Agricultural and Forest Meteorology 248 (2018) 169–176

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Research paper

A new consistent sap flow baseline-correction approach for the stem heat balance method using nocturnal water vapour pressure deficits and its application in the measurements of urban climbing plant transpiration

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ARTICLE INFO

Keywords:
Sap flow
Baseline-correction
Night-time transpiration
Water vapour pressure deficit
Climbing plants
Stem heat balance method

ABSTRACT

The stem heat balance (SHB) method is a widely used sap flow technique to determine the transpiration and the water demands of herbaceous and woody plants, especially those with small diameters (*e.g.* climbers). The accuracy of the sap flow derived by this method (Q_S) depends on correction of the total measured heat input (Q_t) by subtracting unintended heat losses; these heat losses are referred to as “fictitious flow” (Q_{fic}) ($Q_S = Q_t - Qfic$).

We developed a physically consistent baseline-correction approach using minimum nocturnal water vapour pressure deficits (*VPD*). This *VPD* approach was compared to the so-called “night value subtraction” (NVS) approach and direct gravimetric determination for potted climbing plants and an outdoor climbing plant stand. In addition, performance tests were also conducted on artificial model stems and cut plant stems.

In the tests with the outdoor climbing plant stand, sap flow corrected by the NVS approach underestimated daily transpiration by up to 33% compared to direct gravimetric determination. In contrast, the newly developed *VPD* approach underestimated or overestimated transpiration by only 5%–10%. The *VPD* approach makes use of the direct dependence of sap flow on *VPD* during zero-radiation conditions (night). This means, Q_{fic} is the constant of the linear regression of the *VPD* and the lowest recorded Q_t at night. Therefore, the correction is based on all recorded sap flow data from the measurement period itself, which in turn accounts for all factors influencing Q_{fic}, including RH and T_{air}; these latter parameters are often recorded in any case. This also means that this method can be subsequently applied to currently available data sets in order to improve their quality.

Our results suggest that when the raw data are corrected appropriately, the SHB method is viable when attempting to determine transpiration rates of climbing plants. This is especially true for urban areas, with their illumination, typically high *VPD*s and increased T_{air} at night.

1. Introduction

Sap flow measurements are often used to determine water demand and transpiration of plants and plant stands in ecology, forestry, agriculture and horticulture (*e.g.* Pertierra et al., 2002; Matyssek et al., 2009; Rodriguez-Dominguez et al., 2012). They can be installed without great effort and automated easily with continuous recording and high temporal resolution (Smith and Allen, 1996). They function as indirect methods, using heat as a tracer for sap movement in the xylem of intact plant stems. However, the operating principles are basically different according to the various techniques (Smith and Allen, 1996; Vandegehuchte and Steppe, 2013).

One widely used technique, applicable for rather small diameters of herbaceous and woody plant stems, is the stem heat balance (SHB) method. Two needle thermocouples are inserted into a stem and the section around the upper one is heated electrically. While the temperature difference between both thermocouples is kept constant, the amount of heat introduced is directly proportional to the amount of water passing through the stem (Lindroth et al., 1995; Čermák et al., 2004). In order to calculate water transport from the recorded heat input, it is necessary to apply a baseline-correction for unintended heat losses, which would otherwise be interpreted as water flow and ultimately transpiration. These unintended heat losses are caused by conduction through (i) the plant tissue which consists of solid cell material and variable amounts of water (and air), (ii) the sensor material and (iii) the insulation material around the thermocouples, no matter how

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http://dx.doi.org/10.1016/j.agrformet.2017.09.014
Received 23 December 2016; Received in revised form 31 August 2017; Accepted 20 September 2017
Available online 30 September 2017

good it is. These conduction losses occur in radial and vertical directions and cause the detection of a sap flow which does not actually occur; it is referred to as "fictitious flow" (Q_{fic}) (Grime and Sinclair, 1999; Trcala and Čermák, 2012). These losses and their dependencies on boundary conditions such as ambient air temperature have only been studied to a limited degree (Grime and Sinclair, 1999). Instead, Q_{fic} is often determined when water flow in the plant is *assumed* to be zero or negligible. Numerous studies have chosen the lowest measured heat input (Q_t) from measurement periods at night before sunrise as Q_{fic} (*e.g.* Dugas et al., 1994; Lindroth et al., 1995; Langensiepen et al., 2014). This night value subtraction (NVS) assumes that plants close their stomata in the dark and that no transpiration occurs in these periods. However, this assumption has been investigated and hotly debated for a long time (Rawson and Clarke, 1988; Dawson et al., 2007; Fisher et al., 2007). Ultimately, it must be assumed that most plant species do not completely close their stomata and consequently transpire at night. Moreover, it is well known that transpiration through the cuticle is very limited for some plant species, but cannot be ruled out altogether. Forster (2014) concluded that night-time transpiration is common across a wide range of species from all biomes and seasons, making up an average of 12% of the total daily transpiration. Nevertheless, the NVS approach is still used and manufacturers even suggest this procedure in their manuals (*e.g.* EMS Brno, 2010) or sap flow logger software calculates it automatically (*e.g.* Dynamax Inc., 2007).

Other studies assumed zero-flow conditions after a heavy rainfall with high air humidity and intercepted water on the surfaces of leaves (Allen and Grime, 1995). However, Cienciala et al. (1992) revealed that even after rain fall events, sap flow of *Picea abies* still remained significant. Consequently, such assumptions of zero-flow conditions (*e.g.* at night or after rainfall events) should be applied with caution because they probably result in an underestimation of water fluxes and thus water demands.

Q_{fic} can also be measured after cutting the stem at the end of an investigation period to stop sap flow (*e.g.* Urban et al., 2012). This approach promises to be "the most accurate way" to determine zero flow, according to Dawson et al. (2007), but it is somewhat destructive. Furthermore, Q_{fic} may vary from sensor to sensor and from stem to stem. Thus, the results are not transferable to other experiments.

Alternatively, researchers have attempted to approximate Q_{fic} with the help of other instruments, *e.g.* by measuring the stomata conductance with a porometer or a gas exchange system (*e.g.* Leuzinger et al., 2011) or by gravimetric measurements in lysimeters (*e.g.* Caspari et al., 1993). However, these instruments are not able to directly quantify Q_{fic} and these comparisons would rather introduce intermethodical uncertainties. Trcala and Čermák (2012) improved the trunk segment heat balance method by improving the sensor geometry. Such sensors, however, are not applicable to small diameter stems of herbaceous and woody plants.

For this reason, a better method for the determination of Q_{fic} is needed, taking into account the site specific, plant specific and sensor specific influences.

1.1. Facade greening in urban settings as an application example for sap flow measurements

Facade greening with climbing plants has frequently been discussed as a promising countermeasure to mitigate heat stress in cities (Buchin et al., 2015). Shading and transpiration are the most important cooling mechanisms, with the latter directly depending on water availability (Hoelscher et al., 2016). Therefore, the water demand of climbers is of great viable interest. So far, only limited data are available (*e.g.* Leuzinger et al., 2011; Hoelscher et al., 2016), but could be easily obtained from sap flow measurements. However, site conditions in urban areas are very different from natural ecosystems, which make the applicability of the NVS approach questionable. Due to higher water vapour pressure deficits (*VPD*) of the ambient air, urban climbers are hypothesised to exhibit redistribution and transpiration during warm summer nights. Not only transpiration through the stomata is probably high for plants with a high leaf area index (LAI) and thin and smooth leaves, such as *Fallopia baldschuanica* (Hoelscher et al., 2016), but also transpiration through the cuticle. Additionally, artificial light has been detected as global radiation at night (Jänicke et al., 2015). Sap flow measurements could be useful for studying climbing plants in urban areas, provided that they are calibrated correctly.

1.2. Aims

For applied flow rates, we (i) determined Q_{fic} and its detection limits as well as Q_{fic} depending on air temperatures. We then (ii) developed a new viable calibration method for deriving transpiration data from sap flow measurements that uses data from the measurement campaign itself as well as data on air temperature (T_{air}) and relative air humidity (*RH*). Finally, we (iii) assessed the applicability of the common NVS approach and the newly developed *VPD* approach based on simultaneous weight measurements to derive transpiration rates of climbing plants. Thereby, we tested the influence of wind and drought stress on the results.

2. Materials and methods

2.1. Sap flow measurements

Sap flow measurements were conducted using EMS 62 sap flow sensors (EMS Brno, Czech Republic) in two versions for two different stem diameters (8–12 mm and 10–20 mm). Measurements were based on the SHB method, with external heating and internal temperature sensing, described in detail by Lindroth et al. (1995) and Čermák et al. (2004). Two needle thermocouples were installed into the stem and subsequently wrapped with insulation foam and an additional shield to protect against direct solar radiation and precipitation.

While the temperature difference ΔT between both thermocouples was constant at 4 K, the input power was continually recorded at 1 and 10 min intervals, respectively. Sap flow Q_S ($L\,h^{-1}$) expressed on a volume basis, assuming a water density of $1\,g\,cm^{-3}$, was calculated as follows (Lindroth et al., 1995):

$$Q_S = Q_t - Q_{fic} = \frac{P}{\Delta T\, c_w} - Q_{fic}\,, \tag{1}$$

where Q_t is the total measured heat input, P ($J\,h^{-1}$) is the power input to the heater, ΔT (K) is the temperature difference between the two thermocouples, c_w ($J\,L^{-1}\,K^{-1}$) is the specific heat of water and Q_{fic} ($L\,h^{-1}$) is the fictitious water flux.

2.2. Variation of Q_{fic} for different flow rates and T_{air}

We determined the dependence of Q_{fic} on flow rates and air temperatures in the laboratory and climatic chamber experiments, respectively (Table 1).

2.2.1. Experiment 1: variation of Q_{fic} for different flow rates

We performed a continuous flow through a model stem in a laboratory experiment (T_{air} from 24.1 to 26.3 °C and *RH* from 33.7 to 46.9%) to determine Q_{fic}. For the model stem, we took a PVC hose with an inner and outer diameter of 6 and 10 mm, which was filled with water. This simplified model stem can be reproduced easily and enabled us to get very reproducible results that are not possible for real plant stems. We used a syringe pump (Perfusor 8878, B. Braun Melsungen AG, Germany) and applied flow rates between 0.01 and 0.06 $L\,h^{-1}$ (3 repetitions in each case). To minimise heat loss by Brownian motion of heated water in an upward flow direction, we reversed the measuring construction, so that the water flowed downwards. Measurements were recorded at 1 min intervals. The detected Q_t slightly increased with