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Water requirements of short rotation poplar coppice: Experimental and modelling analyses across Europe

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A B S T R A C T

Poplars are among the most widely used short rotation woody coppice (SRWC) species but due to their assumed high water use, concerns have been raised with respect to large-scale exploitation and potentially detrimental effects on water resources. Here we present a quantitative analysis of the water requirements of poplar SRWC using experimental data and a soil water balance modelling approach at three different sites across Europe. We used (i) eddy covariance (EC) measurements (2004–2006) at an irrigated SRWC grown on a previous rice paddy in northern Italy, (ii) Bowen ratio and energy balance (BREB) measurements (2008–2015) and EC (2011–2015) at a SRWC in rain-fed uplands in the Czech Republic, and (iii) EC measurements (2010–2013) at a SRWC on a previous agricultural land with a shallow water table in Belgium. Without any calibration against water balance component measurements, simulations by the newly developed soil water balance model R-4ET were compared with evapotranspiration (*ET*) measurements by EC and BREB with a resulting mean root mean square error (*RMSE*) of 0.75 mm day^{-1}. In general, there was better agreement between EC and the model (*RMSE* = 0.66 mm day^{-1}) when EC data were adjusted for lack of energy balance closure. A comparison of the simulated and measured soil water content yielded a mean *RMSE* of 0.03 m^3 m^{-3}. The mean annual crop coefficient, i.e. the ratio between actual and reference *ET*, was 0.82 (ranging from 0.65 to 0.95) while the monthly maxima reached 1.16. These values indicated that *ET* of poplar SRWC was significantly lower than *ET* of a well-watered grass cover at the annual time scale, but exceeded *ET* of the reference cover at shorter time scales during the growing season. We show that the model R-4ET is a simple, yet reliable tool for the assessment of water requirements of existing or planned SRWC. For very simple assessments on an annual basis, using a crop coefficient of 0.86 (adjusted to a sub-humid climate), representing an average value across the three sites in years with no evident drought stress, is supported by this analysis.

1. Introduction

Short rotation woody coppice (SRWC) cultures of *Populus* (poplars) and *Salix* (willows) are well known for high productivity, which make them suitable as bioenergy crops (Anderson et al., 1983; Isebrands and Richardson, 2014; King et al., 2013). To ensure high SRWC yields, a sufficient water supply is required (Deckmyn et al., 2004; Kim et al., 2008). Maintaining a favorable soil water balance typically relies on adequate and well-distributed precipitation or on access to a shallow water table, which in turn requires careful site selection (King et al., 2013; Lindroth and Båth, 1999; Trnka et al., 2016). In most cases, irrigation of SRWC is economically inefficient and environmentally unsustainable (Kim et al., 2008; Persson, 1997). Moreover, bioenergy is a low-input commodity and any increase of (energy) inputs and carbon footprint inherently linked with intensive management, is undesirable (Djomo et al., 2011; Fischer et al., 2017; King et al., 2013).

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Nomenclature

AWB	Above-ground woody biomass
BE	Belgium
Bowen adj.	Post closure scenario with energy residuum assigned to both turbulent energy fluxes according to Bowen ratio
BREB	Bowen ratio and energy balance
CP	Closed path
CZ	the Czech Republic
EC	Eddy covariance
EP	Enclosed path
ET	Actual evapotranspiration (mm day^{-1})
ET_o	Reference evapotranspiration (mm day^{-1})
FAO-56	Food and Agriculture Organization of the United Nations guidelines for computing crop water requirements
F_r	Stomatal resistance correction factor
G	Soil heat flux (W m^{-2})
h	Mean stand height (m)
H	Sensible heat flux (W m^{-2})
H adj.	Post closure scenario with energy residuum assigned only to *H*
IT	Italy
K_c	Crop coefficient
K_{cb}	Basal crop coefficient
$K_{cb\ full}$	Basal crop coefficient of fully developed canopy
$K_{cb\ h}$	Basal crop coefficient estimated from mean stand height
$K_{c\ min}$	Minimum crop coefficient
K_e	Soil evaporation coefficient
K_{SAT}	Saturated hydraulic conductivity (mm day^{-1})
LAD	Leaf area duration (days)
LAI	Leaf area index (m^2 m^{-2})
LE	Latent heat flux (W m^{-2})
LE adj.	Post closure scenario with energy residuum assigned only to *LE*
ME	Mean error
n	Number of observations
NSE	Nash–Sutcliffe model efficiency coefficient
OP	Open path
p	Crop specific stress parameter adjusted to actual reference evapotranspiration
P	Precipitation (mm)
P.	*Populus*
p_{tab}	Crop specific stress parameter at reference evapotranspiration of 5 mm day^{-1}
PAI	Plant area index (m^2 m^{-2})
r	Stomatal resistance (s m^{-1})
R-4ET	R-package for Empirical Estimate of Ecosystem EvapoTranspiration
R^2	Coefficient of determination
R_G	Incoming short-wave radiation (W m^{-2})
R_n	Net radiation (W m^{-2})
RH_{min}	Minimum daily air relative humidity (%)
RMSE	Root mean square error
SRWC	Short rotation woody coppice
SWC	Soil water content (m^3 m^{-3})
T_a	Air temperature (°C)
u_2	Wind speed measured at 2 m above ground (m s^{-1})
WAI	Wood area index (m^2 m^{-2})
WUE	Water use efficiency (g kg^{-1})

Greek letters

Δ	Slope of saturation vapor pressure curve (kPa °C^{-1})
γ	Psychrometric constant (kPa °C^{-1})
λ	Latent heat of vaporization (J kg^{-1})
θ_{FC}	Water content at the field capacity (m^3 m^{-3})
θ_{SAT}	Saturated water content (m^3 m^{-3})
θ_{WP}	Water content at the permanent wilting point (m^3 m^{-3})

From an ecological perspective, the high water use reputation of poplars and willows is related to their natural habitats near streams, water bodies or wet areas (Isebrands and Richardson, 2014; Stanturf et al., 2001). High water requirements of poplars and willows, exceeding those of traditional crops (Deckmyn et al., 2004), grasslands (Persson, 1997) and forests (Grip et al., 1989), have been reported. Consequently, some concerns have been raised with regards to the economic (Lindroth and Båth, 1999) and ecological sustainability (Hall et al., 1996, 1998; Petzold et al., 2010) of SRWC cultures. It has been hypothesized that the large scale production of SRWC could potentially have detrimental effects on aquifers (Perry et al., 2001) and could decrease the water availability of the agricultural landscape (Hall et al., 1996, 1998). A recent review (Fischer et al., 2013b) showed that some studies (Bungart and Hüttl, 2004; Linderson et al., 2007; Migliavacca et al., 2009) have relatively low *ET*, contrary to fears about exceedingly high SRWC water use. This was recently supported by other studies (Bloemen et al., 2017; Fischer et al., 2015; Schmidt-Walter et al., 2014; Zenone et al., 2015) showing that *ET* of SRWC is lower than reference evapotranspiration (ET_o) – i.e. *ET* of so called "reference grass" which is a typical reference vegetation cover characterized by no nutrient or soil water limitation (Allen et al., 1998). This may imply that water use of SRWC differs little from traditional, highly productive agricultural cropping systems (Fischer et al., 2013b; Horemans et al., 2017). Therefore, SRWC should not be limited by water availability if precipitation matches or exceeds ET_o at annual time scales, assuming an even temporal distribution of precipitation and/or soils with good water holding capacity (Fischer et al., 2013b).

The ratio between actual crop *ET* and ET_o, the crop coefficient (K_c), is a traditional agricultural metric indicating crop water requirements (Allen et al., 1998; Sánchez et al., 2012). It represents a core parameter in the agricultural water balance (Hlavinka et al., 2011; Raes et al., 2009; Rosa et al., 2012; Steduto et al., 2009) and in crop growth models (Brisson et al., 2003; Hlavinka et al., 2015; Liang et al., 2016). The Food and Agriculture Organization of the United Nations guidelines for computing crop water requirements (FAO-56) contains an exhaustive list of agricultural crop K_c values (Allen et al., 1998). For those crops for which K_c is not available (such as poplar), an estimate from plant height, ground cover, or leaf area index (*LAI*) can be applied (Allen et al., 1998).

Among the various studies on SRWC *ET*, only a few were explicitly focused on K_c (Fischer et al., 2013b). Moreover, caution is needed when applying some of the reported K_c values for upscaling and/or land-use management planning, since they were developed for very specific conditions. Early studies focused on intensively managed willows (mostly irrigated and fertilized) in Sweden, and K_c was derived by relating the measured or modeled *ET* to Penman (1948) potential evaporation (Persson, 1997; Persson and Lindroth, 1994). Sap flow based transpiration of poplars and willows in relation to ET_o was investigated during one abnormally hot and dry summer in southwest England (Hall et al., 1998). A more recent lysimetric study on poplars and willows from Italy was less representative for agricultural field conditions since *ET* measurements were carried out in a phytoremediation system with strikingly high *ET* and K_c values (Guidi et al., 2008). Finally, extremely arid conditions in a study from northwest China (Hou et al., 2010) precludes wider extrapolation of poplar K_c to common agricultural systems. The available literature on *ET* of poplars and willows was reviewed (Fischer et al., 2013b) and local experimental data were combined with long-term regional estimates of ET_o (Droogers and Allen,