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原 著 論 文

Comparison of transpiration for *Quercus serrata* estimated based on the sap-flux method and measured based on the cutting-tree experiment*

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Although the sap-flux method has been widely used to estimate tree transpiration, the accuracy of the estimates has not been sufficiently examined, especially for ring-porous species. *Quercus serrata* is a ring-porous species that is widely distributed in warm-temperate forests in East Asia, including Japan. We compared the tree transpiration estimated by the sap-flux method using Granier sensors and by a cutting-tree experiment to evaluate the applicability of the sap-flux method to this species. The transpiration estimated by the sap-flux method correlated well ($r = 0.985$, $p < 0.05$) with that measured in the cutting-tree experiment, indicating that the sap-flux method succeeded in detecting diurnal changes in transpiration. However, the slope of the regression line was 1.84, indicating that transpiration was underestimated by the sap-flux method. These results suggest that Granier sensors can be used to estimate transpiration in ***Q. serrata*** but that calibration is necessary.
Keywords：sap flux, ring-porous, cutting-tree experiment, calibration, transpiration, ***Quercus serrata***

樹液流計測は樹木蒸散を推定するために広く用いられているが、環孔材樹種で用いる際の推定精度に関しては十分に検討されていない。コナラ（*Quercus serrata*）は日本を含む東アジアの温帯林に広く分布する環孔材樹種である。本研究では、樹液流計測（グラニエ法）で推定した樹液流量と切り木実験により得られた吸水量を比較することで、コナラへの樹液流計測の適用可能性を評価した。樹液流量は切り木実験による吸水量と高い相関を示し（r＝0.985, p＜0.05）、樹液流計測は樹木蒸散の日変化を計測できることが示唆された。しかし、その回帰直線の傾きは1.84となり樹液流計測は実際の蒸散量よりも過小評価していることが明らかとなった。以上の結果より、グラニエ法による樹液流計測は、コナラの蒸散を推定可能であるが、正確な蒸散量推定のためにはキャリブレーションを行うことが必要であると示された。
キーワード：樹液流、環孔材、切り木実験、キャリブレーション、蒸散、コナラ

1．Introduction

The sap-flux method has been widely used to estimate tree transpirations. The thermal dissipation method (Granier, 1987), a type of the sap-flux method, is one of the most popular methods because of its methodological simplicity, low costs, and broad applicability to complex terrains (Paudel *et al*., 2013; Renninger and Schafer, 2012). In this method, the temperature difference between sensors is measured and converted to sap flux using an empirical equation. Sap-flux estimates of tree transpiration correlate well with those based on gravimetric measurement (Lu and Chacko, 1998; Lu *et al*., 2002; McCulloh *et al*., 2007). However, several studies have suggested that this method could seriously underestimate tree transpiration (Bush *et al*. 2010; Hultine *et al*., 2010; Steppe *et al*., 2010). This underestimation may result from the fact that the empirical equation assumes a constant flux along a sensor's range, but a steep gradient of sap flux may actually exist in ring-porous species or when the sensors are installed in a non-conductive area (Bush *et al*., 2010; Clearwater *et al*., 1999; Lu *et al*., 2002).

To overcome this problem, researchers have proposed to include a coefficient to adjust the sap flux estimated based on the thermal dissipation method to better estimate the real sap flux. The underestimation by Granier method seems to be species specific because of differences in the heat transfer between sensors, xylem sap and tree trunk depends on tree species, diameters at breast height (DBH) and sap flux (Hultine *et al*., 2010).

This paper reports a comparison of transpiration estimates in *Quercus serrata*, a representative ring-porous canopy species in warm-temperate forests in East Asia, based on the sap-flux method with one measured by a the cutting-tree experiment. Based on the results, we discussed applicability of the sap-flux method to this species.

＊邱　湞瑋・立石麻紀子・小松　光・大槻恭一，樹液流計測と切り木実験により推定した *Quercus serrata* の蒸散量の比較.

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2. Materials and methods

2. 1. Site description

This study was conducted in the Kasuya Research Forest of Kyushu University, Fukuoka, Japan (33°38'N, 130°31'E, 50 m a.s.l.). For the experiment, we selected one *Q. serrata* trees that was located in a mixed forest with a canopy height of 12 m. The DBH was 13.2 cm and tree heights was 8.0 m.

Meteorological data was recorded in an open field located 100 m west of the selected trees. Temperature, air relative humidity (HMP155, Vaisala Inc., Vantaa, Finland) and solar radiation (EKO ML-020VM, EKO Inc., Tokyo, Japan) were recorded every 10 min using a data logger (CR1000, Campbell Scientific Inc., Logan, UT, USA).

2. 2. Methods of analysis

This study comprised two steps. First, we analyzed data derived from a dye-injection experiment. This result enabled us to determine the water conductive area. If the sensor length was less than the depth of the water conductive area, we applied the Clearwater equation (Clearwater *et al.*, 1999) to adjust the sap flux; otherwise, we did not apply the equation. Second, we compared the diurnal changes in transpiration estimated based on the sap-flux method with that measured based on cutting-tree experiments to examine whether the sap-flux method detected changes in sap flux.

2. 3. Cutting-tree experiments

A cutting-tree experiment was performed on September 21, 2013. First, the sample tree was stabilized with ropes fastened to a scaffold installed nearby. After cutting the trunk using a chainsaw at a height of 60 cm at 3:30, we immediately put the lower end of the trunk into a tank filled with water. The trunk was cut again under water with a handsaw to prevent blockage of xylem sap ascent (Hirose *et al.* 2005). The end of the trunk was placed into a small pot which filled with water within the tank without exposing it to air and the pot was sealed with foil paper to prevent evaporation. Every 30 min until 14:30, we replaced water in the pot that was lost to tree transpiration to maintain a constant level and recorded these amounts. These volumes were used to calculate tree transpiration.

2. 4. Dye-injection experiments

After the cutting-tree experiment, we conducted a dye-injection experiment. We put an aqueous solution of 0.1% acid fuchsine into the pot to stain the water conductive area in the trunk from 15:00 to 15:30. We removed the trunk from the pot and cut disks at 50-cm intervals. The sapwood area was assumed to be identical to the dyed area of the disks taken from 10 cm above the end of the trunk. The sapwood depths for four aspects (north, east, south and west) were determined based on the depths of the disk dyed by the fuchsine solution.

2. 5. Sap-flux measurements

Sap-flux measurements were conducted with the thermal dissipation method using hand-made Granier sensors (Granier, 1987) installed in the north aspect of the trunk. Granier *et al.* (1994) reported that the depth of the water conductive area was 1.1 cm for a *Quercus petraea* tree (11.9 cm DBH, 1.9 cm sapwood depth). We thus installed a 1-cm sensor (James *et al.*, 2002) to correspond to the depth of the water conductive area.

Each sensor consisted of a pair of probes: the upper probe contained a heater constantly supplying 0.15 W of heat and a thermocouple, while the lower probe only contained a thermocouple and measured the temperature. The heat was dissipated into the sapwood and vertical sap flux surrounding the probe. The temperature difference (ΔT, °C) between upper and lower probes was then measured and scanned every 30 sec, and 30-min mean values were recorded using a data logger (CR1000) with multiplexers (AM16/32, Campbell Scientific). The mean sap flux along the sensor length ($Fd_{\_sensor}$, $cm^3m^{-2}s^{-1}$) was calculated according to Granier's empirical equation (Granier, 1987):

$$Fd_{\_sensor} = 1.19\times10^{2}[(\Delta T_{Max} - \Delta T)/\Delta T]^{1.23} \quad (1)$$

where ΔT_{Max} is the daily maximum temperature difference. The measurement period was September 19-21, 2013.

3. Results and discussion

Figure 1 shows the dyed depth of the four aspects of the trunk. The position of the sensors (30 cm above the base of the trunk) was fully dyed, indicating that the Clearwater equation was unnecessary. The dyed area was highest in the outer xylem and decreased with depth from the cambium. Further, we found that large earlywood vessels in the outermost annual ring were mainly stained, indicating that water was mainly transported by these vessels (data not shown). Similar results have been reported for *Q. serrata* (Kuroda and Yamada, 1996; Sato *et al.*, 2010) and other Quercus species (Čermák *et al.*, 1992; Umebayashi *et al.*, 2008).

Figure 2 shows the diurnal changes in meteorological conditions and sap fluxes based on the sap-flux method and cutting-tree experiment. We observed clear diurnal variation in solar radiation, temperature, and vapor pressure deficit. The sap fluxes estimated by the two methods were similar in that both peaked around noon. However, the absolute values of the fluxes were notably different.

Figure 3 shows the relationship between tree transpiration estimated by the sap-flux method and the cutting-tree experiment. We observed a clear correlation ($r = 0.985$, $p<0.05$ based on a two-tailed Pearson's correlation coefficient test) between them. The slope for the regression line was 1.84, indicating underestimation by the sap-flux method. The reasons for this underestimation are unclear at this stage, but possible reasons are as follows. First, not all the vessels within annual rings can transport water in ring-porous species (Umebayashi *et al.*, 2008), as determined by our dye-injection experiment. Second, the dyed depth of xylem decreased dramatically as tree height increased (Fig. 1). This implies that a steep gradient in the sap flux between sensors cannot be detected by the Granier method. Such a steep gradient has been observed in other *Quercus* species (Bush *et al.*, 2010; Granier *et al.*, 1994; Renninger *et al.*, 2012). In addition, the underestimation may have resulted from positional differences between the Granier sensors and the outmost earlywood vessels. These vessels have been reported to be primarily responsible for water transport in ring-porous species (Umebayashi *et al.*, 2008). The Granier sensors could not detect the volume of water transported by these vessels if they were installed away from these vessels or only in contact with part of these vessels, the outermost of which were 300–350 μm in diameter (Itoh, 1995).

Quercus serrata is the representative species of warm-temperate forests in Eastern Asia, including Japan (Nakashizuka and Iida, 1995). However, this study was the first comparing transpiration estimated by the sap-flux method with that measured in a cutting-tree experiment to assess the applicability of the former using the Granier sensors. This preliminary study succeeded in detecting diurnal changes in transpiration using the sap-flux method and obtained a clear correlation between transpiration estimated by the two methods. Similar results were reported in previous studies on other ring-porous *Quercus* species, implying the generality of our results. However, the slope of the regression line between transpiration estimated by the Granier sensor and the cutting-tree experiment (i.e., the calibration coefficient) will differ among trees of the same species because the sap flux could vary according to structural parameters of the tree (i.e., DBH, leaf area index, and tree height). This study may offer a starting point for examining the applicability of the sap-flux method to *Q. serrata* trees and therefore has implications for future studies.

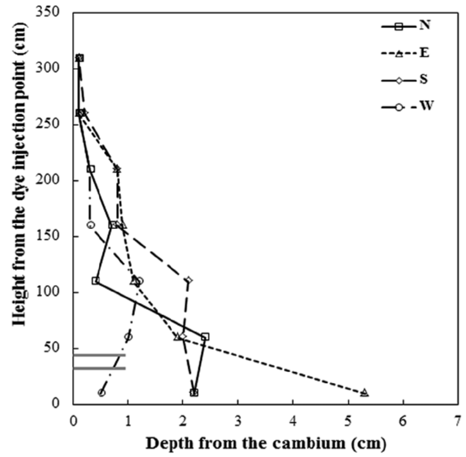

Fig. 1 Dyed xylem depth as a function of height above the dye injection point. Gray bars indicate the positions of the installed sensors.

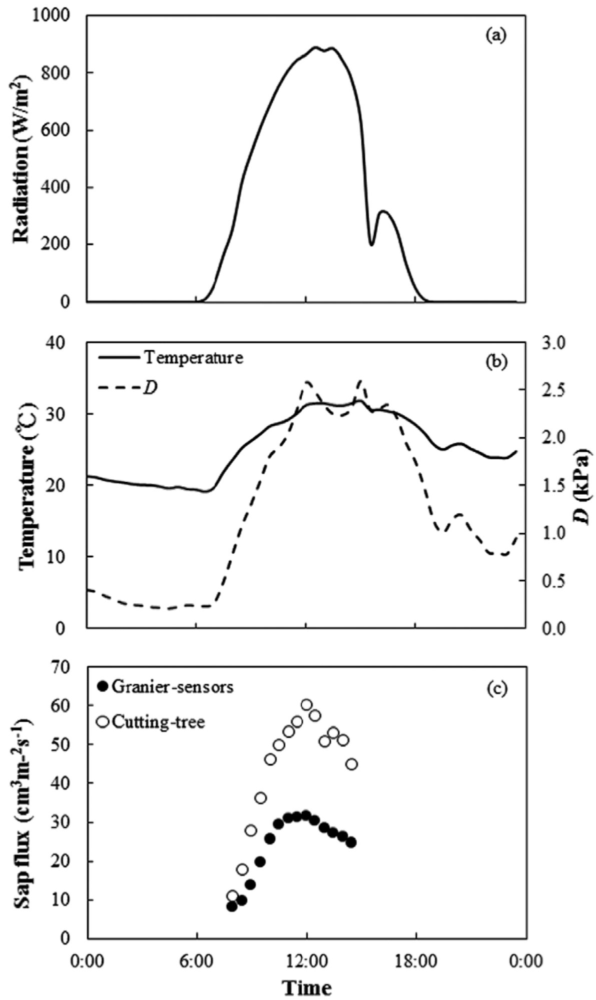

Fig. 2 Diurnal changes in (a) solar radiation, (b) temperature and vapor pressure deficit (D) and (c) sap flux on Sep. 21, 2013.

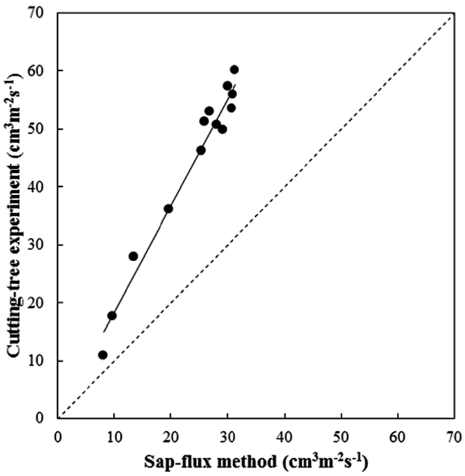

Fig. 3 Relationship between tree transpiration estimated by the sap-flux method and a cutting-tree experiment. The solid line is the regression line (y = 1.84x) determined by the least-squares method. The dotted line indicates y = x.

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