Circumferential sap flow variation in the trunks of Japanese cedar and cypress trees growing on a steep slope

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Abstract:

In this study, we conducted sap flow measurements in Japanese cedar and cypress trees growing on a steep slope to examine circumferential variation. Sap flow measurements were conducted for upper and lower slope aspects and in four directions (north, east, south, and west). We also measured the width of the tree crown to examine the effect of sunlight. Japanese cedar and cypress growing at this site extended their crowns toward the lower slope. Individual trees displayed circumferential variation in sap flux density (Fd). For Japanese cedar and cypress, the maximum daily Fd were 1.92 and 3.80 times as large as the minimum, respectively. However, the circumferential variation in Fd did not appear to be dependent on direction or slope aspect. These results suggest that large errors are produced when circumferential variation in Fd is ignored during the estimation of whole tree transpiration. Therefore, it is necessary to use sensors to capture circumferential variation in Fd, but sensors can be inserted randomly without the need to consider the shape of the tree crown or the direction of the tree trunk.

KEYWORDS granier-type sensors; circumferential variation; slope land; tree crown; Japanese cedar; Japanese cypress

INTRODUCTION

Sap flow techniques are useful for investigating transpiration from forests, particularly in places such as Japan where most forested areas occur in mountainous regions, because they are not limited by complex terrain and spatial heterogeneity (Wilson et al., 2001; Kumagai et al., 2007). However, spatial variation (radial or circumferential) in sap flow in the tree trunk may cause significant errors when scaling-up sap flow measurements to the whole-tree or stand scales. Many studies have described radial variation in sap flow and suggest that sap flow consistently decreases with sapwood depth in some tree species (Phillips et al., 1996; James et al., 2002; Delzon et al., 2004; Kumagai et al., 2005, 2007). However, few studies have investigated circumferential variation in sap flow. Tateishi et al. (2008) and Tsuruta et al. (2010) demonstrated circumferential variation using sap flow techniques, and suggested that a sap flow measurement from only one directional aspect generates an error in the estimation of tree transpiration.

Study site

This study was conducted in the Oborazawa Watershed, which is located in the eastern part of the Tanzawa Mountains, in the western part of Kanagawa Prefecture, Japan (latitude: 35°28′N, longitude: 139°12′E, altitude: 432–878 m). Annual precipitation at this site averages approximately 3000 mm (Shiraki et al., 2007), and snow is usually present on the ground between January and March. The catchments are mainly covered with a mixed stand of 20–30 year old coniferous trees (mainly Japanese cedar and Japanese cypress; Oda et al., 2012). Meteorological measurements were conducted at the study plot, which was in an open space on a ridge of the Oborazawa Watershed. In 2010, the annual precipitation in the area was 3130 mm and the average temperature was 12.5°C.

Sap flow measurements were conducted in Japanese cedar and Japanese cypress stands located on adjoining northwest-facing and southeast-facing slopes: slope angles were 30° and 25°, respectively.

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The width of tree crown

We measured the tree crown widths of nine Japanese cedar trees and nine Japanese cypress trees on the northwest-facing slope, and three Japanese cedar trees on the southeast-facing slope. The width of the tree crown was measured as the horizontal distance from the center of the tree trunk to the edge of the tree crown. We measured the horizontal distance in eight directions (north, northeast, east, southeast, south, southwest, west, and northwest).

Sap flow measurement

Sap flux density ($F_{d}$, cm h$^{-1}$) was measured by the thermal dissipation method using Granier-type sensors (Granier, 1987). A Granier-type sap flow sensor (20 mm long and 2 mm diameter) consists of two sensors that contain a pair of copper-constantan thermocouple thermometers connected by a constantan wire. These sensors were inserted in the sapwood after the bark was removed. Two sensors were inserted with a vertical separation distance of approximately 15 cm. The upper sensor contained a heating element of constantan and was supplied with 0.2 W of constant power. The heat generated by the element was transferred into the sapwood by sap flow. The temperature difference between the two sensors was recorded every 10 s with a data logger (CR10X, Campbell Scientific, Logan, UT, USA) and was averaged over 10-minute intervals. The recorded temperature was converted to $F_{d}$ as described by Granier (1987):

$$F_{d} = 1.19 \times 10^{-4} \times \left( \frac{\Delta T_{\text{max}} - \Delta T}{\Delta T} \right)^{1.23} \times 3600 \times 100$$  (1)

where $\Delta T$ is the temperature difference between the two sensors and $\Delta T_{\text{max}}$ is the maximum temperature difference at midnight, when sap was assumed not to flow. To determine the circumferential variation in $F_{d}$ sensors were installed to measure sap flow for the upper and lower slope aspects and in four directions (north, south, east, and west). Table I lists tree numbers, diameter at breast height (DBH), tree height, sapwood depth, slope aspect, and location of sensors. The region of the trunk where the sensors were installed was fully insulated using aluminum foil, avoiding any effects from direct radiation and natural thermal gradients along the trunk. Measurements were conducted on trees on the northwest-facing slope from 25 June to 19 December 2010, and on trees on the southeast-facing slope from 20 September to 19 December 2010. For analysis, we selected the data for the northwest-facing slope from 21 August to 13 September 2010, and for the southeast-facing slope from 26 September to 18 October. We excluded all data collected on rainy days and interpolated any lost data based on a linear relationship with $F_{d}$ measured in each direction.

Relationship between the number of circumferential measurements and the difference in average $F_{d}$ estimates

To examine the effect of circumferential variation, we examined the relationship between the number of circumferential measurements ($n$) and the difference in average $F_{d}$ estimates (Tsuruta et al., 2010; Kume et al., 2012). We changed $n$ from 1 to 4. For each $n$, we selected $F_{d}$ from all possible combinations of the four measurement directions and estimated the average $F_{\text{d}}$. For example, when $n = 2$, six possible combinations of the measurement aspect exist (i.e., (1) north and east, (2) north and south, (3) north and west, (4) east and south, (5) east and west, and (6) south and west in Japanese cypress). We assumed that an accurate $F_{d}$ was found when $n = 4$. The difference in average $F_{d}$ estimates (%) was calculated as the difference between the accurate $F_{d}$ and the average $F_{d}$ estimated from all possible combinations for each $n$.

RESULTS AND DISCUSSION

The relationship between slope and width of the tree crown

Figure 1 shows the horizontal distance from the center of the tree trunk to the tree crown edge for the northwest-facing slope and southeast-facing slope. On the northwest-facing slope, tree crowns were widest in the west, northwest, north, and northeasterly directions; on the southeast-facing slope, tree crowns were widest in the east, southeast, south, and southwesterly directions. Based on these results, Japanese cedar and Japanese cypress trees at this study site appear to be influenced by light conditions, and to extend tree crown growth toward the lower slope.

Circumferential variations in sap flow

Figure 2 shows the diurnal time course of solar radiation,

| No. | Species      | Diameter at breast height (cm) | Tree height (m) | Sapwood depth (N, S) (cm) | Slope Location of sensors |
|-----|--------------|--------------------------------|-----------------|---------------------------|---------------------------|
| 1008| C. japonica  | 17.3                           | 16.0            | 3.3, 3.7                  | NW, N                     |
| 1018|              | 18.0                           | 15.3            | 3.2, 4.7                  | NW, N, Upper, Lower       |
| 1024|              | 27.3                           | 18.1            | 4.4, 4.7                  | NW, N, Upper, Lower       |
| 1023| C. obtusa    | 18.9                           | 16.3            | 3.8, 2.9                  | NW, N, E, S, W            |
| 1032|              | 19.6                           | 16.1            | 2.4, 2.6                  | NW, N, E, S, W            |
| 1031|              | 19.4                           | 15.9            | 2.4, 3.0                  | NW, N, E, S, W            |
| 2001| C. japonica  | 65.9                           | 32.7            | 4.1, 2.4                  | SE, N, Lower, Upper       |
| 2002|              | 47.4                           | 27.3            | 3.5, 3.1                  | SE, N, Lower, Upper       |
| 2003|              | 53.7                           | 30.5            | 4.6, 3.8                  | SE, N, Lower, Upper       |

Upper: upper slope aspect, Lower: lower slope aspect.
vapor pressure deficit (VPD), and \( F_d \) at 0–20 mm depth for
the four aspects in tree Nos. 1024, 1023, and 2001 on a sunny day. Considerable circumferential variation
was observed in \( F_d \) measured around noon. Figure 3 shows
the relationship between daily \( F_d \) for the northerly aspect and one other aspect in tree Nos. 1024, 1023, and 2001 during all
measurement periods. Daily \( F_d \) for the northerly aspect and one other aspect had a strong linear relationship. This
trend was displayed by all sample trees, and did not change
during the measurement period.

Figure 4 shows the distribution of daily \( F_d \) values and
the coefficients of variation (CV) for all sample trees. The daily \( F_d \) was the measured \( F_d \) averaged from 10:00 to 15:00.
Individual trees exhibited circumferential variation in \( F_d \),
but variations in sap flow in the tree trunk did not appear
to be dependent on direction or upper or lower slope aspects.
For Japanese cedar standing on the northwest-facing slope,
the maximum daily \( F_d \) was 1.92 times as large as the
minimum for tree No. 1018. In the same stand, the CV ranged
from 20.9% to 28.4%. For Japanese cypress standing
on the northwest-facing slope, \( F_d \) exceeded 10 cm
h\(^{-1}\) locally, and the daily \( F_d \) in each tree varied considerably.
The maximum daily \( F_d \) was 3.80 times as large as the
minimum for tree No. 1031. In the same stand, the CV ranged
from 49.2% to 58.9%. For Japanese cedar standing on
the southeast-facing slope, the maximum daily \( F_d \) was
1.60 times as large as the minimum for tree No. 2002. In
the same stand, the CV ranged from 15.3% to 23.7%.
Compared with Japanese cedar, Japanese cypress varied
greatly in \( F_d \), and large local values of \( F_d \) were recorded
in tree trunks. Previous studies have reported circumferential variation in \( F_d \) in some tree species, with coniferous
trees having a larger degree of circumferential variation in \( F_d \)
than broad-leaved trees. In coniferous trees (Kominami and
Suzuki, 1993; Tsuruta et al., 2010), the maximum \( F_d \) tends
to be about 3 times as large as the minimum and the CV
ranges from 30% to 50%. In broad-leaved trees (Lu et al.,
2000; Tateishi et al., 2008; Kume et al., 2012), the maximum
\( F_d \) tends to be about 2 to 3 times as large as the minimum
and the CV ranges from 15% to 30%. The circumferential
variation in \( F_d \) in the Japanese cypress observed in this study
was within, or slightly higher than, the ranges reported
in previous studies. In contrast, the Japanese cedar observed
in this study had smaller circumferential variation in \( F_d \) than
previous reported in coniferous trees. Morikawa (1974)
conducted sap flow measurements in Japanese cypress
standing on flat ground and isolated from other trees and
found similar \( F_d \) values measured in all directions. These
results suggest that Japanese cypress standing on flat ground
have a symmetrical crown, experience uniform sunlight
conditions, and thus have less circumferential variation in
\( F_d \) than in the present or previous studies.

In our study, Japanese cedar and Japanese cypress trees
were growing on a steep slope and extended their tree crowns
toward the lower slope. However, we did not find a relationship
between circumferential variation in \( F_d \) and the shape
of the tree crown. Rudinsky and Vite (1959) conducted
dye injection experiments with 31 conifer trees to examine
patterns of water transport in tree trunks. Kozlowski and
Winget (1963) also conducted dye injection experiments
in four conifer trees and seven broad-leaved trees. They found
some patterns in water transport in each species and
suggested that turning water transport is more common than

![Figure 1. Horizontal distance of the tree crown. (a): Japanese cedar growing on the northwest-facing slope (n = 9), (b): Japanese cypress growing on the northwest-facing slope (n = 9), (c): Japanese cedar growing on the southeast-facing slope (n = 3).](image)

![Figure 2. Diurnal patterns in solar radiation, vapor pressure deficit (VPD), and \( F_d \) for each measurement aspects at 0–20 mm depth. Upper: upper slope aspect, Lower: lower slope aspect. (a): Northwest-facing slope. Data were obtained on 24 August, 2010. (b): Southeast-facing slope. Data were obtained on 6 October, 2010. a-1 and b-1 represent solar radiation (solid line) and VPD (dotted line), respectively, a-2, a-3, and b-2 are \( F_d \) values for four directions in tree Nos. 1024, 1023, and 2001 respectively. In a-2 and b-2 (Japanese cedar), \( F_d \) was measured for the north, south, upper, and lower aspects; in a-3 (Japanese cypress), \( F_d \) was measured for the north, east, south, and west aspects. Results are shown in 10-minute increments (solid line) and symbols represent 30-minute increments.](image)
vertical water transport. Morikawa (1974) performed a dye injection experiment on Japanese cypress and confirmed this finding: the path of ascent in the tree trunk was turning, not straight. Takizawa et al. (1996) conducted a dye injection experiment and suggested that sap flow in tracheids can move more easily in the circumferential direction than in the radial direction. These previous studies suggested that Japanese cedar and Japanese cypress exhibit turning water transport, and thus circumferential variation in $F_d$ would not correspond with the shape of the tree crown or the direction of the tree trunk.

Figure 5 shows the relationship between the number of circumferential measurements and the difference in average $F_d$ estimates. In Japanese cedar and Japanese cypress, the difference was about 20% and 40%, respectively. When the number of circumferential measurements decreased, the difference in Japanese cedar increased sharply compared with Japanese cypress. These results suggest that, by ignoring circumferential variation in $F_d$, we create large errors in estimates of whole tree transpiration in both species, and that Japanese cypress shows larger circumferential variation in $F_d$ than Japanese cedar. Therefore, when estimating whole tree transpiration using the sap flow technique, we need to use sensors to capture the circumferential variation in $F_d$. When we conduct sap flow measurements on a steep slope, we can insert the sensors randomly and need not consider the shape of the tree crown or the direction of the tree trunk.

Previous studies have examined the spatial and tree-to-tree variation in $F_d$, and suggested that the effect of the spatial variation was a minor source of error to estimate stand- and catchment-scale evapotranspiration compared with tree-to-tree variation (Ford et al., 2007; Kume et al., 2012). In this study, we only discussed circumferential variation in $F_d$. We need to conduct additional sap flow measurements to investigate circumferential, radial, and tree-to-tree variation in Japanese cedar and Japanese cypress trees growing on steep slopes.

**CONCLUSIONS**

We conducted sap flow measurements for upper and lower slope aspects and in four directions on a steep slope.

Figure 4. Distribution of daily $F_d$ values and the coefficient of variation (CV) for each sample tree. Upper: upper slope aspect, Lower: lower slope aspect. Solid lines are the average of the daily $F_d$ obtained for each site and species: a is a Japanese cedar; b is a Japanese cypress standing on the northwest-facing slope; c is a Japanese cedar standing on the southeast-facing slope; a-1 to c-1 show the CV and a-2 to c-2 show daily $F_d$.

Figure 5. Relationship between the number of circumferential measurements and the difference in average $F_d$ estimates. Each symbol shows the average of the difference at each $n$. Error bars indicate standard deviations. For Japanese cedar standing on the northwest-facing slope (NW), average value was calculated from two sample trees. For Japanese cypress standing on the northwest-facing slope and Japanese cedar standing on the southeast-facing slope (SE), average values were calculated from three sample trees.
We found that individual trees displayed circumferential variations in \( F_d \). Japanese cypress had large \( F_d \) values, and these values varied more than in Japanese cedar. However, variations in \( F_d \) values did not appear to be dependent on direction or slope aspect. These results suggest that when circumferential variation in \( F_d \) is ignored, large errors are produced during the estimation of whole tree transpiration. Therefore, we need to use sensors to capture the circumferential variation in \( F_d \). Sensors can be inserted randomly without the need to consider the shape of the tree crown or the direction of the tree trunk. At our site, more sap flow sensors need to be used with Japanese cypress to capture circumferential variation in \( F_d \) compared with Japanese cedar.

One limitation of this study is that we did not analyze seasonal changes in \( F_d \) because only about one month of acceptable data was available. Spatial variation in \( F_d \) may vary according to seasonal changes in soil condition and solar radiation (Lu et al., 2000; Ford et al., 2004; Fiora et al., 2006). Therefore, we need to measure the sap flow for longer periods in order to understand seasonal changes in the spatial variation in \( F_d \).

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