (*SM*) at 4 depths (50, 150, 250 and 350 cm) in the soil profile was measured at two locations using soil moisture sensors (Theta Probes, Delta T Devices, UK).

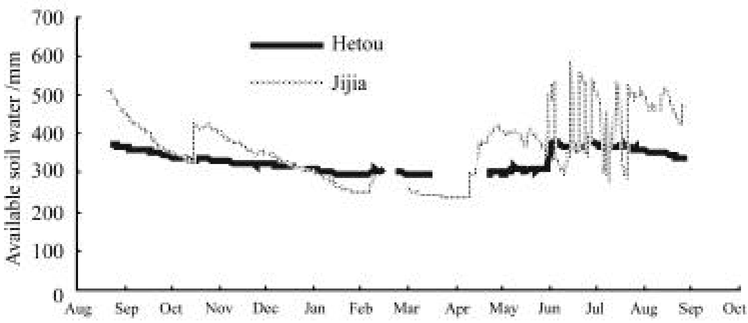


FIGURE 1 Available soil water at the depth of 4 m during the study period at Hetou and Jijia sites

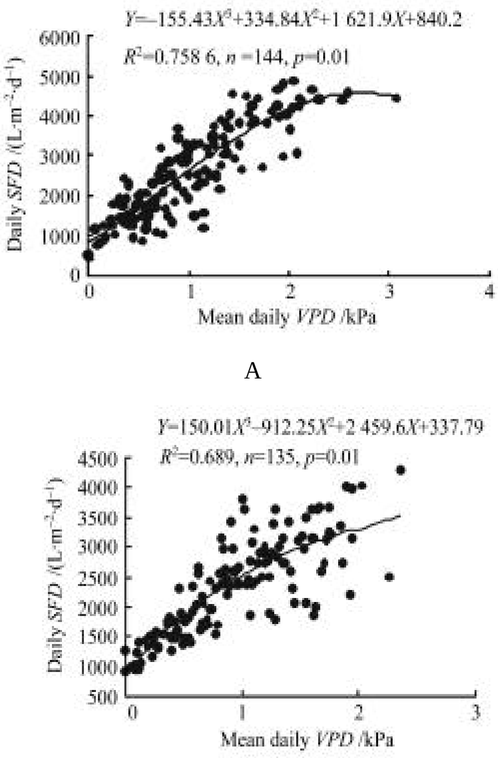
2.4 Selection of materials

In the case of sufficient water supplied in the soil, the plant can draw and evaporate the actual amount of water it needs, because the evaporation from a soil covered with vegetation is very small at both sites. Fig.1 presents the available soil water content at the depth of 4 m at two sites, where the available soil water content is different between field moisture and moisture content at –1 500 kPa matric potential. Fig. 1 testified the fact that, throughout the entire study period, the soil contained sufficient water accessible to the plants. The soil water difference between the two sites was mainly caused by different soil textures, and the hydraulic conductivity of sandy soil at Hetou was much higher than that of clay soil at Jijia. Another possible explanation for this was that the water resistance from the soil to the roots at Hetou site was much smaller than that of Jijia. During the study period, the daily *VPD* ranged between 0–1.68 kPa at Hetou and 0–1.27 kPa at Jijia, *RAD* between 0.02–17.67 $MJ·m^{-2}·d^{-1}$ at Hetou and 0–20.27 $MJ·m^{-2}·d^{-1}$ at Jijia, *T* between 8.50–32.65 ℃ at Hetou and 8.5–31.3 ℃ at Jijia, *WS* 0–0.9 $m·s^{-1}$ at Hetou and 0–1.7 $m·s^{-1}$ at Jijia. The sap flow data under the extremely high or low environmental conditions during this period were selected to analyze the stem water conductivity of eucalyptus plantations at both sites. The average leaf areas of a whole tree at Hetou and Jijia were 21.2 m^2 and 14.9 m^2, and both plantations were 3 years old.

We selected 10 d with higher environmental values (including mean daily *VPD*, *RAD*, *T*, and *WS*) during the observation period, and ordered environmental factors by the mean diurnal *SFD*. The maximum and minimum *SFD* values were the upper and lower threshold of diurnal *SFD* under the selected environments.

3 Results

3.1 Water capacity in extremely high *VPD*



B

FIGURE 2 Daily *SFD* versus mean daily *VPD* at Hetou (A) and Jijia (B) site during the observation period

It was *VPD* that drives water to move from the root to the leaves. Vapor pressure gradient between inside the leaves and the outer boundaries increases with the increase of air *VPD*, leading to a faster transpiration rate. In order to draw out the trends of *SFD* distribution versus daily *VPD*, it is necessary to take all the monitored data into consideration. There was a positive nonlinear correlation between daily *SFD* and mean daily *VPD* at both sites (Fig. 2), $Y = –155.43X^3 + 334.84X^2 + 1\ 621.9X + 840.2$ ($R^2 = 0.758\ 6$, $n = 144$, $p = 0.01$) for Hetou site, and $Y = 150.01X^3 – 912.25X^2 + 2\ 459.6X + 337.79$ ($R^2 = 0.689$, $n = 135$, $p = 0.01$) for Jijia, where *Y* was daily *SFD*, *X* was mean daily *VPD*. The maximum daily *SFD* was 4 739 ± 114.71 $L·m^{-2}·d^{-1}$ with *VPD* of 2 ± 0.79 kPa, and minimum daily *SFD* of 540 ± 70.21 $L·m^{-2}·d^{-1}$ with *VPD* 0 ± 0.87 kPa at Hetou, while the maximum daily *SFD* was 3 414 ± 190.91 $L·m^{-2}·d^{-1}$ with *VPD* 2 ± 0.39 kPa, and minimum daily *SFD* 397 ± 25.61 $L·m^{-2}·d^{-1}$ with *VPD* 0 ± 0.47 kPa at Jijia. The mean daily *SFD* value of eucalyptus plantations at Hetou reached maximum value when mean daily *VPD* was about 2 kPa, the *SFD* values changed little when *VPD* was higher than this value. This suggested that high levels of *VPD* might limit stem water conductivity.

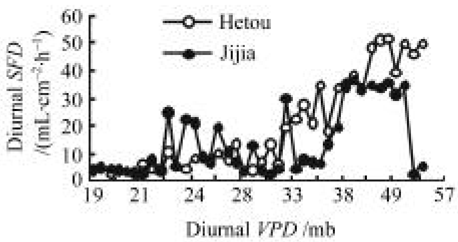


FIGURE 3 The response of diurnal *SFD* to diurnal *VPD* at Hetou and Jijia sites

There existed a similar changing tendency for diurnal *SFD* at both sites during high *VPD* days at both sites. Diurnal *SFD* increased with the increase of diurnal *VPD* at first, and changed little when diurnal *VPD* varied from 54 to 58 mb, and then decreased when diurnal *VPD* was above 58 mb (Fig. 3). The upper threshold of diurnal *SFD* at Hetou site (51.55 $mL·cm^{-2}·h^{-1}$) was higher than that of Jijia site (36 $mL·cm^{-2}·h^{-1}$). One explanation for this might be that the water conductivity of measured young trees was very sensitive to the environment. Another possible explanation was the different soil textures at both sites. The water conductivity of Hetou sandy soil might be much greater than that of Jijia clay soil, and soil water might move more easily in Hetou sandy soil because of larger aerial spacing, which might lessen the water resistance from the soil to the roots. But as for Jijia site, diurnal *SFD* fluctuated more acutely before diurnal *VPD* reached 50 mb and decreased more rapidly after diurnal *VPD* exceeded 58 mb. This might be explained by a larger fluctuation of other environmental factors at Jijia during high *VPD* days. We can regard 51.55 mL·cm^{-2}·h^{-1} as the upper diurnal *SFD* threshold for 3-year-old *E. urophylla* plantations.

3.2 Diurnal *SFD* response to high and low solar radiation

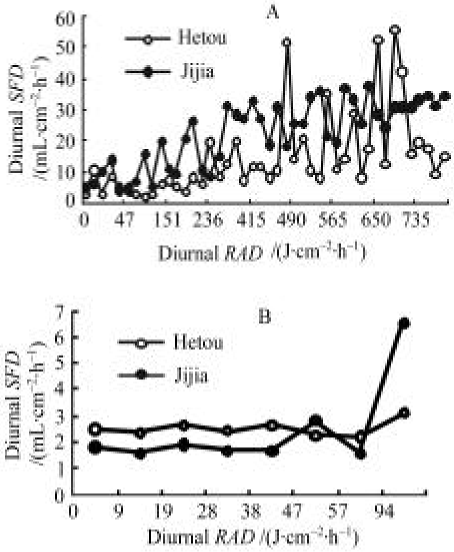


FIGURE 4 The response of diurnal *SFD* to high (A) and low (B) solar radiation (*RAD*) at Hetou and Jijia sites

Fig. 4A showed that the diurnal *SFD* fluctuated acutely with *RAD* at both sites in high *RAD* days, varying from 2.61 to 55.45 mL·cm^{-2}·h^{-1} at Hetou, from 4.45 to 37.6 mL·cm^{-2}·h^{-1} at Jijia when the diurnal *RAD* ranged from 0 to 801 J·cm^{-2}·h^{-1}. Diurnal *SFD* increased with the increase of *RAD* until diurnal *RAD* reached 669 J·cm^{-2}·h^{-1}, beyond which diurnal *SFD* decreased rapidly at Hetou and changed little at Jijia. It indicated that the upper threshold of *SFD* was 55.45 mL·cm^{-2}·h^{-1} at Hetou and 31.03 mL·cm^{-2}·h^{-1} at Jijia, respectively. In low *RAD* days (Fig. 4B), diurnal *SFD* changed little at both sites. The diurnal *SFD* ranged from 2.30 to 3.11 mL·cm^{-2}·h^{-1} at Hetou and from 1.81 to 6.57 mL·cm^{-2}·h^{-1} at Jijia when diurnal *RAD* varied from 0 to 94 J·cm^{-2}·h^{-1}. Solar radiation can increase both air and leaf temperature, which can increase the transpiration rate by increasing the vapor pressure gradient between leaves *in situ* and the environment. As a result, we could conclude that the upper and lower thresholds of diurnal *SFD* were 55.45 and 2.30 mL·cm^{-2}·h^{-1} during the high *RAD* days.

3.3 Heat tolerance

If the relative humidity keeps invariable, the vapor pressure gradient between leaves *in situ* and outside increases with the increase of air temperature, which has made the water inside leaves more easily to escape, and thus increases the transpiration. Most diurnal *SFD* values of *E. urophylla* plantations increased with the increase of air temperature until it reached 34 ℃ at both sites, but much higher at high air temperature (T > 22 ℃) and much lower at low air temperature (T < 20 ℃) at Jijia (Figs. 5A,B). It suggested that the stem water conductivity was more restricted by high air temperature stress at Hetou, and more limited by low air temperature at Jijia. At high air temperature (21.8–40.9 ℃ at Hetou and 22.0–37.8 ℃ at Jijia), the diurnal *SFD* ranged between 1.16 and 51.56 mL·cm^{-2}·h^{-1} at Hetou, 1.62 and 32.99 mL·cm^{-2}·h^{-1} at Jijia (Fig. 5A). At low air temperature (–2.1–23.7 ℃ at Hetou and 0–22 ℃ at Jijia), the diurnal *SFD* ranged between 1.80 and 38.95 mL·cm^{-2}·h^{-1} at Hetou, 2.07 and 23.98 mL·cm^{-2}·h^{-1} at Jijia (Fig. 5B). Here we could conclude that 51.56 and 1.16 mL·cm^{-2}·h^{-1} were the upper and lower thresholds of 3-years-old *E. urophylla* plantations in high and low air temperature stresses.

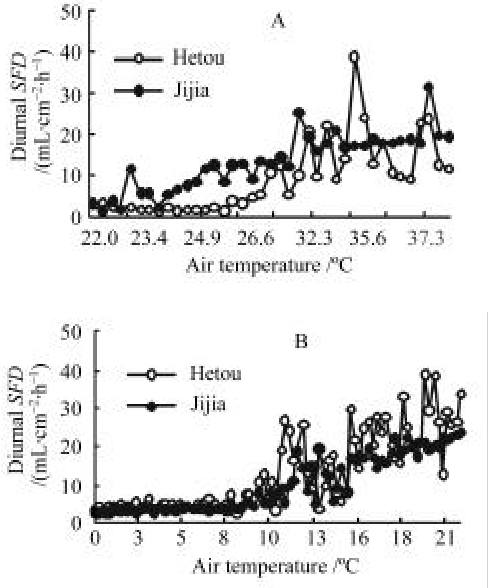


FIGURE 5 The response of diurnal *SFD* to high (A) and low (B) air temperature at Hetou and Jijia sites

3.4 Impact of wind speed

Diurnal *SFD* values at Hetou were much higher than those at Jijia in high wind speed and much lower in low wind speed (Figs. 6A,B), which indicated that stem water conductivity at Hetou site was more sensitive to extreme wind speed. But the hourly *SFD* values reached their maximum values at noon when *VPD* and *RAD* were high at both sites. It suggested that it was quantitatively unpredictable for the impact of wind speed on *SFD*. Gentle wind might accelerate transpiration because it brought the vapor outside the stomas away and compensated the humid air, which made the diffused layers thinner or disappear, as a result, the transpiration increased. While strong wind might result in the stomas' closure and thus slowed down the transpiration. For example, at Hetou, when exposed to a strong wind (1.6 m·s^{-1}), hourly *SFD* was only 1.62 mL·cm^{-2}·h^{-1} (November 7, 1999).

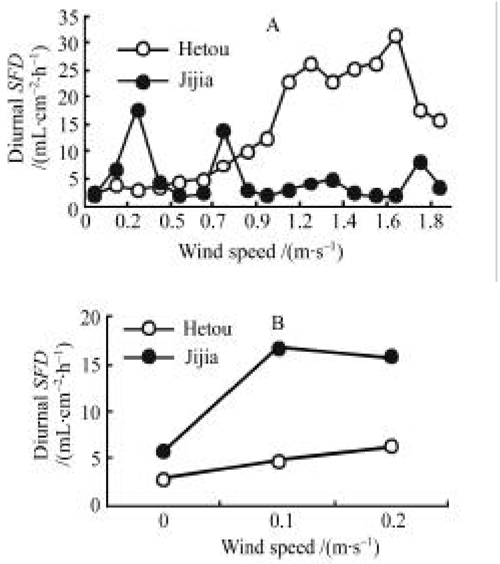


FIGURE 6 The response of diurnal *SFD* to high (A) and low (B) wind speed at Hetou and Jijia sites

4 Discussions

Because environmental factors at Jijia maybe have not reached their extremely high values and the Hetou sandy soil had greater water conductivity, we consider the maximum diurnal *SFD* at Hetou as the upper *SFD* threshold for *E. urophylla* plantations. There had no much difference for *SFD* upper thresholds at both sites, varying between 51.55–55.65 mL·cm^{-2}·h^{-1}. As a result, we can conclude that environmental factors were the main determinants of *SFD*, but there existed an upper *SFD* threshold for *E. urophylla* plantations, 51.55–55.65 mL·cm^{-2}·h^{-1} in Leizhou Peninsula.

Many researchers had studied the influence of light, drought, temperature and soil fertilization on transpiration (Welander and Ottosson 2000, Montero *et al.* 2001), but they were controlled under some special experimental conditions. The data of this paper came from completely natural field conditions. Therefore, the results in this paper may be more practically reasonable. Many empirical hydrological models proved useful to predict canopy fluxes over a wide range of conditions (Engel *et al.* 2002). Further research is needed to verify our findings by models and a longer time's data.

By our analysis, *VPD* and *RAD* were direct factors that determine *SFD*, while air temperature and wind speed were indirect factors, influencing *SFD* weakly, which was in accordance with the studies of Daudet *et al.* (1999) on *Juglans regia* L. A strong positive correlation between daily transpiration rate and mean daily *VPD* for *E. grandis* and *P. radianta* also was found by Myers and Benyon (1998), and they indicated that the upper threshold of mean daily VPD was 1.5 kPa for *E. grandis*, but not for *P. radiant*. The value for *E. urophylla* was slightly higher, 2.0 kPa. This might be caused by different species and climatic conditions.

It was found that the plantation's demand for water would increase as transpiration rate will increase with the increase of sapwood area. A thinning may lead to a faster response to the increase in the light of ground vegetation (Welander and Ottosson 2000). Therefore, except for the environmental factors, a larger sapwood area at Hetou, which was caused by a wider row spacing, might also contribute to the higher *SFD*. Other studies also showed that surplus soil water content might also restrict transpiration rates because of the lack of soil aeration, in turn limited root respiration (Oltchev *et al*. 2002). A further study was required to know the influencing mechanisms on water conductivity from different root distributions at both sites for *E. urophylla* plantations in south China.

In field conditions, turbulence, buoyancy and fluttering might make the leaf boundary layer conductance unpredictable. (Daudet *et al.* 1999). A further understanding on the factors controlling leaf transpiration is needed.

Acknowledgments

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