Transpiration – an Important Contribution to Overall Water Balance of the Hop Plantation

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Abstract

Transpiration of the Czech hop 'Premiant' (*Humulus lupulus* L.) plantation was investigated during three consecutive growing seasons and compared with Penman-Monteith based reference evapotranspiration and transpiration estimated by FAO dual crop approach. We measured the sap flow of the twelve individual bines (using the stem heat balance sensors type EMS SF 62). Actual bine transpiration peaked in August, when the crop was fully developed, at less than 3 mm day^{-1}, which was 60% of the reference evapotranspiration and only 65% of the transpiration estimated by dual crop approach. Seasonally, most of the water was potentially evaporated from the soil surface and transpired by the understory vegetation (i.e. weeds). Less than half of the total amount of vaporized water was transpired (the partitioning depended on a stage of crop development), which makes space for the water-saving techniques in hop growing.

INTRODUCTION

Evapotranspiration is usually the main part of the total water loss from the agriculture based ecosystems. The proportion of the transpiration to the evapotranspiration typically ranges from zero (bare soil) to almost 100% in a fully developed closed canopy. However, especially in open canopies, water evaporation from the bare soil surface or transpiration of understory weeds may be more important than transpiration of the crop itself. Irrigation is often necessary to maintain survival and correct growth of the plants. Therefore, suppression of the evaporative water loss and reduction of understory transpiration may be one of the water-saving techniques, that reduces need for the irrigation.

This contribution is focused on the transpiration of hop bines and its comparison with reference evapotranspiration and FAO based transpiration estimate from the given crop. We measured crop transpiration by the means of sap flow measurements under the assumption of long term equality of sap flow and transpiration. Measurement of the sap flow, with the thermal-based methods, on the small diameter liana vines is 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). However, in our previous contribution (Urban et al., 2012) we proved that used stem heat balance sensors model EMS SF62 was capable of accurate estimation of the sap flow in the hop bines with the mean error of 3% in the broad range of flows up to 0.4 kg h^{-1}. Here we have used a 'baby' trunk heat-balance sensor to measure sap flow in a hop (*Humulus lupulus* L.) plantation. Another way of estimation of transpiration and evapotranspiration is a FAO dual crop approach (Allen et al., 1998). The water loss is estimated as a fraction of Penman-Monteith reference evapotranspiration with respect to the seasonal crop development.

The aims of this paper are: (1) to quantify seasonal development of sap flow in a hop plantation and (2) to compare the measured sap flow in different parts of the season with the theoretical water loss estimated using FAO approach – specifically reference crop evapo-transpiration calculated according to Penman-Monteith and dual crop coefficient-based estimate.

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 (50°19'23"; 13°37'24"). 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 limited in some parts of the growing season (Fig. 1) since the groundwater table was not within reach of plant roots. Soil surface was bare (ploughed). The undestory vegetation (i.e. weeds) appeared during the growth season and fully covered entire soil surface. 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 mm at the time of harvest (i.e. 2nd September) (Fig. 2). Bines reached a maximum height of 7 meters (Fig. 3). Mean leaf area of an individual bine (±standard deviation) was 1.7±0.66 m^2.

Sap Flow Measurements

We used the last modification of a trunk heat balance "baby" sensor (SF 62, manufactu-red by EMS Brno Inc., 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:

$$Q_w = \frac{P}{c_w * dT} - \frac{z}{c_w} \quad (1)$$

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 was released in 2008. Sensors were successfully used on the hop bines (Urban et al., 2012).

Sap flow was measured on 12 bines from 6 June until 28 August 2012 (81 days). The trunk heat balance method was used with external heating and constant temperature difference of 4°C between the heated and reference point (Fig. 4). Sensors were installed 1 m above ground to avoid large temperature gradient effects close to the ground surface (Fig. 4). 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. 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 min.) sums of the sap flow from sample bines [kg n_bines^{-1} h^{-1}] and multiplying by the scaling factor.

Reference Evapotranspiration and FAO Based Transpiration

Reference evapotranspiration was calculated following the Penman-Monteith approach for grass surface (Allen et al., 1998). All necessary meteorological variables like air tempera-ture, relative humidity and wind speed were measured using EMS 33 temperature and humidity sensor (EMS Brno, Czech Republic) and MetOne anemometer (MetOne Inc., USA) respec-tively. Data were measured at 2 m height above short trimmed lawn ca. 200 m from the site. Net radiation was measured with a Schenk net radiometer (model 8110, Schenk, Austria) positioned above studied canopy. Data were collected at 1 minute intervals while ten minute averages were stored and used for the calculation. Transpiration was calculated from the reference evapotranspiration using FAO dual crop coefficient (Allen et al., 1998). Crop coefficients values were used as recommended in FAO brochure however we adjusted length of the phases to reflect the crop development (Fig. 3). Therefore, the period before 31 May was regarded as initial phase and time period from 30 July until 28 August as middle season phase.

RESULTS AND DISCUSSION

The sum of reference evapotranspiration during 81 investigated days (from the early June to the end of August) was 292 mm, while amount of water actually transpired by the bines was only 139 mm. During the spring, from 1 April until 6 June, the reference evapotranspiration was 218 mm. The bines were too small for sap flow measurements in this period. However, we may assume their transpiration generally very low. For example crop transpiration comprised only 19% of the total reference evapotranspiration during the first two weeks of sap flow measure-ment. Ratio of a transpiration to reference evapotranspiration progressively increased towards the end of the season, reflecting the growth of the bines. At the end of the season, in August, hop transpiration comprised 60% of the reference evapotranspiration (Fig. 5).

Two periods of drought stress appeared during the season. First of them occurred at the end of July, second one in the middle of the August (Fig. 1). The fraction of transpiration to the reference evapotranspiration was normally (when the soil water availability was unlimited) about 60% in sunny days and about 80% in partly cloudy days. However during the dry periods transpiration was less than 50% of the reference, thus indicating water stress in a plants (Fig. 5). FAO based estimate of mid-season evapotranspiration in a hop crop is 105% and typical transpiration comprises 100% of the reference evapotranspiration (Allen et al., 1998). In our plantation, however, a portion of crop transpiration to reference evapotrans-piration when the bines were fully developed was less than 60%. Cumulative transpiration from the sap flow measuremets was 139 mm while FAO estimate for the same time period was about two thirds higher – 234 mm (Fig. 6). This discrepancy may be a result of different agronomical techniques (i.e. different bine density resulting in higher the soil surface coverage) in hop growing between Idaho (where the FAO approach was verified) and the Czech Republic. Therefore it is necessary to adjust the calculation of water use in a crop not only to the length of the development stages (as recommended by FAO) but also to the site specific value of the crop coefficient.

This mid-season season ratio of transpiration to the reference evapotranspiration is lower than in other crops – e.g. 70% at wheat and maize (Liu et al., 2002), or 95% at soybean (Sakuratani, 1987). The reason for low partitioning of a transpiration may be low leaf area index of hops (LAI = 1.9 m^2 m^{-2}) and a vertical arrangement for the leaf canopy (Fig. 4). A high portion of solar radiation is therefore transmitted through the canopy and reaches understory vegetation or the soil surface, thus increasing evapotranspiration losses.

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Figures

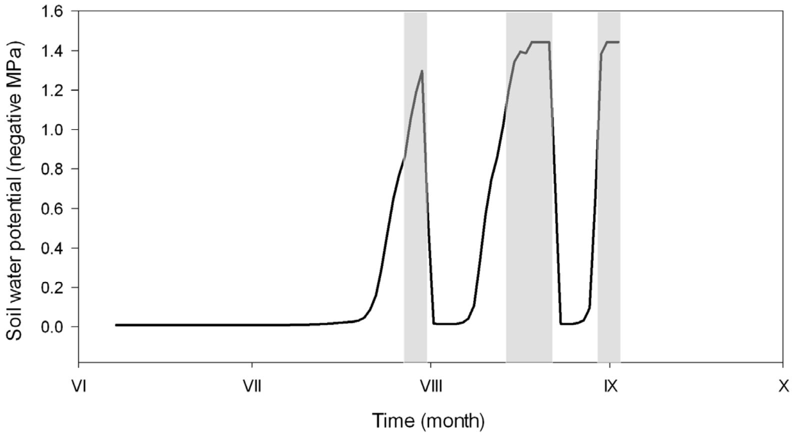

Fig. 1. The soil water potential (- MPa) at depth 20 cm. Dry episodes, which are highlited by gray background, were defined as periods of the water potential lower than -1 MPa.

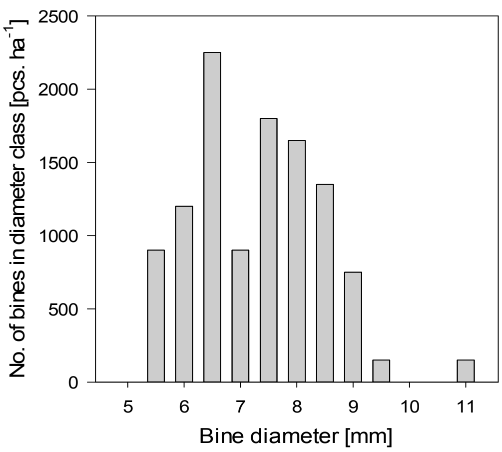

Fig. 2. Size and distribution of the bines from a hop plantation measured at the end of growing season (2nd September 2012).

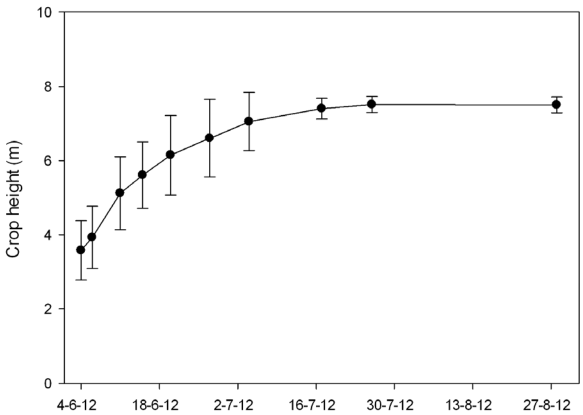

Fig. 3. Height growth of the bines. Data symbols are means of twelve bines used for the sap flow measurements ± standard deviation. The height growth corresponds with increase in the plant transpiration (Fig. 5).

Fig. 4. General view of the plantation with fully developed bines (2nd August), details of sensor installation without and including the radiation cover (6th June) and view of the plantation after harvest (5th September 2012).

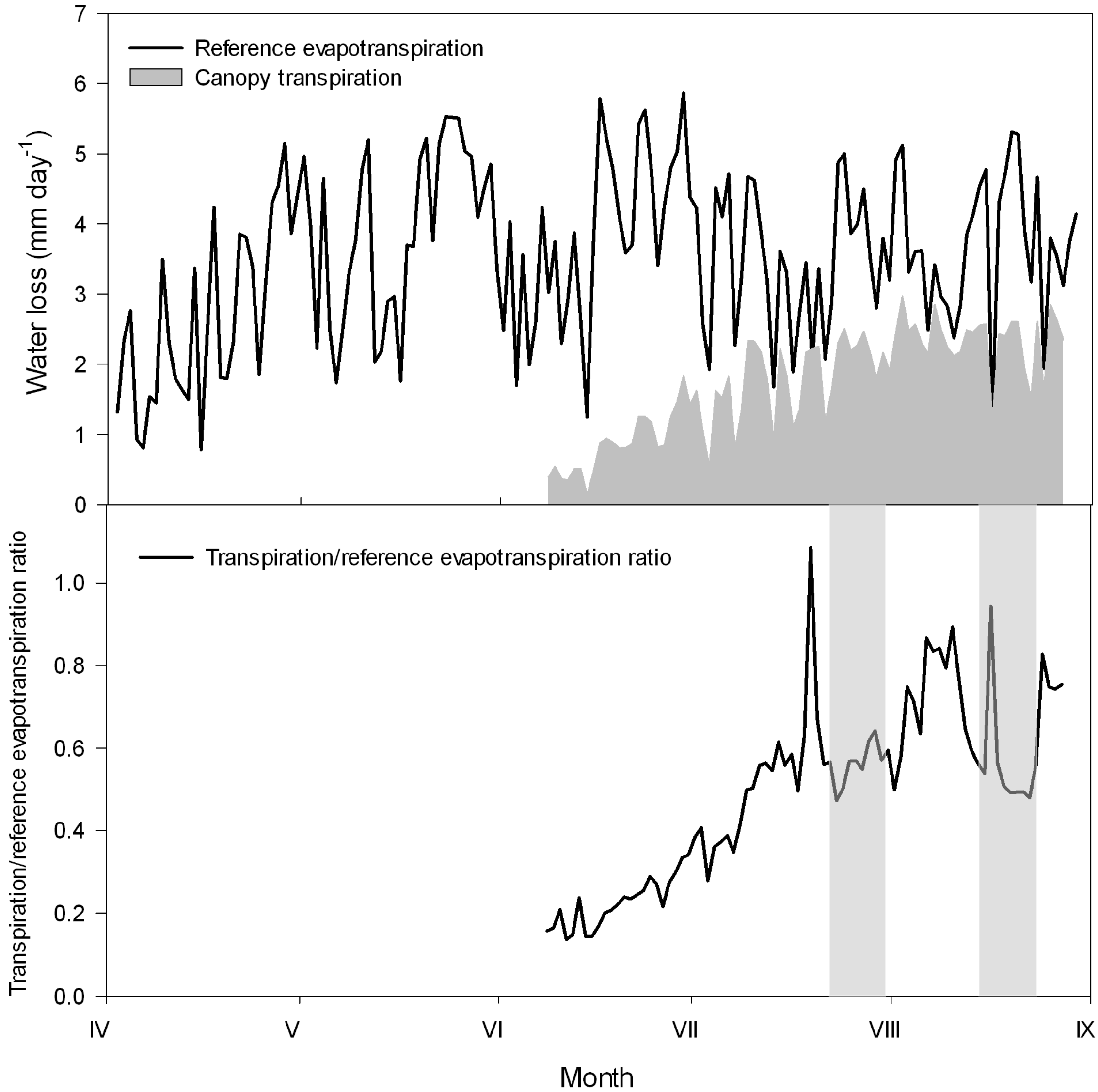

Fig. 5. Upper panel: seasonal development of daily sums of the hop transpiration and reference evapotranspiration. Bottom panel: ratio of the daily sums of sap flow to the sum of reference evapotranspiration. Dry periods corresponding to the Figure 1 are highlighted with gray background.

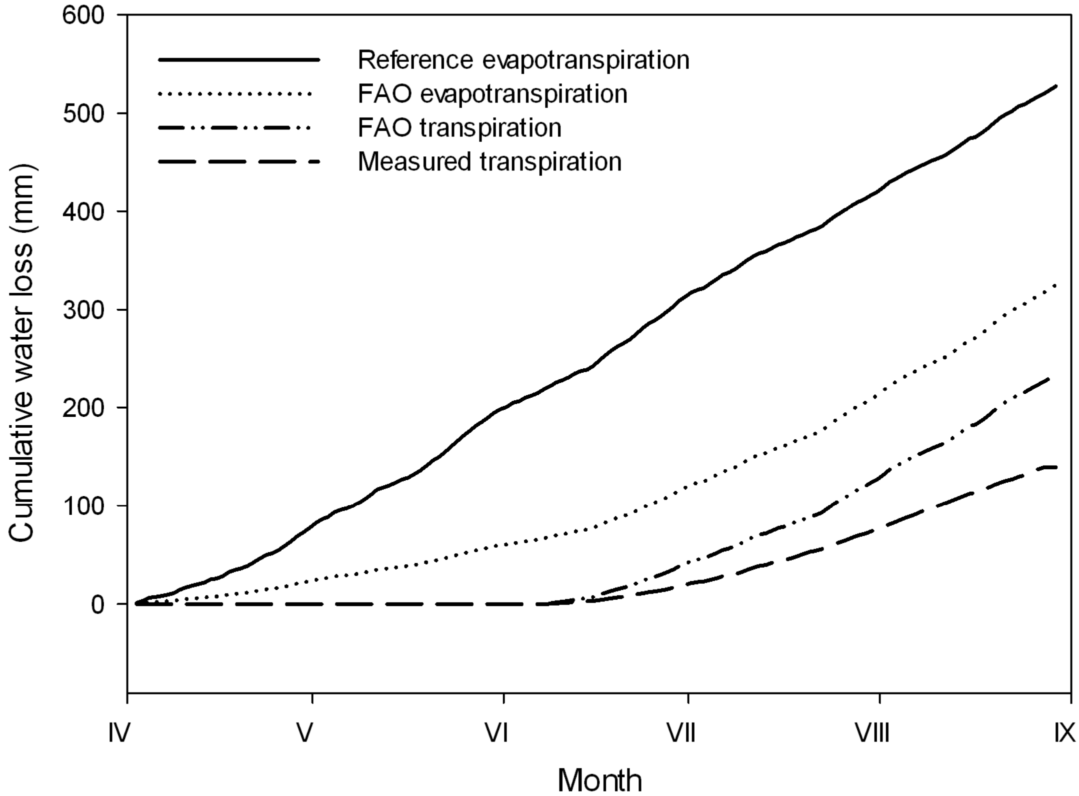

Fig. 6. Cumulative values of reference evapotranspiration, FAO based estimates of crop evapotranspiration and transpiration (using dual crop approach) and actually measured bine transpiration.