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# Measurement of Mass Flow Rate of Sap in *Ligustrum japonicum*

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*Abstract.* **The heat balance method of measuring mass flow of sap was tested on wax leaf ligustrum (*Ligustrum japonicum* Thunb.) to evaluate its usefulness for measuring water use in shrubs. Sap flow measurements were compared with gravimetric estimates of transpiration in growth chamber and field environments. Sap flow measurements in both environments were within 10% of transpiration, which compared favorably with results reported for herbaceous plants by other researchers. Sizable differences in sap flow, due mainly to differences in leaf area, were found among five plants tested in the field. When flow was expressed on a unit leaf-area basis, differences among plants were greatly reduced. Measurements under partly cloudy skies with fluctuating irradiance showed that changes in sap flow matched those occurring in irradiance.**

Little research has been done to quantify water use in landscape environments, due, in part, to the difficulty of the measurements. The heat balance method of Sakuratani (1981), and its modification by Baker and Van Bavel (1987), provide a way of measuring mass flow rate of water (sap) in the xylem, which may be useful for measuring water use in landscape plants.

With the heat balance method, a steady, known amount of heat is applied to a plant stem by a flexible heater that encircles the stem. The heater is enclosed in foam insulation that extends above and below it. Sap flow rate is determined using the heat balance equation: $F = (P - q_u - q_d - q_r)/[C(T_u - T_d)]$, where F ($g \cdot sec^{-1}$) is the sap flow rate; P [in watts (W)] is the power supplied to the stem; $q_u$ and $q_d$ (W) are the respective upward and downward fluxes of heat conducted in the stem tissue; $q_r$ (W) is the radial, outward flow of heat; $T_u$ and $T_d$ (K) are stem surface temperatures above and below the heater, respectively; and C ($J \cdot g^{-1} \cdot K^{-1}$) is the heat capacity of the sap. The gauge design assumes that the temperature of the xylem fluid can be estimated by temperature measurements on the stem surface. Thus, $FC[T_u - T_d]$ is an estimate of the heat carried by the xylem fluid. Detailed discussions of the heat balance method can be found in Sakuratani (1981, 1984), Baker and Van Bavel (1987), and Ham and Heilman (1990).

Sakuratani (1981) and Baker and Van Bavel (1987) demonstrated that sap flow rate in herbaceous plants could be estimated with the heat balance method to within 10% of gravimetric measurements of transpiration. Steinberg et al. (1989) used this method to measure daily water use of small trees to within 4% when flow rates were low to moderate. We tested this method on wax leaf ligustrum in the growth chamber and in the field to evaluate its accuracy and its potential for measuring water use of shrubs in landscape environments.

A stem-flow gauge (model SG10, Dynamax, Houston, Texas) of the Baker and Van Bavel design was attached to a ligustrum growing in a 11.3-liter pot containing fritted clay (Van Bavel et al., 1978). The gauge was attached to the main stem between the soil surface and the lowest branch, and was wrapped in aluminum foil to minimize the effects of radiation on the heat balance of the stem. The plant was 0.67 m tall and had a stem diameter of 0.01 m and a leaf area of 0.23 $m^2$.

The accuracy of the flow measurements was evaluated under well-watered conditions in a growth chamber and in the field. Different rates of transpiration were produced in the growth chamber over 12 hr by creating three levels of irradiance (115, 196, and 280 $W \cdot m^{-2}$) using a combination of incandescent and low-pressure sodium lamps. The air was maintained between 26 and 29C and the relative humidity ranged from 31% to 38%. The pot was wrapped in plastic to reduce soil evaporation and placed on an electronic balance (0.1-g resolution) controlled by a microcomputer. Transpiration was determined

Table 1. Morphological data on wax leaf ligustrum used in tests of stem-flow gauges.

| Plant | Leaf area ($m^2$) | Ht (m) | Stem diam (mm) |
|---|---|---|---|
| 1 | 0.28 | 0.79 | 11.0 |
| 2 | 0.30 | 0.74 | 10.2 |
| 3 | 0.27 | 0.71 | 10.7 |
| 4 | 0.32 | 0.74 | 11.0 |
| 5 | 0.23 | 0.67 | 10.0 |

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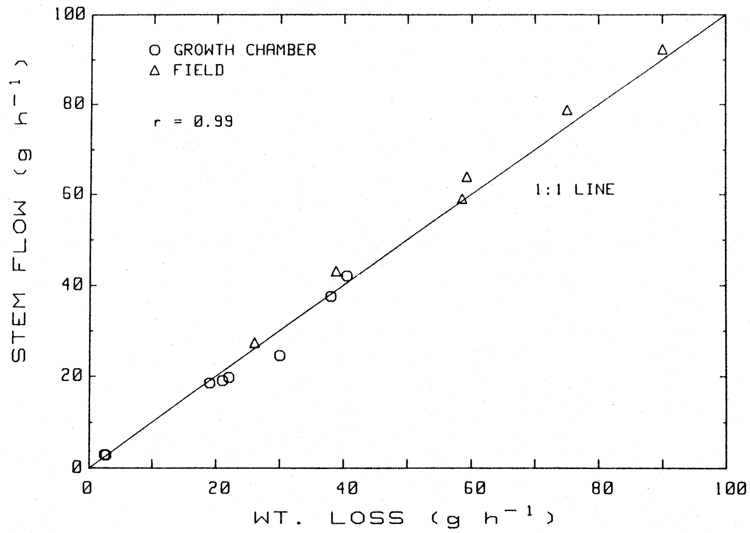


Fig. 1. Heat balance measurements of sap flow in wax leaf ligustrum in the growth chamber and in the field, compared with gravimetric measurements of weight loss.

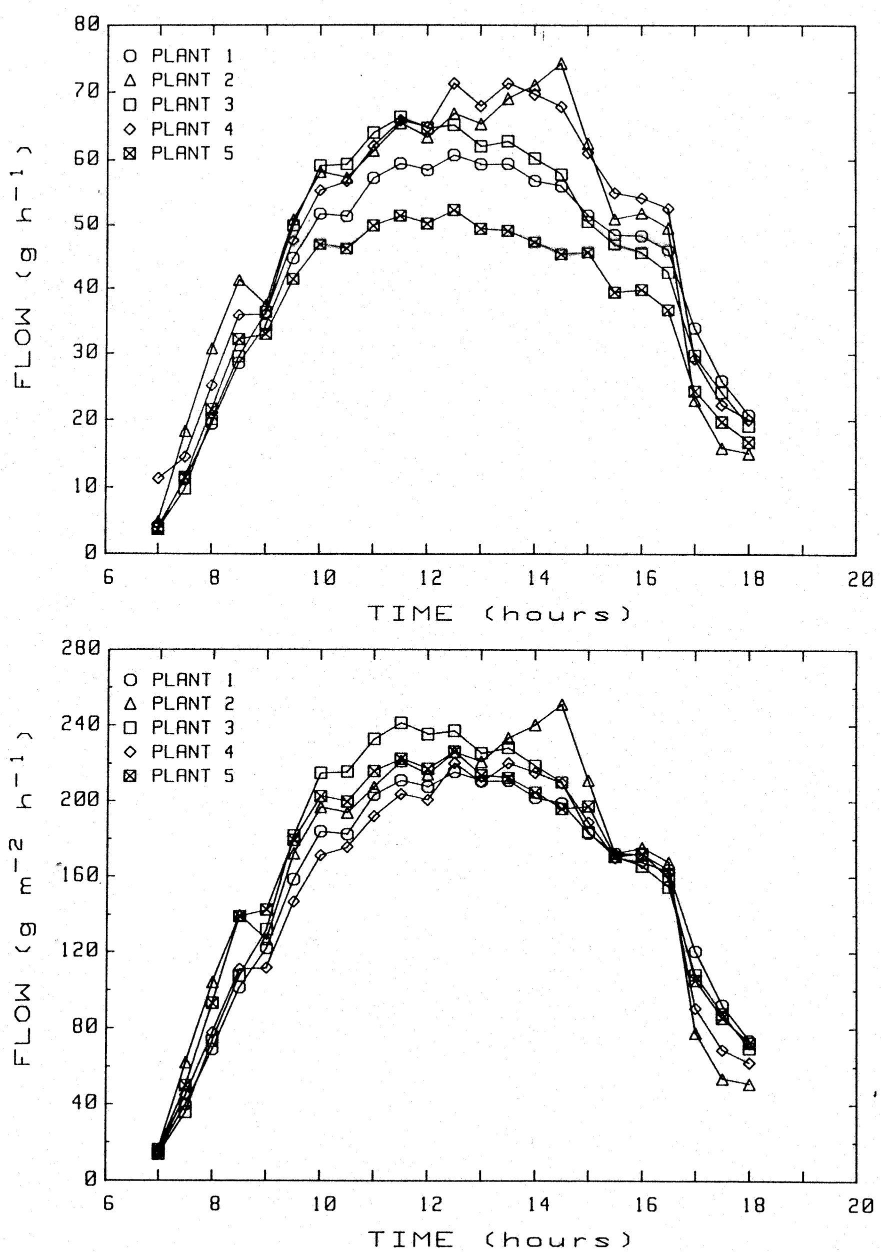


Fig. 2. (**Top**) Sap flow in five ligustrum placed side-by-side in the field. (**Bottom**) Sap flow per unit leaf area in the same plants as adapted from Heilman et al., 1989. (Daytime hours.)

by recording the weight loss at 15-min intervals. Signals from the stem-flow gauge were measured at 15-sec intervals using a model CR7 data logger (Campbell Scientific, Logan, Utah) and averaged over 15-min periods.

Field measurements were conducted at the Texas A&M Univ. Turfgrass Field Laboratory in College Station (lat. 30.4°N, long. 96.2°W). The same ligustrum as noted above was placed on the electronic balance that was read manually at 2-hr intervals to record the weight loss due to transpiration. Additional insulation was placed above and below the gauge to further reduce the effects of the environment on stem heat balance. Stem-flow gauge signals were measured at 15-sec intervals by the CR7 and averaged over 30-min intervals. Irradiance during the field measurements varied from 145 to 990 W·m$^{-2}$, while air temperature and relative humidity ranged from 23.9 to 33.6C and 37% to 87%, respectively. Wind speed varied from 1.7 to 4.4 m·sec$^{-1}$.

The highest transpiration rate measured gravimetrically in the growth chamber was 40 g·hr$^{-1}$, while in the field, transpiration reached 90 g·hr$^{-1}$. Sap flow rates measured by the stem gauge were generally within 10% of the gravimetric measurements of transpiration for both growth chamber and field environments (Fig. 1). These results are consistent with those reported by Sakuratani (1981) and Baker and Van Bavel (1987) for herbaceous plants. We found no evidence of lags between transpiration and sap flow caused by plant capacitance in the well-watered plant.

Additional tests were done in which sap flow rates were measured on five ligustrum placed side-by-side in the field. Gauge signals were measured at 15-sec intervals and averaged over 30-min intervals. Substantial differences in flow existed among the five plants (Fig. 2, top), due primarily to differences in leaf area (Table 1). Cumulative flow for plants 1 through 5 from 0700 to 1800 HR was 0.49, 0.55, 0.51, 0.56, and 0.43 kg, respectively. Mean cumulative flow was 0.51 kg and the coefficient of variation was 10%. When sap flow was expressed on a unit leaf-area basis, differences among plants were reduced (Fig. 2, bottom). Cumulative flow per unit leaf area for plants 1 through 5 was 1.75, 1.87, 1.87, 1.73, and 1.85 kg·m$^{-2}$, respectively. Mean cumulative flow was 1.81 kg·m$^{-2}$, with a coefficient of variation of 4%. Plant 5 was the same ligustrum used in growth chamber and field evaluations discussed previously.

To accurately measure water use in landscapes, heat balance gauges must quickly respond to large changes in transpiration produced by a dynamic urban environment. Plants must contend with irradiance fluctuations caused by partly cloudy skies and shading from adjacent plants and buildings, and with sensible heat and radiation generated in urban landscapes (Heilman et al., 1989). Baker and Van Bavel (1987), in measurements on cotton and sunflower with stem diameters of 10 mm, found that the heat balance method was capable of resolving oscil-

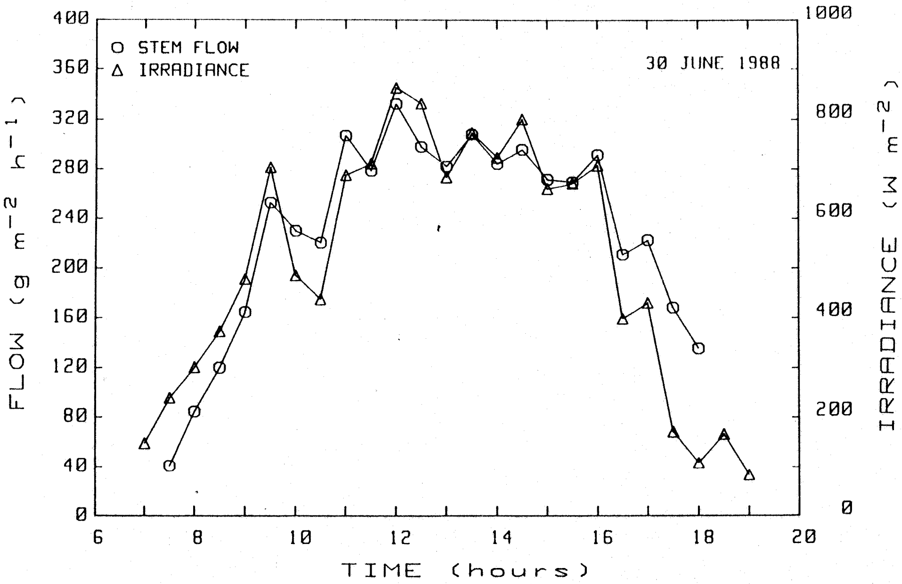


Fig. 3. Comparison of stem flow with irradiance under partly cloudy conditions. The correlation coefficient between stem flow and irradiance was 0.89.

lations in flow with periods as small as 5 to 10 min. Ham and Heilman (1990) found that sap flow measurements in sunflower with 16-mm stem diameters responded within 15 min to a change in transpiration from 35 to 200 $g \cdot hr^{-1}$. Steinberg et al. (1989) obtained a time constant of 20 min, the time required for a gauge to register 63.2% of the total response to a step change in transpiration, on a *Ficus benjamina* with a stem diameter of 45.2 mm.

Figure 3 shows field measurements of sap flow in ligustrum on a day in which skies were partly cloudy and irradiance fluctuated. Diurnal variations in flow matched those occurring in irradiance ($r$ = 0.89), which suggests that the heat balance method has the dynamic response necessary to react to changing environmental conditions.

Our study provides further evidence that the heat balance method is a useful tool for measuring plant water use. Results of our tests on ligustrum compare favorably with those obtained by Baker and Van Bavel (1987), Sakuratani (1981), and Steinberg et al. (1989) on herbaceous and woody plants. Our tests were limited to small shrubs with negligible capacitance. In large plants, where significant capacitance may exist, changes in sap flow may lag behind changes in transpiration and, therefore, will prevent analysis of water use over short periods. However, as shown by Steinberg et al. (1989), accurate measurements of daily water use can be obtained by integrating stem flow over 24 hr.

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