IMPROVED SAP FLOW GAUGE FOR WOODY AND HERBACEOUS PLANTS

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Abstract

The internal wiring of an existing stem or trunk flow gauge was redesigned to obtain greater accuracy of the gauge itself, eliminate errors due to signal loss in connecting cables, and reduce the number of channels and of the computing required of the datalogger. Tests of the gauge conducted on bald cypress (*Taxodium distichum*) and *Ficus retusa* (L.) Nitida trees, in a greenhouse and in an urban backyard, and under well-watered and dry conditions gave daily sap mass flow rates that were within 5% of those obtained by direct weighing.

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Development of a stem flow gauge based on the heat balance method has made it possible to measure absolute, rather than relative, sap flow rates in stems of herbaceous plants (Sakuratani, 1981, 1984; Baker and Van Bavel, 1987) and in branches and trunks of woody plants (Steinberg et al., 1989). In all previous cases the gauge required five analog channels of a datalogger. We present an improved version that increases the accuracy of the principal signal, that requires one less datalogger channel, and that functions independently of the length of cable connecting gauge and datalogger.

Materials and Methods

All tests were made with a commercial version of the stem flow gauge (Model SG35A, Dynamax Inc., Houston, TX[1]), which had the necessary wiring modifications, as shown in Fig. 1. The gauge could be used on 32- to 45-mm diam.

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[1] Trade names are given only for the benefit of the reader and do not imply endorsement by the authors or the Texas Agric. Exp. Stn.

trunks, and featured a 25-mm-wide-foil heater that fitted tightly around the trunk. The gauge provided a constant heating power of 0.4 W, resulting in a rise in trunk temperature, at the position of the gauge, of approximately 1 to 6 °C, depending on ambient conditions and the sap flow rate. The thermocouple temperature sensors were pressed against the trunk by the flexible, insulating sleeve (Baker and Van Bavel, 1987), rather than slightly inserted into the wood (Steinberg et al., 1989).

Figure 1 shows how the two thermojunctions above the heater (A and B) and the pair below (HA and HB) are wired so as to result in two signals, *AH* and *BH* (H being the common ground). The quantity (*BH*−*AH*), which is generally positive, gives the vertical temperature gradient in the trunk away from the gauge from which the vertical conductive heat loss (Q_v) can be calculated, and (*AH*+*BH*)/2, also generally positive, gives the temperature gradient across the heater (*DELT*). The signal *DH* is the voltage applied to the heater, from which the heat input (Q_h) is found. The radial heat loss to the environment (Q_r) was found as $E \times K_{sh}$, in which E is the output of the thermopile around the heater, not shown in Fig. 1, and K_{sh} is the gauge factor. The equation for calculating the sap flow rate (F) has been derived in detail by Sakuratani (1981), Baker and Van Bavel (1987) and Steinberg et al. (1989) as

$$F = \frac{Q_h - Q_v - Q_r}{4.186 \times DELT} \text{ g s}^{-1}. \qquad [1]$$

The factor 4.186 is the specific heat of water in joules gram^{-1} kelvin^{-1}. For the thermal conductivity of the trunk (K_{st}), a value of 0.421 W m^{-1} K^{-1} was used in calculating Q_v, as in Steinberg et al. (1989). This value of K_{st} is lower than the 0.54 W m^{-1} K^{-1} used by Sakuratani (1981) due to the lower water content of woody stems. In any event, the vertical conductive heat loss is the smallest component of the trunk heat balance, and F will not be highly sensitive to changes in K_{st} (Steinberg et al., 1989). Equation [1] shows that the calculation of F is based upon partitioning of the steady state energy balance of the heated stem section. However, the value of K_{sh} is found empirically, by applying Eq. [1] when F is close to, or equal to, zero. In practice this has been done in situ by finding the lowest predawn value of K_{sh} (Steinberg et al., 1989).

The gauge was tested on the trunk of a *Ficus retusa* [L.] Nitida tree and of a bald cypress (*Taxodium distichum*) tree, at a point where the trunk diameter was 35 mm. Both trees were grown in 20-L containers and were weighed at least three times daily on an electronic balance with a resolution of 1 g in 30 kg. Plastic covered the soil surface so that the only water loss was due to transpiration. The following three tests were made: (i) *Ficus* in a greenhouse, well-watered, Calendar Day 167, 1988, (ii) *Ficus* in a greenhouse, severely drought stressed, Calendar Days 188 to 189, 1988, and (iii) bald cypress in an urban backyard, well-watered, Calendar Days 199 to 200, 1988.

We believe that the diurnal shrinkage and swelling of the trunk makes it desirable to install the gauge during the afternoon so as to insure a tight fit and good surface contact between thermojunctions and trunk surface. The latter was smoothed by removing all dead and loose bark and the sand-

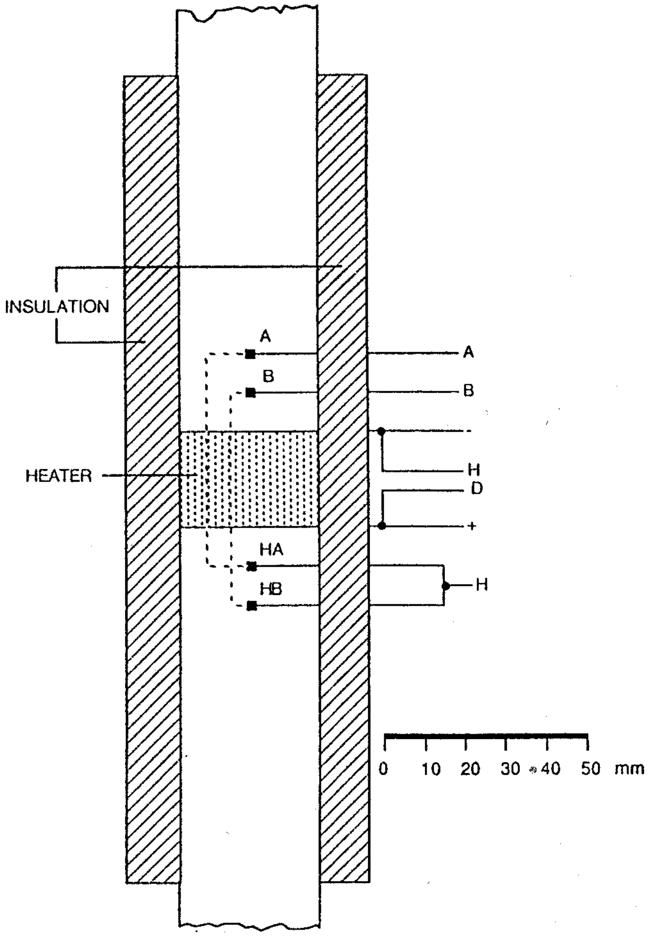

Fig. 1. Trunk section showing the heater (shaded), thermojunctions (■), and the foam insulation (hatched). Constantan wire is shown as ----, copper wire as ——. The voltage to the heater was measured at HD, where H was the common ground. The voltage supply is connected to + and − by a separate cable pair, making the heater a four-wire device.

Table 1. Gauge factor (K_{sh}), total transpiration measured by a balance, and total sap flow measured with a trunk flow gauge for a *Ficus* tree (Tests 1 and 2) and a bald cypress tree (Test 3).

Test no.	Calendar day	K_{sh}	Cumulative transpiration	Cumulative sap flow	Error†
		(W mV^{-1})	(kg d^{-1})		%
1	167	1.40	1.82	1.81	−1
2	188–189	1.46	0.73	0.72	−1
3	199–200	1.28	1.30	1.24	−5

† The error is the deviation of the gauge result from that obtained by direct weighing.

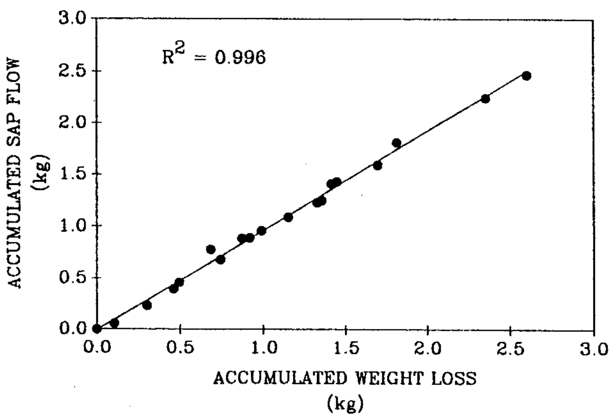

Fig. 2. A comparison of accumulated sap flow with accumulated transpiration or weight loss measured by a balance for Tests 1, 2, and 3. Accumulated weight loss was recorded at least three times per day.

ing of any protrusions, without injuring the living bark. Additional foam rubber insulation was attached to the trunk above and below the gauge to increase protection of the trunk from rapid changes in the ambient conditions after sunrise. In addition, a double layer of aluminum foil covered the entire gauge to shield it from short-wave radiation.

Gauge signals, measured with a 21X datalogger (Campbell Scientific, Logan, UT), were collected every 15 s and averaged over 5 min, prior to calculating the sap flow rate and other outputs. We also recorded the temperature of the trunk surface 80 mm above the center of the heater, the ambient air temperature, and the photon flux density (0.4–0.8 μm).

Results and Discussion

The accuracy of the gauge was evaluated by comparing both accumulated and 24-h totals of sap flow with transpiration, the latter being measured from dawn to dawn. These comparisons are shown in Fig. 2 and Table 1 for each of the three tests, together with the measured values of K_{sh}. Figure 3 gives a detailed record of the conditions and of the data obtained in Test 3, on the bald cypress tree.

Sap flow gauges based on the earlier five-channel

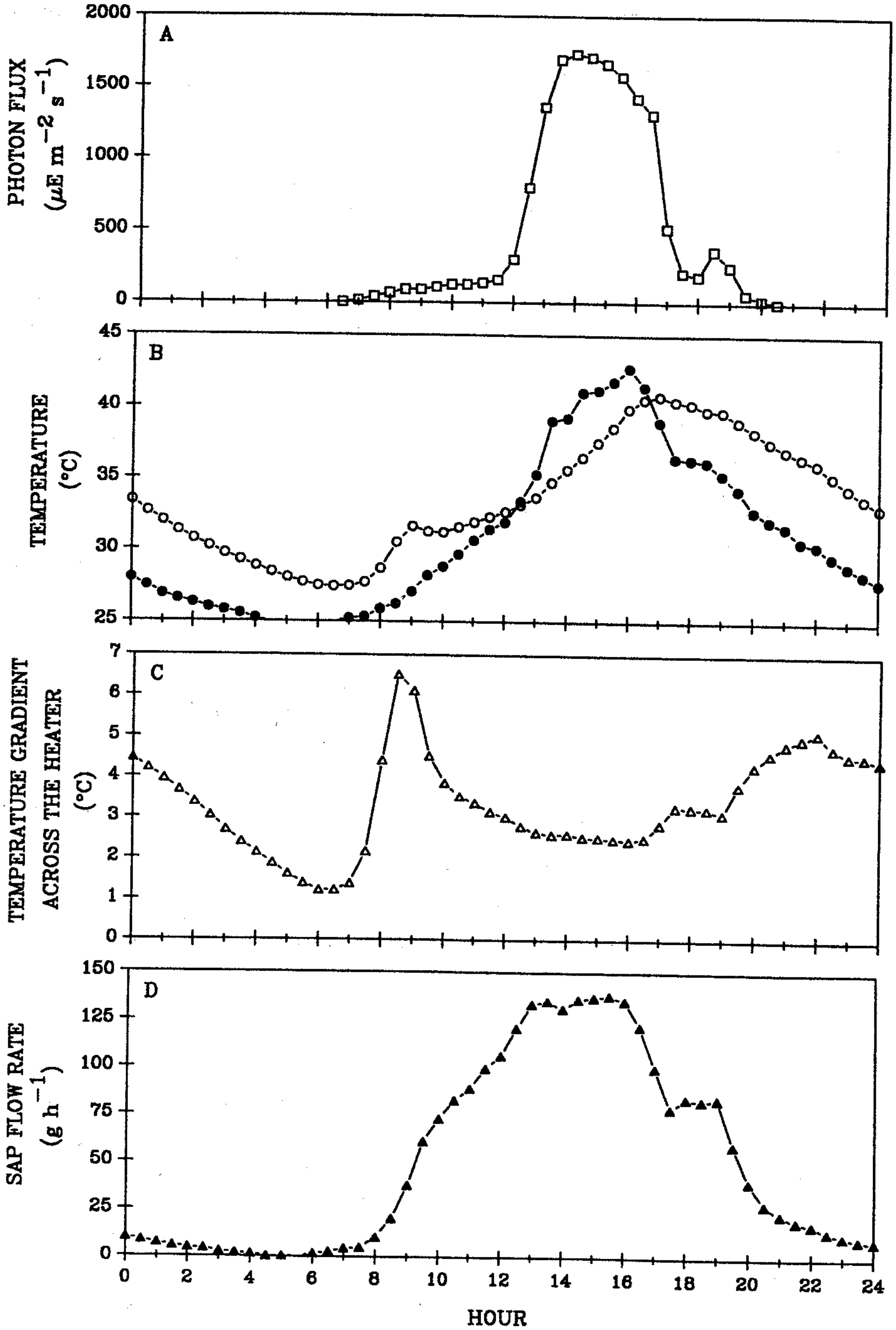

Fig. 3. A 30-min record of A) photon flux density, B) the air temperature in the environment (●) and the trunk temperature above the gauge heater (○), C) the temperature gradient across the heater (*DELT*), and D) the sap mass flow rate. The data were collected on Calendar Day 200, 1988 using a potted bald cypress tree in an urban backyard.

design have generally measured sap flow to within ±10% of water loss as measured by direct weighing (Sakuratani, 1981; Baker and Van Bavel, 1987; Steinberg et al., 1989). The data in Table 1 and Fig. 2 shows that the four-channel design enhances the accuracy of the gauge, as greater absolute agreement and as a higher correlation, both as compared with direct measurement. Since we used a short connecting cable, the improvement in our case is attributed principally to the fact that in the four-channel design the temperature gradient across the heater (*DELT*) is the average of two measurements, rather than a single reading. In addition, the temperature gradient is measured between the precise locations where the vertical fluxes are measured, in contrast to the earlier five-channel design (A. Kano, personal communication). Both improvements may be especially important for gauges of a small diameter, where the size limits the number of thermocouple temperature sensors to a single pair above and below the heater, and where the distance within each pair is relatively large to that between pairs. Two additional advantages of the four-channel design are that (i) the heating power is measured at the heater rather than at the power source, thus eliminating error due to power loss in connecting cables, and that (ii) less datalogger capacity is required.

Interestingly, neither the sudden upward movement, immediately after sunrise, of a mass of heated sap at the gauge location, nor the fact that the ambient temperature exceeded the trunk temperature during the better part of the afternoon, affected the accurate functioning of the gauge (Fig. 3). Table 1 shows typical daily water losses of trees in containers, but these water use rates may not be representative of trees in the open and with well-developed root systems. Therefore, it remains to be shown that the gauge is satisfactory under all conditions. Nevertheless, it is clear that the steady state or heat balance method for measuring sap flow rates is practical and capable of great precision. It requires no empirical calibration, but only a zero set before dawn, and provides a continuous record of the sap flow rate and its accumulation over time.

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