1 **Performance of Stem Flow Gauges in Greenhouse and Desert Environments.**

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Performance of Stem Flow Gauges in Greenhouse and Desert Environments.

Abstract. This study was conducted to evaluate the accuracy and general performance of a heat balance method for estimating transpirational sap flow through plant stems on two tree species in greenhouse and field experiments in Tucson, Arizona. Sap flow through 20-mm diameter stems of oak (*Quercus virginiana* 'Heritage') and mesquite (*Prosopis alba* 'Colorado') trees in containers was measured using stem flow gauges and a precision balance, from January to October, 1991. Overall gauge accuracy, and the effects of gauge location on the tree stem, gauge ventilation, gauge insulation, sheath conductance factor (Ksh) selection method, and increased numbers of vertical thermocouple pairs on gauge performance were evaluated. When many precautions were taken, gauge accuracy was generally within ± 10 percent error on a 24-hour basis in greenhouse experiments. In the field, gauge accuracy for 12 gauges was found to be far less reliable than in greenhouse experiments. In field experiments, gauge error was within ± 10 percent error only 37 percent of the time for oaks, and only 25 percent of the time for mesquites. Significant injury was sustained by many of the trees fitted with gauges, the timing and severity of which being different for the two species used. Results suggest that gauges are not as reliable in the field, especially in a desert environment, as they are in a greenhouse, and that stem flow gauge use in the field should be validated by lysimetric measurement

1 whenever possible. (Abstract ends.)

2 Recent developments in the design of stem flow gauges combined with
3 recent advances made in automatic datalogging technologies, show promise for
4 providing accurate, non-invasive, and continuous measurements of transpiration in
5 herbaceous, as well as woody plants (Steinberg et al., 1989; Baker and van Bavel,
6 1987). Recent studies indicate a ± 10 percent error range when transpiration is
7 considered on a 24-hour basis for experiments in a greenhouse or growth chamber
8 (Senock and Ham, 1991; Ham and Heilman, 1990; Steinberg et al., 1990;
9 Steinberg et al., 1989; Baker and van Bavel, 1987). Reports from field studies
10 have been mixed. While some report that stem flow gauges can provide
11 reasonable estimates of sap flow under field conditions (Lascano et al., 1991;
12 Dugas, 1990; Heilman and Ham, 1990), two recent papers report poor results.
13 Breshears et al. (1991) reported poor results in a field experiment in Los Alamos,
14 New Mexico, and Shackel et al. (1992) reported substantial errors in estimating
15 sap flow as a result of problems in measuring the vertical temperature differential
16 within the gauge, possibly due to effects of ambient conditions on gauge signals.
17 If ambient conditions affect gauge accuracy, then the large diurnal temperature
18 fluctuations found in desert environments should be an extreme testing
19 environment for stem flow gauges. We are aware of only one study in which
20 gauge performance was evaluated in a harsh desert environment. Devitt et al.
21 (1993) reported an average error of 18 percent between stem flow gauge and
22 lysimetry estimates for run-times between 14 to 73 hours during a field experiment

1 in Las Vegas, Nevada.

2 The objectives of this study were to evaluate the accuracy, operational
3 techniques, and general performance of stem flow gauges in greenhouse and field
4 experiments in a desert environment. Specifically, the effects on gauge
5 performance of gauge height on the tree stem, natural gauge ventilation, gauge
6 insulation, increased numbers of vertical thermocouple pairs, and method of Ksh
7 selection were evaluated.

8 Materials and Methods

9 Greenhouse experiments were conducted from January 17 to June 14,
10 1991 in University of Arizona campus greenhouses. Internal air temperature was
11 maintained between 16 and 38 degrees (C) by a heater and evaporative cooler.
12 Field experiments were conducted at the University of Arizona Campus
13 Agricultural Center (CAC) in Tucson, Arizona from July 2 to October 23, 1991.
14 Tucson (32.3 N, 111 W) lies at an elevation of approximately 700 m (2300 ft).
15 Weather during field experiments was characterized by sunny, hot, dry days,
16 interspersed with occasional thunderstorms and warm nights. Average daily
17 maximum temperatures were fairly constant throughout the experiment at
18 approximately 37 °C. The daily minimum temperatures ranged from 13 °C to
19 28 °C.

20 Oak and mesquite trees used in the experiments were approximately 20 mm
21 (3/4 inch) caliper (i.e. diameter at 0.5 m above the ground surface). For

1 greenhouse experiments, all trees were between 150-200 cm in height, and
2 planted in 57 L containers. Containers were wrapped in clear plastic to minimize
3 soil evaporation. For field experiments, oaks were between 150-200 cm in height,
4 and mesquites approximately 300 cm in height. Oaks were planted in 57 L
5 containers and mesquites in 19 L containers until July 9, 1991, when they were
6 transplanted to 57 L containers. Empty 57 L pots were buried up to their top
7 edges to provide sleeves for the potted trees, which allowed the potted soil
8 surface to be at approximately the same level as the surrounding ground surface.
9 A block of wood was placed in the bottom of each sleeve to ensure that the
10 containers did not get stuck in the sleeve. Details of the irrigation and weighing
11 schedules during the field tests are described in Levitt et al. ((1995) in press).

12 Two types of experiments were conducted in this study, greenhouse and
13 field experiments. Additionally, two types of tests were conducted: single-tree
14 tests were conducted in greenhouse and field experiments, where a tree was
15 monitored continuously by both a stem flow gauge and a balance; and multiple-
16 tree tests were conducted in the field only, where tree weight was determined at
17 24-hour intervals using the balance, and compared to cumulative stem flow
18 determined from continuously monitored gauges on each tree. Tree weights were
19 determined with a precision electronic balance (A&D Engineering; model EP-60KB)
20 with a maximum capacity of 60 kg and resolution of 1 g. For single-tree tests, a
21 datalogger (Campbell Scientific, Logan, Utah; model 21X) was used to collect
22 continuous balance data. Balance data was collected every 15 seconds and

1 converted into 30-minute averages by the datalogger. Data were periodically
2 downloaded to cassette tapes and transferred to a desktop computer for analysis.
3 Balance readings were taken manually for periodic field measurements.

4 Continuous stem flow measurements were made using stem flow gauges
5 (Dynamax, Houston, Texas; model SGB-19). All gauge installations and operations
6 were per the recommendations provided by the manufacturer (Dynamax Inc.,
7 1990). For single-tree tests, a gauge was wired to the datalogger which collected
8 data every 15 seconds and stored 30-minute averages. A datalogger program
9 supplied by Dynamax was used to sample the four differential voltage signals (Ch,
10 Ah, Bh, and Vin), and calculate stem flow using standard input parameters. These
11 consisted of stem area (cm^2), a conversion constant consisting of the product of
12 the temperature gradient and gauge area (equal to 2.0 m mV C^{-1} for model SGB-
13 19), stem thermal conductivity ($0.42 \text{ W m}^{-1} \text{ K}^{-1}$ for woody species (Steinberg
14 et al., 1989)), gauge electrical resistance (Ω), and the Ksh setting (W mV^{-1}). Night
15 flow filters were disabled so that night flow rates could be observed.

16 Water use of multiple trees was determined on a daily basis by weighing
17 each containerized tree on the balance. The weighing procedure consisted of
18 lifting a potted tree from its sleeve, placing it on a wheelbarrow, moving it to the
19 balance located in the center of the field site where it was weighed, then returning
20 it to its sleeve. For comparison, daily tree water use was determined from
21 continuous stem flow gauge measurements. Gauges from 12 trees were wired to
22 two 4 x 16 relay multiplexers (Campbell Scientific, Logan, Utah) (6 gauges per

1 multiplexer, maximum capacity 8 gauges), which were wired to a datalogger.

2 Data was collected once every minute from each gauge and stored as 30-minute
3 averages. A datalogger program was written to collect only the four differential
4 voltage signals in order to conserve datalogger memory. The datalogger was
5 connected to a cassette tape recorder for automatic downloading, and periodically,
6 the tape was downloaded to a desktop computer where stem flow calculations
7 were made from the voltage data.

8 The theory behind the heat balance method has been widely discussed
9 (Baker and van Bavel, 1987; Steinberg et al., 1989), however the overall stem
10 flow equation is presented here.

$$\text{Flow} = \frac{(\text{Pin} - Q_v - Q_r)}{(C_p \cdot dT)} \quad (1)$$

11 where Flow is stem flow rate ($\text{g H}_2\text{O s}^{-1}$), Pin is the power input to the heater (W),
12 Q_v is the net vertical heat flux (W), Q_r is the net radial heat flux (W), C_p is the
13 heat capacity of xylem sap ($\text{J g}^{-1} \text{K}^{-1}$) (a constant), and dT is the temperature
14 gradient from the junction above the heater to the junction below the heater,
15 measured by averaging the Ah and Bh signals and then converting them to
16 degrees C. Pin is calculated using Ohms's law ($V_{in}^2/\text{Resistance}$). Q_v is calculated
17 using the vertical voltage difference (Bh-Ah), stem thermal conductivity, stem
18 cross-sectional area, the distance between paired thermocouples, and a
19 thermocouple temperature conversion constant. Q_r is calculated using the voltage
20 difference between the inside and center of the gauge insulation as measured by a

thermopile array (Ch), and an input sheath conductance value.

Overall gauge accuracy was evaluated from gauge error, calculated by

$$\text{Percent Error} = \left(\frac{\text{GAUGE} - \text{BAL}}{\text{BAL}} \right) \times 100 \quad (2)$$

where GAUGE = 24-hour cumulative flow (L d^{-1}) measured by the gauge, and BAL = 24-hour cumulative flow (L d^{-1}) measured by the balance. Attempts were made during the course of the study to improve overall gauge accuracy by modifying the gauges. Analysis of the various components of the stem flow equation under both greenhouse and field conditions indicate that the vertical heat flux (Q_v) is usually only 2-4 percent of the input power during the day, and thus a small contribution to the calculation of stem flow. The radial heat flux component (Q_r), however, usually accounts for 30 to 40 percent of the input power during the day.

Therefore, improvement of Q_r measurements could increase overall gauge accuracy much more than improvement of Q_v measurements.

Two types of modifications were tested in an attempt to improve the measurement of Q_r . In one, an additional layer of pipe insulation (1.27 cm thick) was wrapped around each gauge to act as a buffer against the effects of the changing surrounding environment. This was done to all gauges from September 8 to October 23, 1991. In the second modification, extra layers of pipe insulation were added to one gauge in an attempt to substantially reduce the Q_r component. Valancogne and Nasr (1989) reported that Q_r could be neglected with a well-insulated gauge design, although van Bavel (1991) was critical of their findings.

1 Such a design would reduce datalogger input channels from 4 to 3, and eliminate
2 the zero-set procedure (Ksh) entirely. We attempted to repeat the findings of
3 Valancogne and Nasr (1989). A 10-cm thick layer of pipe insulation was added to
4 one gauge, and four power levels were tested to see if the ratio of Q_r to input
5 power (Q_r/P_{in}) was ever less than 0.01 (assumed to be insignificant).

6 The last remaining term of the stem flow equation that can be modified is
7 the vertical stem temperature differential (dT). The dT was the stem flow
8 component believed to be most affected by a poorly fitting gauge, due to its
9 limited contact with a tree stem. The dT is calculated by measuring the
10 temperature difference between two pairs of thermocouples, one pair above the
11 heater, and one pair below, where both pairs are on one side of the gauge. An
12 attempt was made to improve the measurement of dT by installing two additional
13 thermocouple pairs spaced radially around the stem, separated by about 120° .
14 The value of dT was then calculated as the average of the three thermocouple
15 pairs, rather than based on only one pair, a technique sometimes used on larger
16 diameter stem flow gauges. From October 4 to 24, 1991, gauge accuracy was
17 tested on a mesquite in which three pairs of thermocouples were used in the
18 calculation of dT . Two additional pairs were the most that could be easily installed
19 due to space constraints. One of these pairs was the original thermocouple pair
20 that was built into the gauge, and two other pairs were added to the gauge. The
21 objective was to end up with three pairs of thermocouples located radially around
22 the tree stem. Due to design and space constraints, the thermocouples were

1 placed at approximately 90° intervals, leaving about 1/4 of the gauge
2 circumference unmeasured.

3 Five methods of Ksh selection were evaluated, including three described by
4 Steinberg et al. (1989). These were: 1) minimum pre-dawn Ksh value (KSHmin);
5 2) average night Ksh value (KSHavg); 3) best-fit Ksh value (KSHfit) in which Ksh is
6 manually adjusted until gauge night flow is equal to balance night flow; 4)
7 minimum Ksh value obtained when the entire tree canopy was enclosed in plastic
8 (KSHbag); and 5) the Ksh value measured on a excised test tree trunk (KSHex).

9 The KSHmin method causes minimum night flow rate to equal zero at the time that
10 KSHmin was found. The KSHavg method causes the average night flow rate to be
11 zero, so KSHavg yields the same effect as using night flow filters. The KSHfit
12 method causes the average night flow rate to match the average actual night flow
13 rate, but requires a balance. The KSHbag and KSHex methods assume that the
14 tree transpiration rate is zero, thus yielding an accurate zero set. Evaluation of the
15 five Ksh methods was accomplished using single-tree tests.

16 Results and Discussion

17 Gauge height above the soil surface was found to be critical to gauge
18 accuracy in greenhouse, but not field experiments. With two gauges on one
19 mesquite tree at 50 cm and 15 cm above the soil, the upper gauge yielded
20 reasonable results (14 percent error) while the lower gauge seriously over-
21 estimated sap flow at 58 percent error. A comparison of the radial heat flux

1 components (Q_r) of both gauges revealed that the upper gauge had a positive flux
2 during the day, indicating that it was losing heat, and the lower gauge had a
3 negative flux during the day, indicating that it was gaining heat.

4 Gauge ventilation also was critical to gauge accuracy in greenhouse
5 experiments. In one experiment on an oak, a gauge was located 50 cm above the
6 soil and completely shielded from radiation and air movement, and the resulting
7 error was 34 percent. Q_r remained positive during this test. Lack of ventilation
8 may have also caused the overestimates of stem flow found for gauges located
9 less than 50 cm above the soil surface. When a gauge was located less than
10 50 cm above the soil surface, ventilation may have been substantially reduced due
11 to the fact that the gauge and its shade cover were below the height of the
12 greenhouse benches, and most of the air movement within the greenhouse was
13 above bench level. In general, a gauge located close to the soil surface, and a
14 gauge shielded from air movement yielded consistent overestimates of stem flow.

15 Two possible explanations are offered for these observations. One is lack of
16 convective cooling of the gauge by air movement, the other due to existence of
17 temperature gradients near the soil surface caused by soil heating, or a
18 combination of the two. We estimate, based on equation 1, that a 30 percent
19 overestimate of stem flow on a 24-hour basis (typical for a low-placed gauge)
20 would result from a 22 percent underestimate of measured dT . At a maximum
21 daytime flow rate, this is equivalent to a $0.3\text{ }^{\circ}\text{C}$ underestimate of dT , which
22 corresponds to a temperature gradient of $-6\text{ }^{\circ}\text{C m}^{-1}$ up the stem trunk. To test for

1 the existence of vertical stem temperature gradients near the container, a series of
2 thermocouples were placed against the stem trunk at 5, 10, 15, and 20 cm above
3 the soil surface in several greenhouse experiments. Results typically indicated a
4 temperature gradient of approximately $-0.5\text{ }^{\circ}\text{C}$ per 10 cm, or approximately $-5\text{ }^{\circ}\text{C}$
5 m^{-1} , which could explain the observed overestimation of stem flow. Installation of
6 a gauge 50 cm above the soil, with a horizontal cardboard shade placed directly
7 above the gauge, improved gauge accuracy to within ± 10 percent of balance
8 measurements in greenhouse experiments. Presumably, either there was adequate
9 gauge ventilation in this configuration or the temperature gradient up the stem
10 trunk was minimized at 50 cm above the soil surface, thus keeping any error in
11 stem flow to a minimum. There was no correlation between gauge height and
12 error in field experiments. This was believed to be the result of either: greater
13 wind speed in the field than in the greenhouse, and thus greater convective
14 cooling potential; the tree pots being placed below the ground surface, and kept
15 relatively cool by insulation, thus resulting in a reduced temperature gradient up
16 the trunk stem; or a combination of these factors.

17 The average gauge error of 24-hour tests found during all multiple-tree
18 gauge testing was -3 percent error. The range in errors, however, was very large.
19 The standard deviation from the mean of gauge error was 21 percent for the oaks
20 and 30 percent for the mesquites, indicating that only 68 percent of all 24-hour
21 comparisons between gauge and balance data were within 21 and 30 percent
22 error for the oaks and mesquites, respectively. Ninety-five and a half percent of all

1 comparisons (2 standard deviations) were within 43 and 61 percent error for the
2 oaks and mesquites, respectively. Only 37 percent of oak, and 25 percent of
3 mesquite comparisons with the balance were within ± 10 percent error. Percent
4 error for each day of the experiment is plotted in Figure 1 for oak and Figure 2 for
5 mesquite. Comparisons of gauge versus balance data are plotted in Figure 3 for
6 oak and Figure 4 for mesquite. Lines representing 2 standard deviations from the
7 mean of gauge error are plotted on Figures 3 and 4.

8 The large range in gauge error in the field was different from that found in
9 the greenhouse. In the greenhouse, gauge error was consistently positive in sign,
10 whereas errors were both positive and negative in the field. Very large errors in
11 Q_r (at least ± 50 percent) could explain the gauge errors found in the field.
12 However, there is no valid reason to suspect such large errors in the estimation of
13 Q_r . The estimation of dT appears to be the most likely culprit for the large range
14 in gauge error found in the field due to the limited contact of the two
15 thermocouple pairs on a tree stem, and the fact that only thermocouple pairs are
16 used where a thermopile array is used to estimate Q_r . A gauge installed such that
17 one or more of the dT thermocouples are not in good contact with the tree stem
18 could easily yield inaccurate estimates of dT . This point is supported by the fact
19 that one oak with a particularly smooth trunk surface was used in most of the
20 greenhouse experiments, where results were good (within ± 10 percent error) if
21 gauge height and ventilation were adequate. This same oak was moved to the
22 field where gauge error was always within ± 20 percent, which was considered

1 to be good accuracy relative to most of the gauges in the field. It would appear,
2 therefore, that the contact of the vertical thermocouple pairs was better for a tree
3 with a smooth surface than a rough surface, thus yielding better gauge accuracy.

4 Heat storage was also considered as a reason for the large range in gauge
5 error during the experiment, particularly for the consistently positive errors found
6 during greenhouse tests. Heat storage was found to be significant during very low
7 flow rates (1 to 4 g h⁻¹) by van Bavel and McInnes (1992). However, all daytime
8 flow rates were far above 20 g h⁻¹, the rate at which heat storage becomes
9 insignificant (van Bavel and McInnes, 1992). In addition, there was no evidence
10 of hysteretic flow, which would be expected if heat storage was significant.

11 If total gauge accuracy is considered for several gauges over several days,
12 gauge errors are often compensating, yielding less error than individual gauges for
13 one day. For example, total water measured by five gauges over five days was
14 compared to total water measured by the balance, and the total error was less
15 than one percent. This indicates that gauge estimations of water use by a crop
16 using several gauges over several days is considerably more accurate than gauge
17 estimations of water use for an individual plant for one day.

18 Results of the gauge modification to improve Q_r measurement with one thin
19 layer of insulation indicate that there was no significant difference in overall gauge
20 accuracy when comparisons were made between tests with and without the extra
21 insulation layer. Therefore, the addition of such a layer only resulted in increased
22 labor in the field installing the extra insulation. Results of the attempt to eliminate

1 Qr contradict the work of Valancogne and Nasr (1989) and support van Bavel
2 (1991), in that Qr was never found to be negligible. At four different power
3 levels, Qr was a significant component of the heat balance. However, at power
4 levels less than or equal to 0.16 W, Qr was found to be negative, indicating that
5 the gauge was being heated by its surroundings, and at power levels greater than
6 or equal to 0.27 W, Qr was found to be positive, indicating that the gauge was
7 giving off heat to the surroundings. It would appear, therefore, that at power
8 levels between 0.16 and 0.27 W, gauge temperature was in equilibrium with the
9 surroundings and Qr would approach zero. These results indicate that a new
10 gauge could be designed such that Qr is kept constant at 0 W by continual
11 adjustment of the input power level. This would eliminate the need for the Ksh
12 setting, but would still require the radial thermopile array. Gauge accuracy
13 throughout this test period was within ± 10 percent error on a 24-hour basis,
14 which indicates that it is possible for a gauge to have a negative radial heat flux
15 and maintain good accuracy in the field.

16 Results of gauge testing with additional thermocouple pairs indicate that the
17 best results were consistently obtained from the original thermocouple pair in the
18 gauge. Rotating the tree and adjusting the gauge appeared to have some effect
19 on the response of the original gauge dT, but very little, if any, on the two
20 additional dT sensors. In only 9 out of the 17 days did the average of 3 dT values
21 yield better accuracy than using the original gauge dT value alone. This indicates
22 that the addition of two more thermocouple pairs did not improve overall gauge

1 accuracy. However, the overall good accuracy obtained using only the original
2 gauge dT sensor in this test was not typical of the results found for gauge
3 accuracy in the field. It is believed that given the more typical gauge performance
4 found in the field, additional thermocouple pairs would increase gauge accuracy.

5 If night flow filters are not used, then the accuracy of the Ksh setting is
6 most important at night. The KSHfit method, therefore, provided the most
7 accurate value of Ksh because the gauge accuracy at night is adjusted (fitted) to
8 zero. This does not mean that 24-hour gauge accuracy was best using KSHfit. If
9 gauge error was positive over a 24-hour period, then the KSHavg method tended
10 to yield the smallest error, because this method causes underestimates of night
11 flow. If gauge error was negative over a 24-hour period, then the KSHmin method
12 tended to yield the smallest error, because this method causes overestimates of
13 night flow. The KSHbag method was found to be less accurate than KSHmin,
14 KSHavg, and KSHfit. This method generally yielded under-estimates of 24-hour
15 flow. This was believed to be the result of continued low transpiration rates at
16 night, even though the balance measured no water loss, which caused the zero-
17 set (Ksh) to be erroneously high and thus caused underestimations of flow.
18 KSHbag also required an air-tight bag to be placed over the tree every time Ksh
19 was to be updated, and every time the gauge was removed because Ksh values
20 were found to change significantly every time the gauge was removed and
21 reinstalled, rendering the previous Ksh value obsolete. The KSHex method was
22 found to be the least accurate of the Ksh methods. In fact, Ksh values found

1 using the KSHex method usually caused night flow, and 24-hour flow to be in
2 error by several hundred percent. This was due at least in part, to the fact that
3 the Ksh value changes significantly every time the gauge is reinstalled or adjusted.
4 The results of gauge accuracy using the five Ksh methods were compared for two
5 different tests, one in the greenhouse and one in the field, and summarized in
6 Table 1. These days were selected because the gauge error was low relative to
7 most of the gauge tests. Since KSHfit can only be used if balance data is
8 available, then the next best method depends on the sign of the error. If gauge
9 error is positive, KSHavg yields the least error, and if negative, then KSHmin yields
10 the least error. However, the differences in gauge accuracy among KSHmin,
11 KSHavg, and KSHfit methods were statistically insignificant as long as flow rates
12 were above 20 g h^{-1} . At flow rates less than this, there were significant ($p =$
13 0.01) differences among these Ksh methods, with the best method depending on
14 the sign of the 24-hour gauge error. These same results were found to be valid
15 when night flow filters set night flow rates to zero.

16 Perhaps the most important result of this study was significant tree damage.
17 By September 8, 1991, all of the mesquites were either dying or dead, and
18 showed definite signs of trunk constriction where the gauge had been located.
19 The first six mesquites fitted with gauges died within four weeks of gauge
20 installation, and each replacement mesquite also died within four weeks of gauge
21 installation. None of the oaks died or showed any sign of gauge damage at this
22 time. Since it was unclear if the original mesquites were damaged and ultimately

1 killed by the gauges, the silicone grease used under the gauges, the heat applied
2 to the gauges, or some combination of these factors, an experiment was set up
3 using a new supply of mesquites. Five possible combinations of gauge installation
4 were tested using six mesquites. These various combinations are summarized in
5 Table 2. This mesquite damage test was conducted from October 4 to 12, 1991.
6 By three weeks after the end of the test, five of the six mesquites used in the
7 damage test showed various signs of damage from the gauges. The only tree that
8 appeared undamaged was the tree which only had silicone grease applied to its
9 trunk. All other combinations of gauge, power, and grease resulted in damage to
10 the mesquites. It was unclear at this time if the mesquite damage was due to the
11 youth of these trees and thin outer bark, or if there was some inherent problem
12 using gauges on mesquites in general. In a separate study in Las Vegas, Nevada,
13 mesquites were reported to also be damaged by stem flow gauges (Devitt et al.,
14 1993).

15 After 11 months, damage became apparent to oaks that had been fitted
16 with stem flow gauges. Trees appeared to have constricted growth where the
17 gauges had been located, and one oak was dead above the constricted area. All
18 trees had numerous new shoots growing below where the gauge had been
19 installed. These results indicate that even fairly limited use of the gauges, with
20 frequent adjustment to account of tree growth, can damage or kill mesquites and
21 oaks.

22 In summary, overall accuracy of the gauges was not as good as that

1 reported in most of the literature. Errors less than ± 10 percent were achieved in a
2 greenhouse only after taking special precautions. Results in the field were
3 considerably worse. Only 37 percent of oak, and 25 percent of mesquite
4 comparisons with the balance were within ± 10 percent error, which is
5 substantially greater than the ± 10 percent error reported in previous work and by
6 the manufacturer. Numerous field experiments suggest that gauges are not as
7 reliable in the field, especially in desert environments, as they are in a greenhouse.
8 Hence, it is recommended that stem flow gauges used in the field need to be
9 validated by lysimetric measurement when possible, and preferably be done on a
10 number of plants in order to average out errors. In addition, significant injury was
11 sustained by many of the trees fitted with gauges, which may be a far more
12 substantial problem than poor gauge accuracy.

Literature Cited

- Baker, J.M. and C.H.M. van Bavel. 1987. Measurement of mass flow of water in the stems of herbaceous plants. *Plant Cell Envir.* 10: 777-782.
- Breshears, D.D., S.R. Tarbox and F.J. Barnes. 1991. Water use in Colorado Pinyon Pine and Oneseed Juniper. Presented at 1991 ASA/SSSA/CSA Annual Meeting, Denver, Colorado.
- Devitt, D.A., M. Berkowitz, P.J. Schulte, and R.L. Morris. 1993. Estimating transpiration for three woody ornamental tree species using stem-flow gauges and lysimetry. *HortScience* 28(4): 320-322.
- Dugas, W.A. 1990. Comparative measurement of stem flow and transpiration in cotton. *Theoretical and Applied Climatology* 42: 215-221.
- Dynamax Inc. 1990. Dynagage Installation and Operation Manual. DYNAMAX Inc., Houston, Texas.
- Ham, J.M. and J.L. Heilman. 1990. Dynamics of a heat balance stem flow gauge during high flow. *Agronomy Journal* 82:147-152.
- Heilman, J.L. and J.M. Ham. 1990. Measurement of mass flow rate of sap in *Ligustrum japonicum*. *HortScience* 25: 465-467.
- Lascano, R.J., R.L. Baumhardt, and W.N. Lipe. 1991. Stem gauge measurements of sap flow in grapevines. *Symposium on Sap Flow Measurements. Collected Summaries of Papers at the 83rd Annual Meeting of the American Society of Agronomy.* pp. 13-14.
- Levitt, D.G., J.R. Simpson, and J.L. Tipton. 1995 (in press). Water use of two

1 landscape tree species in Tucson, Arizona. J. Amer. Soc. Hort. Sci.

2 Senock, R.S. and J.M. Ham. 1991. Heat balance sap flow measurements in small
3 diameter stems. Symposium on Sap Flow Measurements. Collected
4 Summaries of Papers at the 83rd Annual Meeting of the American Society
5 of Agronomy. pp. 21-22.

6 Shackel, K.A., R.S. Johnson, C.K. Medawar, and C.J. Phene. 1992. Substantial
7 errors in estimates of sap flow using the heat balance technique on woody
8 stems under field conditions. J. Amer. Soc. Hort. Sci. 117(2): 351-356.

9 Steinberg, S.L., C.H.M. van Bavel, and M.J. McFarland. 1989. A gauge to
10 measure mass flow rate of sap in stems and trunks of woody plants. J.
11 Amer. Soc. Hort. Sci. 114(3): 466-472.

12 Steinberg, S.L., C.H.M. van Bavel, and M.J. McFarland. 1990. Improved sap flow
13 gauge for woody and herbaceous plants. Agronomy Journal 82: 851-854.

14 Valancogne, C. and Z. Nasr. 1989. Measuring sap flow in the stem of small trees
15 by a heat balance method. Hort. Sci. 24(2): 383-385.

16 van Bavel, C.H.M. 1991. Radial and vertical heat conduction in stem and trunk
17 flow gauges. HortScience 26: 73.

18 van Bavel, C.H.M and K.J. McInnes. 1992. Significance of heat storage in the use
19 of stem flow gauges. Symposium on Sap Flow Measurements. Collected
20 Summaries of Papers at the 83rd Annual Meeting of the American Society
21 of Agronomy. pp. 29-30.

Tables

Table 1. Effects of different Ksh selection methods on gauge error (percent).

Greenhouse Experiment: May 19 - 20, 1991

Method	Ksh Value (W/mV)	24-hr Error (Night Flow Filter Off):	24-hour Error (Night Flow Filter On):	Night Error
KSHmin	1.064	7.8	7.2	57
KSHavg	1.077	6.0	5.5	-37
KSHfit	1.072	6.7	6.0	0
KSHbag	1.411	-42	-18	< -100
KSHex	2.820	< -100	< -100	< -100

Field Experiment: July 26 - 27, 1991

KSHmin	1.174	3.8	3.5	-48
KSHavg	1.183	3.1	2.9	-73
KSHfit	1.157	5.2	4.7	0.0
KSHbag	1.411	-15	2.0	< -100
KSHex	2.820	< -100	-59	< -100

Table 2. Summary of various combinations of gauge installation for mesquite damage experiment.

Tree	Gauge	Power	Grease
1	Yes	No	Yes
2	Yes	Yes	Yes
3*	Yes	Yes	Yes
4	Yes	Yes	No
5	Yes	No	No
6	No	No	Yes

* denotes a replicate

Figure Captions

- Figure 1. A 24-hour gauge error for all field tests on oak. Six oak were used from July 3 to August 1, 1991, and 8 oak were used from September 8 to October 23, 1991. Different symbols denote different trees.
- Figure 2. A 24-hour gauge error for all field tests on mesquite. Six mesquite were used from July 3 to August 1, 1991, and 4 mesquite were used from September 8 to October 23, 1991. Different symbols denote different trees.
- Figure 3. A 24-hour gauge error for all field tests on oak. The lines represent 2 standard deviations from the mean of gauge error. $r^2 = 0.73$.
- Figure 4. A 24-hour gauge error for all field tests on mesquite. The lines represent 2 standard deviations from the mean of gauge error. $r^2 = 0.80$.

Fig. 2

Fig. 1