Calibration of Stem Heat Balance Sensors upon a Study of Water Balance of the Hop Plantation

J. Urban
Department of Forest Botany,
Dendrology and Geobiocenology
Mendel University in Brno
Zemědělská 3, 61300 Brno
Czech Republic

K. Krofta
Hop Research Institute Co. Ltd
Žatec
Czech Republic

J. Kučera
EMS Brno
Turistická 5, Brno
Czech Republic

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Abstract

Evapotranspiration of the Czech hop cultivar Agnus (*Humulus lupulus* L.) plantation was investigated during three consecutive growing seasons. We measured two components of the water balance: total evapotranspiration (using the Bowen ratio energy balance method) and transpiration of the bines (using the stem heat balance sensors type EMS SF 62). Actual evapotranspiration peaked when the crop was fully developed, at 80 - 90% of the potential evapotranspiration. Most of the water was evaporated and less than half of the total amount of vaporized water was transpired (the partitioning depended on a stage of crop development). EMS heat balance sensors don't require any empirical calibration. However, to ensure the correctness of the sap flow measurements, a calibration of the sap flow sensors was performed. Just before the harvest, a total of eighteen bines were removed from the plants and their water uptake was measured potometrically (volumetrically). Accuracy of the sap flow measurement was -3 % when compared against potometry.

INTRODUCTION

Transpiration and evaporation usually comprise the major part of the water loss from natural ecosystems. The ratio of the transpiration to the total evaporative water loss typically ranges from zero (e.g. a pre-emergent field crop) to almost 100% (e.g. a fully-closed canopy). The total evapotranspiration and the transpiration (or sap flow) of the vegetative cover can be measured separately and the evaporation can be calculated as a difference between these two values. As there is no direct method to measure the evaporation from the plant surfaces, the precise and correct measurements and up-scaling of the sap flow is necessary. Measurement of the sap flow, with the thermal-based methods, on the small diameter liana vines presents a significant challenge because the high flow rates increases the discrepancy between the needle-based and volume-heating based methods (Lundblad et al., 2001; Tatarinov et al., 2005).

In this paper we assess the performance of the last modification of trunk heat balance "baby" sensor (SF 62, manufactured by EMS Brno, Czech Republic) to the measurements of sap flow in hop bines. This sap flow system is based on purely physical principles and therefore calculation of sap flow doesn't require any empirically derived coefficients. Sap flow (Q_w [kg cm^{-1} h^{-1}]) is calculated from heating power (P [W]), temperature difference between heated and reference part of the measuring point (dT [K]) and specific heat of water (c_w [J kg^{-1} K^{-1}]) following the equation:

$$Q_w = \frac{P}{c_w * dT} - \frac{z}{c_w}$$

The term z/c_w represents heat losses from the heated part of the measuring point.

Those heat loses are estimated as the heat losses at the period when there is certainly no sap flow through the stems (i.e. during rainy periods or during the night with zero vapor pressure deficit). This heat loss is usually constant in the longer time period (i.e. several weeks). Even the positive night flows are measured in this way. This type of sensor was used for the first time to measure sap flow of a reed (Rychnovska et al., 1980). An improved version of the sensor was used on willow stems (Cienciala and Lindroth, 1995) and then successfully compared to eddy-covariance measurements (Lindroth et al., 1995). The commercially available sensor was first marketed in 1992 and the last upgrade, which decreases the chances of poor installation, was in 2008.

Here we have used a 'baby' trunk heat-balance sensor to measure sap flow in a hop (*Humulus lupulus* L.) plantation. At the same time, evapotranspiration was measured using the Bowen Ratio Energy Balance method. In order to assure the reliability of the measured transpiration and the calculated evaporation, we also performed a potometrical calibration of the sensors. The aims of this paper are: (1) to quantify sap flow and evaporation losses from a hop plantation and (2) to provide a calibration of the sap flow sensors for vines and branches with diameters between 6 to 20 mm.

MATERIAL AND METHODS

Experimental Site and Stand

The research site was located on an experimental farm at the Hop Research Institute in Steknik, (5 km from Zatec) Czech Republic. The altitude of the plot is 201 m a.s.l. Mean annual temperature is 9°C and the annual precipitation is 458 mm. Soil water availability at the site was unlimited throughout entire growing season since the groundwater table was within reach of plant roots. Soil surface was bare (ploughed) and usually wet. The hop bines were planted in 3 m wide rows at spacing of 1 m between the individual plants. Typically there were 4 bines on each plant, and approximately 11100 bines per ha. The mean diameter of the bines, measured in a height of 1 meter above ground, was 7.1 cm at the time of harvest (i.e. 9th September) (Fig. 1). Bines reached a maximum height of 7 meters (Fig. 2). Mean leaf area of an individual bine was 1.7±0.66 m^2.

Sap Flow Measurements

Sap flow was measured during the three consecutive seasons 2008-2010, using 8 to 12 bines. The trunk heat balance method was used with external heating and constant temperature difference of 4°C between the heated and reference point (SF 62, EMS Brno, Czech Republic, Fig. 3). Sensors were installed 1 m above ground to avoid large temperature gradient effects close to the ground surface (Fig. 2b). Data were collected every minute and 10 minute averages were stored in the memory of the datalogger (Edgebox V12, EMS Brno, Czech Republic). The approach of Čermák et al. (2004) was used to upscale sap flow data from individual bines to the unit of area of the plantation: (1) Regression analysis was used to derive a relationship between bine diameter [mm] and seasonal sap flow (Fig. 4). The number of bines per hectare was estimated by counting the bines at four randomly selected rectangular plots (area of each plot was 650 m^2) and corresponding diameter distribution was sampled. Bine diameters were sorted into diameters classes of 0.5 mm resolution. (2) Transpiration losses were calculated from the product of bine number in each diameter class multiplied by the corresponding sap flow of a single bine with the class-average diameter, as estimated from the regression. (3) The total seasonal sap flow from all diameter classes was divided by the total sap flow of the sample bines during the same period. This calculation was used to derive a scaling factor that links water transpired by the sample bines and by the entire stand. Diurnal courses of sap flow for the entire stand [kg ha^{-1} h^{-1}] were derived by taking actual (i.e. 10 minute) sums of the sap flow from sample bines [kg n_bines^{-1} h^{-1}] and multiplying by the scaling factor.

Evapotranspiration Measurements

Air temperature and relative humidity data for the Bowen ratio method was measured at the three heights above the experimental stand using EMS 33 temperature and humidity sensor (EMS Brno, Czech Republic), that were mounted at heights of 5.5, 7.5 and 9.5 meters above ground. Net radiation was measured with Schenk net radiometer (model 8110, Schenk, Austria). Data were collected at 1-minute intervals and ten-minute averages were stored and used for the calculation. Consistency among different heights assured the reliability of the measurements and values of the evapotranspiration from the different height were used to complete any gaps in the dataset. Reference evapotranspiration was calculated following the Penman-Monteith approach for grass surface (Allen et al., 1998). For the purpose of calculation wind speed (which hadn't been measured) was set to a constant value 1 m s^{-1}.

Calibration of Sap Flow Sensors

Accuracy of the sap flow sensors was tested by direct comparison between sap flow measured by the sensor and sap flow estimated potometrically (volumetrically). Measurements were performed on a total of 18 bines in three periods - 27th August 2008 (4 bines), 6th September 2009 (2 bines) and 11th September 2010 (12 bines). Bines already equipped with sap flow sensors (sensors were installed at the beginning of season) were cut under water and immediately immersed into a measuring cylinder (Fig. 5). Water consumption from the cylinder ($SF_{potometer}$) was measured at one-hour intervals during 3-4 subsequent hours. Data from the sap flow probes (SF_{probe}) were obtained every minute and ten-minute averages were recorded. The heat losses from the measuring point were assumed the same as previous day. Sap flow values obtained by these two methods were then directly compared and the corresponding error [%] was calculated as:

$$Error = \frac{SF_{probe} - SF_{porometer}}{SF_{porometer}}.100$$

The mean error of the sap flow probe was calculated as a mean value from the absolute values of the errors calculated for the individual sensors.

RESULTS AND DISCUSSION

Transpiration and Evapotranspiration

During an almost cloudless day (3rd July 2009) the total evapotranspiration loss (ET) from the hop plantation reached 5.4 mm per day. Transpiration losses from the hop bines accounted for just 1.5 mm (29% of the total ET), while the remaining 71% of water loss was attributed to evaporation from the ground surface, which was ploughed and bare. Last precipitation (14 mm) occurred 3 days ago on 30th June (Fig. 6). The fraction of transpiration to total ET progressively increased towards the end of the season, reflecting the growth of the bines. Towards the end of the growing season (August), hop transpiration comprised 44% of the total vaporized water loss from the plantation. This end of season value is quite low compared with data from other crops – e.g. 70% at wheat and maize (Liu et al., 2002), or 95% at soybean (Sakuratani, 1987). Low partitioning of transpiration is the result of a low leaf area index of hops (LAI = 1.9 m^2 m^{-2}) and a vertical arrangement for the leaf canopy (Fig. 2a). A high portion of solar radiation was transmitted through the canopy and reached the soil surface, thus increasing soil evaporation losses.

Calibration

Transpiration losses from individual bines varied between 30 and 305 g h^{-1}. The average transpiration loss from the 16 bines measured potometrically was 123 g h^{-1} while the EMS sap flow system measured 119.3 g. The average error of the heat balance measurements was -3 %. The average error of individual bine measurements was ±10.2% (Fig. 7). Our calibration tests showed the EMS SF62 sensors have great applicability to the measurements of sap flow in small diameter stems (up to 20 mm) over a broad range of sap flow rates, at least up to 0.3 kg h^{-1}.

CONCLUSIONS

1. Transpiration losses from hop bines, even when the leaf canopy is fully developed, are less than 50% of the total evapotranspiration from the hop plantation.
2. SF62 trunk heat balance sensors are suitable to accurately (+/- 10%) measure sap flow in stems of small diameter (up to 2 cm) over the wide range of the flow rates, up to 0.4 kg h^{-1}.

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Figures

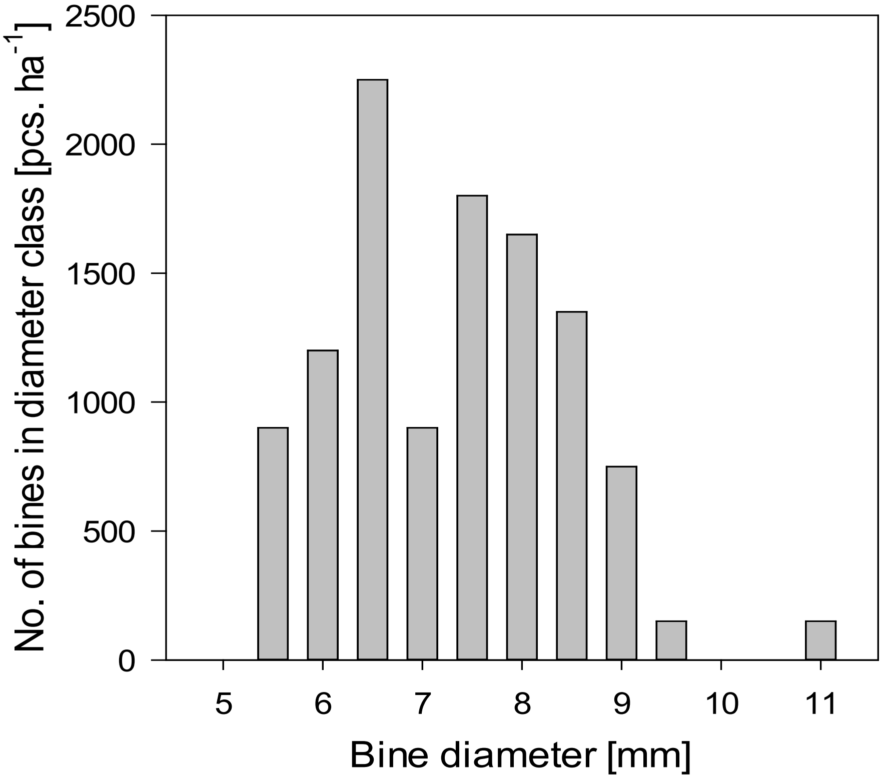

Fig. 1. Size and distribution of the bines from a hop plantation measured at the end of growing season (2nd September 2009).

Fig. 2. A – left: arrangement of hop bines in a plantation (2nd August). B – right: example of installed EMS SF62 sensors covered with the radiation shield (7th June).

Fig. 3. View of the EMS SF62 sensors with external heating.

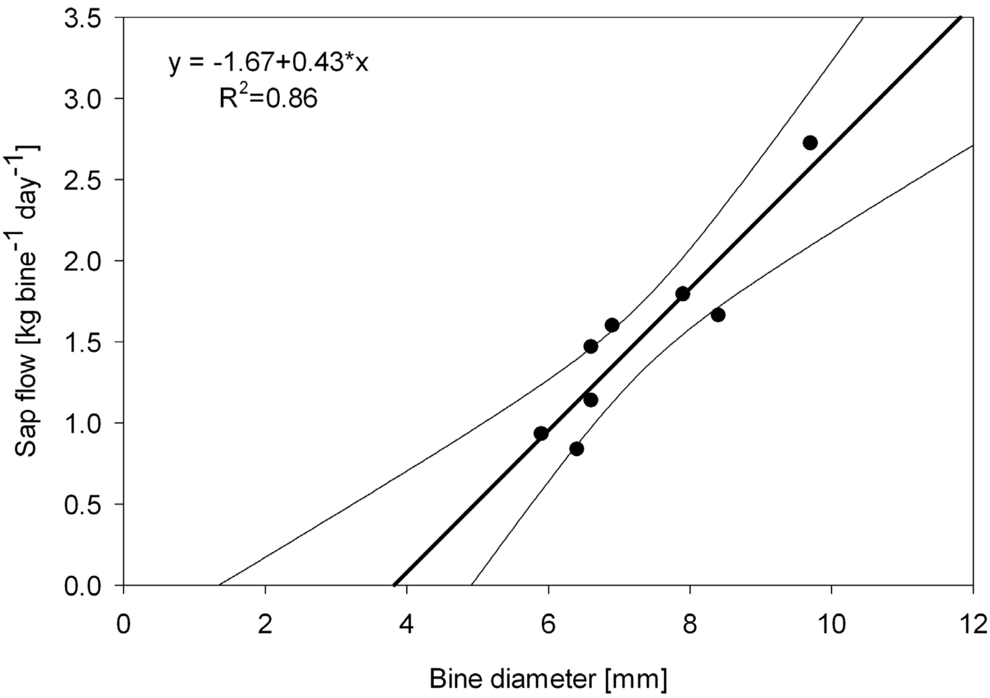

Fig. 4. Regression between diameter of the bine and daily mean value of the sap flow (estimated as sum of sap flow during the entire period divided by the number of days) over the period 29/6/2009 – 7/9/2009.

Fig. 5. Potometrical measurements of sap flow.

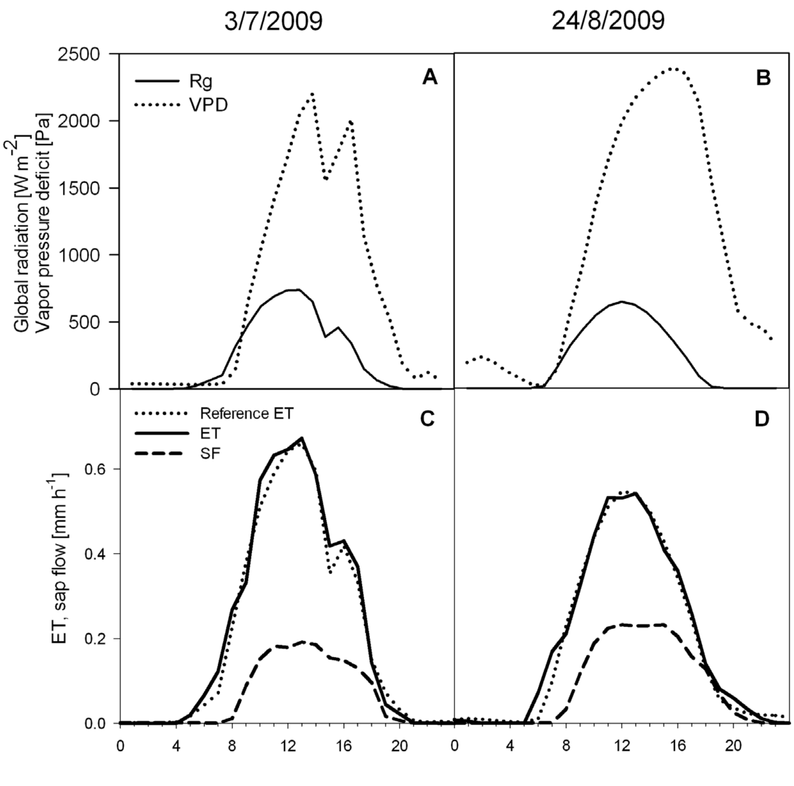

Fig. 6. Diurnal courses of Penman-Monteith based reference evapotranspiration, stand evapotranspiration (ET) calculated using the Bowen Ratio method, and sap flow during two days – 3rd July (panel C - low proportion of the sap flow to total ET in a beginning of the growth of the bines) and 28th August (panel D - higher proportion of the sap flow to the total ET in the end of the season). Corresponding curves characterizing the global radiation (Rg) and vapor pressure deficit (VPD) are on the panels A and B.

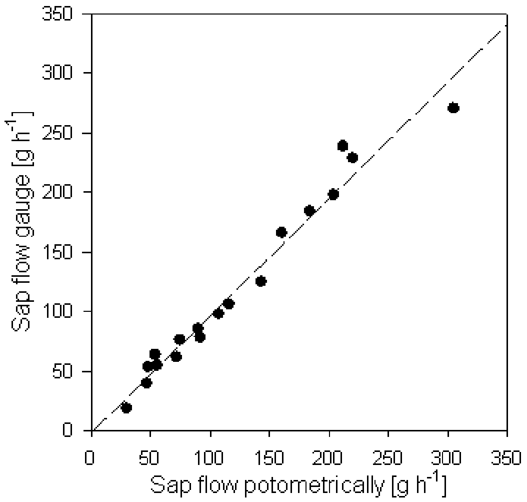

Fig. 7. Regression between sap flow measured potometrically and by the EMS SF62 sap flow system.