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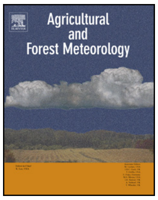

Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech–Moravian Highlands

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ABSTRACT

This study reports on 3.5 years (2008–2011) of actual evapotranspiration (*ET*) measurements of two short-rotation poplar coppice (SRC) plantations in comparison with two reference grass covers (clipped turf grass and permanent grassland) in a rain-fed area of the Czech–Moravian Highlands in the Czech Republic. The Bowen ratio/energy balance method (BREB) was used to measure the *ET* of all the four investigated covers. Although the *ET* of the SRCs sometimes exceeded that of grass vegetation or the reference evapotranspiration (ET_0) on an hourly, daily or monthly time scale, it was always lower over an entire annual cycle. The cumulative annual *ET* of the SRCs ranged from 344 to 549 mm year^{-1}, whereas that of the turf grass ranged from 561 to 573 mm year^{-1}, and the *ET* of the grassland reached up to 619 mm year^{-1}. The wide range of the annual *ET* totals for the SRCs was determined mainly by the different rotation periods and ages of the stands, along with the leaf area index (*LAI*), the state of the canopy closure, and tree heights. The lowest annual *ET* (344 mm) was observed during the 1st year of the 2nd rotation (following the winter harvest) in 2010. During that year, the SRC regrowth started only after mid-June, and the maximum *LAI* of the canopy, which was approximately 2 m in height and was not completely closed, reached 3.7. In contrast, in the case of a mature stand approximately 12 m in height in 2009, i.e., the 8th year of the 1st rotation, the maximum canopy *LAI* reached 7.5, and the annual *ET* reached its highest observed value (549 mm). The leaf area duration of the SRCs was always lower than that of the grass covers, and this seemed to be the main reason for the significantly lower annual *ET* totals of the SRCs. The absolute maximum daily *ET* of 6.3 mm day^{-1} was achieved by the SRC in July 2011 when the stand was in the 2nd year of the 2nd rotation cycle. The highest daily *ET* of the grass covers (5.9 mm day^{-1}) was reached by turf grass in June 2011. The maximum monthly *ET* occurred in July 2009 when the weather was wet and relatively warm; the *ET* was identical for the SRCs and the turf grass, reaching 107 mm month^{-1}, just slightly lower than the ET_0 (109 mm month^{-1}). These results are in the middle range of *ET* values from 21 recent studies on poplar and willow cultures. The results of this study indicate that conversion of arable land into poplar SRCs instead of grasslands does not result in significant differences in *ET* of the agricultural landscape.

1. Introduction

The term “short-rotation coppice (SRC)” is generally used for any high-yielding fast-growing hardwood species managed in a coppice system, grown intentionally for bioenergy or for the purpose of the paper and pulp industry (Hansen, 1991). Typically, these crops are harvested in a 1–15 years long rotation cycle and remain viable for 15–30 years (Perry et al., 2001; Deckmyn et al., 2004). SRC plantations in central Europe are usually based on poplar or willow species at high planting densities (∼1000 to 40,000 trees ha^{-1}) grown mainly on abandoned, underused or contaminated arable land (Al Afas et al., 2008; Broeckx et al., 2012). These SRC plantations

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Nomenclature

ANOVA	analysis of variance
BREB	Bowen ratio energy balance
DMC	dry matter content
e	water vapor pressure (kPa)
ET	actual evapotranspiration (mm)
ET_0	reference evapotranspiration (mm)
EU	European Union
G	soil heat flux ($W\,m^{-2}$)
H	sensible heat flux ($W\,m^{-2}$)
K_c	crop coefficient dimensionless
K_H	eddy diffusivity for heat ($m^2\,s^{-1}$)
K_{LE}	eddy diffusivity for water vapor ($m^2\,s^{-1}$)
LAI	leaf area index ($m\,m^{-2}$)
LSD	least significant difference
MBE	mean bias error
p	p-value
P	energy used in photosynthesis ($W\,m^{-2}$)
P.	*Populus*
R^2	coefficient of determination
RMSE	root mean square error
R_n	net radiation ($W\,m^{-2}$)
S	heat storage in vegetation ($W\,m^{-2}$)
S.	*Salix*
sp.	species
SRC	short-rotation coppice
T	temperature (K)

Greek letters

β	Bowen ratio dimensionless
γ	psychrometric constant ($kPa\,K^{-1}$)
λ	latent heat of vaporization ($J\,kg^{-1}$)
λET	latent heat flux ($W\,m^{-2}$)

have come to be seen in recent years as a promising and relatively inexpensive source of bioenergy (Aylott et al., 2008; Ericsson et al., 2009; Njakou Djomo et al., 2011). The replacement of fossil fuels with biomass in the generation of “carbon-neutral” energy and heat has recently become an important strategy promoted by the European Union (EU) to mitigate the effects of climate change (IEA, 2003; IPCC, 2007). Furthermore, biomass—and in particular, energy crops—has attracted attention as a promising renewable and mainly local energy source. It is believed that bioenergy from biomass could help the EU to reduce its dependency on external energy sources, i.e., on the main oil-exporting and gas-exporting countries, and thus enhance the security of the energy supply and the diversification of energy sources (EU Commission, 2005; Gasol et al., 2007; Njakou Djomo et al., 2011). Last but not least, SRCs have additional positive impacts from the socio-economic and environmental points of view; e.g., enhancements in the local employment rates, regional energy independence and security, the improved aesthetics of the countryside, potentially increased biodiversity, nutrient capture, soil protection from wind and water erosion, air quality, and carbon sequestration (Isebrands and Karnonsky, 2001). In contrast to the above-mentioned positive aspects, the possible impact of large-scale bioenergy production, mainly from SRCs, on the water balance has become the subject of on-going discussions (Grip et al., 1989; Persson, 1997; Hall et al., 1998; Allen et al., 1999; Lindroth and Båth, 1999; Perry et al., 2001; Linderson et al., 2007; Dimitriou et al., 2009; Sevigne et al., 2011; King et al., 2013).

On the one hand, poplar and willow SRC cultures are characterized by inherently low rates of nitrate leaching and are thus recommended as suitable crops for nitrate-sensitive areas or for groundwater protection zones around water supply boreholes (Hall et al., 1996). This results from the low- to moderate-input management of SRCs. However, low nitrogen concentrations in drainage water, well below the limits for drinkable water, have been documented under full-grown SRCs even after intensive fertilization, as is typical for traditional agricultural crops (Sugiura et al., 2008; Dimitriou et al., 2009) or after the application of sewage sludge and wastewater (Hall et al., 1996; Dimitriou et al., 2009). Likewise, owing to the potentially deep root system and vigorous growth linked with high nutrient and water uptake, poplars and willows have been found to be the most suitable vegetation to grow at landfills and other waste disposal sites and their borders for so-called phytoremediation (Zalesny et al., 2006; Mirk and Volk, 2010). The same factors make poplars and willows ideal candidates for application of wastewater, sewage sludge, ash, and landfill leachate that cannot be used for food crops (Guidi et al., 2008; Dimitriou and Aronsson, 2011).

On the other hand, the water use of SRCs is substantially higher than that of traditional agricultural crops or grasslands, according to experimental and modeling studies that have been carried out in various countries across Europe. It has therefore been argued that the large-scale culture of SRCs can have detrimental impacts on the regional water budget, including reduced aquifer recharge and reduced river flows (Hall et al., 1996, 1998; Allen et al., 1999; Perry et al., 2001; Petzold et al., 2010). These and other studies have concluded that water availability constitutes one of the main constraints for biomass yields and for the profitability of SRCs grown on arable land with an inaccessible water table (Lindroth and Cienciala, 1996; Persson, 1997; Lindroth and Båth, 1999; Deckmyn et al., 2004; Lasch et al., 2010). In contrast to these claims, other studies have reported water consumption by SRCs that is comparable to or lower than that of agricultural crops, grasslands and comparable to or lower than the reference crop evapotranspiration (Meiresonne et al., 1999; Bungart and Hüttl, 2004; Linderson et al., 2007; Dimitriou et al., 2009; Migliavacca et al., 2009; Tricker et al., 2009).

As a consequence of the transformation in Czech agriculture after 1990, there has been a continuing conversion of arable land into permanent grassland (the area of meadows and pastures has increased by ~20% to date). Recently, an alternative for land use with SRCs based on poplar and willow species has been introduced in the Czech Republic and elsewhere. The issue of the impact of SRCs on the use of water should be taken into account prior to further large-scale implementation. Although the areas of SRC plantations in the Czech Republic are still small compared with those in neighboring countries (Havlíčková et al., 2010), the popularity of SRCs has increased substantially over the last five years, and intentions of planting more of them have been stimulated. Therefore, the issue of the ecological impacts of SRCs on their surroundings is becoming a concern.

Because of the aforementioned contradictory evidence provided by the literature on the water use of SRCs, we designed an experimentally based study and attempted to contribute to one of the key arguments related to SRC cultures. The main objective of this study was to quantify the actual evapotranspiration (ET) of poplar SRCs and compare it with the ET of grass vegetation growing in identical pedo-climatic conditions in the Czech–Moravian Highlands in the Czech Republic. To assess the ET of these two contrasting ecosystems situated at one experimental site, the same measuring technique—namely, the Bowen ratio/energy balance method (BREB)—was used for both types of covers, making this study unique. The yields of the SRCs at the site are within the range of 10–14 $t\,ha^{-1}$ of dry matter content (DMC; Trnka et al., 2008) which can be considered economically effective and sustainable, as well as representative of the likely yields of future SRCs in the region. Knowledge of the water use under pedo-climatic conditions seen as viable for large-scale SRC biomass production could prove valuable, especially for future site selection and other growing and decision-support purposes and, more generally, for water and energy balance modeling studies.

2. Materials and methods

2.1. Experimental site and plantations

This study was conducted in a typical rain-fed area of the Czech–Moravian Highlands at the research locality Domanínek (Czech Republic, 49°31′N, 16°14′E, altitude 530 ma.s.l.) in the western part of the town of Bystřice nad Pernštejnem. The region has a cool and relatively wet temperate climate typical for this part of central Europe, with mingling continental and maritime influences. According to the long-term (1981–2010) climatic data, the mean annual temperature at the locality is 7.2 °C, the mean annual precipitation 609.3 mm, and the mean annual reference evapotranspiration (Allen et al., 1998) is 650 mm. The length of the growing season (when the daily mean air temperature is above 5 °C) is, on average, 217 days, beginning on March 30 and lasting to November 1, with a total effective temperature sum of 1644.6 °C. These values are based on daily weather data obtained from the Czech Hydrometeorological Institute Station of Bystřice nad Pernštejnem, which is situated approximately 1 km from the experimental site. Although the area in general does not provide optimal conditions for SRC with *Populus* (mainly due to relatively low precipitation), the experimental site itself is highly suitable for planting, due to its relatively deep soil profile (Trnka et al., 2008). The soil conditions at the location are representative of the wider region, with deep luvic Cambisol influenced by gleyic processes and with relatively few stones in the profile. The site topography is characterized by rolling hills with mild eastward slopes of 3–5°.

A first planting of the investigated operational high-density monoclonal poplar (*Populus nigra* × *P. maximowiczii*; clone J-105) plantation was established over a total area of 2.85 ha (Fig. 1) in April 2002. This plantation (hereinafter referred to as SRC 1) was

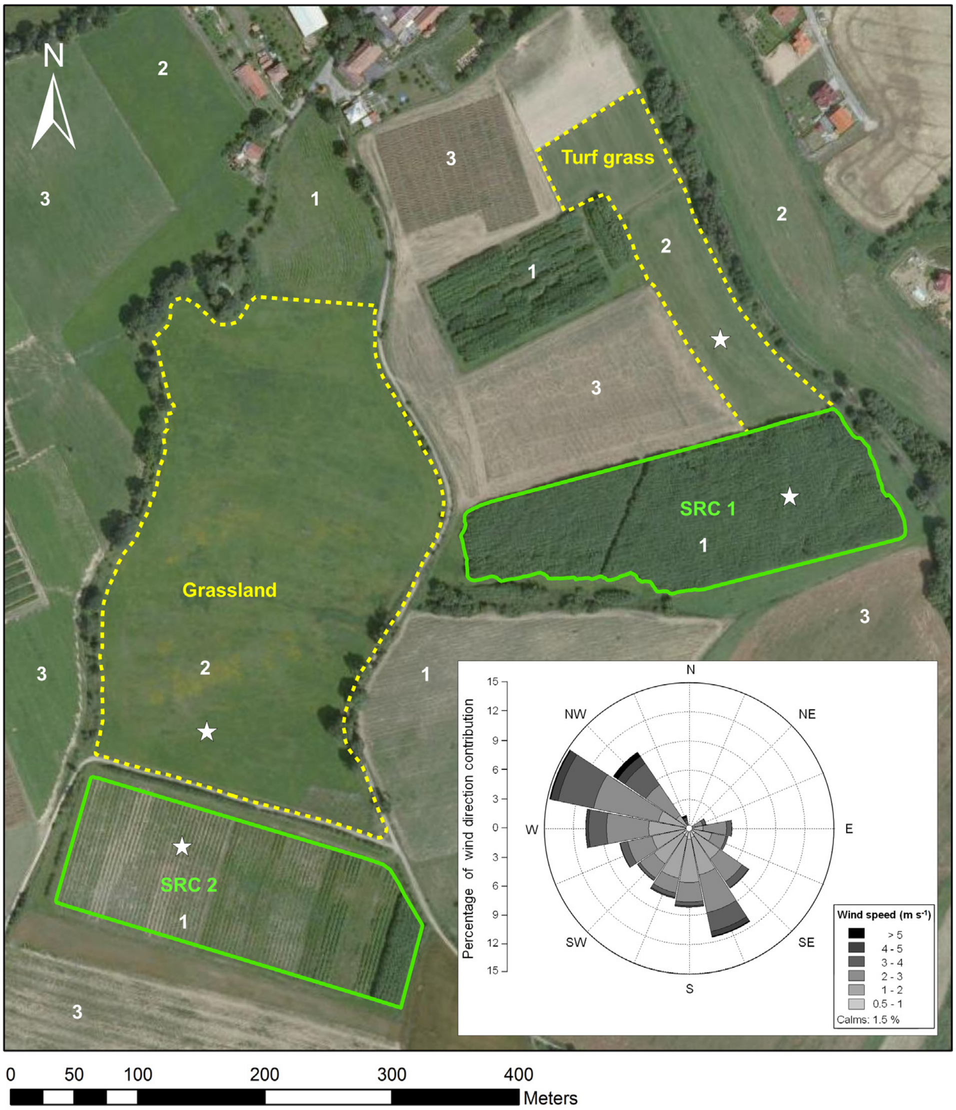

Fig. 1. Site map with the investigated covers indicated and a wind rose depicting the percentage (0–15%) of the mean half-hourly wind speeds and the directions measured above the turf grass at a standard height of 2 m. Only values measured from April to October, when the global radiation was greater than $50\,\mathrm{W\,m^{-2}}$, are depicted (diurnal cases). Short-rotation coppices (SRC 1 and 2) are marked by solid green lines, and grass vegetation is marked by dashed yellow lines. White stars indicate the particular Bowen ratio energy balance systems. The white numbers 1, 2, and 3 denote short-rotation coppice, grassland and cropland, respectively, as the main type of surrounding land use. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

established on agricultural land previously cropped predominantly for cereals and potatoes. During the last year of cropping, an oat-pea mixture was used as a pre-crop to prepare the field for plantation establishment. Following conventional tillage practices, the hardwood cuttings were planted in a double-row pattern with inter-row distances of 2.5 m and within-row spacings of 0.7 m to produce a theoretical density of 9216 trees ha^{-1}. In keeping with the anticipated extensive management of future SRC cultures, no irrigation, no fertilization and no herbicide treatments (except for the local application of glyphosate on the most vigorous and tenacious weeds) were applied during the experiment. Subsequent mechanical weeding was carried out two times per growing season until canopy closure in 2005. The most problematic weed species were *Cirsium arvense*, *Rumex crispus*, *Rumex obtusifolius*, *Artemisia vulgaris*, *Tanacetum vulgare*, *Elytrigia repens*, and *Arrhenatherum elatius*. As a consequence of the drastic weed competition, the rotation period was prolonged to 8 years, and the first harvest was carried out at the end of the winter of 2009–2010.

A second planting of the investigated coppice cultures (hereinafter referred to as SRC 2) was established in April 2001. SRC 2 was situated less than 300 m southwest and upslope of SRC 1 (Fig. 1), at a location with similar soil conditions, a similar slope angle (3.5°), the same exposure and the same land use history. Note that the numbering of the SRCs (1 and 2) does not reflect their ages but rather the chronology of the analyses of this study. The total planted area of SRC 2 consisted of a 1.2-ha monoclonal block of hybrid poplar clone J-105 and a 1.6-ha block with a mixture of four *Populus* spp. and three *Salix* spp. hybrid clones, described in details by Trnka et al. (2008). Approximately 7 m from the edges of the plantation, a wire fence and a continuous line of single trees (poplars and willows) was placed along the periphery of the SRC 2. The same management as for SRC 1, including management of the field preparation, weed control, rotation length and spacing, were used during the first rotation. However, after the first coppice during the winter of 2008–2009, a small-scale plot fertilization experiment was established, arranged in a randomized plot design within the block planted with clone J-105. The fertilization experiment included four treatments—nitrogen, phosphorus and potassium inorganic fertilizer; mixture of sewage sludge and ash; lime; and control—in three replications. The total area affected by this experiment constituted 18% of the whole SRC 2.

In addition to these two SRC cultures, two reference grass covers were considered in this study. The first of these was turf grass that was regularly clipped (at 3- to 10-day intervals) and fertilized, with an estimated mean annual above-ground biomass productivity of ~3 t ha^{-1} year^{-1} of DMC. This turf grass land covered a total area of 2.4 ha, consisting of ~60% *Lolium perenne* and ~40% *Festuca rubra*, and was situated north of SRC 1 (Fig. 1). The second reference cover was a grassland with a total area of 7.6 ha, situated north of SRC 2 (Fig. 1). This grassland was managed with 1–2 cuts per year and had an estimated mean annual hay yield of 3–4 t ha^{-1} year^{-1} of DMC. During 2011, only one cut was carried out, on 13 June, with the hay being removed three days later. The species composition was *Lotus corniculatus* (~40%), *Trifolium hybridum* (~30%), *Dactylis glomerata* (~15%), and *Taraxacum officinale* (~10%) with a small amount (less than ~5% in total) of species such as *Achillea millefolium*, *F. rubra*, and *Plantago lanceolata*.

2.2. Micrometeorological and ancillary measurements

The intensive monitoring campaign started in June 2008, when two BREB systems (EMS Brno, Czech Republic) for estimating *ET* were positioned at SRC 1 and the turf grass reference site. Table 1 summarizes the components of the BREB systems, enhanced with a number of auxiliary instruments. All the BREB systems used in this study incorporated fixed-position combined thin-film polymer capacitive relative humidity and adjacent resistance temperature sensor instruments for measurement of humidity and temperature gradients. Recent progress in the development of capacitance probes has enabled the wider application of these BREB systems, whose attributes include their low cost, low energy consumption, long-term stability and reliability, resulting in low demand for attendance. However, it should be remembered that due to non-alternating positions and the fact that in order to obtain the water vapor concentration, temperature and relative humidity measurements, along with their errors, are carried out individually, these systems are susceptible to systematic errors if proper mutual sensor calibration is not carried out. Similar BREB designs with capacitive non-alternating hygrometers have been successfully validated by independent methods, e.g., by Herbst (1995), Chen and Novak (1997), Li et al. (2008), and Zhang et al. (2008), and have been thoroughly analyzed and validated by Savage (2010). In this study, the temperature and humidity gradients were measured by combined instruments EMS 33 placed in radiation shields AL 070/1 (EMS Brno, Czech Republic). The accuracy of the EMS 33 is guaranteed by the manufacturer to be ±0.3 °C and ±2% for temperature and relative humidity, respectively. These levels of accuracy can be doubled when considering gradient measurements. However, thanks to laboratory calibration of the sensors against each other, most systematic errors given by the sensors' accuracy were eliminated. As a result, the mutual error of any pair of sensors used in this study—expressed as the unsystematic root mean square error (Willmott, 1982)—was less than 0.2 °C for temperature measurements (between 0 and 50 °C) and 0.5% for relative humidity measurements (between 5% and 90%). It should be noted that the errors in vapor pressure gradient measurement are a product of

Table 1
Set-up of the micrometeorological stations with Bowen ratio energy balance (BREB) systems above the short-rotation coppice cultures (SRC 1 and SRC 2) and grassland vegetation, with the number of instruments, their types and manufacturers.

BREB	SRC 1	SRC 2	Turf grass	Grassland	
Air temperature and humidity	3	2	2	2	EMS 33: EMS Brno, Czech Republic
Net radiation	1		1		NR 8110: Philipp Schenk GmbH Wien, Austria
Soil heat flux	1		1		HFP01: Hukseflux Thermal Sensors, Netherlands
Other meteorological instruments					
Global radiation	1	1	1	1	EMS 11: EMS Brno, Czech Republic
Precipitation			1		MetOne 370: MetOne Instruments, USA
				1	R.M. Young 52202: R. M. Young Company, USA
Wind speed and direction			1		MetOne 034B: MetOne Instruments, Inc., USA
Soil temperature	3		3		PT 100: EMS Brno, Czech Republic
Volumetric soil water content	3	3	3	3	EC-10: Decagon Devices, Inc., USA
Soil water potential	6	3	6	3	GB 2: Delmhorst Instrument Co. Moisture Meters, USA
Data logger	1		1		ModuLog 3029: EMS Brno, Czech Republic
		1		1	V12: EMS Brno, Czech Republic

both relative humidity and temperature measurements errors and increase with temperature (Savage, 2010). The median of these errors was 18 Pa, with 14 and 21 Pa for the lower and upper quartile, respectively, throughout the growing seasons 2008–2011. The measurement accuracy of the EMS 33 instruments were checked annually to rule out any drift effect of the sensors.

In November 2010, two similar BREB systems were installed at SRC 2 and at the grassland reference site with the instrumentation described in Table 1. Assuming no significant differences in the net radiation and the soil heat flux patterns between the pairs of similar covers, the values of these two variables for SRC 1 and the turf grass were applied to SRC 2 and the grassland, respectively, to derive latent and sensible heat fluxes and *ET* in particular. The validity of this assumption was supported by a three-week simultaneous measurement of net radiation above SRC 1 and SRC 2, and above the turf grass and the grassland during the peak of the growing season. This comparison revealed that a systematic root mean square deviation was less than −0.5 and −2% for the grassland and the SRC 2, respectively, leading to an identical error in the *ET*. All of the aforementioned sensors were connected to solar energy-supplied data loggers (Table 1) with a measurement interval of 1 min and averages stored every 10 min.

The BREB above the two SRCs were placed on 14-m-high aluminum masts with vertically adjustable arms to follow the vigorous growth of the poplars. The lowest arms were kept at a height of approximately 0.3 m above the top of the canopy to reduce the footprint of the flux measurements to the area of interest (for a justification of the measurement in the roughness sublayer, see the next section). In the case of the BREB at SRC 1, the middle and upper arms were positioned 1 and 3 m, respectively, higher than the lower arm. The BREB at SRC 2 had only two arms with a vertical distance of 2 m. For the precise height adjustment of the BREB systems above the SRCs, the heights of 40 randomly selected trees close to the mast were recorded using a telescopic fiberglass measuring pole (Sokkia, Japan) extendable to 12 m. The BREB systems above the grass covers were placed on 2-m-high poles with only two fixed levels for the gradient measurements, positioned at 0.4 and 2 m above the ground surface.

The leaf area index (*LAI* in $m^2\,m^{-2}$) of SRC 1 was measured regularly (usually weekly) using a SunScan ceptometer system (Delta-T Devices Ltd., Cambridge, UK), successfully validated by litter-fall collection measurements. The *LAI* was calculated as the difference between the plant and skeleton area indexes, measured during foliated and defoliated periods, respectively (for more details, see Fischer, 2012). For SRC 2, which was primarily intended as a fertilization experiment, only several occasional measurements, from August to leaf fall, were carried out to detect possible differences in the fully developed *LAI* between particular fertilization treatments. During the regular *LAI* measurements, visual assessments were made and recorded looking for the potential damage resulting from any pests and diseases. At the end of each season, a complete stem inventory took place in order to estimate aboveground woody biomass productivity and stand mortality.

2.3. BREB method

The BREB method, originally proposed by Bowen (1926), is characterized by its low demand on instrumentation and thus its low costs, limited operator skill required, and need for few corrections to the data. The method has been applied in numerous studies for various surfaces and conditions: e.g., irrigated bermudagrass (Heilman et al., 1989); sparse pine forest (Lindroth and Halldin, 1990); spruce-fir-beech forest (Bernhofer, 1992); bare soil and soybean canopy (Cellier and Olioso, 1993); high-density willow SRC (Iritz and Lindroth, 1996); irrigated and unirrigated maize canopies (Steduto and Hsiao, 1998); prairie wetland (Burba et al., 1999); irrigated alfalfa (Todd et al., 2000); tallgrass prairie (Brotzge and Crawford, 2003); irrigated rice paddy (Guo et al., 2007) and montane grassland (Savage et al., 2009).

The basis of the BREB method is the energy balance equation and the theory of turbulent diffusion (K-theory). The energy balance equation is as follows:

$$R_n = \lambda ET + H + G + S + P \tag{1}$$

where R_n is the net energy gained through radiative exchanges, allowing for the absorption of both downward and upward components of long- and short-wave radiation; λET is the evapotranspiration rate multiplied by the latent heat of vaporization to express evapotranspiration in units of energy, or the latent heat flux; H is the heat lost by turbulent transfer, or the sensible heat flux; G is conduction of heat in the soil, or the soil heat flux; S is the rate at which heat goes into storage within the vegetation; and P is the rate at which energy is being trapped in chemical bonds by photosynthesis. All the terms are expressed in appropriate units of energy flux, preferably $W\,m^{-2}$ (Grace, 1983).

The Bowen ratio, β (Bowen, 1926) is defined as the ratio of the sensible heat flux to the latent heat flux:

$$\beta = \frac{H}{\lambda ET} \tag{2}$$

which, by applying the K-theory, can be written as follows:

$$\beta = \frac{\gamma K_H \Delta T}{K_{LE} \Delta e} \tag{3}$$

where γ is the psychrometric constant ($\sim$0.066 kPa K^{-1} at sea level); K_H and K_{LE} are the eddy diffusivity coefficients ($m^2\,s^{-1}$) for heat and water vapor, respectively; and ΔT (K) and Δe (kPa) are the corresponding air temperature and vapor pressure vertical differences, respectively, assuming vertical distances so that the dry adiabatic lapse rate (0.01 K m^{-1}) can be neglected. According to the Bowen ratio similarity principle (Bowen, 1926; Dyer, 1974; McNaughton and Laubach, 1998) $K_H \approx K_{LE}$ for all types of stratification (except strongly stable quasi-laminar, i.e., non-turbulent, conditions) because the scalars are assumed to be carried by the same eddies if they have identical or very similar source and sink distributions. Note that the similarity of eddy diffusivity coefficients is also considered to be valid within the roughness sublayer in conditions of dense and uniform canopy, where homogeneous source and sink distributions can be expected (Denmead and Bradley, 1985; Raupach and Legg, 1984; Cellier and Brunet, 1992; Iritz and Lindroth, 1996; Iwata et al., 2010). This has an important implication for the BREB footprint issue: it can be minimized by positioning the lower sensor as low as possible above the canopy top while positioning the upper sensor at an adequate distance to enable reliable measurement of the vertical differences (Stannard, 1997). The principles of the K-theory, namely, the proportionality of the turbulent fluxes to the gradients of the corresponding scalars, are strongly dependent on the assumption of a horizontal, homogeneous and nearly infinite area. This is important to ensure that the net fluxes are entirely vertical and not horizontal. Nevertheless, these conditions can only be fulfilled to a certain degree. If the area of study is fairly homogeneous and large enough to enable accurate determinations of the temperature and humidity gradients within the internal boundary layer (preferably within the so-called equilibrium sublayer), the BREB method gives at least good estimates of the fluxes of interest.

Taking the above-mentioned issue into account, Eq. (3) can be written in a simpler form as follows:

$$\beta \approx \frac{\gamma \Delta T}{\Delta e} \tag{4}$$

Eq. (4) makes it possible to calculate the Bowen ratio by measuring air temperature (T in K) and water vapor pressure (e in kPa) at two or more different levels in the atmosphere. To solve Eq. (4), the actual water vapor pressure is determined from the relative humidity using a variation of Tetens's formula for saturated vapor pressure if the capacitance probes are used (see e.g., Allen et al., 1998; Savage, 2010). Furthermore, combining Eqs. (1) and (4) (i.e., the radiation balance and the Bowen ratio) results in an equation for the latent heat flux:

$$\lambda ET \approx \frac{(R_n - G - S - P)}{(1+\beta)} \tag{5}$$

The latent heat flux resulting from Eq. (5) is divided by the latent heat of vaporization (λ in J kg^{-1}) as a function of temperature, T (K), following $\lambda = 3.145931 \times 10^6 - 2361T$ to obtain ET in mm of water column (Shuttleworth, 2007).

2.4. ET calculation and data processing

In this study, the entire calculation procedure was performed in the graphically oriented Mini32 software (EMS Brno, Czech Republic), using the program's calculation utility. After the necessary visual control, screening and de-spiking of the original 10-min data, the half-hourly means of the described input variables were used to calculate the rough fluxes according to set of equation listed in the previous section. When no measurements of stem wood and leaf temperature are available, air temperature from the lower measuring level can be used for estimates of S (Gay et al., 1996). Using this approach, we calculated that the maximum values of S for the SRC 1 during the year before harvest reached 20–40 W m^{-2} in the morning, then typically varied within ±10 W m^{-2}, before dropping to about −20 W m^{-2} in the evening. Since using the air temperature instead of the biomass temperature leads to increased amplitude and creates a time shift in S (Moderow et al., 2009), and considering that the BREB method needs to be gap-filled during the early morning and late evening when S reaches the highest values while ET is small, we simplified the Eqs. (1) and (5) by neglecting S. The same was done for P since we lack any consistent method for its estimate and since it is generally considered negligible compared to R_n even for these types of high productive stands (Lindroth and Iritz, 1993).

The calculations of the rough fluxes were followed by several post-processing steps. First, calculated fluxes with the wrong signs, i.e., those that did not obey the flux–gradient relationship, were rejected (Ohmura, 1982; Perez et al., 1999). Second, data corresponding to Bowen ratios close to−1 were excluded, using the analytical variable filter proposed by Perez et al. (1999) and later adopted and corrected by Guo et al. (2007). This step ensured that the sum of the temperature and humidity gradient measurement errors divided by the actual vapor pressure vertical difference defined the range around −1, which has to be excluded due to physically inconsistent results caused by zero or very low values in the denominator of Eq. (5). Finally, the data were plotted against the reference evapotranspiration (ET_0, see below), and the remaining outliers and inconsistent values were removed using a visual screening technique similar to that recommended by Allen (1996) for radiation data. The data removed in this way represented only a small portion (less than 4%) and was typically encountered when ΔT, Δe or $R_n - G$ were small.

The gaps were subsequently filled with the ET_0 multiplied by the crop coefficient (K_c), i.e., the ratio between ET and ET_0, parameterized separately for each particular day and night (global radiation threshold = 0 W m^{-2}) using least-squares linear regression. If less than 50% and 30% of the data for diurnal and nocturnal cases, respectively, were available, the linear regression function was parameterized from the measurements that were closest in terms of time and weather conditions, defined by the cloudiness (the maximum allowed deviation in the clear sky index was set at 30%). Days with and without rain were treated separately.

The ET_0 was calculated according to the recently recommended short-time-span (half-hourly in our case) method, based on the Penman–Monteith model for the reference grass (Allen et al., 2006). Firstly, for the screening and gap-filling purposes only, the input meteorological variables for ET_0 calculation (R_n, T, and e) were taken from the upper measuring level of the particular BREB system, from which the ET was calculated, and G from the corresponding heat flux plate. Surface resistance was set at 50 and 200 s m^{-1} for the diurnal and nocturnal cases, respectively (Allen et al., 2006). The aerodynamic resistance was computed from the wind speed at the turf grass site with the standard parameterization for 0.12 m high reference grass (Allen et al., 2006). Secondly, for the comparison of ET_0 and ET of the particular covers, we calculated ET_0 entirely from the data from the turf grass BREB using the parameters for the surface resistance mentioned above, according to the standard methodology Allen et al. (2006).

As an additional tool for the fetch adequacy assessment, a footprint model proposed by Hsieh et al. (2000) was used. The zero plane displacement and the roughness length were considered as 0.67 and 0.12 of the mean canopy height, respectively (Allen et al., 1998; Foken, 2008). The measurement height was computed as the geometric mean of the upper and lower arms above zero plane displacement (Stannard, 1997; Horst, 1999). The same values of the zero plane displacement and measurement height were used to determine the fetch-to-height ratios. The half-hourly non-gap-filled ET data were subsequently split into two groups according to the fetch quality criteria based on the results of this footprint model; i.e., into more and less fetch adequate categories. Only the data for dry canopy conditions, $R_n > 150$ W m^{-2} and wind speed >1 m s^{-1} were considered. During each month, two K_c were found as the slopes of linear regression (anchored by zero) between ET_0 (the same as for gap-filling) and ET of the particular fetch categories. These K_c values enabled us to obtain half-hourly theoretical values of ET corresponding to two fetch categories. In this way, the impact of the inadequate fetch could be quantified in mm of ET.

2.5. Statistical analyses

The resulting continuous data series were integrated into daily, monthly, seasonal and yearly totals. Additional data analyses were performed using the statistical package STATISTICA 10 (StatSoft, Inc., USA). To identify significant differences in the ET of different covers, an analysis of variance (ANOVA) was applied in a manner similar to that described by Khamzina et al. (2009) and Zha et al. (2010). For this purpose, only the data from the growing season (1 April to 31 October) were used because of their higher reliability and relevance. Prior to the ANOVA, the data were checked for normality using the Shapiro–Wilks test and normalized using a Box–Cox transformation if necessary. The daily ET values were included as replicates of the dependent variable, and the type of cover and particular months were treated as the independent variables. Finally, Fischer's post hoc least significant difference (LSD) test was applied to contrast the interactions between the replicates and treatments at $p < 0.05$, $p < 0.01$, and $p < 0.001$. Because ET inherently differed between the months, only the differences in ET between various covers in particular months were of interest. Other general statistical methods applied were linear regression, calculation of the coefficient of determination (R^2) as the square of Pearson's correlation coefficient, and calculation of the mean bias error (MBE) and the root mean square error (RMSE) for use in evaluating systematic and random errors, respectively (Willmott, 1982).

2.6. Literature survey

To compare the *ET* results of this study with the literature, we surveyed the most important peer-reviewed publications on the water use of poplars and willows from the last 20 years. Because not all of the studies provided complete annual *ET* data and because some of them only included transpiration data, we attempted to normalize them. Based on the results of several studies (Persson and Lindroth, 1994; Hall et al., 1996; Petzold et al., 2010; Fischer, 2012), it was assumed that transpiration represented, on average, approximately 80% of the seasonal *ET* and that the *ET* outside the growing season represented approximately 10% of the annual *ET*. Other factors making the comparison of the reviewed studies less straightforward are the different latitudes and climates of the different study sites. With respect to that, ET_0 appears to be the most suitable variable to use in normalizing *ET* results for different climatic conditions. Because ET_0 was quoted in only 10 of the studies, the 10-arc-min-resolution annual ET_0 data calculated by FAO (Droogers and Allen, 2002), based on the Climate Research Unit CL 2.0 Global Climate Dataset for the normal period 1961–1990 (New et al., 2002) were used. Finally, we calculated the K_c as the ratio between the actual *ET* and the ET_0 on an annual scale to provide information about the relative water use of poplar and willow stands in the studies reviewed.

3. Results

3.1. Weather conditions and stand characteristics

The air temperature during the growing seasons (1 April to 31 October) of 2008–2011 was usually higher than the long-term average for the period 1981–2010. The warmest season occurred in 2009, with a mean air temperature of 13.9 °C (1.2 °C above long-term average), and the coolest growing season in 2010 had an air temperature of only 12.0 °C (0.7 °C below long-term average). This was also well demonstrated by the effective temperature sum above 5 °C, which reached 1945 and 1629 °C in 2009 and 2010, respectively. Bud burst occurred in all 4 years when the effective temperature sum approached approximately 100 °C, with 13 April 2009 and 30 April 2008 being the earliest and the latest dates, respectively. The total annual rainfall and ET_0 are summarized in Table 2. While the precipitation in 2008 (519 mm) and 2011 (521 mm) was below the long-term average, the precipitation totals in years 2009 (778 mm) and 2010 (694 mm) were well above this average. The highest monthly rainfall totals during our study were recorded in summer 2009, when 138 and 170 mm of rain fell in June and July, respectively. The evaporative demand, expressed as ET_0, was highest in 2011 (660 mm) and lowest in 2010 (558 mm). Note that these annual ET_0 values were integrated from ET_0 calculated on a half-hourly basis (Allen et al., 2006). This short-time-step approach resulted in estimates almost 5% lower than those obtained by calculating ET_0 from daily meteorological data (Allen et al., 1998). This discrepancy can be explained by the typical diurnal variability of the weather at the locality, which results in less accurate predictions from the daily input data. Therefore, comparison of the ET_0 between the years 2008–2011 and the long-term 1981–2010 reference period, i.e., the values used in the site description, is not straightforward and was not an objective of this study.

The canopy heights of SRC 1 were ∼10 m and ∼12 m at the end of 2008 and 2009, respectively. During the winter of 2009–2010, the plantation was cut for the first time. The stumps started to resprout at the end of June 2010, and the new shoots achieved a maximum height of 2.7 m at the end of the season. The mean canopy height, taken as the average of the heights of the most vigorous shoots of

Table 2

Overview of the main water balance components of the studied vegetation covers for every month of the years 2008–2011 represented by actual evapotranspiration (*ET*) and rainfall. Reference grass evapotranspiration (ET_0) is provided for comparison. From 2008 to 2010, *ET* of one short-rotation coppice (SRC 1) and one turf grass were assessed using the Bowen ratio energy balance method (BREB). These observations were extended using other BREB measurements for SRC 2 and for grassland in 2011. The maxima are marked in bold font.

Month	2008				2009				2010				2011			
	$ET_{SRC\,1}$	$ET_{Turf\ grass}$	ET_0	Rainfall	$ET_{SRC\,1}$	$ET_{Turf\ grass}$	ET_0	Rainfall	$ET_{SRC\,1}$	$ET_{Turf\ grass}$	ET_0	Rainfall	$ET_{SRC\,1\ (SRC\,2)}$	$ET_{Turf\ grass\ (Grassland)}$	ET_0	Rainfall
January	–	–	–	–	3.5	4.7	4.5	21.6	1.8	5.0	2.5	71.9	2.7 (3.5)	5.0 (2.7)	4.0	37.6
February	–	–	–	–	3.7	2.5	9.2	41.2	12.4	15.3	11.0	18.1	8.9 (14.6)	15.3 (10.9)	14.5	7.1
March	–	–	–	–	15.3	15.1	22.8	81.6	32.6	46.2	37.2	35.6	22.9 (28.2)	25.7 (26.3)	41.0	45.6
April	–	–	–	–	59.3	82.2	98.7	16.4	32.1	59.8	65.3	66.2	40.3 (52.4)	59.7 (70.5)	73.2	23.1
May	–	–	–	–	78.3	78.3	85.1	67.0	38.0	58.2	51.3	101.8	76.1 (82.1)	92 (99.5)	**106.4**	42.7
June	–	–	–	–	88.1	80.0	79.3	138.2	34.3	97.1	104.7	73.0	**107.1 (83.8)**	**95.2 (97.8)**	105.8	80.0
July	**95.0**	**103.3**	**113.5**	**81.2**	**107.2**	**106.9**	**108.7**	**170.4**	**67.1**	**101.9**	**117.0**	68.6	94.8 (76.4)	78.2 (89.8)	91.1	**106.7**
August	92.3	91.7	102.0	41.8	92.3	100.6	102.5	74.7	62.1	81.8	80.1	**106.6**	90.3 (85.8)	88 (95.5)	98.3	61.1
September	48.9	40.0	56.7	39.4	62.6	61.1	61.8	21.2	34.2	50.3	49.6	67.8	51.1 (62.4)	62.4 (73.6)	72.7	55.2
October	15.0	16.4	26.9	22.6	24.1	25.2	21.4	61.0	21.0	31.7	27.4	8.2	16.1 (24.7)	31.2 (34.4)	34.3	39.5
November	5.8	3.6	8.8	47.6	11.9	11.4	9.0	35.5	7.7	12.1	9.5	31.4	6.1 (11.4)	13.1 (12.8)	13.2	3.1
December	2.4	2.0	4.8	22.0	2.9	4.8	3.8	50.0	1.0	2.0	2.1	45.2	2.8 (4.0)	5.1 (4.7)	5.2	18.9
Seasonal total[a]	251.2[b]	251.4[b]	299.1[b]	185.0[b]	511.9	534.3	557.5	548.9	288.8	480.8	495.4	492.2	475.8 (467.6)	506.7 (561.1)	581.8	408.3
Yearly total	259.4[b]	257.0[b]	312.7[b]	254.6[b]	549.2	572.8	606.8	778.8	344.3	561.4	557.7	694.4	519.2 (529.3)	570.9 (618.5)	659.7	520.6

[a] The growing season is defined as the period from the 1st of April to the 31st of October.

[b] All data for 2008 are summed from the 1st of July only.

selected stumps, was 2.1 m at the end of the season of 2010. At the end of 2011, the maximum height of the resprouts was 5.0 m, with a mean canopy height of 4.1 m. In the case of SRC 2, the mean canopy height increased from 5.2 to 6.8 m during the growing season of 2011.

The time evolution of *LAI* in SRC 1 is depicted in Fig. 2. For both the years 2009 and 2010, the peak in *LAI* occurred at the beginning of September, with values of 7.5 and 3.7, respectively. Nevertheless, in 2011, the maximum *LAI* of 5.6 was recorded one month earlier. This pronounced early *LAI* decline in August 2011 (Fig. 2) was most likely due to a *Melampsora* infestation that was favored by a combination of a high leaf area density (*LAI* of 5 distributed within 3 m^3, with additional leaf area of weeds) and the rainy weather, with low evaporation resulting in a very humid microclimate and low ventilation of the lower canopy parts. The occurrence of *Melampsora* rust was recorded also in 2010, but almost one month later than in 2011, and thus, it did not contribute significantly to early defoliation. However, the rust infection most likely led to an increase in the mortality (from 9.9% to 20.4% of the originally planted cuttings) during the following year 2011, as evidenced by the symptoms of black stem diseases. In fact, *Melampsora* and other stress factors, such as late spring frosts, are among the most important predispositions for black stem diseases (Stanturf et al., 2001). Apart from the two mentioned diseases, poplar leaf beetles (*Chrysomela populi*)

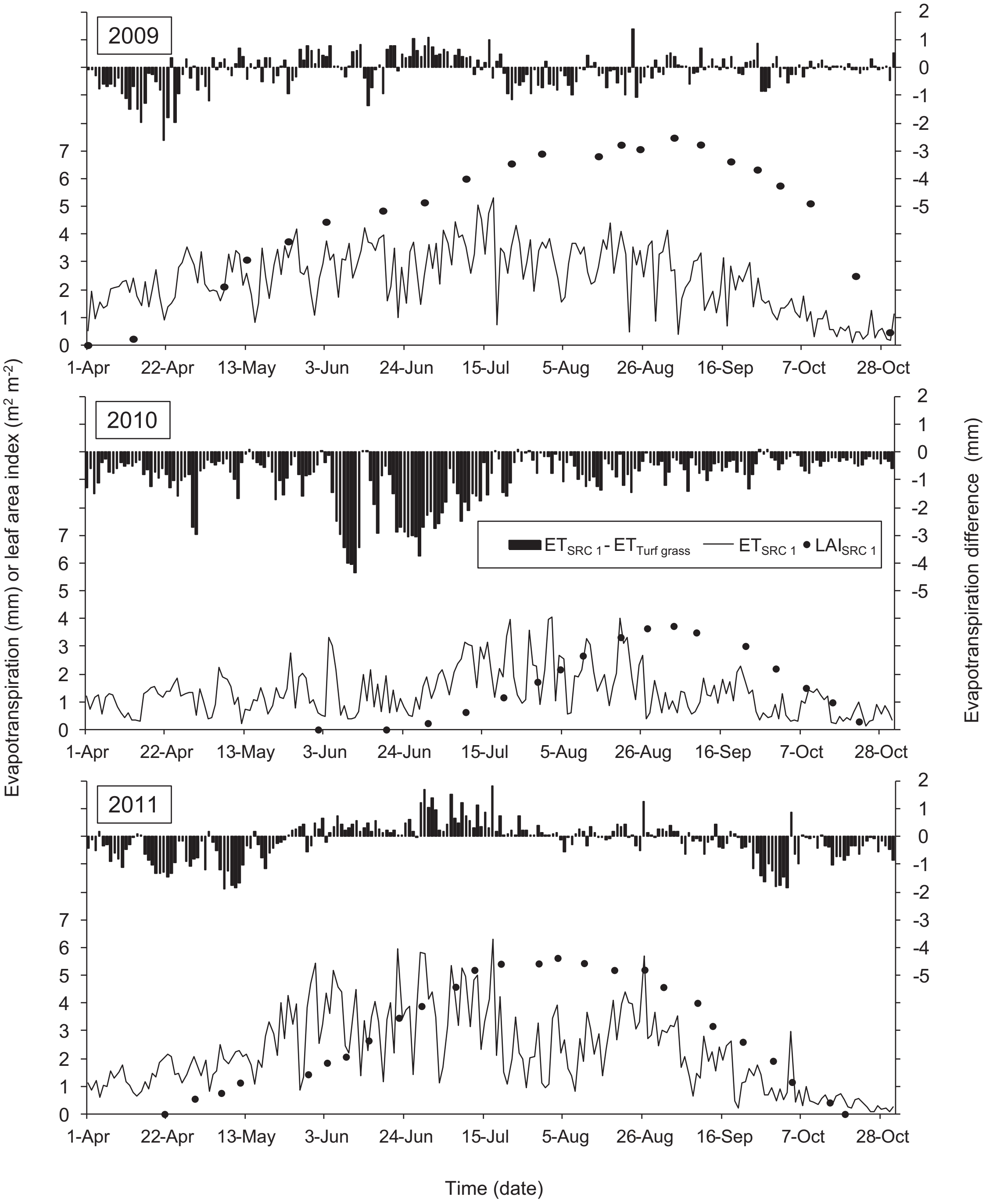

Fig. 2. Time courses of the evapotranspiration (*ET*) of the short-rotation coppice (SRC 1) from the beginning of April to the end of October (black solid line). The vertical columns represent the differences between the *ET* of SRC 1 and that of the turf grass. The closed black circles represent the time evolution of the mean canopy leaf area index (*LAI*), measured using a ceptometer.

and flea beetles (*Crepidodera aurata aurata* and *Crepidodera aurea*) were observed feeding on the leaves of the resprouting stumps in 2010. However, the amount of the damage caused by these latter species was judged to be not significant. These pests and diseases were not noticed during the first rotation (2002–2009) when the still single-stem stand was more ventilated.

In the case of SRC 2, the highest mean canopy *LAI* of 7.3 ± 0.5 (the mean of four fertilization treatments ± the standard deviation) was recorded at the beginning of August 2011. Since we did not find any statistically significant effect of the fertilization experiment on *LAI*, tree height and biomass productivity, we considered the SRC 2 as a homogeneous cover from the micrometeorological point of view.

3.2. Assessment of fetch and gradient measurements constraints

The wind predominantly blows from the west to northwest (~35% of the time) and the south to southeast directions (~25% of the time) (Fig. 1). As Fig. 1 shows, the west to northwest direction was quite favorable in the case of SRC 1, where the fetch ranged between 62 and 230 m, corresponding to a fetch-to-height ratio 13–48 in 2009, and 36–132 in 2010, i.e., during the years with the tallest and the smallest canopy heights throughout the study. Nevertheless, the second prevailing direction, from south to southeast, was less favorable, as the fetch extended only 54–60 m, resulting in a fetch-to-height ratio around 12 and 24 in 2009 and 2010, respectively. In SRC 2, the layout with respect to more adequate and less adequate fetches was different, as lengths of 50–93 m (fetch-to-height ratio 16–30) and 86–156 m (fetch-to-height ratio 28–50) were observed for the two prevailing wind directions, respectively. The fetch was probably the most critical issue for the micrometeorological measurements at the turf grass site, where it extended only 26–90 m (fetch-to-height ratio 31–108) from the prevailing west to northwest directions and only 22 m (fetch-to-height ratio 26) from the southwest direction. From the south to the southeast, the distance from the neighboring covers ranged between 37 and 74 m (fetch-to-height ratio 44–88). Again, an opposite arrangement of more favorable and less favorable fetches was observed for the grassland site, with fetch lengths of 84–126 (fetch-to-height ratio 140–211) and 25–51 m (fetch-to-height ratio 42–85) for the two mentioned directions, respectively.

Results of the footprint model indicated slightly faster equilibration under neutral stratification in the case of the SRCs compared to the grass covers as a consequence of their higher aerodynamic roughness. In the SRCs with respective fetches 20, 30, 50, and 100 m, the fluxes were equilibrated by 48, 61, 75 and 86%, whereas above the aerodynamically smoothest turf grass by 38%, 52%, 68%, and 82%. The 90% equilibration was then reached within a fetch of 132 and 176 m for the SRCs and the turf grass, respectively.

Assuming that most of the diurnal conditions (mainly those with high fluxes) were unstable, the 90-m fetch was judged as adequate and the *ET* data were split into two categories using this threshold (see Section 2.4). The differences between the theoretical monthly sums of *ET* related to the fetch length below and above 90 m varied typically within ±4.2 mm and ±1.6 mm for SRC 1 and SRC 2, respectively. Maximum difference was observed at SRC 1 in April 2009 when the *ET* values from longer fetches were 14 mm lower. Over the entire growing seasons 2009 and 2010, the cumulative *ET* from the fetches below 90 m exceeded that from longer fetches by 20 mm and only by 11 mm in 2011. At SRC 2, the shorter fetches resulted in 1.6 mm higher *ET* over an entire growing season 2011.

Since the 90-m fetch threshold resulted in very unequal data distribution within the two fetch categories for both of the grass covers, a threshold of 70 m was used as a surrogate. For the turf grass site, the monthly difference between *ET* for two fetch categories typically varied within ±1.6 mm; and for the grassland site, within ±2.3 mm. The highest observed monthly difference at the turf grass site occurred in April 2009 with 7.9 mm higher *ET* for the longer fetches. Over the entire 2009 growing season, cumulative *ET* at the turf grass site was 7 mm higher for fetches longer than 70 m. In contrast, the cumulative *ET* coming from these fetches was lower by 13 and 3 mm during the growing seasons 2010 and 2011, respectively. At the grassland site, the highest monthly difference of 7 mm occurred in May 2011 with higher *ET* for the longer fetches. Over the entire 2011 growing season, the *ET* was 19 mm less for the shorter fetches.

Considering that the wind never blew only from the shortest fetches during the whole month, the differences should be even less pronounced than the values listed above. Due to relatively small deviations in *ET* from two groups of fetches, no filtering of the data with regard to the fetch length was applied. Instead, the comparison with ET_0 and the duplication of the two contrasting types of cultures (the two SRCs versus the two grass covers) with different azimuthal orientations of the favorable fetch were used as auxiliary pieces of evidence.

Another potential error in the *ET* measurements by the BREB method was the magnitude of *T* and *e* gradients. Typical gradients above the grass covers during the growing season and when $ET > 0$ were −0.29, −0.12, and −0.52 K m^{-1} for the temperature and −37, −16, and −62 Pa m^{-1} for the water vapor pressure, both expressed as median, upper and lower quartile, respectively. The gradients above the SRC sites were −0.17, −0.07, and −0.31 K m^{-1} for the temperature and −13, −7, and −24 Pa m^{-1} for the water vapor pressure expressed in the identical order and for the same conditions. In 2010, the absolute magnitude of the gradients above the SRC 1 was about 30% larger for the temperature and about 15% smaller for the humidity. Despite the larger distance between the measuring levels above the SRCs, the smaller gradients above aerodynamically rougher canopy—due to more effective mixing and larger distance of the measuring levels from the zero plane displacement—affected the portion of the data which had to be rejected and subsequently gap-filled. Nevertheless, the gap-filling procedure did not change the relation between *ET* of the different covers (Table 6 in Supplementary data).

3.3. Comparison of actual evapotranspiration

Fig. 3 depicts the typical daily patterns of *ET* rates calculated as the means of the half-hourly values during specific months of the growing season. Obviously, ET_0 can serve as a very good approximation of the upper boundary of *ET* rate trends for the SRCs, although it was exceeded in some exceptional half-hour intervals. The highest *ET* rates were usually recorded during the summer, which presents higher evaporative demand. The highest rates of ET_0 occurred in July 2010 and May 2011, in both cases reaching up to 0.74 mm h^{-1}. The highest *ET* rate measured in this study, 0.76 mm h^{-1}, was achieved by SRC 1 on 5 July 2011. The maximum *ET* rates of SRC 2 reached up to 0.74 mm h^{-1} during August 2011, the same as for the grassland site. In the case of the turf grass site, the highest rates, 0.75 mm h^{-1}, were recorded in July 2008. Neither the particular half-hours of the highest actual *ET* values nor their monthly trends coincided with the highest evaporative demand, expressed as ET_0. This might be explained by reduced water availability (Fig. 4) occurring just during the periods with highest ET_0, as well as by the not completely developed *LAI* in the SRCs (Fig. 2). As a result of this low *LAI*, the soil evaporation and thus the soil moisture of the superficial layer played a pivotal role in the overall *ET* loss. The effect of the low *LAI* on the *ET* rates of poplars is clearly visible at the beginning and at the end of the growing season, namely in April 2009, April and May 2011, and October 2011 (Figs. 2 and 3).

The 2010 growing season was unique in that the plantation was coppiced during the winter at the beginning of the year, which affected several aspects of the microclimate at the plantation. First,

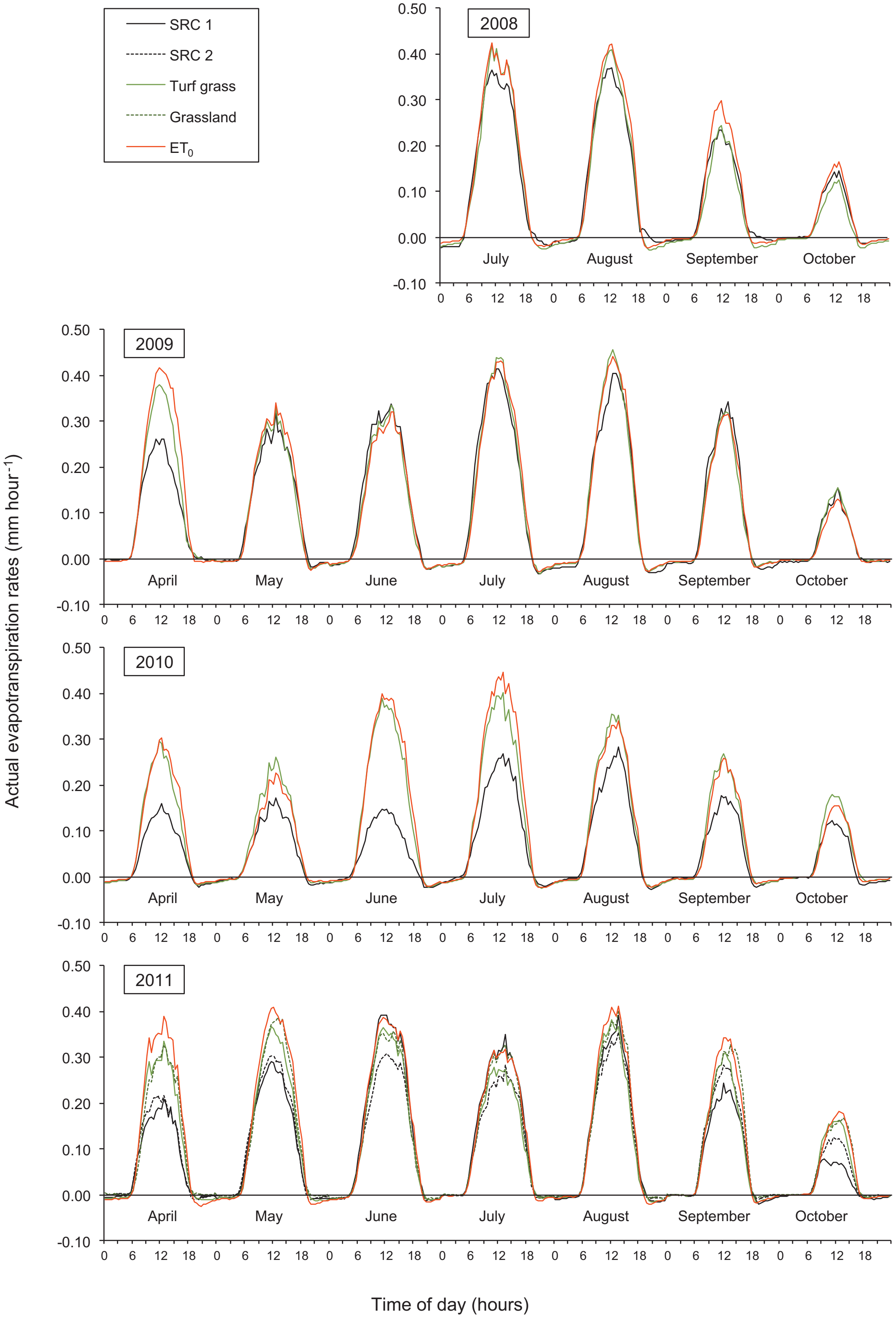

Fig. 3. Mean daily courses of evapotranspiration (*ET*) rates for the months of April through October for two contrasting types of vegetation cover. Short-rotation coppices are represented by solid (SRC 1) and dashed (SRC 2) black lines. Grassland vegetation types are represented by solid (turf grass) and dashed (grassland) green lines. For comparison, the potential *ET* of the hypothetical reference grass cover is shown (solid red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

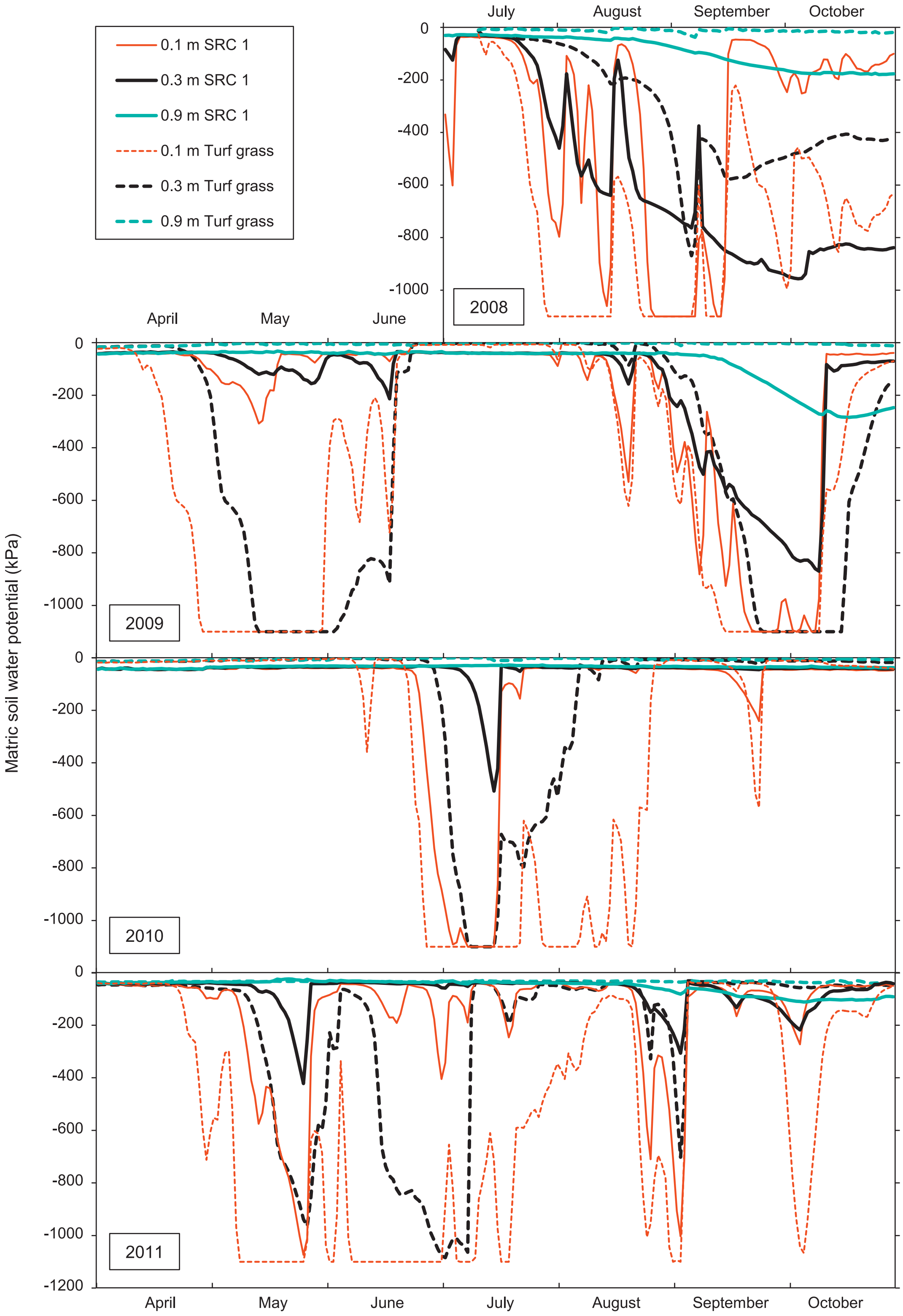

Fig. 4. Matric soil water potential measured by gypsum blocks for the short-rotation coppice culture (SRC 1 – solid lines) and the turf grass (dashed lines) at depths of 0.1 (red), 0.3 (black) and 0.9 m (blue) below the surface. Note that the lower limit of 1100 kPa is artificially created by the limit of the sensor resolution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

throughout the entire spring there was only bare soil with stumps (∼0.1 m in height) covered by pieces of branches and woody chips after the winter harvest. Beside these, there were only a few annual weeds, predominantly dandelions (*T. officinale*), which are typical spring plant species growing in the plantation before developing full foliage. This period was characterized by high soil moisture levels (Fig. 4) and frequent precipitation events (24 days with rain during May 2010). As a result, soil evaporation was very high during this period and led to similar *ET* rates for both of the covers compared. From mid-June onward, soil moisture started to

Table 3
Results of the ANOVA post hoc Fischer's LSD test showing the interactions and statistical significance (p-values) between daily evapotranspiration (ET) of contrasting covers (short-rotation coppice and turf grass) within particular months in particular growing seasons in the years 2008–2011. Single, double, and triple asterisks denote significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

	ET of SRC 1 vs. turf grass			
	2008	2009	2010	2011
April		0.003**	<0.001***	0.007**
May		0.892	0.002**	0.071
June		0.25	< 0.001***	0.194
July	0.656	0.912	<0.001***	0.069
August	0.695	0.4	0.012*	0.813
September	0.059	0.813	0.013*	0.083
October	0.951	0.815	0.029*	0.001**

decrease due to low amounts of precipitation and a high evaporative demand. This resulted in very rapid drying of the soil surface layer and a substantial decrease in soil evaporation. At the same time, the stumps started to resprout, and a very fast growth of new shoots was initiated (on average, 0.15–0.2 m of height growth per week). It is reasonable to assume that the vigorous growth of the shoots was linked to an increase in the transpiration–soil evaporation ratio, which resulted in the progressive increase in the *ET* of SRC 1. Despite the progressive shoot development, the canopy did not close during that year, and the *ET* rates of SRC 1 did not exceed the *ET* of the turf grass. This situation is well illustrated by the temporal variation in the daily *ET* of SRC 1 and its *LAI* development and particularly the differences between the daily *ET* totals of SRC 1 and the turf grass (Fig. 2). Apart from the aforementioned dry period in 2010 and the beginning of the remaining growing seasons (2009 and 2011), when the daily *ET* of the turf grass exceeded that of SRC 1 by up to 4.3 and 2.6 mm day^{-1}, respectively, the differences usually varied within the range of ±1 mm day^{-1}. It is noteworthy that the period in the last ten days of July 2009, when the higher *ET* of SRC 1 suddenly declined, coincided with two substantial rainfalls with very strong windstorms. The total precipitation during these two events were 66 and 10 mm, and the 10-min-averaged wind speeds exceeded 7 and 6.3 m s^{-1}, respectively, while, the wind gusts were almost three times higher. It was therefore hypothesized that the strong winds on these two occasions could have caused damage to the upper canopy parts. During the second half of June and the first two decades of July 2011, *ET* of SRC 1 was notably higher than the *ET* of the turf grass (Fig. 2). In particular, it was most pronounced on 17 July 2011, when the *ET* of SRC 1 exceeded the *ET* of the turf grass by 1.8 mm day^{-1} and reached the highest *ET* recorded in this study, i.e., 6.3 mm day^{-1}. The overall maximum *ET* of the turf grass, 5.9 mm day^{-1}, was recorded during the same period, on 22 June 2011, when the highest ET_0 of 6 mm day^{-1} was also registered.

ANOVA conducted considering the particular days as the replicates and months and covers as the treatments confirmed the differences at the beginning (April 2009 and 2011) and end of the growing season (October 2011), as well as during the entire growing season of 2010 (Table 3). Although the *ET* of SRC 1 was clearly higher than that of the turf grass during the period of June to July 2011 (Figs. 2 and 3), the difference was not statistically significant. However, the *ET* of SRC 1 was significantly higher than the *ET* of SRC 2 during that same period. The *ET* of the grassland never differed significantly from that of the turf grass, although it was usually higher. Finally, in contrast with SRC 1, the *ET* of SRC 2 was more consistent with respect to the *ET* of the grass covers from which it significantly differed only in April 2011.

The trends of the main water balance components represented by *ET*, ET_0, and the precipitation accumulated in the years 2009–2011 are depicted in Fig. 5, while their monthly, seasonal and yearly totals are summarized in Table 2. Most of the time, the accumulated precipitation exceeded the ET_0 in 2009 and 2010, while in 2011, the accumulated rainfall was usually less than the ET_0. This may suggest that the available water was not a limiting factor during 2009 and 2010, whereas in 2011 it might have been. Indeed, during the drier months, when ET_0 was higher than the precipitation (compare Table 2 with Fig. 4), the *ET* of the turf grass diverged from ET_0 more than during the months with excessive or sufficient water supply (Fig. 5). In some of the months, namely in June 2009 and in May, August and September 2010, the *ET* of the turf grass even exceeded ET_0. This may be explained by the humid weather, with substantial and well distributed rainfalls, resulting in a higher *ET* due to the much lower surface resistance of the intercepted water. However, the agreement between the ET_0 and *ET* of the turf grass during the humid periods was generally good, increasing the confidence in this fetch-limited measurement. At the seasonal or yearly level, the *ET* of the SRCs did not exceed the ET_0

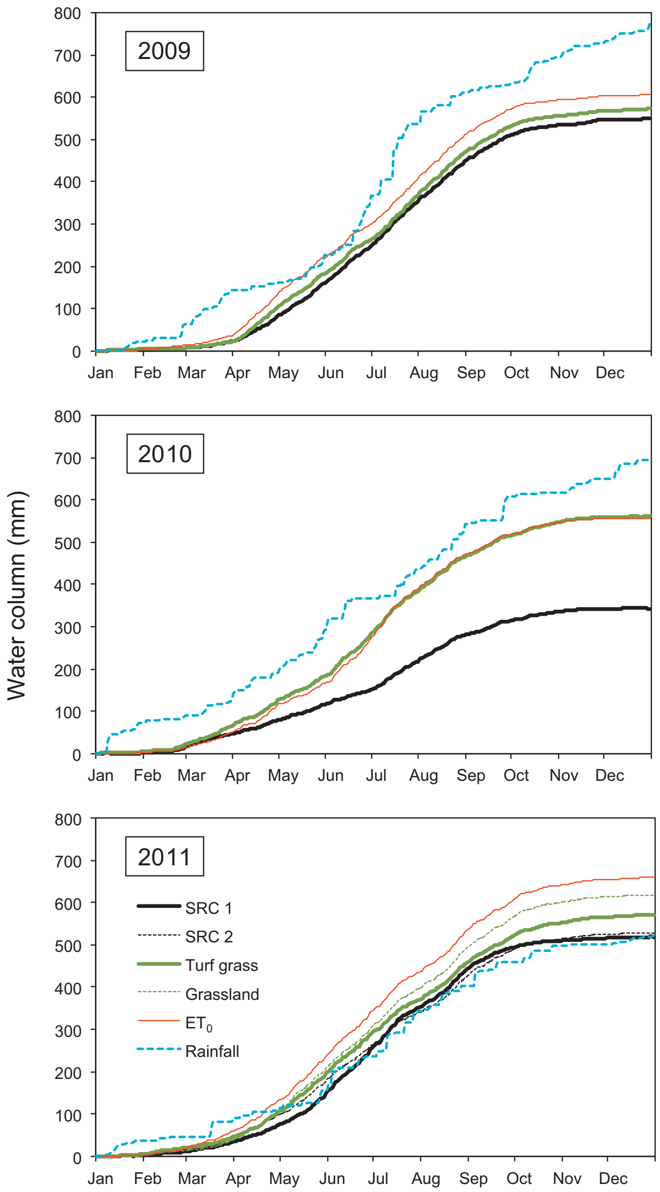

Fig. 5. Cumulatively expressed evapotranspiration of different vegetation covers (SRC 1 – solid black line; SRC 2 – dashed black line; turf grass – solid green line; grassland – dashed green line), the reference ET_0 (solid red line) and the amount of precipitation (dashed blue line) during the years 2009–2011. All values are expressed in mm of water column. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

and neither did the *ET* of the grassland nor the *ET* of the turf grass, although it was higher during some months (the most prominent being June and July 2011). The parts of the season characterized by no or low *LAI* of the SRCs seemed to be the main reasons for the differences between the *ET* seasonal totals of the SRCs and grass covers.

As a last step, we compared our results with other studies on poplar and willows (Table 5). Annual *ET* of 549 mm and corresponding $K_c = 0.81$ as the highest values from our study matched the median of the listed values. We found that the 10-arc-min-resolution of annual ET_0 usually overestimated the ET_0 reported in the studies by 10–20%. Moreover, this overestimation significantly ($p < 0.05$) increased by 1.8% per latitudinal degree northward. Although, this resulted in an almost systematic increase of K_c by 13 ± 5%, the rankings of the studies remained nearly unaltered (see the K_c values in brackets in Table 5).

Table 4

Results of the ANOVA post hoc Fischer's LSD test showing the interactions and statistical significance (*p*-values) between daily evapotranspiration (*ET*) of contrasting covers (two short-rotation coppices, one turf grass, and one grassland) within particular months of the growing season of 2011. Single, double, and triple asterisks denote significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

		SRC 1	SRC 2	Turf grass
April	SRC 2	0.092		
	Turf grass	0.012*	0.405	
	Grassland	<0.001***	0.034*	0.198
May	SRC 2	0.502		
	Turf grass	0.078	0.274	
	Grassland	0.009**	0.052	0.396
June	SRC 2	0.011*		
	Turf grass	0.203	0.208	
	Grassland	0.324	0.122	0.774
July	SRC 2	0.040*		
	Turf grass	0.077	0.778	
	Grassland	0.619	0.12	0.203
August	SRC 2	0.581		
	Turf grass	0.816	0.749	
	Grassland	0.571	0.263	0.424
September	SRC 2	0.117		
	Turf grass	0.111	0.977	
	Grassland	0.003**	0.166	0.175
October	SRC 2	0.084		
	Turf grass	0.006**	0.304	
	Grassland	0.001**	0.139	0.653

4. Discussion

The maximum canopy *LAI* of 7.5 of SRC 1 during 2009 fell well within the range of 4–12 for well-established high-density stands of poplar or willow species with a closed canopy, as reported in various studies (Lindroth et al., 1994; Ceulemans et al., 1996; Liberloo et al., 2006; Petzold et al., 2010). For open canopies of SRCs—usually in the first year after planting or coppicing, just as in the year 2010 in the present study—the maximum *LAI* varies within the range of 0.5–6 (Ceulemans et al., 1996; Broeckx et al., 2012). The time of canopy closure and prominent *LAI* development depend on the planting density, the management intensity, the clone variety, the plant vitality and weed competition. Similar dynamics of *LAI* development, with a peak in the last part of the summer, have been described for poplars and willows in other studies (e.g., Lindroth et al., 1994; Ceulemans et al., 1996; Guidi et al., 2008). Although no significant reduction in *LAI* was observed following the two windstorms after which the *ET* of SRC 1 declined in the last ten days of July 2009 (Fig. 2), it is likely that the hydraulic conductivity of the upper part of the canopy, which is generally considered to be the most active, was negatively affected. The top of the canopy is typically the most exposed to high-speed winds, and it also carries the largest and heaviest (even more so when wet) leaves on not yet completely lignified shoots (Christersson, 1996). Tacamahaca (or Balsam) poplars are well known for their vulnerability to wind damage, especially *P. nigra* × *P. maximowiczii*, which is characterized by brittle branches and large leaves (Eckenwalder, 2001; Petzold et al., 2010). The fact that no changes in *LAI* were measured might be explained either by the resolution of the instrument or by the fact that the leaves did not have to die and fall immediately.

In general, *LAI* development is closely related to *ET* patterns and to the available energy partitioning (Iritz and Lindroth, 1996; Blanken et al., 2001). The mean diurnal trends of *ET* calculated on a monthly basis (Fig. 3), as well as the maximum diurnal peaks, were very similar to those reported for willow SRC (*Salix viminalis*) in southern Sweden (Lindroth and Iritz, 1993) and for poplar plantations (*Populus* × *euramericana*) in northern and central Italy (Migliavacca et al., 2009; Tricker et al., 2009). If we consider the differences in latitudes between our study location and the aforementioned locations, we find that the daily sums of solar radiation during the period around the summer solstice are very similar. However, compared to the maximum diurnal peaks of irradiance in the Czech Republic, those in southern Sweden and in northern Italy are at least 10% lower and less than 5% higher, respectively (Allen et al., 1998). It may be therefore concluded that the partitioning of the available energy during the summer period in willow SRCs in Sweden was significantly different, considerably favoring the latent heat flux versus the sensible heat flux. *ET* rates comparable to those presented in this study were reported for an adult poplar stand (*P. trichocarpa* × *P. deltoides*) in Belgium (Meiresonne et al., 1999) and for two willow SRCs (*S. viminalis* and *S. dasyclados*) in southern England (Finch et al., 2004), with midday peaks of canopy transpiration rates of 0.5–0.6 mm h^{-1}. Lower values were reported for a 70-year-old aspen overstory (*P. tremuloides*) located in southern Canada (Black et al., 1996; Blanken et al., 2001), in an area characterized by a cold climate and a maximum monthly *ET* midday peak of 0.3 mm h^{-1}. Apart from the diurnal and seasonal trends of *ET*, Fig. 3 additionally suggests what the available energy partitioning was between the latent and sensible heat flux, if *ET* rates are compared with the ET_0, which usually makes up approximately 70% of the net radiation at this locality. The seasonal evolution of the energy partitioning follows the typical pattern for broadleaved forests with insignificant understories, where during the early spring most of the available energy is converted into sensible heat flux, which sharply decreases at the expense of the latent heat flux as the *LAI* develops (Lindroth and Iritz, 1993; Blanken et al., 2001). The same patterns were observed in the present study (Figs. 2 and 3, and Tables 3 and 4), where the *ET* of the grass covers, characterized by relatively constant energy partitioning during the entire season, favoring latent heat flux (Fig. 3), was significantly higher during the initial season stage, whereas it was very similar during the summer. From this perspective, an SRC acts as a deciduous forest when the canopy is well developed and closed. However, during periods after the harvest, such as in 2010, the energy partitioning more closely resembles that of a conventional cropping system, characterized by occasional periods of bare soil or other non-transpiring covers that favor the conversion into sensible heat when the conditions are rather dry. The *ET* and energy partitioning at the end of the seasons are again strongly dependent on the magnitude of *LAI* and the dynamics of leaf fall. Therefore, the *ET* of SRC 1 and turf grass also remained comparable during the late growing season periods in 2008 and 2009. Although during the entire growing season of 2010, the *ET* of SRC 1 was significantly lower than that of the turf grass, we did not observe a shift in the ratio between the two cultures' *ET* (or any change in energy partitioning) later, toward the

Table 5

A comparative literature survey of water use by poplars and willows in reference to the present study (marked by bold font).

Species	Location	Method used	ET (mm year^{-1})	ET_0 (mm year^{-1})	K_c	Max. ET (mm day^{-1})	Reference
Populus							
General *P.* sp.	United Kingdom, England	Modeling	627	568 (482)	1.10 (1.30)		Finch et al. (2004)
General *P.* sp.	Belgium	Modeling	585	662 (567)	0.88 (1.03)		Deckmyn et al. (2004)
P. euphratica	Uzbekistan	Porometer + modeling	1030^s (1144)	1435 (1443)	0.80 (0.79)	10.5	Khamzina et al. (2009)
P. euphratica	China, Inner Mongolia	BREB	447^s	1180 (1172)	0.42 (0.42)	6.7	Hou et al. (2010)
P. fremontii	USA, California	Remote sensing + sap flow	1240^s (1378)	2234 (2637)	0.62 (0.52)	11.8	Nagler et al. (2007)
P. tremula	Germany	Modeling	441	667 (560)	0.66 (0.79)		Lasch et al. (2010)
P. tremuloides	Canada, Saskatchewan	Eddy covariance	403	700 (579)	0.58 (0.70)	5.6	Black et al. (1996)
P. deltoides × *P. petrowskyana*	Canada, Alberta	Eddy covariance	298	687 (562)	0.43 (0.53)		Cai et al. (2011)
P. nigra × *P. maximowiczii*	Germany	Sap flow	$475^{s,\ T}$ (660)	684 (588)	0.96 1.12)	6.7^T	Petzold et al. (2010)
P. nigra × *P. maximowiczii*	USA, Wisconsin	Sap flow	$885^{s,\ T}$ (1229)	815 (765)	1.51 (1.61)		Zalesny et al. (2006)
P. nigra* × *P. maximowiczii	**Czech republic**	**BREB**	**549**	**678 (597)**	**0.81 (0.92)**	**6.3**	**Present study**
P. trichocarpa × *P. deltoides*	Germany	Modeling	542	727 (620)	0.75 (0.87)		Bungart and Hüttl (2004)
P. trichocarpa × *P. deltoides*	United Kingdom, England	Sap flow		569 (483)		7.9^T	Allen et al. (1999)
P. trichocarpa × *P. deltoides*	United Kingdom, England	Sap flow		576 (493)		10.7^T	Hall et al. (1998)
P. trichocarpa × *P. deltoides*	USA, Washington	Sap flow		854 (781)		4.8^T	Hinckley et al. (1994)
P. trichocarpa × *P. deltoides*	United Kingdom, England	Sap flow + modeling	498^s (553) – dry	576 (493)	0.96 (1.12)		Hall et al. (1996)
P. trichocarpa × *P. deltoides*	United Kingdom, England	Sap flow + modeling	772^s (858) – wet	576 (493)	1.49 (1.74)		Hall et al. (1996)
P. trichocarpa × *P. deltoides*	Belgium	Sap flow + modeling	$320^{s,T}$ (444)	667 (575)	0.67 (0.77)	4.9^T	Meiresonne et al. (1999)
Populus × *euroamericana*	Italy	Eddy covariance	448^s (498)	774 (732)	0.64 (0.68)		Migliavacca et al. (2009)
Populus × *euroamericana*	Italy	Sap flow + eddy covariance		988 (981)		7.2^T	Tricker et al. (2009)
Unspecified *P.* sp.	China, near Beijing	Eddy covariance	550^s (611)	1100 (1150)	0.56 (0.53)	6.7	Wilske et al. (2009)
Salix							
General *S.* sp.	United Kingdom, England	Modeling	533	568 (482)	0.94 (1.11)		Finch et al. (2004)
General *S.* sp.	United Kingdom, England	Modeling	499	594 (503)	0.84 (0.99)		Stephens et al. (2001)
S. viminalis	Sweden	Modeling	488^s (542)	559 (424)	0.97 (1.28)	9.4	Persson and Lindroth (1994)
S. viminalis	Sweden	Modeling	346^s (384) – dry	594 (470)	0.65 (0.82)		Persson (1997)
S. viminalis	Sweden	Modeling	497^s (552) – wet	577 (457)	0.96 (1.21)		Persson (1997)
S. viminalis	Sweden	BREB + modeling	541^s (601)	559 (424)	1.08 (1.42)		Lindroth et al. (1994)
S. viminalis and hybrids	Sweden	Sap flow	$220^{s,\ T}$ (306)	570 (456)	0.54 (0.67)		Linderson et al., 2007

The species, locations, methods used, annual actual evapotranspiration (*ET*), annual reference grass evapotranspiration (ET_0), their ratio as the annual crop coefficient (K_c), maximum daily *ET* and the literature references are summarized. Note that the highest annual *ET* from 2009 in our study is shown here to provide nearly potential values of the water use. General species refers to modeling studies where the input parameters were gathered across several hybrids or pure spp. The superscript 's' signifies that only data for the growing season or the main portion of the growing season were available, and the superscript '*T*' signifies that only transpiration data were available, not whole *ET* data. *ET* values in brackets provide data normalized to the entire annual *ET*, assuming that at the seasonal level, transpiration accounts for 80% of *ET* and that the *ET* of the growing season covers 90% of the whole annual cycle. ET_0 and K_C in brackets express the corrected values since we observed that the 10-arc-min-resolution ET_0 data typically overestimated the local values as a function of latitude (for more details see the text). The words "dry" and "wet" indicate water availability scenarios within the modeling studies.

end of the season. In contrast, in 2011, when SRC 1 was extensively infected by *Melampsora* rusts, its *ET* systematically decreased compared to that of the grass covers as a consequence of the early *LAI* decline (Figs. 2 and 3), and more energy was converted into sensible heat. Nevertheless, this was not the case of the one-year-older, taller and thus better-ventilated SRC 2.

Although the plant–water relations of poplar and willow SRCs have been extensively documented in the literature (see e.g., the recent review by King et al., 2013), comparisons of SRC *ET* with grassland *ET* are rare. Moreover, the comparison of *ET* between SRC and grassland using the same measurement technique at the same locality has, to our knowledge, never been conducted before. The results of this study show that, at least for the given pedo-climatic conditions, the half-hourly, daily and cumulative seasonal *ET* of the grass covers were comparable or surprisingly even higher than the *ET* of the SRCs. These important findings contradict the results of studies of poplar and willow SRCs in southern England (Hall et al., 1996, 1998; Hall and Allen, 1997; Allen et al., 1999; Finch et al., 2004) and studies of willow SRCs in Sweden (e.g., Grip et al., 1989; Persson and Lindroth, 1994; Persson, 1997; Lindroth and Båth, 1999).

Based on the literature review (Table 5), the most water-consuming species can be identified as the poplar SRC used in the phytoremediation of landfill leachate reported by Zalesny et al. (2006) and the poplar SRC growing on arable land in the modeling study reported by Hall et al. (1996) for an unlimited water scenario. The modeling study by Finch et al. (2004) found poplars to be greater water consumers than willows, based on parameters derived from sap flow measurements in poplars (obtained from Hall et al., 1996) and on parameters derived from their own eddy covariance and sap flow measurements for willows. However, although the maxima in Table 5 were reported for poplars, it is not possible to make any general statement regarding the differences between these two species, due to very high variability of the results reviewed. This is consistent with the findings of Hall et al. (1998), who did not detect any significant differences in the sap flow-based transpiration of poplars and willows. The lysimetric study by Guidi et al. (2008) showed that the water use of willows and poplars was very similar and the observed differences in *ET* were a consequence of differences in management. Despite the large plasticity in the genus *Populus* (Ceulemans et al., 1988), no significant differences between specific hybrids or between hybrids *versus* pure species were identified, due to the large variability in the results of the available studies. Indeed, it seems that the type of management as well as the planting density and other environmental factors are of major importance when the annual water cycle of operational stands is assessed.

Although lysimetric studies can provide excellent insights into physiological behavior and potential water use (Pauliukonis and Shneider, 2001; Guidi et al., 2008), they were not included in the comparison shown in Table 5 due to their inherent exposure to the so-called “clothesline” or “oasis” effect, which results in extremely high *ET* (e.g., four times greater than ET_0) as a result of advected sensible heat (Lindroth and Iritz, 1993; Allen et al., 1998). Such an enhancement by sensible heat flux from local sources is theoretically not possible in any larger-scale vegetation (Allen et al., 1997). However, it still plays an important role in the water use of smaller plantations, which might be more likely in the future (Lindroth and Iritz, 1993; Hall et al., 1998; Finch et al., 2004). On the other hand, the conversion of advected sensible heat into latent heat might be seen as having a positive cooling effect on the surroundings of SRCs and thus also as a reduction in the bulk atmospheric evaporative demand in the agricultural landscape. It is obvious that the results of our study were also to some extent biased by advection from the surrounding fields. However, the cumulative errors related to insufficient fetch were relatively small (see Section 3.2) and any form of the fetch filtering would not bring any significant quantitative change and in no case would change the relation between *ET* of the different covers. This was most likely due to the similar surface conditions of the areas surrounding the experimental fields (see the land use map in Fig. 1).

Although our results constituted median values for the annual *ET* and K_c in the list of reported values (Table 5), they were the lowest from the three studies dedicated to *P. nigra* × *P. maximowiczii*. However, our SRC plantations could possibly have consumed more water without the effects of disturbance by wind damage or if the *Melampsora* infection had not occurred. As the year 2011 was most likely limited by water availability, it can be assumed that the *ET* in 2009 might serve as an exemplary one—apart from the decline after the windstorms—for a year with excess water. It is noteworthy that even during such more or less unlimited water conditions (see Table 2 and Fig. 4), the *ET* of the SRCs did not exceed ET_0. However, because precipitation is usually not optimally distributed with respect to actual plant water requirements, we can expect that during the year 2009 as well, short periods of *ET* decline due to reduced water availability could have occurred.

Our review (Table 5) shows that modeling and sap flow techniques are the most common methods used to assess the water use of poplar and willow SRCs. Interestingly, the sap flow measurements provided the highest water use estimates in the reviewed studies, and they are significantly higher than the estimates based on micrometeorological methods such as eddy covariance or BREB. This is in contrast with a more recent study reporting a large underestimation of three analyzed sap flow techniques (Steppe et al., 2010). Nevertheless, apart from the nature of such comparisons, the high water use estimates obtained using the sap flow technique may also be a consequence of the assumptions made in scaling from the measuring point to the whole tree and to the entire canopy, such as in Zalesny et al. (2006), for example, where the whole cross-sectional stem wood area was considered equally conductive sap wood. In view of the remarks made above, a need remains for more *in situ* (field) experiments focused on the water use of SRCs and bioenergy crops in general. In particular, combinations of different techniques and approaches for various pedo-climatic conditions are needed to ensure reliable conclusions and general recommendations.

Due to the comparable water use of SRC and grassland measured in this study, there is most likely no reason for concern for water scarcity in the agricultural landscape of the Czech Republic or elsewhere as a result of a shift in land use toward SRCs rather than grasslands. Moreover, due to comparable water use but potentially deeper root systems (Jackson et al., 1996; Hall et al., 1996; Dickmann et al., 2001; Zalesny et al., 2006), SRCs may be better adapted to future climate change conditions, which may be characterized by more frequent drought spells.

ET_0 may be a very suitable proxy for poplar SRC water consumption in areas where the rainfall exceeds the ET_0. In the opposite case, rainfall, due to soil water availability, will dictate the *ET* rates and limit the yields. This has important consequences for proper site selection for the long-term ecological and economic sustainability of SRCs.

Our results pertain entirely to the hybrid clone J-105 (*P. nigra* × *P. maximowiczii*), which is currently the most common poplar clone in central Europe. However, *Populus* is a very broad genus, and caution is advised in applying these results to other clones.

5. Conclusions

(1) Based on the BREB measurements of *ET* above two SRCs and two grass vegetation sites, we found that although the *ET* of

SRCs sometimes exceeded the *ET* of grass covers or ET_0 on an hourly, daily or monthly basis, the *ET* of grass vegetation and ET_0 was always greater over an entire annual cycle.

(2) The maximum annual *ET* of the SRCs reached 549 mm year^{-1}, whereas it reached 573 and 619 mm year^{-1} for turf grass and grassland, respectively. For comparison, the maximum yearly ET_0 was 660 mm year^{-1}, and the rainfalls ranged from 521 to 779 mm year^{-1}. The highest monthly values, 107 mm month^{-1}, were identical for the two contrasting vegetation. On a daily time scale, the maximum total *ET* of the SRC was 6.3 mm day^{-1}—0.4 mm higher than the maximum *ET* of the grass vegetation and 0.3 mm higher than the maximum ET_0. The highest *ET* rates, close to 0.75 mm h^{-1}, were common for all covers as well as for ET_0.

(3) Significantly higher values of the grass vegetation *ET* were typically observed during the months at the beginning and end of the growing seasons and over the entire growing season when the plantation was resprouted after the winter coppice. The low *LAI* of the SRCs was found to be the main reason for these significant differences. In no case did the *ET* of the SRCs significantly exceed the *ET* of the grass covers on a monthly time scale.

(4) There is no evidence of negative hydrological impacts associated with intensive water use when the conversion of arable land into grassland is substituted by the establishment of new SRCs with water use comparable to those in our study.

(5) In reviewing the literature, we found that the *ET* of the SRCs described in this paper was in the middle of the range reported for poplar and willow SRCs worldwide. Because the range of results in the literature is rather broad and does not permit any general statements about the water use of SRCs, more experimental research using the most recently developed methods and approaches across a broad range of environmental conditions is needed. ET_0 values should be reported in such studies to facilitate comparisons of water use studies and make the results more transferable.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2013.07.004.

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