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Evapotranspiration of a willow cultivar (*Salix miyabeana* SX67) grown in a full-scale treatment wetland

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ABSTRACT

Since woody plants like willow are used increasingly in treatment wetlands, there is a growing need to characterize their ecophysiology in these specific growing conditions. For instance, evapotranspiration (ET) can be greatly increased in wetlands, due to factors like high water availability as well as oasis and clothesline effects. Few studies report willow ET rates measured in full-scale constructed wetland conditions, and fewer still in a temperate North-American climate. The objective of this study was to measure and model evapotranspiration of a commonly used willow cultivar, *Salix miyabeana* (SX67), to provide the ET rates and crop coefficient for this species. During two growing seasons, we studied a 48 m^2 horizontal subsurface flow willow wetland located in eastern Canada, irrigated with pretreated wood preservative leachate. Over two seasons, from May to October, we measured a mean monthly evapotranspiration rate of 22.7 mm/day (16.5 mm/d modelled), for a seasonal cumulative ET of 3954 mm (2897 mm modelled) and a mean crop coefficient of 6.4 (4.2 modelled). Both the evapotranspiration results and leaf area index (LAI) were greater than most results reported for open field willow plantations. Maximal stomatal conductance ($\bar{G}_s$) was higher than that expected for deciduous trees and even for wetland plants, and mean values correlated well with temperature, solar radiation, relative humidity and day of the year. We demonstrated that an ET model using $\bar{G}_s$, LAI and water vapor pressure deficit (VPD) as parameters could predict the evapotranspiration rate of our wetland. This simplification of traditional ET models illustrates the absence of evapotranspiration limitations in wetlands. Furthermore, this study also highlights some factors that can enhance ET in treatment wetlands. Our results should both improve the design of treatment wetlands using willows, and provide a simple ET predictive model based on major evapotranspiration drivers in wetlands.

1. Introduction

Treatment wetlands, or vegetation filters, are now commonly used for treatment of various types of wastewater (Valipour and Ahn, 2017). “Artificial” wetlands are generally planted with herbaceous plants like *Phragmites, Typha*, graminoids or other aquatic and semi-aquatic species (Kadlec and Wallace, 2008). More recently, woody species of the *Salix* genus (willows), generally studied for biomass production, are being tested and used for wastewater treatment purposes. *Salix* species are used in stream restoration projects (Pezeshki et al., 2007). They are mostly hydrophilic, tolerate hypoxic conditions and great water fluctuations well, have a high growth rate and develop a vigorous root system (Kuzovkina et al., 2008), making them good candidates for treatment wetland purposes. Another advantage of using woody plants for water treatment is the added value of biomass production that can be used for bioenergy and biofuel processes (Duggan, 2005). Consequently, there is growing interest in willow for use in treatment of landfill leachate, domestic wastewater or other nitrogen rich wastewaters (Białowiec et al., 2003; Dimitriou and Aronsson, 2011; Nissim et al., 2014). Fast growing willows are also known for their great evapotranspiration (ET), which led to the development of a new specific type of treatment wetlands called “zero-discharge wetlands” (ZDWs; Dotro et al., 2017). The design of ZDWs is based mainly on the ET capacity of the plant selected. They operate without liquid effluent, immobilizing and concentrating contaminants in the wetland substrate and preventing any release of residual contamination in the environment. Depending on the type of water contamination, ZDWs can function as the final step of a treatment plant or as a secondary treatment. Such wetlands are now well implanted in Scandinavian countries, mainly in Denmark, where the concept was first developed (Gregersen

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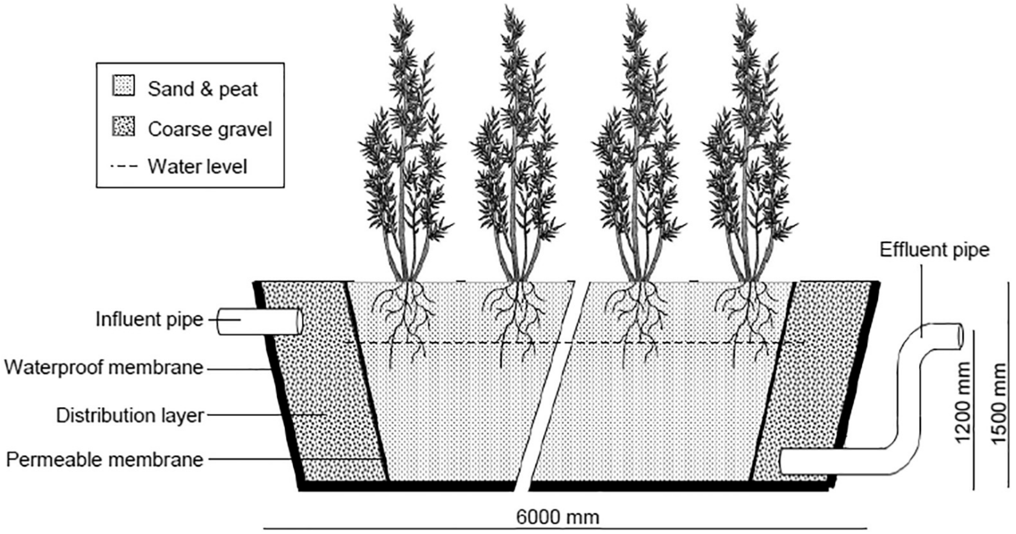

Fig. 1. Section view of the horizontal subsurface flow wetland used to measure and model evapotranspiration of *S. miyabeana* in treatment wetland conditions.

and Brix, 2001; Brix and Arias, 2005), and Ireland (Curneen and Gill, 2014). Conclusive tests have also been performed in Mongolia, under very cold climatic conditions (Khurelbaatar et al., 2017), and zero-discharge wetlands are currently being tested in other locations.

Sound scientific knowledge of the ET rate of the species used is an essential tool to design a treatment wetland because of the direct impact it will have on the wetland hydraulics (Kadlec and Wallace, 2008) and its removal performance (Beebe et al., 2014; Białowiec et al., 2014). It is even more important for zero-discharge wetlands, where ET is the main "treatment" process, ensuring that no liquid waste will flow out of the wetland. While many studies have been published on willow ET, very few concern willows growing in full-scale treatment wetland conditions. However, ET in artificial wetlands can differ greatly from ET measured in a plantation, and can significantly surpass potential ET (Dotro et al., 2017).

The willow species most studied for ET is *Salix viminalis,* its hybrids and their numerous cultivars (Frédette et al., 2017). Although widely used in Europe, some long-term studies have pointed out that, in North America, cultivars of *S. viminalis* are more prone to diseases and insect attacks than other cultivars (Labrecque and Teodorescu, 2005; Nissim et al., 2013). Instead, other cultivars from species like *Salix eriocephala, S. purpurea*, *S. nigra* and *S. miyabeana* are frequently used (Smart and Cameron, 2008). In eastern Canada, Nissim et al. (2013) concluded that *S. miyabeana* and some indigenous species were more suited for plantation than *S. viminalis*. *Salix miyabeana* has also shown high biomass production (Labrecque and Teodorescu, 2005; Pitre et al., 2010), good phytoremediation capacity and high tolerance to various contaminants like petroleum hydrocarbons (Grenier et al., 2015), metals and metalloids (Pitre et al., 2010; Purdy and Smart, 2008) and nitrogen rich wastewater (Nissim et al., 2014). Considering that some cultivars of this species, such as SX67 and SX64, have been proven to be well suited for some regions of North America, there is now interest in using *S. miyabeana* for treatment wetlands (Lévesque et al., 2017; Grebenshchykova et al., 2017), ET cover (Mirk and Volk, 2009) and zero-discharge wetlands (Frédette et al., 2017). However, we found a single study that reported ET rates for this species, based on the cultivar SX64 grown on a contaminated site for leachate minimization in the north-eastern United States (Mirk and Volk, 2009). For all species of willow combined, we found four studies reporting ET rates in treatment wetland conditions, most of them conducted in Europe and none in the Americas. There is thus a clear lack of knowledge regarding the ET capacity of economically important North American willow cultivars, like *S. miyabeana*, growing in treatment wetland conditions.

The first objective of our study was to measure the ET rate and provide a crop coefficient (K_{ET}) for *Salix miyabeana* (SX67) grown in treatment wetland conditions in a sub-boreal temperate climate. The second objective was to propose a predictive ET model, based on simple meteorological and leaf parameters, which would be coherent with the wetland growing conditions and physiology of fast growing willow species like *S. miyabeana.* While the first objective would serve as a practical tool for development of a better treatment wetland design and add to our knowledge of the ET of North American willow cultivars, the predictive model would enable the transfer of our results to different climatic scenarios and to other willow species that are physiologically similar but have different leaf and phenological parameters.

2. Material and methods

2.1. Study site

The wetland studied is located in an industrial part of the city of Laval, Québec, where mean annual precipitation and temperature are 1000 mm and 6.8 °C, respectively, elevation is 91 m above sea level and the growing season is about 170 days. This willow wetland was established in 2012 and serves as a final polishing step connected to a series of other constructed wetlands treating leachate contaminated with utility wood pole preservatives (chromated copper arsenate and pentachlorophenol). The treatment system receives contaminated leachate from an open storage tank situated directly under the stored wood poles, and this, only during the plants' growing season and when there is no risk of water freezing in the system. The rest of the year, the wastewater is stored in the open tank until the next season. More details about the experimental treatment project are provided in Levesque et al. (2017). The willow wetland is a horizontal subsurface flow wetland 8 m wide by 6 m long (Fig. 1), lined with a waterproof membrane and filled with a mix of black peat (20%) and sand (80%) with a porosity of 50% (determined by measurement of pore volume by liquid imbibition).

Throughout this study, the mean hydraulic loading rate of the willow wetland was 55 $L\,m^{-2}\,d^{-1}$ during the operating season, for a mean daily flow of 2.6 m^3. Water flowing into the willow wetlands contained residual contamination from the treatment wetlands upstream, including pentachloro dibenzodioxins/furans (94.5 pg TEQ/L), arsenic (0.12 ppm), chromium (0.01 ppm) and copper (0.02 ppm), and was relatively poor in nutrients (N: 0.12 ppm, P: 0.05 ppm, K: 3.93 ppm). The willows did not display any significant phytotoxic symptoms, but did show signs of nitrogen deficiency.

The wetland was fertilized in 2014, and again at the beginning of

2017, with a slow-acting fertilizer in (Acer 21–7-14). The shoots were cut back at the end of the 2014 season to maintain a juvenile state and high productivity (Nyland, 2016; Abrahamson et al., 2002). A monitoring station (Campbell Scientific, various sensors) was present on site for basic meteorological data measurement (rainfall, temperature, relative humidity, solar radiation and wind speed).

2.2. Plant material

The wetland was planted with 112 stools of *S. miyabeana* SX67 at a planting density of 2.3 plants/m^2. *Salix miyabeana* is native to Asia and the cultivar SX67 was developed at the University of Toronto, in Canada (Cameron et al., 2007). It is usually grown from dormant cuttings, and only male clones with no seed production are produced (Cameron et al., 2007). Although it can reproduce vegetatively, it does not propagate laterally (*e.g.* stolon), so the planting density does not change over time. However, the stools produce new stems when they are cut back. They produce 6 stems on average (Tharakan et al., 2005), ranging from 2 to 12 (Fontana et al., 2016). Tharakan et al. (2005) reported a mean leaf area index of 4.9 for this cultivar at the end of a three-year rotation cycle. SX67 present stomata on both abaxial and adaxial sides of leaves (amphistomatic) at the early development stage, and adaxial stomatal density decreases as the leaves mature (Fontana et al., 2017).

2.3. Physiological measurements

To model transpiration of *S. miyabeana*, we measured two main physiological parameters, *i.e.* stomatal conductance and leaf area index.

2.3.1. Stomatal conductance

Instant stomatal conductance ($\bar{g}_s$), representing the exchange rate of vapor water from leaf to the boundary layer (mmol m^{-2} s^{-1}), was sampled on the abaxial side of leaves using a steady state porometer (Decagon, SC-1). In 2016, we sampled $\bar{g}_s$ on 34 days from May 15 to October 11, with measurements in the lower, middle and upper parts of the canopy, both inside and at the border of the wetland, and from 6 AM to 9 PM, for a total of 4003 measurements. Data from 2016 allowed us to optimize sampling for the 2017 campaign, with measurements performed from 10 AM to 2 PM, where mean values of $\bar{g}_s$ were observed, and only in middle and upper part of the canopy, because of the low influence of the lower part in the general stomatal conductance ($\bar{G}_s$) of the wetland. In 2017, sampling took place on 43 days from May 11 to October 27, for a total of 3579 measurements. Also, because *S. miyabeana* presents amphistomatic characteristics (Fontana et al., 2017), 150 measurements were made on both adaxial and abaxial sides of the leaves (75 pairs of measurements, taken on four days from May to August 2017) to establish a ratio of transpiration occurring on the upper versus the lower side of the leaf.

2.3.2. Leaf area index

Leaf area index (LAI), which expresses the leaf area covering a given ground area (m^2 leaf/m^2 ground), was estimated once a month, in the middle of the month, from May to November and for both growing seasons. We calculated the LAI of the entire wetland based on extrapolation of individual willow leaf area and considering that there could be a significant difference between leaf area of willows growing on the border and those growing in the center of the wetland:

$$LAI = (N_{border} LA_{wborder} + N_{center} LA_{wcenter})/A_{wetland} \tag{1}$$

where *N* is the number of willows growing either on the border or in the center, and mean leaf area per willow (LA_w), and $A_{wetland}$ is the wetland area. For our wetland, we considered only the willows growing directly at the edges as the "border section", which represented 40 willows, compared 72 growing in the center, and a border width of 0.75 m. LA_w was estimated for 15 individual willows, seven growing on the border of the wetland and eight growing in the center, as follows:

$$LA_w = A_{leaf}(S_{<1m}N_{leaf} + S_{1-3m}N_{leaf} + S_{>3m}N_{leaf}) \tag{2}$$

A_{leaf} is the average single leaf area and is measured each month based on 30–40 randomly collected leaves and using the software, Mesurim Pro v3.4.4.0. The number of stems (*S*) was counted on the individuals and divided in 3 height classes (< 1 m, 1–3 m, > 3 m). Finally, the average number of leaves (N_{leaf}) present on stems was estimated by direct counting on 5 random stems of each class. Afterwards, we examined the spatial variation of the leaf area by comparing individual area of stools on the edge and stools in the center of the wetland. Because the leaf cover seemed to exceed the actual area of the wetland, we also calculated and adjusted value of LAI based on the projected canopy area (Allen et al., 2011).

2.4. Evapotranspiration calculation

2.4.1. Actual wetland evapotranspiration

To estimate actual ET of the wetland, we used the water balance method, based on the following mathematical equation (Kadlec and Wallace, 2008):

$$ET_{wet} = \frac{Q_i + IQ_p + Q_r - Q_d - Q_o - \Delta L}{A} \tag{3}$$

where *ET* is the ET rate (mm/d), Q_i the influent rate (mm/d), Q_p the precipitation (mm d^{-1}) adjusted by a canopy interception factor (*I; unitless*), Q_r the flowrate of runoff entering the wetland (mm/d), Q_d the underground drainage rate (mm/d), Q_o the effluent rate (mm/d), ΔL the net variation of the water level in the wetland (mm/d) and *A* the wetland area in m^2 (Fig. 2).

We considered an interception factor of 25%, determined with an equation from Martin and Stephens (2006) and based on leaf area index (see Section 2.3.2; $I = 3.01LAI + 1.12$), meaning that only 75% of the rainfall reaches the wetland substrate, the rest being evaporated directly from the leaf and thus not considered as tree ET *per se*. As we will demonstrate below, rapid closure of the wetland canopy makes this high interception factor very suitable. Because of the waterproof membrane, it is assumed that Q_r and Q_d are equal to zero. The net water level variation is obtained by multiplying the water level measured in the wetland by the substrate porosity. Water level was measured hourly with two probes (Levelogger Junior Edge, Solinst) placed at two points in the wetland, from May 27 to December 9 in 2016 and from April 21 to November 29 in 2017. Both influent and effluent volume of the willow wetland were monitored with pulse meters (Omega, FTB8000B) throughout the operating season (the system was completely shut down in winter) which represented 214 and 220 days for 2016 and 2017 respectively. Due to a malfunction of the flow meters, 2016 water balance

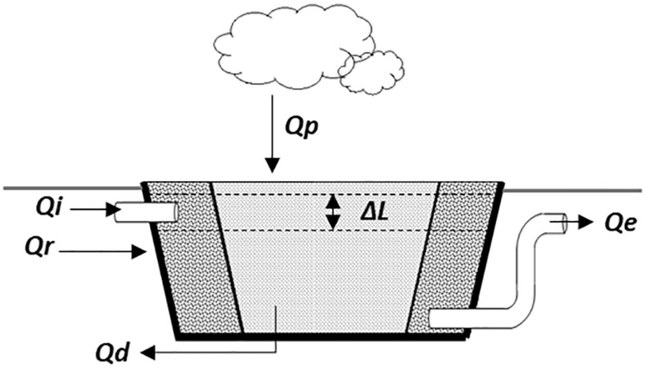

Fig. 2. Schematic representation of the components of a typical water balance equation. ΔL: water level variation, *Qd*: drainage, *Qe*: effluent, *Qi*: influent, *Qp*: precipitation, *Qr*: runoff. In a treatment wetland lined with waterproof material (as depicted in this figure), runoff and drainage components are not relevant.

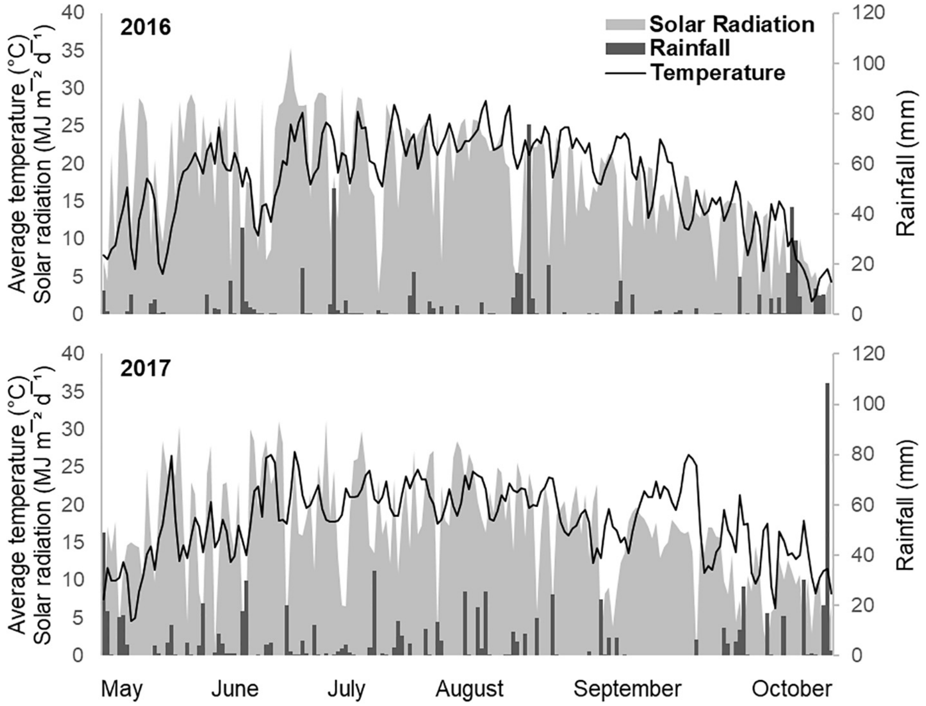

Fig. 3. Summary of the meteorological conditions at the experimental site for the 2016 and 2017 growing seasons.

results were probably overestimated, particularly for late season results (September and October). The meters were conditioned and calibrated by the supplier in 2016 and measurements for 2017 were considered more accurate.

2.4.2. *Evapotranspiration modelling*

In a treatment wetland, there are few limitations on ET. Available energy is greater than direct solar radiation because of both “oasis” and “clothesline” effects (Dotro et al., 2017; Kadlec and Wallace, 2008) that increase ET potential (Allen et al., 1998). Oasis effect provides a vertical energy transfer in the form of sensible heat from the air surrounding the wetland because its moist condition and transpiration make it cooler than the ambient air. The clothesline effect results from the tall wetland plants being surrounded by smaller vegetation and provides a horizontal energy transfer due to wind (Kirkham, 2014). The clothesline effect and the small size of the wetland also increase plant exposure to wind, which results in constant disturbance of the boundary layer of plant leaves (Kadlec and Wallace, 2008), meaning that water vapor excreted by the leaves is automatically replaced with fresh air and transpiration potential increases. As illustrated in Fig. 1, water flows out of the wetland only when the water level exceeds 1.2 m (30 cm below the ground surface), meaning that with constant inflow, the wetland substrate should be saturated with water most of the time. Therefore, we hypothesized that water availability is high and that ET is not limited by water stress. Based on these non-limited conditions, we hypothesized that transpiration of willows in a treatment wetland should be highly correlated to stomatal conductance (*i.e.* water vapor exchange rate between leaf and air; $\bar{G}_s$). $\bar{G}_s$ is generally measured in a volume of water per surface of leaf per time unit (*e.g.* mmol m^{-2} s^{-1}), meaning that leaf area capable of transpiring (LAI_{active}) is also required for ET calculation. Because of the relatively constant disturbance of the boundary layer by wind, transpiration rate should also be driven mainly by water vapor pressure deficit (VPD) in the ambient air. Otherwise, the irrigation of the wetland being below the surface, there is no open contact between water and the atmosphere. According to Shuttleworth and Wallace’s energy partitioning model (1985), the high average LAI of *S. miyabeana* (> 4 m^2; Tharakan et al., 2005) implies that most of the energy available for ET is intercepted by the willows, reducing soil evaporation potential to close to zero. Therefore, in this study, we assumed that soil evaporation insignificant and that willow transpiration can be treated as ET. Daily ET of *S. miyabeana* grown in a treatment wetland (mm/d) could then be estimated with the following leaf parameter based equation:

$$ET_{SX67} = \bar{G}_s \cdot LAI_{active} \cdot (VPD/p) \tag{4}$$

Active leaf area can be calculated throughout the season according to the seasonal leaf development curve and the abaxial/adaxial ratio established by measurements presented in Section 2.3. Vapor pressure deficit (kPa) is calculated with daily temperature and relative humidity data (Allen et al., 1998) and expressed in a unitless coefficient by dividing it by the sea level barometric pressure (p; 101,325 kPa). To estimate stomatal conductance, we chose an empirical approach based on environmental parameters known to influence stomata openings (Buckley and Mott, 2013). We wanted those parameters to be easily accessible, to allow the transpiration rate to be predicted with minimal resources. Through linear regressions, we tested the statistical relation between mean daily stomatal conductance measured on site and the following daily parameters: solar radiation, average and maximal air temperature, average and minimal relative humidity, wind speed and day of the year. Parameters presenting a significant relation with stomatal conductance ($p < 0.05$) were combined to predict canopy general conductance as follows:

$$\bar{G}_s = \sum a\bar{g}_s^{x} \tag{5}$$

where partial stomatal conductance ($\bar{g}_s$) was calculated according to previously selected parameters (x) having their own relative influence (α) on the general stomatal conductance of the wetland canopy ($\bar{G}_s$). $\bar{G}_s$ (mmol s^{-1} m^{-2}) was first converted in mm per hour unit with a coefficient (0.0648) that we determined based on the molar volume of H_2O (1 mol = 18 ml) and the fact that 1 L represents 1 mm over 1 m^2. Then we expressed $\bar{G}_s$ in mm per day unit (mm/d) using the mean monthly hours of bright sunshine per day (HBS).

2.4.3. *Reference evapotranspiration and plant coefficients*

Reference ET was calculated according to the modified Penman-

Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0,408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0,34u_2)} \tag{6}$$

In this model, ET_0 is supposed to represent water loss of a surface covered with 12 cm high well-watered turf grass (Allen et al., 1998). Calculation of this value makes it possible to determine crop coefficient (Kadlec and Wallace, 2008):

$$K_{\mathrm{wet/SX67}} = ET_{\mathrm{wet/SX67}}/ET_0 \tag{7}$$

where K is the crop, or plant, coefficient, ET is the actual or modelled ET rate of the willow stand as calculated with equation (3) and (4) and ET_0 the reference crop ET provided by equation (6).

2.5. Statistical analysis

The relation between meteorological parameters and $\bar{G}_s$ was tested with linear, quadratic and power regressions. The influence of parameters on a given variable (*e.g.* influence of leaf face on $\bar{G}_s$ variation) was tested with two-way ANOVAs analysis with a 0.05 significance threshold ($\alpha = 0.05$). Tukey's post-hoc statistical test was used when necessary to better interpret the results of the analysis of variance ($\alpha = 0.05$). All statistical analyses were performed using R 3.5.1 software.

3. Results

The summer of 2016 was hot and dry, with a mean temperature of 18.0 °C (± 6.0) and 569 mm of rainfall from May to October. Mean temperature was similar in 2017 (17.9 °C ± 4.8), but with less days on which maximum temperature rose above 30 °C. Also, 2017 saw much higher rainfall, with 819 mm for the same period. A summary of solar radiation, rainfall and daily mean temperature for both growing seasons is shown in Fig. 2.

Average reference crop ET was 4.5 mm/d in 2016 and 4.1 mm/d in 2017, for a total of 819 mm and 750 mm respectively, from May to November. For the willow wetland, we calculated a mean daily ET rate of 28.7 mm/d and a seasonal total ET of 5047 mm from May 9 to October 31 in 2016, and 16.8 mm/d and a seasonal total of 2860 mm from May 15 to October 31 in 2017 (Fig. 4; Tables 1A and 1B).

3.1. Physiological measurements

Stomatal conductance values were generally higher and more variable in the 2016 season, with a mean value of 418 (± 124) $\mathrm{mmol\,m^{-2}\,s^{-1}}$ compared to 309 (± 59) $\mathrm{mmol\,m^{-2}\,s^{-1}}$ in 2017. The adaxial/abaxial stomatal conductance ratio was relatively high (0.33 ± 0.17) and variable in the early season, decreasing to relatively constant and low values (0.14 ± 0.06) for the rest of the summer (Fig. 5).

Thus, overall seasonal transpiration occurring on the upper part (adaxial) of the leaf represents about 20% of that on the lower side (abaxial), and actual stomatal conductance equals approximately 120% of the values measured on the abaxial side of the leaf only. In both the 2016 and 2017 seasons, leaf cover established rapidly, attaining its highest value in July, with 10.4 and 11.4 m^2 of leaves per m^2 of soil respectively. The canopy extended beyond the wetland borders by about 50 cm meter on each side, for a projected canopy area of 63 m^2 compared to the actual wetland area of 48 m^2. Peak LAI measured using the projected canopy area was 7.9 in 2016 and 8.7 in 2017. In 2017, the global leaf area was a little higher than in 2016, attained its maximal value earlier and retained active foliage later in the season (Fig. 6). Trees on the edge of the wetland grew up to three times more stems and leaf area than those in the center (Fig. 7).

3.2. Evapotranspiration modelling

We found a significant effect of temperature, solar radiation, relative humidity and day of the year on stomatal conductance (Table 2), but no effect of wind speed.

For temperature and relative humidity, mean daily values were better predictors than maximum and minimum values respectively. Correlation between $\bar{G}_s$ and each factor separately was relatively weak (r^2 from 0.05 to 0.21), but together they explained half of stomatal conductance variation throughout the season (Fig. 8), which can be considered satisfying due to the many other factors driving this parameter but not measured here (Buckley and Mott, 2013).

The stomatal conductance predictive model, based on Eq. (5) and using mathematical relations presented in Table 2, was good at predicting mean $\bar{G}_s$, with a predicted mean seasonal value of 428 $\mathrm{mmol\,m^{-2}\,s^{-1}}$ over 418 $\mathrm{mmol\,m^{-2}\,s^{-1}}$ measured in 2016, and 329 $\mathrm{mmol\,m^{-2}\,s^{-1}}$ predicted over 309 $\mathrm{mmol\,m^{-2}\,s^{-1}}$ measured in 2017. Daily variation was captured more accurately in 2017 than in 2016 (Fig. 9).

Using the general stomatal conductance calculated with equation (4) and the previously established leaf area parameters, we calculated the ET rate (Eq. (3)) and the corresponding crop coefficient (Eq. (6); Tables 1A and 1B). Modelled willow ET was higher in 2016, as was reference ET, with a mean daily rate of 19.5 mm/d compared to 13.5 mm/d in 2017 (Tables 1A and 1B). Calculated seasonal ET was 3434 mm in 2016 and 2361 mm in 2017 (Fig. 4). Crop coefficients were also higher in 2016 than in 2017, with an average value of 5.2 and 3.1 respectively (Tables 1A and 1B). Highest daily ET rates were calculated in August in 2016 (44.8 mm/d on August 13) and in July in 2017 (34.3 mm/d). Modelled ET results are very close to those calculated with the water balance for most of the 2017 season (Fig. 4), but lower than water balance ET in 2016, probably due to the overestimation of actual ET for this season (Section 2.4.1).

4. Discussion

The mean monthly ET rate measured by water balance for *Salix miyabeana* in treatment wetland conditions ranged from 22.7 to 38.8 mm/d in 2016 and from 9.7 to 28.7 mm/d in 2017, with a mean

Table 1A

Mean daily Penman-Monteith reference evapotranspiration (ET_0), active leaf area index of the 48 m^2 treatment wetland (LAI), actual wetland (ET_{wet}) and modelled willow evapotranspiration (ET_{SX67}) and crop coefficient (K_{wet} and K_{SX67}) presented as monthly and seasonal averages, for the 2016 growing seasons.

	ET_0	LAI_{active}	ET_{wet}	K_{wet}	ET_{SX67}	$K_{(SX67)}$
May	5.2 ± 1.6	3.3 ± 1.3	22.7 ± 18.0	4.2 ± 3.0	8.9 ± 6.6	1.8 ± 1.3
June	5.5 ± 2.4	8.2 ± 1.4	35.6 ± 23.9	9.0 ± 9.7	20.8 ± 10.5	5.2 ± 3.8
July	5.4 ± 1.7	11.6 ± 0.5	29.5 ± 12.1	6.7 ± 5.8	30.0 ± 10.7	6.8 ± 5.8
August	5.0 ± 1.6	10.1 ± 0.3	29.5 ± 19.6	6.2 ± 3.9	32.3 ± 10.8	8.2 ± 7.8
Sept.	3.9 ± 0.9	9.5 ± 0.9	38.8 ± 20.4	11.4 ± 10.7	17.2 ± 6.1	4.7 ± 2.4
October	1.8 ± 1.0	4.5 ± 1.9	32.1 ± 30.1	29.5 ± 45.3	6.1 ± 2.6	3.7 ± 2.7
Average	4.5 ± 2.1	7.9 ± 3.2	28.7 ± 25.6	7.7 ± 26.0	19.5 ± 13.1	5.2 ± 5.0

*Values over-estimated due to flow-meter malfunctioning.

Table 1B

Mean daily Penman-Monteith reference evapotranspiration (ET_0), active leaf area index of the 48 m^2 treatment wetland (LAI), actual wetland (ET_{wet}) and modelled willow evapotranspiration (ET_{SX67}) and crop coefficient (K_{wet} and K_{SX67}) presented as monthly and seasonal averages, for the 2017 growing seasons.

	ET_0	LAI_{active}	ET_{wet}	K_{wet}	ET_{SX67}	$K_{(SX67)}$
May	3.9 ± 2.1	3.4 ± 1.9	9.7 ± 0.9	2.8 ± 1.9	8.6 ± 5.4	1.8 ± 0.7
June	5.0 ± 2.1	12.1 ± 2.0	11.5 ± 1.4	3.1 ± 2.0	14.4 ± 7.1	2.9 ± 0.8
July	4.9 ± 1.6	13.3 ± 0.5	28.7 ± 17.2	7.0 ± 5.4	18.6 ± 6.4	4.1 ± 1.3
August	4.7 ± 1.2	10.7 ± 0.7	14.3 ± 10.2	3.4 ± 3.2	20.1 ± 4.7	4.1 ± 0.7
Sept.	3.6 ± 1.1	9.1 ± 0.8	21.8 ± 4.4	6.9 ± 4.4	12.9 ± 4.7	3.5 ± 0.9
October	2.3 ± 1.0	4.8 ± 1.4	11.8 ± 6.0	6.1 ± 6.3	6.3 ± 4.5	2.4 ± 1.2
Average	4.1 ± 1.7	8.9 ± 3.9	16.8 ± 11.3	5.1 ± 4.6	13.5 ± 7.4	3.1 ± 1.2

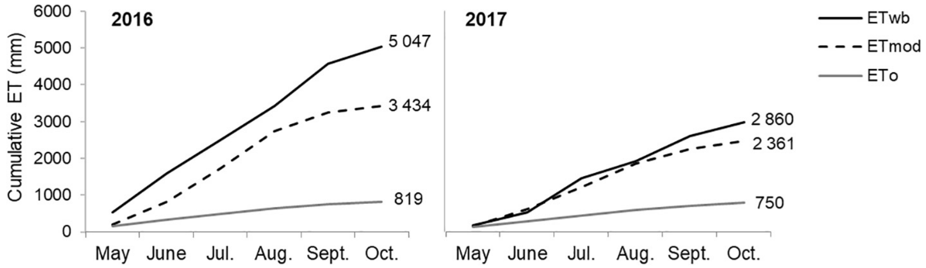

Fig. 4. Seasonal cumulative evapotranspiration of a 48 m^2 willow wetland calculated by water balance (ETwb) and modelling (ETmod) for 2016 and 2017 vegetation seasons. Penman-Montheith reference evapotranspiration (ETo) is also reported for the same period.

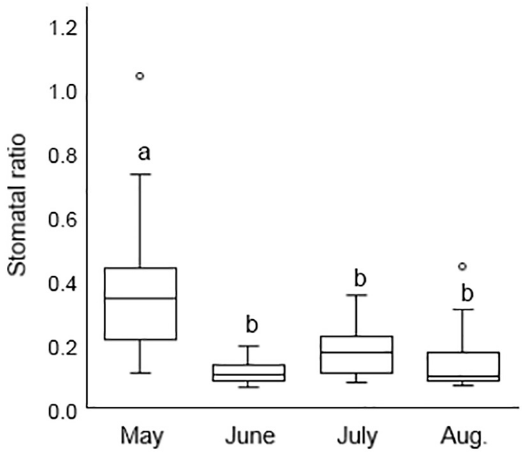

Fig. 5. Adaxial/abaxial stomatal conductance ratio of *S. miyabeana* growing in treatment wetland conditions for the 2017 summer season. Different letters represent statistically different values.

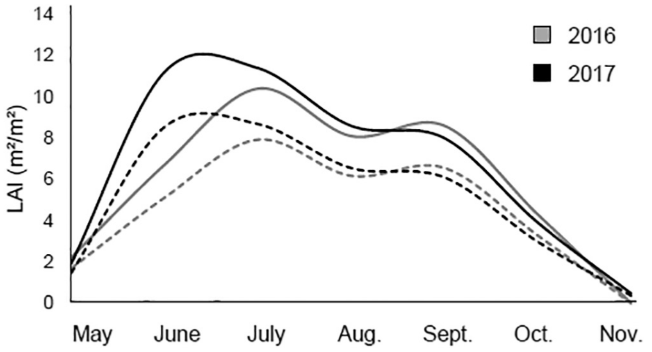

Fig. 6. Evolution of the leaf area index of a 48 m^2 wetland (solid line) planted with *S. miyabeana* throughout 2 successive growing seasons, and the corresponding values adjusted for a 63 m^2 projected canopy area (dashed line).

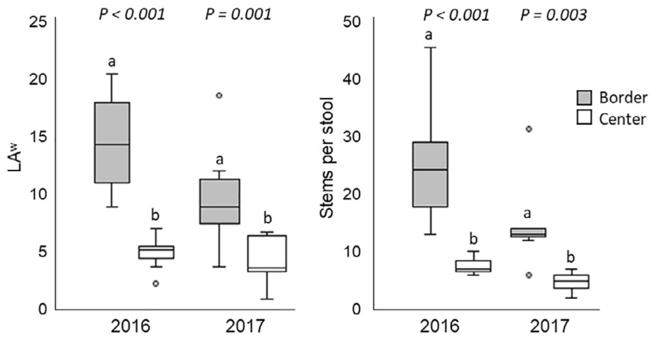

Fig. 7. Leaf area (LA_w) and number of stems per stool of 15 *S. miyabeana* individuals growing either at the border or in the center of a 48 m^2 constructed wetland, measured in the month of July, in 2016 and 2017. Different letters represent statistically different values.

Table 2

Parameters of the relations found between stomatal conductance of *S. miyabeana* and temperature (T), day of year (DOY), solar radiation (Rad) and relative humidity (RH). Parameter importance (α) and predictive equations used for stomatal conductance modelling are presented.

Parameter	Type of relation	p_{value}	R^2	α	Equation
T	Power	< 0.001	0.21	0.48	$88.4x^{0.5}$
DOY	Quadratic	0.002	0.13	0.30	$-0.02x^2 + 9x - 572$
Rad	Quadratic	0.05	0.05	0.11	$-0.005x^2 + 2x - 177$
RH	Linear	0.03	0.05	0.11	$2.9x + 168$

seasonal cumulative ET of 5047 mm in 2016 and 2860 mm in 2017. Crop coefficients were also higher in 2016 than in 2017, with an average value of 7.7 and 5.1 respectively. These results are higher than those reported in the very few studies conducted in comparable conditions but in different climate, while our modelled results are similar (Curneen and Gill, 2014; Gregersen and Brix, 2001; Brix and Arias, 2005; Kučerová et al., 2001; Table 3). However, both measured and modelled results presented here are even higher in comparison to the only study we found for another cultivar of *S. miyabeana* (SX64; Mirk and Volk, 2009; Table 3), grown in open field plantation, with low

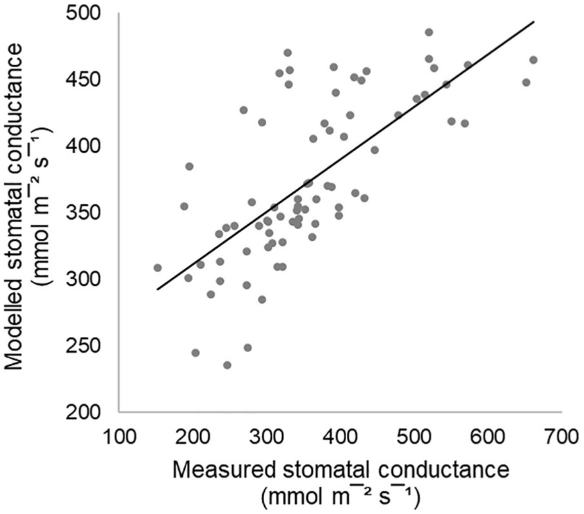

Fig. 8. Results of $\bar{G}_s$ modelling, based on temperature, solar radiation, relative humidity and day of year, compared to $\bar{G}_s$measured on the field under the same parameters.

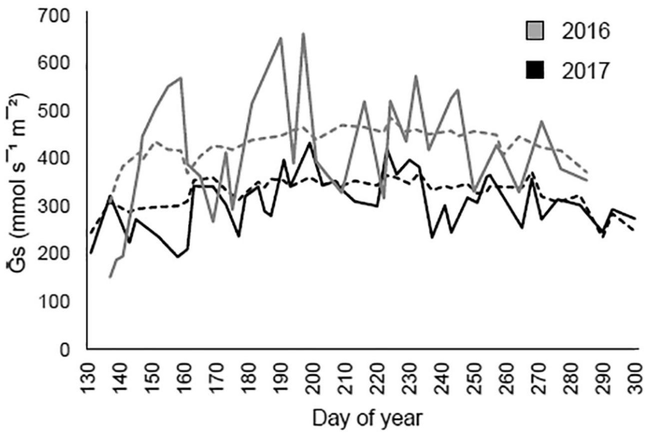

Fig. 9. Stomatal conductance ($\bar{G}_s$) field measurements (solid line) and modelling results (dashed line) over the 2016 and 2017 growing seasons.

water input and soil contamination, but in a very similar climate.

Average seasonal ET rates reported for other fast growing willow cultivars grown in field plantation are also generally much lower than our results (1.4 mm/d, Linderson et al., 2007; 3.0 mm/d, Lindroth et al., 1994; 2.9 mm/d, Persson, 1995; 1.0 mm/d, Mata-Gonzalez; 3.1 mm/d, Budny and Benscoter, 2016). In comparison, similar rates (from 10 to 23 mm/d) were measured for young *S. babylonica* grown in water saturated conditions in the north-eastern United States (Pauliukonis and Schneider, 2001). Such high ET rates can be explained by both enhancing factors linked to the treatment wetland itself (*i.e.* oasis and clothesline effect, high water availability, important border effect) and by *S. miyabeana* ecophysiology (*i.e.* high stomatal conductance and leaf area index).

In this study, a simple model based mainly on two leaf parameters (stomatal conductance and leaf area index) was sufficient to model ET. As expected, the model ET results were lower than the water balance results in 2016 (see Section 2.4.1). However, 2017 simulation results closely resembled water balance results (Fig. 3). The fact that our simplified ET model yielded conclusive results supports our premise that typical ET limiting factors like water and energy availability are greatly attenuated in small wetlands. Other studies presenting ET modelling methods for willows often include several limiting factors (Irmak et al., 2013; Iritz et al., 2001), ignore heat advection effect (Přibáň and Ondok, 1986) or focus on soil hydrology (Persson, 1995; Hartwich et al., 2016; Borek et al., 2010) or complex physiological processes (Tallis et al., 2013). Although based on sound scientific assumptions, those models hardly apply in treatment wetland conditions where water level typically ensures a high water availability and heat advection effect is very important (increased available energy). The few input parameters required for operation of the model also represent simple method for managers working with treatment wetlands to include ET estimation in their planning activities. However, to be used for other taxa, a basic knowledge of the LAI dynamic and general stomatal conductance for the species is needed, and could require additional $\bar{g}_s$ measurement in the field to adjust the model.

Regarding ET related characteristics specific to *S. miyabeana*, we found that mean stomatal conductance (0.4 mol $m^{-2} s^{-1}$) was consistent with published results for other willows (0.4 mol $m^{-2} s^{-1}$, Budny and Benscoter, 2016; 0.2–0.7 mol $m^{-2} s^{-1}$, Hall et al., 1998), or higher (0.2 mol $m^{-2} s^{-1}$, Kučerová et al., 2001). Leaf area index values were higher than those reported in the literature for other willow cultivars, even when using the projected canopy area for the calculation (Fig. 10).

As for stomatal conductance, it is also interesting to note that the highest mean daily value measured (661 mmol $m^{-2} s^{-1}$) is much higher than the values proposed for deciduous trees and even plants from wet habitats (Jones, 2013). The ratio between the conductance of the upper and lower side of the leaf is consistent with the literature predicting higher adaxial activity or adaxial stomatal density in younger leaves (Fontana et al., 2017). Meteorological factors could only explain about half of the stomatal conductance values and variability. Stomatal aperture is also driven by many biochemical and environmental factors (Buckley and Mott, 2013) that were not studied here. Aging of the willows, or negative effects of contaminant accumulation in the substrate are also factors that affect long term variability of $\bar{G}_s$ in a wetland, and should be considered. A sampling campaign (data not shown) conducted in June of 2017 in Denmark on *S. viminalis* clones used for zero-discharge wetlands showed significantly greater stomatal conductance in willows recently coppiced, compared to older individuals growing in the exact same conditions, which supports the aging hypothesis. Such factors should be investigated thoroughly in the future. Leaf area of the willow wetland attained its maximal value (complete canopy closure) with two-year-old shoots, peaking in July at around 12 m^2 of leaves per m^2 of ground. Planting density and

Table 3
Evapotranspiration results obtained for fast growing willow in treatment wetland conditions (ref. 1 to 4) or in open field plantation (ref. 5).

Species (cultivar)	Country	Seasonal ET	Peak K_{ET}	Seasonal K_{ET}	Annual K_{ET}	Ref.
S. miyabeana (SX67)	Canada (QC)					1
Measured		3954 mm	9	6.4	3.7	
Modelled		2897 mm	8.2	4.2	2.5	
S. viminalis (Bjorn, Tora, Jorr)	Denmark	1113 mm	–	–	2.5	2
S. viminalis	Ireland	669 mm	5.1	3.0	–	3
S. cinerea	Belgium	–	6.7	–	–	4
S. miyabeana (SX64)	USA (NY)	515 mm	1.4	1.2	–	5

Note: 1: present article; 2: Gregersen and Brix (2001): 3: Curneen and Gill (2014), 4: Kučerová et al. (2001): 5: Mirk and Volk (2009).

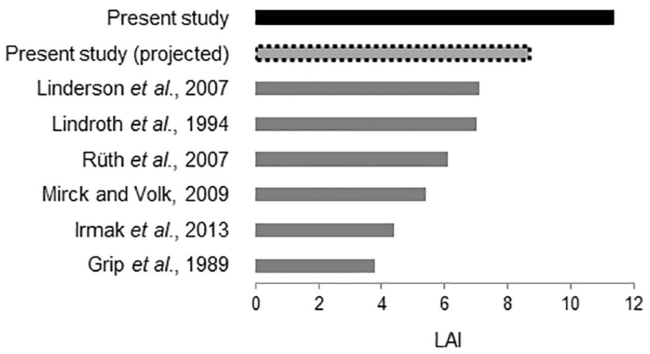

Fig. 10. Maximal leaf area index (LAI) reported for willow stands (different cultivars) in various studies including the present results, and the corresponding value adjusted with projected canopy area. (See above-mentioned references for further information.)

methodological differences could partially explain why LAI of our wetland was very high compared to findings reported in the literature. Furthermore, all results presented in Fig. 8 are based on field plantation or natural river bands of much greater size than our wetland, and the effect of increased leaf area at the border is negligible. In our wetland, trees growing on the border had more space and light resources available to support their growth, which explains the significant leaf area difference we observed for trees growing at the border of the wetland compared to those in the middle, that are laterally limited by the growth and light interception by their neighbours. Our finding comparing individual leaf area at the edges versus in the center of the wetland is also interesting, because it means we could modulate ET rate directly in the wetland design. Indeed, if ET is directly related to LAI as demonstrated here, adjusting the edge or aspect ratio of the surface area of a wetland could enhance (higher ratio) or limit (lower ratio) ET per ground unit, according to management objectives. Fertilization applied at the beginning of 2017 seemed to have accelerated the establishment of the leaf cover but did not significantly increase maximal LAI. Since the fertilizer used consisted of solid granules applied directly on the soil, with dissolution regulated by rainfall and temperature, it is possible that rapid closure of the canopy and high rain interception by willows prevented the fertilizer from dissolving appropriately and penetrating the substrate. In 2016, the canopy already seemed completely closed by mid-season and it is possible that maximum leaf area index was already attained. Indeed, in 2017, stems grew higher but there was little or no leaf development at the bottom of the stems (as was observed in 2016), probably because canopy closure was achieved and all available light was intercepted in the upper part of the trees. Therefore, we conclude that maximal LAI was achieved with two-year-old shoots, without a need for fertilization, and that coppicing should be scheduled on a two-year basis.

5. Conclusions

S. miyabeana ET in treatment wetland conditions was very high throughout this study. We highlighted several factors related to treatment wetlands that can significantly increase potential ET. Because there are few limitations on ET in wetlands, a model exclusively based on leaf parameters successfully predicted ET values and calculated crop coefficients for the studied willow wetland. Because these results are based on a full-scale wetland, they can be used as design parameters for treatment wetlands using *S. miyabeana,* and the equation presented for ET calculation can be adjusted for other fast-growing willow species used in similar growing conditions. However as we demonstrated earlier, the edge effect on evapotranspiration through leaf area, clothesline and oasis effects should be taken into consideration prior to extrapolating from our results. We also presented a strategy to optimize ET per ground area by changing the aspect ratio of the wetland (and consequently its leaf area index) as well as regularly coppicing the stems. In the future, other parameters that may affect ET in treatment wetlands, such as tree aging, substrate type and contaminant toxicity, could be investigated. This study is a first step towards better ecophysiological characterization of woody plants used in treatment wetlands.

Declarations of interest

None.

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