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Subject Category: Soil-Plant-Water Relationships

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

whenever possible. (Abstract ends.)

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

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

Materials and Methods

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

Oak and mesquite trees used in the experiments were approximately 20 mm (3/4 inch) caliper (i.e. diameter at 0.5 m above the ground surface). For greenhouse experiments, all trees were between 150-200 cm in height, and planted in 57 L containers. Containers were wrapped in clear plastic to minimize soil evaporation. For field experiments, oaks were between 150-200 cm in height, and mesquites approximately 300 cm in height. Oaks were planted in 57 L containers and mesquites in 19 L containers until July 9, 1991, when they were transplanted to 57 L containers. Empty 57 L pots were buried up to their top edges to provide sleeves for the potted trees, which allowed the potted soil surface to be at approximately the same level as the surrounding ground surface. A block of wood was placed in the bottom of each sleeve to ensure that the containers did not get stuck in the sleeve. Details of the irrigation and weighing schedules during the field tests are described in Levitt et al. ((1995) in press).

Two types of experiments were conducted in this study, greenhouse and field experiments. Additionally, two types of tests were conducted: single-tree tests were conducted in greenhouse and field experiments, where a tree was monitored continuously by both a stem flow gauge and a balance; and multiple-tree tests were conducted in the field only, where tree weight was determined at 24-hour intervals using the balance, and compared to cumulative stem flow determined from continuously monitored gauges on each tree. Tree weights were determined with a precision electronic balance (A&D Engineering; model EP-60KB) with a maximum capacity of 60 kg and resolution of 1 g. For single-tree tests, a datalogger (Campbell Scientific, Logan, Utah; model 21X) was used to collect continuous balance data. Balance data was collected every 15 seconds and converted into 30-minute averages by the datalogger. Data were periodically downloaded to cassette tapes and transferred to a desktop computer for analysis. Balance readings were taken manually for periodic field measurements.

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

Water use of multiple trees was determined on a daily basis by weighing each containerized tree on the balance. The weighing procedure consisted of lifting a potted tree from its sleeve, placing it on a wheelbarrow, moving it to the balance located in the center of the field site where it was weighed, then returning it to its sleeve. For comparison, daily tree water use was determined from continuous stem flow gauge measurements. Gauges from 12 trees were wired to two 4 x 16 relay multiplexers (Campbell Scientific, Logan, Utah) (6 gauges per multiplexer, maximum capacity 8 gauges), which were wired to a datalogger. Data was collected once every minute from each gauge and stored as 30-minute averages. A datalogger program was written to collect only the four differential voltage signals in order to conserve datalogger memory. The datalogger was connected to a cassette tape recorder for automatic downloading, and periodically, the tape was downloaded to a desktop computer where stem flow calculations were made from the voltage data.

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

$$Flow = \frac{(Pin - Qv - Qr)}{(Cp * dT)} \qquad (1)$$

where Flow is stem flow rate (g H_2O s^{-1}), Pin is the power input to the heater (W), Qv is the net vertical heat flux (W), Qr is the net radial heat flux (W), Cp is the heat capacity of xylem sap (J g^{-1} K^{-1}) (a constant), and dT is the temperature gradient from the junction above the heater to the junction below the heater, measured by averaging the Ah and Bh signals and then converting them to degrees C. Pin is calculated using Ohms's law (Vin^2/Resistance). Qv is calculated using the vertical voltage difference (Bh-Ah), stem thermal conductivity, stem cross-sectional area, the distance between paired thermocouples, and a thermocouple temperature conversion constant. Qr is calculated using the voltage 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

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

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 (Qv) 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 (Qr), however, usually accounts for 30 to 40 percent of the input power during the day. Therefore, improvement of Qr measurements could increase overall gauge accuracy much more than improvement of Qv measurements.

Two types of modifications were tested in an attempt to improve the measurement of Qr. 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 Qr component. Valancogne and Nasr (1989) reported that Qr could be neglected with a well-insulated gauge design, although van Bavel (1991) was critical of their findings.

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

The last remaining term of the stem flow equation that can be modified is the vertical stem temperature differential (dT). The dT was the stem flow component believed to be most affected by a poorly fitting gauge, due to its limited contact with a tree stem. The dT is calculated by measuring the temperature difference between two pairs of thermocouples, one pair above the heater, and one pair below, where both pairs are on one side of the gauge. An attempt was made to improve the measurement of dT by installing two additional thermocouple pairs spaced radially around the stem, separated by about 120°. The value of dT was then calculated as the average of the three thermocouple pairs, rather than based on only one pair, a technique sometimes used on larger diameter stem flow gauges. From October 4 to 24, 1991, gauge accuracy was tested on a mesquite in which three pairs of thermocouples were used in the calculation of dT. Two additional pairs were the most that could be easily installed due to space constraints. One of these pairs was the original thermocouple pair that was built into the gauge, and two other pairs were added to the gauge. The objective was to end up with three pairs of thermocouples located radially around the tree stem. Due to design and space constraints, the thermocouples were placed at approximately 90° intervals, leaving about 1/4 of the gauge circumference unmeasured.

Five methods of Ksh selection were evaluated, including three described by Steinberg et al. (1989). These were: 1) minimum pre-dawn Ksh value (KSHmin); 2) average night Ksh value (KSHavg); 3) best-fit Ksh value (KSHfit) in which Ksh is manually adjusted until gauge night flow is equal to balance night flow; 4) minimum Ksh value obtained when the entire tree canopy was enclosed in plastic (KSHbag); and 5) the Ksh value measured on a excised test tree trunk (KSHex). The KSHmin method causes minimum night flow rate to equal zero at the time that KSHmin was found. The KSHavg method causes the average night flow rate to be zero, so KSHavg yields the same effect as using night flow filters. The KSHfit method causes the average night flow rate to match the average actual night flow rate, but requires a balance. The KSHbag and KSHex methods assume that the tree transpiration rate is zero, thus yielding an accurate zero set. Evaluation of the five Ksh methods was accomplished using single-tree tests.

Results and Discussion

Gauge height above the soil surface was found to be critical to gauge accuracy in greenhouse, but not field experiments. With two gauges on one mesquite tree at 50 cm and 15 cm above the soil, the upper gauge yielded reasonable results (14 percent error) while the lower gauge seriously over-estimated sap flow at 58 percent error. A comparison of the radial heat flux components (Qr) of both gauges revealed that the upper gauge had a positive flux during the day, indicating that it was losing heat, and the lower gauge had a negative flux during the day, indicating that it was gaining heat.

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

Two possible explanations are offered for these observations. One is lack of convective cooling of the gauge by air movement, the other due to existence of temperature gradients near the soil surface caused by soil heating, or a combination of the two. We estimate, based on equation 1, that a 30 percent overestimate of stem flow on a 24-hour basis (typical for a low-placed gauge) would result from a 22 percent underestimate of measured dT. At a maximum daytime flow rate, this is equivalent to a 0.3 °C underestimate of dT, which corresponds to a temperature gradient of -6 °C m^{-1} up the stem trunk. To test for the existence of vertical stem temperature gradients near the container, a series of thermocouples were placed against the stem trunk at 5, 10, 15, and 20 cm above the soil surface in several greenhouse experiments. Results typically indicated a temperature gradient of approximately -0.5 °C per 10 cm, or approximately -5 °C m^{-1} , which could explain the observed overestimation of stem flow. Installation of a gauge 50 cm above the soil, with a horizontal cardboard shade placed directly above the gauge, improved gauge accuracy to within ± 10 percent of balance measurements in greenhouse experiments. Presumably, either there was adequate gauge ventilation in this configuration or the temperature gradient up the stem trunk was minimized at 50 cm above the soil surface, thus keeping any error in stem flow to a minimum. There was no correlation between gauge height and error in field experiments. This was believed to be the result of either: greater wind speed in the field than in the greenhouse, and thus greater convective cooling potential; the tree pots being placed below the ground surface, and kept relatively cool by insulation, thus resulting in a reduced temperature gradient up the trunk stem; or a combination of these factors.

The average gauge error of 24-hour tests found during all multiple-tree gauge testing was -3 percent error. The range in errors, however, was very large. The standard deviation from the mean of gauge error was 21 percent for the oaks and 30 percent for the mesquites, indicating that only 68 percent of all 24-hour comparisons between gauge and balance data were within 21 and 30 percent error for the oaks and mesquites, respectively. Ninety-five and a half percent of all comparisons (2 standard deviations) were within 43 and 61 percent error for the oaks and mesquites, respectively. Only 37 percent of oak, and 25 percent of mesquite comparisons with the balance were within ± 10 percent error. Percent error for each day of the experiment is plotted in Figure 1 for oak and Figure 2 for mesquite. Comparisons of gauge versus balance data are plotted in Figure 3 for oak and Figure 4 for mesquite. Lines representing 2 standard deviations from the mean of gauge error are plotted on Figures 3 and 4.

The large range in gauge error in the field was different from that found in the greenhouse. In the greenhouse, gauge error was consistently positive in sign, whereas errors were both positive and negative in the field. Very large errors in Qr (at least ± 50 percent) could explain the gauge errors found in the field. However, there is no valid reason to suspect such large errors in the estimation of Qr. The estimation of dT appears to be the most likely culprit for the large range in gauge error found in the field due to the limited contact of the two thermocouple pairs on a tree stem, and the fact that only thermocouple pairs are used where a thermopile array is used to estimate Qr. A gauge installed such that one or more of the dT thermocouples are not in good contact with the tree stem could easily yield inaccurate estimates of dT. This point is supported by the fact that one oak with a particularly smooth trunk surface was used in most of the greenhouse experiments, where results were good (within ± 10 percent error) if gauge height and ventilation were adequate. This same oak was moved to the field where gauge error was always within ± 20 percent, which was considered to be good accuracy relative to most of the gauges in the field. It would appear, therefore, that the contact of the vertical thermocouple pairs was better for a tree with a smooth surface than a rough surface, thus yielding better gauge accuracy.

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

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

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

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

Results of gauge testing with additional thermocouple pairs indicate that the best results were consistently obtained from the original thermocouple pair in the gauge. Rotating the tree and adjusting the gauge appeared to have some effect on the response of the original gauge dT, but very little, if any, on the two additional dT sensors. In only 9 out of the 17 days did the average of 3 dT values yield better accuracy than using the original gauge dT value alone. This indicates that the addition of two more thermocouple pairs did not improve overall gauge accuracy. However, the overall good accuracy obtained using only the original gauge dT sensor in this test was not typical of the results found for gauge accuracy in the field. It is believed that given the more typical gauge performance found in the field, additional thermocouple pairs would increase gauge accuracy.

If night flow filters are not used, then the accuracy of the Ksh setting is most important at night. The KSHfit method, therefore, provided the most accurate value of Ksh because the gauge accuracy at night is adjusted (fitted) to zero. This does not mean that 24-hour gauge accuracy was best using KSHfit. If gauge error was positive over a 24-hour period, then the KSHavg method tended to yield the smallest error, because this method causes underestimates of night flow. If gauge error was negative over a 24-hour period, then the KSHmin method tended to yield the smallest error, because this method causes overestimates of night flow. The KSHbag method was found to be less accurate than KSHmin, KSHavg, and KSHfit. This method generally yielded under-estimates of 24-hour flow. This was believed to be the result of continued low transpiration rates at night, even though the balance measured no water loss, which caused the zero-set (Ksh) to be erroneously high and thus caused underestimations of flow. KSHbag also required an air-tight bag to be placed over the tree every time Ksh was to be updated, and every time the gauge was removed because Ksh values were found to change significantly every time the gauge was removed and reinstalled, rendering the previous Ksh value obsolete. The KSHex method was found to be the least accurate of the Ksh methods. In fact, Ksh values found using the KSHex method usually caused night flow, and 24-hour flow to be in error by several hundred percent. This was due at least in part, to the fact that the Ksh value changes significantly every time the gauge is reinstalled or adjusted. The results of gauge accuracy using the five Ksh methods were compared for two different tests, one in the greenhouse and one in the field, and summarized in Table 1. These days were selected because the gauge error was low relative to most of the gauge tests. Since KSHfit can only be used if balance data is available, then the next best method depends on the sign of the error. If gauge error is positive, KSHavg yields the least error, and if negative, then KSHmin yields the least error. However, the differences in gauge accuracy among KSHmin, KSHavg, and KSHfit methods were statistically insignificant as long as flow rates were above 20 g h^{-1}. At flow rates less than this, there were significant ($p = 0.01$) differences among these Ksh methods, with the best method depending on the sign of the 24-hour gauge error. These same results were found to be valid when night flow filters set night flow rates to zero.

Perhaps the most important result of this study was significant tree damage. By September 8, 1991, all of the mesquites were either dying or dead, and showed definite signs of trunk constriction where the gauge had been located. The first six mesquites fitted with gauges died within four weeks of gauge installation, and each replacement mesquite also died within four weeks of gauge installation. None of the oaks died or showed any sign of gauge damage at this time. Since it was unclear if the original mesquites were damaged and ultimately killed by the gauges, the silicone grease used under the gauges, the heat applied to the gauges, or some combination of these factors, an experiment was set up using a new supply of mesquites. Five possible combinations of gauge installation were tested using six mesquites. These various combinations are summarized in Table 2. This mesquite damage test was conducted from October 4 to 12, 1991. By three weeks after the end of the test, five of the six mesquites used in the damage test showed various signs of damage from the gauges. The only tree that appeared undamaged was the tree which only had silicone grease applied to its trunk. All other combinations of gauge, power, and grease resulted in damage to the mesquites. It was unclear at this time if the mesquite damage was due to the youth of these trees and thin outer bark, or if there was some inherent problem using gauges on mesquites in general. In a separate study in Las Vegas, Nevada, mesquites were reported to also be damaged by stem flow gauges (Devitt et al., 1993).

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

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

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Tables

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

Method	Ksh Value (W/mV)	24-hr Error (Night Flow Filter Off):	24-hour Error (Night Flow Filter On):	Night Error
Greenhouse Experiment: May 19 - 20, 1991				
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

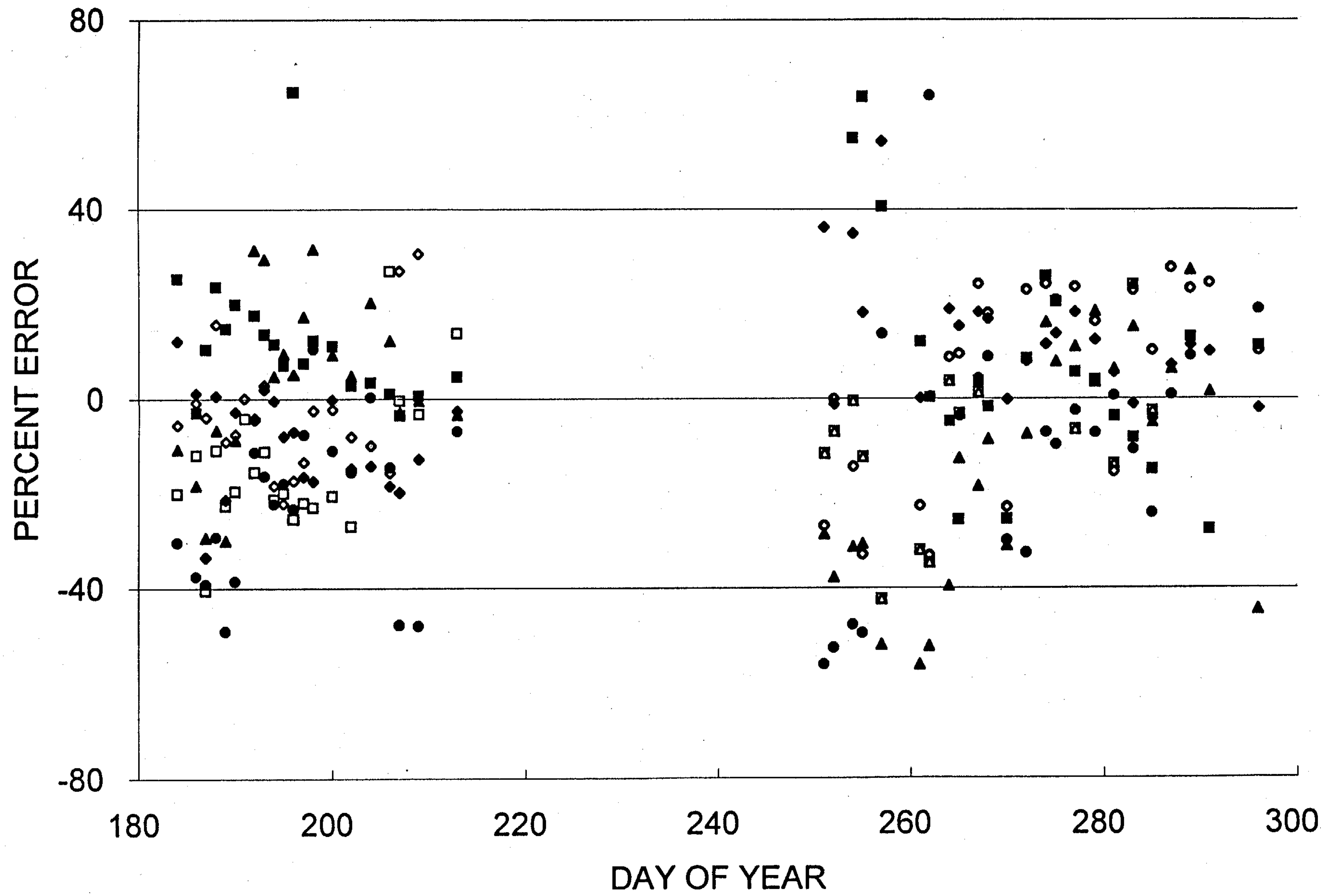
Figure 1. A 24-hour gauge error for all field tests on oak. Six oak were used from July 3 to August 1, 1991, and 8 oak were used from September 8 to October 23, 1991. Different symbols denote different trees.

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. $r^2 = 0.73$.

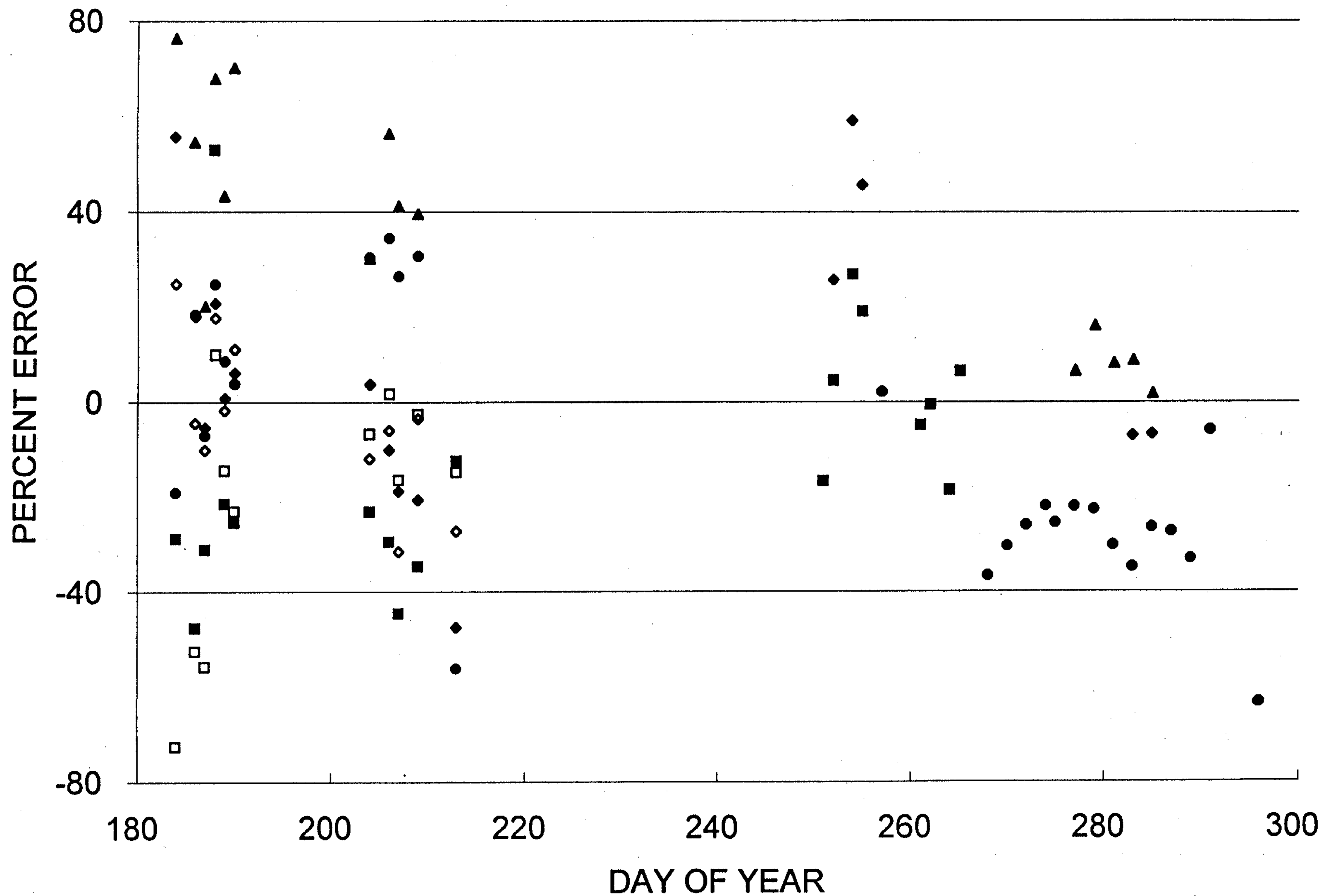
Figure 4. A 24-hour gauge error for all field tests on mesquite. The lines represent 2 standard deviations from the mean of gauge error. $r^2 = 0.80$.

Fig 1

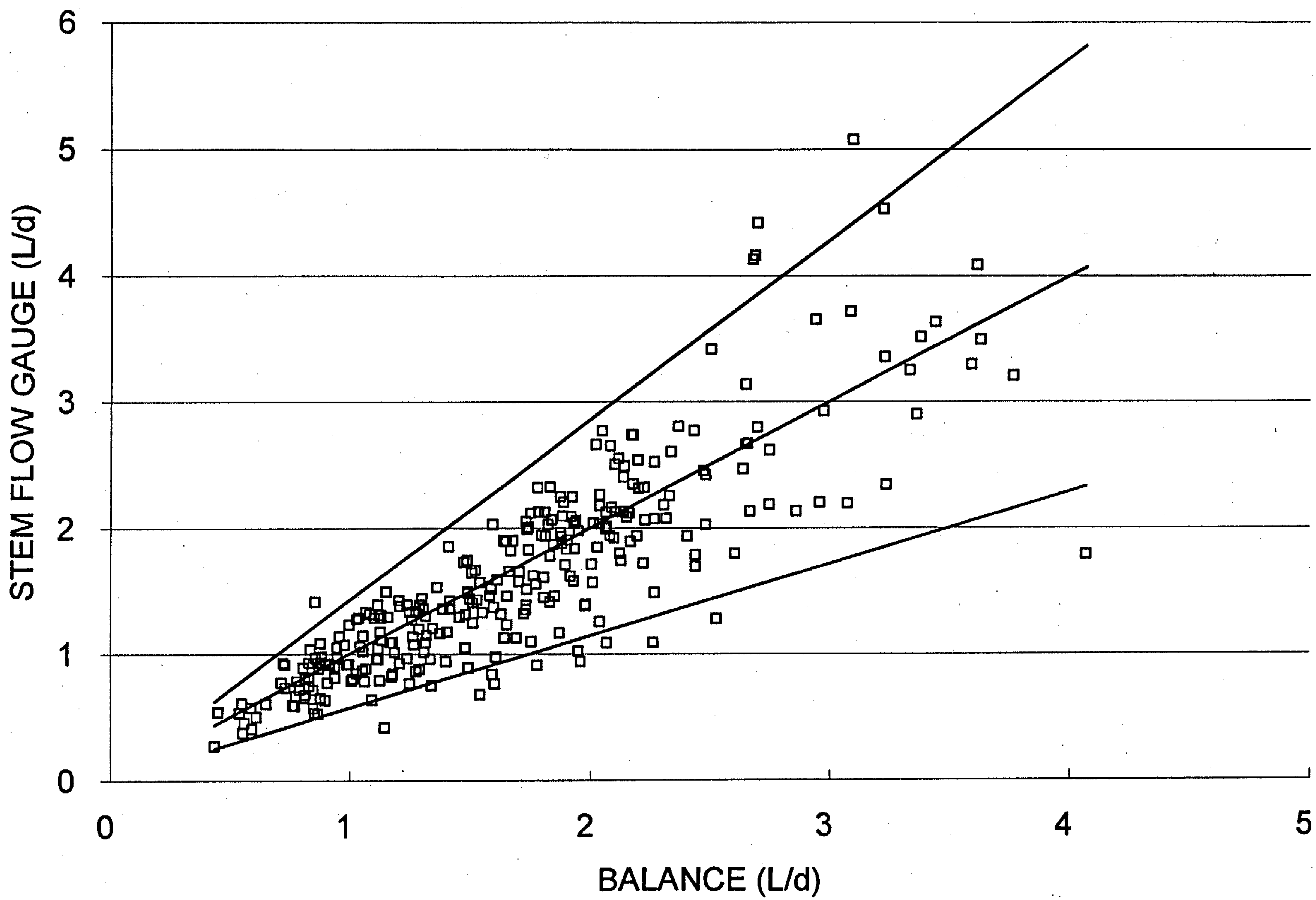


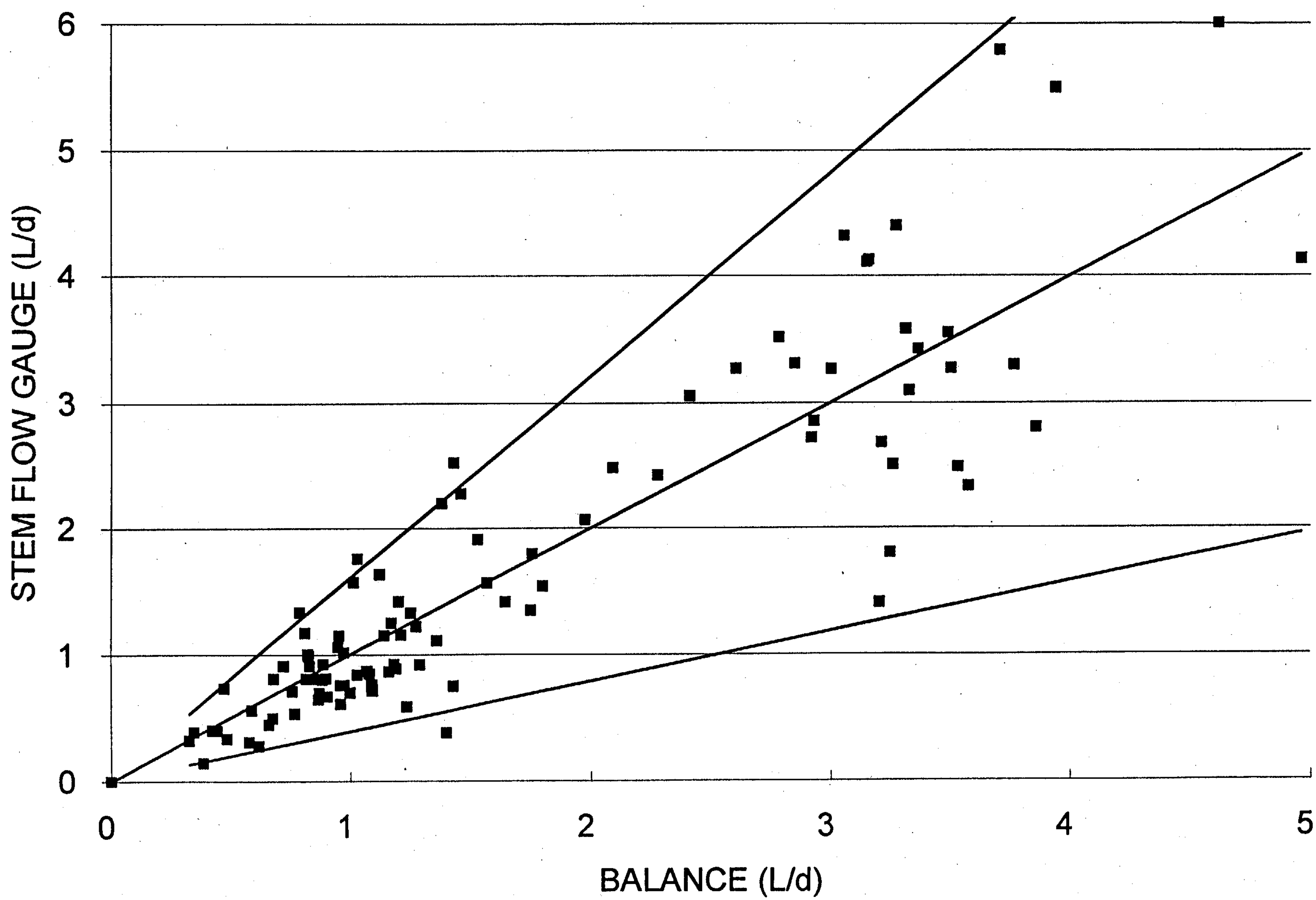
80
40
0
-40
-80
PERCENT ERROR
180
200
220
240
260
280
300
DAY OF YEAR

Fig. 2



80
40
0
-40
-80
PERCENT ERROR
180
200
220
240
260
280
300
DAY OF YEAR


STEM FLOW GAUGE (L/d)
6
5
4
3
2
1
0
0
1
2
3
4
5
BALANCE (L/d)



STEM FLOW GAUGE (L/d)
0
1
2
3
4
5
6
BALANCE (L/d)