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Original article

Effect of the span length of Granier-type thermal dissipation probes on sap flux density measurements

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Keywords:
thermal dissipation technique / sensor alteration / thermal conduction / underestimation of sap flux density

Abstract

• Granier-type thermal dissipation sensors measure sap flux density (u) by using the temperature difference between the heater and the reference probe. To detect u correctly, heat must not be transferred to the reference probe by thermal conduction. The distance across which heat can be transferred by conduction is important for the span length of a sensor and spacing of a number of sensors.

• To validate span lengths and spacing of sensors, we used numerical simulations to calculate the potential distance across which heat can be transferred by conduction. We compared measurements with an original and a modified sensor for a Japanese red pine (*Pinus densiflora*) from December 2004 to May 2005. The span length of the original and the modified sensor is 15 and 4 cm, respectively.

• Numerical simulations showed that span length and spacing of Granier sensors should be more than 10 cm for trees in which u ceases for a few hours before the predawn period. The modified sensor underestimated u by 18–46% in winter (December–March) because its reference temperature was increased by heat transferred by conduction. The modified sensor measured u correctly in warm seasons, and only underestimated the annual amount of transpiration by 6%.

Mots-clés :
technique de dissipation thermique / altération du capteur / conduction thermique / sous-estimation de la densité de flux de sève

Résumé – Effet de la longueur de la portée des sondes de dissipation thermique de type Granier sur des mesures de densité de flux de sève.

• Les capteurs de dissipation thermique de type Granier mesurent la densité du flux de sève (u) en utilisant la différence de température entre le radiateur et la sonde de référence. Pour détecter u correctement, la chaleur ne doit pas être transférée à la sonde de référence par conduction thermique. La distance à travers laquelle la chaleur peut être transférée par conduction est importante pour la longueur de la portée d'un capteur et l'espacement de nombreux capteurs.

• Pour valider les longueurs des portées et l'espacement des capteurs, nous avons utilisé des simulations numériques pour calculer la distance potentielle à travers laquelle la chaleur peut être transférée par conduction. Nous avons comparé les mesures faites à l'aide d'un capteur original et d'un capteur modifié pour un pin rouge du Japon (*Pinus densiflora*) de Décembre 2004 à Mai 2005. La longueur des portées est de 15 cm et de 4 cm respectivement pour l'original et le capteur modifié.

• Des simulations numériques ont montré que la longueur de la portée et l'espacement des capteurs Granier devraient être supérieurs à 10 cm pour les arbres dans lesquels u cesse pendant quelques heures avant la période précédant l'aube. Le capteur modifié sous-estime u de 18 à 46 % en hiver (Décembre-Mars), car sa température de référence a été augmentée par la chaleur transférée par conduction. Le capteur modifié mesurée u correctement pendant les saisons chaudes, et seulement sous-estime la transpiration annuelle totale de 6 %.

1. INTRODUCTION

The transpiration of forest vegetation is generally the largest source of evapotranspiration from a forest ecosystem (e.g., Granier et al., 2000). Quantitative evaluations of transpiration are essential for understanding forest hydrologic cycles.

Granier-type thermal dissipation probes (Granier, 1985; 1987) are commonly used to observe sap flux density (u) and to estimate transpiration at the individual-tree scale (e.g., Goldstein et al., 1998) to the forest-canopy scale (e.g., Granier et al., 2000). Compared to the heat pulse method (Closs, 1958;

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Marshall, 1958), the Granier method has certain advantages. Because the Granier method uses a lower heat power than the heat pulse method, damage to the conducting tissue of the stem can be avoided and longer-term measurements of u are possible. The measuring system of the Granier probe is also simpler than that of the heat pulse method; in the Granier method, the heater has a constant heat power, and only one variable (the temperature difference between probes [ΔT]) is needed to obtain u.

A Granier sensor uses a pair of thermocouples to measure ΔT; one probe has a constant heating power and measures its temperature, whereas the other probe measures the reference temperature of the xylem and is not influenced by heat transferred from the heater. Therefore, the reference temperature is measured at a lower height than the heater, i.e., at an upstream point. Granier (1987) determined that the span length between probes (S) is from 10 to 15 cm. The sensors detect the mean u along the probe length (L). Granier (1985) obtained the following calibration curve between ΔT and u ($m^3/m^2/s$):

$$\begin{array}{l} u = 1.19 \times 10^{-4} \left(\frac{\Delta T_0 - \Delta T}{\Delta T}\right)^{1.231} \\ R^2 = 0.96 \end{array} . \qquad (1)$$

where ΔT_0 is ΔT when u equals zero. As sap moves upwards, i.e., during transpiration, the heat transfer from the heater toward the lower part of the tree is weakened by the advection effect of sap movement, whereas the reference temperature is not affected by the heater. However, when sap movement stops, heat is transferred by conduction both vertically and horizontally. Thus, the potential distance across which heat can be transferred by conduction must be determined.

To evaluate the amount of sap flow in a single tree from sap flux measurements, the radial variations in u within deep sapwood (e.g. Granier et al., 1996b; Köstner et al., 1998) and the azimuthal variations in u in the trunk, especially when growing in open canopy space like an orchard (Lu et al., 2000), must be determined. These variations of u can be measured by inserting a number of Granier sensors at the same height into a single tree. Because heat transfer by conduction occurs in all directions, care must be taken to place the reference probes away from the influence of the heaters (Lu et al., 2000). Thus, as a prerequisite, the potential distance across which heat can be transferred by conduction must be determined, not only to define the span length between probes of a single sensor but to ensure the correct spacing of a number of sensors at the same height.

Several companies commercially produce the original version of the Granier sensor and modified versions, and Lu et al. (2004) doubted whether the modified version can detect the correct u. Wilson et al. (2001) estimated forest transpiration using a modified sensor (the thermal dissipation probe, TDP-30, Dynamax, Inc., Houston, TX, USA; hereafter referred to as a TDP), and compared its results with evapotranspiration as measured by the eddy covariance and water balance methods. The amount of transpiration measured by the TDP was much less than the amount of evapotranspiration, and the TDP underestimated u. Although the authors suggested that the modification of the sensor was responsible for this underestimation, the exact reason was unclear (Wilson et al., 2001). The span length of TDP is 4 cm, which may not be large enough to avoid heat transfer by conduction from the heater to the reference probe during nighttime, when the u reaches zero. If heat arrives at the reference probe and increases the reference temperature, the TDP underestimates u.

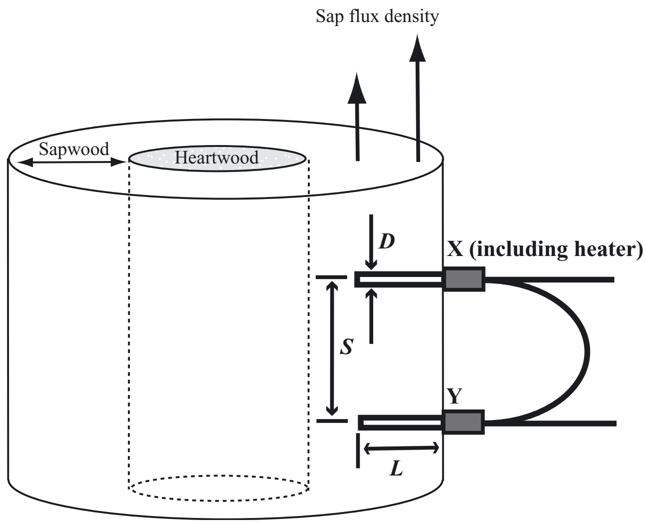

Figure 1. Schematic of Granier-type thermal dissipation probes.

The present study was mainly focused on the winter period, when sap movement apparently stops and heat transfer by conduction prevails. The specific objectives of the study were:

(i) Calculation of the potential distance across which heat can be transferred by conduction using numerical simulations when sap movement stops, and confirmation of the reasonability of the recommended span length of the original replica sensor (a type M sapflow sensor; UP GmbH, Cottbus, Germany; hereafter referred to as SFS).

(ii) A comparison of data obtained with the original replica sensor and the modified sensor (Dynamax TDP-30), based on recordings from a Japanese red pine (*Pinus densiflora*) tree, and a quantitative evaluation of the underestimation obtained with the modified sensor.

(iii) An estimation of the potential extent of the underestimations of u that arise from the increased reference temperature.

2. MATERIALS AND METHODS

2.1. Differences in sensor construction between the original replica and the modified sensor, and a hypothesis explaining the underestimation of sap flux densities by the latter

The main alterations of the TDP are its probe length (L) and span length (S; Tab. I). These modifications may affect measurements of u (e.g., Lu et al., 2004). Conifer species generally have a radial gradient of u (Phillips et al., 1996); thus, the alteration of L in the TDP may lead to differences in SFS and TDP measurements. To compare

Table I. Diameter (D), span length (S), length (L) and features of the SFS and the TDP.

	SFS	TDP
D (mm)	2.0	1.2
S (mm)	150	40
L (mm)	20	30
Hearter	Wound heater	Line heater
Material of tube	Aluminum	Stainless steel
Sensor coating	None	Teflon

u measured by the SFS and TDP, we must first clarify its radial gradient. However, the S between the TDP probes is only 4 cm, which is much less than that for the SFS probes (Tab. I). During daytime on unclouded days, sap movement carries heat from the heater to higher parts of the stem; that is, there is convective cooling. Thus, the reference temperature can be measured correctly by the TDP under these conditions. However, from late night to predawn, when u is near zero and some of the heat is transferred to the lower part of the stem by thermal conduction, heat can reach the reference probe and increase the reference temperature. The effect of this heat on the reference probe leads to an underestimation of ΔT_0 and, ultimately, of u (see Eq. (1)). We evaluated the effect of altering S on measurements of u by observing the radial gradient and by performing numerical simulations of thermal conduction.

2.2. Sap flux density measurements

We measured u using an SFS and a TDP in a secondary forest of Japanese red pine (*P. densiflora*) adjacent to the Terrestrial Environment Research Center (TERC), University of Tsukuba, Japan (36° 07′ N, 140° 06′ E). We have provided details of this forest in our previous studies (Iida et al., 2005; 2006). We selected a Japanese red pine test tree and inserted two SFSs and a TDP into the stem at a height of 1 m above the ground. Note that a total of three sensors were inserted, with more than 20 cm spacing between them. The test tree had a diameter at breast height of 23.7 cm. The sapwood width was 5.5 cm, based on wood core sampling with an increment borer, and the corresponding sapwood area was 283 cm^2. u was calculated using Equation (1). Iida et al. (2003) obtained u for a red pine tree at this site with SFS, regarding ΔT_0 as the daily maximum value of ΔT, and found reasonable correspondence between u measured by SFS and by the heat pulse method. Thus, we used ΔT_0 as the daily maximum value of ΔT in this study.

The SFS and TDP measured the average u along the fixed sensor length (L, Tab. I), i.e., from depths of 0 to 20 mm ($u_{SFS0-20}$) and 0 to 30 mm (u_{TDP}) in the sapwood, respectively. To test our hypothesis, we required SFS observations in the same range (*i.e.*, $u_{SFS0-30}$) as the TDP observations. To estimate $u_{SFS0-30}$, we inserted an SFS at 20–40 mm and measured u within this range ($u_{SFS20-40}$). Although the mean u from the depth of 20–30 mm by the SFS ($u_{SFS20-30}$) was needed to obtain $u_{SFS0-30}$, this value was not possible to measure due to the fixed L = 20 mm of the SFS. Considering the radial gradient of u, $u_{SFS0-30}$ was calculated as the weighted mean value of $u_{SFS0-20}$ and $u_{SFS20-40}$:

$$u_{SFS0-30} = a \cdot u_{SFS0-20} + b \cdot u_{SFS20-40}, \tag{2}$$

where a is the weight of the sapwood area from depths of 0–20 mm to that of 0–30 mm (a = 0.7), and b is the weight of the sapwood area from depths of 20–30 mm to that of 0–30 mm (b = 0.3).

Observations were conducted from December 2004 to May 2005. Values of ΔT measured by the SFSs and TDP were sampled at 1-min intervals, and their 30-min average values were recorded by a data logger (CR10X; Campbell Scientific Inc., Logan, UT, USA). To detect clear diurnal changes in u, ΔT values for unclouded days were selected for the following analysis. Table II shows the monthly number of unclouded days.

2.3. Measurement of volumetric soil water content

We measured a vertical profile of volumetric soil water content using the time domain reflectometry (TDR) method (type 6050X1 with multiplexer type 6020B05, Soil Moisture Equipment Co., Ltd., Santa Barbara, CA, USA), and calculated the relative extractable soil water (*REW*) for depths from 0 to 70 cm, which correspond to the extent of the root system. Details on TDR measurements and *REW* calculations are described in Iida et al. (2006).

2.4. Numerical simulation of thermal conduction

In our hypothesis, heat from the heater of the TDP may arrive at the reference probe from late night to predawn when u reaches zero and only thermal conduction occurs. We carried out simple numerical simulations to obtain the potential distance across which heat can be transferred for SFS and TDP, and to validate field measurement data obtained at one test tree. We simulated the thermal conduction in xylem according to the method of Campbell (1985). Both the thermal conduction in xylem having radial and longitudinal uniform thermal conductivity (λ_{GW}) and the volumetric specific heat (C_{GW}) are expressed by the following equation:

$$\frac{\partial T}{\partial t} = \frac{\lambda_{GW}}{C_{GW}} \cdot \frac{\partial^2 T}{\partial^2 z}, \tag{3}$$

where T is the xylem temperature, t is the duration of thermal conduction, and z is the vertical distance from the heater.

We measured the specific gravity of oven-dried wood (r_{DW}) and the volumetric water content of green wood (θ_{water}) sampled by wood coring (n = 20) and obtained r_{DW} = 0.49 (Mg/m^3) and θ_{water} = 0.3 (m^3/m^3). Using the relationships among λ_{GW}, r_{DW}, and θ_{water} (Kollmann and Malmquist, 1956; Maku, 1961), we determined λ_{GW} = 0.23 (W/m/°C). Although green wood includes wood substances, water, and airspace, the airspace is generally small enough to ignore (e.g., Koshijima et al., 1983). Thus, C_{GW} can be obtained by

$$C_{GW} = C_{DW} \cdot \theta_{DW} + C_{water} \cdot \theta_{water}, \tag{4}$$

where C_{DW} is the volumetric specific heat of oven-dried wood (see below), C_{water} is the volumetric specific heat of water (4.18 MJ/m^3/°C), and θ_{DW} is the volumetric content of oven-dried wood (θ_{DW} = 1 − θ_{water}). C_{DW} is defined as the product of the specific gravity (r_{DW}) and the specific heat of dry wood (H_{DW}), i.e., $C_{DW} = r_{DW} \times H_{DW}$. Using the equation $H_{DW} = 1.11 + 0.00485T$ (Dunlap, 1912) and assuming T = 10 (°C), estimated from typical mean air temperature, H_{DW} (J/g/°C) was calculated as 1.16 (J/g/°C). We obtained C_{DW} = 0.568 (MJ/m^3/°C) and finally determined C_{GW} as 1.65 (MJ/m^3/°C) by Equation (4).

The specific heats of aluminum (=2.43 [MJ/m^3/°C]) and stainless steel (=3.69 [MJ/m^3/°C]) were used for the SFS and TDP simulations, respectively. For the initial condition of the simulation, we assumed a uniform ambient xylem temperature of 10 °C. The boundary

Table II. Comparison of the monthly mean values for u between the SFS ($u_{SFS0-30}$) and TDP (u_{TDP}) on clear days. Monthly minimum values of daily mean relative extractable soil water (*REW*) are also shown.

Year	Month	Number of data (days)	Monthly mean sap flux density (cm³/cm²/h)		Ratio of sap flux densities	Minimum of daily mean *REW*
			$u_{SFS0-30}$	u_{TDP}	$u_{TDP}/u_{SFS0-30}$	
2004	Dec.	19	0.85	0.70	0.82	0.53
2005	Jan.	18	0.56	0.33	0.59	0.54
	Feb.	17	0.52	0.28	0.54	0.56
	Mar.	17	1.1	0.86	0.78	0.55
	Apr.	17	1.7	1.7	1.00	0.57
	May	22	1.9	1.9	1.00	0.50

conditions were no heat flow at the centre of the stem and constant temperature near the surface of the heater (Campbell, 1985). Considering the observation results of ΔT by the SFS and TDP, we assumed constant temperatures of 27 °C and 17 °C for the heaters of the SFS and TDP, respectively. The difference in the constant temperatures was caused by differences in the geometric characteristics, heating power, and sensor coating between SFS and TDP (Tab. I). SFS has a non-coated sensor, including the wound heater, of 0.2 W. However, TDP has a Teflon-coated sensor, including the line heater, of 0.15–0.2 W, which is the manufacturer's rough value; while our sensor included the heater at 0.18 W.

3. RESULTS

3.1. Average diurnal variations in ΔT measured by the SFS and TDP

Figure 2 shows the average diurnal variations in ΔT measured by the original sensor, SFS, and the modified one, TDP. When the solar radiation began to increase at dawn and transpiration activity started, $\Delta T_{SFS0-20}$ began to decrease due to sap movement and reached minimum values in the afternoon. Declining radiation from noon to evening resulted in a decrease in u and an increase in $\Delta T_{SFS0-20}$: the increasing trends of $\Delta T_{SFS0-20}$ were more obvious in the spring of April and May 2005 (Figs. 2E and 2F) than in the winter from December 2004 to March 2005 (Figs. 2A–2D). These obvious trends showed that u likely stopped just before sunrise and slight sap movement continued during nighttime until $\Delta T_{SFS0-20}$ reached its daily maximum value in spring. In the middle of winter, in January and February 2005, $\Delta T_{SFS0-20}$ reached a plateau during the late night to predawn period and sap movement in the test tree likely ceased for a few hours before sunrise (Figs. 2B and 2C).

Diurnal trends in ΔT measured by the TDP (ΔT_{TDP}) and the time of observed maximum values were roughly similar to those of $\Delta T_{SFS0-20}$ in the spring (Figs. 2K and 2L). However, in the winter the increasing trend of ΔT_{TDP} during nighttime was different from that of $\Delta T_{SFS0-20}$ (Figs. 2G–2J). Although ΔT_{TDP} increased from the evening to late night, reflecting the decline in u, its trend was smaller than that of $\Delta T_{SFS0-20,}$ and ΔT_{TDP} started to decrease earlier than $\Delta T_{SFS0-20}$. In particular, during the late night to predawn periods in the middle of winter, ΔT_{TDP} gradually decreased followed by a sudden increase before the start of sap movement (Figs. 2H and 2I). The differences in the nighttime trend between $\Delta T_{SFS0-20}$ and ΔT_{TDP} were not observed in the spring (Figs. 2K and 2L).

3.2. Comparison of sap flux densities observed by the SFS and TDP

Comparisons of u for 0–30-mm depths, calculated by Equation (2) from SFS ($u_{SFS0-30}$) and TDP (u_{TDP}) observations, revealed seasonal differences (Fig. 3). Values for u_{TDP} were clearly smaller than those of $u_{SFS0-30}$ in the winter (Figs. 3A–3D), especially in the middle of winter, when the ratios of u_{TDP} to $u_{SFS0-30}$ were less than 60% (Tab. II). However, in the spring, u_{TDP} was equal to $u_{SFS0-30}$ (Figs. 3E and 3F). Note that at this study site, Kobayashi and Tanaka (1996) measured azimuthal variations in u with the heat pulse method and reported that the variations in u at 1 and 2 cm inside from the outermost sapwood were within 9%. The differences between $u_{SFS0-30}$ and u_{TDP} were clearly larger than the azimuthal variations, and thus we could safely conclude that the observed u_{TDP} values were correct in the spring, but that TDP underestimated u in winter. The daily mean *REW* values were more than 0.50 throughout the measurement period (Tab. II). Iida et al. (2006) indicated that transpiration activity at this site was depressed by the lack of soil water when *REW* was less than 0.4. Thus, the soil water was sufficient and the variations in u were likely constant (Lu et al., 2000).

3.3. The degree of sap flux density underestimation resulting from heater-induced increases in the reference temperature

Table III indicates the degree to which u was underestimated due to increases in the reference temperature; this table was created by calculating u with artificial decreases of ΔT_0 from 0 to 0.1 °C at steps of 0.01 °C. The degree of underestimation for the SFS was 1–2% when the reference temperature increased by 0.01 °C or ΔT_0 decreased by 0.01 °C, and 7–18% when temperature increased by 0.1 °C. The degree of underestimation for the TDP was 2–8% when the reference temperature increased by 0.01 °C or ΔT_0 decreased by 0.01 °C, and was 16–56% when the temperature increased by 0.1 °C. The magnitude of the TDP underestimations was larger than that

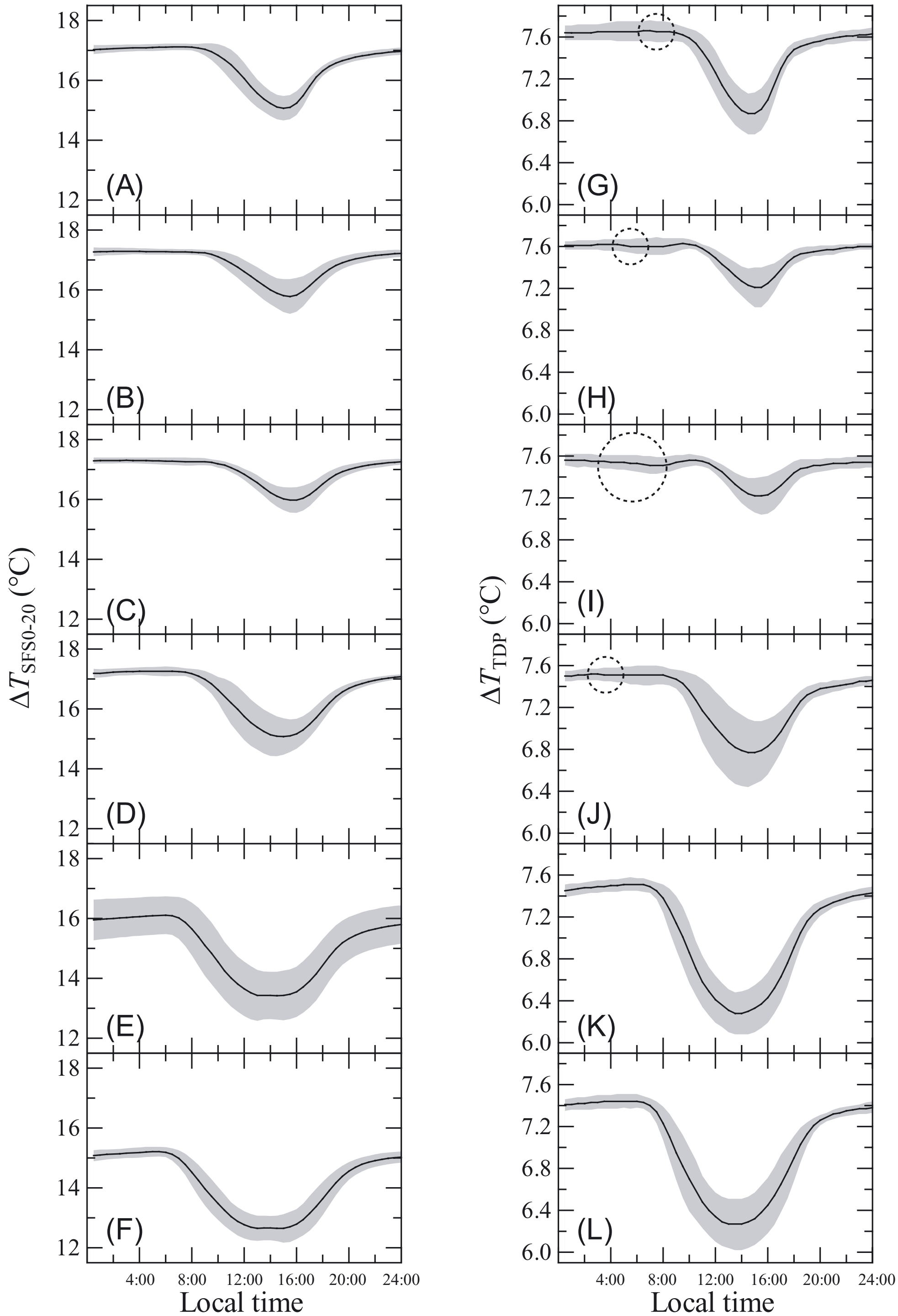

Figure 2. Monthly variations in ensemble-mean diurnal changes in ΔT measured by the SFS (A–F) and the TDP (G–L) for December 2004 (A and G), January (B and H), February (C and I), March (D and J), April (E and K), and May 2005 (F and L). The solid line shows the ensemble mean, the grey area shows the range of standard variation, and the dashed-line circles show the decrease in ΔT_{TDP} observed before the predawn.

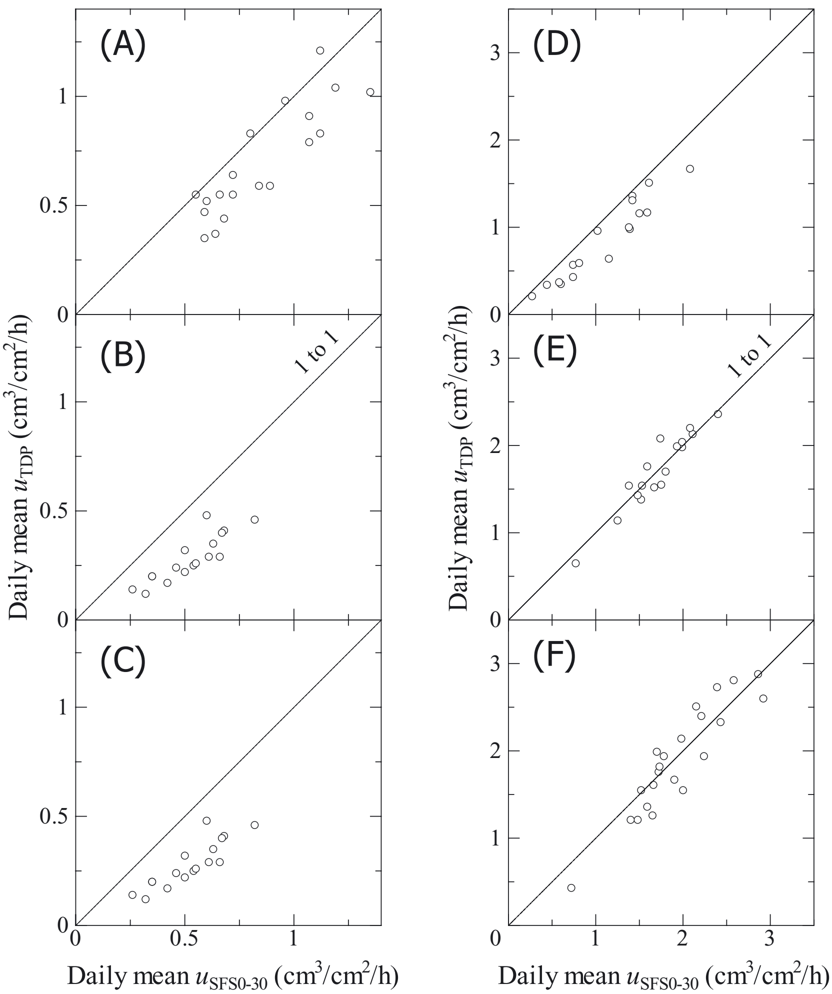

Figure 3. Comparisons of the daily mean values of u between the SFS ($u_{SFS0-30}$) and TDP (u_{TDP}) for December 2004 (A), and January (B), February (C), March (D), April (E), and May 2005 (F).

of SFS underestimations because the TDP had smaller ΔT values than the SFS (Eq. (1)). Researchers must recognize that u is underestimated significantly by a very small increase in the reference temperature.

3.4. Numerical simulations of thermal conduction

Figure 4 shows the vertical profiles of the heater-induced increase of xylem temperature calculated based on SFS and TDP data. To detect the heater-induced increase of xylem temperature at high resolution, we found the relationship between the increase and the duration of the only occurrence of thermal conduction for SFS and TDP (Figs. 5A and 5B, respectively). If sap movement stopped completely and thermal conduction continued for 20 h, heat did not reach the SFS reference probe (Figs. 4A and 5A). In this case, the reference probe is not affected by the heat transferred from the heater, and the SFS detects u correctly.

The reference temperature of the TDP, which was the xylem temperature at a distance of 4 cm from the heater, increased when thermal conduction continued only for more than 2 h (Figs. 4B and 5B). Three hours of occurrence of thermal conduction resulted in an increase in the reference temperature of the TDP of about 0.04 °C (Fig. 5B). If thermal conduction continued for more than 2 h, the TDP underestimated u due to the increased reference temperature and decreased ΔT_0 caused by the heat transferred by conduction.

4. DISCUSSION

4.1. Underestimation of sap flux densities by the TDP and its causes

Comparisons between $u_{SFS0-30}$ and u_{TDP} clearly showed that u_{TDP} was smaller than u_{SFS} in winter (December 2004–March 2005; Figs. 3A–3D; Tab. II). The magnitude of this underestimation was greater in the middle of winter in January and February 2005 (Figs. 3B and 3C; Tab. II). In the spring (April–May 2005), however, u_{TDP} nearly corresponded with $u_{SFS0-30}$ (Figs. 3E and 3F); underestimation did not occur.

Table III. Degree of underestimating $u_{SFS0-20}$ and u_{TDP} due to the artificial decrease in ΔT_0.

	Degree in underestimation (%) in $u_{SFS0-20}$ caused by the decrease of ΔT_0					
	2004	2005				
Decrease of ΔT_0 (°C)	Dec.	Jan.	Feb.	Mar.	Apr.	May
0.00	0	0	0	0	0	0
0.01	1	2	2	1	1	1
0.02	3	4	4	2	2	2
0.03	4	5	6	3	2	2
0.04	5	7	8	4	3	3
0.05	6	9	10	5	4	4
0.06	8	10	11	6	5	5
0.07	9	12	13	7	6	5
0.08	10	13	15	8	6	6
0.09	11	15	16	9	7	7
0.10	12	16	18	10	8	7
	Degree in underestimation (%) in u_{TDP} caused by the decrease of ΔT_0					
	2004	2005				
Decrease of ΔT_0 (°C)	Dec.	Jan.	Feb.	Mar.	Apr.	May
0.00	0	0	0	0	0	0
0.01	4	7	8	3	2	2
0.02	7	14	16	6	4	4
0.03	10	20	22	9	6	5
0.04	13	25	28	12	7	7
0.05	16	30	34	14	9	9
0.06	19	35	39	17	11	10
0.07	21	39	44	19	12	12
0.08	24	43	48	22	14	13
0.09	26	47	52	24	15	15
0.10	28	50	56	26	17	16

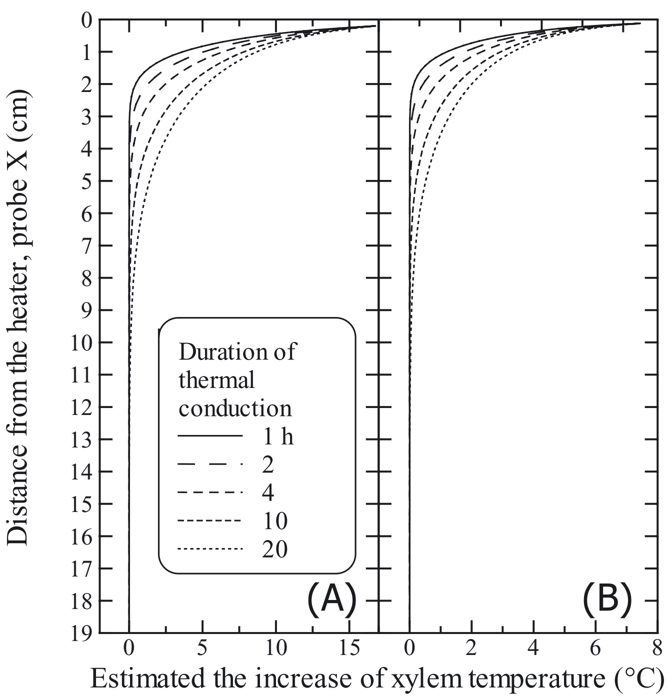

Figure 4. Vertical profiles of the heater-induced increase of xylem temperature estimated by numerical simulations of the thermal conduction for the SFS (A) and the TDP (B) heaters.

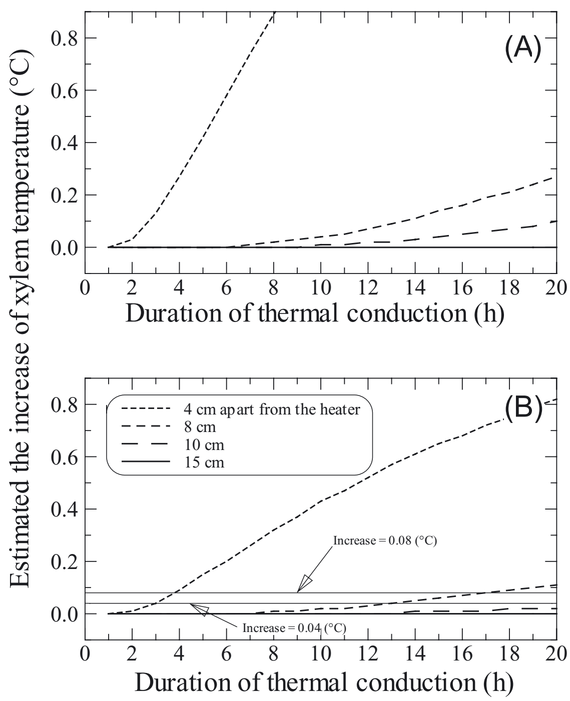

Figure 5. Relationship between the duration of thermal conduction and the heater-induced increases of xylem reference temperature obtained from the numerical simulations of thermal conduction for the SFS (A) and the TDP (B).

Note that we assumed that $u_{SFS20-30}$ was equal to $u_{SFS20-40}$ to calculate $u_{SFS0-30}$ using Equation (2). In reality, $u_{SFS20-40}$ may be slightly smaller than $u_{SFS20-30}$ due to the radial trend in u. However, b has much less weight than a in Equation (2), which may make the difference between the true and calculated values of $u_{SFS0-30}$ negligibly small. Moreover, the slightly smaller calculated value of $u_{SFS0-30}$ would not overcome the underestimation of TDP, and therefore the winter underestimation was valid.

The underestimation found only in the winter period is consistent with the slight decrease in ΔT_{TDP} during the late night observed in the corresponding period (Figs. 2G–2J). We hypothesized that the heat of the TDP heater would be transferred to the reference probe by thermal conduction and that ΔT_{TDP} would decrease according to the increased reference temperature. In particular, during the middle of winter in January and February 2005, there was a gradual decrease in ΔT_{TDP} from late night to around the predawn period, followed by a sudden increase in ΔT_{TDP} around sunrise (Figs. 2H and 2I). This sudden increase in ΔT_{TDP} could include the decrease in the reference temperature; when sap begins to move upwards, the reference probe would be free of the heat transferred by conduction. In the spring, however, the slight decrease of ΔT_{TDP} during late night was not measured (Figs. 2K and 2L) and calculated u_{TDP} corresponded to $u_{SFS0-30}$. The natural thermal gradients in the stem affect $\Delta T_{SFS0-20}$ and ΔT_{TDP} (e.g., Köstner et al., 1998). However, the effect of these gradients is not significant for the comparison between SFS and TDP. Even if the thermal gradient caused an effect, this would be reflected in both $\Delta T_{SFS0-20}$ and ΔT_{TDP}, and the comparison would still be valid.

The observed degree of TDP underestimation ($1 - u_{TDP}/u_{SFS0-30}$ = 0.18 in December 2004, 0.41 in January 2005; and 0.46 in February, 0.22 in March) corresponded to the effect of the increase in the reference temperature of 0.04–0.08 °C (Tabs. II and III). A simulation of thermal conduction showed that this increase was due solely to the heat transfer by conduction, which continued for 3–4 h (Fig. 5B). A nearly constant $\Delta T_{SFS0-20}$ was observed for about 3–4 h in late night in the winter (Figs. 2A–2D); this average diurnal variation in $\Delta T_{SFS0-20}$ indicated that sap movement nearly stopped and its duration, due solely to thermal conduction, was about 3–4 h. No discrepancy was observed between these durations, determined from observations of $\Delta T_{SFS0-20}$ and the degree of the underestimation, and the simulation of thermal conduction. We thus concluded that at the study site, TDP underestimations occurred in winter when ΔT_0 decreased due to the heat transferred by conduction when u reached zero.

4.2. Sap movement continued from late night to the predawn and stopped just before sunrise in warm seasons: it reduced heat transfer by conduction to the lower stem

The underestimations of u by the TDP occurred only in the winter period at the test site. In this subsection, we discuss the generality of this phenomenon. Kobayashi and Tanaka (2001) noted that the red pines at our site maintained their transpiration activity by consuming water stored in the stem; they also reported that to refill water storage, sap movement continued from late night to the predawn period and stopped just before sunrise in summer. We believe that in the spring, when transpiration is more active than in the winter, the test tree used part of its stored stem water and that sap movement continued from late night to the predawn to refill water stores (e.g., Granier et al., 2000). In the spring, $\Delta T_{SFS0-20}$ had an increasing trend from evening to predawn and after that it had a daily maximum value (Figs. 2E and 2F). This trend clearly shows that a small u remained from evening to predawn and stopped just before sunrise. However, in winter, because of the decline in transpiration activity (Iida et al., 2006), the magnitude of stem water storage consumed by transpiration was likely smaller than in the spring. Observations showed that $\Delta T_{SFS0-20}$ was nearly constant during the late night to the predawn period, which suggested that sap movement had ceased (Figs. 2A–2D).

Heat transfer by conduction to the lower part of the stem will occur when u stops for a few hours during the predawn period (Fig. 5B). However, particularly in warm seasons (e.g., from spring to autumn), sap movement continued from evening to the predawn and stopped just before sunrise. This phenomenon has been confirmed for tropical broadleaved trees (Granier et al., 1996a; Lu et al., 2004), temperate coniferous trees (Delzon and Loustau, 2005; Granier et al., 1996b; Kobayashi and Tanaka, 2001; Köstner et al., 1998; Kumagai et al., 2005; Phillips et al., 1996; 2003), temperate broadleaved trees (Bréda et al., 1993; Granier et al., 1996b; 2000; Phillips et al., 1996), and boreal conifers (Lopez et al., 2007; Zimmerman et al., 2000). Taken together, these data strongly suggest that the heat was not transferred to the lower part of the stem due to the remaining u during the predawn period and the underestimation of u by the TDP does not occur during the warm seasons.

4.3. Avoiding underestimation of sap flux densities by the modified sensor, and recommendations for the sensor span and sensor spacing

The numerical simulation indicates that the heater-induced increase in xylem temperature, recorded 10 cm away from the heater, occurred with thermal conduction durations of 9 and 13 h for the SFS and TDP, respectively (Figs. 5A and 5B). These were much longer than the duration of 3–4 h when u seemed to cease (Figs. 2A–2D). Because heat was transferred in all directions by conduction, we recommend that neither the SFS nor the TDP sensor be inserted less than 10 cm away from the heaters (Figs. 5A and 5B). The sensitivity analysis for the numerical simulation of thermal conduction, in which θ_{water} was varied for the possible range by up to 50% and λ_{GW} was changed according to θ_{water}, revealed that an S of more than 10 cm was enough to avoid the heater-induced increase in the reference temperature (data not shown). A simple solution to the underestimation of u by the TDP is to place the reference probe at least 10 cm from the heater. However, because of its fixed S, it is difficult for researchers to alter the S of the TDP and to carry out the simple solution. Although the underestimation also can be corrected by estimating the heater-induced increase in the reference temperature by numerical simulation with a valid duration when *u* is zero, the correction is complicated and is therefore not recommended.

As discussed above, the underestimation by the TDP is not significant in the warm seasons. Also, when the objective of the measurement is to evaluate the annual amount of transpiration, the application of the TDP is not a significant problem. For example, we estimated the proportion of winter transpiration with respect to the annual amount of transpiration based on previous measurements conducted at this site (Iida et al., 2003). The proportion was 21%, and the contribution of the winter underestimation to the annual amount was only 6%. Wilson et al. (2001) indicated that the TDP underestimated transpiration more significantly. However, their results cannot be explained by the alteration of the S; rather, their target included ring-porous species, which should not be studied using Granier-type sensors (e.g., Clearwater et al., 1999). Although Wilson et al. (2001) pointed out that the inclusion of ring-porous species was one of the reasons for the underestimation, our findings suggest that it was the main reason; the underestimation was not caused by the alteration of S. Note that the sensor length in the TDP is 3 cm, which is 1 cm longer than that of the SFS (Tab. I); therefore, the effect of radial variations in *u* on the TDP is larger than on the SFS.

The underestimations by TDP occurred due to the heat transferred to the reference probe by conduction. This suggests that caution is necessary when the TDP is inserted into trees in which *u* ceases at night during seasons with high transpiration rates; for example, into small trees that have low capacities for water storage in the stem. Accordingly, we recommend that researchers using the TDP or Granier-type sensors densely inserted at the same height of a tree confirm that *u* ceases in the tree, by determining if the tree has a nearly constant trend in ΔT for a few hours before the predawn period. If this is the case, the researchers should avoid inserting sensors at a distance less than 10 cm away from the heater.

5. CONCLUSIONS

The following conclusions address the objectives set out in the introduction:

(i) Numerical simulation of thermal conduction showed that the span length of the Granier-type sensors should be more than 10 cm for trees in which *u* ceases for a few hours before the predawn period.

(ii) Sap flux densities in Japanese red pine were underestimated by the modified sensor compared with the original sensor. Underestimations of 18–46% occurred only in the winter (December 2004–March 2005), whereas the annual amount of transpiration was underestimated by 6%.

(iii) The 0.1 °C increase in reference temperature caused a 7–18% underestimate of *u* by the original sensor and a 16–56% underestimate by the modified sensor. Researchers must recognize that the Granier-type sensor is very vulnerable to heater-induced increases in the reference temperature.

In the winter at the test site, *u* ceased for a few hours before the predawn, resulting in an increase in the reference temperature caused by heat transferred from the heater. This led to underestimation of *u* by the modified sensor. Generally, in spring, summer, and autumn, *u* is maintained before the predawn and stops just before sunrise; thus, there is no such underestimation. We carried out a comparison of *u* between original and modified sensors at one test tree, and the measurements were confirmed by the results of simple numerical simulation. However, testing the methods in more sample trees and/or other tree species is recommended for future studies.

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