Agricultural and Forest Meteorology 211–212 (2015) 2–12

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

An analysis of Granier sap flow method, its sensitivity to heat storage and a new approach to improve its time dynamics

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ARTICLE INFO

Article history:
Received 11 September 2014
Received in revised form 29 April 2015
Accepted 8 May 2015
Available online 25 May 2015

Keywords:
Granier sensor
Nusselt number
Sap flow
Thermal dissipation
Xylem transport

ABSTRACT

Granier sap flow method is a simple and easily applicable method to monitor sap flow in trees in field conditions, and is thus in wide use. However, it has been suggested that the method is slow to capture transient changes in actual sap flux density due to heat storage and release within the stem. We show here how this may lead to biases in the estimation of the dynamics of sap flux density especially at low flow rates when thermal diffusivity is low. We also demonstrate how the traditional Granier sap flow method could be modified to improve the temporal precision of the sap flow measurement. In the new system, the temperature difference between the heated and the reference needle is kept constant by varying the heating power and the sap flux density is calculated from the power consumption. This leads to reduced changes in the heat content of stem. These modifications also make the method more robust in terms of stability of power supply and reduce power consumption during low flow conditions. The time dynamics of the Granier method and the new "steady temperature method" are simulated with a previously published numerical model of xylem heat balance and tested in a laboratory experiment with cut pieces of stem. The numerical model is also used to demonstrate that the relation between parameter *K*, calculated from instantaneous sensor temperature and maximum sensor temperature, and actual sap flux density is not constant for either the traditional Granier or the new modified sensor, but is dependent on the range of sapflow rates examined and on the value of thermal diffusivity. Continuous measurements of thermal diffusivity of the sapwood along with the needle temperature/power consumption could help to improve the accuracy of the sap flow measurements.

1. Introduction

Sap flow measurements are a widely used method for studying tree-level water fluxes and water use of forest ecosystems. The most common measurement systems are based on detecting convective heat transfer (heat carried with the sap stream) inside the tree stems. This class of measurements can be divided into three groups depending on the heating and signal detection method: I) heat balance methods, II) heat dissipation methods and III) heat pulse methods. Both heat balance methods such as Dynamax and Cermak-methods (Cermak et al., 1973, 2004) and heat dissipation methods like the Granier-method (Granier, 1985, 1987) use the temperature difference between two or more sensors, one heated and the other(s) not, to estimate the heat transfer due to the sap flow and consequently calculate the flow rate, while heat pulse methods (e.g., Burgess et al., 2001) determine the sap flux density from the transfer time of a heat pulse between two or more sensors.

The Granier heat balance method is one of the most widely applied methods for measuring xylem sap flux density in trees. In the Granier method the temperature difference between two needles, of which the upper one is heated with a constant heat source, is measured, and the sap flux density is calculated from this temperature difference. The method is very easy to implement technically due to simple installation and calculation of sap flux density from the raw data (Smith and Allen, 1996). It is also applied to up-scaling water use of forest stands. Despite its great value and wide use, the theoretical understanding on the functionality of the method and the underlying assumptions used in the calculation of the sap flux density remain somewhat obscure, although recent modeling studies of the heat transport within the stem (Tatarinov et al., 2005; Sevanto et al., 2009; Wullschleger et al., 2011) have shed light onto the details of the method. It is well acknowledged that the method shows systematic biases; the equation relating

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http://dx.doi.org/10.1016/j.agrformet.2015.05.005
0168-1923/

sap flux density to the temperature difference between the needles depends, at least, on the thermal properties of the wood, radial distribution of the sap flux density within the stem, and wounding (e.g., Goulden and Field, 1994; Clearwater et al., 1999; Steppe et al., 2010; Wullschleger et al., 2011; Vergeynst et al., 2014). These factors may cause large errors in the evaluation of daily water use of trees and forests stands, yet most of the time the standard equation provided by Granier (1985) is used without further consideration. The method has also been suggested to be slow to pick up on changes in sap flux density (Braun and Schmid, 1999b; Sevanto et al., 2008, 2009) although in some cases fast responses to changes in sap flux density have been observed (Phillips et al., 2009; Chu et al., 2009; Steppe et al., 2010). These contradictions in results may be due to differences in xylem structure of the species measured as well as differences in maximum and typical sap flux densities as both affect thermal properties of the wood (see e.g., Swanson, 1994). The slowness of the method has been hypothesized to result from transient heat storage and release of the surrounding sapwood. The inaccuracy resulting from the slowness of the sensor response to estimates of whole tree or canopy water use may be small compared to the effects of sensor placement to catch a representative sample of the conductive sapwood, but it will cause errors in the estimation of stem water capacitance (Burgess and Dawson, 2008), leading to loss of information about the short time scale sap flow dynamics (Braun and Schmid, 1999b), and to cause an apparent hysteresis between the morning and afternoon sap flux density (Sevanto et al., 2008). Therefore, it is important to understand the causes of slowness and magnitudes of the error related to it, and try to improve the method.

Here we 1) discuss the theoretical background behind the semi-empirical formula in connection with Granier sap flow method relating needle temperature to sap flux density and the time lags associated with it, 2) present a new modification of the Granier sap flow method that keeps the temperature difference of the needle pair constant by adjusting the heating power to the upper needle thus improving its temporal resolution, 3) study the heat balance of the sapwood and its relation to the sap flux density for both the traditional Granier method and the new modification by applying a previously published numerical model (Sevanto et al., 2009) of heat transport within the stem and 4) compare the dynamics of these two methods in responding to a step change in the actual measured sap flow rate in controlled laboratory experiments using Scots pine (*Pinus Sylvestris*) stems.

2. Materials and methods

2.1. Granier sap flow theory

Heat flux from the heated needle, can be expressed as

$$Q = h\Delta T \quad (1)$$

where h is the heat transfer coefficient, and ΔT is the temperature difference between the needle and the ambient surroundings (e.g., Bird et al., 2007). ΔT is taken here to be the temperature of the reference needle. Heat transfer from the heated needle occurs by conduction and convection with xylem sap flow. The heat balance equation can be broken down into these two components (Lu et al., 2004)

$$Q = h_0\left(1 + av^b\right)\Delta T \quad (2)$$

where $h_0\Delta T$ is heat transfer in the absence of sap flow, i.e., due to conduction alone, h_0 is the heat transfer coefficient at zero flow conditions, v is sap flux density ($m^3\,m^{-2}\,s^{-1}$), and a and b are empirical coefficients. The term av^b represents the ratio of heat transfer by convection to heat transfer by conduction. In fluid dynamics, this ratio is called the Nusselt number (Bird et al., 2007). The values for the coefficients a and b (and hence the term av^b) are semi-empirical, as the actual fluid dynamics/heat transfer problem involving both heat conduction and convection is, in many cases, too complicated to be solved analytically (Bird et al., 2007). Yet this functional form has been found to be suitable in describing heat transfer in the coupled convective and conductive heat transfer situation, and one can find approximations of the Nusselt number and its dependency (i.e., coefficients a and b) on the geometry and thermal properties of the system and the flow rate regime (e.g., Bird et al., 2007).

For a constant heating power ΔT reaches its maximum value ($\Delta T = \Delta T_{max}$) when sap flux density is zero ($v = 0$) and h_0 can be solved from Eq. (2) to be

$$h_0 = \frac{Q}{\Delta T_{max}} \quad (3)$$

Combining Eqs. (2) and (3), and solving for the sap flux density gives

$$\Delta T_{max} = \left(1 + av^b\right)\Delta T \Leftrightarrow \frac{\Delta T_{max}}{\Delta T} - 1 = av^b \Leftrightarrow \frac{\Delta T_{max} - \Delta T}{\Delta T} = av^b \Leftrightarrow v = a^{-1}K^{b^{-1}} \quad (4)$$

Writing $\alpha = 1/a$, $\beta = 1/b$ gives

$$v = \alpha K^{\beta} \quad (5)$$

where K is

$$K = \frac{\Delta T_{max} - \Delta T}{\Delta T} \quad (6)$$

For a specific case of experiments conducted with *Pseudotsuga menziesii* (Mirb.) Franco, *Pinus nigra* Arnold and *Quercus pedunculata* Ehrh, values of and $\alpha = 119 \times 10^{-6}\,m^3\,s^{-2}\,s^{-1}$ and $\beta = 1.231$ were obtained in Granier (1985) based on a gravimetric comparison. However, experience has shown that species or tree specific empirical calibration and determination of α and β are required (e.g., Lundblad et al., 2001; Vandegehuchte and Steppe, 2013). For example, Bush et al. (2010) found that the actual calibration equation coefficients differed by as much as two to almost three orders of magnitude when compared with the original Granier coefficients. Sun et al. (2012) demonstrated a 9–55% discrepancy in absolute sap flux densities using the original Granier coefficients versus the actual species-specific coefficients.

2.2. A new modification to the Granier method: steady temperature (ST) thermostat

To reduce the effect of heat storage and release, which affect both h and ΔT in Eq. (1), we developed a new method where the temperature difference between the two needles is kept constant, by actively adjusting the heating power to maintain the desired temperature difference. The advantage of this new method, which we call the steady temperature thermostat, abbreviated "ST" hereafter, is that the amount of heat storage and release should be lower than in the traditional Granier sensor. Consequently, the delays related to changes in heat storage in the trunk should be reduced, reducing the bias in the measurements of the sap flux. The concept of maintaining a constant temperature difference while varying heating power has also been utilized in some earlier applications of the heat balance method to estimate sap flux densitiy (e.g., Kucera et al., 1977; Fichtner and Schulze, 1990).The heat balance equation for the ST method is the same as for the Granier method, Eq. (2). For the ST method, the heating power is at its minimum ($Q = Q_{min}$)