A Mariotte-based Verification System for Heat-based Sap Flow Sensors

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Abstract

Determination of the accuracy of commonly used techniques for measuring sap flux density in trees often presents a challenge. We therefore designed and built a verification system for heat-based sap flow sensors typically used at stem level. In the laboratory, a Mariotte's bottle device was used to maintain a constant flow rate of water through freshly cut stem segments of American beech (*Fagus grandifolia* Ehrh.). This verification system was used to determine the accuracy of three heat-based sap flux density techniques: heat pulse velocity, thermal dissipation and heat field deformation. All three techniques substantially underestimated sap flux density when compared against gravimetric measurements. On average the actual sap flux density was underestimated by 35% using heat pulse velocity, 46% using heat field deformation and 60% using thermal dissipation. These differences were consistent across sap flux densities ranging from 5 to 80 cm^3 cm^{-2} h^{-1}. Field measurements supported the relative sensor performance observed in the laboratory. Applying a sensor-specific correction factor based on the laboratory test to the field data produced similar estimates of sap flux density from all three techniques. We concluded that a species-specific calibration is therefore necessary when using any of these techniques to insure that accurate estimates of sap flux density are obtained, at least until a physical basis for error correction can be proposed.

INTRODUCTION

Sap flow measurements are used worldwide to assess transpiration losses from individual trees, to scale from a tree to a stand or catchment level, and to understand the tree's contribution to total ecosystem transpiration (Ford et al., 2008; Mitchell et al., 2009). Thermal sap flow methods, typically used at the stem level and supplying either instantaneous or continuous heating to the sapwood, allow quantification of whole-tree water use with minimal disruption to the transpiration conditions (Schurr, 1998; Smith and Allen, 1996). Quantification of the accuracy of commonly used techniques to measure sap flux density presents a challenge in current sap flow research. The objective of this work was to design and build a verification system to test the performance and accuracy of three types of heat-based sap flow sensors.

MATERIALS AND METHODS

Plant Material

Three commercially available methods for measuring sap flux density were tested in the laboratory of the Warnell School of Forestry and Natural Resources (WSFNR) of the University of Georgia near Athens, Georgia. The tests were done using cut stem segments of American beech (*Fagus grandifolia* Ehrh.). Two sample trees, respectively 70- and 66-years old and having a stem diameter at breast height of 15 and 21 cm, were harvested from the University of Georgia's Whitehall forest. Eight stem segments, approximately 1 m in length, were brought back to the laboratory, wrapped in black plastic bags to minimize stem dehydration.

Mariotte-based Verification System

A 25-cm long section was cut from each stem segment just prior to measurement. Both cut surfaces were re-wet and then trimmed using a razor blade to re-open the end vessels. A 2 cm strip of bark at the top of the stem segment was removed to ensure that water only passed through the stem xylem. A 30-cm high plastic cylinder was fixed over the inlet end of the stem using silicone and double-sided adhesive tape as a sealant. The silicone was left to dry for approximately 18 hours. The upper and lower ends of the stem were moistened to reduce dehydration. Thereafter, the stem segment was prepared for sensor installation.

Three sets of commercially available sap flow sensors were tested simultaneously: heat pulse velocity (HPV), thermal dissipation (TD) and heat field deformation (HFD). While the HFD method typically uses multi-point sensors (six depths below the cambium in this study), the other two methods used single-point sensors. The working principles of these sensors are described in detail in Steppe et al. (2010). In order to avoid any misalignment of the heater and sensor needles, all holes for the sensors were made using a drill press. Note that the holes were 1.8 mm for HPV, 1.2 mm for TD and 1.6 mm for HFD, while the total wound width equalled drill size plus 0.2 mm for HPV in contrast to the observed 0.6 mm of Barrett et al. (1995).

The prepared stem segment was subsequently suspended in the Mariotte device (Fig. 1) and the sensor probes were carefully installed with the aid of silicone grease. The sensors were then thermally insulated with open-cell foam, which was a prerequisite for accurate measurements, despite the constant air temperature inside the laboratory. Since the TD method requires a period of zero flow, all sensors installed were logged for a period of approximately 2 hours before any water was passed through the stem segment. Each stem segment was then flushed with distilled water for 15-30 min. Once the balance readings stabilised, the water was removed and constant flow rates were then applied by maintaining a constant pressure head of water on the cut stem segments using the Mariotte bottle principle (McCarthy, 1934) (Fig. 1). A closed 5-L Erlenmeyer flask filled with water was equipped with two glass tubes located at the same depth: one tube functioned as an air inlet, while the other tube was connected via flexible tubing to a third glass tube that functioned as a siphon. A constant head of water (h = distance between the bottom of the air inlet and the surface of the cut stem segment) was established by adjusting the height of the flask (and thus the bottom of the air inlet tube). Hydraulic heads of 2, 5, 10, 15 and 25 cm were maintained on each cut stem segment for at least half an hour and the efflux of water was measured every 2-3 min using an electronic balance. Simultaneous estimates of sap flux density obtained with the three thermal methods, converting first point data from HPV and TD to profile-averaged sap flux densities as described in Steppe et al. (2010), were compared to the actual sap flux densities. These were obtained from the rate of change in the mass of water collected, normalised by the conducting sapwood area. The Mariotte device was used to test sap flux densities ranging from 5 to 80 $cm^3\ cm^{-2}\ h^{-1}$, which is within the range of values reported in the literature (Granier, 1985). Conducting sap wood area was estimated at the end of the experiment using a dye stain (food colour) that was introduced into the water and allowed to flow through the stem segment. In total, nine cut stem segments were used for testing the accuracy of the three thermal methods.

Field Experiment

In addition, a field comparison of the three methods was conducted over a five-day period (21-25 July 2008) by placing the sensors simultaneously in a living American beech tree in Whitehall forest. Stem diameter at sensor height was 19.9 cm. All sensors were placed in a horizontal plane approximately 90 cm above soil surface. The sensors were arranged around the stem circumference, spaced 90° from each other: two HPV sensors were installed on opposing sides of the stem, while the TD and the HFD sensor were installed perpendicular to this direction, also on opposing sides of the stem.

RESULTS AND DISCUSSION

Accuracy of Thermal Sap Flow Sensors in Cut Stem Segments

Strong linear relationships ($R^2 > 0.98$) were observed between gravimetric measurements and the corresponding sap flux density estimates for all nine experiments (Fig. 2). Despite the use of the same stepwise increasing hydraulic heads in each experiment, different sap flux densities were observed for different stem segments, ranging from 5 to 80 $cm^3\ cm^{-2}\ h^{-1}$. The highest sap flux densities were only achieved in stem segments of larger diameters, while the lower part of this range was observed in the smaller diameter stem segments. Because the slope of the individual relationships differed, a large overall variability was observed.

There were significant differences in the estimates of sap flux density from each of the three methods (Fig. 2). All sensors underestimated the actual sap flux density and this error became more pronounced with increasing sap flux density. Higher potential errors with higher sap flux densities were also reported for TD by Clearwater et al. (1999). Overall, the most accurate measurements were made with HPV. A total wound width of 2 mm (drill hole (1.8 mm) plus twice the transverse wound width (2 × 0.1 mm)) was used in this study to calculate the wound correction of Swanson and Whitfield (1981). This might have been an underestimation, as Barrett et al. (1995) suggested to use drill hole plus twice a transverse wound width of 0.3 mm (2 × 0.3 mm) based on scanning electron micrographs of wounding caused by implantation of temperature and heater probes into the sapwood of saplings of two rainforest and one eucalypt species. Other causes for the observed deviation for HPV might have been thermal heterogeneity of the sapwood (Steppe et al., 2010) or stem hydraulic anisotropy. The least accurate measurements proved to be TD, which is presently the most commonly used method. This is probably related to the fact that the method is not based on physical principles of heat transfer. There was an average error between actual and estimated sap flow density of 35% using HPV, 46% using HFD and 60% using TD. The reciprocal of the calculated slopes yielded correction factors of 1.548, 1.846 and 2.507, respectively (Fig. 2d).

Field Test on an Actively Transpiring American Beech Tree

In order to verify the lab findings, a comparison was made of concurrent sap flux density measurements acquired by the three thermal methods in an actively transpiring beech tree. The field data provided results comparable to those obtained in the lab: while the diurnal pattern of sap flux density for HPV and HFD was similar (with values of either HPV or HFD being the greatest), the diurnal pattern for TD was typically lowest (Fig. 3). The strong agreement in daily HPV pattern measured at the opposite sides of the tree stem might be an indication that circumferential variability in the sampled beech tree was rather low. That similar conclusions regarding sensor performance can be drawn from the laboratory and field studies suggest that the correction factors obtained on cut stem segments might also be applicable in the field. Therefore, the respective factors were used to correct the sap flux densities (Fig. 3b) resulting in almost identical actual sap flux densities for each method. Noteworthy is that these actual sap flux densities were almost double of the originally calculated values.

Although in this study, this transfer of correction factors appeared to be valid, it should still be determined if they are also applicable for other species. Given the magnitude of the obtained correction factors, validation of sap flow methods remains an important concern when accurate estimates of the water budget of tree-dominated ecosystems are required.

CONCLUSIONS

A Mariotte-based verification system was successfully used to test the accuracy of three commonly used thermal sap flow techniques. There appeared to be no single reason why the three methods underestimated actual sap flux density. Rather, multiple errors occurred, compounding to reduce the overall accuracy of each technique. Despite the ideal test environment in this study (i.e., constant flow rates and not variable as in sun/shade conditions or changing vapour pressure deficits, constant and isothermal stem and air temperatures), the errors were of a magnitude to be concerned about the accuracy of all three techniques. Errors encountered in field studies are likely to be even greater. All techniques used today, ranging from the empirical TD to the more physically based HPV and HFD, remain simplifications of reality. Recalibration for each new tree species on which these techniques are used is recommended, at least until a physically based error correction protocol is established or new sap flux density calculation approaches emerge. Pressure within the sap flow community for a greater accuracy in whole tree-water use estimates are likely to provide a real impetus for more intensive studies that take account of the errors involved and suggest ways to solve them.

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Figures

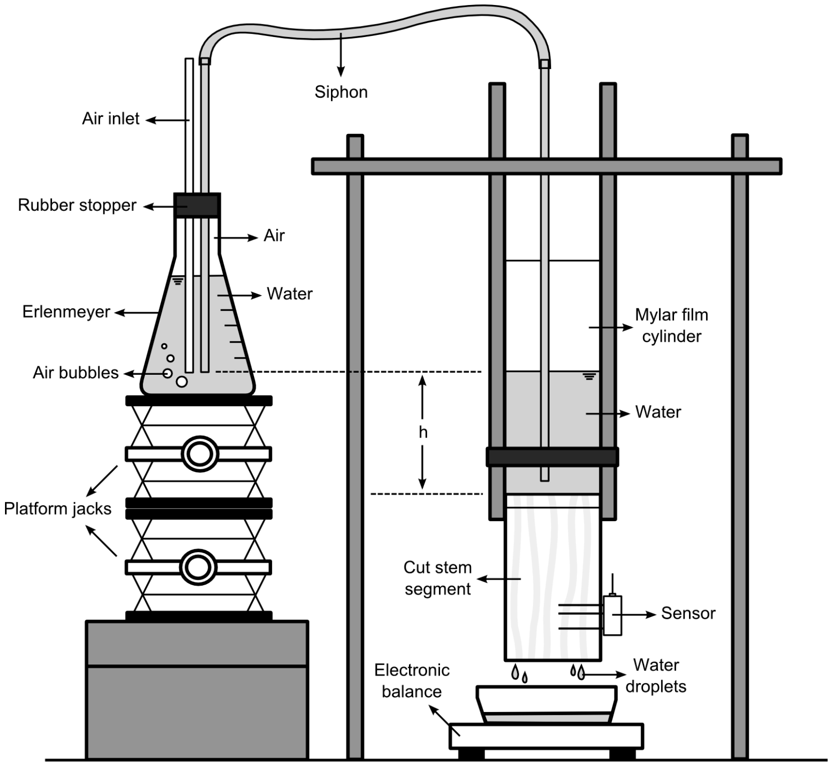

Fig. 1. Schematic diagram of the Mariotte-based verification system used for testing the accuracy of the three sap flow methods (from Steppe et al., 2010).

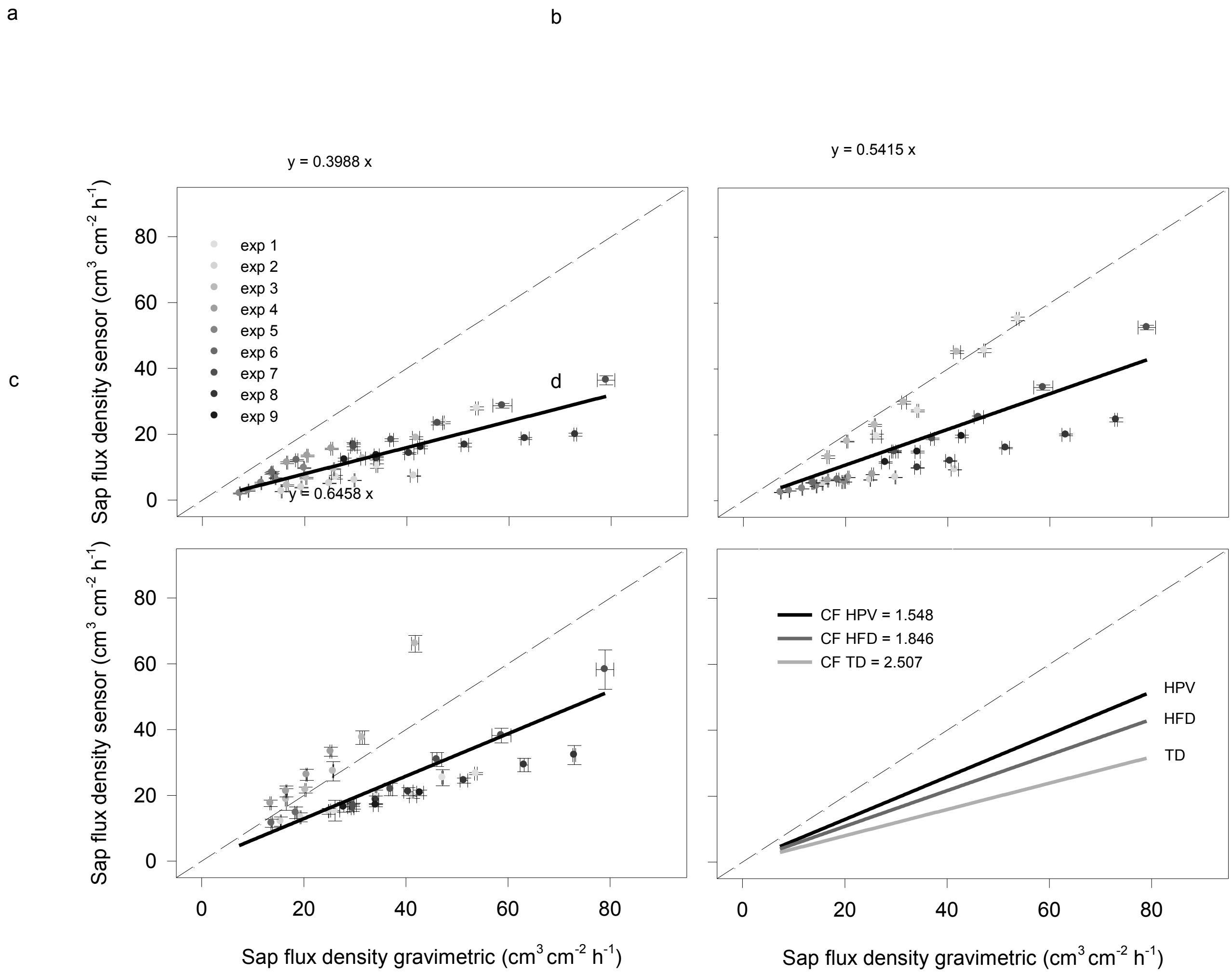

Fig. 2. Comparison of sap flux densities measured with the TD (a), the HFD (b) and the HPV (c) method and actual sap flux densities measured with the balance (gravimetric). Nine cut stem segments of American beech were used and in each experiment at least four different constant heads of water pressure were applied. Single point measurements were corrected for the radial sap flux profile and averaged over the depth (according to Steppe et al., 2010). A correction factor (CF) for each method was calculated as the inverse of the slopes of each regression line (d) (adapted from Steppe et al., 2010).

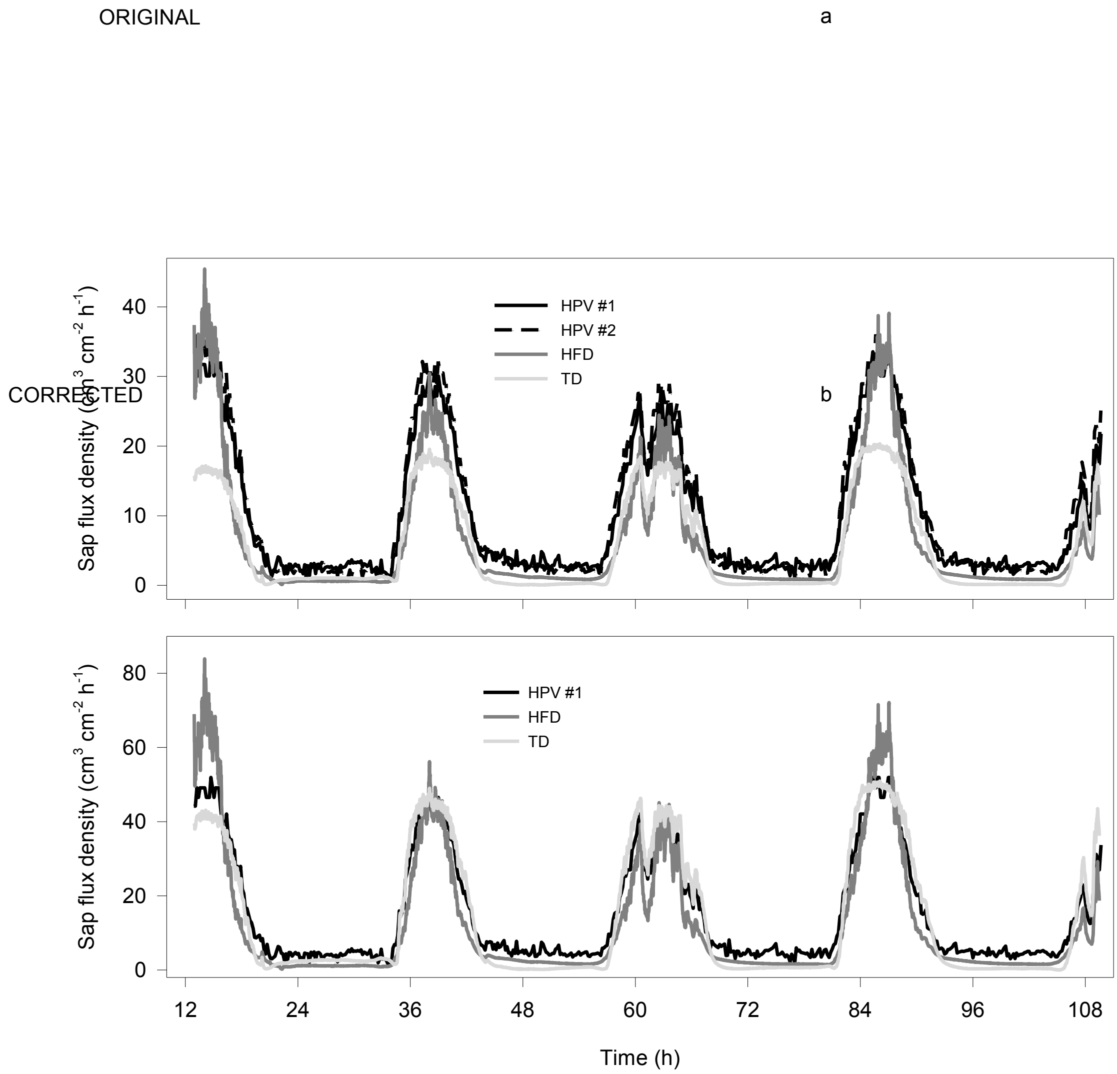

Fig. 3. A comparison of concurrent sap flux density measurements acquired by the HPV, TD and HFD method in an actively transpiring American beech tree in the field: (a) originally calculated sap flux densities; (b) corrected sap flux densities using the correction factors determined in validation experiment (Fig. 2d). HPV#1 and HPV#2 in (a) are two sensors installed on opposing sides of the stem, of which only HPV#1 is shown in (b) because of the strong agreement in daily pattern of both sensors (from Steppe et al., 2010).