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Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees

Sebastian Fuchs, Christoph Leuschner, Roman Link, Heinz Coners, Bernhard Schuldt*

Plant Ecology, Albrecht von Haller Institute for Plant Sciences, University of Goettingen, Untere Karspüle 2, 37073 Goettingen, Germany

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ABSTRACT

Sap flow probes are routinely used in forest and horticulture hydrology for estimating tree water use. This requires unbiased measurements when upscaling from tree to stand level, but accuracy and comparability of different thermometric methods have been questioned. Three sap flow measuring techniques were compared against gravimetric flow measurement in cut stem segments: 'Granier-type' thermal dissipation probes (TDP; three different sensor types), the heat field deformation method (HFD), and the heat ratio method (HRM). For the empirical methods (TDP and HFD), new calibration parameters were estimated using a nonlinear hierarchical modelling approach. 66 stem segments from five temperate, diffuse-porous tree species (9–16 cm stem diameter, 100 cm stem length) were exposed to a wide range of flux densities by applying subatmospheric pressure (−50 to −650 hPa) analogous to natural flow conditions in the field.

All TDP probes underestimated flux density by 23–45% when calculated with Granier's original calibration parameters, with the deviation increasing with flux rate. The accuracy was significantly improved by estimating new calibration parameters, especially for probes differing from Granier's original sensor design. Species-specific parameters further improved accuracy, although the species differences might partially be explained by variation in the observed ranges of sap flux. The HFD sensor overestimated gravimetric flow by ~11%; empirical calibration did not improve its accuracy compared to the manufacturer's equation. At low to medium flow rates, the HRM system achieved higher accuracy than the other probes (0.8% underestimation), while performing poorly at high flux rates under our measurement settings (energy input of 25 J). Both for TDP and HFD sensors, we observed a surprisingly large variability in calibration parameters between different stems of the same species.

We conclude that (i) TDP and HFD sensors require species-specific calibration to measure sap flux with high accuracy, (ii) the original Granier equation cannot be used for TDP probes with deviating design, and (iii), at low to medium flow rates, the highest accuracy can be achieved with HRM sensors. Our results help to increase the accuracy of tree sap flow measurements with thermal dissipation probes, and to assess various levels of errors related to the different thermometric methods. This is important when synthesizing forest transpiration data on regional and global scales.

1. Introduction

In the face of a warming climate with more frequent drought exposure in summer, precise information on the water consumption of trees and forests is of fundamental importance for biological, forestry, agricultural, and horticultural research. A variety of sap flow techniques are routinely used in tree ecophysiology for estimating whole-tree transpiration and extrapolating water loss to the stand and catchment level, and for optimizing irrigation management. Most techniques install sensors in the trunk using heat as a tracer for sap movement in the xylem because the stem is the 'bottleneck' in the water flow path along the soil plant atmosphere continuum. The earliest attempts of thermometric sap flow measurement in stems date back to the 1930s, when Huber (1932) used the travelling time of an externally induced heat pulse to a certain point downstream as a measure for sap velocity (see also Marshall, 1958). On this basis, the widely used 'compensation heat pulse method' (CHPM) was developed (Swanson, 1962; Swanson and Whitfield, 1981). This method has the disadvantage that reverse flow and low or very high flux densities cannot be measured because a temperature equilibrium between upstream and downstream probe does not establish under those conditions (Bleby et al., 2004; Vandegehuchte and Steppe, 2013). Another heat pulse method, the

* Corresponding author.
E-mail address: bernhard.schuldt@plant-ecology.de (B. Schuldt).

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heat ratio method (HRM), was developed by Burgess et al. (2001) as a modification of the CHPM method, capable of measuring reverse flow and low flux densities. Instead of directly measuring the travelling time of a heat pulse, the temperature ratio of two equidistant sensors alongside a heater after a certain amount of time is used to calculate sap velocities.

Simultaneously, constant heating methods were developed which relate sap flow to the amount of dissipated thermal energy from a constantly heated source rather than to the velocity of a heat pulse. First attempts by Vieweg and Ziegler (1960) did not result in quantitative measurements of sap flow because they did neither entail empirical calibration nor calculations based on the physics of heat transfer. A simple but budget-friendly and therefore still widely used constant heating method (TDP, 'thermal dissipation probe') was developed by Granier (1985), who empirically related the dissipation of heat from a single heated probe to sap flux density. The latest iteration of constant heating techniques is the heat field deformation (HFD) method (Nadezhdina et al., 1998, 2012). Changes in the heat field around a linear heater are recorded by three measuring probes with multiple thermocouples along the radial profile and are then related to sap flux density in the xylem. By now, empirical calibrations of HFD measurements are still missing and the method so far has primarily been used for the investigation of radial variation in sap flux density.

To employ sap flow measurements for extrapolating transpiration rate to the stand level, high measurement accuracy is needed (Mitchell et al., 2009; Steppe et al., 2010). Several studies have tested the accuracy of different sensor systems by comparison to gravimetrically measured flow rate, typically using potted plants or excised stem or branch segments. The HRM system was tested in a potted plant experiment (Bleby et al., 2004) and directly compared to the older CHPM system. While both methods were found to achieve a high accuracy when estimating sap flow at medium flow rates, HRM showed a better performance at low flow rates. For high sap flow rates in highly conductive roots, however, Bleby et al. (2008) reported strong limitations of the HRM method. Steppe et al. (2010) tested CHPM, HFD and TDP sensors simultaneously on cut stems of the diffuse-porous tree species *Fagus grandifolia* and found underestimations of flux densities by 35%, 46% or 60%, respectively. So far, no other study has tested the accuracy of the HFD method against an independent reference, but Vandegehuchte and Steppe (2012) reviewed the equation given by Nadezhdina et al. (1998, 2012) and concluded that some of its variables are physically misinterpreted, e.g. the use of thermal diffusivity and sapwood depth. In consequence, they argued that this method should be considered merely empirical, as there is no valid physical justification for the linear relationship between measured HFD temperature difference ratios and sap flux density proposed by Nadezhdina et al. (1998, 2012). Instead, based on the results of a 3D-Finite Element Model simulation, Vandegehuchte and Steppe (2012) provide evidence for a nonlinear relationship between sensor temperature ratio and sap flux density and suggest to describe it with second-order polynomials with 2–4 parameters. While several authors performed experimental validations of the TDP method (e.g., Granier, 1985, 1987; Cabibel and Do, 1991), there have been no analogous studies of the relationship between the HFD temperature ratio and sap flux density so far.

The TDP method has been tested in various experiments on a wide range of species including ring- and diffuse-porous trees, and has repeatedly been found to underestimate sap flux density by 6–90% (de Oliveira Reis et al., 2006; Taneda and Sperry, 2008; Bush et al., 2010; Hultine et al., 2010; Steppe et al., 2010; Renninger and Schäfer, 2012; Sun et al., 2011). Possible reasons for these systematic errors are deviations from the original sensor design (Lu et al., 2004), species-specific differences in wood properties (Lu et al., 2004; Vandegehuchte and Steppe, 2013), differences in radial sap flux density profiles (Clearwater et al., 1999; Bush et al., 2010) and wound effects (Wullschleger et al., 2011). Very steep radial sap flux density gradients are often found in ring-porous species, which can result in large parts of the sensors being located in non-conducting tissue. Consequently, the calculated flux rates often vary widely, and flux may be underestimated by up to 90% (Bush et al., 2010), even when the 'Clearwater-correction' for sensors exceeding the sapwood depth is applied (Clearwater et al., 1999). Because of simplicity and cost-efficiency, TDP sensors are often custom-made, with the sensors partly deviating in shape and size from the original sensor design described by Granier (1985). This is also true for some commercially available TDP sensors (e.g., UP GmbH, Germany and Dynamax Inc., USA) which differ in geometry or heating power from the original (Lu et al., 2004), thus demanding for a test as to whether these altered systems need recalibration (Granier, 1996; Lu et al., 2004). Moreover, the original assumption of Granier (1985) that his calibration parameters are species-independent has been questioned by several studies (de Oliveira Reis et al., 2006; Taneda and Sperry, 2008; Bush et al., 2010) and reviews (Lu et al., 2004; Vandegehuchte and Steppe, 2013).

The main objective of this study was to compare the accuracy of three commonly used sap flow sensor systems (TDP, HFD and HRM) against gravimetrically measured water flow in cut stem segments. The approach of Steppe et al. (2010) was extended by including the improved HRM instead of the CHPM technique, by applying vacuum to simulate a wide range of sap flux densities comparable to natural flow conditions in the field, and by increasing the species number to five common temperate diffuse-porous broad-leaved tree species. The match between gravimetrically and thermometrically determined flux density was assessed using a set of evaluation statistics that quantify precision, bias and overall accuracy of the measurements. We conducted a series of calibration experiments both for three different commercially available and custom-made sensor designs of the most widely distributed TDP method and one commercially available design of HFD sensors. As the equations used to calculate sap flux from HRM measurements are directly derived from the physics of heat dissipation (Burgess et al., 2001), we did not perform an independent empirical calibration for this method. We used non-linear mixed models to obtain stem-independent estimates of the calibration parameters and their uncertainty and simultaneously tested the hypotheses that the empirically estimated calibration parameters differ from the original parameters given by Granier (1985), and that there are species-specific differences in calibration parameters. For the HFD method, we analogously tested the hypotheses that the measured temperature ratio does not linearly depend on sap flux density after controlling for stem-specific covariates, and that calibration parameters differ between species. Based on the output of our models, we additionally were able to quantify the between-stem variability in calibration parameters, which is of crucial importance for the development of uncertainty budgets for these sap flux methods.

2. Material and methods

2.1. Plant material, sample preparation and validation apparatus

Validation experiments were carried out with stem segments from five temperate broad leaved tree species with diffuse-porous sapwood, *Fagus sylvatica* L. (FS), *Tilia cordata* L. (TC), *Acer pseudoplatanus* L. (AP), *Acer campestre* L. (AC) and *Populus nigra* L. (PN). *Fagus*, *Tilia* and *Acer* tree individuals were selected in a limestone beech forest near Göttingen (Göttinger Wald at 190–380 m a.s.l.; 51°35 N, 9°59 E; mean annual precipitation (MAP) 650–700 mm, mean annual temperature (MAT) 7.0–8.5 °C), and *Populus* tree individuals harvested in a young poplar plantation on limestone close to Erfurt (189 m a.s.l.; 51°02 N, 10°47 E; 549 mm MAP, 9.4 °C MAT; Schmidt-Walter et al., 2014).

For each tree individual, 2–5 segments of 1.4 m length and 8.6–16 cm diameter were cut with a chainsaw. Only straight and branch- and knotless stem segments were selected. Both segment ends were wrapped with wet sponge cloths and sealed with cling film immediately after cutting. Subsequently, stems were stored in large