

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

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Received: 30 March 2009 / Accepted: 24 March 2010 / Published online: 28 April 2010  
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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

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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<sup>-1</sup>. 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 ( $F_d$ ; cm<sup>3</sup> m<sup>-2</sup> s<sup>-1</sup>) 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 <sup>a</sup> (cm)	Tree height (m)	Sapwood thickness <sup>b</sup> (cm)	Sapwood area <sup>c</sup> (cm <sup>2</sup> )	Leaf area (m <sup>2</sup> )
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

<sup>a</sup> Diameter at breast height (1.3 m above the ground)

<sup>b</sup> We assumed sapwood thickness as dyed thickness, which was determined by the dye injection method

<sup>c</sup> 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  $\Delta T_{\max}$  and  $\Delta T$  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

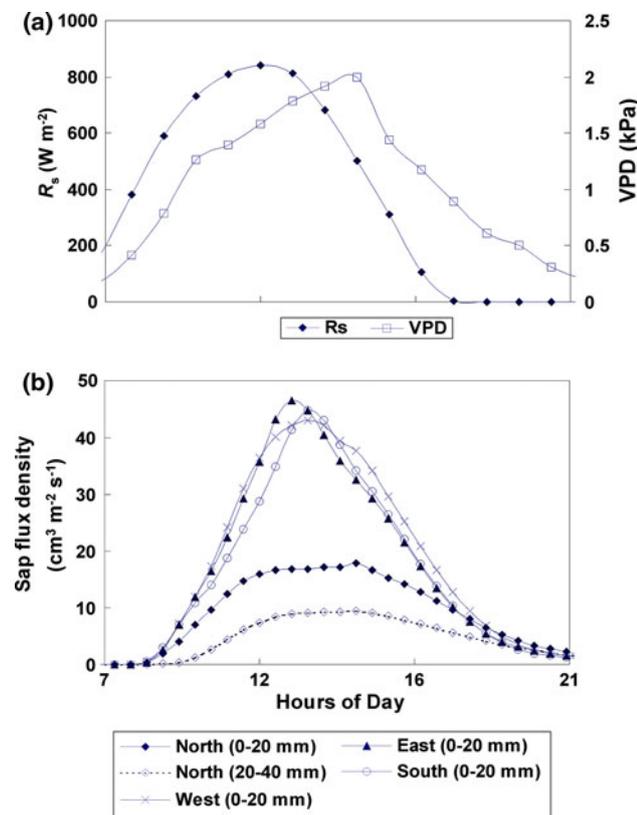
that there was only one combination from which  $Q_4$  can be calculated.

### 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.



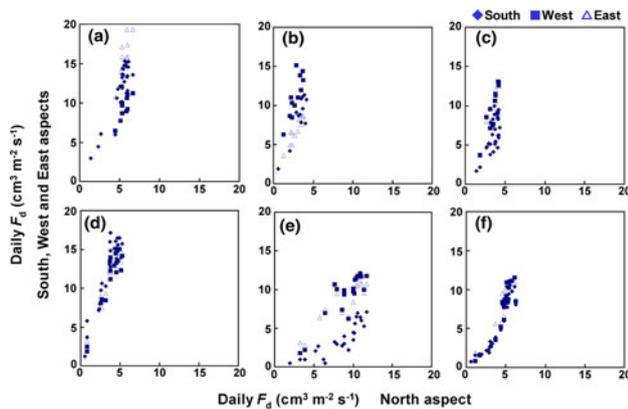
**Fig. 1** Diurnal patterns of **a** vapor pressure deficit and solar radiation and **b** sap flux density ( $F_d$ ) for four azimuth directions at 0–20 mm depth, and for north aspect at 20–40 mm depth. Data were obtained from tree L3 on 25 September, 2006

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



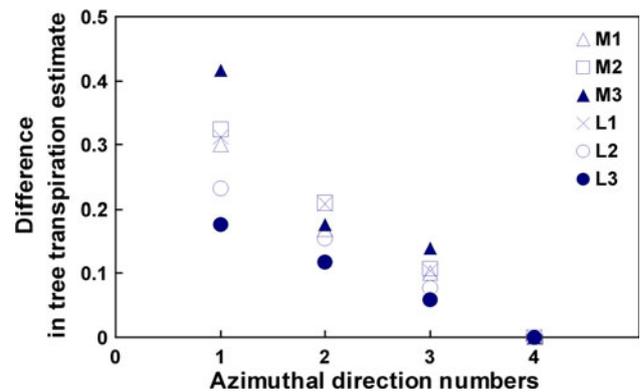
**Fig. 2** Relationship between daily  $F_d$  at north and other aspects for trees **a** M1, **b** M2, **c** M3, **d** L1, **e** L2 and **f** L3. Coefficients of determination between north and south, between north and east, and between north and west were 0.70–0.78 (M1), 0.70–0.77 (M2), 0.43–0.77 (M3),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

**Acknowledgments** The authors are grateful to Mr. Yasuki Shiiba, Mr. Hisami Nagasawa and Mr. Kiyohiro Kaji (Kasuya Research Forest, Kyushu University) for their help in felling trees. We are also grateful to members of the Laboratory of Ecohydrology, Kasuya Research Forest, Kyushu University, for their assistance with leaf area measurements. Thanks are also due to two anonymous reviewers whose comments were helpful. This research was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through a Grant-in-Aid for Scientific Research (#20780119) and by Global COE Program (Center of excellence for Asian conservation ecology as a basis of human-nature mutualism), MEXT, Japan and by Core Research for Evolution, Science and Technology of the Japan Science and Technology Agency.

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