Pergamon

0961-9534(94)00085-9

Biomass and Bioenergy Vol. 8, No. 1, pp. 7–15, 1995

0961-9534/95 $9.50 + 0.00

SAP FLOW BY THE HEAT BALANCE METHOD APPLIED TO SMALL SIZE *SALIX* TREES IN A SHORT-ROTATION FOREST

ANDERS LINDROTH,* JAN CERMAK,† JIRI KUCERA,† EMIL CIENCIALA* and HENRIK ECKERSTEN‡

*Department of Ecology and Environmental Research, Section of Biogeophysics, Swedish University of Agricultural Sciences, P.O. Box 7072, S-750 07 Uppsala, Sweden

†Institute of Forest Ecology, University of Agriculture, 64400 Brno-Sobesice, Czech Republic

‡Department of Soil Sciences, Swedish University of Agricultural Sciences, P.O. Box 7014, S-750 07 Uppsala, Sweden

(Received 11 January 1994; revised received 15 August 1994; accepted 3 September 1994)

Abstract—The introduction of rapidly growing trees in so-called short-rotation forestry requires knowledge about their water use in order to select suitable land for plantations and to manage the stands in a proper way. In Sweden, different clones of *Salix* are usually used in short-rotation forestry today. The diameter of trees in such stands is much smaller compared with trees in traditional forestry. This requires new methods to be developed in order to study water relations at the tree level. The aim of this study was to modify, apply and test the stem tissue heat balance method for long-term sap flow measurements on small size *Salix* trees. Sap flows measured on two trees were compared to stand evaporation determined by the Bowen ratio method and to other climatic variables. Diurnal courses of sap flow and evaporation corresponded well to each other but with a pronounced lag of sap flow behind evaporation in the morning. Also, the daily integrals of sap flow, evaporation and global radiation showed good correlation over a two month period. Maximum sap flow rate of 30 mm diameter trees was about 0.2 kg h^{-1} or 2 kg day^{-1}. The size of the pool of easily available water in the trees was estimated to be 0.2 kg. This value constitutes about 1/4 of the mean daily transpiration, a value similar to those found for much larger trees. The conclusion of this study was that the stem tissue heat balance method with externally placed heater and internally sensed temperature is an appropriate method for measurement of sap flow and transpiration of individual small size *Salix* trees.

Keywords—sap flow; transpiration; short-rotation forestry; evaporation; radiation; Bowen ratio method; heat balance method; *Salix viminalis*

1. INTRODUCTION

Short-rotation forestry, consisting of *Salix viminalis* and *Salix dasyclados* species, has been introduced today in Sweden on relatively large land areas. The plantations are managed intensively and the wood biomass will be used for energy production. The stands are coppiced every 3–5 years which means that the trees are relatively small in size compared with traditional forests. The water requirement of *Salix* will be an important factor when selecting suitable land for the plantations.

Previous studies have shown that evaporation from *Salix* stands is higher than from traditional agricultural crops and forests.[1] It is therefore possible that water will be a growth-limiting factor at many locations. A proper establishment and management of short-rotation forests thus requires knowledge about the water uptake of the plants as well as the relationships between transpiration and growth (water use efficiency).

There are several methods available to study this, e.g. micrometeorological or physiological methods, but they all have different disadvantages in this respect. One seemingly attractive method would be to measure the sap flow in the stems. This would make it possible to relate actual transpiration to actual growth on a tree basis under *in situ* conditions.

The sap flow measurement method was first introduced by Huber,[2] who adopted the heat pulse velocity (HPV) technique to measure the sap velocity within tree stems. The method was gradually improved[3–6] so that it could also be used for indirect mass-flow measurements provided the conducting area and the xylem water content were known. Further development of this approach led to the stem tissue heat balance (THB) method[7–12] which gave the sap mass flow directly without needing additional information. The THB method has been applied during the last two decades for short- as well as long-term measurements on mostly large stems of deciduous and coniferous trees.

For stems of relatively small diameter, the stem tissue heat balance method, with internal sensing of temperature gradient, has so far only been used for short-term field measurements.[13,14] Baker and van Bavel[15] presented a sap flow gauge, DYNAMAX, suitable for long-term measurements on small diameter stems. Their gauge was also based on the heat balance method, but with external sensing of temperature gradient. There have been, however, several recent papers, e.g. Ref. 16, reporting serious problems with the latter method when applied to field conditions.

The aim of this study was to modify the THB technique utilizing internal sensing of stem temperature gradient and to verify application of this method for long-term field measurements on small diameter, but rapidly growing trees, typical for short-rotation forests. The impact of ambient temperature gradients on such measurements was also evaluated. Measurements of sap flow were made on two trees of 2 year old *Salix viminalis* during a two month period in summer 1989. Verification of the method was made by comparing sap flow with evaporation determined by the Bowen ratio method and with solar radiation.

2. MATERIAL AND METHODS

2.1. *Site and stand*

The research site is situated at Ultuna (lat. 59.3°N, long. 17.4°E), Sweden. The stand was planted in 1984 with mixed clones of *Salix viminalis* and with a density of 2 plants per m^2 on a 2.7 ha area of a clay soil. It was harvested for the first time in January 1987. The production during 1989 was 12.6 t ha^{-1} of stem biomass (dry weight) and the leaf area index varied between 6 and 8 (Verwijst, personal communication, 1990) during the period when the measurements were made. The stand was irrigated and fertilized with a balanced nutrient solution from 27 May to 30 August using a drip irrigation system. The Bowen ratio measurement system was situated in the centre of the stand. The sap flow measurements were made on a 24 m^2 sub-plot located about 50 m south of the mast.

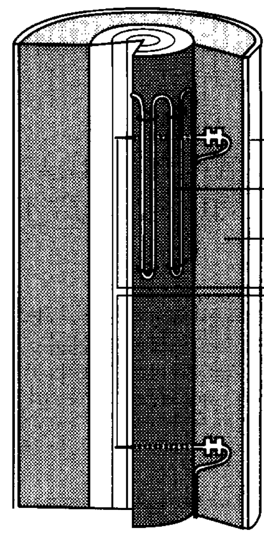

Fig. 1. Schematic drawing showing a cross-section of a stem with installed heat balance device.

2.2. *Heat balance method*

2.2.1. *Installation procedure and measurement device*. The sap flow gauges and measurement device were developed at the Institute of Forest Ecology, Agricultural University, Brno, Czech Republic.* The THB method as described here had externally applied heat and internally sensed temperature. The 80 mm long electric heating element, made from 0.1 mm diameter resistance wire, was mounted around the surface of a stem at about 150 cm above the ground. The heating element was in close but gentle contact with the stem and it was made flexible to allow the tree to grow freely during the measurement period. Two temperature sensors were inserted into the conductive xylem of the stem, one just at the upper edge of the heating element and the other 150 mm below the first one (Fig. 1). The temperature sensors were made from fine wire thermocouples (0.1 mm copper/constantan) which were inserted in a waterproof manner near the tip of 1 mm diameter stainless steel (hypodermic) needles. The two thermocouples were connected differentially to allow direct measurement of the temperature difference between the maximum in the heated part of the stem and a point in the non-heated part, respectively. Holes were drilled radially into the stem and the needles were inserted so that the sensors were positioned in the middle of the conductive xylem at the opposite side of the stem from which the drilling was made (see Fig. 1). In this way, the heat conduction along the needle from the outside surface into the xylem was kept at a minimum. The measuring points were

*Now commercially available from Ecological Measuring Systems, Inc., Brno.

insulated with a 20 mm thick polyurethane foam wrapped around the stem. The insulation extended 50 cm above and below the position of the heating element. The insulation was covered on the outside with 0.5 mm aluminum tubing plus a polyethylene foil which was fastened in a watertight manner around the stem to protect the installation from rain and stemflow. Installation was made on two trees, of about 30 mm diameter. These trees belonged to the upper quartile of the size distribution of the stand.

2.2.2. *Natural temperature gradient within the tree*. In one of the trees where the sap flow gauge was installed, a second pair of differentially connected "needle" thermocouples was inserted into the non-heated part of the stem. This pair, which had a separation between sensors of 150 mm, was installed just below the lower sensor shown in Fig. 1. Pairs of differentially connected thermocouples were also installed on five non-gauged trees at heights between 70 and 160 cm above ground. These measurements were used to check the size of the "natural" temperature gradients in the stem, to estimate the possible influence of such gradients on the calculated sap flow and to judge the most suitable height for installation of the gauges. Information about the magnitude and direction of "natural" temperature gradients relative to the gradients obtained from the THB measuring point will also help in determining where a possible compensating thermocouple should be installed.

2.2.3. *Calculation of sap flow*. According to the above-cited papers, the sap mass flow in the tree, Q_S, can be estimated as:

$$Q_S = \frac{P}{\Delta T c_w} - Q_{fic}, \tag{1}$$

where Q_{fic} represents the heat losses from the measuring point, ΔT the temperature difference between the two needles, c_w the specific heat of water and P the power input to the heater. The heating elements developed a power of 0.25 W. The second term of eqn (1) can also be regarded as a "fictitious" flow, Q_{fic}. Assuming that the actual sap flow was zero just before sunrise during nights with zero vapour pressure deficits, Q_{fic} could be estimated for a number of occasions. The variation of Q_{fic} was small and linear interpolation was therefore made to obtain a continuous time series of Q_{fic} values. Actual sap flow during the day was then calculated as the recorded value minus Q_{fic}.

2.3. *Stand evaporation by Bowen ratio method*

The Bowen ratio method is well known, e.g. Ref. 17, and only a short outline and some specific features of the measurement system are given here. The energy balance at a certain height above the stand can be expressed as:

$$R_n = H + \lambda E + S, \tag{2}$$

where R_n is net radiation, H is sensible heat flux, λE is latent heat flux (energy used for evaporation) and S is the rate of change of energy storage below the level where net radiation is measured and down to a level in the soil where the heat flux is negligible.

Now, the Bowen ratio, β, is defined as:

$$\beta = \frac{H}{\lambda E}. \tag{3}$$

Combining eqns (2) and (3) gives:

$$\lambda E = (R_n - S)/(\beta + 1). \tag{4}$$

According to flux-gradient theory, the fluxes of sensible and latent heat are proportional to the temperature and humidity gradients, respectively. Assuming equality between the proportionality (transfer) coefficients for sensible and latent heat fluxes, the Bowen ratio can be determined as the quotient between the temperature and humidity gradients. Thus, if net radiation and storage terms are measured, the evaporation can be estimated according to eqn (4).

The measurements of temperature and humidity gradients above the canopy were made using a thermometer interchange system, described in detail by Lindroth and Halldin.[18] The temperature and humidity differences were measured at two consecutive height intervals with the lowest level about 50 cm above the top of the canopy. The height difference of each interval was 75 cm. The measurement levels were adjusted upwards at weekly intervals in pace with the growth of the stand. The net radiation was measured at about 2 m above the canopy using a net radiometer (Ersking type). The storage terms of air, biomass and soil were estimated by the calorimetric method using temperature measurements in the respective compartments. Evaporation was estimated from hourly averages. Details about measurements, fetch requirements and calculations are given by Lindroth and Iritz.[19]

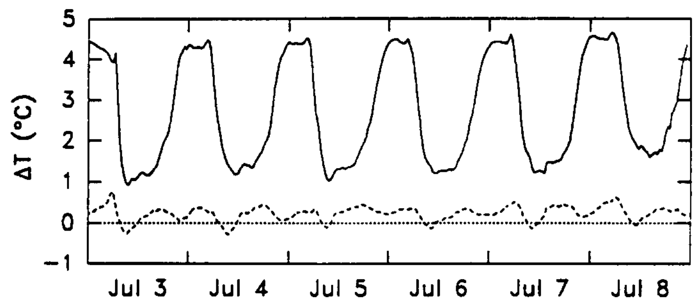

Fig. 2. Diurnal variation of temperature difference of the measuring point (solid line) and of the non-heated part of the stem (broken line), respectively. The differences were measured over a vertical distance of 150 mm within the trunk.

3. RESULTS

3.1. *Temperature gradients of heated and non-heated trunk*

During a 6 day period with good weather, the temperature difference over the measuring point of the THB gauge showed a consistent diurnal variation with values ranging between 1 and 4.5K (Fig. 2). The lowest difference normally occurred at noon, when sap flow usually is highest, and the largest difference occurred during night-time when sap flow is zero or close to zero. At the end of the night periods, small peaks in temperature difference were observed in both heated and non-heated thermocouples. This peak is associated with the commencement of sap flow. A short time after the sap begins to rise slowly in the stem in the morning, sap of lower temperature, probably originating from parts of the tree below ground, reaches the lower sensor of the pair. This will be seen as an increase of temperature difference. When this front of low-temperature sap has passed both sensors, the system stabilizes again with smooth temperature changes as a consequence. Another cause of this temperature peak is that during the night, when sap flow is zero, the maximum of the heated part of the stem is shifted downwards and when the sap begins to rise, this warmer sap reaches the upper sensor of the pair and thus will be seen as an increased temperature difference. In daytime, temperature peaks occur naturally because of changes in climate which effect transpiration rates, which in turn have an impact on sap flow.

The temperature difference the non-heated part of the trunk showed much smaller values compared with the difference over the measuring point (Fig. 2). The difference ranged between about 0.5 and −0.2K with maximum difference in the morning and in the afternoon and a minimum value at noon. Assuming that this natural gradient would also exist over the measuring point, the "true" temperature difference over the measuring point should, in principle, be calculated as the measured difference over the measuring point minus the difference over the non-heated part of the trunk. Based on this assumption, it can be shown that the corrections of estimated sap flow due to this effect would be typically in the order of 10–20%. This is, however, probably a maximal value, because in reality, the temperature regime of the measuring point is entirely different compared with that of the non-heated part of the trunk and there are several factors tending to decrease this effect. Natural temperature gradients, as measured on the additional non-gauged trees, were generally larger near the ground; this motivated installation of gauges at least higher than 1 m above the ground.

3.2. *Diurnal variations of sap flow and evaporation*

Three dry days with different weather were selected to show the diurnal variation of flow rates in relation to evaporation and meteorological conditions. Comparison between evaporation and sap flow is only relative because the sap flow data were not scaled to unit ground area. It was judged that the material was too limited to do such a scaling.

On 6 July, the sky was practically clear all day with a maximum global radiation of about 750 W m^{-2} at noon (Fig. 3). The air temperature was in the range 13–25°C and the vapour pressure deficit ranged between 0.4 and 2.0 kPa. The wind, as measured about 1 m above the canopy, was relatively low, about 1.5 m s^{-1} before noon and then it increased to about 2–2.5 m s^{-1} after noon with gusts reaching 3.5 m s^{-1}. Both the evaporation and the sap flow increased rapidly in the morning with the latter lagging about 1.5–2 h. In the afternoon there was

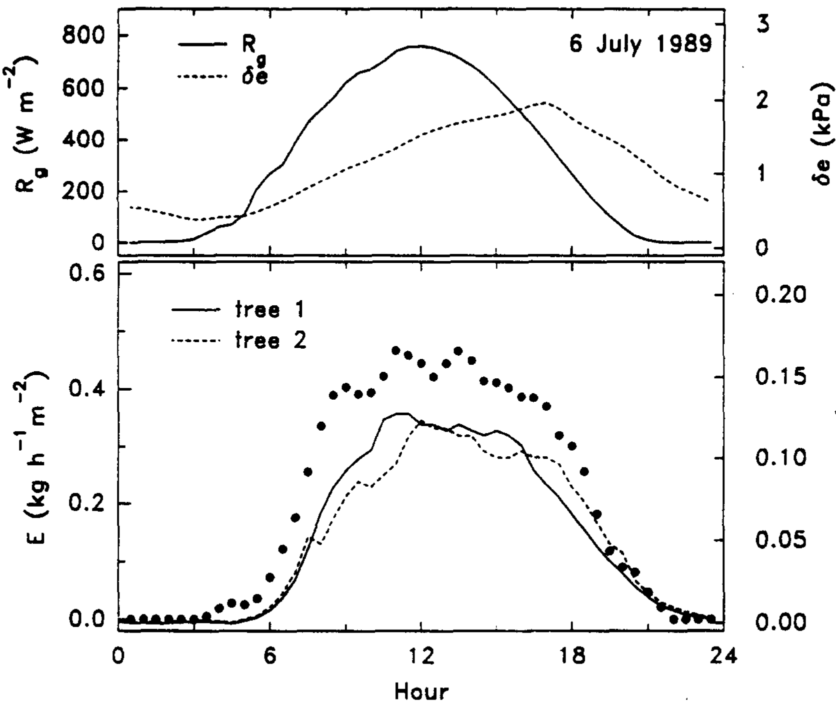

Fig. 3. Upper: diurnal course (30 min mean values) of global radiation, R_g, and vapour pressure deficit, δe on 6 July 1989. Lower: hourly values of evaporation (●), and sap flow.

practically no lag between evaporation and sap flow. The sap flow was similar for the two trees with peak values of 0.12–0.13 kg h^{-1}. In spite of the smooth variations of radiation and vapour pressure deficit over the day, there were some small short-term variations in evaporation and

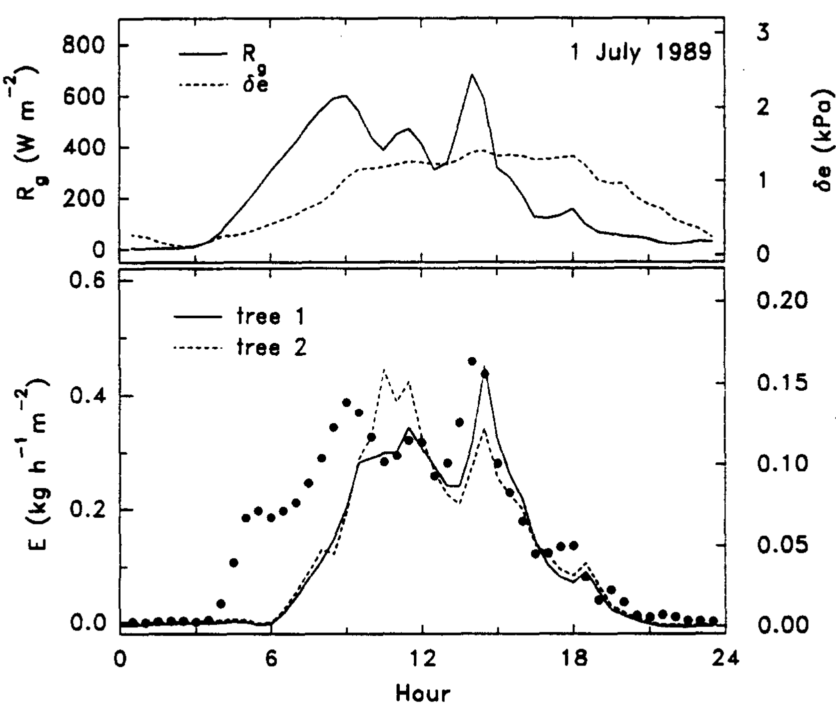

Fig. 4. Same as in Fig. 2 but for 1 July 1989.

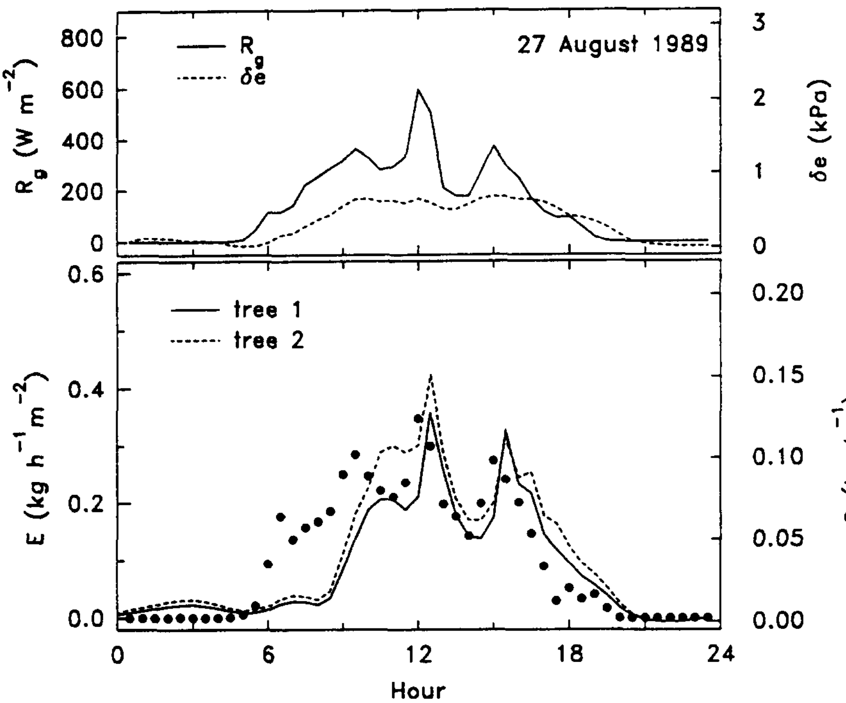

Fig. 5. Same as in Fig. 2 but for 27 August 1989.

sap flow which might be related to wind speed variations.

On 1 July (Fig. 4), the sky was clear until about 09:00 h and then clouds appeared which caused a considerable variation in radiation intensity throughout the rest of the day. A maximum global radiation of about 700 W m^{-2} was observed at about 14:30 h. Air temperature ranged between 7 and 19°C and vapour pressure deficit between 0 and 1.4 kPa. Wind speed was around 1.5 m s^{-1} during the daytime. The lag between evaporation and sap flow was similar to that during 6 July. The peaks in evaporation corresponded well to the peaks in global radiation. Considering the time lag between evaporation and sap flow, the corresponding peaks could also be found in the latter variable. The difference in sap flow between the two trees was relatively small. The maximum sap flow was about 0.16 kg h^{-1} for both trees. On 27 August (Fig. 5), the radiation intensity varied considerably all day but with three pronounced peaks. Temperature was relatively low, between 5 and 14°C. Wind speed was also low, about 1.5 m s^{-1} during daytime. The evaporation and sap flow compared similarly with the two previous example days with respect to time lag and response to radiation. Tree 2 had a slightly larger sap flow throughout the day. Maximum sap flow was 0.13 and 0.15 kg h^{-1} for trees 1 and 2, respectively.

A time lag between evaporation and sap flow in the morning is normal because there is always a pool of easily available water in a tree accessible for transpiration. The time lag of sap flow behind transpiration allows the size of this pool to be calculated. When using data on evaporation for calculation of this pool, the size is probably slightly overestimated because evaporation also includes evaporation from soil and plant surfaces. For the sample trees in this study, the pool was, thus, estimated to be about 0.2 kg of water. This corresponds to 1/4 of the mean daily transpiration during the studied period.

3.3. *Seasonal variation of sap flow and evaporation*

The daily totals of sap flow, evaporation and global radiation were estimated as the sum of the hourly values. The day to day variation in sap flow during the period from 29 June to 27 August was well correlated to evaporation, as well as to global radiation (Fig. 6). The sap flow, especially of tree 2, showed high correlation to the global radiation throughout the period. The high sap flows relative to the global radiation at the end of August are probably due to the fact that the maximum leaf area normally occurs at that time, i.e. as long as radiation is not limiting for transpiration, the trees can transpire more per

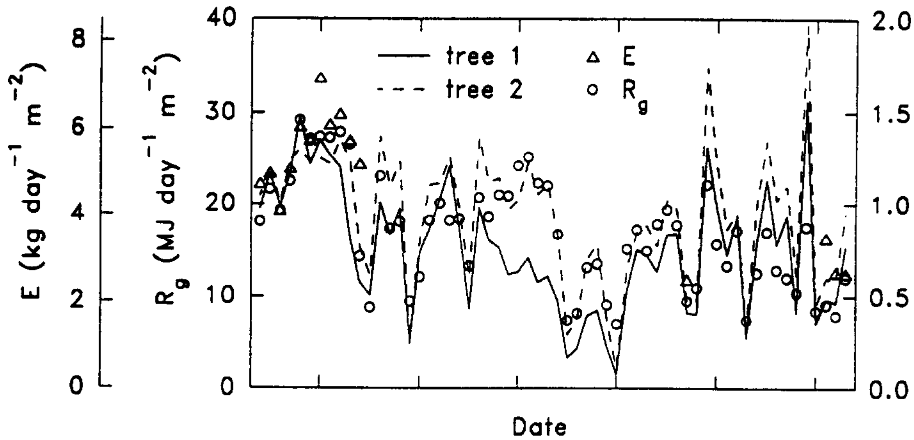

Fig. 6. Daily sums of evaporation, global radiation and sap flow during the period from 29 June to 27 August 1989.

unit of global radiation the more leaves there are. The linear regression between the sap flow of trees 1 and 2 gave an r^2 of 0.864 and a slope of 0.835 with tree 2 as the dependent variable (Fig. 7). The correlation between sap flow and evaporation was not as good as the previous correlation (Fig. 8). This is in accordance with expectations because evaporation includes transpiration and interception and soil evaporation. Dew formation during night-time is relatively common at this site and this will be seen in the evaporation measurements but not in the sap flow measurements. Soil evaporation was probably small because the leaf area index was high, between 6 and 8, during the study period.

4. DISCUSSION AND CONCLUSIONS

Disregarding the time lag between evaporation and sap flow, there was high correlation between the two flows when the canopy was dry. Both evaporation and sap flow responded in a similar way to variations in radiation intensity. The comparison between evaporation and sap flow could only be made in a relative manner because scaling of sap flow to unit ground area would be very uncertain because of the limited number of trees measured. A rough estimate can, however, be made as follows; the mean cross-sectional area of the two sap flow trees was 830 mm^2 and the total cross-sectional area per

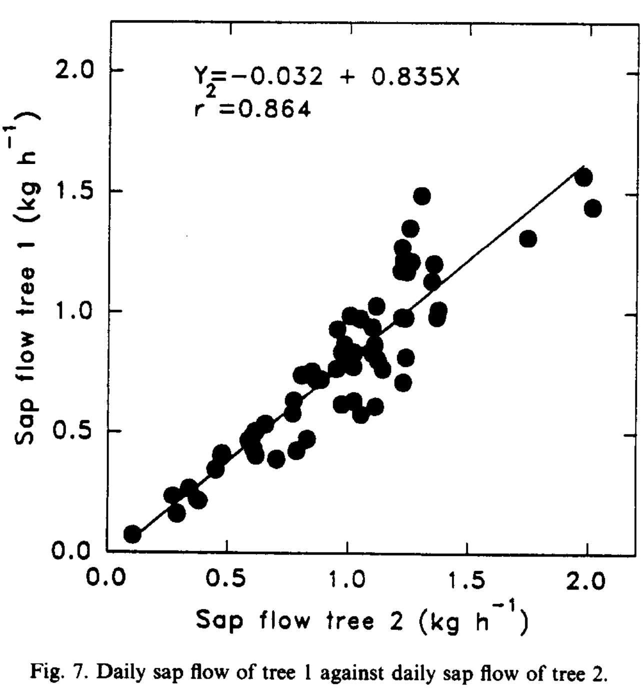

Fig. 7. Daily sap flow of tree 1 against daily sap flow of tree 2.

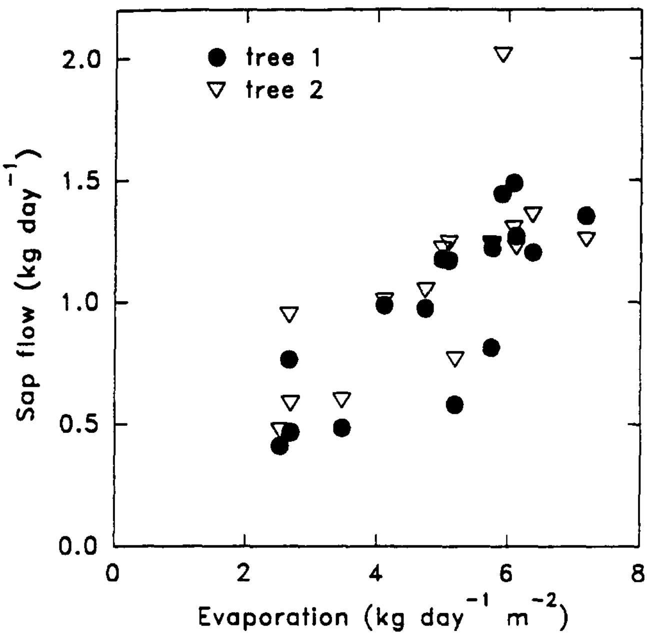

Fig. 8. Daily sap flow of the two trees against daily evaporation.

unit ground area of all living trees was 2520 mm^2. Now, assuming that transpiration is directly proportional to cross-sectional area, this would give a multiplicative factor of 3 for the measured trees which gives a transpiration per unit ground area of about 65% of the measured evaporation. Also considering the contribution of soil, dew and interception evaporation to the evaporation term, the agreement between the two measures must be considered as reasonably good.

The method of determining the conductive heat losses (Q_{fic}) used in this paper might also contribute to a small underestimation of sap flow during daytime. According to Ishida *et al.*,[20] both axial and radial conductive heat losses vary slightly with sap flow. The Q_{fic} estimated here was typically about 25% of sap flow at noon and, accordingly, a small error in this term does not affect the estimated sap flow to any large extent.

The value found for the pool of easily available water, expressed relative to the mean daily transpiration, is similar to corresponding values found for larger trees. Cermak *et al.*,[11] when comparing transpiration and sap flow, found values ranging between 14 and 22% of mean transpiration during the growing season for a large oak tree (60 cm in diameter at breast height, DBH) in a floodplain forest. Cienciala *et al.*[21] found a value of about 1/4 for young *Picea abies* trees (15–18 cm DBH) in the South of Sweden growing under non-limiting or partially limiting soil water conditions. Shulze *et al.*[22] found values of 1/4 and 1/7 for larger *Larix* and *Picea* trees, respectively (26 and 28 cm DBH, respectively). Thus, it seems that the relative size of the pool is relatively similar irrespective of tree size.

The installation of the sap flow measurement device was relatively simple. The flexible heating element, insulation and cover allowed the trees to grow freely without any visible interference. It is possible to apply external heating to small trees because the power requirements are still reasonable. However, there is one disadvantage with heating the whole circumference of a trunk segment; with this design it is not possible to install compensating thermocouples at the same height as that at which the thermocouples of the measuring point are located.

In larger trees, where only a segment of the trunk is heated, the compensating thermocouples can be placed at both sides of the heated part of the trunk and at the same height as that of the measuring point.[23] However, another way of reducing interference with ambient temperature gradients in the trunk would be to increase the temperature difference over the measuring point. This would require the power to be regulated because otherwise the temperature of the heated part of the trunk could reach harmful levels, especially at night when sap flow is low.

It was found that condensation could occur in the insulation which made it necessary to open the units now and then to let them dry. For long-term measurements, a regular check, say, once every two weeks, would be necessary. Otherwise, there were no problems with the devices.

Our conclusions from this study are that the stem tissue heat balance method with externally placed heater and internally sensed temperature is an appropriate method for estimation of sap flow and transpiration of individual small size *Salix* trees. For this type of short-rotation stand, a larger number of trees has to be measured in order to make possible an accurate estimation of values per unit ground area.

Acknowledgements—This research was sponsored by the Swedish Natural Research Council under contracts S-FO 09382-319 and G-GU 09382-318 and by the Swedish National Board for Industrial and Technical Development. Grants for the participation of Jan Cermak and Jiri Kucera from Czech Republic were given by the Royal Academy of Forest and Agricultural Sciences.

REFERENCES

1. G. Persson and A. Lindroth, Simulating evaporation from short-rotation forest. Variations within and between seasons. *J. Hydrol.* **156,** 21–45 (1994).
2. B. V. Huber and E. Schmidt, Eine Kompensationsmetode zur thermoelektrischen Messung langsammer Saftströme. *Ber. Dtsch. Bot Ges.* **55,** 514–529 (1937).
3. D. C. Marshall, Measurements of sap flow in conifers by heat transport, *Plant Physiol.* **33,** 385–396 (1958).
4. Y. Morikawa, Seasonal variation and diurnal changes in transpitration of *Chamaecyparus obtusa* on clear days, *J. Jpn For. Soc.* **53,** 219–221 (1971).
5. R. H. Swanson, Seasonal course of transpiration of Lodgepole pine and Engelman spruce. W. E. Sopper and H. W. Lull (eds), *Forest Hydrology. Proc. National Science Foundation Advanced Science Seminar*, Pennsylvania State University, University Park, PA., 29 August–10 September 1965, pp. 419–433. Pergamon Press, Oxford (1967).
6. R. H. Swanson, Numerical and experimental analyses of implanted-probe heat pulse velocity theory. Ph.D. Thesis, Edmonton, Alberta (1983).
7. C. R. Daum, A method for determining water transport in trees. *Ecology* **48,** 425–431 (1976).
8. J. Cermak and M. Deml, Method of water transport measurements in woody species, especially adult trees. Patent CSFR, Certification of Authorship No. 155622 (P.V. 5997-1972). (In Czech) (1972/74).
9. J. Kucera, J. Cermak and M. Penka, Improved thermal method of continual recording the transpiration flow rate dynamics. *Biologia Plantarum (Praha)* **19,** 413–420 (1977).
10. J. Cermak, M. Demi and M. Penka, A new method of sap flow rate determination in trees. *Biologia Plantarum (Praha)* **15,** 171–178 (1973).
11. J. Cermak, J. Ulehla, J. Kucera and M. Penka, Sap flow rate and transpiration dynamics in the full-grown oak (*Quercus robus* L.) in floodplain forest exposed to seasonal floods as related to potential evapotranspiration and tree dimensions. *Biologia Plantarum (Praha)* **24,** 446–460 (1982).
12. T. Sakuratani, A heat balance method for measuring water flux in the stem of intact plants. *J. Agr. Met.* **40,** 273–277 (1981).
13. M. Rychnovska, J. Cermak and P. Smid, Water output in a stand of Phragmites communis Trin. A comparison of three methods. *Acta Sci. Nat. (Brno)* **14**(2), 1–27 (1980).
14. J. Cermák, J. Jenik, J. Kucera and V. Zidek, Sap flow in a crack willow tree (*Salix fragilis* (L.)) in relation to diurnal changes of environment. *Oecologia (Berlin)* **64,** 145–151 (1984).
15. J. M. Baker and C. H. M. van Bavel, Measurement of mass flow of water in stem of herbaceous plants. *Plant, Cell Environ.* **10,** 777–782 (1987).
16. H. A. Schakel, R. S. Johnson, C. K. Medawar and C. J. Phene, Substantial errors in estimates of sap flow using the heat balance technique on woody stems under field conditions. *J. Am. Horticult. Soc. Horticult. Sci.* **117,** 351–356 (1992).
17. N. J. Rosenberg, B. L. Blad and S. B. Verma, *Microclimate. The Biological Environment.* Wiley, New York (1983).
18. A. Lindroth and S. Halldin, Gradient measurements with fixed and reversing temperature and humidity sensors above a forest. *Agric. For. Meteorol.* **53,** 81–103 (1990).
19. A. Lindroth and Z. Iritz, Surface energy budget dynamics of short-rotation willow forest. *Theor. Appl. Climatol.* **47,** 175–185 (1993).
20. T. Ishida, G. S. Campbell and C. Calissendorff, Improved heat balance method for determining sap flow rate. *Agricul. For. Meteorol.* **56,** 35–48 (1991).
21. E. Cienciala, H. Eckersten, A. Lindroth and J. E. Hällgren, Simulated and measured water uptake by *Picea abies* under non-limiting soil water conditions, *Agricul. For. Meteorol.* **71,** 147–164 (1994).
22. E. D. Schulze, J. Cermak, R. Matysek, M. Penka, R. Zimmermann, F. Vasicek, W. Gries and J. Kucera, Canopy transpiration and water fluxes in the xylem of the trunk of *Larix* and *Picea* trees—a comparison of xylem flow, porometer and cuvette measurements. *Oecologia (Berlin)* **66,** 475–483 (1985).
23. J. Cermak and J. Kucera, The compensation of natural temperature gradient at the measuring point during the sap flow rate determination in trees. *Biologia Plantarum (Praha)* **23,** 469–471 (1981).