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Evaluation of heat balance and heat dissipation methods for sapflow measurements in pine and spruce

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Abstract – The tissue heat-balance method (Čermák) and the heat-dissipation method (Granier) were compared in three Scots pines and two Norway spruces in a forest in central Sweden. The Granier system measured up to 50% lower sapflow than the Čermák system at high flow rates. New coefficients for the Granier system were estimated, based on sapflow density from the Čermák measurements. Without compensation, natural temperature gradients may cause large errors in measurements made by the Granier system. By using a horizontal reference sensor, no compensation was necessary. It was also shown that radial flow patterns must be considered when calculating total tree sapflow. Transpiration of two adjacent stands, one measured by the Granier method and the other by the Čermák method, showed good agreement internally and with total evaporation measured by the eddy-correlation method.

THB / HD / sap-flow / transpiration / *Picea abies* / *Pinus sylvestris*

Résumé – Évaluation des méthodes des équilibres thermiques et de dissipation thermique concernant la mesure de flux de sève pour le pin et l'épicéa. La méthode des équilibres thermiques (Čermák), et la méthode de dissipation thermique (Granier) ont été comparées pour trois Pins sylvestres et deux épicéas dans une forêt du centre de la Suède. Le système Granier a donné des valeurs de flux de sève jusqu'à 50 % plus faible que le système Čermák pour les flux élevés. De nouveaux coefficients basés sur les mesures de densité de flux obtenues avec le système Čermák ont été estimés pour le système Granier. Le système Granier sans compensation pour les gradients naturels de température dans le tronc peut présenter de larges erreurs, mais si un capteur de référence horizontal est utilisé, les compensations ne sont pas nécessaires. Il a aussi été démontré que les variations radiales de flux doivent être prises en compte lors des calculs de flux de sève pour l'arbre entier. Les transpirations de deux couverts adjacents, l'un mesuré avec la méthode Granier, et l'autre avec la méthode Čermák, sont en accord entre elles et avec l'évaporation totale mesurée par la méthode des corrélations turbulentes.

THB / HD / flux de sève / transpiration / *Picea abies* / *Pinus sylvestris*

1. INTRODUCTION

During the past few decades, there has been a growing awareness of the importance of land-surface processes in global climate modelling. Models are very sensitive to changes in many surface parameters and in particular, to the partitioning of energy between sensible heat and energy used for evaporation. An increased understanding of the interactions between the vegetation and the

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hydrological cycle is therefore of great importance. Boreal forests have been the subject of especial interest, and at least two major land-surface experiments; NOPEX [23] and BOREAS [43] have been conducted in such areas. In these studies, and many others, tree transpiration is commonly measured by the sapflow technique. This is a technique which has become very popular as an elegant tool for measuring tree water uptake [26, 45, 50]. Assessment of the performance and accuracy of such methods is important in assuring the quality of knowledge gained from such studies.

Several methods for measuring sapflow are now available. Two of these methods, often used on large trees, utilise heating of the xylem: the Čermák method [7, 8, 10] and the Granier method [17, 18]. Both systems have been widely used on different species, such as *Picea abies* (L.) Karst. [1], *Pinus sylvestris* L. [20, 25] and *Quercus robur* L. [3, 9] under different climatic conditions.

The Čermák method is directly quantitative and needs no calibration; flow is calculated from applied energy, temperature change and the specific heat of water [45]. The Čermák method has been validated by volumetric techniques on *Picea abies* [11] and on *Quercus petraea* Lieb. [5]. Good agreement with porometer measurements was found by Schulze et al. [42] on *Larix leptolepis* Sieb. & Zucc. × *decidua* Mill. and *Picea abies*. Flow rate, scaled up to stand transpiration, showed good agreement with chamber measurements at branch level and evapotranspiration measured by the eddy-covariance method during dry conditions for a stand in the same forest as the present study [22].

The Granier radial flow-meter is a relative method based on heat dissipation around a heated probe, and was developed from empirical calibrations made in the laboratory [17, 18]. It was calibrated on five species (*Pseudotsuga menziesii* (Mirb.) Franco, *Pinus nigra* Arnold, *Quercus robur*, *Castanea sativa* Mill., *Prunus malus* (sec)) and saw dust and it was assumed to be valid for all tree species. Later, other studies have found that calibration should be done for species were the original calibration had not been verified [44].

Several attempts have been made to validate the Granier method, with varying results. Few laboratory tests have been performed between measured sapflow and gravimetric measurements of water loss. A cut-tree comparison on grapevine (*Vitis vinifera* L.) [2] and a lysimeter study on mango (*Mangifera indica* L.) [29] showed good agreement with the original calibration at flow rates up to 225 g m^{-2} s^{-1}. Clearwater et al. [13] found that heat dissipation probes used with the original Granier calibration underestimated water flow through excised stems from several species if the probe was in partial contact with non-active xylem. The empirical calibration was re-evaluated and confirmed in stems of three tropical species, when the entire sensor was in contact with conducting xylem. Transpiration obtained from sapflow measurements agreed well with transpiration calculated from micrometeorological methods [19, 41]. The Granier method and the Heat Pulse Velocity (HPV) method [40] were applied in the same stem of the tropical tree *Gliricidia sepium* and showed similar results [46]. In an aspen (*Populus tremuloides* Michx.) stand, the Granier system tended to underestimate sapflow compared to HPV-measurements [24]. In another study, the relationship between ground area transpiration and the sapflow signal varied among stems of *Quercus durata* Jeps. and *Q. agrifolia* Nee., and the original calibration was not confirmed [16].

A few comparisons, mostly at stand level, have been made between the Čermák method and the Granier method. Similar transpiration rates were found in studies on stands of *Pinus sylvestris* [25] and *Picea abies* [27]. Comparisons between the two systems installed in the same trees were made on *Quercus petraea* [20] and *Picea abies* [26]. No significant difference was reported between the two systems.

The aim of this study was to assess the performance of the Granier method by comparing the sapflow rates to the rates measured on the same trees with the Čermák method. The Granier system is quite simple and therefore attractive to use in large numbers, whereas the Čermák system is more complex and also more expensive and, accordingly, more limited in its application. It is therefore of great interest to evaluate the Granier system both in terms of absolute accuracy and in terms of practical applicability.

2. MATERIALS AND METHODS

2.1. Site description

The measurements of sapflow were made in the Norunda forest, ca 30 km north of Uppsala in central Sweden (60º5' N, 17º29' E, alt. 45 m). The stand was 50 years old, with a basal area of 29 m^2 ha^{-1} of which 33% was Norway spruce (*Picea abies* (L.) Karst.), 64% Scots pine (*Pinus sylvestris* L.) and 3% deciduous trees.

Table I. Description of the trees used in the study at Norunda, Sweden.

	Pine 1	Pine 2	Pine 3	Spruce 1	Spruce 2
Circumference[1], breast height (cm)	78	70	52	78	61
Circumference[1], Čermák measuring point (cm)	73	61	45	74	58
Circumference, Granier measuring point (cm)	74	63	49	72	59
Height above ground, Čermák measuring point (cm)	165	155	140	145	140
Height above ground, Granier measuring point (cm)	260	250	240	250	265
Xylem depth, Granier measuring point (cm)	8.3	4.6	4.2	6.5	9.1
Sapwood area, Granier measuring height, A_s (cm^2)	329	194	119	344	237
Tree height (m)	17.0	16.7	16.9	19.0	16.5
Height to living crown (m)	8.0	8.8	10.6	3.7	2.8
Length of the Čermák electrodes (cm)	8	7	7	8	7

[1] The rough bark of the pines was smoothed before the circumference was measured.

Dominant tree height was 20 m and average diameter at 1.3 m was 20 cm. The projected leaf-area index (LAI) was ca. 5 (corrected LAI-2000, Li-Cor Inc., Lincoln, Ne.). The soil is a deep, boulder-rich sandy glacial till. Three pines and two spruces were selected to compare sapflow rates estimated by the Tissue Heat Balance-method (THB) according to Čermák et al. [7, 8, 10], here denoted "Čermák system" and the heat dissipation method according to Granier [17, 18], here denoted "Granier system".

2.2. Sapflow measurements

The trees used for sapflow measurements are described in *table I*. The Čermák sapflow system was installed in July 1998. Granier sensors were installed in July 1998 and in May to July 1999. Measurements used in this study covered the period April to August 1999.

2.2.1. Čermák system

The Čermák system was a commercial version from Ecological Measuring Systems (model P4.1, Brno, Czech Republic). Five electrodes, inserted parallel into the stem and separated by 2 cm, are used to heat a segment of the stem. Alternating current is passed through the xylem at a voltage regulated to give a constant power of 1 W (*figure 1a*). The temperature difference between the heated and the unheated part of the xylem is measured with a thermo battery consisting of four pairs of thermocouples (*figure 1b*). Two pairs sense the difference between the heated and the unheated part of the xylem at two depths (h1 and h2 in *figure 1b*). The other two pairs are installed parallel with the first pairs to compensate for natural temperature gradients in the stem (n1 and n2 in *figure 1b*) [4]. The thermocouples are connected differentially in such a way that the pairs used for compensation automatically subtract the natural temperature difference.

The thermo battery voltage is read every 60 s and data are stored as 15-min means. The flow rate (Q_w) for the heated segment is calculated from the energy balance of the segment:

$$Q_w = \frac{P}{c_w \Delta T} - \frac{k}{c_w} \quad (\text{kg s}^{-1}) \tag{1}$$

where P (W) is the heat input, c_w is the specific heat of water (4 186.8 J kg^{-1} K^{-1}), ΔT (K) is the temperature difference and k (W K^{-1}) is the coefficient of heat loss

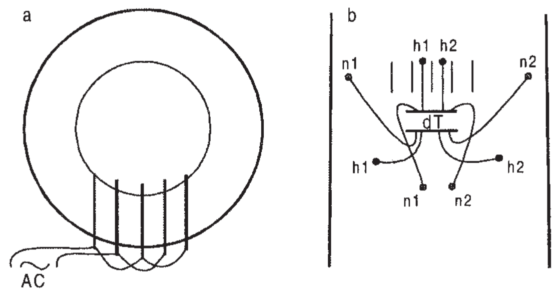

Figure 1. (a) Scheme of the heating of the Čermák measuring point using five electrodes. (b) The placement of the thermocouples around the heated segment; h1 and h2 sense the difference between heated and unheated parts and n1 and n2 subtract the natural temperature gradient.

from the heated segment obtained under zero-flow conditions.

The electrodes were installed on the western and the eastern sides of the stems, respectively, at 140–165 cm above ground. The part of the electrodes in contact with the phloem was insulated by a plastic film, to reduce the influence of phloem flow on the heat exchange. The size of the electrodes used was 80 × 25 × 1 mm (length × width × thickness) for Pine 1 and Spruce 1, for the other trees 70 × 25 × 1 mm. The electrodes were inserted 45 and 35 mm, respectively, into the xylem. The thermocouples were inserted 11 and 34 mm, respectively, into the xylem for trees with long electrodes and 9 and 26 mm for trees with the shorter ones. The stem was insulated with 3 cm thick polyurethane foam and 0.5 mm aluminium that extended ca 30 cm above and below the installations.

Only one tree of each species (Spruce 1 and Pine 1, respectively) was continuously measured on both sides. On the other trees the sensed side was shifted twice in 1999. To calculate a mean flow based on both sides of the tree (Q_{mean}), the relationship between the measured flow and the mean sapflow in the tree of the same species sensed on two sides (Spruce 1 or Pine 1) (Q_{wref}), was used. Before and after each shift, 14 days of daily sums of sapflow were used to determine the relation between the measured side and the reference tree (Spruce 1 or Pine 1). The relations were determined from a linear least-squares fit, forced through the origin ($Q_{\mathrm{w}} = Q_{\mathrm{wref}} \times b$). To calculate the flow on the opposite side (Q_{wopp}), the relation to the reference tree (b_1) can be used to obtain the flow on the reference tree ($Q_{\mathrm{wref}} = Q_{\mathrm{w}} / b_1$). Then the relation for the period with measurements on the opposite side (b_2) can be used to obtain the flow on the opposite side ($Q_{\mathrm{wopp}} = Q_{\mathrm{wref}} \times b_2$), Q_{wopp} expressed in terms of Q_{w} will then be:

$$Q_{\mathrm{wopp}} = Q\mathrm{w}(b_2 / b_1). \quad (2)$$

The mean sapflow rate based on measurements on both sides, Q_{mean}, was then calculated as:

$$Q_{\mathrm{mean}} = \frac{Q_{\mathrm{w}} + Q_{\mathrm{wopp}}}{2} = \frac{1 + b_2 / b_1}{2}. \quad (3)$$

The term $(1 + b_2 / b_1)/2$ is hereafter referred to as the Correction Factor (CF). In 1999, the side on which measurements were made was shifted on 16 June and 5 August. For each shift, two CF were calculated, for transforming the flow before and after the shift to mean sapflow. For the period between the shifts, there is one CF for the first shift and one for the second. For this period, the CFs used were interpolated between the values for the two shifts.

To make the comparison with the Granier system independent of scaling-up to tree level, sapflow density (Q_{s}) was calculated, by dividing Q_{mean} by the heated cross-sectional area (i.e. the length of the electrodes in the xylem (3.5 or 4.5 cm) × the width of the heated segment (8 cm)).

Tree transpiration was estimated by first dividing Q_{mean} by the width of the heated segment and then multiplying with the circumference at the height of the measuring point inside the bark. To show the transpiration conditions during the measurement period, the sapflow obtained from the Čermák system was scaled up to stand-level transpiration, and was compared to evaporative demand according to Turc [47]. Five additional trees, not described in this study, were used for this purpose. The total transpiration of the measured trees was scaled up to stand level by the relationship between total needle biomass for the stand and for the measured trees, as given in Cienciala et al. [12]. This was done for pine and spruce separately; the deciduous trees (ca 3%) in the stand were ignored.

2.2.2. Granier system

The Granier system [17, 18] consists of a pair of fine-wire copper-constantan thermocouples. Each thermocouple was installed in the centre of a 1.5 mm diameter, 21 mm long, hollow steel needle. Around one of the needles, a constantan heating wire was coiled, covering the whole length. The needle with the heating wire, the heated sensor, was inserted in a 2.1 mm diameter, 22 mm long steel tube. Both sensors were then installed horizontally in the conducting xylem with the unheated, reference sensor, ca 10 cm below the heated sensor.

The pair of thermocouples is connected differentially so that the measured voltage difference between the copper leads represents the temperature difference between the thermocouples. The heating wire is supplied with a constant power of 200 mW, which is dissipated as heat into the sapwood. During nights, when sapflow density is assumed to be zero, the measured temperature difference, ΔT_{i} (K), represents the steady state when heat is dissipated into sapwood with zero flow ΔT_0 (K). Any sapflow causes a decrease in temperature difference as the heated thermocouple is cooled, and sapflow density, Q_{s}, can be calculated as [17, 18]:

$$Q_{\mathrm{s}} = 119K^{1.231} \quad (\mathrm{g\ m^{-2}\ s^{-1}}) \quad (4)$$

$$K = \frac{\Delta T_0 - \Delta T_i}{\Delta T_i} \quad (5)$$

where K is referred to as the sap flux index.

The Granier sensors were installed on the northern side of the stems, 70–120 cm above the Čermák system. In each tree, one pair of thermocouples was inserted at 0–2 cm depth and another pair at 2–4 cm depth below cambium. One extra pair of unheated sensors was installed, at 0–2 cm depth in all trees, with a 10 cm horizontal separation from the heated pairs, to monitor the vertical natural temperature difference, ΔT_n, in the xylem:

$$\Delta T_n = T_u - T_d \tag{6}$$

T_u and T_d is the temperature at the upper and the lower thermocouple, respectively. The natural temperature gradient, T', was calculated as:

$$T' = \frac{\Delta T_n}{d_n} \tag{7}$$

where d_n is the distance between the unheated sensors. The natural temperature gradient was used to correct the measured temperature difference as:

$$\Delta T_{corr} = \Delta T_i - T' d_i \tag{8}$$

where d_i is the vertical distance between the reference sensor and the heated sensor. It was assumed that the natural temperature gradient at 0–2 cm and at 2–4 cm depth was the same. With this installation it was also possible to analyse the consequence of using a horizontal reference, ΔT_h (*figure 2*) instead of a vertical one. To analyse further the effect of natural temperature gradients and variations in vertical separation distance, three extra, unheated sensors were inserted at 15, 17.5 and 20.2 cm distance from the heated sensor in Pine 1.

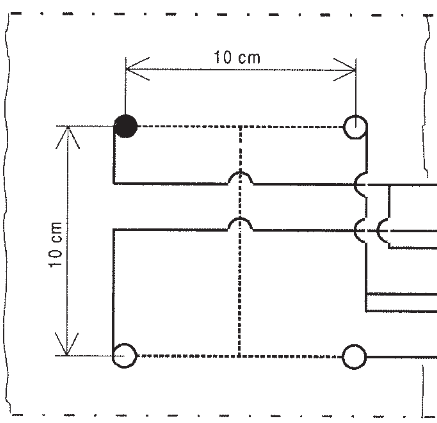

Figure 2. Set-up of Granier sensors to measure vertical (ΔT_v), horizontal (ΔT_h) and natural (ΔT_n) temperature differences. Heated sensor (•), reference sensors (o), copper wire (——) constantan wire (– – – –).

The whole stem was insulated with 3 cm polyurethane foam and 0.5 mm aluminium that extended ca. 20 cm above and below the thermocouples, to prevent exposure to rain and sun. The ΔT-values were recorded as a voltage difference every minute and averaged every 15 minutes with a Campbell CR10-datalogger (Campbell Scientific, Inc., NE, USA) and a Campbell AM32-multiplexer (Campbell Scientific, Inc., NE, USA). Tree-level flow rate, Q, was obtained by multiplying the calculated sapflow density, Q_s, by the sapwood area, A_s, at the measuring height:

$$Q = Q_s A_s. \tag{9}$$

Sapwood area was calculated as:

$$A_s = \pi(r^2 - (r - d_h)^2) \tag{10}$$

where r is the radius inside bark calculated from circumference measurements and bark thickness. Average thickness of the hydroactive part of the xylem, d_h, was determined using a wax crayon with water-soluble green dye, on cores taken with an increment corer in three directions at measurement height in late September 1999.

Granier sap flux index, K, was compared to sapflow density, Q_s, obtained from the Čermák system to verify the Granier calibration (equation 4) or to establish a new relationship between K and Q_s for the Granier system. Since the length of the Čermák electrodes inserted in the xylem is 3.5 or 4.5 cm, a mean sap flux index, K_{mean}, for the 0–2 mm sensor and the 2–4 cm sensor was estimated for the comparison. No measurements were made at 2–4 cm depth simultaneously with the comparison measurements in July; therefore, a relationship between the sap flux index at 0–2 cm and 2–4 cm depth was established from the radial study in June:

$$n = \frac{K_{2-4\,\mathrm{cm}}}{K_{0-2\,\mathrm{cm}}} \tag{11}$$

K_{mean} was calculated as:

$$K_{mean} = \frac{K_{0-2\,\mathrm{cm}} + K_{2-4\,\mathrm{cm}}}{2} = K_{0-2\,\mathrm{cm}}\left(\frac{1+n}{2}\right) \tag{12}$$

2.3. Meteorological measurements

Meteorological variables, except soil moisture, were measured in the stand at 20 m height. Variables and sensors are listed in *table II*. All sensors were sampled every 60 seconds by a Campbell CR10-datalogger (Campbell Scientific, Inc., NE, USA), recording 10-min averages of all variables.

Table II. Climate station instrumentation.

Quantity	Instrument
Air temperature and relative humidity	Hygromer MP probe (Rotronic instruments Ltd., Horley, UK)
Wind direction and windspeed	Young model 05103 (R.M. Young Company, Traverse City, MI)
Global radiation	LI-190SZ Quantum sensor (LI-COR Inc., Lincoln, NE)
Net radiation	Q-6 Net Radiometer (Campbell Scientific, Ltd., Shepshed, UK)
Precipitation	IS200W rain gauge (In Situ, Ockelbo, Sweden)
Soil water content at 10–15 cm depth	ML1 ThetaProbes (Delta-T Devices Ltd., Cambridge, UK)

2.4. Test application

The reliability of the new established coefficients for equation 4 (α and β) was tested on sapflow data from an adjacent stand where Granier sensors were installed in six pines and six spruces. The stand was 50 years old, had a basal area of 37 m^2 ha^{-1}of which 44% was Norway spruce, 50% Scots pine and 6% deciduous trees. Stand level transpiration from this stand (denoted E_{test}) was compared to transpiration from the comparison stand (E_{comp}) measured by the Čermák system and to total evaporation (E_{tot}) measured by an eddy correlation system at 35 m above ground in a tower [21] situated 500 m north-east of the plots. A period from 14 June to 14 July 1998, with prevailing winds from south-west, was used for the comparison.

3. RESULTS AND DISCUSSION

3.1. Weather conditions

The growing season of 1999 started with a high groundwater level and there was sufficient soil water content to maintain transpiration in accordance with the demand (*figure 3*). Precipitation was below normal from May to July, and from mid-July a decline in stand transpiration, due to soil water deficit, was observed. After some rainy days in July and August, transpiration recovered temporarily. The period from 1 July to 31 July, a period that covers a wide range in VPD, soil moisture and radiation conditions, was used for comparison of the two systems.

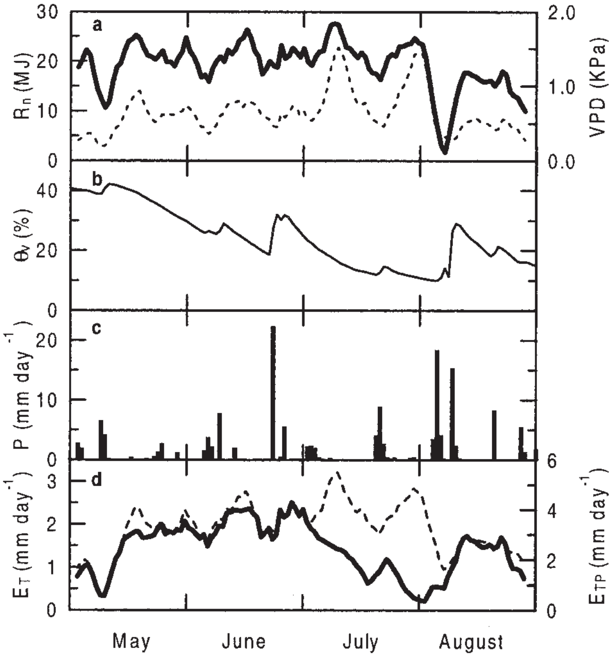

Figure 3. Running mean (5 days) of (a) Daily total net radiation, R_n, (——) and daily mean VPD (– – – –), (b) soil water content, θ_v, at 10–15 cm depth, (c) daily precipitation, P, (d) measured stand transpiration by the Čermák system, E_T, (———) and potential transpiration according to Turc (1961), E_{TP}, (– – – –).

3.2. Correction of Čermák measurements

The R^2 values for the regression, the Correction Factors (CF) and the corresponding ratios between opposite sides, are presented in *table III*. During the period between the shifts of the measured side (17 June to 4 August), the ratios between western and eastern side changed moderately, at most by 21% (Spruce 2). The highest ratios between opposite sides were found in Spruce 1 (1:1.7) and Pine 2 (1:1.6). Čermák and Kucera [5] reported a ratio of 1:3 on a large spruce during a dry summer; under conditions of water sufficiency, the ratio decreased to 1:1.5.

Table III. Correction Factors (CF) and R^2 values for the relation to the reference trees and corresponding ratios between flow on western and eastern side of the Čermák measurements. The CF transfers the flow measured on one side to a mean flow for both sides.

	First shift					Second shift				
	2 Jun–15 Jun Eastern side		17 Jun–30 Jun Western side		Ratio W:E	22 Jul–4 Aug Western side		6 Aug–19 Aug Eastern side		Ratio W:E
	CF	R^2	CF	R^2		CF	R^2	CF	R^2	
Pine 2	0.82	0.96	1.28	0.98	1:1.56	1.15	0.76	0.88	0.96	1:1.30
Pine 3	1.06	0.98	0.94	0.91	1:0.88	0.98	0.83	1.02	0.97	1:0.96
Spruce 2	0.93	0.97	1.08	0.94	1:1.16	0.96	0.67	1.04	0.96	1:0.92

3.3. Radial variation of Granier measurements

There was relatively large radial variation in sapflow density, calculated with the Granier calibration (equation 4), in each of the five experimental trees. Examples of diurnal variation between the two depths are shown for Pine 1 and Spruce 1, respectively, for one day in June 1999 (*figure 4*). There was an average (45 days) decrease, from 0–2 to 2–4 cm, of 35.0%, 32.6% and 35.0%, respectively, in sapflow density for Pine 1,2 and 3, respectively. In Spruce 1 the decrease was 71.7% while in Spruce 2 there was an increase of 6.7%. The different radial patterns of flow in the spruces may be an effect of varying water availability within the stand. Čermák and Nadezhdina [6] showed how flow can be redistributed when a spruce is affected by water deficit. This indicates that n may have been overestimated during the comparison period, since the radial study was made under different soil-moisture conditions. Spruce 2 had two large branches, just above the Granier measuring point, which may have also affected the flow pattern as compared to Spruce 1, where there were no large branches near the measuring point. The radial variation in sapflow density was in the same range as those found in several studies on pine and spruce [6, 25, 34, 37]. A sensor that covered the whole sapwood depth, and integrated the variation in sapflow, would probably best account for the radial variations in sapflow density. As this necessitates a large number of sensors of variable length, an acceptable compromise would be to distribute two or more 2 cm long sensors throughout the entire depth of the sapwood [30]. It has been suggested that measurements with sensors that partly cover the conducting xylem should be scaled using a correction factor [13, 25]. The relation between sapflow density at different depths can be used to estimate a linear relationship that can be used to scale measurements of sapflow density in trees where only single-depth sensors are used.

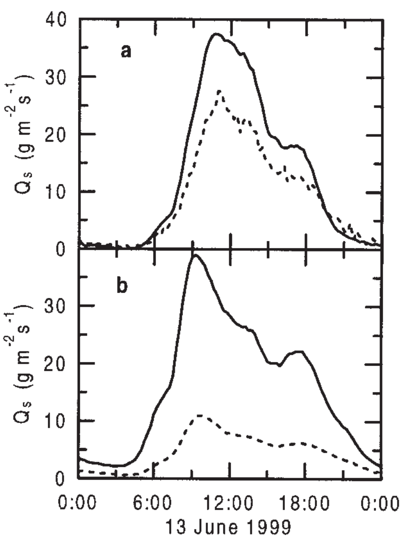

Figure 4. Sapflow density measured using the Granier system in outer 0–2 cm of xylem (——) and at 2–4 cm depth (– – – –) on 13 June 1999 (a) Pine 3 (b), Spruce 1.

3.4. Natural temperature gradient and sensor separation

The natural temperature gradient in the xylem was large in all trees and varied between ca –0.08 and 0.08 K cm^{-1} (*figure 5b*). Both Čermák and Kucera [4] and Goulden and Field [16] report a typical maximum temperature difference of 0.5 °C at a distance of 10 cm (0.05 K cm^{-1}). A typical diurnal pattern was a positive gradient late at night, and when sapflow increased in the morning, the gradient decreased rapidly and became negative. During the afternoon the gradient increased continuously (*figure 5b*). Sapflow measured by the Granier system, when corrected for natural temperature gradients, was up to 30% lower than that without corrections

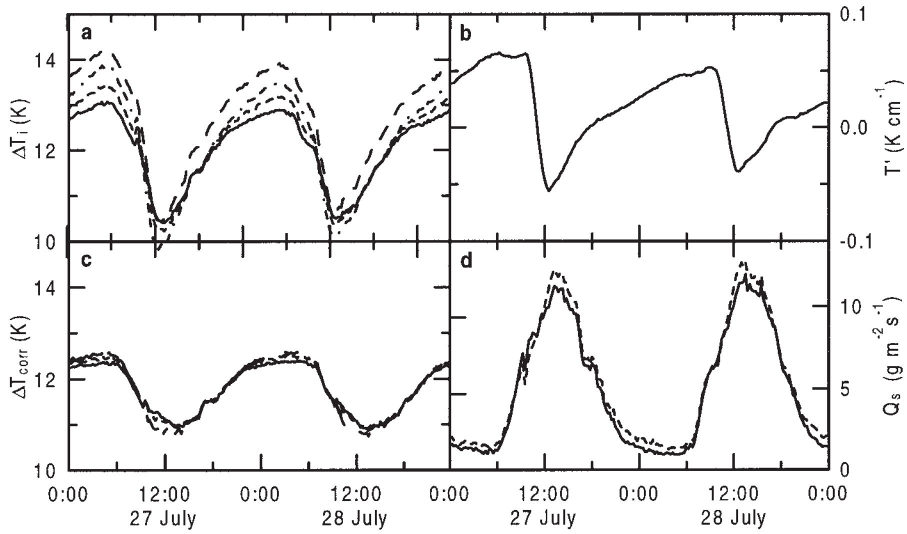

Figure 5. (a) Measured temperature differences between the heated and the reference probes located at a distance of 11 cm (——), 15 cm (- - - -) 17.5 cm (– – –) and 20.2 cm (– · – · –) respectively, (b) natural temperature gradient for the 11 cm reference sensor, (c) Corrected temperature gradients at different distances (as in (a)), (d) Sapflow density measured with vertical (——) and horizontal (– – – –) reference sensor. All data from Pine 3.

(*figure 6a*), but followed the diurnal dynamics of the Čermák measurements better (*figure 6b*). The R^2 value for the Granier-Čermák comparison increased from 0.87 to 0.97 after correction in the non-linear regression ($y = \alpha x^{\beta}$). Peschke et al. [36] found that sapflow rates changed +/– 25% on an hourly basis after correction in Norway spruce. Also the zero flow, ΔT_0, was more distinct with the correction. The impact of natural vertical temperature gradients was not minimised by using different insulation techniques, either in this study or in the study by Goulden and Field [16]. A method used to compensate for temperature gradients when using the Granier system, is to switch off the heating for a few days, and to use those data for compensating the data obtained when the sensors were under normal operation [36, 46]. This assumes that the daily course of the natural temperature gradient is similar from one day to another. In several studies, the natural fluctuations in temperature are assumed to be the same at the position of the heated and the reference sensor [25] or to be negligible [35, 37]. A comparison of the measured temperature differences ΔT_i , for sensor separations of 11, 15, 17.5 and 20.2 cm, showed clearly that sensor distance was important (*figure 5a*). The maximum difference at zero flow was typically 1 K (between 11 and 20.2 cm sensors) and this was about 10% of the "correct" difference as measured by the 11 cm sensor. Now, when the measured differences (*figure 5a*) were corrected for the natural temperature

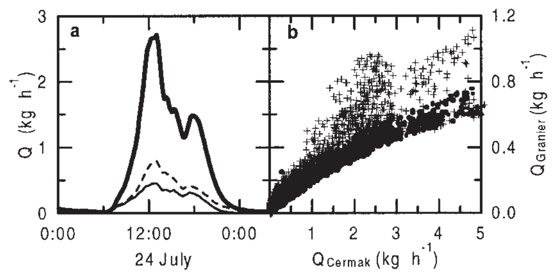

Figure 6. (a) Total tree sapflow in Pine 2. Čermák (——), uncorrected Granier (– – – –) and Granier corrected for natural temperature gradients (——), (b) Total tree sapflow in Pine 2 of uncorrected Granier vs. Čermák (+), Granier corrected for natural temperature gradients vs. Čermák (•).

gradient (*figure 5b*), they all compared favourably (*figure 5c*). Granier [18] suggested that the distance between the heated and the reference sensor should be large enough to prevent direct heating of the reference sensor, and short enough to limit the influence of natural temperature gradients. He recommended 10–15 cm. Nothing is said about how sensitive the calibration is to this distance, implying that it is insensitive. The results in the present study show that the measured temperature difference was strongly dependent on the sensor separation distance, if natural temperature gradients occurred. However, our results also show that it can be corrected for, provided that the natural temperature gradient is known.

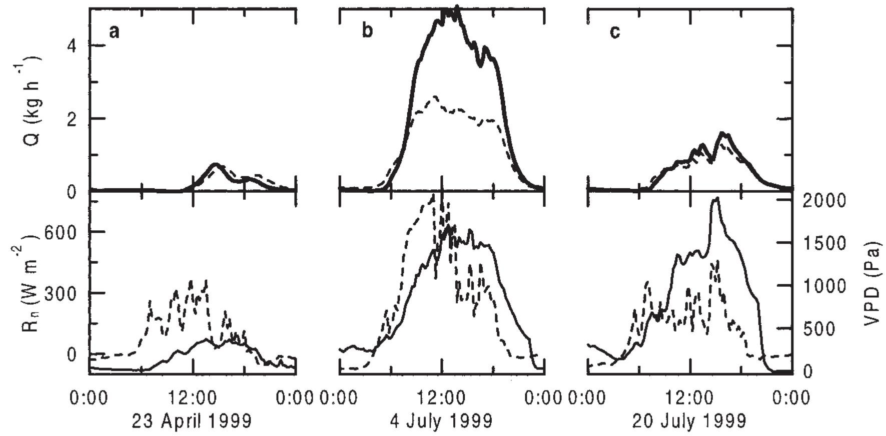

Figure 7. Total tree sapflow in Pine 2 according to Čermák (——) and Granier (– – – –) for three different days with variable weather and soil-moisture conditions. Net radiation (– – – –) and vapour pressure deficit (——).

3.5. Horizontal reference

The sapflow density measured with a vertical reference, corrected for the natural temperature difference, was close to the sapflow density obtained using a horizontal reference sensor (*figure 5d*). This implies that under conditions when large natural temperature gradients in the xylem can be expected, and when the number of reference sensors or logger channels for measurements is limited, a horizontal reference sensor is preferred. In that case, adequate insulation may be more important, since the influence of sun and wind is more variable around than along the stem [4].

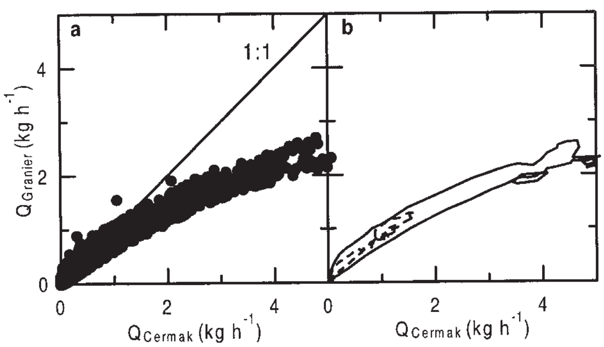

Figure 8. Total tree sapflow in Pine 1, Čermák vs. uncorrected Granier. (a) 15-min values (b) Two single days, 4 July (——) and 20 July (– – – –).

3.6. Comparison of the two systems

At the beginning of the growing season, when the transpiration rate was low, the Čermák system and the Granier system showed similar quantitative and qualitative diurnal responses (*figure 7a*). However, when the measured tree level sapflow exceeded 0.9–1.8 kg h^{-1}, corresponding to a sap flow density of ca 15 g m^{-2} s^{-1}, the daily curves began to diverge. Under conditions of maximum water loss, the Čermák system measured sapflow rates up to 100% higher than the Granier system (*figure 7b*). At the end of July, when a strong water deficit developed, the two systems measured almost the same fluxes again (*figure 7c*). A regression between the calculated fluxes showed a slightly logarithmic behaviour; here illustrated with data from one tree (*figure 8a*). A small hysteresis effect could also be seen (*figure 8b*), which was probably caused by the flow being measured on different sides of the stem. We found no reason to believe that the Čermák system should malfunction at high flow rates, since in earlier comparisons with independent methods, it showed good agreement [22]. This implies that the difference in response had to do with the flow rate and not with sensor malfunction due to temperature or humidity. Most other studies report good agreement between the two systems, but the range of studied trees and range of sapflow densities in those other studies was rather limited [20, 26]. Measured sapflow density was rarely higher than 30 g m^{-2} s^{-1} in most earlier studies on Scots pine and Norway spruce, whereas in this study, sapflow density reached 60 g m^{-2} s^{-1}. Granier et al. [20] reports that the two systems agree well, but the sapflow rates in that study were rather low. In Alsheimer et al. [1] there is a tendency to a divergence in the comparison illustrated for days with high sapflow. During conditions of high flow, Offenthaler et al. [33] noted that the Čermák system gave values 3 to 4 times those of the Granier. In another comparison [24], when sapflow density exceeded 4 g m^{-2} s^{-1}, the Granier system measured only half of that measured by the Heat Pulse Velocity technique [45]. Our studies, as well as others, suggest that the Granier system loses sensitivity at higher flow rates. However, it has been shown that the original calibration is valid even for high flow densities in grape vines (225 g m^{-2} s^{-1}) [2] and in mango (120 g m^{-2} s^{-1}) [29]. The original calibration does not show any large errors up to 150 g m^{-2} s^{-1} [17, 18].

The differences observed may either be real or caused by the specific way that the probes were placed during the comparison. Ideally, the systems should have been installed close to each other in the same segment of the xylem, to ensure that they were measuring exactly the same sapflow. However, this is not possible, because the systems would affect each other in an unpredictable fashion, and if the vertical distance is increased, the presence of spiral grain must also be considered [15, 48]. It was therefore decided to install the systems using standard set-ups at different heights. Sapflow densities were not significantly different when measured in different azimuthal directions in three other trees in the same stand (Lundblad, unpublished results). Loustau et al. [28] also pointed out that circumferential variability in sapflow decreased with height. The differences found between the Granier system with the original coefficients and the Čermák system, were systematic in a consistent fashion over time, and there is no reason to believe that the placement in different azimuthal directions should cause such systematic behaviour. As a consequence, our comparison, although not ideal, does suggest that it is indeed meaningful to compare the two estimates of sapflow density, although a perfect correspondence should not be expected.

The sensitivity of the Granier sensor depends on the contact between the sensor and the conducting xylem. Inadequate contact between the sensor and the conducting xylem will inevitably lead to errors. Errors may increase with sapflow rate and with the proportion of the probe not inserted into the active xylem. Clearwater et al. [13] found that if half of the sensor was inserted into non-conducting sapwood, sapflow density could be reduced by up to 50%. It is therefore important to make sure that the whole sensor is inserted into the conductive xylem. Non-uniformity of sapflow over the length of the sensor may have an effect similar to that when part of the sensor is in non-conducting xylem. Sapwood in conifers does contain concentric bands of non-conducting latewood, which can occupy up to 50% of the width of a growth ring [14, 49]. Consequently, the number and width of growth rings along the sensor may be important for the sensitivity of the system. The number of growth rings at 0–2 cm depth is typically 10–15 in trees in this study. Since the growing season is relatively short in the boreal climate, it may be assumed that up to half of the width of a growth ring can consist of non-conducting wood. This reduces the sensor length in contact with transporting sapwood, and the accuracy of the measured sapflow density may be largely reduced for this reason alone. To explain fully the importance of this feature, effects of the contribution of latewood on sapflow, should be tested under standardized conditions.

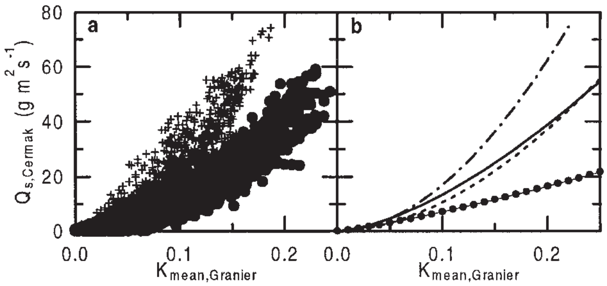

Figure 9. Čermák sapflow densities as a function of Granier sap flux index *K*. (a) Individual 15-min values for all trees except Spruce 2 (¡), Spruce 2 (+), (b) Granier calibration (-•-•-), new coefficients used for all trees (——), spruce (– · – · –) and all trees, Spruce 2 excluded (– – – –).

The relation between Granier mean sap flux index, K_{mean}, and sapflow density measured by the Čermák system, $Q_{s,Čermák}$, was analysed by regression (*figure 9a*). The relationship was best described by a power function, $Q_s = \alpha K^{\beta}$. Spruce 2 was excluded from the all-tree regression, because uncertainty about the relationship, *n*, between the two measured depths existed. A separate regression for the three pine trees showed almost the

Table IV. Parameters and R^2 values for the Granier system, K_{mean} compared against the Čermák system sapflow density, Q_s, $Q_s = \alpha K^{\beta}_{mean}$.

	α (g m^{-2} s^{-1})	β	R^2
Pine 1-3	702.3	1.822	0.95
All trees	464.5	1.542	0.80
All trees except Spruce 2	691.2	1.816	0.95
Granier calibration	119	1.231	0.96

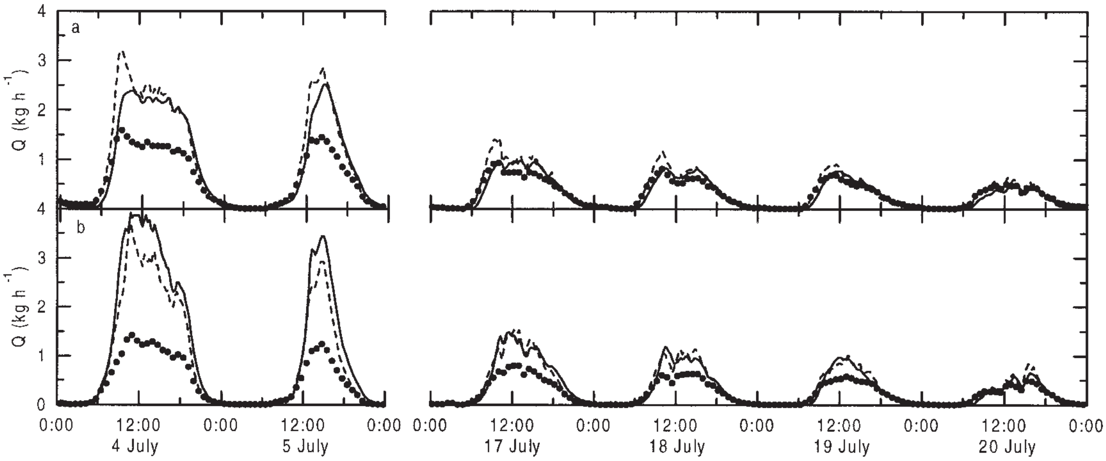

Figure 10. (a) Total tree sapflow for Pine 3, measured with the Čermák system (––), measured with the Granier system using the new coefficients (– – – –) and the original Granier calibration (●●●●). (b) Total tree sapflow for Spruce 1, measured with the Cermak system (——), measured with the Granier system using the new coefficients (– – – –) and the original Granier calibration (●●●●).

same result as the all-tree regression. The results are shown in *table IV*, together with the parameters from the original calibration. A more steeply exponential behaviour, compared to the original Granier calibration, was found for all regressions (*figure 9b*). The same behaviour can be seen in Clearwater et al. [13], where tests with sensors partly inserted in non-conducting wood were made. Applying the new coefficients (all trees, Spruce 2 excluded) to the Granier measurements showed much better agreement with the tree sapflow rates measured by the Čermák system (*figure 10*), both during a period of unlimited water availability (4–5 July) and when the trees were exposed to drought (17–20 July). The Granier system still underestimated sapflow at very high flow rates (*figure 10*, 4–5 July), but there was a significant improvement as compared to the original Granier calibration.

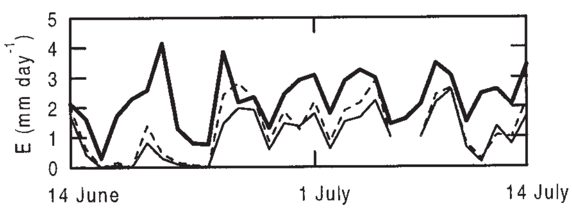

Figure 11. Total evaporation measured with eddy-correlation technique at 35 m height (——), stand transpiration measured with the Čermák method (– – – –), and stand transpiration measured with the Granier method for an adjacent stand (——) for a period (14 June to 14 July) in 1998.

The transpiration comparison with the adjacent test stand showed good agreement both dynamically and in absolute values (*figure 11*). The linear least-squares fit between the two estimates of stand transpiration for the compared period resulted in $E_{comp} = 1.18E_{test} + 0.07$ (R^2 = 0.95), i.e., the test stand showed about 15% lower transpiration with the new coefficients. Using the original calibration gave 55% lower transpiration, and since the age and composition of the two stands were quite similar, it was judged that the former value was much closer to reality. The transpiration part (measured by the sapflow techniques) of the total evaporation, E_{tot} measured by the eddy-correlation system, was 74% (ΣE_{comp} / (ΣE_{tot}) and 61% (ΣE_{test} / (ΣE_{tot}) for all days with transpiration above 1 mm day^{-1}. This is in the same range as reported for water balance studies in other coniferous forest [19, 22, 31]

3.7. Interpretation of sapflow measurements

The interpretation of sapflow measurements is difficult, because a number of assumptions are made in the instrument design and evaluation processes. When scaling-up Čermák measurements to tree level, by multiplying by the circumference, it is assumed, for instance, that the area of the heated xylem represents a sector of a circle, but the heated electrodes are inserted in parallel. The electrodes are also assumed to cover the whole depth of the conductive xylem, but in this study, the depth of active xylem exceeds the depth of the electrodes by 7 to 45 mm. The area measured (between the electrodes) therefore differs from that assumed to be measured (a segment in the conductive xylem) by –25 to +20% in our case. If the radial flow pattern were uniform, this would cause an error of that magnitude, but since sapflow decreases inwards, the error is much less. This effect is most pronounced in small stems with deep sapwood, and under such conditions it should be considered when scaling-up sapflow data to tree level.

A number of assumptions also exist in the Granier system. Radial flow patterns occur, which result in non-uniform sapflow density along the probe. This may not be a problem if the sensor covers most of the conducting xylem, but may cause under– or overestimation if the length of the sensor and the xylem depth differ [13]. If nocturnal transpiration is present, the determination of a baseline for the zero flow is crucial. The original calibration is assumed to be valid for all tree species of all sizes, but relatively small trunks were used and only a small number of species were tested in the calibration. In many field studies, the trees are full-grown, as were the trees in the present study, and the hydraulic properties of pine and spruce have been shown to change with age and tree size [32, 38, 39].

There are always errors in measurements but since the Čermák method is an absolute method and since a number of precautions have been taken to reduce possible errors, it is judged that this method gives quite accurate absolute values for the stem section where it is applied. The Granier method is based on an empirical calibration made once, on a limited number of species and a narrow range of size classes. In many studies it gives reasonable results, in some not. We are therefore of the opinion that it is appropriate to use the Čermák measurements to establish new coefficients for the Granier system for the conditions and tree properties we are dealing with.

4. CONCLUSIONS

- Use of a Granier system without compensation for natural temperature gradients can cause errors up to 30%.
- The distance to the reference sensor in the Granier system is not crucial if the natural temperature gradient is known and the measured difference is properly compensated for. If a horizontal reference sensor is used, no compensation is necessary.
- Radial flow patterns must be considered when calculating total tree sapflow for both methods.
- In this study, at high flow rates in Norway spruce and Scots pine, the Granier system measured consistently lower flow rates than the Čermák system, when the original calibration was used. It was, however, possible to adjust the Granier system measurements using sapflow density data from the Čermák measurements. The new Granier coefficients, shown here, can probably be used for Scots pine and Norway spruce under similar climatic conditions and stand properties as those in the present study, but it is recommended that independent calibration is performed for maximum accuracy.

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