

Effects of tree-to-tree and radial variations on sap flow estimates of transpiration in Japanese cedar

Tomo'omi Kumagai^{a,*}, Sayaka Aoki^b, Hisami Nagasawa^a, Tetsuya Mabuchi^a,
Katsuyoshi Kubota^a, Sachiko Inoue^a, Yasuhiro Utsumi^a, Kyoichi Otsuki^b

^aShiiba Research Forest, Kyushu University, Shiiba-son, Miyazaki 883-0402, Japan

^bKasuya Research Forest, Kyushu University, Sasaguri, Fukuoka 811-2415, Japan

Received 9 December 2004; received in revised form 31 October 2005; accepted 5 November 2005

Abstract

To scale sap flux density (F_d) measurements of individual trees to stand level transpiration (E), the mean stand F_d (J_S) is among the most important factors, because E is frequently estimated as a product of J_S and stand sapwood area. Major uncertainties in J_S estimations are caused by tree-to-tree and radial variations in F_d . Thus, by using the Monte Carlo sampling technique with original tree-to-tree F_d data measured at several depths, we examined how many trees and radial depths need to be sampled for calculation of appropriate J_S . In this study, F_d was measured in 14 mature Japanese cedar (*Cryptomeria japonica*) trees at several radial depths, 0–2, 2–4 and 4–6 cm, using Granier-type sensors. The results revealed that the potential error in J_S with the largest available sample size was not stable even though radial profiles in F_d for all sample trees were measured. They also showed that to consider radial variation in F_d it might be necessary to sample at least six trees, but not necessarily more than this. The results imply that, for E estimations, there is more tree-to-tree variation in F_d than in radial variation in F_d .

© 2005 Elsevier B.V. All rights reserved.

Keywords: Transpiration; Sap flow; Flow variability; Scaling; Granier-type sensor; Monte Carlo simulation

1. Introduction

Forests cover 64% of the total land area of Japan, and 44% of the total forest area is composed of plantation forests (World Resources Institute, 2004). *Cryptomeria japonica* (Japanese cedar) is the main plantation species in Japan, and it covers about half of the plantation forest area. Most forest areas are situated in mountain regions in Japan; therefore, the sap flow technique is among the most useful means for obtaining information on forest water use because application of this technique is not limited by complex terrains or spatial heterogeneity. Nonetheless, the sap flow technique to study water use

in *C. japonica* trees at both single-tree and stand scales remains uncertain, and is thus the subject of our investigation.

Despite the robustness of the sap flow technique, scaling procedures are required to extrapolate stand level estimates from sap flux density (F_d) measurements of individual trees. Transpiration is scaled up to the stand level using the following equation (Granier et al., 1996b; Wilson et al., 2001; Wullschlegel et al., 2001; Pataki and Oren, 2003):

$$E = J_S \frac{A_{S_stand}}{A_G} \quad (1)$$

where E is the stand transpiration, J_S the mean stand sap flux density, A_{S_stand} the stand sapwood area and A_G is the ground area. In short, scaling procedures need to

* Corresponding author. Fax: +81 983 38 1004.

E-mail address: kuma@forest.kyushu-u.ac.jp (T. Kumagai).

account for two major sources of error: determinations of the total sap flow per unit stand sapwood area (J_S) and the total sapwood area of the stand (A_{S_stand}).

Conventionally, A_{S_stand} is estimated by integrating all the individual tree sapwood area (A_{S_tree}) estimates in the stand; species-specific allometric equations describing the relationship between stem diameter (DBH) and A_{S_tree} are used for this purpose (Vertessy et al., 1995; Cienciala et al., 2000; Roberts et al., 2001; Wullschleger et al., 2001). In a previous study (Kumagai et al., 2005), the sample size necessary for developing an appropriate species-specific allometric equation for estimating E was examined using the Monte Carlo sampling technique. The results revealed that potential errors in the E estimate were almost stable with a sample size of over 20 for both *C. japonica* and *Chamaecyparis obtusa*, and the coefficients of variation (CV) were approximately 4% for both species.

Evaluation of tree-to-tree variations in F_d is important for estimating J_S because, for technical reasons, only a small number of trees can be sampled (e.g., Granier et al., 1996a). Further, because F_d is known to vary throughout sapwood (e.g., Phillips et al., 1996), evaluation of its spatial variation (radial and circumferential or azimuthal) is necessary for calculating individual tree water use (Hatton et al., 1990, 1995; Zang et al., 1996; Pausch et al., 2000; Lu et al., 2000; Wullschleger and King, 2000; Delzon et al., 2004). Wullschleger and King (2000) examined tree-to-tree variations in the radial gradients of F_d and the fraction of functional sapwood; this information is necessary for accurate extrapolation of F_d in individual tree to stand scale studies (Köstner et al., 1996).

When using Eq. (1), the sources of error in predicting both A_{S_stand} and J_S need to be evaluated to provide an estimate of the potential error in E estimates and sap flow measurements and sampling strategies. In a previous study, we investigated how errors in A_{S_stand} estimates are generated by predictions from available data (Kumagai et al., 2005). The goal of this study, therefore, is to examine how many sample trees and radial depths are needed for taking into account tree-to-tree and radial variations in F_d for *C. japonica* during J_S estimates.

2. Materials and methods

2.1. Site description and sapwood analysis

The experiments were carried out in an even-aged 32-year-old *C. japonica* stand in the Shiiba Research Forest, Kyushu University (32°22'N, 131°09'E). The

study site, situated in the central Kyushu mountain range at approximately 860 m above sea level, has a mean annual temperature of 13.6 °C and a mean annual precipitation of 3500 mm.

An experimental plot of 23 m × 9 m containing 24 *C. japonica* trees, with a mean DBH (1.3 m above-ground) of 32 cm (range 18–48 cm) and a mean canopy height of about 20 m, was used for the study. Fourteen trees were selected for F_d measurements (Table 1). Sapwood thickness (in mm) of each sample tree was measured with a ruler on a core extracted with a 0.5-cm increment borer at 1.3 m above-ground, and assessed as the mean of two orthogonal measurements. Distinct color differences were used to identify the boundary between sapwood and heartwood. A_{S_tree} was obtained by the difference between the stem cross-sectional area beneath bark and heartwood area assuming that the stem cross-sections were circular.

2.2. Sap flux density and meteorological measurements

F_d measurements were made with the thermal dissipation method using Granier-type sensors (e.g., Granier, 1987). Each sensor consists of a pair of probes of 2 cm long and 2 mm in diameter. They were inserted in the sapwood approximately 15 cm apart. The upper probe with a heater was supplied with 0.2 W constant power. The heat was dissipated into the sapwood and vertical sap flux surrounding the probe. The temperature difference between the upper heated probe and lower unheated reference probe was measured and converted to F_d according to Granier (1987).

Table 1
Characteristics of the 14 Japanese cedar (*Cryptomeria japonica*) trees studied, and the number and positions of sensors

Tree no.	Diameter (cm)	Sapwood depth (cm)	Depths measured (cm)
601	18	4.0	0–2, 2–4
604	19	3.3	0–2, 2–4
605	38	4.3	0–2, 2–4
607	48	5.2	0–2, 2–4, 4–6
608	40	4.1	0–2, 2–4
610	27	3.1	0–2, 2–4
611	37	5.5	0–2, 2–4, 4–6
612	37	5.4	0–2, 2–4
614	30	3.5	0–2, 2–4
615	31	4.2	0–2, 2–4
617	29	3.8	0–2
618	27	3.8	0–2, 2–4
621	32	4.2	0–2, 2–4
622	29	3.9	0–2, 2–4

One to three sensors were inserted in each selected tree at depths of 0–2, 2–4 and 4–6 cm so that they could cover the sapwood (Table 1). The sensors for these depths were positioned about 15 cm circumferentially from each other at about 1.3 m height. *C. japonica* tree in the plantation is commonly characterized by its perfectly circular stem cross-section and circumferentially constant sapwood thickness, so we assumed that azimuthal variation in F_d is small. Also, we assumed that in terms of estimating E , the azimuthal variation in F_d is included in the tree-to-tree variation in F_d . Thus, we did not measure F_d at different orientations within a tree trunk. To avoid the sun-exposed side of the trunk, all sensors were placed on the north-facing side of the trees. In addition, the part of the trunk into which the probes were inserted was fully insulated to prevent any direct radiation. There were little natural thermal gradients along the trunk, probably because of the closed canopy, and therefore the data have not been corrected for that.

A solar radiometer (CM06E, Kipp & Zonen, Delft, Netherlands) and a temperature and relative humidity sensor (HMP45D, Vaisala, Helsinki, Finland) were installed at the top of a 18-m research tower located on a 4-m mound adjacent to the experimental plot. Both sap flow signals and micrometeorological data were recorded on a data logger (CR10X, Campbell Scientific, Logan, UT) with a multiplexer (AM16/32, Campbell Scientific) sampling every 30 s and averaging for 30 min.

The study period was considered as spanning from 10 to 14 in August 2004 because of the then present ideal environmental conditions, such as no rainfall, moist soil condition, and little day-to-day variations in temperature and humidity; thus, we could evaluate the potential error in J_S estimates caused by tree-to-tree and radial variations in F_d independently of environmental conditions.

2.3. Data analysis

To obtain information on how many trees and depths are needed for adequate J_S estimates, we first examined tree-to-tree and then radial variations in F_d . Intrinsically, J_S is calculated with the sample size n , and for each sample tree, F_d is measured at all depths of sapwood:

$$J_S = \frac{\sum_{i=1}^n A_i u_i + \sum_{i=1}^n B_i v_i + \sum_{i=1}^n C_i w_i}{\sum_{i=1}^n (A_i + B_i + C_i)} \quad (2)$$

where i is the number of the sample tree, and A_i and u_i , B_i and v_i , and C_i and w_i are the sapwood areas and F_d at depths of 0–2, 2–4 and 4–6 cm, respectively. Note that Eq. (2) is calculated using the F_d measured at each

depth for all sample trees. When the radial variations in F_d are obtained in only (m) trees of (n) sample trees, by defining the ratio of the sap flows at depths of 2–4 and 4–6 cm to that at depth of 0–2 cm, J_S can be calculated as

$$J_S = \frac{\sum_{i=1}^n A_i u_i + f_m \sum_{i=1}^n B_i u_i + g_m \sum_{i=1}^n C_i u_i}{\sum_{i=1}^n (A_i + B_i + C_i)} \quad (3)$$

in which

$$f_m = \frac{\sum_{i=1}^m B_i v_i}{\sum_{i=1}^m B_i u_i} \quad (4)$$

and

$$g_m = \frac{\sum_{i=1}^m C_i w_i}{\sum_{i=1}^m C_i u_i} \quad (5)$$

where f_m and g_m are the ratios of sap flow at depths of 2–4 and 4–6 cm, respectively, to that at a depth of 0–2 cm obtained with sample size m .

In this study, for each sample size, the probability density functions (PDFs) of J_S calculated using Eq. (2) or Eq. (3) were estimated by stratified Monte Carlo sampling with replacement from the original data sets of 12 trees in which F_d was measured at two to three depths. For Eqs. (2) and (3), the PDFs were generated by randomly sampling $n = 1, \dots, 12$ values and $n = 12$ and $m = 1, \dots, 12$ values from the original data pool, respectively. Hence, the PDFs for Eqs. (2) and (3) denote the impacts of tree-to-tree and radial variations in F_d , respectively, on errors associated with sample size in calculations of J_S . Whenever a value was sampled it was immediately returned to the pool so each value could potentially be chosen multiple times in any given sampling run (e.g., Vertessy et al., 1997). The linear congruential method was employed as the algorithm of random number generation. For each sample, the procedures were repeated 1000 times. Thus, for a range of sample sizes, the standard deviations (S.D.) of J_S were obtained from PDFs, and the CV values were compared.

3. Results and discussion

Diurnal variations in the average F_d of 14 trees, solar radiation (R_s) and the vapor pressure deficit (VPD) on given days (10–14 August 2004) are shown in Fig. 1. F_d measurements at a depth of 2–4 cm were consistently lower than F_d at 0–2 cm over the diurnal courses, with larger standard errors of average F_d values at 2–4 cm than at 0–2 cm (Fig. 1a). The patterns of F_d at depths of both 0–2 and 2–4 cm were similar to those of R_s . Although the peak of F_d at 0–2 and 2–4 cm for each day

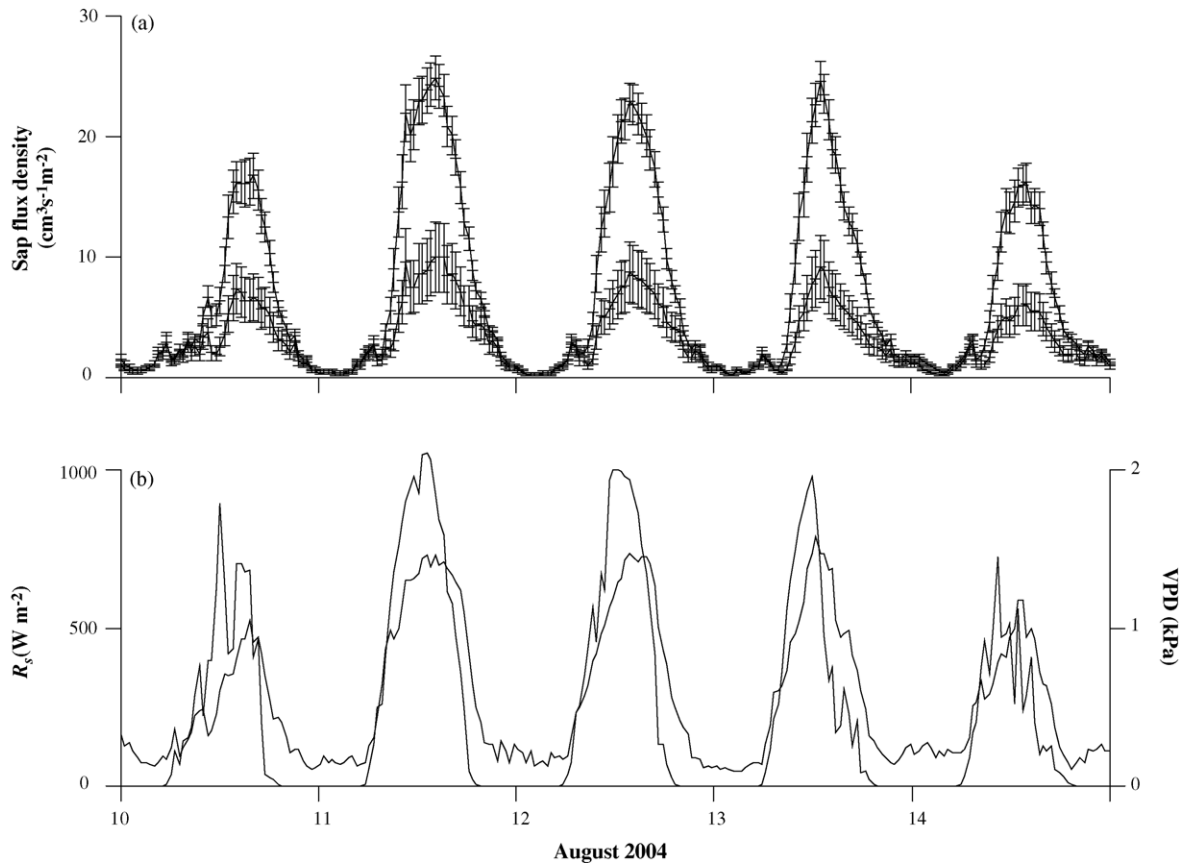


Fig. 1. Diurnal variations in (a) the 30-min average sap flux density of 14 Japanese cedar (*Cryptomeria japonica*) trees monitored at depths of 0–2 (thin line) and 2–4 cm (thick line), and (b) solar radiation (R_s ; thin line) and vapor pressure deficit (VPD; thick line) in Shiiba Research Forest for the period 10–14 August 2004. Vertical bars represent two standard errors.

corresponded to that of R_s , the difference between day-to-day peaks of F_d values at 2–4 cm was small (Fig. 1a and b). F_d was prolonged during the evening, probably because of changes in stored water in the sapwood (e.g., Kumagai, 2001).

Tree-specific F_d averaged over sapwood area (F_{d_avg}) varied between 3.1 and 8.0 $\text{cm}^3 \text{s}^{-1} \text{m}^{-2}$ (Fig. 2). There was no relationship between F_{d_avg} and sapwood thickness (Fig. 2), or between F_{d_avg} and DBH (data not shown). Vertessy et al. (1995) and Roberts et al. (2001) suggested that while there was no systematic relationship between A_{S_tree} and F_d , single-tree transpiration was strongly related to A_{S_tree} . Our results also suggest that tree-to-tree variations in F_d were independent of variations in sapwood thickness and A_{S_tree} .

The relationships between F_d at 0–2 and 2–4 cm were variable (Fig. 3), and they were, on average, categorized into three types. Type I: when F_d was low, F_d at 2–4 cm was almost the same as at 0–2 cm (see 1:1 line); however, as F_d increased, F_d at 2–4 cm linearly decreased against F_d at 0–2 cm. Type II: F_d at 2–4 cm

were F_d at 0–2 cm or less with large variations, but when F_d at 0–2 cm was beyond a certain value, F_d at 2–4 cm linearly decreased against F_d at 0–2 cm. Type III: the relationship between F_d at 0–2 cm and F_d at 2–4 cm

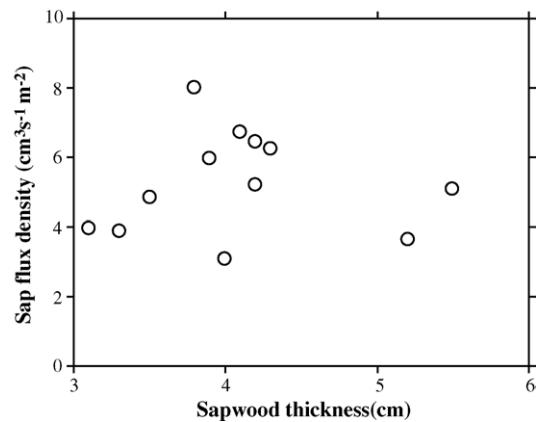


Fig. 2. Tree-to-tree variations in the sap flux density averaged over sapwood area and plotted as a function of sapwood thickness.

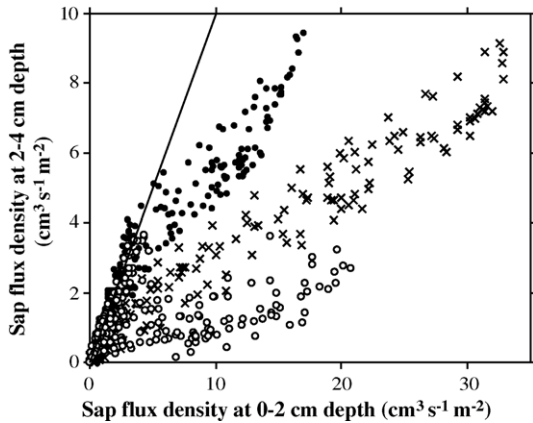


Fig. 3. Three typical relationships between sap flux density at 2–4 cm and that at 0–2 cm. The solid circle, open circle and cross refer to tree numbers 614 (Type I), 610 (Type II) and 622 (Type III), respectively. The 1:1 line (solid line) is also shown.

was always linear, and its slope was less than unity. In fact, situations that result in Types I and II might be common when one section of the Granier probes at 2–4 cm does not come in contact with the sapwood (see Table 1). Moreover, in sapwood of *C. japonica*, a “white zone”, in which moisture content is much lower than in heartwood, exists adjacent to the heartwood (e.g., Nobuchi and Harada, 1983; Nakada et al., 1999). Our experiment using dye solution injected into a radial hole bored into a tree trunk confirmed that there was no water movement in the white zone, and from other observation results at some *C. japonica* stands, its width can be assumed to be about 1 cm (data not shown). Hence, even though the Granier probes at a depth of 2–4 cm were fully in contact with sapwood, they might not have covered the hydroactive xylem because of large width of the white zone, and thus Type I and II situations might have occurred.

Clearwater et al. (1999) showed that F_d averaged along the probe was underestimated when part of the probe was in contact with the non-conducting xylem, and proposed an alternative method for calculating the mean F_d in the portion of the sapwood. On the other hand, according to Lu et al. (2004), Granier originally assumed that Granier-type sensors integrated one section of the probe intercepting active F_d while the other section came in contact with non-conducting xylem. That is, the sap moves at a mean F_d over a fictitious depth of sapwood, which is equal to 2 cm (Lu et al., 2004). In our study, because we examined radial variation in F_d including the uncertainty in determining the sapwood area, we adopted Granier’s assumption.

Hatton and Vertessy (1989) and Lu et al. (2000) found a high correlation between F_d at any two depths.

Zang et al. (1996) pointed out that the distribution of F_d through stems is well defined and amenable to a relatively simple analysis for calculating $F_{d,avg}$. Also, Delzon et al. (2004) reported that the correction factor, which can produce $F_{d,avg}$ by multiplying F_d at 0–2 cm, linearly decreased with increasing DBH. However, Fig. 3 shows that there are no systematic procedures for determining regularities in the distribution of F_d within an individual tree.

Uncertainties in calculating J_S are dependent mainly on the sample size of F_d measurements because there is no systematic explanation of tree-to-tree and radial variations in F_d (Figs. 2 and 3). The relationships between sample size and S.D. and CV of J_S as a function of time were estimated by the Monte Carlo sampling approach using Eqs. (2) and (3). The S.D. was low and scarcely changed with increasing sample size when J_S was low, but it was high and declined rapidly with increasing sample size when J_S was high. On the other hand, CV was high from midnight to early morning because S.D. was high compared to the low J_S . At night, although the CV was high, investigation of appropriate

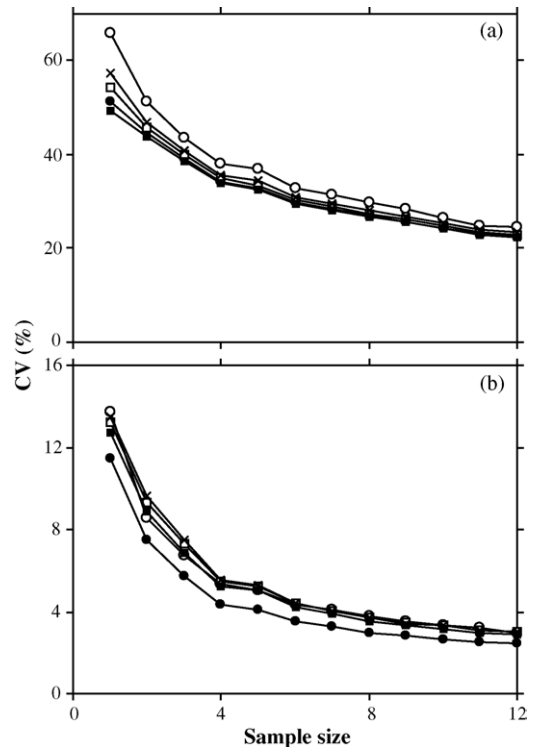


Fig. 4. Relationships between sample size and the coefficient of variation (CV) in mean stand sap flux density at 12:00 h on 10 (open circle), 11 (closed circle), 12 (open square), 13 (closed square) and 14 (cross) August 2004 from results calculated using Eq. (2) (a) and Eq. (3) (b).

sample sizes is not suitable for estimating J_S because of low J_S . Hence, we examined CV as a function of sample size at midday (12:00 h) (Fig. 4). When using Eq. (2), the CV at $n = 1$ was about 50–65% (Fig. 4a). It declined rapidly with increasing sample size n , but always remained more than 20%. This implies that, even though radial profiles of F_d for all sample trees were measured, a sample size of 12 was still insufficient for explaining tree-to-tree variation in F_d . When using Eq. (3), the CV at $m = 1$ was about 12–14%, and was almost stable (3–4%) with a sample size of over six (Fig. 4b). These results indicate that radial variation in F_d is stable across trees and needs no more than six trees to get that variation pattern, and that we need only measure F_d at 0–2 cm for the rest of trees to cover the tree-to-tree variation in F_d .

4. Conclusions

Using a Monte Carlo sampling technique with original tree-to-tree F_d data measured at several depths in the sapwood, we examined how many trees and radial depths should be sampled for accurately calculating J_S and estimating E in *C. japonica* stands. As a result, we determined a F_d measurements strategy for estimating E : (1) the potential errors in J_S with a sample size of 12 trees were not stable even though radial profiles in F_d for all sample trees were measured and (2) radial profiles of F_d should be measured in at least, but not necessarily more than, six trees.

The F_d measurements in this study permitted explanation of tree-to-tree and radial variations in F_d , which affect appropriate J_S estimates. For example, on average, F_d at a depth of 2–4 cm was consistently about 40% of that at 0–2 cm. This might enable explanation of radial variation in F_d when calculating J_S with a relatively small sample size (i.e., six sample trees), despite larger standard errors in F_d at 2–4 cm than at 0–2 cm. However, since there are relatively large tree-to-tree variations in F_d and no key relationships that tie F_d with tree dimensions, such as sapwood thickness and DBH, we have no alternative but to sample as many F_d measurements at 0–2 cm as possible to obtain appropriate J_S . It is known that radial profile of F_d changes under different soil moisture conditions and atmospheric evaporative demands (Nadezhdina et al., 2002). Therefore, radial variation in F_d was stable partly because we used an “elite” data set, for example, the studied trees were well-kept plantation species under constant ideal environmental conditions. Also, it should be noted that our conclusions resulted from studying even-aged single coniferous species. Further research is now required on

the effects of different environmental conditions, ages and different species using extensive experiments.

Acknowledgements

This work was supported in part by a Grant-in-Aid for Scientific Research (Nos. 14360088, 17380096 and 17510011) from the Ministry of Education, Science and Culture, Japan. Tomo'omi Kumagai is grateful to A. Christopher Oishi, Joshua Uebelherr and Ram Oren for giving instructions in Granier-type sap flow sensor.

References

- Cienciala, E., Kučera, J., Malmer, A., 2000. Tree sap flow and stand transpiration of two *Acacia mangium* plantations in Sabah, Borneo. *J. Hydrol.* 236, 109–120.
- Clearwater, M.J., Meinzer, F.C., Andrade, J.L., Goldstein, G., Holbrook, M., 1999. Potential errors in measurement of nonuniform sap flow using heat dissipation probes. *Tree Physiol.* 19, 681–687.
- Delzon, S., Sartore, M., Granier, A., Loustau, D., 2004. Radial profiles of sap flow with increasing tree size in maritime pine. *Tree Physiol.* 24, 1285–1293.
- Granier, A., 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.* 3, 309–320.
- Granier, A., Biron, P., Breda, N., Pontailier, J.-Y., Saugier, B., 1996a. Transpiration of trees and forest stands: short and long-term monitoring using sapflow methods. *Global Change Biol.* 2, 265–274.
- Granier, A., Biron, P., Köstner, B., Gay, L.W., Najjar, G., 1996b. Comparisons of xylem sap flow and water vapour flux at the stand level and derivation of canopy conductance for Scots pine. *Theor. Appl. Climat.* 53, 115–122.
- Hatton, T.J., Catchpole, E.A., Vertessy, R.A., 1990. Integration of sap flow velocity to estimate plant water use. *Tree Physiol.* 6, 201–209.
- Hatton, T.J., Moore, S.J., Reece, P.H., 1995. Estimating stand transpiration in a *Eucalyptus populnea* woodland with the heat pulse method: measurement errors and sampling strategies. *Tree Physiol.* 15, 219–227.
- Hatton, T.J., Vertessy, R.A., 1989. Variability of sapflow in a *Pinus radiata* plantation and the robust estimation of transpiration. In: *Hydrology and Water Resources Symposium*, Australian Institute of Engineers, Christchurch, New Zealand, pp. 6–10.
- Köstner, B.M.M., Biron, P., Siegwolf, R., Granier, A., 1996. Estimates of water vapor flux and canopy conductance of Scots pine at tree level utilizing different xylem sap flow methods. *Theor. Appl. Climat.* 53, 105–113.
- Kumagai, T., 2001. Modeling water transportation and storage in sapwood—model development and validation. *Agric. For. Meteorol.* 109, 105–115.
- Kumagai, T., Nagasawa, H., Mabuchi, T., Ohsaki, S., Kubota, K., Kogi, K., Utsumi, Y., Koga, S., Otsuki, K., 2005. Sources of error in estimating stand transpiration using allometric relationships between stem diameter and sapwood area for *Cryptomeria japonica* and *Chamaecyparis obtusa*. *For. Ecol. Manage.* 206, 191–195.
- Lu, P., Müller, W.J., Chacko, E.K., 2000. Spatial variations in xylem sap flux density in the trunk of orchard-grown, mature mango trees under changing soil water conditions. *Tree Physiol.* 20, 683–692.
- 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, 631–646.

- Nadezhdina, N., Čermák, J., Ceulemans, R., 2002. Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors. *Tree Physiol.* 22, 907–918.
- Nakada, R., Fujisawa, Y., Hirakawa, Y., 1999. Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D. Don. I. General description of water distribution. *J. Wood Sci.* 45, 188–193.
- Nobuchi, T., Harada, H., 1983. Physiological features of the “white zone” of sugi (*Cryptomeria japonica* D. Don)—cytological structure and moisture content. *Mokuzai Gakkaishi* 29, 824–832.
- Pataki, D.E., Oren, R., 2003. Species differences in stomatal control of water loss at the canopy scale in a mature bottomland deciduous forest. *Adv. Water Res.* 26, 1267–1278.
- Pausch, R.C., Grote, E.E., Dawson, T.E., 2000. Estimating water use by sugar maple trees: considerations when using heat-pulse methods in trees with deep functional sapwood. *Tree Physiol.* 20, 217–227.
- Phillips, N., Oren, R., Zimmermann, R., 1996. Radial patterns of xylem sap flow in non-, diffuse- and ring-porous tree species. *Plant Cell Environ.* 19, 983–990.
- Roberts, S., Vertessy, R., Grayson, R., 2001. Transpiration from *Eucalyptus sieberi* (L. Johnson) forests of different age. *For. Ecol. Manage.* 143, 153–161.
- Vertessy, R.A., Benyon, R.G., O’Sullivan, S.K., Gribben, P.R., 1995. Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. *Tree Physiol.* 15, 559–567.
- Vertessy, R.A., Hatton, T.J., Reece, P., O’Sullivan, S.K., Benyon, R.G., 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. *Tree Physiol.* 17, 747–756.
- Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D., Wullschleger, S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agric. For. Meteorol.* 106, 153–168.
- World Resources Institute, 2004. EarthTrends 2003. Available online at: <http://earthtrends.wri.org>.
- Wullschleger, S.D., Hanson, P.J., Todd, D.E., 2001. Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *For. Ecol. Manage.* 143, 205–213.
- Wullschleger, S.D., King, A.W., 2000. Radial variation in sap velocity as a function of stem diameter and sapwood thickness in a yellow-poplar trees. *Tree Physiol.* 20, 511–518.
- Zang, D., Beadle, C.L., White, D.A., 1996. Variation of sapflow velocity in *Eucalyptus globulus* with position in sapwood and use of a correction coefficient. *Tree Physiol.* 16, 697–703.