Agricultural and Forest Meteorology 186 (2014) 34–42

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Improving the stem heat balance method for determining sap-flow in wheat

Matthias Langensiepen[a,*], Moritz Kupisch[a], Alexander Graf[b], Marius Schmidt[b], Frank Ewert[a]

[a] Crop Science Group, Institute of Crop Science and Natural Resource Protection, Faculty of Agriculture, University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany
[b] Agrosphere, Institute of Bio- and Geosciences, Jülich Research Center, 52425 Jülich, Germany

ARTICLE INFO

Article history:
Received 10 April 2013
Received in revised form 18 August 2013
Accepted 21 November 2013

Keywords:
Sap flow
Triticum aestivum
Stem heat balance
Numerical simulation
Eddy correlation
Validation

ABSTRACT

A novel micro-sensor for measuring sap-flow in thin plant stems designed by Dynamax Inc. based on the heat-balance theory was applied in wheat (*Triticum aestivum*) grown under ambient field conditions. The sensor measures axial and radial temperature changes in a constantly heated and thermally insulated stem section. The temperatures are altered by sap-flow activity and this information is used to solve the stem energy balance equation with respect to its convective heat flow residual which indicates sap-flow. Results from four different field experiments show that the majority of heat energy input was diverted to radial heat flow, leaving only little energy partitioned to convective heat flow. Determinations of gravimetric sap-flow were extremely noisy in consequence, rendering the method unreliable for practical application. Temperature differences across the heater consistently correlated with fluctuating net-radiation however, which motivated us to establish an empirical method for determining gravimetric sap-flow based on this temperature information alone. Numerical simulations showed that gravimetric sap-flow and temperature difference are nearly linearly and positive correlated within an observed sap flow range between 0 and 1.7 g h^{-1}, beyond which the relation became non-linear and even inverse at higher velocities. It remains to be tested whether such higher fluxes can be reached in practice and we provide a solution for these cases. Statistical noise overrode the error introduced by assuming a linear relation between sap flow and temperature difference within the range between 0 and 1.7 g h^{-1}. The resulting factors were determined under stable sap flow conditions greater than 1 g h^{-1} and used for generating daily cycles of sap flow using temperature information alone. The approach was successfully validated in 2011 and 2012 against independent measurements of latent heat flux conducted in closed and dense wheat fields using the eddy-covariance technique. We thereby improved the application of the new micro-sensor in wheat. Suggestions for further enhancements of the method are discussed.

1. Introduction

Thermoelectric methods for measuring sap flow in plants are frequently applied in studies of plant-water relations (Cohen, 1994; Smith and Allen, 1996). The constant power stem heat balance method is particularly recommended for application when sap flow is low (Cohen, 1994) or stem diameters are smaller than 10 mm (Senock and Ham, 1993). Automated temperature measurements across defined axial and radial dimensions of a stem section are taken in this method for determining the partitioning of input energy from a circular heater into convective heat which indicates sap-flow and conductive heat (Sakuratani, 1981; Baker and van Bavel, 1987). It has been successfully applied in a large variety of plant species (Dynamax Inc. Houston, Texas, USA) including soybean (Sauer et al., 2007), maize (Cohen al., 1993), cotton (Dugas, 1990), coffee (Meinzer et al., 1992), grapewine (Escalona et al., 2000), maple (Wullschleger et al., 1998), peach (Massai and Remorini, 2000), beech (Steppe and Lemeur, 2004), oak (Katul et al., 1997) and tropical trees (Meinzer et al., 1993).

Dynamax Inc. (2009) offers stem heat balance sensor models for different stems sizes and has recently introduced a new micro-sensor to facilitate sap-flow measurements in thin stems with diameters ranging between 2.1 and 5 mm (SGA2 and SGA3 models, Dynamax, 2009). We used this sensor type for determining sap-flow in commercially grown winter wheat (*Triticum aestivum*) and tested the results against independent measurements of latent heat flux. When initially applied under sunny midday weather conditions, 8% of the available input energy was partitioned to conductive

* Corresponding author. Tel.: +49 228732871.
E-mail address: matthias@langensiepen.net (M. Langensiepen).

0168-1923/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agrformet.2013.11.007

heat. Average partitioning was typically less than 2%. Since convective flux is calculated as the residual of the stem heat balance equation, slight changes in conductive heat caused drastic fluctuations in calculated sap flow. We hypothesize that these fluctuations do not originate from thermal noise which would result from insufficient shielding of the measuring device against ambient air or loose contacts between sensors and stems, but are instead an inherent property of the micro-sensor method when applied to wheat.

Reported partitioning of heat input energy to convective heat flux is normally far higher in other plant species than observed in this study and typically ranges between 30% and 60% under midday conditions, depending on soil water availability (Senock et al., 1996; Herzog et al., 1997; Gerdes et al., 1994; Kjelgaard et al., 1997). In a numerical exercise, Baker and Nieber (1989) examined the effects of sap flow and vascular bundle distribution on the heat field deformation around the stem heater. They concluded that the theoretical assumptions of the heat balance method are more applicable to dicotyledonous plants with vascular tissues located at the stem periphery, than to monocotyledonous plants in which they are distributed across the stem cross-sectional area. However, this is not the case for wheat and other grass species of the monocotyledonous *Poaceae* family in which vascular tissues are located within the hollow stem perimeter, as it is also the case in dicotyledonous plants. Thermal disequilibrium (i.e. heat storage), an error source when the stem heat balance method is applied to plant species with medullary and vascular parenchyma (Grime and Sinclair, 1999; Steppe et al., 2005), cannot occur in these plants because the heat storage capacity of stem air is negligible. In contrast to other observations reported in the literature (Senock and Ham, 1993) we noted marked diurnal patterns of temporal changes in temperature differences across the heater during all days which closely correlated with diurnal patterns in canopy net radiation which drives transpiration.

The aim of this study was to examine and improve the heat balance technique for application in thin, hollow wheat stems. In particular we test two hypotheses: (1) The low values of convective heat are caused by the thermal properties of the thin, hollow wheat tillers and (2) the observed changes in temperature differences across the heater are caused by variations in sap flow.

2. Theory

The installation of a heat-balance sensor around a hollow, thin wheat internode is illustrated in Fig. 1. Heat input from a circular heater (Q_h) is conducted outwards (Q_r) and inwards from the heater surfaces, the rate depending on the thermal properties of the adjacent materials (see Smith and Allen (1996) for further details). Convective sap flow (J_w) in the thin internode wall insufficiently cools down the heating element which is why most heat is emitted radially (Q_r) into the sheath material and inwards through the stem wall into the internode air. Heat convection in the trapped stem air can, however, only insufficiently cool the heater due to its low specific heat (Table A1). The major portion of available heat (Q_h) is thus conducted outwards into the sheath material as radial heat (Q_r), leaving only little energy partitioned to convective heat (Q_f) which indicates sap flow (Fig. 2).

The mathematical solution of the heat balance equation for determining sap flow in plants is only briefly summarized here since it has been covered extensively in the literature (Sakuratani, 1981; Baker and van Bavel, 1987; Ishida et al., 1991).

Assuming a steady state condition for stem temperature during a small time interval, water flux J_w (g s^{-1}) through vascular tissues can be quantified with (Senock and Ham, 1993)

$$J_w = \frac{Q_h - Q_v - Q_r}{C_w(T_d - T_u)} \quad (1)$$

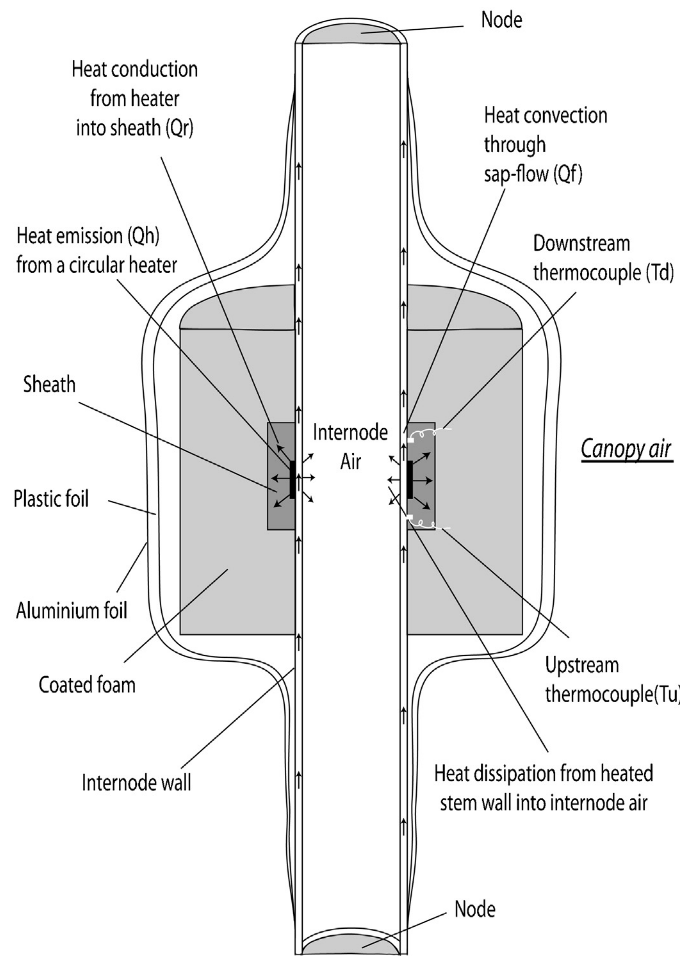

Fig. 1. Illustration of a heat-balance sensor installation on a hollow wheat internode. Heat emitted from a circular heating element is partitioned into conductive heat (Q_r) and convective heat (Q_r) which indicates sap flow. Only one pair of thermocouples is used for measuring downstream (T_d) and upstream (T_u) temperatures of the sap-conducting internode wall which is why, by design, axial heat conduction (Q_v) is set to zero. The low specific heat of the entrapped air prevents significant radial heat emission into the internodium. Heat exchange with the canopy air is prevented by using cork, coated foam, and silver foil insulation material. We additionally wrapped a layer of plastic foil around the device to prevent intrusion of rainwater.

where Q_h is the constant energy input into a stem section generated by a circular heater, Q_r the radial heat loss determined in the insulating sheath material of the sensor determined during nighttimes and set constant during the day, and Q_v the apical and basal heat conduction along the stem axis quantified with Fourier's equation (all expressed in W). As recommended by the manufacturer (Dynamax, 2009), thermal conductivity of a hollow tiller is set to a constant value (0.28 W m^{-1} K^{-1}) and sheath conductance determined under zero flow conditions during night time. T_d and T_u are the stem temperatures (K) measured at defined distances downstream and upstream from the heater, respectively, and C_w is the specific heat of water (4.18 J g^{-1} K^{-1}).

In contrast to larger heat balance sensors distributed by Dynamax, in which two pairs of thermocouples are embedded in the inner sensor wall for measuring T_d and T_u, the new sensor SGA3 tested in this study uses only one pair of thermocouples for this purpose. By design, Q_v was set to zero and Q_r compensates for any missing energy in the heat balance (Dynamax, 2009). Q_v is thus lumped into a residual term that is estimated from the output of the radial thermopile.

A typical daily cycle is shown in Fig. 2 which is characterized by strong fluctuations of these variables. The marked diurnal