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Sap flow of *Castanopsis jianfengensis* and its relationship with environmental factors in a tropical montane rainforest

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Abstract Using thermal dissipation and the ICT-2000TE equipment made in Australia, the sap flow of *Castanopsis jianfengensis* and various environmental factors were measured simultaneously in a mixed tropical montane rainforest at Jianfengling Nature Forest Reserve (18°36'N, 108°52'E, 860 m elevation) during the dry and rainy seasons of 2002. The results show that sap flow velocity of *C. jianfengensis* exhibited a mono-peak pattern on clear days and a multi-peak pattern on cloudy or rainy days. Sap flow velocity had significant positive correlations with solar radiation, air temperature, vapor pressure deficit and wind speed and a negative correlation with air relative humidity. In the dry season, sap flow velocity had a significant positive correlation with soil temperature and poor correlation with soil moisture; it was the opposite in the rainy season, indicating that precipitation clearly affected sap flow. Linear regression models between sap flow and environmental factors were established and were significant at the 0.005 level of probability. The mean transpiration rates of *C. jianfengensis* were 103.5 and 41.3 kg/d in our single tree and 1.94 and 0.77 mm/d in stand level in the dry and rainy season, respectively.

Keywords sap flow velocity, environmental factor, transpiration, *Castanopsis jianfengensis*, tropical montane rainforest

1 Introduction

Sap flow is important in research on water use by trees (Meng et al., 2005). Sap flow velocity refers to the speed of sap flow measured at a point or along a probe (Clearwater et al., 1999). Sap flux in single tree refers to the volume or mass of sap flowing through a stem per unit of time; it is important in transpiration that includes three levels: leaf, single tree and stand levels (Cienciala et al., 1995; Köstner et al., 1996; Li, 1997; Alarcón et al., 2003; Chen et al., 2003; Berry et al., 2004; Lu et al., 2004; Barbour et al., 2005). Research on the three scales of transpiration improves our understanding of the rules of transpiration. It is difficult to scale-up water use from leaf level to single tree or stand level (Sun et al., 2002, 2004; Čermák et al., 2004; Su and Kang, 2004; Tognetti et al., 2004; Yan et al., 2004; Barbour et al., 2005; Xiao et al., 2005). Sap flow is part of the mid-scale of transpiration in leaf and stand.

The tropical montane rainforest is an important biome that can be found on Hainan Island and in Yunnan Province, China. To estimate transpiration of single trees of this tropical rainforest, sap flow and environmental factors were monitored by the Granier thermal dissipation method.

2 Study site

Sap flow and environmental factors were measured in a mixed tropical montane rainforest at the 8901 Long-term Plot in Jianfengling Nature Forest Reserve (18°36'N, 108°52'E, 860 m elevation) on Hainan Island, China. The mean annual precipitation was 2568 mm, with rainy period from July to October. Mean annual relative humidity, air temperature and wind speed were 67%–88%, 19.5°C and 1.5 m/s (Chen et al., 2000) respectively. The study was performed in two phases. In Phase 1, from April 20 to May 11, 2002, data were collected to estimate sap flux of a single tree during the dry period. In Phase 2, from October 3 to 21, 2002, data were collected to estimate sap flux during the

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rainy period. The stand was a regenerative complicated stand which was clearcut in 1964 and is now composed of *Castanopsis jianfengensis*, *C. fissa*, *Psychtria tubra*, *Lasianthus chinensis* and other species.

3 Materials and methods

3.1 Sample tree

C. jianfengensis as a pioneer species was selected because it is of great importance in the stand at the study site. At age 40, our sample tree with a 38.6 cm diameter at breast height (DBH) has reached about 17.6 m high. The crown base of the sample tree measured 6.71 m in a N–S direction and 10.14 m from E–W above the soil surface. Its importance value was 18 in the stand at the site. The sapwood and bark thickness were 6.2 and 1.1 cm respectively. The basal areas of sapwood and heartwood were 587.6 and 451.8 cm², respectively. The leaf area index of our sample tree was 4.1 (Li, 1997).

3.2 Sap flow measurements

The Granier thermal dissipation method can collect data of sap flow continuously while keeping the trees under their natural growth conditions (Granier, 1985). Köstner had estimated water vapor flux of Scots pine at the three levels utilizing three sap flow methods. Maximum sap flow rates per sapwood area of trees varied least for the Grainer-system (11–17 g/(cm²·h)) and was of similar magnitude as the Čemárk-system (8–21 g/(cm²·h)) and Čemárk/Schulze-system (4–14 g/(cm²·h)) (Köstner et al., 1996). The result indicates that Grainer thermal dissipation was a reliable method in sap flow measurement (Ma et al., 2005).

The temperature difference (dT , °C) between probes was measured with four pairs of thermal dissipation probes inserted radially into the stem to a depth of 80 mm at a height of 1.3 m. These probes were joined at the constantan side. Copper leads connected to a data logger were set to record the temperature difference every minute and store the mean every 10 or 30 min.

3.3 Environmental measurements

Environmental factors were monitored by the ICT-2000TE system (ICT International Pty Ltd, Australia) simultaneously with sap flow. The environmental factors included the canopy air temperature (T_a , °C), relative humidity (RH , %), soil temperature (T_s , °C), soil moisture (M_s , %) and wind speed under the canopy (V_a , m/s). The precipitation data (P , mm) were obtained from the Tianchi Weather Station of Jianfengling at the Long-term Research Station for Tropical Forest Ecosystems, Hainan Island, China.

3.4 Data analyses

If a portion of the probe was inserted into the non-conducting xylem while the remainder was in sapwood with relatively uniform sap flow velocity, then it could be assumed that the measured temperature difference (dT') was a weighted mean of temperature differences in the sapwood (dT) and temperature differences in the inactive xylem (dT_m):

$$dT' = adT + bdT_m \quad (1)$$

where a and b are proportions of the probe in sapwood and inactive xylem ($b = 1 - a$), respectively. This approach assumed that the thermal properties of the inactive xylem were the same as those in sapwood when $V_s = 0$. If the depth of sapwood was known, then Eq. (1) could be rearranged to find the actual temperature difference in the sapwood:

$$dT = (dT' - bdT_m)/a \quad (2)$$

The sap flow velocity (V_s , g/(cm²·h)) was calculated using the same approach by Granier (1985) and Clearwater et al. (1999):

$$V_s = 0.0119 \times 3600 \times (dT_m/dT - 1)^{1.231} \quad (3)$$

The diurnal sap flux (F , kg/d) was calculated as:

$$F = 0.001 \times \sum_{i=0}^{23} V_{si} \times A (i=0, 1, 2, \dots, 23) \quad (4)$$

where V_{si} is the mean sap flow velocity at the i th hour, and A the cross-sectional area of sapwood (cm²).

The vapor pressure deficit (VPD , kPa) was calculated according to the Goff and Gratch formula (Hogg et al., 1997):

$$E = 0.611 \times e^{12.27 \times T/(T+237)} \quad (5)$$

$$VPD = E - E \times RH/100 \quad (6)$$

where E (kPa) is vapor pressure of saturation and T leaf temperature. Usually, it can be assumed that the leaf temperature (T) is equal to canopy air temperature (T_a).

4 Results and analysis

4.1 Sap flow of *C. jianfengensis*

The sap flow velocity (V_s) of *C. jianfengensis* varied regularly during the dry season, exhibiting a mono-peak pattern on clear days and a multi-peak pattern on cloudy or rainy days (Fig. 1(a)). The V_s on clear days began to

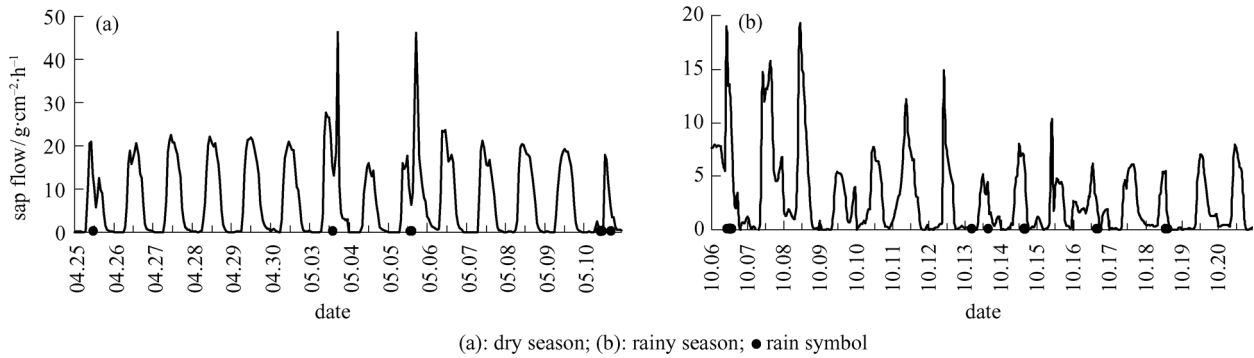


Fig. 1 Variation of sap flow velocity of *C. jianfengensis* during the observation period

increase from a minimal value at about 6:00, reached a peak value between 11:00 and 13:00, then dropped to a lower value at about 19:00 that was maintained subsequently until 6:00 on the next day. The peak values of V_s were about 20 $\text{g}/(\text{cm}^2\cdot\text{h})$ on clear days. As a whole, the V_s during the rainy season was similar to that during the dry season, but the peak values were about 8 to 10 $\text{g}/(\text{cm}^2\cdot\text{h})$, generally less than those during the dry season (Fig. 1(b)).

During the dry season, the diurnal sap flux (F) of *C. jianfengensis* was 103.5 kg/d and varied from 41.8 to 151.7 kg/d . The transpiration (T_r) was 0.47 mm/d and varied from 0.19 to 0.69 mm/d at leaf level, but was 1.94 mm/d at stand level varying from 0.78 to 2.84 mm/d (Fig. 2(a)). During the rainy season, the sap flux was 41.3 kg/d and varied from 17.9 to 86.0 kg/d , while T_r was 0.19 mm/d , varying from 0.08 to 0.39 mm/d at leaf level. The T_r was 0.77 mm/d , varying from 0.34 to 1.61 mm/d at stand level (Fig. 2(b)).

4.2 Environment factors in a tropical montane rainforest

During the dry season, the R , VPD , T_a , RH and T_s varied regularly as mono-peak or multi-peak patterns. The R , VPD and T_a began to increase at about 6:00, R reached a peak value at about noon and dropped to 0 at about 19:00. The VPD and T_a lagged behind R for 1–2 h at peak

value and then dropped gradually until about 6:00 on the next day. The M_s remained constant at about 17% and increased for a while after it rained. The wind speed varied randomly from 0.2 to 0.7 m/s and, in general, the wind was unsteady (Fig. 3(a)). The means were 182.1 $\text{J}/(\text{cm}^2\cdot\text{s})$ (R), 21.6 $^{\circ}\text{C}$ (T_a), 85.5% (RH), 22.7 $^{\circ}\text{C}$ (T_s), 16.7% (M_s), 0.08 m/s (V_a) and 0.1657 kPa (VPD) during the dry season, respectively.

During the rainy season, the variations in environmental factors were similar to those during the dry season, with their means at 142.6 $\text{J}/(\text{cm}^2\cdot\text{s})$ (R), 19.5 $^{\circ}\text{C}$ (T_a), 87.3% (RH), 22.2 $^{\circ}\text{C}$ (T_s), 29.8% (M_s), 0.09 m/s (V_a) and 0.143 kPa (VPD), respectively.

4.3 Relationship of sap flow velocity with environmental factors

Correlation analysis indicated that V_s correlated significantly with R , T_a , RH , V_a , VPD during the observation period, with T_s during dry season and with M_s during rainy season (Table 1). Regression patterns were established to predict sap flow velocity from environmental factors as follows:

During dry season:

$$V_s = 115.406 + 0.017R - 0.108RH + 1.468M_s - 6.593T_s + 0.450P \quad (7)$$

(correlation coefficient $r = 0.916^{**}$, $F = 286.643$, $n = 360$)

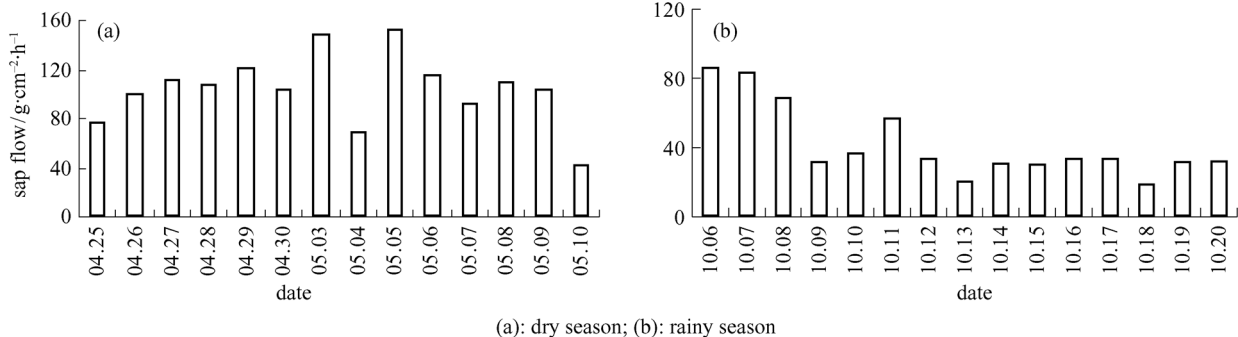


Fig. 2 Diurnal sap flux of *C. jianfengensis* during the observation period

Rainy season:

$$V_s = -19.173 + 0.006R + 0.437T_a - 0.027RH + 0.506M_s \quad (8)$$

($r = 0.818^{**}$, $F = 179.262$, $n = 360$).

Table 1 Correlation between sap flow velocity and environmental factors

observation period	R	T_s	M_s	T_a	RH	V_a	VPD
dry season	0.838**	-0.389**	0	0.767**	-0.705**	0.558**	0.707**
rainy season	0.661**	-0.052	0.356**	0.435**	-0.595**	0.432**	0.599**

** significant correlation ($\alpha < 0.01$)

5 Conclusions

The sap flow velocity of *C. jianfengensis* exhibited a mono-peak pattern on clear days and a multi-peak pattern on cloudy or rainy days during the observation period. This was inconsistent with findings of Liu et al. (1999) and Chen et al. (2003) that transpiration at leaf level exhibited a multi-peak pattern or “midday dormancy” on clear days. Several major reasons for this difference can be cited. First, the transpiration at leaf level and sap flow belonged to two stages of soil-plant-atmosphere-continuum (SPAC) and their driving force was different. Second, the transpiration at leaf level reflected water use of partial leaves and the sap flow reflected water use of single tree. The driving force of transpiration at leaf level was derived from the kinetic energy of molecules and vapor pressure difference between interior and exterior of stoma. About 90% of water use transpires through stoma (Zhang, 2000). The switch of the stoma considerably affected transpiration, i.e., while solar radiation intensity increased adequately, partial stoma would close and its resistance would increase (Liu et al., 1999; Chen et al., 2000; Zhang et al., 2004a). On clear days, transpiration at “midday dormancy” at leaf level could occur possibly at partial leaves, but not at all leaves due to differences of radiation energy accepted by leaves. Generally, it cannot happen as well that transpiration of a single tree exhibits a multi-peak pattern. The driving force of sap flow is derived from the water capacity deficit of the tree and water pressure around the root. While partial leaf transpiration dropped, the water capacity deficit was still large and sap flow retained its high value to offset the water deficit of the tree. It is difficult to cause sap flow “midday dormancy” on clear days (Sun et al., 2002; Čermák et al., 2004; Fetene and Beck, 2004; Barbour et al., 2005; Meng et al., 2005; Xiao et al., 2005).

On cloudy or rainy days, the V_s generally exhibited a multi-peak pattern. For example, at about 11:00 on April 25, the sky was overcast and it rained. The wind speed had reached 0.2 m/s inside the forest. V_s dropped until 14:00,

when cloudiness was reduced, R increased and V_s rose, so a multi-peak pattern appeared and was similar to that on other cloudy or rainy days. The value of the second peak of V_s ranged from 12.4 to 46.4 g/(cm²·h) in the dry season and from 0.2 to 3.5 g/(cm²·h) in the rainy season. These results clearly indicate that precipitation affected the second peak in the dry season. The second peak of V_s was lower in the morning than in the afternoon because water capacity deficit is generally smaller in the morning than in the afternoon. Large amounts of precipitation kept V_s high for a long period of time.

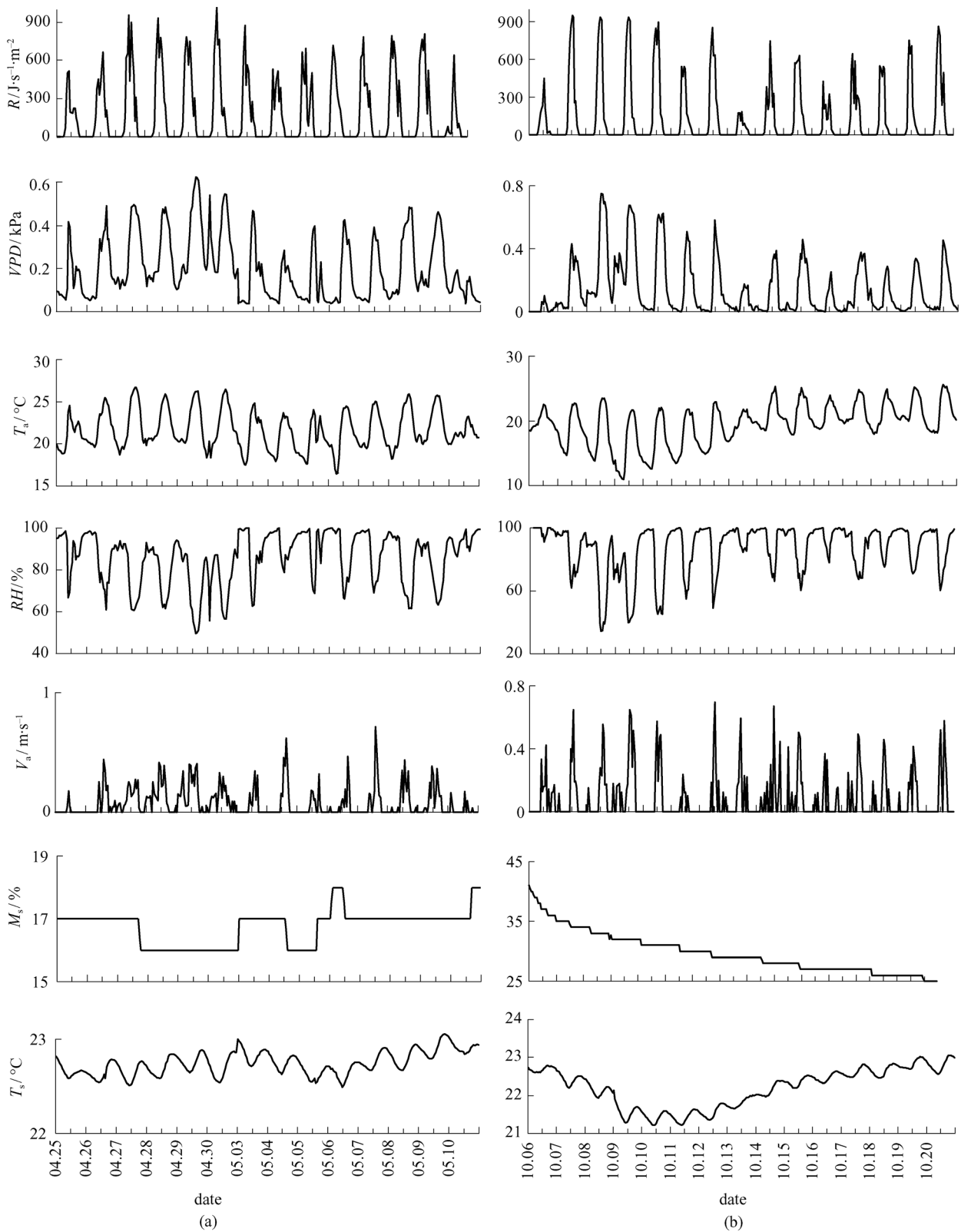
The transpiration value at stand level was close to the value that Xu and Zeng (1989) had estimated at the same site with other methods in 1989. The transpiration speed of *C. jianfengensis* as a tropical pioneer species was larger than that of other trees at other zones (Sun et al., 2002; Fetene and Beck, 2004; Yan et al., 2004; Barbour et al., 2005; Schipka et al., 2005).

Usually, the environmental factors, which are considerably affected by transpiration, are R , T_a , V_a , RH and M_s (Zhao et al., 2003). During the observation period, the correlation between the sap flow of *C. jianfengensis* and environmental factors was similar to the correlation between the sap flow of *Pinus tabulaeformis*, *Malus pumila*, *Cinnamomum camphora*, and *Acacia mangium* with the same environmental factors (Liu et al., 1999; Yan et al., 2004; Zhang et al., 2004b; Meng et al., 2005; Xiao et al., 2005; Zhao et al., 2005).

Sap flow had a significant negative correlation with T_s in the dry season, but poor correlation in the rainy season. This is related to the effect of the stand on soil absorption of solar radiation energy. Due to canopy closure and soil moisture, the temperature of the soil fluctuated less in the dry season than in the rainy season and appeared at a minimum at noon and was maximum at about 20:00 in the dry season (Fig. 3). The result is inconsistent with that of Zhao et al. (2005), who thought that the sap flow of *Choerospondias axillaria* and soil temperature had the same variation. A possible reason was that the stand of this study was different from the stand studied by Zhao et al. (2005) – an agro-forestry stand with a simple structure and small canopy cover.

In the dry season, sap flow (V_s) had a poor correlation with soil moisture (M_s) because the M_s remained constant and increased for a while after a rain. In the rainy season, V_s had a significant correlation with M_s because soil moisture was significant and reduced with interflow and transpiration at the same time that sap flow also declined. The result indicates that M_s clearly affected V_s (Zhao et al., 2003; Zhao et al., 2005).

The F values of the two regression models were significantly greater than the critical F value of 3.35 at $\alpha = 0.005$. The result indicates that the regression models predicted V_s quite well with environmental factors. In the dry season, the maximum difference between measured V_s and predicted V_s was 40.3 g/(cm²·h), while the other



(a): dry season; (b): rainy season

Fig. 3 Variation of environmental factors during the observation period in different seasons
 R : solar radiation; VPD : vapor pressure deficit; T_a : air temperature; RH : relative humidity; V_a : air velocity; M_s : soil moisture; T_s : soil temperature.

differences were small from 0.002 to 8.811 g/(cm²·h) and the mean difference was 2.039 g/(cm²·h). If the V_s values of rainy days were removed, the maximum difference would have been 8.811 g/(cm²·h) and the mean difference 1.552 g/(cm²·h). These results show that precipitation clearly affected sap flow in the dry season. The differences ranged from 0 to 10.886 g/(cm²·h). The mean difference was 1.377 g/(cm²·h) in the rainy season.

It is difficult to scale-up water use from leaf level to the single tree or to stand level (Clearwater et al., 1999; Čermák et al., 2004; Barbour et al., 2005). The authors monitored water use of one tree species in a tropical forest. To scale-up water use from single tree to stand level correctly, it is necessary to estimate water use of numerous other tree species and to set up corresponding, optimum regression models about V_s with environmental factors.

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