

Azimuthal variations of sap flux density within Japanese cypress xylem trunks and their effects on tree transpiration estimates

Kenji Tsuruta · Tomonori Kume · Hikaru Komatsu ·
Naoko Higashi · Toshihiro Umebayashi ·
Tomo'omi Kumagai · Kyoichi Otsuki

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Abstract Sap flow techniques are practical tools for estimating tree transpiration. Though many previous studies using sap flow techniques did not consider azimuthal variations of sap flux density (F_d) on xylem trunk to estimate tree transpiration, a few studies reported that ignoring the azimuthal variations in F_d could cause large errors in tree transpiration estimates for some tree species. Therefore, examining azimuthal variations in F_d for major plantation tree species is critical for estimating tree transpiration. Using the thermal dissipation method, we examined azimuthal variations in F_d in six trees of Japanese cypress *Chamaecyparis obtusa* (Sieb. et Zucc.) Endl., which is one of the most common plantation tree species in Japan. We recorded considerable variations among F_d at four different azimuthal directions. The F_d value for one aspect was more than 100% larger than those for the other aspects. We calculated differences between tree transpiration estimates based on F_d for one to three azimuthal directions and those based on F_d for four aspects. The differences relative to tree transpiration estimates based on F_d for four aspects were typically 30, 20, and 10% in

accordance with the F_d for one, two, and three measurement aspects, respectively. This finding indicates that ignoring azimuthal variations could cause large errors in tree transpiration estimates for Japanese cypress.

Keywords Azimuthal variation · Granier-type sensor · Japanese cypress · Sap flux density · Tree transpiration

Introduction

Transpiration is a major component of the forest water cycle and also significantly affects the forest carbon cycle (e.g. Hattori et al. 1993; Komatsu et al. 2007; Kumagai et al. 2008). Thus, accurate methods for estimating transpiration are essential.

Sap flow techniques are useful tools for investigating transpiration (e.g. Wullschlegel and Hason 2006; Kume et al. 2007; Ewers et al. 2008; Oishi et al. 2008). When estimating tree and stand transpiration with sap flow techniques, scaling-up from within-tree to tree (e.g. Phillips et al. 1996; Lu et al. 2000; Tateishi et al. 2008) and from tree to stand (e.g. Oren et al. 1998; Ewers et al. 2002; Poyatos et al. 2007) are required. There are considerable errors that must be taken into account at each scaling step. Hatton et al. (1995) showed that within-tree variations in sap flow could be a major source of error for stand transpiration estimates. This suggests that within-tree scaling procedures are very important for accurately assessing transpiration of the forest stand.

Many previous studies on sap flow have examined spatial variations in sap flux density (F_d) based on the thermal dissipation method. These studies showed significant variations in radial profiles of F_d , suggesting that it is necessary to account for these profiles of F_d in tree

K. Tsuruta (✉) · T. Kume · H. Komatsu · N. Higashi ·
T. Umebayashi · T. Kumagai · K. Otsuki
Kasuya Research Forest, Kyushu University, 394 Tsubakuro,
Sasaguri, Fukuoka 811-2415, Japan
e-mail: tsuruta@forest.kyushu-u.ac.jp

T. Kume
School of Forestry and Resource Conservation, National Taiwan
University, 1, Sec. 4, Roosevelt Road, 10617 Taipei, Taiwan

T. Umebayashi
Graduate School of Frontier Science, University of Tokyo,
5-1-5 Kashiwa-no-ha, Kashiwa, Chiba 277-8563, Japan

transpiration estimates (e.g. James et al. 2002; Delzon et al. 2004; Ford et al. 2004a, b). In contrast, few studies have examined azimuthal variations in F_d . In many previous studies, a sap flow sensor was inserted in the trunk on only one aspect without considering the azimuthal variations in F_d (e.g. Granier et al. 1990, 1996; Granier and Loustau 1994; Schäfer et al. 2000; Oren and Pataki 2001; Lu et al. 2004). Such studies implicitly assume minor azimuthal variations in F_d within the trunk. However, Tateishi et al. (2008) measured F_d at four azimuthal directions in evergreen oak trees and reported that tree transpiration estimates based on one azimuthal direction could result in relative errors of up to 20%.

In Japan, there are large areas of coniferous plantations throughout the country, and *Chamaecyparis obtusa* (Sieb. et Zucc.) Endl. (Japanese cypress) is one of the most common plantation tree species. Therefore, accurate estimates of transpiration of Japanese cypress are crucial to evaluate the water cycle. Although several sap flow studies on Japanese cypress employing the thermal dissipation method have been undertaken (e.g. Fujiyama et al. 2005), no previous studies have examined azimuthal variations in F_d on Japanese cypress based on this method.

In this study, we measured F_d at four azimuthal directions for Japanese cypress. We evaluated differences between tree transpiration estimates based on F_d at one to three azimuthal directions and those based on F_d at four azimuthal directions. Based on these results, the validity of ignoring azimuthal variations in F_d for Japanese cypress is discussed.

Materials and methods

Site description

The study was carried out at the Geisha site in the Kasuya Research Forest, Kyushu University (33°38'N, 130°31'E,

50 m a.s.l.). The annual mean air temperature and annual mean precipitation recorded between 2000 and 2004 were 16.2°C and 1,560 mm, respectively. We conducted measurements in two adjacent existing Japanese cypress stands with different tree sizes, designated as the M and L stands. We utilised these two stands, because azimuthal variations in sap flux density might vary with tree size. Three sample trees were selected from each stand (Table 1). These trees were of typical size in the stands and were not located near the stand edge. The stem density of the M stand was 1,000 tree ha⁻¹. The stem density of the L stand could not be defined because trees were unevenly distributed in the stand. In both stands, the understory vegetation was sparse.

Measurements

Meteorological factors

Meteorological measurements were conducted at an open field located approximately 1 km north from the Geisha site. Solar radiation was measured using a solar radiometer (LI-200 pyranometer sensor; Li-Cor, Lincoln, NE, US). Solar radiation was not measured within the stands. Air temperature and relative humidity were measured using a thermohygrograph (HMP45A; Vaisala, Helsinki, Finland). Data were collected every 10 s and 10 min means were stored in a data logger (CR10X; Campbell Scientific, Logan, US).

Sap flux density

Sap flux density (F_d ; cm³ m⁻² s⁻¹) was measured by the thermal dissipation method with Granier-type sensors (Granier 1987), which we made ourselves. Each sensor consisted of a pair of copper–constantan thermocouple thermometers 20 mm long and 2 mm in diameter; these thermocouple thermometers were connected together. The thermometers were inserted vertically into the sapwood

Table 1 Characteristics of studied Japanese cypress trees

No.	Age (years)	DBH ^a (cm)	Tree height (m)	Sapwood thickness ^b (cm)	Sapwood area ^c (cm ²)	Leaf area (m ²)
M1	26	19.7	11.3	2.6 ± 0.36	137.2	61.5
M2	26	17.2	11.5	2.2 ± 0.21	103.6	25.1
M3	26	18.7	11.5	2.0 ± 0.16	104.8	39.7
L1	43	29.0	16.4	2.7 ± 0.21	219.6	85.8
L2	43	34.0	17.3	3.5 ± 0.21	330.7	96.7
L3	43	25.5	18.1	2.1 ± 0.04	155.8	41.8

^a Diameter at breast height (1.3 m above the ground)

^b We assumed sapwood thickness as dyed thickness, which was determined by the dye injection method

^c Sapwood areas were calculated by DBH and sapwood thickness averaged over four azimuthal directions

and were separated vertically along the trunk by approximately 0.15 m. The upper thermometer contained a heating element of constantan that was supplied with 0.2 W constant power. The heat was dissipated into the sapwood and vertical sap flux surrounding the thermometers. The temperature difference between the upper thermometer and lower unheated reference thermometer was recorded every 30 s on a data logger (CR1000; Campbell Scientific) with a multiplexer (AM16/32; Campbell Scientific), and averaged over 30 min. The recorded temperature was converted to an F_d value as described by Granier (1987):

$$F_d = 1.19 \times 10^2 \left(\frac{\Delta T_{\max} - \Delta T}{\Delta T} \right)^{1.23}$$

where ΔT_{\max} and ΔT are the temperature differences between the two thermometers for no sap flow and positive sap flow, respectively. As derived here, F_d is the mean sap flux density of the sensor length. Electricity was supplied to the Granier-type sensors via photovoltaic generation and car batteries. The car batteries were replaced with charged ones every 3 days.

To measure azimuthal variations in F_d , the sensors were installed in north, east, west, and south aspects at 0–20 mm depth. The part of the trunk where the sensors were inserted was fully insulated to avoid direct radiation and natural thermal gradients along the trunk using an aluminum cover (25 cm × 16 cm) and foil as described in previous studies (Kumagai et al. 2008; Tateishi et al. 2008). These measurements were conducted on trees in the M stand from 27 October to 10 November 2006, and on trees in the L stand from 24 September to 26 October 2006.

Previous studies reported that radial variations in F_d occur across the sapwood (e.g. Phillips et al. 1996; James et al. 2003; Ford et al. 2004a, b). To cover the sapwood depth, additional sensors were inserted at 20–40 mm depth in the six sample trees. Radial variations in F_d were measured from 22 August to 10 November 2006. All sensors were inserted approximately 1.3 m above the ground.

Xylem water-conducting region in sapwood

We used a dye injection method to determine not only the sapwood and heartwood of each tree but also the xylem water-conducting region and non-conducting region within the sapwood (Umebayashi et al. 2007, 2008; Tateishi et al. 2008). The stem of the sample trees was drilled under water at a distance 30 cm below the insertion points of the Granier-type sensors. An aqueous solution of 0.2% acid fuchsin was injected into the stems through the holes. After perfusion for 1 h, sample discs of 5 cm thickness were taken at 10-cm intervals from the injection point to the maximum height of the stained xylem. We used a

stereomicroscope to observe the stained region. The sample discs more than 10 cm from the injection point were used to determine sapwood thickness (Umebayashi et al. 2007). Dye injection experiments were conducted on sunny days on 20 December 2006 for the M stand and 11 January 2007 for the L stand.

Leaf area measurements

Measurements of leaf area were conducted after the sap flux measurements and the dye injection experiments. We first sampled all the leaves and measured the fresh weight. We dried some parts of the leaves at 60°C for 48 h to determine relationships between fresh and dry weight of the leaves and between dry weight and leaf area. Determination of leaf area was conducted using a scanner and Scion Image image-editing software (Scion, Frederick, MD, US). Using leaf fresh weight data and the relationships between fresh and dry weight and between dry weight and leaf area, total leaf areas of the sample trees were estimated. Note that we did not use the relationship between fresh weight of leaves and leaf area when determining leaf area, because fresh weight of leaves could vary spatially and temporally.

Tree transpiration estimates

We evaluated differences in tree transpiration estimates according to the number of measurement points as follows. We first extracted F_d data at four azimuthal directions for sunny days satisfying daytime mean solar radiation $>200 \text{ Wm}^{-2}$ and daytime mean vapor pressure deficit (VPD) $>1.0 \text{ kPa}$ when high transpiration rates were expected. Based on these data, we calculated mean daily F_d for sunny days (\bar{F}_d) for each azimuthal direction. Tree transpiration based on n azimuthal directions (Q_n) was calculated as follows:

$$Q_n = A_{si} \sum_{i=1}^n \bar{F}_{di} / n,$$

where A_s is sapwood area, and i indicates the four different azimuthal directions. There were four, six, and four ways to calculate Q_n for $n = 1$, $n = 2$, and $n = 3$, respectively, based on possible combinations of aspects. Q_1 can be calculated from F_d data for (1) north, (2) south, (3) west, or (4) east aspects. Q_2 can be calculated from F_d data for (1) north and east, (2) north and south, (3) north and west, (4) east and south, (5) east and west or (6) south and west aspects. Q_3 can be calculated from F_d data for (1) north, east and south, (2) north, east and west, (3) north, south and west, or (4) east, south and west aspects. The difference was defined as \bar{Q}_n / Q_4 , where \bar{Q}_n was the mean Q_n . Note

that there was only one combination from which Q_4 can be calculated.

Results and discussion

Azimuthal variations in F_d

Figure 1a shows the diurnal time course of solar radiation and vapor pressure deficit (VPD) on a sunny day. Figure 1b shows F_d at 0–20 mm depth for the four aspects in tree L3. This figure also shows F_d at 20–40 mm depth. Higher F_d values were obtained during daytime when VPD and solar radiation were greater compared to early in the morning and late afternoon. Higher daytime F_d values were also recorded for the other sample trees. Considerable azimuthal variations in F_d among the four different aspects were recorded. The value of F_d at 20–40 mm depth was much smaller than that at 0–20 mm (Fig. 1b). Lower F_d values at 20–40 mm depth were also obtained for the other sample trees.

Figure 2 compares daily F_d for the north aspect at 0–20 mm with those for the other aspects at 0–20 mm.

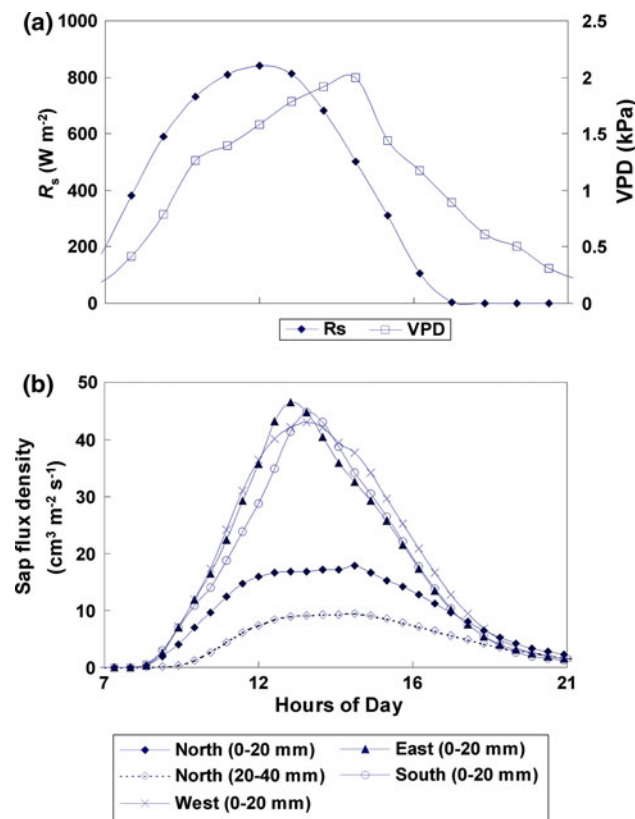


Fig. 1 Diurnal patterns of **a** vapor pressure deficit and solar radiation and **b** sap flux density (F_d) for four azimuth directions at 0–20 mm depth, and for north aspect at 20–40 mm depth. Data were obtained from tree L3 on 25 September, 2006

There was a positive correlation between F_d at the north aspect and those at the other aspects ($P < 0.001$ for all cases). In tree L2, F_d values at the west and east aspects were comparable to that at the north aspect, and F_d at the south aspect was smaller than that at the north aspect (Fig. 2e). In the other trees, F_d values at the south, west, and east aspects were more than 100% larger than that at the north aspect (Fig. 2a–d, f). We found no clear relationship in azimuthal F_d variations between the M and L stands.

The dye injection experiments also showed that there are considerable differences in both maximum dye height and volume of infused dye solution among the four azimuthal directions (data not shown). However, correspondence between F_d and the maximum dye height and between F_d and the volume of infused dye solution was weak. The reasons for the poor correspondence are unclear at this stage. One plausible reason would be that the period of dye injection measurements were performed outside the period of sap flux density measurements. Azimuthal variations of F_d could vary with meteorological and soil water conditions (Ueda and Yoshikawa 1994; Lu et al. 2000). To examine this possibility, we recommend further studies that perform dye injection experiments concurrently with F_d measurements.

The coefficient of variance (CV) of \bar{F}_d across the azimuthal directions for each tree was not related to DBH (data not shown). The CV was correlated to that of sapwood thickness across the azimuthal directions ($R^2 = 0.49$, $P < 0.1$). This agrees with the findings of Vertessy et al. (1997) that variations in F_d corresponded to variations in sapwood thickness across the azimuthal directions in mountain ash. The large variations of F_d in the present study (Fig. 2) might be related to the large variation in sapwood thickness observed, which in turn implies high variation in tracheid diameter and density. Tateishi et al. (2008) showed that azimuthal variations of sap flux density were caused by variations in hydraulic conductivity estimated by vessel diameters and density in evergreen oaks. This suggests that azimuthal variations in F_d in Japanese cypress (Fig. 2) could be caused by hydraulic conductivity, which is determined by tracheid diameter and density.

Though light environments surrounding each tree might be a factor determining azimuthal variations in F_d , in this study the light environments did not explain the azimuthal variation in F_d for two reasons. First, as all sample trees were not situated near the edge of the stands, the light environment would not differ among the sample trees. Even so, the azimuthal variations in F_d for tree L2 were different from those for the other trees. This implies that the azimuthal variations in F_d would not correspond to variation in the light environment surrounding the tree. Second, F_d showed large azimuthal variations even on

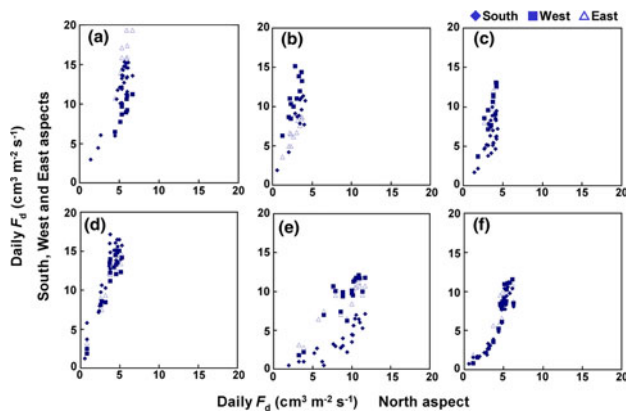


Fig. 2 Relationship between daily F_d at north and other aspects for trees **a** M1, **b** M2, **c** M3, **d** L1, **e** L2 and **f** L3. Coefficients of determination between north and south, between north and east, and between north and west were 0.70–0.78 (M1), 0.70–0.77 (M2), 0.43–0.77 (M3), 0.88–0.91 (L1), 0.73–0.77 (L2) and 0.82–0.87 (L3)

cloudy days (data not shown). The diffused component of solar radiation relative to the solar radiation on cloudy days is greater than that on sunny days. If the variation in F_d was primarily caused by the variation in the light environment, the azimuthal F_d variations on cloudy days could be less than those on sunny days. However, the azimuthal F_d variations on cloudy days were as significant as those on sunny days (data not shown). This also suggested that the light environment around the trees is not the primary factor determining azimuthal F_d variations.

Differences in tree transpiration estimates according to the number of measurement points

When calculating the differences in tree transpiration estimates for each tree, we did not use F_d data at 20–40 mm depth for Q_n calculations for two reasons. First, F_d at 20–40 mm was much smaller than that at 0–20 mm depth (Fig. 1b), suggesting the contribution of F_d at 20–40 mm was insignificant. Second, the major part of sensors at 20–40 mm depth touched the heartwood. In such cases, the F_d at 20–40 mm might not be very accurate, even when the F_d data were modified on the basis of Clearwater et al.'s (1999) method. As we did not use the F_d data at 20–40 mm depth, the sapwood thickness of the sample trees was assumed to be equal to the sensor length (i.e. 20 mm) in calculations of A_s .

Figure 3 shows the relationship between azimuthal direction number (n) and the differences in tree transpiration estimates for each tree. The difference was typically 30% for $n = 1$, 20% for $n = 2$, and 10% for $n = 3$. This finding indicates that ignoring azimuthal variations in F_d causes large errors in tree transpiration estimates for Japanese cypress, even though many previous studies have ignored such variations.

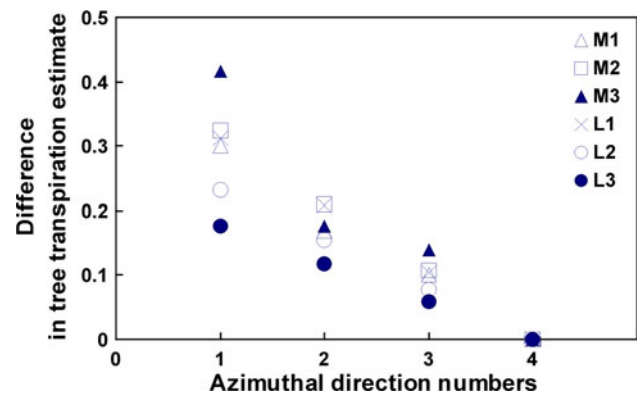


Fig. 3 Relationship between azimuthal direction number (n) and the differences in tree transpiration estimates. These calculations were made on the basis of 7-day and 14-day data for trees M1–M3 and L1–L3, respectively

It is unclear at this stage whether these results are applicable to Japanese cypress growing under other meteorological and soil water conditions, because azimuthal variations of F_d could vary according to these conditions (e.g. Ueda and Yoshikawa 1994; Lu et al. 2000). Thus, further studies under a variety of environmental conditions are required to generalise the results.

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