植 物 学 报
Acta Botanica Sinica 2002, **44** (12) : 1418 - 1424

Radial Variation in Sap Flux Density as a Function of Sapwood Thickness in Two Eucalyptus (*Eucalyptus urophylla*) Plantations

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Abstract: Radial variation in sap flux density (SFD) as a function of sapwood thickness is of importance in accurately estimating sap flux through sapwood area which, in turn, decides the precision of heat pulse application. However, until now, only a few studies have evaluated the magnitude and significance of sampling errors associated with radial gradients in SFD, which were based on the small monitoring measurement data from a few trees. Based on one year of heat pulse observation of two 3 - 4 years old *Eucalyptus urophylla* S. T. Blake plantations in Leizhou Peninsula, Guangdong Province, China, a way of data processing was developed to treat with the lots of SFD data measured from 39 trees. It was found that the radial variation in SFD as a function of sapwood thickness in the two eucalyptus plantation sites could be expressed as $y = 3.6675x^3 - 7.2955x^2 + 3.6826x + 0.5674$ ($R^2 = 0.9391$, $n = 80$, $P = 0.01$), where y is the ratio of SFD of a sensor to the average of four data in different depths, x is the ratio of a sensor depth to the radial sapwood thickness. It was the same (as in the following equation) in Jijia site, $y = 5.0062x^3 - 9.1161x^2 + 4.4544x + 0.4634$ ($R^2 = 0.8069$, $n = 72$, $P = 0.01$) in Hetou site. From cambium to heartwood, SFD showed some increases at first and then decreases continuously. However, because the trees were very young, the maximum SFD was only 0.33 - 0.36 times more than the minimum.

Key words: radial variation; sap flux density; sapwood thickness; eucalyptus trees

There have been lots of publications dealing with sap flux analysis. Most of them were on water use of trees and transpiration of stand (Granier, 1987; Granier *et al*, 1996; Oren *et al*, 1998), but not until the 1960s, sap flow measurements had rarely been used to estimate transpiration of an entire stand (Ladefoged, 1963; Doley and Grieve, 1966). More recently, the studies on sap flux had focused more on the combination of stomatal conductance and stand transpiration (Kostner *et al*, 1992; Pataki *et al*, 1998; Ewers and Oren, 2000; Oren *et al*, 2001). Such extrapolation requires not only accurate measurements of sap velocity, but also detailed inventories of stand-level attributes including tree domain, defined either by distance between stems or crown area (Hatton and Vertessy, 1990), basal area, leaf area or sapwood area (Phillips *et al*, 1996).

Although extrapolations, based on sapwood area, are conceptually simple, estimates of tree and forest water use derived in this manner are subject to uncertainties (Smith and Allen, 1996; Kostner, 1998). The foremost among these uncertainties is the actual proportion of sapwood functional in water transport (Wullschleger and King, 2000). Previous studies have shown that radial variation in sap velocity clearly existed in many woody species (Dye *et al*, 1991; Becker, 1996; Phillips *et al*, 1996; Oren *et al*, 1999), with sap velocities being greatest in outer sapwood and progressively lower with increasing proximity to heartwood. Zang *et al* (1996) reported that, on average, only 78% of sapwood was active in water transport for an eucalyptus species. The studies that do recognize radial variation as an important consideration in extrapolating sap velocity to the canopy scale often use only limited measurements (one to two trees) to quantify this parameter. Very few studies have evaluated the magnitude and significance of sampling errors associated with radial gradients in sap velocity (Dye *et al*, 1991; Hatton *et al*, 1995; Wullschleger and King, 2000).

This study is to assess radial variation in sap flux density as a function of sapwood thickness in two eucalyptus (*E. urophylla*) plantations. It has been suggested that excessive water used by eucalypt plantations contributes to the depletion of ground water resources, and soil moisture shortage as a result of high water use is also believed to limit tree growth during the dry season (Calder, 1992; Davidson, 1995; Bruijnzeel, 1997; Landsberg, 1997). However, there has been few direct and quantitative studies of the water use or water balance of eucalypt plantations in southern China. It is the objective of China-Australia joint project (FS 1997), "Eucalyptus and Water", that is being carried out both in

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Received: 2001-12-21 Accepted: 2002-04-04
Supported by China-Australia Joint Project (FST1997), the National Natural Science Foundation of China (39928007), Preliminary Project of the State Key Basic Research and Development Plan of China (2001CCB00600), Overseas Talent Chinese Foundation, The Chinese Academy of Sciences, and Natural Science Foundation of Guangdong Province (010567).

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Leizhou Peninsula, Guangdong Province, China and Australia. *E. urophylla* has several desirable characteristics: stem radius is symmetrical and sapwood thickness is uniform around the stem circumference. The sapwood interfaces with heartwood and cambium are easily distinguished based on coloration.

The experiment was finished in two different places. For each place, about 19 trees of different thickness were selected, each two trees were monitored for 1 - 2 months, and 4 sensors with different depths in a tree were installed. All measurement results in each place were properly treated to make the data of radial variation of sap velocity to be only the results of relative radial position of sensors (see the data processing).

1 Materials and Methods

1.1 Description of the sites of plantation

The climate of Leizhou Peninsula, Guangdong Province, China, is tropical, with monthly mean temperature 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; year to year variation is also high. Over 80 % of the rain-falls between April and September, up to half of this in typhoons which occur about seven times per year on average. Plantation water use studies have been initiated at two sites in the Nandu River catchment. One site is on a basalt-derived clay soil within the Jijia demonstration catchment area, while the other is approximately 40 km north near Hetou on a sandy soil of sedimentary origin. In both sites, the monitored plantations were *E. urophylla* planted in 1996. A 40 m × 40 m plot was defined at each site in September 1999, tree diameters recorded and a set of trees selected to match the diameter distribution of the stand.

1.2 Sap flux density monitoring

Two trees in each plot were implanted with heat pulse probes, and sap flux density was recorded at 30 min intervals using the HeatPulser system developed by Edwards Industries of New Zealand. The HeatPulser system is a new development in heat pulse instrumentation which has not been used in a major project previously, but it offers superior accuracy and reliability compared to alternative equipment. Development and customization of software for convenient data collection and analysis with the HeatPulser system has been carried out by CFTT (Centre for Forest Tree Technology, Victoria 3084, Australia) in Jijia and Hetou plantations as testing grounds.

The probes were removed and reimplanted on a new pair of trees at intervals of approximately 4 - 6 weeks throughout the year. Four sensors were distributed in a tree in four directions (North, South, East and West) and depths. The depth of sensor was determined by the positions of cambium and heartwood so that all four sensors would be located in different positions of the xylem (Fig. 1). During September 12, 1999 to September 24, 2000, 18 and 20 trees in total at Hetou and Jijia sites, respectively were monitored by the HeatPulser system.

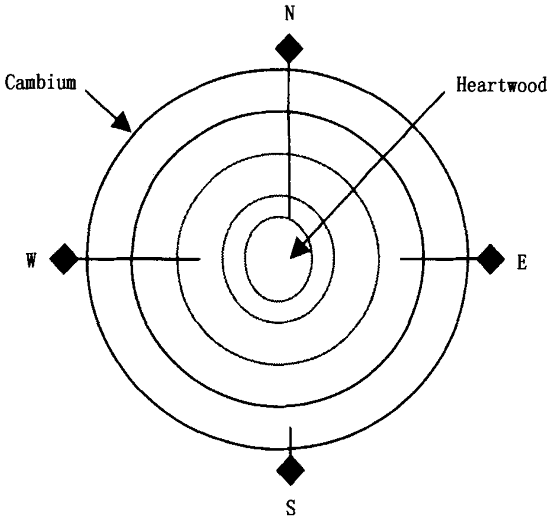

Fig. 1. A schematic diagram showing probe placement in sapwood annulus.

The sensor depths in four directions were randomly arranged.

1.3 Measurements of sapwood area and other supplementary data

In addition to sap flux density, the growth of sapwood area of the stands was tracked by repeated diameter measurements and the relationship between the sapwood area and diameter in individual tree was derived. Supplementary measurements of probe separation, wound size and volume fractions of water and wood in the monitored trees were routinely collected to derive the sap flux density observations.

1.4 Monitoring of environmental factors

Environmental monitoring equipment was installed at the Jijia and Hetou water use monitoring sites in September 1999 for intensive climate and soil moisture observations. At each site, a data logger collects half-hourly readings of solar radiation, rainfall, wind speed, relative humidity and air temperature at tree canopy level, and soil moisture content at 50, 150, 250 and 350 cm depth with buried Thetaprobe sensors. Customized software had been developed for the management and condensation of this large dataset.

Soil samples were collected from 30 cm depth intervals at each site to 390 cm in September 1999 and again in April 2000, i.e. at the end of the wet season and the end of the dry season respectively. The moisture content and matric potential of each sample were determined to characterize the moisture release properties of the two soils. Moisture content data were also used to calibrate the Thetaprobe sensors used for monitoring the change in soil moisture distribution through time.

1.5 Data processing

For each monitored tree, the ratio of sensor depth (X, in the unit of cm) to xylem ring thickness (Y, in the unit of cm) was taken to represent the relative position of a sensor in the xylem. The ratio would be 0 to 1. Zero means the position of cambium, 0.5 means the middle of xylem and 1 means the interface of sapwood and heartwood, which would be suitable to all monitored trees even if their diameters are different (Table 1). After deleting the apparently abnormal heat pulse recordings in some days for several trees, we averaged the measurement results of all days in each tree at same time and same sensor depth. For comparison of sap flux density among the trees of various diameters, it is necessary to standardize the monitored result of each sensor. The data processing was carried out as follows: the ratio of sap flux density (in the unit of mL·cm^{-2}·h^{-1}) of a sensor to the average of four sensors (in the unit of mL·cm^{-2}·h^{-1}) (Table 2) in the same recording was taken as the relative value of sap flux density (no unit) of the sensor.

Tables 1 and 2 are the demonstration of data processing.

2 Results

2.1 Sapwood area and thickness

There was significant correlation ($P = 0.01$) between stem diameter (dbh) and sapwood area (defined as the cross-sectional area between the inner bark surface, i.e., the cambium and the outer heartwood) for both in Jijia and Hetou. Sapwood areas could be estimated from a power function of dbh based on regression (Fig. 2).

Compared with sapwood area, sapwood thickness (y) was a linear function of cambium diameter (x). The regression relationships were $y = 0.138x + 0.996$ ($R^2 = 0.460$, $n = 18$) and $y = 0.140x + 0.725$ ($R^2 = 0.644$, $n = 18$) for Jijia and Hetou, respectively. Four replicate cores taken from every one of 18 trees revealed sapwood thickness was uniform around the circumference of each tree (Fig. 3).

2.2 Wood and water fractions in sapwood

For each wood core described above, the volumes of wood and water were measured to check how the components of xylem affect sap flux velocity. Unfortunately, not any significant change of wood and water fraction with cambium diameters were detected. There might be two causes for this result. One was that the two plantations were very young, and thus, no much difference in water and wood contents existed through xylem in radial direction. The other might result from the accuracy of measurement (Fig. 4).

2.3 Effects of sensor depth on sap flux density

Sap flux density (SFD) is differently distributed between the sapwood surface and the outmost of heartwood. Estimating the mass-flow rates through cross-section of trunk needs accurate determination of the distribution of SFD.

Figure 5 shows the results incidentally selected from the data measured in Jijia and Hetou sites. SFD was highly dependent on the depth of probe insertion into the sapwood during daytime, but no much difference in the

Table 1 Standardization way of sensor relative radial position in xylem

Tree number		Tree 1	Tree 2	······	Tree N
Sensor 1	Depth (cm)	X_{11}	X_{12}	······	X_{1n}
	Relative position	X_{11}/Y_1	X_{12}/Y_2	······	X_{1n}/Y_n
Sensor 2	Depth (cm)	X_{21}	X_{22}	······	X_{2n}
	Relative position	X_{21}/Y_1	X_{22}/Y_2	······	X_{2n}/Y_n
Sensor 3	Depth (cm)	X_{31}	X_{32}	······	X_{3n}
	Relative position	X_{31}/Y_1	X_{32}/Y_2	······	X_{3n}/Y_n
Sensor 4	Depth (cm)	X_{41}	X_{42}	······	X_{4n}
	Relative position	X_{41}/Y_1	X_{42}/Y_2	······	X_{4n}/Y_n

Table 2 Standardization way of sap flux density recordings for a tree (taking tree 1 as example)

<table>
<tr><td colspan="10">Original data sample</td><td></td></tr>
<tr><td></td><td colspan="4">Day 1</td><td>······</td><td colspan="4">Day N</td><td></td></tr>
<tr><td></td><td>8:00</td><td>8:30</td><td>······</td><td>20:00</td><td>······</td><td>8:00</td><td>8:30</td><td>······</td><td>20:00</td><td></td></tr>
<tr><td>Sensor 1</td><td>$A_{1,1}$</td><td>$A_{1,2}$</td><td>······</td><td>$A_{1,25}$</td><td>······</td><td>$A_{N,1}$</td><td>$A_{N,2}$</td><td>······</td><td>$A_{N,25}$</td><td></td></tr>
<tr><td>Sensor 2</td><td>$B_{1,1}$</td><td>$B_{1,2}$</td><td>······</td><td>$B_{1,25}$</td><td>······</td><td>$B_{N,1}$</td><td>$B_{N,2}$</td><td>······</td><td>$B_{N,25}$</td><td></td></tr>
<tr><td>Sensor 3</td><td>$C_{1,1}$</td><td>$C_{1,2}$</td><td>······</td><td>$C_{1,25}$</td><td>······</td><td>$C_{N,1}$</td><td>$C_{N,2}$</td><td>······</td><td>$C_{N,25}$</td><td></td></tr>
<tr><td>Sensor 4</td><td>$D_{1,1}$</td><td>$D_{1,2}$</td><td>······</td><td>$D_{1,25}$</td><td>······</td><td>$D_{N,1}$</td><td>$D_{N,2}$</td><td>······</td><td>$D_{N,25}$</td><td></td></tr>
<tr><td>↘</td><td colspan="4">Average for different days, i.e.,
$a_{1,1} = (A_{1,1} + \cdots + A_{N,1})/N$
······
$d_{1,25} = (D_{1,25} + \cdots + D_{N,25})/N$</td><td rowspan="5">→</td><td colspan="4">Standardization to the recordings,
$E_{1,1} = 4a_{1,1}/(a_{1,1} + \cdots + d_{1,1})$
······
$H_{1,25} = 4d_{1,25}(a_{1,25} + \cdots + d_{1,25})$</td><td>Mean</td></tr>
<tr><td>Sensor 1</td><td>$a_{1,1}$</td><td>$a_{1,2}$</td><td>······</td><td>$a_{1,25}$</td><td>$E_{1,1}$</td><td>$E_{1,2}$</td><td>······</td><td>$E_{1,25}$</td><td>x_{11}</td></tr>
<tr><td>Sensor 2</td><td>$b_{1,1}$</td><td>$b_{1,2}$</td><td>······</td><td>$b_{1,25}$</td><td>$F_{1,1}$</td><td>$F_{1,2}$</td><td>······</td><td>$F_{1,25}$</td><td>x_{21}</td></tr>
<tr><td>Sensor 3</td><td>$c_{1,1}$</td><td>$c_{1,2}$</td><td>······</td><td>$c_{1,25}$</td><td>$G_{1,1}$</td><td>$G_{1,2}$</td><td>······</td><td>$G_{1,25}$</td><td>x_{31}</td></tr>
<tr><td>Sensor 4</td><td>$d_{1,1}$</td><td>$d_{1,2}$</td><td>······</td><td>$d_{1,25}$</td><td>$H_{1,1}$</td><td>$H_{1,2}$</td><td>······</td><td>$H_{1,25}$</td><td>x_{41}</td></tr>
</table>

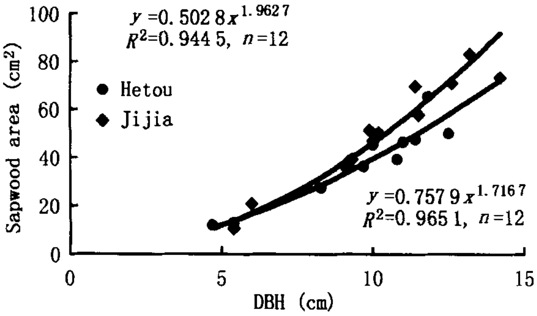

Fig. 2. Relationship between measured stem diameter (dbh) and cross-sectional sapwood area in Jijia and Hetou.

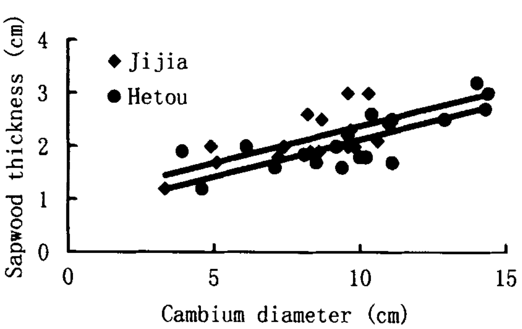

Fig. 3. Relationship between measured cambium diameter and sapwood thickness in Jijia and Hetou.

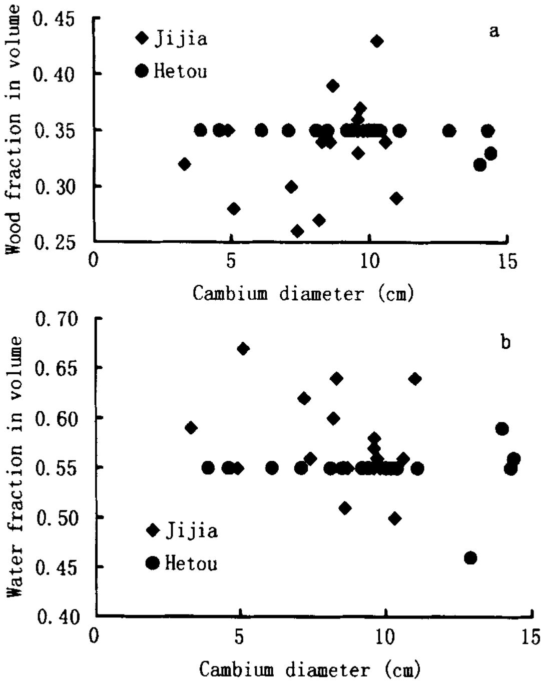

Fig. 4. The influences of cambium diameter on wood and water fractions.

other time of the day. From all measured data, SFD measured by S4 were almost all (except few ones) the smallest, that measured by most of S2 were the biggest, and then, S1 and S3. These results demonstrated some statistical trends for the radial distribution of SFD.

For the purpose of drawing out the trends of radial distribution of SFD, it is necessary to take the monitoring data of all trees into consideration. Based on the data processing explicated above, the relative values of sap flux density during 08:00 - 20:00 of each sensor were averaged for all the recordings of September 12, 1999 to September 24, 2000. The results are shown in Fig. 6.

Figure 6 showed that SFD in sapwood distributed with radial sapwood thickness in the pattern of $y = ax^3 + bx^2 + cx + d$ (y, sap flux density, x, distance from cambium in xylem, a, b, c, d are the four constants) for *E. urophylla* plantations in Hetou and Jijia.

There was no significant difference in plantations of both places, although the two sites are 40 km far from each other and the soil origins are totally different. The result might demonstrate that the distribution of SFD in radial sapwood thickness is independent on environment and determined only by the characteristics of the species.

The biggest SFD located in 0.3 - 0.4 times of radial sapwood thickness (RST) started from cambium, no matter what diameter of the trunk was. From cambium to 0.3 - 0.4 times of RST, sap flux density increased continuously, which might demonstrate that the vessels were gradually empty and easy to conduct water. Between 0.4 times of RST to the outmost of heartwood, sap flux density was lessening. And until 0.8 - 0.9 times of RST, the sap flux density reduced to 0.68 - 0.72 of the average. In this experiment, the sensor depth was set to 0.94 of RST, which was close to the heartwood and the sap flux density was found to be 0.28 of the average. Due to lacking of the measurement on water and wood fraction throughout sapwood, it could not be concluded that the distribution pattern of SFD in radial xylem had any relationship with them.

3 Discussion

SFD exhibited substantial variation in relation to sapwood depth (Cohen *et al*, 1981; Dye *et al*, 1991; Becker, 1996; Oren *et al*, 1999; Wullschleger and King, 2000). Many measurements showed the SFD was several-fold higher in outer sapwood than that in inner sapwood. However, the change pattern of SFD with probe depths was different with the results of different authors.

Wullschleger and King (2000) found, through the observations for several single yellow-poplar trees, that the sap velocity (mm/s) was the highest and very close to cambium, and then, decreased greatly and gradually to zero until 5 cm in radial depth from cambium. Only in two trees, there was a maximum located between the cambium and the depth of 5 cm in radial direction in their study.

Jones *et al* (1988) studied the effect of sensor depth on temperature rise in the stem at certain distance from the heater, based on few single trees. He discovered a similar change pattern to ours but found the temperature changes were not very sensitive to sensor depth, even though mass-flow rates tend to be greatest in the youngest wood, decreasing rapidly through the older annual rings as described by Zimmermann (1983) and Swanson (1975).

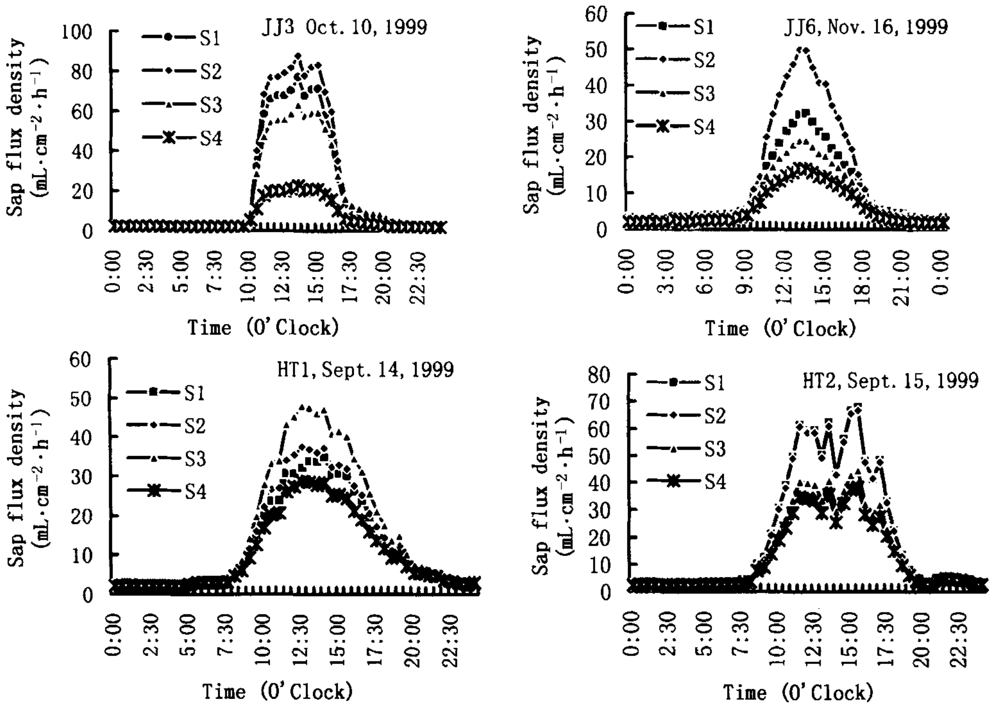

Fig. 5. Diurnal variation in sap flux density measured at four sapwood depths in four eucalyptus trees selected from Jijia and Hetou sites. S1-S4 represented the four probes and their depths were gradually deeper.

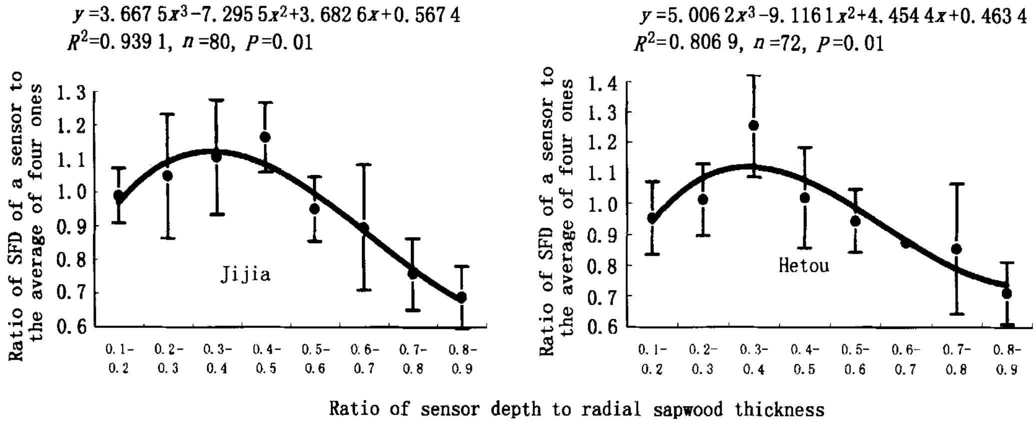

Fig. 6. Maximum probability for distribution of sap flux density in all trunks of *E. urophylla* plantations of Hetou and Jijia.
Horizontal axis represents the ratio of sensor depth to radial sapwood thickness (arbitrary unit). Vertical axis represents the ratio of sap flux density of a sensor to the average of four ones in the same recording (arbitrary unit), which deleted the probable difference caused by different diameter of trunks, climatic pattern of monitoring duration, etc. Vertical bar shows standard error.

It can be rationally expected for 3 - 4 years old of *E. urophylla* trees that the distribution of SFD should be continuous throughout the xylem, and SFD will not be of much difference for any two very nearby points no matter whether the two points are located in the same or different annulus. Even though for springwood and summerwood, there is a transition area continuously linking these two parts. Figure 6 supported our hypothesis. Based on the anatomy of xylem structure, it is also easy to explain the phenomenon what Fig. 6 explicated. Because the outmost annulus of xylem was newly formed and the vessels often contained more remnants from original living cells, water conductivity of the annulus was more of resistance than the former xylem, and thus, its SFD was smaller. From 0.3 - 0.4 times of RST to heartwood, the xylem was usually formed in several years ago and various invasions often filled the vessels gradually, so that the water conductivity would decrease to zero until the outmost of heartwood.

How to comprehensively analyze the data from the measurement of various trees and dates is another key problem for studies on radial variation in SFD. Unfortunately, so far to my knowledge, no publication dealing with efficient data processing based on heat pulse sensor recordings could be found. Due to the difference in diameter, soil water content and solar radiation, the probe depths and results of observations among various monitored trees would be greatly different. If the sensor recordings were not managed well, the radial variation in SFD could not be demonstrated well. This paper showed a valuable way of data processing.

In our study, because the trees for observation were very young, wood and water fractions in sapwood, on the average, were not detected to be related to tree diameter. Perhaps the situation is universal even though trees are very old, but we are not certain.

It is regret that we have no data of the change of wood and water fraction with radial depths in sapwood. It was impossible to analyze the relationship between radial variation in SFD and water fractions in the sapwood.

Acknowledgements: Special thanks to Mr. CHU Guo-Wei and Dr. YAN Jun-Hua for their field works related to this studies, and Dr. ZHAO Ping for providing a lot of references.

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桉树人工林树液流动密度随边材径向深度的变化

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摘要: 树液流动密度(SFD)随边材径向深度的变化对于准确估测流经边材的树液通量是非常重要的,后者又制约着 Heat Pulse 的应用精度。但迄今为止,只有很少的研究估计了由于 SFD 随径向的梯度变化而带来的误差,SFD 沿树干径向分布规律的获得往往依靠对少数几棵树的观测资料。基于在广东雷州半岛对两块 3～4 年生桉树(*Eucalyptus urophylla* S.T. Blake)人工林 1 年的 Heat Pulse 观测,探讨了对来自 39 株立木大量观测资料的综合处理方法,发现这两个样地(纪家和河头)的林分中 SFD 随边材径向深度的变化可以用如下回归方程来描述:

纪家: $y = 3.6675x^3 - 7.2955x^2 + 3.6826x + 0.5674$ $(R^2 = 0.9391,\ n = 80,\ P = 0.01)$

河头: $y = 5.0062x^3 - 9.1161x^2 + 4.4544x + 0.4634$ $(R^2 = 0.8069,\ n = 72,\ P = 0.01)$

式中: y ——某一树液感应器所测得的 SFD 与不同深度的 4 个感应器所测得的 SFD 的平均值之比; x —某一树液感应器在边材中的深度与边材厚度之比。从形成层到心材,SFD 最初有所增加,随后持续减小,但由于树木年龄很小,最大的 SFD 只比最小的 SFD 大 0.33～0.36 倍。

关键词: 径向变化; 树液流量密度; 边材厚度; 桉树

中图分类号: Q945 **文献标识码**: A **文章编号**: 0577-7496(2002)12-1418-07

收稿日期:2001-12-21 接收日期:2002-04-04
基金项目:中澳合作项目(FST1997);国家自然科学基金(39928007);科技部基础研究前期专项(2001CCB00600);中国科学院海外杰出青年基金;广东省自然科学基金联合资助。

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