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Response of canopy stomatal conductance of *Acacia mangium* forest to environmental driving factors

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Abstract Granier's probes were applied to measure the sap flow of 14 sample trees in an *Acacia mangium* forest on the hilly lands in Heshan City, Guangdong, during the time period of October, 2003. The photosynthetically active radiation (*PAR*), air relative humidity (*RH*) and temperature of air (*T*) above the forest canopy were recorded. The sap flow measurement was used in combination with morphological characteristics of tree and forest structure to calculate the whole-tree transpiration (*E*), stand transpiration (*E_t*), and mean canopy stomatal conductance (*g_c*). Analyses on the relationships between tree morphological characters and whole-tree water use, and on the responses of *g_c* to *PAR* and vapor pressure deficit (*D*) were conducted. The results showed that whole-tree transpiration correlated significantly and positively with tree diameter at breast height (*DBH*) ($p < 0.0001$), with sapwood area ($p < 0.0001$), and with canopy size ($p = 0.0007$) logarithmically, but exponentially with tree height ($p = 0.014$). The analyses on the responses of canopy stomatal conductance showed that the maximum *g_c* (*g_{cmax}*) changed with *PAR* in a hyperbolic curve ($p < 0.0001$) and with *D* in a logarithmic one ($p < 0.0001$). The results obtained with sap flow technique indicate its reliability and accuracy of the methods of estimation of whole-tree and stand transpirations and canopy stomatal conductance.

Keywords sap flow, whole-tree transpiration, canopy stomatal conductance, *Acacia mangium*, vapor pressure deficit

1 Introduction

Canopy stomatal conductance is an important parameter in modeling ecological, meteorological and air quality

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monitoring (Running and Coughlan, 1988; Pataki et al., 1998). In a shorter temporal scale (such as daily), its response to environmental factors is mainly affected by the atmospheric conditions. Nevertheless, its long-term (e.g. seasonal) response is mainly controlled by soil moisture conditions, root characteristics and root distributions in the soil (Schulze, 1986; Pataki et al., 1998). Among the environmental factors, radiation and air vapor pressure deficit are considered as the main driving factors for canopy stomatal conductance. Electronic technology promoted the progress of plant ecophysiology researches and enabled relevant methods to refresh continuously, for example, the emergence of porometer, portable photosynthesis system and so on (Zhao et al., 1997). These measurement systems that are on the basis of the accurate measurement of stomata gas exchange in plant leaves are able to measure leaf photosynthesis, transpiration rate and other important physiological ecological index accurately, which are extensively applied in many ecological research fields (Zhao et al., 1997; Deng et al., 2000; Sun et al., 2001; 2004). However, these instruments fail to measure the whole-tree and stand transpiration due to heterogeneity of canopy structure and technical limitations. Significant errors also arise when scaling up and transforming the results from leaf to canopy or stand. Moreover, these instruments can only measure the instantaneous transpiration and other parameters but not perform a long term monitoring. The system sap flow measurement is popular with physiological scientists since its invention, which is widely used in the studies on energy and water flux of forest ecosystems (Köstner et al., 1992; Granier et al., 1996; Lu et al., 2004; Ma et al., 2005).

Acacia mangium is a widely used tree species in southern China for re-vegetation (Zhao et al., 2002). It is an ideal species for researches on physiological characteristics because of its large water consumption and sensitive response of stomatal gas exchange to the environments. So far, there have been many studies on *A. mangium* about transpiration, photosynthesis and respiration characteristics, the important role as pioneer species in south degraded ecosystems as well as the physiological and ecological responses to the global warming change (Zhao et al., 1997; Zeng et al., 2000a; 2000b; Zhao et al., 2002; 2003; Zhao, 2003). These findings were

mainly based on the leaf gas exchange, so it lacks research at whole-tree and stand-level. No research about the long-term water use and canopy stomatal conductance response to the environmental factors was reported. This paper firstly applied the Granier measurement system to monitor sap flow of *A. mangium* in large area. The main purposes are to: a) understand the effect of morphology on the sap flow and whole tree transpiration; b) quantify sensitivity of *A. mangium* canopy stomatal conductance response to major driving factors, for a better understanding of mechanism how canopy environmental factors affect water use of *A. mangium*.

2 Materials and methods

2.1 Experiment materials

Field monitoring experiment was carried out in Heshan Hilly Land Interdisciplinary Experimental Station (22°40'N, 112°54'E), Chinese Academy of Sciences. The natural conditions of the station can be found in the references (Zhao et al., 1997; Zeng et al., 1999). *A. mangium* forest was planted in 1983–1984, with a plot area of 620.4 m², and 48 trees in the plot. Whole tree sap flow was measured continuously on 14 trees of different diameters at breast using Granier's thermal dissipation probe method. Two probes were typically inserted radically into the stem sap wood 10 cm apart, the upper probe was wound around with heating wire and was heated with 0.12 A constant power source, while the lower probe was left unheated. The relationship between temperature difference and the sap flux density was expressed as follows

$$J_s = 119 \times 10^{-6} \left(\frac{\Delta T_M - \Delta T}{\Delta T} \right)^{1.231} \quad (1)$$

This formula was derived under strict experimental conditions by France tree physiologists Granier and independent on tree species. In the formula, J_s is sap flow density (gH₂O/(m²·s)), ΔT_M is the maximum temperature difference over a day and ΔT is the instantaneous temperature difference between the two probes (Granier, 1987; Lu et al., 2004). All probes were connected to Delta-T DL2e Data logger using shielding cable. Sap flow signals were measured at 10 s intervals and 30 min means were stored.

2.2 Monitoring on environmental factors

The sensors for soil water content (m³/m³), photosynthetically active radiation (*PAR*, mol/(m²·s)), air temperature (T , °C) and relative humidity (*RH*, %) were connected to another data logger with same reading frequency as sap flow. Air vapor pressure deficit (D , kPa) can be calculated as follows

$$D = ae^{\left(\frac{bT}{T+c}\right)}(1 - RH) \quad (2)$$

where a , b and c are 0.611 kPa, 17.502 and 240.97, respectively.

2.3 Tree morphology and stand leaf area index

Tree height was measured with PM-5/1520P altimetry ruler, tree diameter at breast height was measured with ruler and stand leaf area index was determined with digital plant canopy imager (CID-10, made in USA). Sapwood area was determined with increment borer by drilling 5 mm in diameter in 24 trees adjacent to the experimental plot, sapwood depth can be measured with diameter tape, for the boundary line between the sapwood and the heartwood was identified based on the different colors. Species-specific allometric equation was developed for estimating sapwood area from the measured diameter at breast of the 24 trees.

$$A_s = k(DBH)^b \quad (3)$$

where diameter at breast height (DBH) is measured tree diameter at breast height, k and b species-specific coefficients as determined with regression techniques. Here, k and b is 0.1930 and 1.1844 respectively.

3 Results and discussion

3.1 Sap flow measurement and calculation of whole-tree and stand transpiration

Experiment was conducted during October in 2003, 31 days in total. We should convert the voltage value into the sap flux density using Eq. (4) transformed from Eq. (1) because the data documented in the data logger voltage signal.

$$J_s = 119 \times 10^{-6} \left(\frac{\Delta mV_M - \Delta mV}{\Delta mV} \right)^{1.231} \quad (4)$$

Sap flow density was calculated by putting the voltage into the Eq. (4). Diurnal variation of sap flux density on five trees of different DBH from the second to the fourth day in October was shown in Fig. 1. For trees 1–4 the thermal dissipation probes were installed on the four azimuths, but for tree 5, only installed on the north and south azimuths to avoid the influence of the adjacent heated probes because of smaller DBH . From Fig. 1, we can see that sap flux was significantly different due to DBH , and for a given tree, J_s in different azimuths also showed large differences, but the relationship between the difference and the DBH was not clear, and so be the azimuths and the difference, namely these differences are random. However, J_s of different azimuths show clear linear correlation and reached significant difference ($p < 0.0001$) (Fig. 2). We can make use of this correlation to calculate the mean sap flow using only measurement on the north side of the tree trunk so as to save probes.

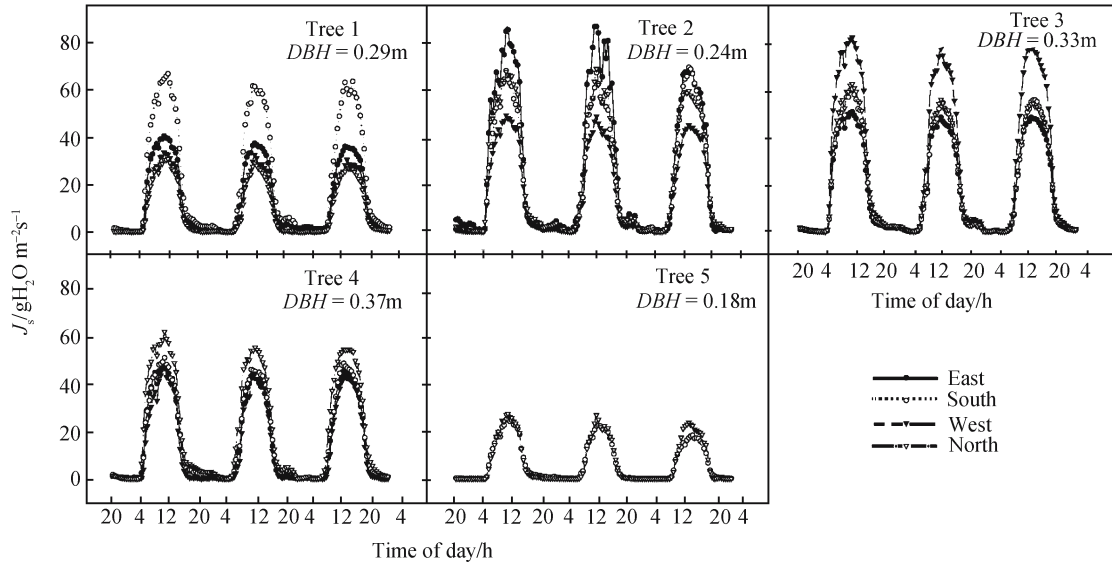


Fig. 1 Azimuthal changes of sap flux density of *A. mangium* with time (October 2–4, 2003)

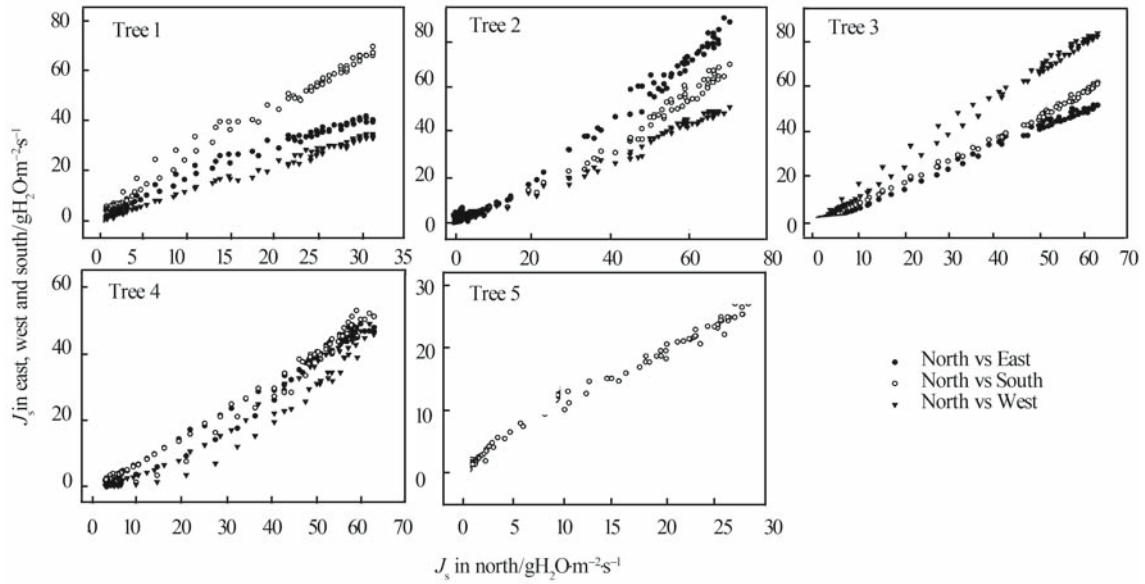


Fig. 2 Correlations between the sap flux density in north and those in east, south and west of tree trunk

Sap flux density reflects the relative water transport rate of per xylem area. Whole-tree transpiration was estimated as the product of sap flow density and sapwood area

$$E = \bar{J}_s \times A_s \quad (5)$$

where \bar{J}_s is the mean sap flux density that is averaged from sap flow measurement of different azimuths.

$$\bar{J}_s = \frac{J_s^E + J_s^S + J_s^W + J_s^N}{4} \quad (6)$$

As far as the cost was concerned, it is impossible and unnecessary to install probes on four sides. We can acquire

the sap flow on the other three orientations on the basis of the ratio of sap flow between the north and the other three sides. Normally, probes were only installed on the north, and the mean sap flow density was estimated from the ratio in practice. Therefore, in experiment, we calculated the ratio of mean sap flux density between each azimuth of the five sample trees and those on the north azimuth of 14 trees firstly.

$$R_{\frac{1}{N}} = \frac{\sum_{j=1}^{4,5} \bar{J}_{sj}^1}{\sum_{i=1}^{14} \bar{J}_{si}^N} \quad (7)$$

In the equation, the molecule is sap flow of a certain azimuth (south, north, east and west) of the five sample trees (1–5), the denominator is the averaged sap flow on northern side of the fourteen trees. Based on the averaged ratio, we can calculate J_s on each side as well as the mean J_s of any tree. However, the formula is calculated in a straight forward way and restricted by some conditions: for a given azimuths, the regression slope for J_s of a tree to all of the trees is independent on the DBH , that is to say, the slope did not show clear variation with the change of DBH . The driving force for transpiration of each tree is identical and the relationship between transpiration rate of every tree and total transpiration is steady because evaporative demand changes with radiation and temperature. Accordingly, we established the linear correlation of J_s of every tree and mean J_s of the fourteen trees on the north (Fig. 3), using the slope values and corresponding DBH to plot the scatters so as to analyze the correlation between the slope and the DBH . The results indicated that there was no significant correlation between the slope and the DBH ($p = 0.2084$) (Fig. 4). Therefore, we can calculate the ratio of J_s of all trees in the stand on a given azimuth to mean J_s of the fourteen trees on northern side by direct use of the Eq. (7).

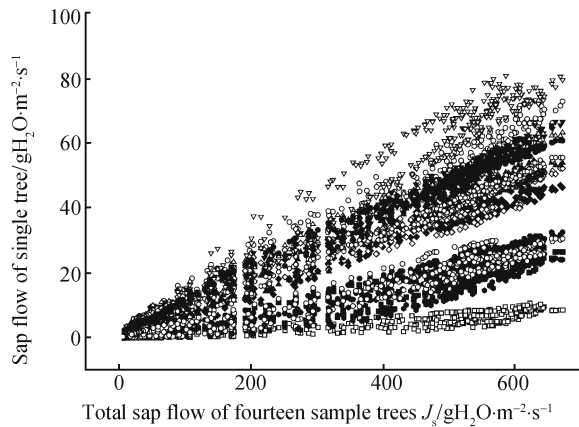


Fig. 3 Linear correlation between sap flux density (J_s) of each and total J_s of examined 14 samples

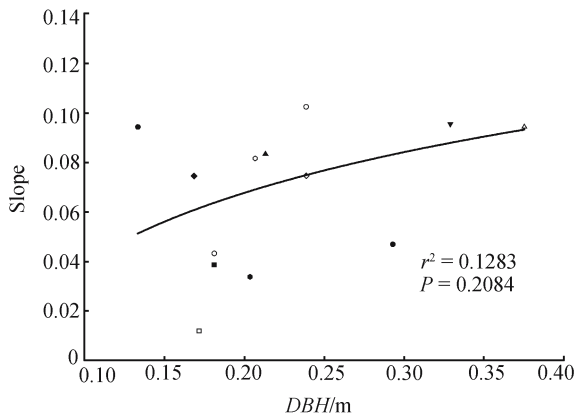


Fig. 4 Correlation between the slope of $J_s / \text{Total } J_s$ and DBH

The actual and sap flow-calculated stand transpirations would be obvious of disparity if the latter were estimated based on mean J_s and the total sapwood area because the among-tree variations of J_s are great as indicated in Fig. 1. Hence, all trees in the experimental plot were divided into tree classes according to DBH (I: $DBH < 0.15$ m; II: $0.15 \text{ m} \leq DBH < 0.20$ m; III: $0.20 \text{ m} \leq DBH < 0.25$ m; IV: $0.25 \text{ m} \leq DBH < 0.30$ m and V: $0.30 \text{ m} \leq DBH$), and each rank has 12, 14, 10, 7 and 5 individuals respectively. We determined the sapwood area for all the trees in the stand using Eq. (3). The product of the mean J_s and the sapwood area of each class is the ultimately transpiration rate of this class ($E_i, I = 1, 2, 3, 4, 5$), the sum of five class transpiration rate is total transpiration rate of the stand (E_t)

$$E_t = \sum_{i=1}^5 E_i = \sum_{i=1}^5 \bar{J}_{si} \cdot A_{si} \quad (8)$$

where \bar{J}_{si} is the average sap flow of trees from the fourteen sample trees attributed to the class i , A_{si} the total sapwood area of trees from the fourteen sample trees attributed to the class i . The sum of transpiration of each rank of DBH and its proportion in the total transpiration of whole stand of *A. mangium* during October are given in Fig. 5. According to the results, we concluded that transpiration of the two larger ranks was higher and exceeded half of the stand transpiration (56.73%) in spite of less numbers, which can be attributed to larger sapwood area. In community, taller trees exhibit higher water use due to morphological dominance, besides water, light and nutrient conditions all favor the taller trees. Gradually, suppressed trees secede because growth space and survival conditions are lost. Therefore, whole-tree water use is closely related to morphology.

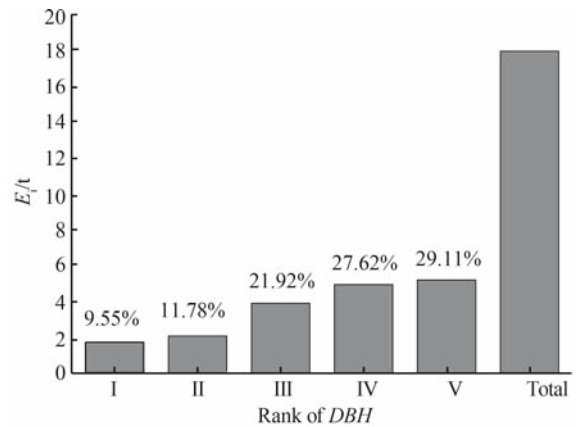


Fig. 5 Sum of transpiration of each rank of DBH and its proportion in the total transpiration of whole stand of *A. mangium*

3.2 Relationship between morphological features of tree and whole-tree transpiration

We singled out a sunny day (October 2, 1996) for analysis. We calculated daily transpiration (E) of the fourteen sample

trees firstly, compared daily transpiration with *DBH*, sapwood area, height and canopy projected area (the canopy projected area was taken as an ellipse and the longest and shortest diameters as prolate and minor axes) separately in scattering plot. Whole-tree transpiration was in a logarithmic relationship with *DBH*, sapwood area, canopy size; and was positively related to the height in a way of power function. Correlation analysis can to some extent explain why the transpiration of taller comprised the larger proportion even though they had a less individual number. The transpiration of the first two largest *DBH* classes was more than the total amount of the stand as we can see in the calculated values above. What we should bear in mind is that the above analysis was conducted under the condition of unchanged leaf area. Fitted regression curve indicated that the transpiration cannot increase infinitely as a result of limited increment of independent variable (including *DBH*, sapwood area and canopy size); furthermore, the extent of transpiration increment may be slower when compared to the independent variable. As for the relationship between whole-tree transpiration and tree height, transpiration increased in an exponential way with tree height increment. Schäfer ever concluded that sap flow of *Fagus sylvatica* was negatively and exponentially related to tree height, which is inconsistent with our findings. The discrepancy can be attributed to species-specific sapwood characteristics. Mature *A. mangium* sapwood depth is relatively thin and rarely exceed 3 cm, on the contrary, but that of *F. sylvatica* is extraordinarily thick and can be as thick as 120 cm. The thicker the sapwood's depth is, the wider the

crossed section where water flows through. According to dynamics principle, the taller the tree is the more driving force it needs to transfer water upward within the trunk. Larger sap wood area needs more driving force at certain height for water transfer upward. As for *A. mangium*, the height increment can receive more light energy which in turn favors transpiration because of thin sapwood.

3.3 Responses of canopy stomatal conductance to *PAR* and vapor pressure deficit (*VPD*)

Among the environmental factors, *PAR* and *VPD* are the main driving force for plant transpiration at smaller temporal scale (hourly, daily) (Granier and Bréda, 1996). Better understanding how *VPD* and *PAR* response to sap flow and canopy stomatal conductance can set up the research framework to analyse forest transpiration. It was not likely to study forest canopy water use until sap flow measurement system was applied into ecology (Granier and Bréda, 1996). Canopy stomatal conductance has been calculated using sap flow and corresponding *VPD* by some scholar (Köstner et al., 1992; Granier and Bréda, 1996; Schäfer et al., 2000). *A. mangium* is accustomed to humid tropical region and high water-consuming. It was widely planted in hilly region of southern china as pioneer species since it was successfully introduced into this country (Zeng et al., 2000b). The rainfall of this region is plenty enough for *A. mangium* growth. The experimental plot of *A. mangium* forest is a plantation, of which individual distribution is quite uniform and leaf area index

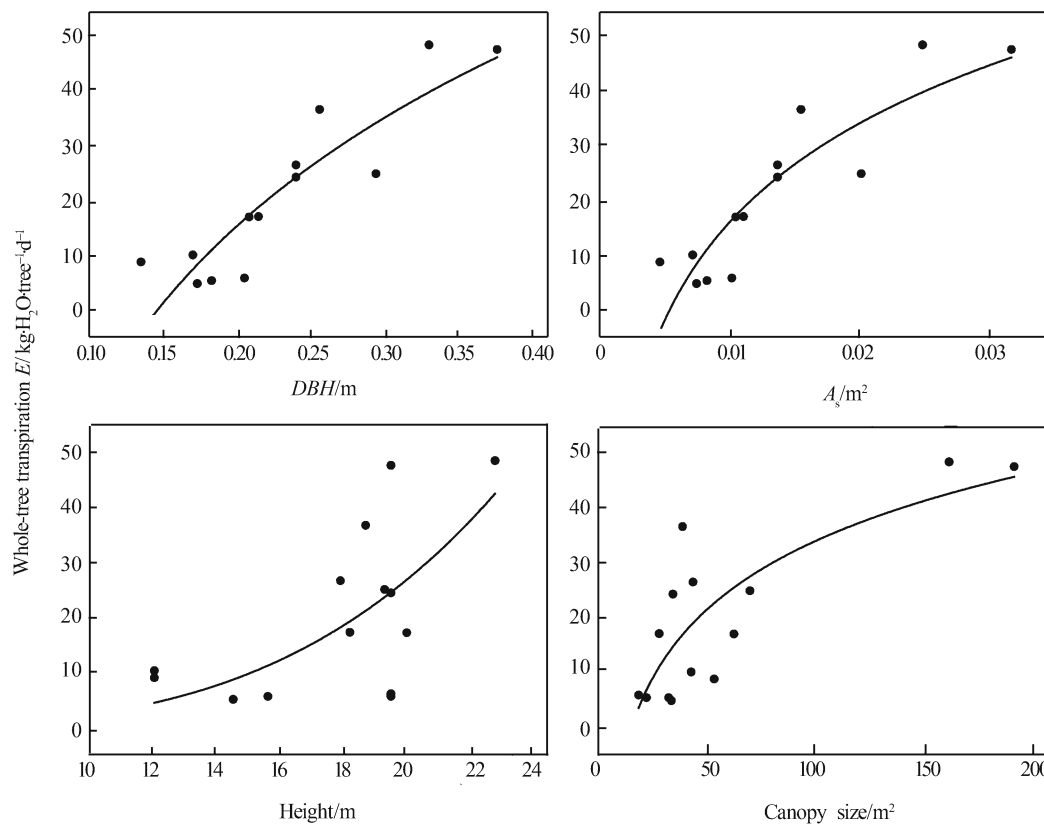


Fig. 6 Regression between whole-tree transpiration and *DBH*, sapwood area, tree height as well as canopy size

Table 1 Results of regression analyses between whole-tree transpiration rate and *DBH*, sapwood area, tree height and canopy size using different forms of equations

Correlation analysis and regression equation	<i>DF</i>	<i>F</i>	<i>r</i> ²	<i>p</i>
<i>E</i> versus <i>DBH</i> : $y = 93.6187 + 48.3092\ln x$	13	47.2933	0.7976	<0.0001
<i>E</i> versus <i>A_s</i> : $y = 136.4645 + 26.1229\ln x$	13	47.0966	0.7969	<0.0001
<i>E</i> versus height: $y = 0.0007x^{3.5053}$	13	8.2543	0.4075	0.0140
<i>E</i> versus canopy size: $y = -48.5402 + 17.9655\ln x$	13	20.4245	0.6299	0.0007

is between 2.2 and 3.1, with a well-ventilated canopy and understorey so that a vertical profile of *VPD* gradient can be ignored. It means that all requirements were met when applying the simplified equation supposed by Köstner to calculate canopy stomatal conductance (Köstner et al., 1992).

Therefore, we achieved the mean canopy stomatal conductance by using Eq. (9) (Köstner et al., 1992; Granier and Bréda, 1996; Pataki et al., 1998).

$$g_c = \frac{E_t}{A_g \times LAI \times 18} \times \rho \times G_v \times \frac{T + 273}{D} \quad (9)$$

where E_t is the stand transpiration, which was estimated using Eq. (6); A_g stand area, LAI the leaf area index of stand, ρ the water specific density, T the air temperature, G_v the gas constant, and D the vapor pressure deficit.

E_t is instantaneous value estimated from sap flow, the calculated canopy stomatal conductance is instantaneous according to Eq. (7) as well. The variation of g_c can reflect the continuous trend of stand water use. Monthly variation during October 2003 and daily variation on 29 October of stand transpiration, mean stomatal conductance, *PAR* and *VPD* above-canopy were shown in Figs. 7 and 8 separately. The result of *A. mangium* canopy stomatal conductance is

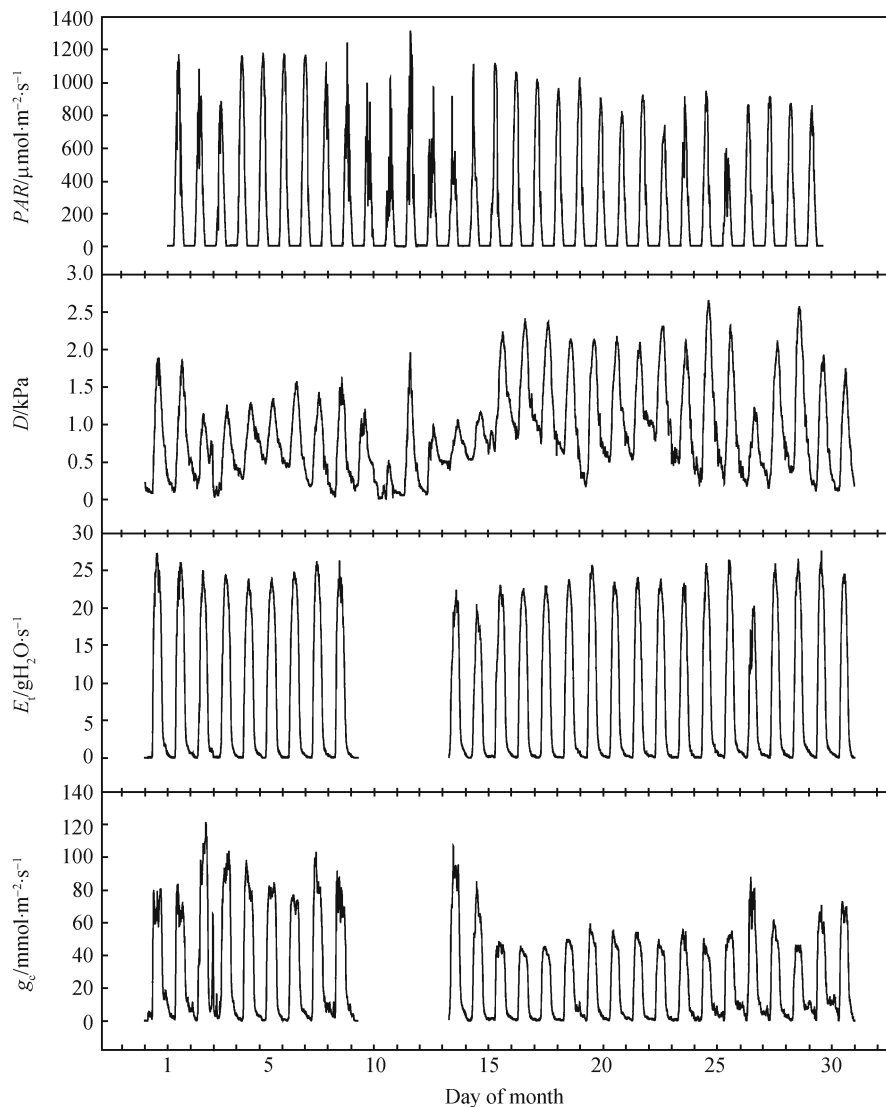


Fig. 7 Monthly changes of stand transpiration, mean canopy stomatal conductance, photosynthetically active radiation and vapor pressure deficit of *A. mangium* in October 2003 (Missing of data was the results of lightning-induced equipment failure)

consistent with broadleaf forest according to other scientists (Pataki et al., 1998; Schäfer et al., 2000). October is the last phase for plant growth, when leaf area index of community reaches the maximum (slight defoliating in spring and winter) and soil water is relative stable, thus leaf area index and soil water content can be ignored when analyzing canopy stomatal conductance response to PAR and D (Köstner et al., 1992; Schäfer et al., 2000).

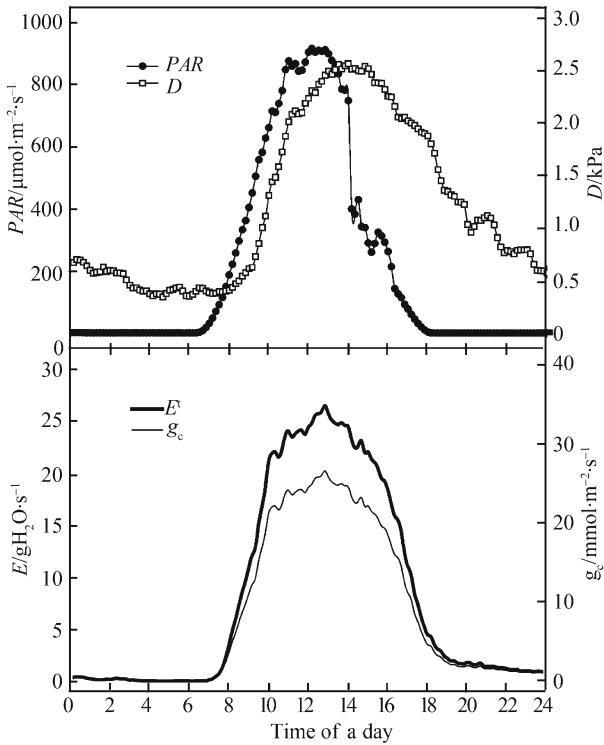
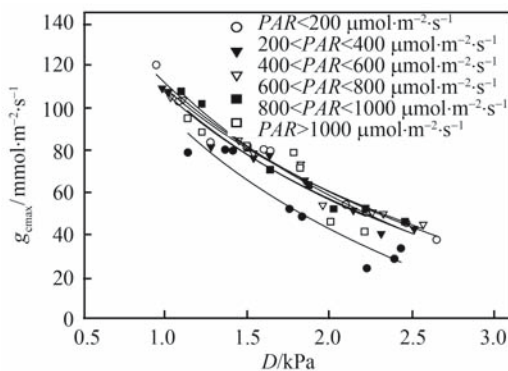


Fig. 8 Daily changes of stand transpiration, mean canopy stomatal conductance, photosynthetically active radiation and vapor pressure deficit of *A. manium* on October 29, 2003

To clearly describe the responses of PAR and D to g_{cmax} , those data were eliminated from the data series when D was lower than 1 at which the estimated g_c is either to low or unstable. Response of g_c to D exhibited regular trend if only D is higher



than 1 (Granier, 1987; Zhao and Peng, 2001) according to other scholars' researches and our analysis. PAR is ranked from low to high and classified into six levels at $200 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ intervals. Then D was rearranged from low to high in each PAR rank, correlation and regression analyses between g_{cmax} and corresponding D were conducted in an order at 0.2 kPa interval (Fig. 9). The D data were similarly ranked into four levels at 0.5 kPa intervals from low to high in the same way as PAR ranking with arraying PAR and g_c from small to large at each D level. Responses of g_{cmax} to corresponding PAR and D are shown in Fig. 9. g_{cmax} is negatively related to D in a nonlinear way ($p < 0.001$) (Fig. 9), which can be expressed as $g_{cmax} = a + b \ln D$ ($b < 0$). g_{cmax} decreased by 70% as D increased from 1 to 2 kPa, which indicated that the sensitivity of canopy stomatal conductance response to D is higher when D is between 1 and 2. At a given D , g_{cmax} under a PAR less than $200 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ is significantly lower than at other PAR ranks, which implied PAR exerts stronger control on stomata when PAR was lower than $200 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$. For other PAR ranks, g_{cmax} responses to D were quite identical and no difference was found among different PAR ranks. G_{cmax} response to PAR as PAR increment tended to be a saturated hyperbola, which was expressed in $g_{cmax} = (a \times PAR) / (b + PAR)$ ($p < 0.0001$). Canopy stomatal conductance reached to a plateau when PAR was between $350\text{--}400 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ and the sensitivity of g_{cmax} to D declined gradually with D increment. According to the analyzed results above, we concluded that the variation of g_c associated with that of D was the dominant combination factor controlling whole-tree transpiration and stand transpiration and light radiation is essential environment factor for regulating canopy stomata activity.

4 Conclusions

Sap flow measurement system has better application and distinctive advantages in the researches on water use by forest. Both whole-tree transpiration and stand transpiration can be acquired based on the sap flow density by integrated the among-tree and among-class variations to the stand

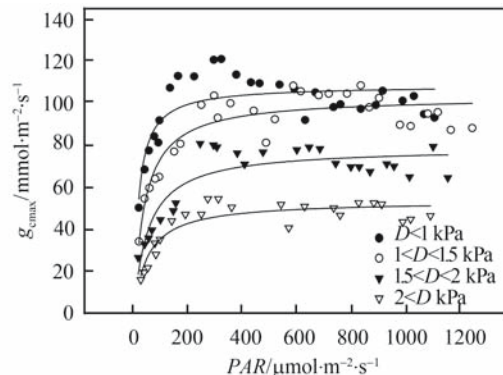


Fig. 9 Responses of maximum canopy stomatal conductance to photosynthetically active radiation and vapor pressure deficit

canopy level. Besides, sap flow can provide continuous measurement, whole-day transpiration or even longer period transpiration can be obtained through simple summation. It can also avoid the error as a result of time lag between sap flow and canopy transpiration (Kubota et al., 2005) and therefore is applicable in large area of plantation. Sap flow measurement can distinguish transpiration among-individual and among-class in the stand, which is convenient for determining the ratio of a certain class or layer along the vertical profile. Tree form has significant effects on *A. mangium* transpiration. As for the whole-tree water transpiration, taller trees possess predominance. The sap flow-based canopy stomatal conductance can provide a way of linkage relating canopy stomatal conductance to environment factors, which will help to explain the mechanism of water use of forests in different habitats.

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References

- Deng H P, Wu Z F, Zhou D W (2000). Response of broad-leaved *Pinus koraiensis* forest in Xiao Xing An Ling Mt to global climate change—a dynamic modeling. *Chin J App Ecol*, 11: 43–46 (in Chinese)
- Granier A (1987). Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Phys*, 3: 309–319
- Granier A, Biron P, Köstner B, Gay LW, Najjar G (1996). Comparison of xylem sap flow and water vapor flux at the stand level and derivation of canopy conductance forest Scots pine. *Theor Appl Climatol*, 53: 115–122
- Granier A, Bréda N (1996). Modeling canopy conductance and stand transpiration of an oak forest from sap flow measurements. *Ann Sci For*, 53: 537–546
- Köstner B, Schulze E D, Kelliher F M (1992). Transpiration and canopy conductance in a pristine broad-leaved forest of Nothofagus: An analysis of xylem sap flow and eddy correlation measurements. *Oecologia*, 91: 350–359
- Kubota M, Tenhunen J, Zimmermann R, Schmidt M, Adiku Samuel, Kakubari Y (2005). Influences of environmental factors on the radial profile of sap flux density in *Fagus crenata* growing at different elevations in the Naeba Mountains, Japan. *Tree Phys*, 25: 545–556
- Lu P, Urban L, Zhao P (2004). Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. *Acta Bot Sin*, 46(6): 631–646
- Ma L, Zhao P, Rao X Q, Cai X A, Zeng X P (2005). Main determination methods of tree transpiration. *Chin J App Ecol*, 24(1): 88–96 (in Chinese)
- Pataki D E, Oren R, Katul G, Sigmon J (1998). Canopy conductance of *Pinus taeda*, *Liquidambar styraciflua* and *Quercus phello* under varying atmospheric and soil water conditions. *Tree Phys*, 18: 307–315
- Running S W, Coughlan J C (1988). A general model of forest ecosystem processes for regional application. I. Hydrologic balance, canopy gas exchange and primary production process. *Ecol Model*, 42: 125–154
- Schäfer K V R, Oren R, Tenhunen J D (2000). The effect of tree height on crown level stomatal conductance. *Plant Cell Environ*, 23: 365–375
- Schulze E D (1986). Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. *Ann Rev Plant Phys*, 37: 247–274
- Sun G C, Zhao P, Zeng X P, Peng S L (2001). Influence of elevated atmospheric CO₂ concentration on photosynthetic and leaf nitrogen concentration partition in process of photosynthetic carbon cycles in *Musa paradisiacea*. *Chin J App Ecol*, 12: 429–434 (in Chinese)
- Sun G C, Zhao P, Zeng X P, Peng S L (2004). Variation of photosynthetic parameters in CO₂ acclimation of *Citrus grandis* leaves, *Chin J App Ecol*, 15: 9–14 (in Chinese)
- Zeng X P, Peng S L, Zhao P (2000a). Measurement of respiration amount in artificial *Acacia mangium* forest in a low subtropical hill forest region of Guangdong. *Acta Phytoecol Sin*, 24(4): 420–424 (in Chinese)
- Zeng X P, Zhao P, Peng S L (1999). Study on the water ecology of three understory plants in a leguminous mixed forest in Heshan, Guangdong. *Ecol Sci*, 18(4): 1–5 (in Chinese)
- Zeng X P, Zhao P, Peng S L (2000b). Study on the water ecology of artificial *Acacia mangium* forest in the Heshan hilly region, Guangdong Province. *Acta Phytoecol Sin*, 24(1): 69–73 (in Chinese)
- Zhao P (2003). Advance in plant ecophysiological studies on re-vegetation of degraded ecosystems. *Chin J App Ecol*, 14(11): 2031–2036 (in Chinese)
- Zhao P, Peng S L (2001). Species and species diversity in relation with restoration and persistence of degraded ecosystem function. *Chin J App Ecol*, 12(1): 132–136 (in Chinese)
- Zhao P, Zeng X P, Cai X A, Peng S L (2002). Report on measurement of leaf area index of low subtropical forests by using digital plant canopy imager. *Guihaia*, 22(6): 485–489 (in Chinese)
- Zhao P, Zeng X P, Peng S L (2003). Ecological adaptation of leaf gas exchange of trees used for re-vegetation under different experimental light regimes. *Chin J Ecol*, 22(3): 1–8 (in Chinese)
- Zhao P, Zeng X P, Yu Z Y (1997). Relationship between transpiration of shrubs under artificial *Acacia mangium* stand on hilly land of South China and its microclimate during wet season. *Chin J App Ecol*, 8(4): 365–371 (in Chinese)