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Sap flow measurements by thermal dissipation method using cyclic heating: a processing method accounting for the non-stationary regime

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Abstract

- ***Context*** The thermal dissipation method to measure sap flow in tree stems can be used with cyclic heating to reduce electricity consumption and/or to account for natural temperature gradients. Nevertheless, errors in sap flow estimation can be introduced because the thermal equilibrium has not been reached at the measurement time.
- ***Aim*** We propose a method to assess this error and to estimate sap flow density. It is based on Granier's (Ann For Sci, 42:193–200, 1985) non-species-specific calibration.
- ***Methods*** This work was performed on silver fir trees (*Abies alba* Mill.) with low sap flux densities (maximum of 0.68 $\mathrm{Ldm}^{-2}\ \mathrm{h}^{-1}$). To estimate the error, we developed a calibration procedure using the experimental set-up in trees. This approach is based on a pair of sensors having similar temporal patterns in sap flux density, one being under cyclic heating while the other is continuously heated.
- ***Results*** Applying Granier's calibration without correction led to large errors (relative error reached 200%). After correction, the error was greatly diminished; it was lower than 0.042 $\mathrm{Ldm}^{-2}\ \mathrm{h}^{-1}$ when using short heating cycles (0.5 h).
- ***Conclusion*** The correction was applicable to all silver fir trees monitored. However, this method can be easily repeated to investigate the validity domain of the correction.

Keywords Sap flow · Thermal dissipation method · Cyclic heating · Error correction · Silver fir

1 Introduction

Sap flow measurement is the only method to assess water fluxes in the soil–vegetation–atmosphere continuum at the tree scale or over complex terrain where the soil water balance or micrometeorological methods cannot be implemented. There are several techniques for measuring sap flow (Köstner et al. 1998), including heat pulse velocity, tissue heat balance (Čermák-type) and radial flowmetry (Granier type). Granier's method (Granier 1985, 1987) is one of the most commonly used for trees because of its simplicity, low cost and reliability (Andrade et al. 1998; Braun and Schmid 1999; Do and Rocheteau 2002a; Lu et al. 2004). This technique uses a thermal dissipation probe radially inserted into the stem. The equation for calculating sap flux density is applicable to every tree species when the sensor geometry and electrical power remain identical and when the entire length of the probe is surrounded by the hydroactive xylem, creating a high thermal conductivity between the probe and the wood (Granier 1987; Lu et al. 1996; Lu et al. 2004). The main drawback of the Granier method is its relatively high electricity consumption, which may be a critical issue in the experimental design because several repetitions are needed to scale up the measurements made at the tree level to an entire forest stand.

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Granier (in Köstner et al. 1998) first proposed cyclic heating to diminish power consumption. Do and Rocheteau (2002a, b) further developed the cyclic heating method to reduce both power consumption and the effect of ambient thermal gradients. However, cyclic heating limits temporal resolution. Therefore, using a cyclic heating method implies making a trade-off between spatial and temporal sampling. This method also requires recalibration because the thermal stationary regime is not always reached at the end of a heating or cooling cycle. Do and Rocheteau (2002a, b) established a non-species-specific calibration (D&R calibration) fitted to non-stationary regimes using short cycles. The D&R calibration was built with measurements on artificial columns filled with sawdust and was confirmed on tropical trees by Isarangkool Na Ayutthaya et al. (2010). However, they found an overestimation of 30% under low flow conditions and proposed an updated calibration relationship. The time needed to reach the stationary regime is determined by the heat exchanges between probes, wood and xylem sap. Therefore, this time may depend on the tree species, the sap flow rate and the trunk diameter. It is possible, then, that D&R calibration cannot be generalised to all tree species and dimensions.

The aim of this study was to assess whether cyclic heating can be applied to measure sap flow with the Granier method on silver fir trees with low sap flow rates. Unlike the D&R calibration approach, which is based on a specific calibration for cyclic measurements, we used the calibration relationship proposed by Granier (1985). Use of this relationship is strongly supported by its successful application with numerous tree species. A primary objective of the present study was to analyse how a non-stationary regime impacts temperature measurements and the resulting sap flow calculations in relation to the timing of the heating cycle. A generic correction method, based on in situ measurements, was then developed and evaluated. This correction method involves building parameters from the previous error assessment to extrapolate the non-stationary regime to the stationary regime. Finally, a comparison was made with the D&R calibration method.

2 Materials and methods

2.1 Granier's method

Sap flow is measured with a thermal dissipation sap flowmeter composed of two probes. These probes are inserted radially into the xylem, just beneath the tree bark. One of the two probes is heated with a constant energy input, while the other is not heated and remains at the same temperature as that of the wood. Sap flux density is a function of the temperature difference (ΔT) between the two probes. Under no-flow conditions, the temperature of the heated probe stabilises at a maximum value, ΔT_0, when heat dissipation by conduction through the wood equals the heat input. An accurate measurement of ΔT_0 is necessary for the calculation of sap flux density. Under no-zero flow conditions, heat convection increases and ΔT decreases. Granier (1985) calibrated the following relationship to estimate sap flux density (J_t in litres per square decimetres per hour) at time t:

$$J_t = \alpha . \left(\frac{\Delta T_0 - \Delta T_t}{\Delta T_t} \right)^{\beta} = \alpha K^{\beta} \tag{1}$$

where α=4.2841 Ldm^{-2} h^{-1}, β=1.231, ΔT_0 is the maximum temperature difference between both probes under zero flow conditions and ΔT_t is the temperature difference between probes at time t.

2.2 Experimental design

This study was conducted on silver fir (*Abies alba* Mill.) trees at Mont Ventoux (southern France, 44°10′28″ N, 5°16′ 44″ E), an area with both mountain and Mediterranean climate conditions. Four trees, separated by a few metres, were chosen in a plot at 1,360 m in elevation. On average, the trees were 18 m in height and 38 cm in diameter at breast height. On one tree, two sensors were inserted at breast height between 0- and 2-cm depth at the north and west azimuths. Care was taken to place the sensors far enough apart to avoid interference between the probes. On the three other trees, one sensor was inserted at the north azimuth at breast height (Table 1). Additional information on the studied trees is given in Table 1.

In another plot at 1,020 m in elevation, one tree was instrumented with three sensors at the north, east and west azimuths, and two other sensors were installed on the north sides of two other tree stems. These trees were included in the experimental design to test the validity of the correction.

2.3 Characterisation of the impact of non-stationary regime on ΔT measurement and sap flow calculation

The aim of the experiment was to characterise how far a sensor's thermal regime from the stationary condition is at the end of the heating cycle and what the consequences are for sap flow calculation when Granier's calibration is used. To achieve these aims, we designed a specific measurement configuration based on the use of two sensors with similar temporal behaviours, one being heated continuously and the other with cyclic heating.

Because it can take a long time to reach a stationary regime, waiting for this moment compromises the time

Table 1 Characteristics of the investigated trees and of the set-up of the sensors, and mean differences of the sap flux density variations between all sensors

	Sensor 1	Sensor 2	Sensor 3	Sensor 4	sensor 5
Sensor 1		0.065	0.056	0.030	0.017
Sensor 2			0.009	0.053	0.050
Sensor 3				0.042	0.039
Sensor 4					0.017
Azimuth on the stem	N	W	N	N	N
Stem diameter at breast height (cm)	28.5	44.1	44.1	42	40.1
Mean sap flux density (L dm^{-2} h^{-1})	0.30	0.22	0.24	0.32	0.24

Sensors 1 and 4 form pair 1. Sensors 2 and 3 are those on the same trees and form pair 2. Sensors 3 and 4 are the continuously heated sensors

resolution of measurements from cyclic heating. Therefore, we wanted to estimate the error that arises when performing ΔT measurements before the stationary condition is reached. This error is defined as the difference between $\Delta T_{t\text{-cyclic}}$ at time t, corresponding to the end of a heating cycle, and a reference ΔT_{ref}, which is the value of ΔT that would be obtained if the stationary regime was reached. The difficulty resides in the estimation of this last term, which must be determined with the same sensor to avoid sap flow variability between sensors installed either on the same tree or on different trees. In this study, ΔT_{ref} was established by extending the heating period until t_{m}, the time required to reach the stationary regime. This time depends on the heat exchanges between probes, wood and xylem sap. This length of time increases when the sap flow is low. This is shown in Fig. 1, in which the ΔT variations obtained at night and near midday are displayed. The figure clearly shows that after 1 h of heating, the thermal stationary regime had not been reached and that the ΔT stabilised more quickly when fluxes were high. To be confident that the stationary conditions were reached, the heating period (t_{m}) during the night was set to 6 h (after a 3-h non-heating period), while it was set to t_{m}=3 h (after a 2-h non-heating period) during the day. We found in the night measurements that when the sap flow was close to zero, 3 h of heating was sufficient to reach the stationary regime, thus confirming that the selected t_{m} was appropriate.

The difference in temperature at t_{m} (ΔT_{t_m}) is not a direct estimator of ΔT_{ref} because the ΔT may vary between t and t_{m} due to the natural daily sap flow fluctuations. To estimate such variations, we used the continuously heated sensor. On this sensor, the ΔT values were selected at the same times, t and t_{m} (Fig. 2).

The errors were calculated separately for both terms of Eq. 1: ΔT_0 and ΔT_t. The error is defined as the difference between ΔT_{ref} and the value of $\Delta T_{t\text{-cyclic}}$, measured at the end of the heating cycle. The value for the ΔT_{ref} is estimated by ΔT_{t_m} (measured by the sensor under cyclic heating) which is corrected by the natural difference resulting from the transpiration course derived from the continuously heated sensor (Fig. 2). The error ($E_{\Delta T}$) was estimated for days and nights separately:

$$E_{\Delta T} = \Delta T_{\text{ref}} - \Delta T_{t-\text{cyclic}} \tag{2}$$

with

$$\Delta T_{\text{ref}} = \Delta T_{t_m-\text{cyclic}} - (\Delta T_{t_m} - \Delta T_t)_{\text{continuous}} \tag{3}$$

giving

$$E_{\Delta T} = (\Delta T_{t_m} - \Delta T_t)_{\text{cyclic}} - (\Delta T_{t_m} - \Delta T_t)_{\text{continuous}} \tag{4}$$

Sap flux density derived from cyclic heating is then corrected as follows:

$$J_{t\_corr} = \alpha.\left(\frac{(\Delta T_0 + E_{\Delta \text{T0}}) - (\Delta T_t + E_{\Delta \text{T}t})}{\Delta T_t + E_{\Delta \text{T}t}}\right)^{\beta} \tag{5}$$

where $E_{\Delta T_0}$is the error in probe temperature difference during the night and $E_{\Delta T_t}$ during the day.

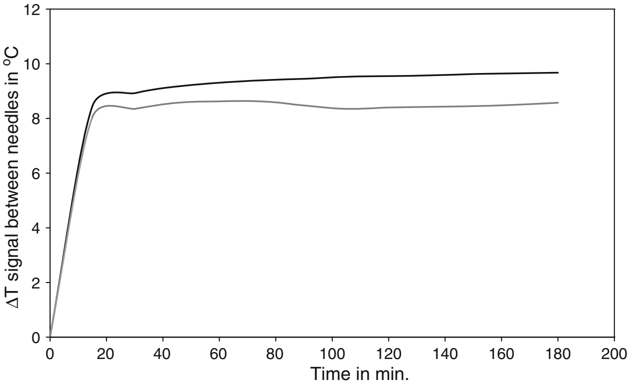

Fig. 1 Kinetics of sensor temperature difference during the non-stationary period (1) under zero flow conditions (*black line*) and (2) under medium, midday flow conditions, J=0.7 Lm^{-2} h^{-1} (*grey line*)

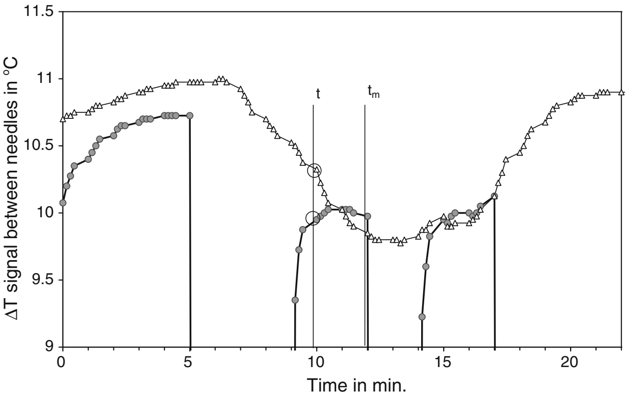

Fig. 2 Illustration of the error calculation method over a day. *Grey points* and *line* represent cyclic heating and *black triangles* and *line* represent continuous heating. Frequency of measurements is at 15-min intervals. In this example, measurement at time *t* is performed 1 h after turning on the heat

The effectiveness of this correction on sap flux density is determined by a comparison of the errors made before and after correction. Errors are calculated as follows:

$$E_J = (J_m - J_t)_{\mathrm{cyclic}} - (J_m - J_t)_{\mathrm{continuous}} \tag{6}$$

$$E_{J\_\mathrm{corr}} = (J_m - J_{t\_\mathrm{corr}})_{\mathrm{cyclic}} - (J_m - J_t)_{\mathrm{continuous}} \tag{7}$$

where E_J is the error in the sap flux density calculation before the correction, expressed in litres per square decimetre per hour, E_{J_corr} is the error in the sap flux density calculation after correction, expressed in litres per square decimetre per hour, J_m is the sap flux density at the stationary regime and J_t is the sap flux density calculated from the cyclic or continuous heating methods at the end of a given cycle, both in litres per square decimetre per hour.

We performed the measurements over 15 days. Three heating cycles were monitored per day: one during the night and the other two during the day. Different combinations of night and day cycles were tested. During each heating period, the values of $\Delta T_{t\text{-cyclic}}$ were retained at times t=1, 3, and 5 h after heating began during the night and t=0.5, 1, 1.5, and 2 h after heating began during the day.

As with the D&R calibration, a direct relationship between K, computed with the uncorrected cyclic ΔT, and the reference sap flux density, J_t, calculated from continuously heated sensors, would have been possible.

2.4 Comparison of sap flow dynamics between sensors

The method for assessing error and developing a correction technique assumes the use of a pair of sensors presenting similar variations in sap flux density between t and t_m. This similarity was assessed by monitoring the sap flow dynamics during a 3-month period with all of the sensors installed on the five trees of the plot at 1,360 m. The sap flow dynamic of each sensor was characterised by the variation in sap flux density (using a 1-h heating and 1 h cooling protocol without correction) between 10:00 a.m. and 12:00 p.m. and between 12:00 p.m. and 4:00 p.m. The differences in these variations between the two sensors of each pair were calculated for each day and at each period. The results were then averaged over a 3-month period for each pair. The time intervals of 2 and 4 h were chosen to be representative of or larger than the time lag between t and t_m. Moreover, the selected periods of measurement corresponded to periods of high sap flux variation during the day.

2.5 Validation of the applicability of the corrections on other trees

The rationale of the correction method is to estimate the error in ΔT when conditions are non-stationary at the end of the heating period. To further assess the validity of this approach, we evaluated whether the increase in the ΔT during the heating process is mainly driven by sap flux, implying that the thermal properties of the wood, the quality of the probe contact and local site influences are second-order factors. We made this evaluation on ten sensors installed on the seven different silver fir trees located at the two Mont Ventoux sites presenting different climatic conditions (1,360 and 1,020 m in elevation) and with similar diameters (ranging from 30 to 45 cm). The measurements were carried out for more than 6 months in 2009. From these measurements, we computed the difference in ΔT after 15 min vs. 1 h of heating. This difference can be considered as an indicator of the heat exchange at the sensor level and the time required to reach stationary conditions. The results were related to the sap flux density calculated without making the proposed correction of ΔT.

2.6 Data analysis

Analysis of the data was made by computing the following statistical quantities: the mean absolute error, to estimate the accuracy of the measurements; the standard deviation, to characterise the error distribution and the bias, to assess systematic errors. The mean relative error (absolute error divided by sap flux density) is also displayed to represent the weight of the error in comparison to the measurements. However, under low flux conditions, the relative error may be particularly strong. As the fluxes were often very low, interpretations of the mean relative error should be made with caution.

3 Results

3.1 Comparison of sap flow dynamics

The mean differences in sap flux density variations were calculated and are displayed in Table 1. The best results were achieved when the sensors were on the same tree. In this case, the difference in sap flux density variations was very low and corresponded to a low proportion of mean sap flux density (4%). For the other pairs, this proportion was higher and varied between 7% and 25% of the mean sap flux density of the pair. These results highlight the difficulties in determining a priori which trees had similar sap flow dynamics. Using a pair of sensors installed on the same tree is therefore recommended. In the following sections, analyses were done considering two pairs of sensors: one installed on trees with similar sap flux density dynamics (pair 1 in Table 1) and the other installed on the same tree (pair 2 in Table 1).

3.2 Estimation of sap flux density error

During the night, the error made in temperature difference between sensors, $E_{\Delta T_0}$, appeared to depend only on the duration of heating (Table 2). This can be explained by a very low and stable night sap flow. The longer the heating period and the closer the conditions of measurement are to the stationary regime, the lower the error is. For instance, with a heating period of 5 h, we obtained a low average absolute and constant error, $E_{\Delta T0}$=0.03°C. With a 1-h heating, the mean $E_{\Delta T_0}$ was much higher but was also relatively stable, with a standard deviation representing 17% of the mean error (Table 2). We did not find obvious factors explaining $E_{\Delta T_0}$ variability, and it was therefore considered to be constant.

During the day, $E_{\Delta T_t}$ depended on the sap flow rate (J_t). For a given combination of night and day heating duration, the relationship between the error before correction, $E_{\Delta T_t}$, and the sap flux density is linear. Because J_t is calculated from ΔT measured during the night and during the day, the coefficients of the relationship are different according to the heating durations of both night and day. The linear relationships obtained with the two pairs of sensors were found to be identical, and a single set of coefficients is shown in Fig. 3 and Table 3. This demonstrates that the lack of accuracy in the choice of sensors to form pair 1 had little consequence on the $E_{\Delta T_t} = f(J_T)$ relationship. For 1.5- and 2-h heating cycles during the day, the error can be considered to be constant.

Table 2 Mean absolute error in ΔT_0 during the night for increasing heating durations, in degrees Celsius

Night heating duration	Pair 1	Pair 2
1 h	0.42 (0.12)	0.51 (0.085)
3 h	0.088 (0.048)	0.12 (0.053)
5 h	0.029 (0.024)	0.025 (0.017)

Standard deviations are in parentheses

When considering the value of the ΔT between sensors before reaching the stationary regime, the mean error, E_J, in the sap flux density calculation was important: it could lead to an average error of 0.17 $\mathrm{L\,dm^{-2}\,h^{-1}}$ for pair 1 and 0.16 $\mathrm{L\,dm^{-2}\,h^{-1}}$ for pair 2 (Table 4), which are high in comparison to the mean sap flux density measured on continuously heated sensors during the experiment: 0.22 $\mathrm{L\,dm^{-2}\,h^{-1}}$ for sensor 4 of pair 1 and 0.25 $\mathrm{L\,dm^{-2}\,h^{-1}}$ for sensor 3 of pair 2. Depending on the combination of day and night cycles and on sap flux conditions, a lack of correction would lead to an overestimation or an underestimation (Table 4). The error was higher for the short cycles of the day (0.5 and 1 h of heating) except when the duration of night heating was 1 h. In this case, the errors in night and day measurements were balanced, and the compensation led to a small error in the fluxes (Table 4). The best results were obtained with a heating period equal to or longer than 1.5 h during the day and 3 h during the night. Because there was a poorer assessment of the natural temporal ΔT variation for pair 1 compared to the estimation for pair 2, there was an overestimation of the error for pair 1.

3.3 Correction of the sap flux density

In Fig. 3, the linear relationship between $E_{\Delta T_t}$ and J_t suggests that $E_{\Delta T_t}$ can be estimated as follows, and as shown in Table 2, we can assume that $E_{\Delta T0}$ is constant:

$$E_{\Delta Tt} \cong a.J_t + b \tag{8}$$

$$E_{\Delta T0} \cong c \tag{9}$$

where a and b are derived from the linear regression equation, J_t is the sap flux density calculated before correction and c is the mean constant error calculated for the night-time.

The results of the evaluation of the error after correction are only presented for pair 2, the pair for which the reference was more accurately estimated. The correction was done using coefficients from the linear regression fitted to this pair.

With the coefficients from the regression, the mean error in the sap flux density calculations decreased after the correction for each tested cycle (Table 5). There was a clear overall improvement: the maximum mean error was reduced almost by a factor of 4. For cycles with the longest periods of heating (3 or 5 h of night heating and 2 h of day

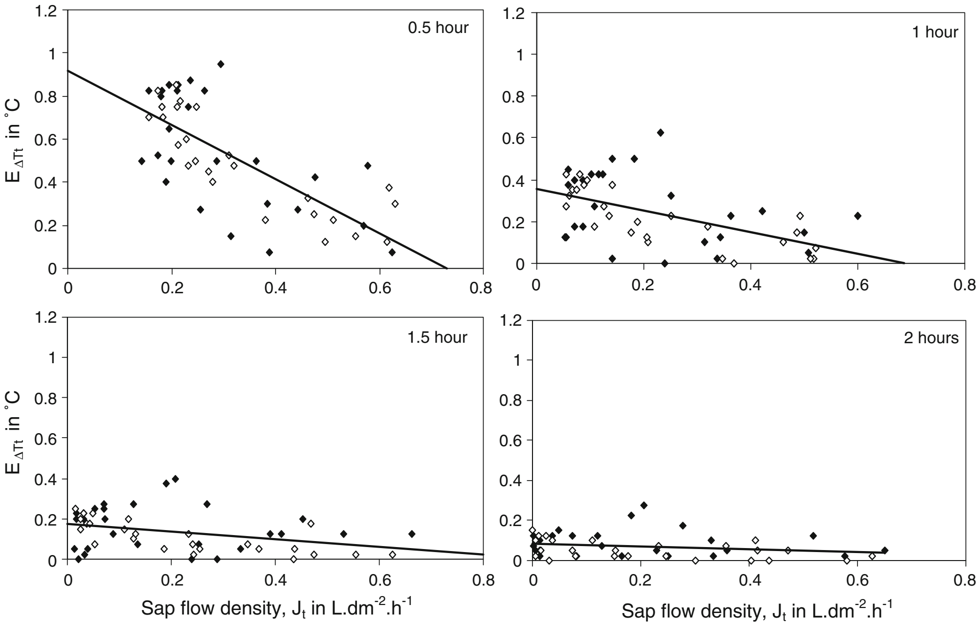

Fig. 3 Relationships between day error, $E_{\Delta T_t}$, and sap flux density, J_t, before correction for each day heating cycle (corresponding to indications of time on the graph) and for 3 h of heating during the night. Results are presented for the two pairs (pair 1, *black unfilled circles*; pair 2, *filled circles*). *Black line* shows the linear regression for both pairs 1 and 2. Coefficients of regression are in Table 3

heating), little improvement was obtained, with the error only reduced by 10%, but the errors were already much lower before the correction than those obtained for shorter heating cycles. For these cycles, the improvement was greater, leading to a remaining error close to that of the longest heating cycle (Tables 4 and 5). The remaining mean absolute error was always lower than 0.042 Ldm^{-2} h^{-1} (Table 5), which should be compared to the mean sap flux density over the experiment, at 0.23 Ldm^{-2} h^{-1}, and to the maximum sap flux density, at 0.68 Ldm^{-2} h^{-1}. After the correction, the mean relative error was lower than 30% in most cases (Table 5) while it could represent more than 100% of the reference sap flux density before the correction (Table 4). The accuracy is comparable to that obtained by Do and Rocheteau (2002b) and Isarangkool Na Ayutthaya et al. (2010). In the latter, a relative error of 41% was found when sap fluxes were lower than 0.5 Ldm^{-2} h^{-1}.

In most cases, the value of the bias was close to the mean absolute error (Table 5). This means that, after correction, there was a systematic overestimation of the sap flux density. The bias decreased with an increase of the duration of the night-time heating period. Therefore, errors during night measurements are one of the reasons for such a bias.

Table 3 Coefficients *a* and *b* and R^2 of the linear relationship between $E_{\Delta T_t}$ and J_t of Fig. 3 for a night heating period of 3 h

Day heating period (h)	*a*	*b*	R^2
0.5	−1.25	0.92	0.54
1	−0.51	0.35	0.29
1.5	−0.19	0.17	0.12
2	−0.07	0.086	0.058

3.4 Accounting for maximum ΔT_0 at night

When using the longest heating cycles (3 or 5 h) during the night, we minimised the error in the ΔT_0 estimation. However, we ignored night transpiration if it occurred because we considered only one value per night. An additional error should be considered in such a case because a single value may not be enough to identify the maximum ΔT. An analysis of the night course of ΔT from the continuously heated sensors showed that the maximum night ΔT_0 never occurred at the same time (Fig. 4). Thus, when arbitrarily setting the time of night measurement, an additional error is made in the estimation of ΔT_0 resulting from not selecting the actual night maximum. For example, this additional error was estimated by the difference between ΔT at 3:00 a.m. and the actual night maximum ΔT detected by the continuously heated sensors, 0.08°C, on average (standard deviation, 0.08°C), representing an error of 0.031 Ldm^{-2} h^{-1} under the maximal sap flux density (0.68 Ldm^{-2} h^{-1}) and of 0.013 Ldm^{-2} h^{-1} under the minimal sap flux density (0.017 Ldm^{-2} h^{-1}). More than 50% of the night maximal ΔT occurred at 6:00 a.m., before dawn (Fig. 4), but selecting these data did not decrease the error in ΔT_0. Statistically, the minimum error occurred when ΔT_0 was measured between 1:00 a.m. and 3:00 a.m. The decreased accuracy when estimations of ΔT_0 estimation (0.023°C) were made at predawn remained low compared to the optimal estimator at 2 a.m. To determine the best time for the measurement of ΔT_0, the statistical analysis of the occurrence of the minimum error should be repeated.

Table 4 Means and standard deviations of the absolute error, bias (mean error) and mean relative error in sap flux density calculations before correction (Eq. 6)

Night heating period	Day heating period (h)	Mean absolute error (L dm^{-2} h^{-1})		Standard deviation absolute error (L dm^{-2} h^{-1})		Bias (L dm^{-2} h^{-1})		Mean relative error	
		Pair 1	Pair 2	Pair 1	Pair 2	Pair 1	Pair 2	Pair 1	Pair 2
1 h	0.5	0.076	0.062	0.044	0.044	−0.039	0.013	1.81	0.77
	1	0.064	0.109	0.046	0.064	0.033	0.109	0.36	0.51
	1.5	0.077	0.144	0.058	0.060	0.066	0.144	0.28	0.53
	2	0.085	0.163	0.052	0.054	0.085	0.163	0.25	0.49
3 h	0.5	0.152	0.124	0.075	0.060	−0.152	−0.123	1.74	1.69
	1	0.070	0.040	0.051	0.026	−0.064	−0.023	1.41	1.77
	1.5	0.044	0.028	0.035	0.022	−0.029	0.009	1.01	0.65
	2	0.028	0.029	0.024	0.024	0.025	−0.010	0.21	0.30
5 h	0.5	0.172	0.163	0.079	0.054	−0.172	−0.163	1.94	2.12
	1	0.083	0.060	0.054	0.032	−0.081	−0.060	1.47	1.52
	1.5	0.053	0.029	0.036	0.018	−0.045	−0.025	1.14	1.25
	2	0.029	0.014	0.025	0.011	−0.023	−0.008	0.57	0.66

3.5 Applicability of the corrections on other trees

The relationship between sap flux density before correction and the slope of the increase in ΔT during the heating period is an indicator of the trees' thermal properties. A linear relationship (R^2=0.6) fits for all trees at both sites (Fig. 5). Considering the relationships of every tree separately (Fig. 5), the coefficients are not significantly different (p value>0.9). The kinetics of heat exchanges were therefore similar for all the monitored fir trees, allowing us to apply the coefficients of Eqs. 8 and 9 estimated from a single tree to all of the others.

4 Discussion

4.1 Performance of the sap flux density correction method

The proposed method demonstrates that Granier's calibration can be used when the appropriate corrections are made to the ΔT measurements to account for non-stationary regime. It opens the possibility of extrapolating a thermal equilibrium from short heating cycles. We obtained a relative error in sap flux density lower than 30% in most cases. This experiment was carried out on trees with low sap flux densities during the measurement period; the maximum sap flux density was

Table 5 Means and standard deviations of the absolute error, bias (mean error) and mean relative error in sap flux density calculations after correction (Eq. 7)

Night heating period	Day heating period (h)	Mean absolute error (L dm^{-2} h^{-1})	Absolute error standard deviation (L dm^{-2} h^{-1})	Bias (L dm^{-2} h^{-1})	Mean relative error
1 h	0.5	0.031	0.031	0.026	0.51
	1	0.040	0.033	0.035	0.24
	1.5	0.042	0.034	0.041	0.19
	2	0.030	0.027	0.024	0.27
3 h	0.5	0.032	0.028	0.017	0.21
	1	0.026	0.024	0.018	0.26
	1.5	0.026	0.024	0.021	0.23
	2	0.025	0.021	0.020	0.21
5 h	0.5	0.030	0.029	−0.010	0.55
	1	0.021	0.018	0.011	0.35
	1.5	0.021	0.018	0.016	0.20
	2	0.015	0.013	0.009	0.12

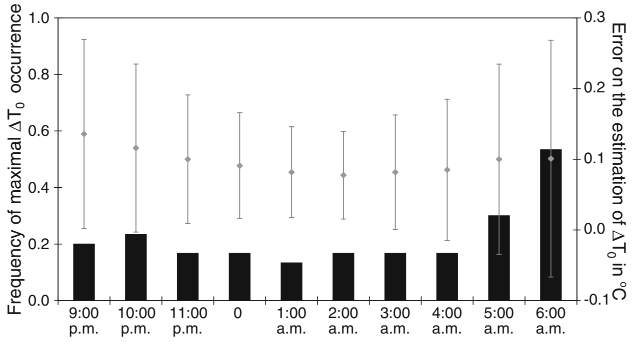

Fig. 4 Frequency of the maximal ΔT_0 occurring for each night period, measured from continuously heated sensors (*black bars*). Maximums can occur at different times of night. Error is calculated by comparison to maximal ΔT_0 and is represented by *grey points*

0.68 $\mathrm{L\,dm^{-2}\,h^{-1}}$, whereas it is typically between 1 and 2 $\mathrm{L\,dm^{-2}\,h^{-1}}$ for coniferous trees (Lu et al. 1996; Köstner et al. 1998; Čermák et al. 2004; Delzon and Loustau 2005; Nadezhdina et al. 2007). The error before correction would have been lower with higher fluxes. Indeed, in our case, the length of time necessary to reach a stationary regime was long.

Furthermore, applying a long heating period during the night, even if it reduces the remaining error, limits data collection to a single value per night. As a result, it is not possible to detect night transpiration, leading to an increase in the risk of error when night transpiration occurs at the time of measurement. In the end, the duration of heating should be chosen based on a trade-off between time resolution, precision after correction and energy saving. One recommendation is to use a 5-h heating cycle during the night, with ΔT_0 measured at predawn, and a 1-h heating and 1-h cooling cycle during the day to minimise bias and absolute error, and to have a rather good time resolution during the day. Additionally, to guarantee a valid correction, attention should be paid to the choice of sensors that form pairs on trees with the same sap flux dynamics. This aspect of the method can compromise its precision. When the temporal pattern of sensors does really not match, the correction is far less accurate (results not shown).

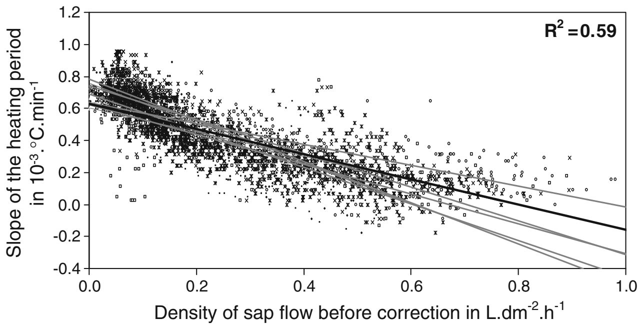

Fig. 5 Relationship between the slope of the heating period (difference of measured ΔT between 15 min and 1 h of heating) and sap flux density (calculated without correction) for each tree. The *black line* corresponds to the linear relationship for all trees together

The applicability of the relationship established has been validated for the silver fir trees of Mont Ventoux, but it is not certain whether it is suitable for fir trees with higher growth rates or different trunk diameters or for other tree species. The strength of the proposed method is that it can be implemented on existing experimental setups by simply changing the configuration of the acquisition protocol to have one or several pairs of sensors. It is therefore easy to repeat the method, collect references on the correction coefficients a, b and c and analyse their variations in relation to tree characteristics. An experiment in the laboratory with a controlled J_t would be interesting to test the hypothesis of reaching the stationary regime at t_m and adding accuracy to the calibration.

4.2 Comparison with the D&R calibration

In addition to the proposed correction method, we computed sap flow densities using the D&R calibration on the cyclic sensor and using Granier's calibration on the continuous sensor of pair 2 to obtain a reference sap flux density. The D&R calibration was applied using ΔT measurements after 0.5 h of heating and cooling to reproduce D&R heating protocols. To be as close as possible to the D&R heating protocol, we applied the proposed correction method with measurements from a cycle of 0.5 h of heating during the day and 1 h at night. The results are displayed in Fig. 6. There is a clear overestimation when the calculation is done with D&R calibration and a poor relationship (R^2=0.52) with the reference measurements. This overestimation was already observed by Isarangkool Na Ayutthaya et al. (2010) for low sap flow rates, but the difference was much smaller. The sap

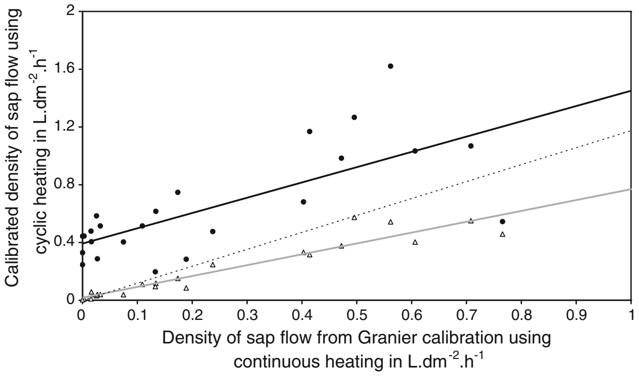

Fig. 6 Relationships between the sap flux density using a continuous heating and Granier's calibration and (1) the sap flux density using a cyclic heating calculated based on the proposed method (*triangles* and *grey continuous lines*) and (2) the sap flux density calculated based on D&R calibration (*black points* and *black linear regression*). Cyclic measurements were performed using a heating period of 0.5 h during daylight and 0.5 h during the night to implement D&R and 0.5 and 1 h for the proposed method

flux densities obtained with the proposed method were correlated closely to the reference (R^2=0.90), showing the efficiency of the calibration procedure. The purpose here is not to compare a calibrated (the proposed method) to an uncalibrated (D&R) method, but to highlight that the wood temperature dynamic under cyclic heating can depend on the sap flux density rates and on the tree species. Therefore, care should be taken in applying the D&R calibration in different contexts.

Do and Rocheteau (2002b) also highlighted the importance of the cyclic method to account for the natural temperature gradients. We took advantage of two several-day periods without heating to estimate these gradients: a hot period in July and a cooler one in May. There were significant gradients, and they presented daily cycles. The cycles were variable from one day to another and between sensors. The mean natural gradients were 0.16°C in July and 0.125°C in May. It is possible to measure them at the end of the cooling period when using cyclic heating. The question is whether equilibrium is attained and if the ΔT measured at the end of the cooling phase reflects the natural temperature gradients. In July, the thermal equilibrium at the end of the cooling period was attained faster as fluxes were higher, and the mean ΔT measured (after 1 h of cooling) at the end of the cooling phase was 0.20°C. In this case, the natural gradients represented 78% of the ΔT measured. In May, the ΔT measured at the end of the cooling phase was higher (0.25°C), as the equilibrium is not reached, and the proportion of the natural gradient in ΔT was lower (50%). Accounting for these natural gradients can be accomplished when calculating the corrected sap flux density by subtracting, as proposed by Do and Rocheteau (2002a), values of ΔT_{off} to each ΔT of Granier's equation. When applying this to the sap flux density calculation (with correction for a cycle of 5-h heating and 3-h cooling during the night, and 2-h heating and 2-h cooling during daylight), the mean difference with the initial corrected calculation was 0.037 $\mathrm{L dm^{-2}\ h^{-1}}$ (standard deviation, 0.047 $\mathrm{L dm^{-2}\ h^{-1}}$), with a positive or a negative bias depending on the sensor. In our experiment, the natural temperature gradients had a moderate influence on the sap flux density calculation. However, that may have been interesting to take them into account. With this perspective, the proposed cyclic method offers advantageous possibilities in comparison to the classical Granier approach.

5 Conclusion

Cyclic heating is of great interest for saving energy, an issue that can be a limiting factor in some experiments. If short heating cycles are applied, the stationary regime is not always reached, leading to errors in sap flux calculations. The correction method is easy to implement and the calibration period must cover the encountered range of sap flux density. The only constraint is to implement two heating protocols concurrently during the calibration period because the calibration protocol is based on a pair of sensors. Once calibrated, the correction method can be applied to all sensors under similar heating cycles in trees of the same species but located at different places in a forest, and short heating cycles can be used. The proposed correction method is flexible in terms of heating cycle characteristics but should be calibrated for each cycle characteristics. As the correction calibration can be repeated easily, its validity can be established by considering other tree species.

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