

Sap flow estimates of stand transpiration at two slope positions in a Japanese cedar forest watershed

TOMO'OMI KUMAGAI,^{1,2} SAYAKA AOKI,³ TAKANORI SHIMIZU⁴ and KYOICHI OTSUKI³

¹ Shiiba Research Forest, Kyushu University, Shiiba-son, Miyazaki 883-0402, Japan

² Corresponding author (kuma@forest.kyushu-u.ac.jp)

³ Kasuya Research Forest, Kyushu University, Sasaguri, Fukuoka 811-2415, Japan

⁴ Kyushu Research Center, Forestry and Forest Products Research Institute, Kumamoto 860-0862, Japan

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Summary We determined the amount of information needed to estimate watershed-scale transpiration in a Japanese cedar (*Cryptomeria japonica* D. Don) forest from sap flow measurements of individual trees. Measurements of tree biometrics (diameter at breast height (DBH) and tree sapwood area (A_{S_tree})), and tree-to-tree and radial variations in xylem sap flux density (F_d) were made in two stand plots, an upper slope plot (UP) and a lower slope plot (LP), during a growing season characterized by significant variations in environmental factors. We then investigated how mean stand sap flux density (J_S) and a tree stem allometric relationship (DBH– A_{S_tree}) varied between the stands. Appropriate sample sizes for estimating representative J_S values were determined. Both a unique and a general function allowed description of the allometric relationship along the slope, but the data for its formulation was required for both the UP and LP. Values of J_S in the UP and LP were similar during the study period despite differences in tree density and size between the plots, implying that J_S measured in a partial stand in a watershed is a reasonable estimate of J_S in other stands in the watershed, and that stand sapwood area calculated from A_{S_tree} is a strong determinant of water use in a forest watershed. To estimate J_S in both the UP and LP, it was necessary to sample at least 10 trees in each plot.

Keywords: *Cryptomeria japonica*, Granier-type sensor, Monte Carlo simulation, sap flux, sapwood, scaling.

Introduction

Forests cover 64% of the total land area of Japan (World Resources Institute 2004), and 22% of the total forest area comprises *Cryptomeria japonica* D. Don (Japanese cedar), the main plantation species in Japan (Japan Forestry Agency 2002). Because most of these forest areas are situated in mountain regions that serve as water supply catchment areas, quantifying the water use of montane *C. japonica* forests is important for water resource management.

Among several methods for investigating forest water use at

both temporal and spatial scales, the sap flow technique is the most promising, especially in a mountainous country like Japan, because complex terrain and spatial heterogeneity does not limit its applicability (e.g., Wilson et al. 2001). However, appropriate scaling procedures are required to extrapolate stand-level estimates from sap flow measurements made on individual trees. The scaling procedure requires: (1) estimation of the total sapwood area of the stand (A_{S_stand}) from the relationship between the stem diameter at breast height (DBH; measured for all trees in the stand) and tree sapwood area (A_{S_tree}) measured in the sampled trees; (2) estimation of mean stand sap flux density (J_S) from tree-level measurements of xylem sap flux density (F_d) in a limited sample size in the stand; and (3) calculation of stand transpiration (E) as the product of A_{S_stand} and J_S . Scaling can be difficult because of tree-to-tree variations in F_d (Granier et al. 1996, Wullschlegel et al. 2001, Pataki and Oren 2003) and A_{S_tree} (Kumagai et al. 2005a) and radial variation in F_d across the sapwood of individual trees (Zang et al. 1996, Lu et al. 2000, Wullschlegel and King 2000, Delzon et al. 2004, Kumagai et al. 2005b).

It is known that topographic gradients influence soil nutrient cycling and texture, resulting in plant–soil system patterns along a slope (Sabate et al. 1995, Tokuchi et al. 1999, Luizao et al. 2004, Tateno et al. 2004). Thus, the relationships between DBH and A_{S_tree} , and radial and tree-to-tree variations in F_d may vary along a slope. If so, the slope effects will increase the uncertainties in estimating A_{S_stand} and J_S and will likely make scaling in a forest watershed more complicated. In particular, uncertainties about the water use of *C. japonica* and its response to environmental factors will be accentuated (e.g., Kumagai et al. 2005b, Komatsu et al. 2006a, 2006b).

The goal of our study was to obtain sufficient information to extrapolate watershed-scale E in a *C. japonica* forest from F_d measurements of individual trees. To achieve this goal, we conducted tree-level measurements of F_d at several depths of sapwood and biometric measurements in upper and lower slope plots of a watershed during the growing season of 2005. The data were used to examine differences in J_S and the relationship between DBH and A_{S_tree} between the two slope plots

and to determine what factors caused the differences. Appropriate sample sizes for estimations of representative mean stand values were also determined.

Materials and methods

Study site

The experiments were carried out at Kahoku Experimental Watershed (KHEW), a 2.63 ha evergreen coniferous plantation on Kyushu Island, Japan (33°08' N, 130°43' E, 150–220 m a.s.l.). The watershed is underlain by crystalline schist, and the slopes on both sides of the valley are steep (20–40°). Mean annual precipitation for the period 1999–2004 was around 2150 mm with a rainy season from mid-June to early July. In the study year, the rainy seasons lasted from mid-June to mid-July. Mean annual temperature for the period 1999–2004 was around 15 °C with a minimum mean monthly temperature of about 4 °C in January–February and a maximum mean monthly temperature of about 26 °C in August.

The forest in the watershed consists mainly of even-aged 50-year-old *C. japonica* stands, and secondarily of *Chamaecyparis obtusa* Endl. (Japanese cypress) stands ranging from 27–50 years old. Understory vegetation is dense and consists of various species of evergreen *Quercus* and *Castanopsis* trees. Two *C. japonica* stand plots, an upper slope plot (UP) and lower slope plot (LP), were selected for study (Figure 1a; see Table 1 for plot characteristics). The UP and LP have a similar ground area and support trees of similar age; however, although the number of trees in UP is larger than in LP, stand basal area and individual tree sizes in UP are smaller than in LP (Table 1 and Figure 1b). In particular, the frequency distributions of DBH in UP trees and LP trees barely overlap (Figure 1b). The silhouette area index of leaves plus stems and branches (plant area index; PAI) was measured in LP trees from April 2003 to March 2004 with a plant canopy analyzer (LAI-2000, Li-Cor, Lincoln, NE). The PAI ranged from 4.4 in October to 3.8 in March, implying only minor seasonal variation.

Micrometeorological conditions were measured at the top of the canopy with the aid of 50-m-tall canopy tower located in the center of the watershed. A solar radiometer (CM14B, Kipp & Zonen, Delft, Netherlands) and ventilated psychrometer (NH020L, EKO, Tokyo, Japan) were installed at the top of the tower and at a height of 42 m, respectively. Samples were taken every 30 s for solar radiation (R_s) and every 1 min for temperature and relative humidity, and averaged over 30 min (CR10X, Campbell Scientific, Logan, UT). Maximum and mean total daily R_s during the experimental period, day-of-year (DOY) 139 (May 19) to DOY 263 (September 20), 2005, were 29.8 and 16.5 MJ m⁻² day⁻¹, respectively, and the maximum and mean vapor pressure deficits (D) averaged over daylight hours were 2.48 and 1.09 kPa, respectively. Volumetric soil water content (θ) and soil matric potential were measured at three depths in each plot. Weighted average θ over a 0–0.5 m soil layer in UP and LP during the experiment ranged

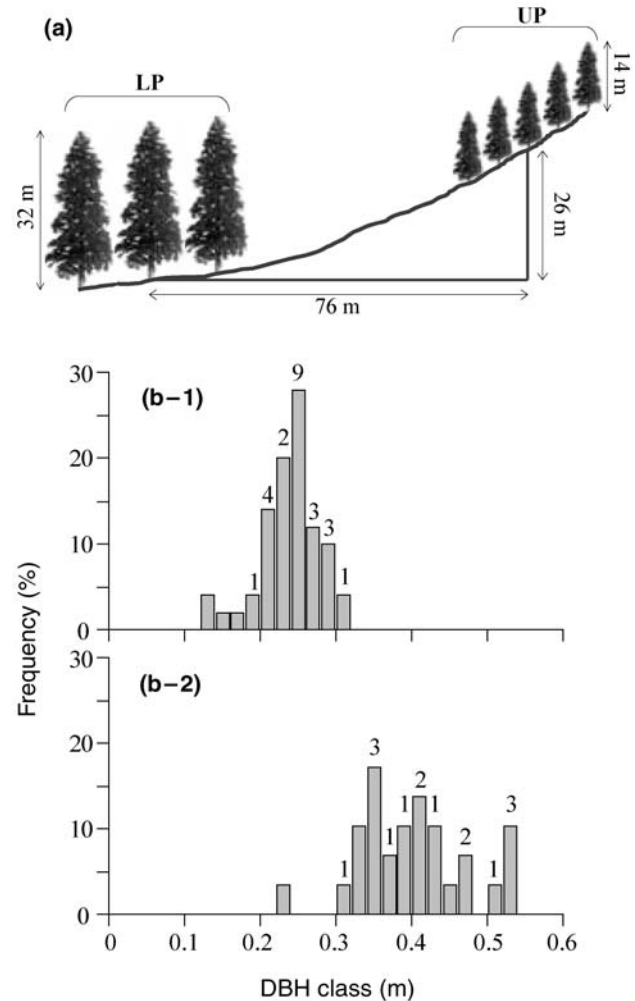


Figure 1. Schematic representation of the slope positions of the study plots, UP (upper slope plot) and LP (lower slope plot) (a) and frequency distributions of stem diameters at breast height (DBH) in UP (b-1) and LP (b-2). Note that (a) is scaled, and that the number at the top of each bar in (b-1) and (b-2) denotes the number of trees used for the sap flow measurements in each DBH class.

from 0.087 to 0.166 and from 0.115 to 0.243, respectively, suggesting an appreciable difference in soil water conditions between UP and LP.

Sap flux measurements and sapwood analysis

We measured F_d by the thermal dissipation method with Granier-type sensors (Granier 1987). Each sensor consisted of a pair of probes 20 mm long and 2 mm in diameter. The probes were inserted in the sapwood about 0.15 m apart. The upper probe included a heater that was supplied with 0.2 W constant power. The temperature difference between the upper heated probe and the lower unheated reference probe was measured and converted to F_d according to Granier (1987). Sap flow signals were recorded on a data logger (CR10X, Campbell Scientific) with a multiplexer (AM16/32, Campbell Scientific) every 30 s and averaged over 30 min.

Table 1. Stand characteristics of the upper slope plot (UP) and the lower slope plot (LP).

Characteristic	UP	LP
Plot area (m ²)	318	321
Age (year)	50	50
Density (trees ha ⁻¹)	1575	904
Basal area (m ² ha ⁻¹)	71.7	118.7
Mean diameter at 1.3 m height (cm)	23.8	40.3
<i>Stand sapwood area ratio at xylem band</i> ¹		
0–20 mm	0.50	0.41
20–40 mm	0.41	0.36
40–60 mm	0.09	0.23
Mean height (m)	14	32
Sap flux measurements (trees)	23	15

¹ Ratio of stand sapwood area at each xylem band to the total sapwood area of all xylem bands.

We measured F_d in 23 and 15 trees in the UP and LP, respectively, so that the number of trees measured in each DBH class corresponded to the frequency distributions of DBH in UP and LP (Table 1; Figure 1b). One to three sensors were inserted in each selected tree at depths of 0–20, 20–40 and 40–60 mm to cover the entire sapwood. Twenty UP trees and 10 LP trees were used for determination of radial F_d profiles. The sensors were positioned about 0.15 m circumferentially apart at a height of about 1.3 m.

The *Cryptomeria japonica* trees in the plantation are characterized by a circular stem cross section and circumferentially constant sapwood thickness; therefore, we assumed the azimuthal variation in F_d to be small (e.g., Vertessy et al. 1997). To avoid the sun-exposed side of the trunk, most sensors were placed on the north side of the trees, and the part of the trunk into which the sensors were inserted was fully insulated to prevent direct radiation. Although some sensors were not placed on the north side because of topographical obstacles, the natural thermal gradient along the trunks of all measured trees was small, probably because of the closed canopy and shade of the steep slope; therefore, the data were uncorrected for this variation. It is known that F_d is often underestimated from sensors positioned on the shaded side of tree crowns (e.g., Oren et al. 1999), particularly when the conduits are straight. However, dye solution injected into a radial hole bored into the tree trunk indicated that the conduits in *C. japonica* are spiral (data not shown). Therefore, we assumed that F_d would not be systematically underestimated by placing sensors only on the north-facing side of the tree trunks and that the azimuthal variation in F_d was included in the tree-to-tree variation in F_d .

Sapwood thickness (in mm) of each sample tree was measured with a ruler on a core extracted with a 5-mm increment borer at about 1.3 m aboveground, and assessed as the mean of two orthogonal measurements. Distinct color differences were taken to identify the boundary between sapwood and heartwood. The A_{S_tree} was obtained as the difference between stem

cross-sectional area beneath the bark and stem cross-sectional heartwood area assuming that the stem cross sections were circular. In sapwood of *C. japonica*, a “white zone,” the water content of which is much lower than that of the heartwood, exists adjacent to the heartwood (e.g., Nobuchi and Harada 1983, Nakada et al. 1999). There is no water movement in the white zone (Kumagai et al. 2005b) and its width was assumed to be constant at about 10 mm in the study trees. The point of insertion of the sensors in the sapwood therefore took account of this width to ensure coverage of the hydroactive area.

Calculations of stand transpiration and sap flux density

All measured F_d values were integrated over one day; thus, all values related to sap flow or transpiration are daily rates. Transpiration was scaled up to the stand level as (Wilson et al. 2001, Wullschlegler et al. 2001, Schäfer et al. 2002, Pataki and Oren 2003):

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

where A_G is ground area.

We computed J_S from sapwood areas at xylem depths of 0–20, 20–40 and 40–60 mm for each measured tree, i (A_i , B_i and C_i , respectively), and the mean F_d for the xylem bands at 0–20, 20–40 and 40–60 mm for all measured trees within each plot (J_{S_A} , J_{S_B} and J_{S_C} , respectively) as:

$$J_S = \frac{J_{S_A} \sum_{i=1}^N A_i + J_{S_B} \sum_{i=1}^N B_i + J_{S_C} \sum_{i=1}^N C_i}{\sum_{i=1}^N (A_i + B_i + C_i)} \quad (2)$$

where

$$J_{S_A} = \frac{\sum_{i=1}^n A_i F_{d_A_i}}{\sum_{i=1}^n A_i}, \quad (3)$$

$$J_{S_B} = \frac{\sum_{i=1}^m B_i F_{d_B_i}}{\sum_{i=1}^m B_i} \quad (4)$$

and

$$J_{S_C} = \frac{\sum_{i=1}^l C_i F_{d_C_i}}{\sum_{i=1}^l C_i}, \quad (5)$$

where N is the total number of *C. japonica* trees in each plot, n , m and l are the numbers of measured xylem bands at 0–20,

20–40 and 40–60 mm, respectively, and F_{d,A_i} , F_{d,B_i} and F_{d,C_i} are F_d values at depths of 0–20, 20–40 and 40–60 mm, respectively, for each sample tree, i .

Results and discussion

Sapwood area estimates in UP and LP

The A_{S_tree} of UP trees ranged from 0.0154 to 0.0349 m² with a mean of 0.0249 m², and values ranged from 0.0327 to 0.0896 m² with a mean of 0.0568 m² in LP trees. As for the DBH classes between plots, the A_{S_tree} classes in UP and LP barely overlapped. Figure 2 shows the relationships between DBH and A_{S_tree} in UP and LP (DBH and A_{S_tree} were measured in more than 20 trees per plot (Kumagai et al. 2005a)). Power functions of DBH (e.g., Vertessy et al. 1995) were fitted to A_{S_tree} in UP (Equation 1), LP (Equation 2), and in UP + LP (Equation 3) by nonlinear regression analysis. The R^2 values of Equations 1–3 were 0.93, 0.95 and 0.97, respectively.

The A_{S_stand}/A_G ratio in UP, estimated from Equation 1 and DBH measured for all *C. japonica* trees in the plot, was 36.3 m² ha⁻¹, whereas the ratio in LP, estimated from Equation 2, was 46.0 m² ha⁻¹. The ratio of stand sapwood area in xylem bands 0–20, 20–40 and 40–60 mm to the total sapwood area of all xylem bands in UP and LP trees are shown in Table 1. We found some effects of competition. For example, A_{S_tree} values

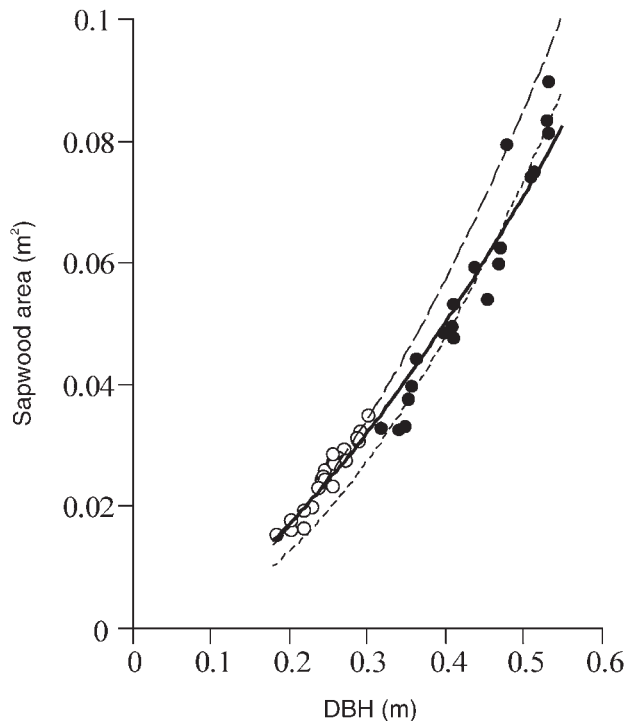


Figure 2. Relationship between stem diameter at breast height (DBH) and individual sapwood area in UP (○) and LP (●). Dashed, dotted and solid lines were determined from least squares nonlinear regression based on data from UP ($y = 0.824 x^{1.77}$, $R^2 = 0.93$), LP ($y = 0.402 x^{1.92}$, $R^2 = 0.95$), and UP + LP ($y = 1.658 x^{1.55}$, $R^2 = 0.97$), respectively.

in UP were likely lower than in LP because of the larger number of UP trees (see Table 1). This implies that estimates of total stand basal area and A_{S_stand} across the altitudinal gradient within the watershed will not vary greatly.

Total A_{S_stand}/A_G in UP + LP, estimated from the mean A_{S_stand}/A_G of each study plot (estimated from Equation 1 in UP and from Equation 2 in LP) was 41.1 m² ha⁻¹. The total A_{S_stand}/A_G of UP + LP estimated from Equation 1 was 23% larger than that estimated from Equation 2 ($P < 0.05$). On the other hand, the values of A_{S_stand}/A_G in UP and LP estimated from Equation 3 were similar to the value in UP estimated from Equation 1 ($P = 0.69$) and the value in LP estimated from Equation 2 ($P = 0.69$), and so the total A_{S_stand}/A_G in UP + LP estimated by Equation 3 was 41.1 m² ha⁻¹. These findings imply that only a single equation is needed to describe the allometric relationship along a slope, but the allometric data must be obtained from different areas along the slope.

Radial variations in xylem sap flux density in UP and LP

To identify the factors responsible for the difference in J_S and tree size between UP and LP, we examined how the radial F_d profiles of the UP and LP trees differed.

Daily J_{S_A} , J_{S_B} and J_{S_C} data with tree-to-tree variations (plus standard deviation; SD) in UP and LP during the study are shown in Figure 3. Mean stand F_d measured at radial depths of 0–20, 20–40 and 40–60 mm consistently decreased with depth over the study period. Seasonal patterns of sap flow in UP and LP trees were apparently similar despite the significant difference in soil water content between plots. In the rainy season, DOY 175–195, sap flow was appreciably reduced in both UP and LP trees.

Tree-specific F_d averaged over sapwood area for the period DOY 213–238 (F_{d_avg}) in UP and LP varied between 0.21 and 0.50 m³ m⁻² day⁻¹ and between 0.21 and 0.69 m³ m⁻² day⁻¹, respectively. There was no relationship between F_{d_avg} and A_{S_tree} in trees at either plot, or between F_{d_avg} and slope position (data not shown), suggesting that tree-to-tree variations in F_d were independent of variations in A_{S_tree} or tree size, both within and between slope positions (see Kumagai et al. 2005b).

Figure 4 compares daily J_{S_B} and J_{S_C} against J_{S_A} in UP and LP. A high correlation between F_d at any two depths has been observed (Zang et al. 1996, Lu et al. 2000, Delzon et al. 2004). Although Kumagai et al. (2005b) reported that there were no systematic procedures for determining distribution patterns of F_d within individual *C. japonica* trees because of the existence of a white, non-conducting, zone in the sapwood (see Nobuchi and Harada 1983), we found that J_{S_B} and J_{S_C} were linearly related to J_{S_A} at both UP and LP ($r^2 = 0.84–0.93$), probably because the F_d data were integrated as daily values. The ratio of J_{S_B} to J_{S_A} , i.e., the regression coefficient forced through the origin fitted between J_{S_A} and J_{S_B} values in Figure 4, was about 52% in LP and 37% in UP, even though the LP trees were significantly smaller. Figure 5 shows that the decrease in F_d with increasing sapwood depth was steeper in UP trees than in LP trees. Because stand ages in UP and LP were similar, the

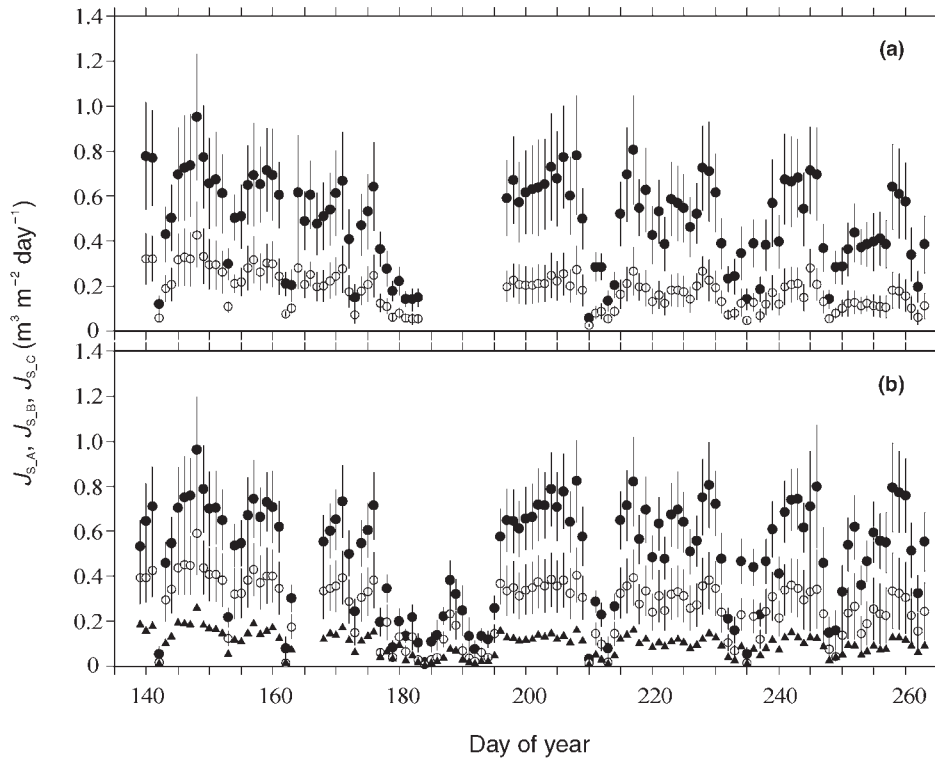


Figure 3. Mean daily sap flux densities for xylem bands 0–20 (J_{S_A} ; ●), 20–40 (J_{S_B} ; ○) and 40–60 mm (J_{S_C} ; ▲) for all measured *C. japonica* trees in UP (a) and LP (b) for the period DOY 139 (May 19) to DOY 263 (September 20), 2005. Vertical bars represent ± 1 standard deviation (SD). As a result of power system failure, data are missing for some days.

number of annual rings per 20 mm of sapwood depth was larger in UP trees than in LP trees. Thus, the relationship between the shape of the radial F_d profile and the number of annual rings might be similar in UP trees and LP trees.

Comparisons of J_S and E in UP and LP

The F_d values at the same sapwood depth, e.g., the 0–40 mm xylem band, were higher in LP trees than in UP trees (Figure 3). However, unlike the UP trees, sapwood in LP trees was observed at a depth of more than 40 mm, although F_d was significantly reduced at this depth (see Table 1; Figure 5). Delzon et al. (2004) reported that the decrease in the ratio of F_d at a given depth to that at an outer depth (f_R) increased with increasing DBH. Although Delzon et al. (2004) studied trees of different DBHs corresponding to different ages, their results suggest that F_d is significant throughout the sapwood area in small trees, but is insignificant at greater depths in large trees.

Therefore, we predicted that, despite the larger F_d averaged over the 0–40 mm sapwood depth in LP trees, F_d averaged over the total sapwood area might be similar in UP and LP. When daily J_S in UP and LP were compared by performing a repeated measures ANOVA, J_S values were found to be similar in UP and LP ($P = 0.58$). Thus, the J_S values averaged over the study period in UP and LP were 0.35 and 0.34 $\text{m}^3 \text{m}^{-2} \text{day}^{-1}$, respectively, with a mean difference of only about 3%.

The J_S values were appreciably higher on DOY 148 (Figure 3), and moreover, all values measured independently at different sapwood depths and at both slope positions were higher on DOY 148 than on any other day (Figure 4). We determined relationships between J_S in UP and LP and D and R_s .

Although the effect of R_s on J_S was relatively minor, J_S increased linearly with increasing D (see Oren et al. 1999), reaching its highest value when D was highest, i.e., on DOY 148 (Figure 6). These findings imply that F_d was reliably mea-

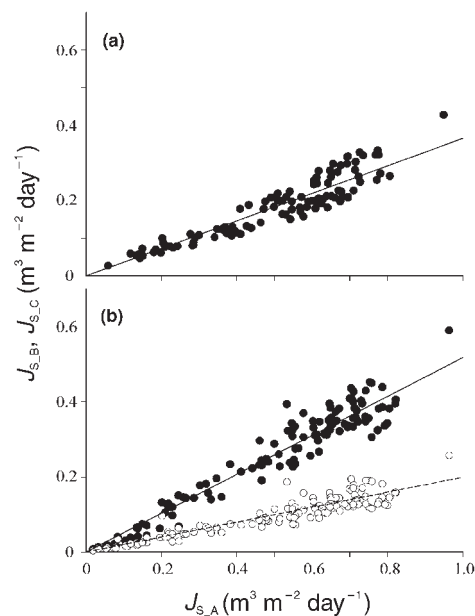


Figure 4. Mean sap flux densities at 0–20 (J_{S_A}) versus 20–40 (J_{S_B}) (●), and at 40–60 mm (J_{S_C}) (○) in UP (a) and LP (b). Linear regressions were forced through the origin: (a) solid line; $y = 0.366x$, $r^2 = 0.87$, (b) solid line; $y = 0.518x$, $r^2 = 0.93$ and dashed line; $y = 0.198x$, $r^2 = 0.84$.

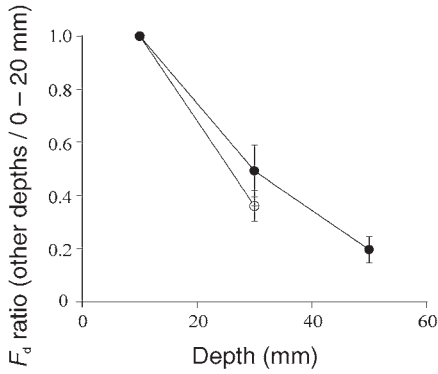


Figure 5. Depth profiles of mean sap flux density at 0–20 mm versus other depths (F_d ratio) in UP (○) and LP (●). The F_d ratios were averaged over the experimental period (DOY 139–263). Vertical bars represent one standard deviation.

sured even at high flux rates, despite changing environmental conditions.

As a result, we concluded that, within a watershed, J_S measured in one plot is a reasonable estimator of J_S in other plots. Delzon et al. (2004) reported that a correction factor (C_R), which gives the tree-specific F_d averaged over sapwood area by multiplying F_d at 0–20 mm by C_R , linearly decreased with increasing DBH. In our study, although the decrease in F_d was steeper in small trees in UP than in large trees in LP, F_d at deep positions in the sapwood was insignificant in large trees (Figure 5). Therefore, J_S values in UP and LP, obtained by averaging the F_d values over the sapwood area, were similar despite the difference in tree size between plots. Thus, because F_d at 0–20 mm was higher in large trees in LP than in small trees in UP, the C_R in our study was presumed to be lower for LP trees than for UP trees because of the higher DBH of LP trees compared with HP trees.

The similar values of J_S in UP and LP indicate that the response of stand transpiration to soil water content was less sensitive in UP than in LP, because soil water conditions were consistently drier in UP than in LP during the study period. Bréda et al. (1995) found that water uptake by an oak stand oc-

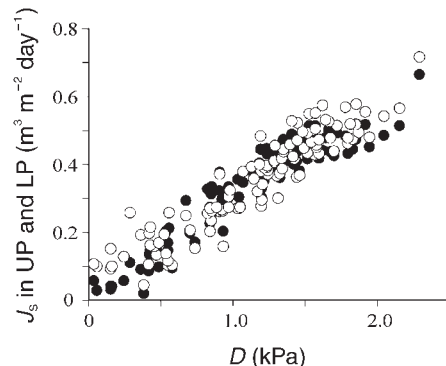


Figure 6. Relationship between mean daily daytime vapor pressure deficit (D) and mean stand sap flux density (J_S) in UP (○) and LP (●).

curred from progressively deeper soil horizons as the length of drought increased, and that limited rooting depth resulted in a negative transpiration response even under moist soil conditions. Therefore, a likely reason for the insensitivity to drought in UP trees was that water uptake occurred from deeper soil horizons in UP trees than in LP trees.

Daily variations in E in UP and LP calculated from A_{S_stand}/A_G and J_S for each plot during the study period are shown in Figure 7. Although J_S values in UP and LP were consistently similar, with some exceptions, E was higher in LP than in UP because A_{S_stand}/A_G was larger in LP than in UP (see Table 1; Figure 2). When D was low (< 0.5 kPa), J_S was apparently higher in UP than in LP (Figure 6), resulting in higher E in UP than in LP (Figure 7). Previous studies have suggested that, in forests, transpiration is a conservative process because differences in forest stand status mainly affect partitioning of the components of canopy transpiration but not its magnitude (Roberts 1983, Oren et al. 1998a, Delzon et al. 2005). Understory trees were larger in UP than in LP, probably because of competition with dominant *C. japonica* trees. Therefore, higher transpiration rates of understory trees in UP might compensate for the difference in E between UP and LP.

Sample size required to estimate J_S

Previous studies have shown that, based on examinations of tree-specific f_R or C_R , F_d at an outer depth can be extrapolated to whole-tree sap flux (Köstner et al. 1996, Lu et al. 2000, Wullschlegel and King 2000, Nadezhdina et al. 2002, Delzon et al. 2004). However, f_R and C_R change with time because of changes in soil water conditions and atmospheric evaporative demands (e.g., Lu et al. 2000, Nadezhdina et al. 2002). Delzon et al. (2004) reported that tree-to-tree variations were related to DBH. In addition, Oren et al. (1998b) examined the covariance between F_d and sapwood area index and suggested that it should also be taken into consideration for scaling and variance calculations. However, we found no clear relationship between the F_d values published by Oren et al. (1998b) and tree size (cf. Vertessy et al. 1995, Wullschlegel and King 2000, Roberts et al. 2001, Kumagai et al. 2005b). Thus, assuming no systematic explanation for tree-to-tree and radial variations in F_d , we determined how many trees must be sampled to calculate a reliable J_S for UP and LP during the study period with variations in environmental factors.

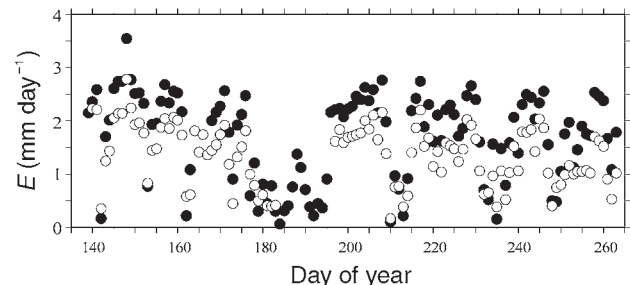


Figure 7. Daily stand transpiration (E) in UP (○) and LP (●) for the period DOY 139 (May 19) to DOY 263 (September 20), 2005.

For each sample size, the probability density functions (PDFs) of J_S were calculated with Equation 2 and J_{S_A} , J_{S_B} and J_{S_C} obtained by Monte Carlo sampling from their probability distributions represented by a Gaussian distribution with their means and standard deviations (see Figure 3). For 10 days, based on measurements with J_S values ranging from the highest to 10th highest for each plot, PDFs were generated by randomly sampling $n = 1 \dots 20$ values from the Gaussian distributions. Hence, the PDFs denote the impacts of tree-to-tree variations in F_d averaged over the sapwood area on errors associated with sample size in calculations of J_S (see Kumagai et al. 2005a, 2005b). For each sample size, the procedures were repeated 1000 times. Thus, for a range of sample sizes in UP and LP, the standard deviations of J_S were obtained from the PDFs over a 10-day period; the coefficients of variation (CV) are compared in Figure 8. Because tree sizes in UP were smaller than in LP, fewer F_d measurements within a tree were required to estimate sapwood area-averaged F_d in UP. Nevertheless, in both UP and LP, the CVs were almost stable at about 10% for a sample size of over 10, indicating that no more than 10 trees are needed to estimate J_S in UP or LP. However, a stable CV of around 10% with a sample size of 10 will not necessarily be applicable to other forests (e.g., Oren et al. 1998b).

The estimated J_S values in UP and LP were similar. Hence, after an appropriate estimation of J_S in either UP or LP, watershed-scale E could be estimated from J_S based on a partial A_{S_stand} obtained over the watershed.

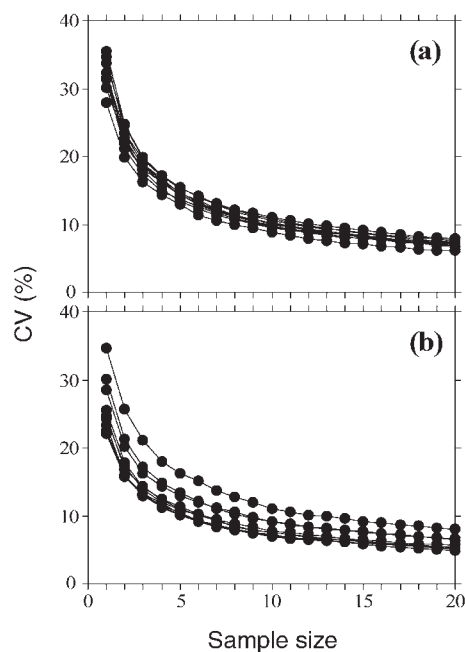


Figure 8. Relationship between sample size and the coefficient of variation (CV) of mean stand sap flux density over 10 days based on the uppermost to 10th highest F_d values during the study period in UP (a) and LP (b).

Conclusions

By using biometric and F_d measurements in an upper slope and a lower slope plot, we examined variations in A_{S_stand} and J_S in a watershed. Based on these data, we developed an approach for scaling tree-level sap flow estimates to watershed-scale transpiration. (1) Only one function is needed to describe the allometric relationship between DBH and A_{S_tree} along a slope, but the allometric data (DBH and A_{S_tree}) must be obtained from different positions along the slope. (2) The values of J_S in UP and LP were similar during the study despite significant variations in environmental factors. The finding that J_S was similar in trees spanning the altitudinal gradient allowed us to extrapolate watershed-scale E based on J_S estimated from F_d measurements of a partial stand. (3) Within the watershed, J_S measured in a partial stand was a reasonable estimator of the J_S values of other stands. For a reliable measurement of J_S in a stand plot; no more than 10 trees were needed to estimate J_S in UP or LP.

These findings suggest that A_{S_stand} and A_{S_tree} are major determinants of water use in a forest watershed. For example, comparisons of different forest stands have indicated that, although F_d does not appear to vary, A_{S_stand} changes systematically (Dunn and Connor 1993, Vertessy et al. 1995, 1997, Roberts et al. 2001). Therefore, it is important to consider the presence of sapwood variability in the watershed as well as how to obtain an appropriate J_S .

Although we investigated only two stand plots in the watershed, we measured tree-to-tree and radial variations in F_d in 23 and 15 sample trees in UP and LP, respectively, and the study period covered a large part of the growing season of *C. japonica* with significant variations in environmental factors. We demonstrated that J_S was similar in UP and LP throughout the study period, which provides a means of estimating watershed-scale E . It remains to be determined if watershed-scale E estimates based on J_S estimated from F_d measurements of a partial stand can be applied to other landscapes.

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