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Sap flow response of Eucaylyptus (*Eucalyptus urophylla*) to environmental stress in South China*

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Abstract: Sap flow and environmental conditions were monitored at two Eucalyptus (*Eucalyptus urophylla* S.T.Blake) plantations at Hetou and Jijia, located in Leizhou, Zhanjiang, Guangdong Province. It was found that daily sap flux density (SFD) of Eucalyptus was closely related to daily atmospheric vapor pressure deficit (VPD) (R^2=0.76, P=0.01 at Hetou and R^2=0.7021, P=0.01 at Jijia) at both sites. No significant relationship existed between daily SFD and mean daily air temperature at both sites. Daily SFD varied with wind speed $Y=-17585X^3+15147X^2-1250.7X+2278.4$ (R^2=0.68; P=0.01) at Hetou and $Y=-101.67X^3-1.65X^2-376.4X+1914.8$ (R^2=0.40, P=0.05) at Jijia, where Y was daily SFD, X was daily wind speed. Experimental observations yielded the following data: (1) the critical lower and upper daily VPD threshold were 0 and 2 kPa, within which daily SFD varied from 540±70 L/(m^2·d) to 4739±115 L/(m^2·d) at Hetou site, from 397±26 L/(m^2·d) to 3414±191 L/(m^2·d) at Jijia site; (2) Diurnal SFDs at Hetou site were much higher under low relative humidity (<30%) and slightly lower under high relative humidity (>80%) compared with those at the Jijia site; (3) The upper and lower threshold of daily and diurnal RAD for the optimal water use of *E. urophylla* plantations were 18±2.7 and 2±1 MJ/(m^2·d), 669 and 0 J/(cm^2·h) during the observation period.

Key words: Sap flow, Environmental stress, Eucalyptus plantations, Water conductivity
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INTRODUCTION

Eucalyptus species are important commercial plantation and pioneer tree species used in successful ecological restoration of degraded lands in South China (Yu *et al.*, 1994; Yu and Wang 1995; Zhou *et al.*, 2001). However, concern over excessive water consumption by eucalyptus plantations in China and elsewhere had been noted (Kallarackal, 1992).

Systematic attention has been devoted to the study of transpiration in many scientific disciplines: in the physiology of plants, hydrology, ecology, and meteorology (Pražák *et al.*, 1994; Granier *et al.*, 2000; Lagergren and Lindroth, 2002; Daudet *et al.*, 1999; Montero *et al.*, 2001). Tree transpiration is

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the major pathway for both water and energy leaving the forest ecosystem (Lagergren and Lindroth, 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 analysis of among-tree variation of sap flow (Köstner *et al.*, 1996), which is commonly scaled up to stand level and considered as representing transpiration (Lagergren and Lindroth, 2002). The use of sap flow measurements enable assessment of the variability in tree transpiration, and the quantification of different crown status on total water flux (Granier *et al.*, 2000).

Recent findings suggested that sapflow or transpiration of trees may be closely linked to plant hydraulic variables and environmental factors, especially soil types (Du and Yang, 1995; Cienciala *et al.*, 1997; Lagergren and Lindroth, 2002). There is growing evidence of 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 distribution of rainfall during the growing season very uneven. This may affect both growth and stability of forest ecosystems.

Analytical studies of the functioning of forest ecosystem, and modeling of fluxes are of basic importance (Tenhunen *et al.*, 1998). Forests are more directly influenced by the variation of climate (Granier *et al.*, 2000). There has been increasing evidence on the impact of climatic factors on water fluxes (Oltchev *et al.*, 2002; Devitt *et al.*, 1997; Calder *et al.*, 1997; Welander and Ottosson, 2000). If the environmental factors vary, sap flow can fluctuate widely. It is therefore important to study the sap flow and associated mechanisms under extreme environmental stresses. In field experiments, extreme environments are often time-limited, i.e. the extreme conditions only occur during a certain short time interval. Beside the influence of climatic environments, the sap flow is also controlled by the soil moisture (Lagergren and Lindroth, 2002; Dye, 1996; Pražák *et al.*, 1994). The aim of our research was to evaluate sap flow response to extreme climatic conditions and analyze the potential capacity of water conductivity scaled from the sap flow measurements under abundant soil moisture. We assumed that the plant's capacity of regulating the water output by transpiration was related to the available soil moisture. Our hypothesis was that there existed upper and lower environmental thresholds that determine critical SFD values within a period of time when the soil moisture was sufficient. These thresholds may of course vary for different plant species.

MATERIAL AND METHODES

Site description

A field study was conducted to quantify the response of sap flow of eucalyptus trees (*E. Urophylla*) to environmental stress during September 14, 1999 and September 22, 2000 at two plantation sites (Hetou and Jijia site) in the Nandu River catchment in Leizhou Peninsula, Guangdong Province, China. The Hetou site (21°05′N, 109°54′E) was on a sandy soil of sedimentary origin, while Jijia (20°54′N, 109°52′E) was on basalt-derived clay soil, approximately 40 km away. The climate was tropical, with long term annual air temperature of 23.5 °C, monthly mean air temperatures of around 28 °C in July and 16 °C in January. Annual rainfall varied from 1300 mm in the south to 2500 mm in the north of the peninsula with high annual variation. Over 80% of the rain falls between April and September, up to half associated with typhoons, which occur up to seven times per year. At the study sites, the monitored plantations were *E. urophylla* planted in mid-1996. A 40 m×40 m plot was selected at each site in September 1999. A set of standing trees within each plot were selected for monitoring based on trunk diameters.

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,

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expressed in units of ml/(cm^2·h). During the observed period, heat-pulse sensors were used on representative 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 (produced by Edwards Company, New Zealand) was programmed to provide a heat pulse, and measurements were recorded every 30 min. Full details of sampling regime and analysis are given in Zhou *et al.*(2002).

Environmental measurements

An automatic weather station was installed at each site near the plot in September 1999. Instruments for meteorological observations were installed to include air temperature (*T*), relative humidity (RH), solar radiation (RAD), and wind speed (WS). A data logger was used to collect data every half hour. 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 were measured at two locations using soil moisture sensors (Theta Probes, Delta T Devices, UK).

Materials selection

Fig.1 presents the available soil water content to a depth of 4 meters at both sites, where the available soil water content is the difference between field moisture and moisture content at −1500 kPa matric potential. Fig.1 shows that throughout

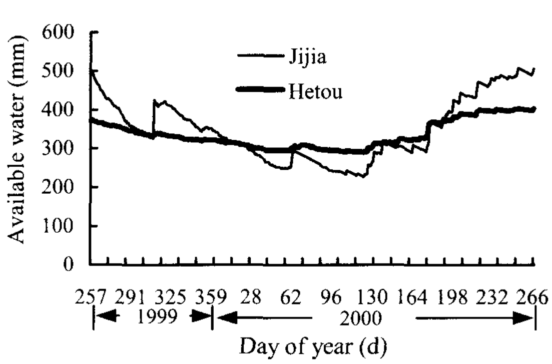

Fig.1 Available soil water to a depth of 4 meters during the study period at the Hetou and Jijia sites

the entire study period, the soil contained sufficient water accessible to the plants. The soil water difference between the Hetou and Jijia site was mainly caused by difference in soil texture. During the study period, the daily air vapor pressure deficit (VPD) ranged from 0 to 1.68 kPa at Hetou and from 0 to 1.27 kPa at Jijia, solar radiation ranged from 0.02 to 17.67 MJ/(m^2·d) at Hetou and from 0 to 20.27 MJ/(m^2·d) at Jijia, air temperature ranged from 8.5 to 32.7 °C at Hetou and from 8.5 to 31.3 °C at Jijia, wind speed ranged from 0 to 0.9 m/s at Hetou and from 0 to 1.7 m/s at Jijia. Sap flow data under these high or low environmental conditions were selected to estimate full stand transpiration of eucalyptus plantations at both sites.

We ordered environmental factors to get a data series of diurnal SFD. The maximum and minimum SFD values were evaluated under the selected environments.

RESULTS

Responses to VPD

In order to draw out the trends in SFD distribution versus daily VPD, it is necessary to take all the monitoring data into consideration. There was positive nonlinear correlation between daily SFD and daytime mean VPD at both sites (Fig.2), $Y=-157.59X^3+353.15X^2+1597.9X+84.622$ ($R^2=0.76$, $n=144$, $P=0.01$) for Hetou site, and $Y=153.5X^3-886.07X^2+2418.2X+347.41$ ($R^2=0.70$, $n=135$, $P=0.01$) for Jijia, where *Y* was daily SFD, *X* was daytime mean VPD. The maximum daily SFD was 4739±115 L/(m^2·d) with VPD of 2.0±0.8 kPa, and minimum daily SFD of 540±70 L/(m^2·d) with VPD 0±0.9 kPa at Hetou site, while the maximum daily SFD was 3414±191 L/(m^2·d) with VPD 2.0±0.4 kPa, and minimum SFD 397±26 L/(m^2·d) with VPD 0±0.5 kPa. The mean daily SFD values for eucalyptus plantations at Hetou site reached maximum value when VPD was about 2 kPa; the SFD values changed little when VPD was higher than this value, which is the possible upper VPD threshold. This suggested that high levels of VPD might limit water use.

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VPD was found to be negatively related to relative humidity at both sites. Diurnal SFD differed between sites under low relative humidity (or high VPD), and were very close when relative humidity was above 80% (Fig.3). The diurnal SFD under high relative humidity was very low, being equal to 2.1±1.5 ml/(cm^2·h) at Hetou and 2.0±0.1 ml/(cm^2·h) at Jijia when relative humidity reached 100%. Diurnal SFDs at the Hetou site were much higher under low relative humidity (<30%) and slightly lower under high relative humidity (>80%) than those of Jijia site. This can be partly explained by differences in solar radiation at both sites. When the relative humidity was 20.4%, a higher solar radiation value at Hetou [669 J/(cm^2·h)] may have contributed to higher transpiration, compared to lower solar radiation values [19 J/(cm^2·h)] measured at Jijia.

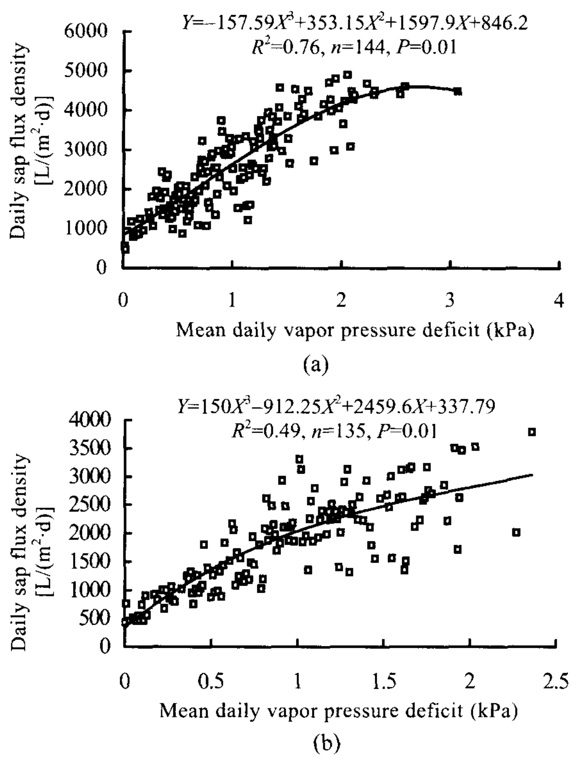

Fig.2 Daily SFD versus mean daily VPD at Hetou (a) and Jijia (b) site during the observation period

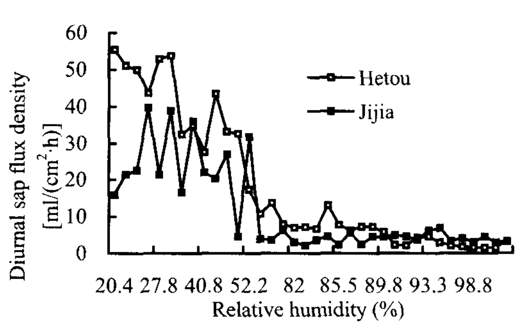

Fig.3 Diurnal SFD response to diurnal relative humidity (%) at Hetou and Jijia site

Responses to solar radiation

Transpiration is generally related to the input of radiant energy. The relationship between daily SFD and daily RAD showed similar linear regression patterns for both sites (Y=214.78X+1169.1, R^2 =0.4561 at Hetou and Y=115.19X+460.6, R^2= 0.5611 at Jijia, where Y was daily SFD, X was daily RAD) (Fig.4). However only 46% to 56% of the variation in SFD could be accounted for based solely on RAD, which suggested other factors must be contributing to SFD. The daytime RAD values, when daily SFD reached its maximum and minimun value, were 18.0±2.7 MJ/(m^2·d) and 0 MJ/(m^2·d) (Fig.4).

Fig.5a shows that the diurnal SFD fluctuated widely with RAD at both sites under high solar radiation. The diurnal SFD values varied from 2.6

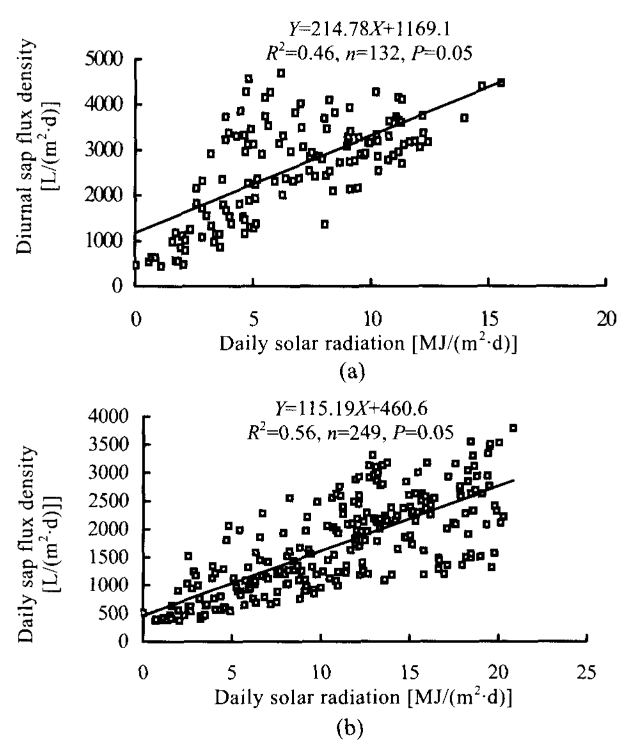

Fig.4 Daily SFD versus mean daily radiation (RAD) at Hetou (a) and Jijia (b) site

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ml/(cm^2·h) to 55.5 ml/(cm^2·h) at Hetou site, and from 4.5 ml/(cm^2·h) to 37.6 ml/(cm^2·h) at Jijia site when the diurnal RAD ranged from 0 to 801 J/(m^2·h). Most of the diurnal SFD values at the Jijia site were slightly higher than those at the Hetou site, but the maximum values occurred at the Hetou site, suggesting that the potential stand transpiration at the Hetou site might be much larger than that at the Jijia site. Diurnal SFD decreased rapidly at Hetou and changed little at Jijia after the radiation exceeded 669 J/(m^2·h). During the selected low RAD days (Fig.5b), the diurnal SFD changed little at both sites. The diurnal SFD ranged from 2.3 to 3.1 ml/(cm^2·h) at Hetou and from 1.8 to 6.6 ml/(cm^2·h) at Jijia when diurnal VPD varied from 0 to 94 J/(cm^2·h).

Temperature response

No significant relationship existed between daily SFD and mean daily air temperature at both site (Fig.6), suggesting daily air temperature was not factor directly influencing daily SFD. The lowest and highest daily SFD occurred on days with air temperatures of (9±1) °C, (28±1) °C at Hetou, and (9±0) °C, (27±1) °C at the Jijia site.

Diurnal SFD of *E. urophylla* plantations increased little when the air temperature was above 34 °C at both sites. When exposed to the same air temperature, diurnal SFDs were much higher at Jijia site during high air temperature days, and lower during the low air temperature days in most cases (Fig.7a, 7b). It suggested that SFD at the Jijia site was more sensitive to air temperature, and the transpiration at the Hetou site was more restricted by high air temperature conditions, while the SFD at the Jijia site was more limited by low air temperatures. During the high air temperature days (21.8~40.9 °C at Hetou and 22~37.8 °C at Jijia), the diurnal SFD ranged from 1.2 to 51.6 ml/(cm^2·h) at Hetou and from 1.6 to 33.0 ml/(cm^2·h) at Jijia site) (Fig.7a). During the low air temperature days (−2.1~23.7 °C at Hetou and 0~22 °C at Jijia), the diurnal SFD ranged from 1.8 to 39.0 ml/(cm^2·h) at Hetou, and from 2.1 to 24.0 ml/(cm^2·h) at Jijia site (Fig.7b).

Wind speed

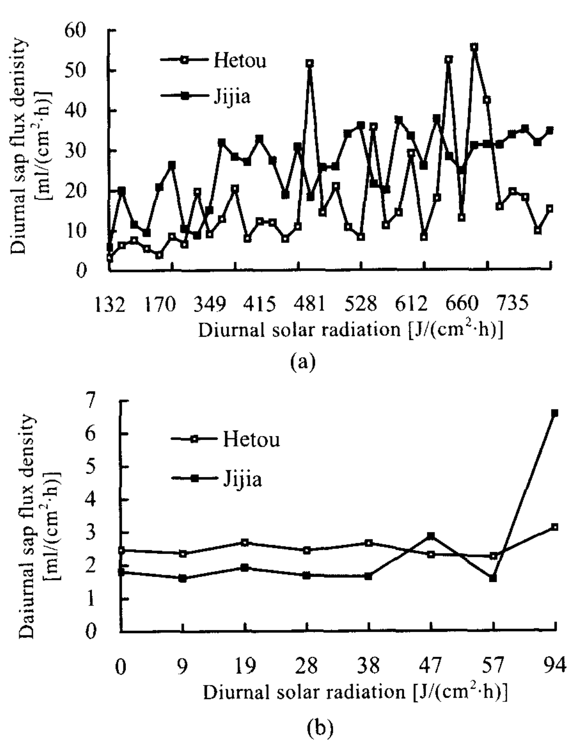

Fig.5 Diurnal SFD response to high (a) and low (b) solar radiation at Hetou and Jijia site

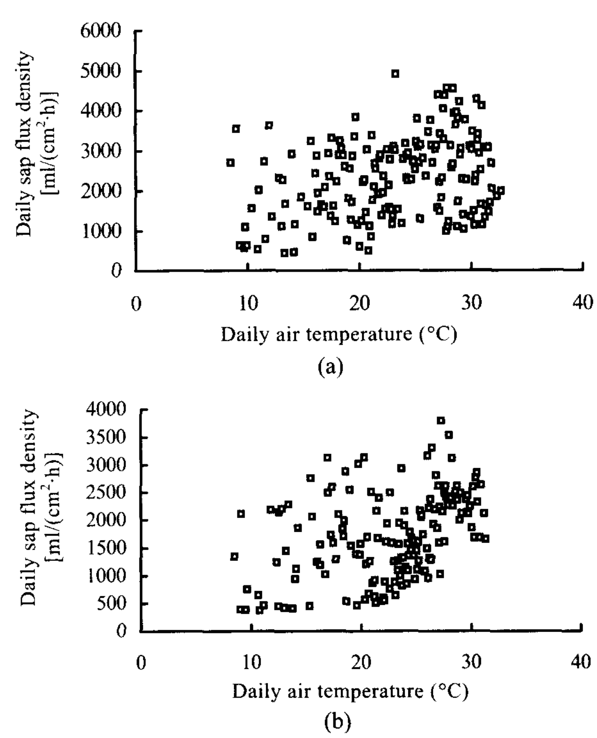

Fig.6 Daily SFD versus air temperature at Hetou (a) and Jijia (b) site

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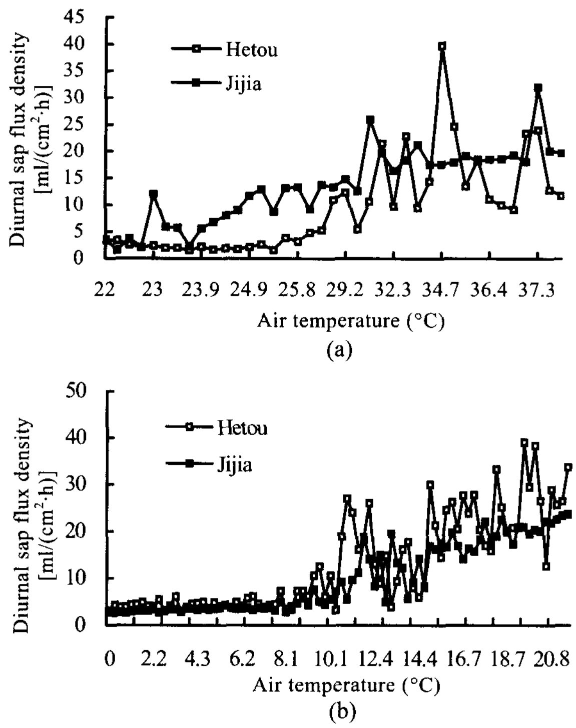

Fig.7 Diurnal SFD responses to high (a) and low (b) air temperature at Hetou and Jijia site

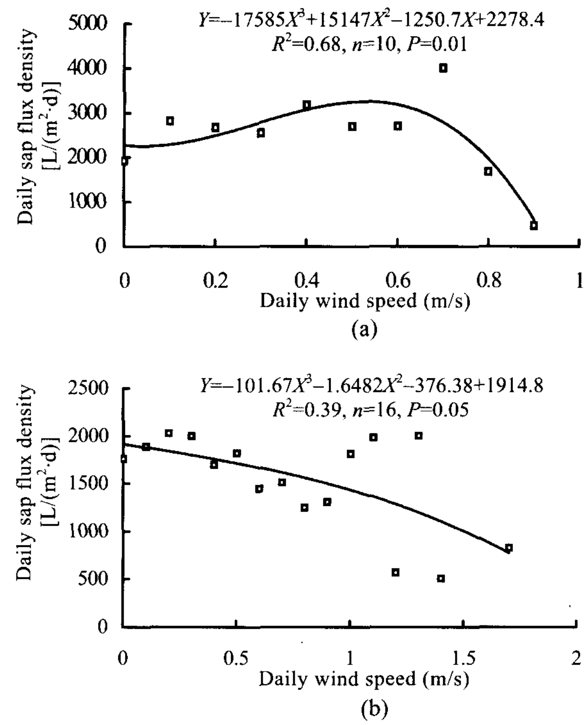

Fig.8 Daily SFD versus wind speed at Hetou (a) and Jijia (b) site

Fig.8 showed that daily SFD varied nonlinearly with wind speed (Y=$-17585X^3+15147X^2-1250.7X+$ 2278.4 for Hetou and Y=$-101.67X^3-1.6482X^2-$ 376.38X+1914.8 for Jijia, where Y was daily SFD, X was daily wind speed), but the correlation at Jijia site (R^2=0.40) was not so significant as that at Hetou site (R^2=0.68). Daily SFD reached maximum with an average daily wind speed of 0.2±0.1 m/s at both sites. Beyond this, the daily SFD values decreased at both sites. Within this range of wind speed, the daily SFD varied greatly at both sites, with a standard deviation of 1198 at Hetou and 818 at Jijia, suggesting that wind speed was only a minor factor in driving daily SFD.

Diurnal SFD reached maximum values when the wind speed reached 1.7 m/s at the Hetou site but the same response was not observed at the Jijia site (Fig.9a). The diurnal SFD values at the Hetou site were much higher than those at the Jijia site under high wind speed and much lower under low wind speed (Fig.9a, 9b), suggesting that diurnal SFD at the Hetou site was more sensitive to wind speed variation. The hourly SFD values reached their

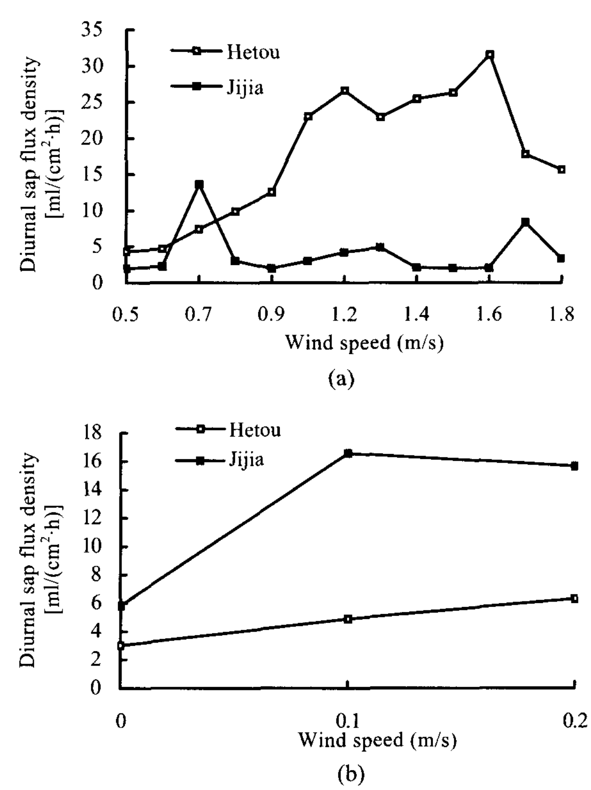

Fig.9 Diurnal SFD response to high (a) and low (b) wind at Hetou and Jijia site

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maximum values at noon when VPD and RAD were high for both sites. For example, at the Hetou site, when exposed to the same wind speed (1.6 m/s), hourly SFD was 1.6 ml/(cm^2·h) at 8:30 (November 7, 1999) and 54.7 ml/(cm^2·h) at 14:30 (October 14, 1999). It further confirmed that wind speed was not a major factor that determined SFD of *E. urophylla* plantations.

DISCUSSION

Many documents reported study on the influence of light, drought, temperature and soil fertilization on transpiration (Welander and Ottosson, 2000; Montero *et al.*, 2001), controlled under some special experimental conditions. The data we report was obtained under field conditions. Therefore, the results in this paper may be more valid. Many empirical hydrological models have been proved useful for predicting canopy fluxes over a wide range of conditions (Engel *et al.*, 2002). Further research is needed to verify our findings using models based on data acquired over longer time periods. The eucalyptus plantations at both sites were only 3 years old, not yet reaching their maximum water use stage; as a result, we are unable to report what true maximum and minimum SFDs' are for *E. urophylla* in South China.

Our results suggested that air VPD and radiation were the major factors determining SFD, while air temperature and wind speed were only minor factors, which accorded with the studies of Daudet *et al.*(1999) on *Juglans regia* L. Strong positive correlation between daily transpiration rate and daytime mean VPD for *E. grandis* and *P. radianta* was also found by Myers *et al.*(1998), in which 1.5 kPa was the daytime mean VPD associated with highest transpiration rate for *E. grandis*, but not for *P. radiant.* In our study a VPD of 2.0 kPa was associated with making SFD's.

Irrigation requirements for Eucalyptus plantations increased with sapwood area. Tree thinning may lead to a faster response, associated with light reaching the lower canopy (Welander and Ottosson, 2000). Therefore, except for the environmental factors, a larger sap wood area at the Hetou site, associated with wider row spacing, may have contributed to the higher SFD's.

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