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Willows for environmental projects: A literature review of results on evapotranspiration rate and its driving factors across the genus *Salix*

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Abstract

Willows are increasingly used for a wide range of environmental projects, including biomass production, leachate treatment, riparian buffers and treatment wetlands. Evapotranspiration (ET), assumed to be high for most willow species used in environmental projects, affects hydrological cycles and is of key interest for project managers working with willows. Here, we present a comprehensive review of ET rates provided in the literature for the genus *Salix*. We aim to summarize current knowledge of willow ET and analyze its variability depending on context. We compiled and analyzed data from 57 studies, covering 16 countries, 19 willow species and dozens of cultivars. We found a mean reported ET rate of 4.6 ± 4.2 mm/d, with minimum and maximum values of 0.7 and 22.7 mm/d respectively. Although results reported here varied significantly between some species, overall interspecific standard deviation (± 3.6 mm/d) was similar to intraspecific variation (± 3.3 mm/d) calculated for *S. viminalis,* suggesting a greater influence of the growing context on ET than species identity. In terms of environmental and management variables, water supply, fertilization and contamination were identified as driving factors of ET across willow species. Effects of root age, experimental context, planting density and soil type were more nuanced. Our findings provide synthetic data regarding willow ET. We encourage practitioners who use ET data from the literature to be aware of the main drivers of ET and to consider the influence of the experimental aspects of a study in order to interpret data accurately and improve project planning.

Keywords: evapotranspiration variability, water use, irrigation planning, wetland design, water loss, willow coppicing

1. Introduction

Willows (genus *Salix*) are comprised of hundreds of species, distributed throughout the world, but mostly in the northern hemisphere (Argus, 1986). They can take various growth forms, from small shrubs to large trees. Although some species are adapted to harsh or arid conditions, they more often colonize humid or wet habitats (Dickmann and Kuzovkina, 2014). Aside from traditional pharmaceutical and artisanal uses, willows also have many environmental and energy applications. For some uses, they are produced in short rotation coppice plantations (Zsuffa *et al*., 1984; Gullberg, 1993; Volk *et al*., 2006; Guidi *et al*. 2013), sometimes irrigated with wastewater (Lachapelle-T. *et al*., 2019), sewage sludge (Dimitriou and Rosenqvist, 2011) or leachate (Duggan, 2005). They are thus suitable for use in prevention of leaching of hazardous wastes in evapotranspirative plantations (ET covers; Rüth *et al*., 2007; Mirck and Volk, 2009), phytoremediation of contaminated soils (Witters *et al.,* 2009; Grenier *et al*. 2015), treatment wetlands (Gregersen and Brix, 2001; Curneen and Gill, 2014), and urban and agricultural catchment runoff systems (Hénault-Éthier *et al*. 2017) or even to prevent erosion (Yoder, 1993). Over time, *Salix* species performance has been enhanced by selection and genetic improvement programs (Lindegaard and Barker, 1997; Kopp *et al*., 2001; Smart and Cameron, 2008), and most environmental projects involving willows have used selected or improved cultivars rather than natural species.

Along with high biomass production, willows are known for their high water consumption. Little information is available to enable comparison of willow transpiration

(T) with that of other woody species, but it is generally accepted that willow species used for biomass production and other wetland or riparian occurring species in a temperate climate transpire much more than other herbaceous crops (Personn, 1997). Although a high evapotranspiration (ET) rate is essential for some of the uses cited above, such as ET covers, it may be undesirable in other cases. In Europe, for instance, rapid expansion of willow plantations for biomass production has raised concerns about potential disturbance of natural hydrological systems (Dimitriou *et al.,* 2009). An example of such disturbance has been documented in Australia, where willow introduction is thought to have increased water shortage problems, and caused other environmental damage (Doody and Benyon, 2011); willows are now even considered an invasive and prohibited species in some parts of the world (Doody *et al*., 2014; Marttila *et al.,* 2018; Tang *et al.,* 2018). ET is also an important factor to consider for the design and performance evaluation of treatment wetlands (Beebe *et al*., 2014; Białowiec *et al*., 2014), which are sometimes planted with willows. ET rate thus represents an essential design and operational tool for practitioners working with willows, as well as an important factor to consider before extensive introduction of willows in a given area.

ET measurement is complex and requires substantial time, as well as human, technical and financial resources (Allen *et al*., 2011). In most cases, it is far more practical to use values provided by the scientific literature to plan a project involving willows. However, ET rate is highly context-specific, meaning that results obtained in a given set of conditions might not be relevant to practitioners working in a different environment. Indeed, ET is driven by meteorological conditions, plant related factors and environmental parameters (Allen *et al.,* 1998), all of which can vary greatly from one site/study to another. Meteorological factors can be partially controlled when plants are grown in greenhouses, but are otherwise mainly governed by geographic location. For environmental projects, willows tend to be treated as a single species, but the numerous cultivars derived from many individual species and their respective morphology and physiology are obviously important plant factors that can influence ET variation across the *Salix* genus. Some environmental conditions can be at least partially controlled, such as irrigation, fertilization and coppicing cycle. These factors are most likely to vary depending on the purpose of the study and management decisions, and thus represent a wide range of possible growing conditions. Although not related to the ET process itself, the method used for measurement or estimation of ET is also known to greatly influence results, as most methodological approaches require a high level of expertise and rigor to provide reliable results (see Allen *et al.*, 2011, for a detailed review on that matter). Presentation of methodology and results is also highly heterogeneous, which makes comparing studies difficult. In the end, it can prove rather challenging to find suitable ET information regarding a willow cultivar for a given environmental purpose.

The first objective of this paper was to gather the available ET rate data published for willow species and synthesize this information in a standardized and comparable way. The second objective was to assess the variation of ET across the genus and identify the main drivers of this variability. This review aims to improve our global knowledge of ET potential in rapid growing woody species like willows, and point out opportunities for further research on this topic. Finally, this review should serve as guide for practitioners working with willows for environmental projects to improve irrigation planning, treatment wetland sizing and other decision-making that requires willow ET information.

2. Methods

2.1 Literature review

Evapotranspiration is, in fact, the combination of both plant T and soil evaporation (E_s). Willows are woody plants that are often fast growing, and thus develop a considerable leaf area. According to Shuttle and Wallace's energy partitioning model (1985), high leaf area index (LAI) implies a reduced Es proportion in ET. This is illustrated in numerous studies presented in this review, as we see the E_s to ET ratio decline in the growing season as the willow leaf cover becomes established (Grip et al., 1989; Iritz et al., 2001; Lindroth et al., 1994; Persson, 1997). For the purpose of this review, T results have been considered along with ET results, under the premise that willow T is a fair estimate of total ET. We are, however, aware that T might represent an under-estimation of the true ET value.

2.1.1 Articles selection

A literature review was performed using the keywords "*willow* OR *Salix*" AND "*evapotranspiration* OR *transpiration* OR *water use*", in the Web of Science, Scopus and Google Scholar databases. We selected peer-reviewed articles presenting original results of ET (or T) rates, or data allowing easy calculation of ET rate (*e.g.* irrigation and drainage volumes). We excluded studies presenting data related to ET but not detailed enough to calculate a daily rate (*e.g.* instantaneous rate of T, water-use efficiency), ET results from plant communities including other species than willows and studies measuring willow T at laboratory or growth chamber scale. For instance, for an ET rate provided as an amount of water transpired by a leaf area per unit of time, the leaf area index as well as the typical daily transpiration period (*e.g.* hours of sunlight per day) would have been necessary to convert the results to a mm/d unit. For studies presenting only stemflow results, scaling-up calculations based on sap wood area and various mathematical equations would have been necessary to convert stemflow into transpiration results. ET rates had to be convertible to mm/d units (see section 2.2), and obtained under experimental conditions that could be described by at least 3 of 8 experimental variables selected for results analysis and interpretation, as detailed in section 2.3 (willow species, age of plantation/root system, experimental conditions, water supply, planting density, dominant soil type, fertilization and contamination).

2.1.2 ET data transformation

As expected, the ET rates gathered from the literature review varied in absolute value, but also in unit of expression. For comparison purposes, we converted each result to a millimeter per day basis (mm/d), the most common unit for ET rate. For studies that presented total ET values for a given period, we divided these values by the number of days of the experiment. As some authors reported ET rates only graphically, some results were extracted from these graphs. For studies that reported ET rates in terms of volume per plant, the conversion in mm/d was calculated based on the soil area of the plant container (*e.g.* lysimeter surface area) or soil area covered by the plant (inferred from canopy area or planting density).

2.2 Comparative analysis based on experimental variables

To interpret the variability of ET rates across studies testing various factors, we used an approach based on a semi-quantitative classification of the experimental and environmental conditions under which the studies were performed. These "conditions", also referred to as "variables" or "factors", include both independent variables and conditions imposed by the authors. We decided to exclude typical meteorological and climatic ET limiting factors such as temperature, solar radiation, wind and water vapor pressure deficit (VPD) of our analysis, since the effect of those factors on potential ET (pET) are already well described in scientific literature related to ET and should mainly be driven by geographic location. We then considered plant related variables and environmental and management variables; each variable was divided into several qualitative or semi-quantitative levels (Table 1).

2.2.1. Plant variables

Different plant species have a different T rate according to their intrinsic ecophysiological properties and environment (Bohnert *et al.,* 1995). Including the plant species in a variance analysis would potentially reveal a difference in ET rate between species of the willow genus. T rate should also vary for a given species according to plant growing conditions. To estimate if differences between species were more likely due to taxonomical differences or to growing conditions, we evaluated inter and intraspecific ET rate variation (α_{inter} and α_{intra} respectively). An interspecific variation greater than intraspecific variation would suggest an influence of the species itself on ET rate. ET rate is closely linked to growth rate, which itself is thought to decrease with age (Willebrand and Verwijst, 1993). Consequently, we also considered the age of the plantation as a potential explanatory factor for ET variation. We divided this variable into 3 categories: the establishment year (*first year*), for willows grown from cuttings that have to develop their root system, *young* and *mature* willows (Table 1). Willows with a root system of 5 years of age or more were considered as *mature* because we supposed that, at this point, the root system should be well established.

2.2.2. Environmental and management variables

In every study, willows are grown under various conditions determined by the experimenter (management variables) or naturally present on the study site (environmental variables). Some variables like planting density or soil type can be either managed or naturally determined depending on the experimental context. Other factors like water supply can be both determined and random, when plants are provided with rainfall and controlled irrigation at the same time, for instance. Fertilization and contamination are normally deliberately provided to the plants.

The *experimental context* variable was chosen to represent the spatial scale of the willow stand, the *plantation* level being the largest scale and the *mesocosm* the smallest. The levels of this variable also indicate if the experimental unit is an open (*floodplain* and *plantation*) or closed (*treatment wetland* and *mesocosm*) system in terms of hydrological and soil processes.

Water supply is typically considered a limiting factor for ET (Payero *et al*., 2008; Novák, 2012). Not all references provided sufficient methodological information to calculate the actual volume of water provided to the plants. Thus, we classified this variable with semi-quantitative levels (Table 1) according to the global volume of water available or provided to the plants. When water supplies were quantified, we calculated the mean daily volume provided to plants and classified it as follows: < 5 mm/d was considered *low*, 5 to 10 mm/d *medium* and > 10 mm/d *high*. When insufficient quantitative information was provided, water supply was considered *low* when the only water input was rain (in semi-arid to arid climate) or when water stress was imposed or reported by the authors; *medium* when input was rain in humid to very humid climate, when a small amount of artificial irrigation was added to rainfall or when the water table was controlled to a high but non-saturating level; and *high* when high levels of irrigation were provided or when the water level saturated the media (*e.g.* in a treatment wetland or a floodplain).

Planting density can affect willows negatively, by increasing competition between individuals for soil resources, or positively, by maximizing light interception (Willebrand and Verwijst, 1993). We categorized a density of 1 plant per m^2 or less as *low*. The *medium* level included a density from 1 to 4, based on common values used for willow plantation (Willebrand *et al*., 1993; Volk *et al*., 2006, Walle *et al*., 2007). A density higher than 4 plants per m^2 was considered *high*.

We also selected soil type as a variable because of its influence on soil water potential and water availability (Novák, 2012). The relation between water and soil depends on the type of soil particles and can act on two levels. The first level, which is referred to in agriculture as field capacity, determine the soil water content after gravitational drainage has occurred. The more sand is contained in the soil, the less water will remain in the soil at field capacity because of the low attraction between sand particles and water molecules, while an increase in clay proportion, and furthermore in organic content, increases soil water retention capacity (Waller and Yitayew, 2015). However on a second level, at the same water content, water will be more easily available to plants in a sandy soil, were water potential is higher (due lower water molecules attraction) than in a clayey or organic soil water that have lower water potential due to the matrix attraction

(Waller and Yitayew, 2015). Because the substrates used in the studies reviewed were never composed of one type of particles alone, we classified this variable according to the dominant type of particles in the media (Table 1). We also treated gravel media separately and excluded articles with a very specific soil type (to avoid having a level of the category with only one observation) or that did not provide information on the media.

The effect of fertilization and contamination were treated for their direct effect on plant T (Feldhake *et al.*, 1983; Trapp *et al.*, 2000). They were treated as a binomial variable (presence or absence; Table 1) because of the disparities between the type of nutrient sources and contaminants and their method of addition. Landfill leachate was a particular case, and was considered here as both a source of nutrients and contamination. Indeed, willow can use ammonia (typically present in leachate) as a source of a nutrient which can become a toxicant when its concentration is too high. Other leachate constituents such as chlorinated compounds can have a similar toxic effect.

2.3 Statistical analysis

When a study tested more than one level of at least one variable, it was considered to have more than one result (n) in the variance analysis. For example, a study measuring ET of two species with two different fertilization levels accounted for four individual results (n=4) in the analysis. When results were reported for many replicates of the same treatment, only the mean value was considered. Using this approach, we built a data base by associating each individual ET rate result to the appropriate level of each variable from Table 1. We then proceeded to the comparative analysis, which consisted of a variance analysis (ANOVA) using R statistical software (version 3.5.1). The model tested in the analysis included all variables, in order to consider their simultaneous effect on ET rate. The ET results followed a Fisher distribution, and a log transformation was used to normalize the data prior to statistical analysis. Missing information for some variables (no observation for one or more variables for a given ET result) yielded an unbalanced statistical plan. However, the most commonly used type of ANOVA (type I) has the effect of giving significantly different results depending on how the variables are ordered in the model when provided with an unbalanced data set. Therefore, we decided to perform a type II ANOVA, which typically gives higher *P* values (less significant results) but is not influenced by the order of the variables in the model. Type II ANOVAs are generally suggested as the best substitute for a type I analysis for unbalanced data (Langsrud, 2003). We also used a correlogram to illustrate possible interactions between the variables of the comparative analysis, except for the variable *plant species*, which is composed of more than fifteen levels. Following the comparative analysis, we also performed linear regression analysis between ET results and both planting density (plants/m^2) and water input (mm/d) for the articles where quantitative information was provided for those two variables. For all analyses, a *P* value lower than 0.05 was considered significant. Finally, α_{intra} was calculated as the standard deviation of the results associated with the most frequently studied species (*S. viminalis*, n=53), while α_{inter} was calculated as the standard deviation between the average ET rate reported for each specie (n=18).

3. Results

3.1 Article selection and data transformation

Out of the 800+ articles analyzed, 57 met our selection criteria. The studies covered the period from 1986 to 2019 and were from 16 countries, although half (27) originated from Northern Europe. Results were obtained for natural willow species (21 articles) and cultivars (36 articles), each articles testing one to four species and up to 6 different cultivars, for a total of 19 species studied (Table 2). Plants growing conditions ranged from wild to cultivated/controlled, stressed to non-stressed. Overall, 20 studies reported results in mm/d, 26 studies were in mm for a given period (most of the time, per season), and the remaining 9 studies required additional calculations to express results in mm/d. Sixteen articles presented plant T results only.

At least 4 of the 8 variables considered for categorization of the results were provided in each article (Table 2). Information regarding planting density was missing in 6 articles, and root system age in six other articles, while both types of information were missing in 13 studies. However, this information was mainly missing from studies conducted on natural willow stands, where age and density are heterogeneous and more difficult to document. The soil type turned out to be very difficult to categorize due to the wide range of substrates used and the ambiguous nature of the dividing line between clayish and sandy soil (*e.g.* a soil with 50% sand particles and 40% clay particles was considered as *sand* even if it varies greatly from pure sand). After extracting information from all the studies according to the different levels of the categorical variables (see Section 2.2 and Table 1), 110 ET rate results could be treated individually (n = 110, Table 2). Thirty-five articles presented results obtained with homogenous experimental variables (1 study = 1 result), and the studies that tested the most factors resulted in nine individual results (Table 2; Martin and Stephens, 2006). Some studies tested different treatments but were still considered as one result in our analysis because variation between the treatments could not be captured with our variable categorization (*e.g.* 3 irrigation rates tested, but all below 5mm/d, which is considered *low* for the variable *water supply*)

3.2 Comparative analysis

According to the 110 observations, ET rates ranged from 0.7 up to more than 20 mm/d. The lowest rate was reported for T (rather than ET), expressed on an annual basis, of *S. fragilis* grown in a gravelly/sandy soil on the banks of a stream (Marttila *et al.*, 2017), while the highest average rate of 22.7 mm/d measured over one growing season by water balance for the species *S. miyabeana* 'SX67' with a mature root system and grown in a treatment wetland with high water supply, medium planting density, organic soil and low contamination and fertilization (Frédette *et al*, 2019). Mean reported ET rate across all studies was 4.6 mm/d (± 4.5), with about 80% of reported ET rates ranging from 0 to 10 mm/d. We observed some trends regarding factors interactions (Figure 1). For example, we observe that willows growing in *floodplain* are almost systematically associated with *mature* trees, *medium* to *high* water supply, *high* planting density and natural conditions (no fertilization or contamination), that *first year* cuttings and *young* willows are mainly used in *mesocosms* studies while most *mature* trees studied are in *plantation*, or that fertilization was more frequently associated with *treatment wetlands* and *mesocosms* rather than *floodplains* or *plantations*.

3.2.1 Plant variables

While 30 and 40 results were reported for *first year* and *young* willows respectively, only 13 pertained to willows with a *mature* root system (Figure 2). The age of the root system did not significantly affect the results, even though fresh stems newly developed from cuttings tended to be associated with slightly lower ET than *young* or *mature* willow plants (4.2 mm/d compared to 5.3 and 5.0 mm/d respectively; Figure 2). Sixteen of the 19 species were associated to 5 results or less, compared to the most studied species, *S. viminalis*, which was associated to 53 results. Three articles did not provide the exact taxonomic identity of the willow studied (*Salix* sp.). There was a significant difference of the results according to species (Figure 2). However, α_{intra} for *S. viminalis* (3.3 mm/d) was very similar to variation between species mean ET rate (α_{inter} = 3.2 mm/d). *Salix amygdalina*, *S. exigua* and *S. psammophila* were the three species with the lowest mean ET rate (< 2 mm/d), while *S. babylonica*, *S. cinerea*, *S. goodgingii, S. miyabeana* and *S. nigra* (all cultivars combined) had the highest (> 7 mm/d; Figure 2).

3.2.2 Environmental and management variables

The majority of the articles reviewed studied willows growing either in mesocosms or in plantations (Figure 3). The effect of experimental context on ET rates was not significant (Figure 3). Nonetheless, *treatment wetlands* were generally associated with higher results (7.9 mm/d on average), followed by *mesocosms* (5.7 mm/d), *floodplain* (3.6 mm/d) and finally *plantation* results (2.9 mm/d; Figure 3). Water supply was found to be a significant experimental variable (Figure 3), with *low* water supplies associated to the lower results (2.4 mm/d on average), compared to *medium* and *high* water supply (5.0 and 7.0 mm/d, respectively; Figure 3). Almost half of the results were measured or calculated for willows that were poorly supplied with water (n=47; Figure 3). Furthermore, we found a significant linear correlation between daily water input and daily ET rate for open systems (r^2 = 0.7, Figure 4). The planting density did not significantly explain ET rate variations in our factorial analysis (Figure 3). However, average ET rates were the same for *medium* and *high* planting density (5.4 mm/d), but slightly lower at *low* density (3.2 mm/d; Figure 3). Linear regression of ET rate over planting density did not show a clear trend either (Figure 5), but the few results reported at very high planting density suggest the existence of a threshold, after which ET is limited (here estimated to be approximately 5 plants/m^2; Figure 5). Regarding the type of soil in which willows were grown, most results were reported for sandy soils, followed by clayey soils. No significant effect of soil type was found (Figure 3), but the following average ET rate gradient could be observed: in organic soil (6.1 mm/d) > in clayey soil (5.3 mm/d) > in sandy soil (4.9 mm/d) > in gravel (1.6 mm/d). We should mention that only 3 results were reported for gravel substrate. Finally, fertilization and contamination both had a significant effect in the comparative analysis (Figure 3). Studies that used some kind of fertilization treatment reported ET rates 40% higher on average compared to unfertilized willows (6.1 mm/d vs. 3.5 mm/d). On the contrary, ET rates were generally lower in the presence of contaminants, although average rates were very similar (4.6 mm/d in the presence of contamination compared to 4.7 mm/d in non-contaminated conditions; Figure 3).

4. Discussion

Our review shows that mean ET rates in willows are generally below 10 mm/d, but may rise well over that value, reaching up to 23 mm/d. According to a factorial analysis performed on 110 ET rate results from 57 articles, we found that water supply, fertilization and contamination significantly affected ET rates. We identified a strong correlation between daily water input and ET rate in open systems. The effects of plant age, experimental context, and planting density were not statistically significant, although some trends could be observed. Soil type in fact was less important than the other variables, when their simultaneous effect on ET was tested. Willow species seemed to significantly affect ET rates, but α_{inter} and α_{intra} variation of ET were equivalent.

Variation of T rate between species is to be expected, because its regulation mechanisms are not the same for every taxa (Sperry, 2000). These mechanisms are generally adapted to the plant environment (Bohnert *et al*., 1995), a good example being xerophytic species, which display various ways of preventing water loss through T (Fahn and Cutler, 1992). This could explain why *S. psammophila*, a willow species adapted to dry environments (Xiao *et al.*, 2005), had one of the lowest ET rates, while *S. nigra*, a water dependent species (Pezeshki *et al*., 2007), had the highest. Overall, different willow species had different ET rate ranges, but in the end there were so few studies on each species and so many other factors that varied between studies that we cannot conclude that taxonomical identity dictates mean ET rate in the willow genus. Furthermore, the fact that ET variation between willows of the same species (*S. viminalis*) was the same as that between different species suggests that species identity is not the most important factor in ET variation across the willow genus, particularly for species adapted to similar environments (*e.g.* wet habitat). However, willow cultivars developed in breeding programs can promote high T rates for environmental applications like phytoremediation (Smart *et al*., 2005) or promote increased water use efficiency (WUE) and tolerance to water limitation for biomass production (Karp *et al*., 2011). This could explain the high variability of ET in the *S. viminalis* species, which in this review is comprised of more than 20 genetically different cultivars.

Regarding the age of the willow root system, our hypothesis was that plants in their *first year* – the establishment year, as well as *mature* shrubs, which should have a lower growth rate, would be associated with lower ET rates compared to young, fast growing plants. Indeed, we observed lower ET for plants newly developed from cuttings, but not for *mature* shrubs. However, it appears that the mean average ET rate for mature trees was driven up mainly by the results of one study (Frédette *et al.* 2019); when those results are set aside, mean ET rate for mature trees drops from 5.9 mm/d to 2.4 mm/d. This difference could be explained by the fact that ET results in Frédette *et al*. (2019) were obtained from a treatment wetland with a high water supply, while all the other results from mature shrubs came from plantations with a low water supply. Furthermore, willows in the Frédette *et al.* study were recently coppiced, while most of the other studies were conducted on willows with much older stems. Coppicing of willows is known to help keep the plants in a juvenile, and thus more productive, state and it could then be responsible of those high ET rates. A decrease in biomass production with time has been documented for willows in the past, even in a coppicing system (Willebrand *et al*., 1993), but our analysis did not allow us to demonstrate this pattern. Further studies should be conducted on this specific issue to provide clearer answers.

Our findings suggest that ET rate is greater in closed and relatively small-scale systems (treatment wetlands and mesocosms) than in open and full-size systems (floodplain and plantations). In open systems, ET is higher in floodplains, where the water table (and thus water availability) is generally high and some flooded conditions can even occur, than in plantations, where water may be limited and will drain to lower soil horizons. In comparison, in closed systems like treatment wetlands or some mesocosms, water supply is often equal to or greater than plants' water demand, meaning that water is not a limiting factor and ET occurs at a rate closer to maximal pET. Furthermore, pET can be exceeded in small scale willow stands by processes like an "oasis" or "clothesline" effect (Allen *et al*., 1998; Frédette *et al*., 2019; Dotro *et al*., 2017). An oasis effect is the result of a difference in temperature between willows and their surroundings, due to the cooling effect of ET, which increases available energy to willows by a heat advection effect (Hao *et al*., 2016; Dotro *et al*., 2017). The clothesline effect increases ET on the edges of the willow stand because of enhanced wind influence, as a result of the height difference between willows and the surrounding vegetation (Brix and Arias, 2011; Dotro *et al*., 2017). Both those effects could partially explain higher ET rates reported in mesocosms and treatment wetlands. Another aspect of the experimental context variable is that it shared many associations with other variable levels (Figure 1). Thus, mesocosms were mainly associated with younger willows and medium to high planting density; treatment wetlands generally had a high water supply, medium to low planting density and organic soil; floodplains had a medium to high water supply, high planting density, sandy or clayish soil, unfertilized and uncontaminated environment; and finally, plantations were associated with low to medium water supply, medium planting density, various soil types, but mainly uncontaminated conditions. When considered as the only explanatory variable, experimental context significantly explains ET variation ($p<0.001$). On the one hand, the experimental context might provide a global indicator of ET rate combining many environmental and management variables, but on the other hand, it might be interesting to replace it by finer variables (*e.g.* experimental unit area and permeability) to add precision to a global analysis.

Of all the chosen variables, water supply was one of the most significant driving factors of ET rate variation. Along with meteorological conditions, water is a direct limiting factor for ET, and the impact of water stress on ET rates is generally well described in the ET literature (Sperry, 2000; Bohnert *et al*., 1995). This review highlights a strong correlation between water supply and ET rate across the willow genus. For open systems where water supplies could be quantified, this factor alone could explain most of the ET rate variation. However, according to the same correlation analysis, the difference between water supply and ET rate increased with increasing water supply, illustrating that the less water is limiting, the more other factors become limiting. This relation may not hold in a closed system, as a lesser effect of water availability on ET has been demonstrated in closed versus open systems (Rana and Katerji, 2000). For example, Guidi and Labrecque (2010) found no increase in ET rate for *S. viminalis* '5027' with very high irrigation rates, compared to "normal" irrigation, in a pot experiment. As previously discussed, water use strategy may also vary from one species to another, depending on its natural environment but also on its breeding strategy. Most of the species studied here are naturally associated with humid habitats, and therefore do not require a very efficient water regulation mechanism, which has given willows their "water-wasting" plant reputation.

Generally, increasing planting density of a crop will also increase biomass yield, until an optimal threshold density is reached; beyond that threshold, a higher density will not produce more biomass due to competition for resources such as for water or light (Assefa *et al*., 2018; Ngouajio, 2001; Willebrand and Verwijst, 1993). As willow biomass is thought to be closely linked to ET (Martin and Stephens, 2006; Marmiroli *et al*., 2012;

Białowiec *et al*., 2007), the same threshold hypothesis could apply to ET rate. Our results strongly suggest that the planting density at which willow ET is maximal is higher than 1 plant/m^2 studies using this density systematically reported lower ET rates. No significant differences were found between *medium* and *high* planting density, but plotting ET rates with the corresponding density suggests a threshold around 5 trees/m^2. However, only 12 of the 57 articles reviewed reported results for densities higher than this potential threshold. Furthermore, yield increases for willow have been documented at a density as high as 11 plants/m^2 (Bullard *et al*., 2002).

In addition to water supply, water availability (often expressed as soil water potential) can affect ET, and the type of soil impacts water potential for a given water supply (Rawls *et al*., 1982). However, the soil effect, through attraction force between soil particles and water, can act on two levels, as described in section 2.3.2 of the present manuscript. This dual effect may explain why we did not observe significantly different ET rates according to soil type in this review. Presence of organic matter in the soil even adds another level of interaction by providing additional nutrients to plants, which can increase growth and, consequently, ET rate, which is supported by the slightly higher ET rates reported here for *organic* soils. For the three studies in which *gravel* was used as a substrate, a high ET rate would have been expected, because the substrate was constantly kept saturated with water that should be highly available because of gravel's physical properties. However, low ET rates were measured, probably due to late season measurements in one case (Jing *et al.* 2010), water contamination in another (Białowiec *et al*., 2003) and ET rates reported on an annual basis (including low ET rates in winter) in the last (Marttila *et al*., 2017). This and the previous explanations highlight the simultaneous effect of multiple factors and suggest that soil type alone is not a strong explanatory variable for ET variation.

As expected, fertilization increased willow ET, probably by increasing growth rate. Only one study used fertilization as the main treatment variation, and it reported a 96% increase in ET due to fertilization (Guidi *et al*., 2008). Pistocchi *et al.* (2009) also reported a 51% increase of willow ET when switching from low to high fertilization. For some studies, the variation in the fertilization treatment was due to amendments to the substrate in various forms, such as compost, mechanical-biological pretreated waste material, sewage sludge or other forms of organic matter addition (Rüth *et al*., 2007; Białowiec *et al*., 2007; Martin and Stephens, 2006). Despite the presence of other interacting factors, the *fertilized* treatment in these studies was always associated with slightly higher ET rates. Interestingly, most of the articles that were associated with fertilization were, in fact, exposing willows to various types of wastewater, mainly landfill leachate or from domestic and agricultural source. These types of water did contain nutrients such as nitrogen and phosphorus, but also contained harmful compounds such as chloride and sulfate, high ammonium and salt concentrations, and metalloids, particularly when leachates were the source of fertilization. A good illustration of the dual effect of this type of effluent is provided by Białowiec *et al.* (2003), describing how a low concentration of landfill leachate had a positive effect on willow ET but increasing concentrations became deleterious to the plants. Conversely, Curneen and Gill (2014) reported an increase in ET when using primary (more concentrated) instead of secondary (less concentrated) effluent from domestic wastewater, probably because the beneficial effect of the high levels of nitrogen and phosphorus in this type of wastewater exceeded other potentially negative water characteristics. This may also explain why average ET rate was similar for contaminated and uncontaminated results; 9 of the 14 studies that measured ET rates in contaminated conditions provided fertilized conditions at the same time. When testing chloride contamination only, Stephens (2000) clearly demonstrated the negative impact of increasing chloride concentration on ET. Furthermore, ET rate is frequently used as a toxicity indicator in lab tests, due to its sensitivity to increasing pollutant concentration (Trapp *et al*, 2000, Clausen *et al*., 2018). Therefore, contamination and fertilization should be considered together to accurately judge their influence on ET in view of their compensatory effect on each other.

ET is a complex process, and despite the numerous factors evaluated here, there are additional variables that were not analyzed numerically but that could provide a better understanding of ET results. As previously mentioned, biogeographical variation along with meteorological conditions are important factors, and a synthetic and theoretical explanation of those variables can be found in ET literature (see for example Holdridge, 1947 and Allen *et al.*, 1998). For example, higher temperatures and smaller seasonal variations correlate with high ET rates reported in regions as such as Arizona (Nagler *et al*., 2003) and Louisiana (Conger and Portier, 2001). In this review, we also found that some results reflected coupling and decoupling of willow T with atmosphere and its associated water vapor pressure deficit, which is variable along with plant development (Mirck and Volk, 2009). Otherwise, ET rates show obvious seasonal variation that is accentuated in northern countries, which have shorter growing periods and little to no ET during winter. ET also varies according to phenology and leaf development during the growing period. Although this concept might seem obvious, we consider it pertinent for practitioners planning a project based only on published ET values. According to most of the articles reviewed here, maximum leaf area of willows is generally reached in late summer months, and ET rate is maximal from July to September in the northern hemisphere. This phenological pattern is quite different from that in typical grass species, which develop their total aerial biomass earlier in the season (Persson, 1997). Therefore, the willow crop coefficient (K_c; *i.e.* ratio between willow ET and a reference well-watered grass surface ET) has proven to be very high late in the season (Curneen and Gill, 2016; Persson, 1995; Irmak *et al.*, 2013; Guidi *et al.*, 2008). The crop coefficient is a thus a very useful tool for irrigation planning or project design, and being aware of the temporal variation of willow K_c is an asset.

Finally, although the methodological approach adopted by researchers to measure ET has no direct influence on ET processes, it can contribute to greater ET measurements and calculations. Allen *et al*. (2011) suggested an error range from 5 to 200% in ET measurement, depending on the method used, experimenter experience and training, as well as equipment reliability. Water balance, when performed in a closed system where water fluxes are controlled (*e.g.* lysimeter, treatment wetlands) should yield the most reliable results; this type of method was the most commonly used among the articles reviewed here. When used alone, open water balance can be imprecise due to a high degree of uncertainty regarding leakage and runoff processes. Sap flow approaches are a subset of methods that estimate plant T based on water transport in stems. The method itself presents a number of potential sources of error (Allen *et al*., 2011), and requires extensive calculations and precautions to scale up the ET values from stems to a whole tree stand (Green *et al*., 2003; Grime and Sinclair, 1999). It can therefore be considered a difficult method that requires great expertise and experimental rigor (Allen *et al.*, 2011). Still, the general homogeneity of sapwood in fast-growing willow shrubs developed for coppice plantations makes scaling up results for them easier and more reliable than for other shrubs or trees with more complex arborescence patterns. Modelling methods comprise several distinct approaches, including micrometeorological methods such as energy balance or Penman methods, and models based on different variables like leaf or soil parameters, or a combination of modelling approaches. In this review, we found that studies based on modelling approaches tended to provide low ET rates and less variation across studies than the two previous approaches. This could be due to the fact that most of these modelling studies were conducted in plantations (associated here with lower ET rates) or to over parameterization of models that tend to limit ET in additive or even multiplicative ways. Still, modelling studies are often based on field measurements and serve as practical and sometimes more realistic tools for irrigation planning.

5. Conclusions

Overall, willow ET rates reported in scientific literature varied mainly according to plant species, water supply, fertilization and contamination, although species influence remains unclear. It can be hypothesized that environmental/experimental factors have more influence on ET of willows that share similar plant life-forms (*e.g.* fast-growing shrubs naturally found in wet habitats) than taxonomical identity. Water supply seems to be the most limiting factor among those investigated here. In open systems and until pET is reached, there is a positive linear relation between water supply and ET rate. The projected use of the willows (*e.g.* ET cover, treatment wetland, biomass production) informs us on many aspects of the growing conditions, such as the relative water availability and the scale of the willow stand. This variable alone could thus be used to estimate whether ET should be expected to be high or low, although it does not allow precise estimation of ET. A planting density of two to five trees per square meter should be favored to maximize ET and avoid excessive competition. Based on the present review, the effect of soil type on ET remains unclear but may not be one of the most important driving factors. Fertilization and contamination levels provided to plants should be compared to estimate their global effect on plant growth and ET, particularly in cases where willows are irrigated with wastewater or leachate. Finally, biogeographic location will always influence potential ET rate and should be considered by project planners, in addition to the plants, environmental and experimental issues pointed out in this review. Future research on willow ET should focus on 1) specifying the root or stem age effect on ET, 2) confirming the optimal density for ET processes, as well as 3) testing whether, under a given set of growing conditions, species or cultivar identity has a significant effect on ET or not.

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WILLOWS FOR ENVIRONMENTAL PROJECTS: A LITERATURE REVIEW OF RESULTS ON EVAPOTRANSPIRATION RATE AND ITS DRIVING FACTORS ACROSS THE GENUS SALIX.

Frédette *et al.*

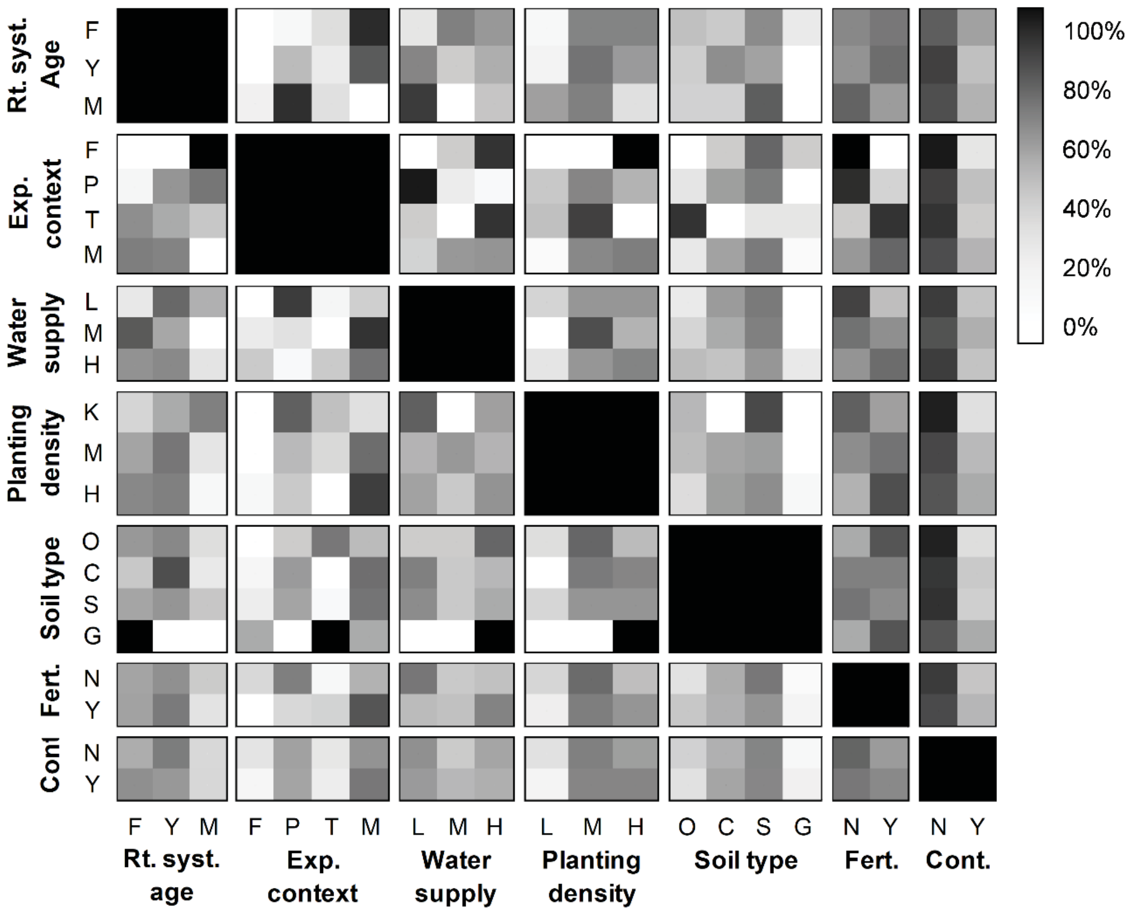

Figure 1. Correlogram illustrating the frequency (%) of association between the levels of nine variables selected to explain the variation of evapotranspiration rate across the willow genus (*Salix* sp.). Darker colors indicate a frequent association between levels of two variables (black = 100%, *i.e.* levels always associated), while pale colors indicate that the levels of the two variables were not likely to be combined (white = 0%, *i.e.* levels never associated). The codes used for variables levels are detailed in table 1 of the present article.

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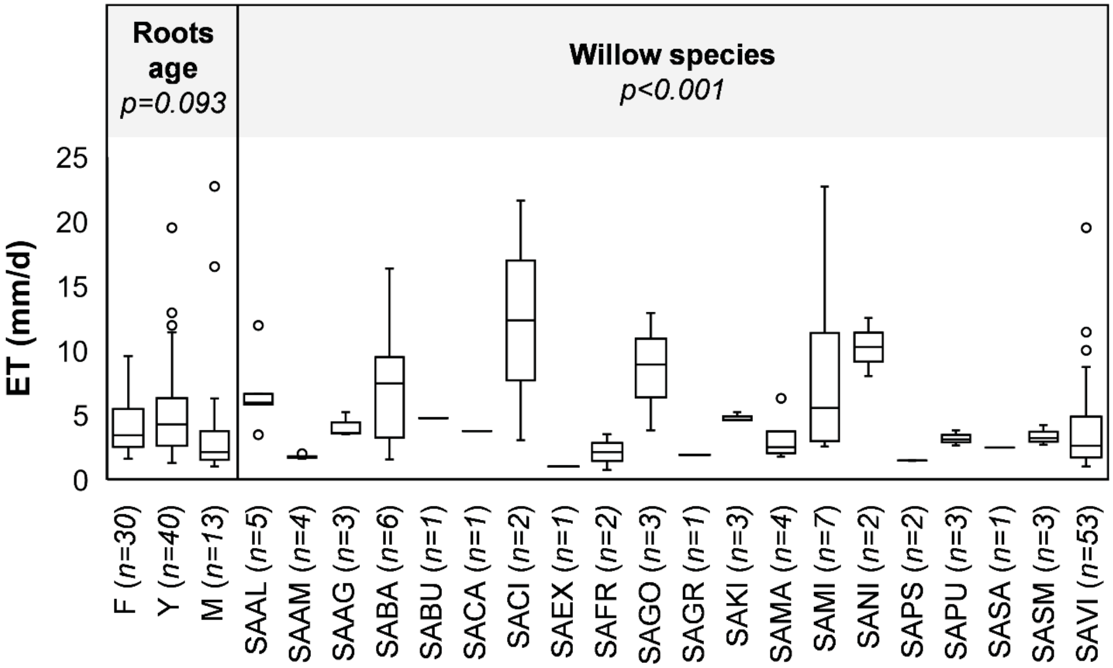

Figure 2. Mean evapotranspiration (ET) rates reported in 57 articles in 16 countries, according to plant related variables (root system age and species). Numbers in parenthesis (n) represent the number of average results considered for each variable level. The codes used for variables levels are detailed in table 1 of the present article. P values indicate if the variables affect significantly (α=0.05) ET results according to a Type II ANOVA analysis testing the simultaneous effect of 10 variables.

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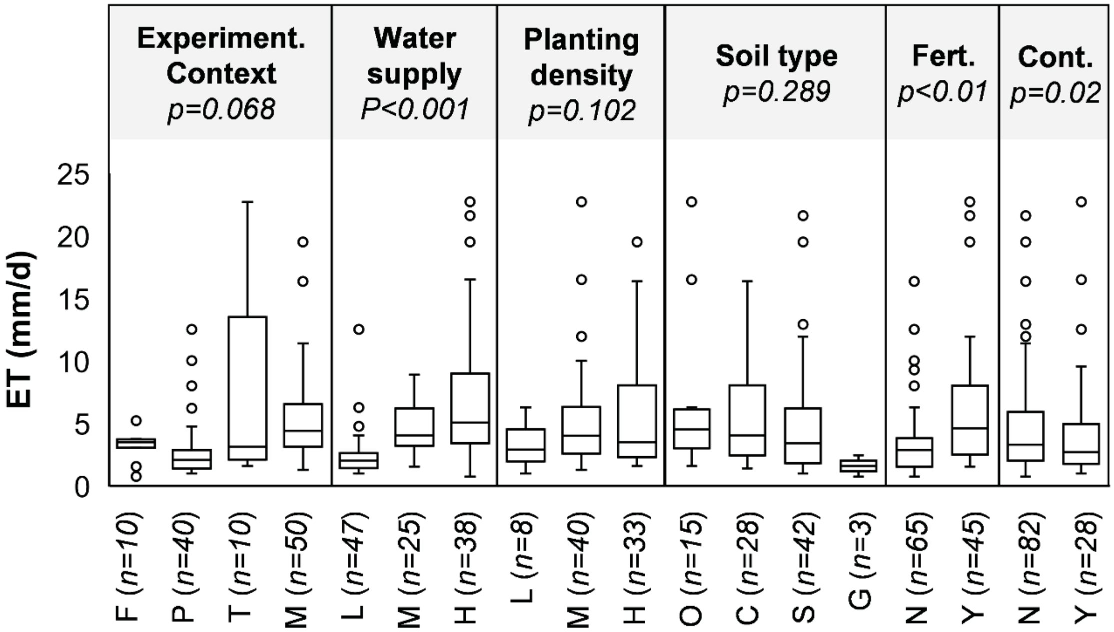

Figure 3. Mean evapotranspiration (ET) rates reported in 57 articles in 16 countries, according to experimental/management variables (experimental context, water supply, planting density, dominant soil type, fertilization and contamination). Numbers in parenthesis (n) represent the number of average results considered for each variable level. The codes used for variables levels are detailed in table 1 of the present article. P values indicate if the variables affect significantly (α=0.05) ET results according to a Type II ANOVA analysis testing the simultaneous effect of 10 variables.

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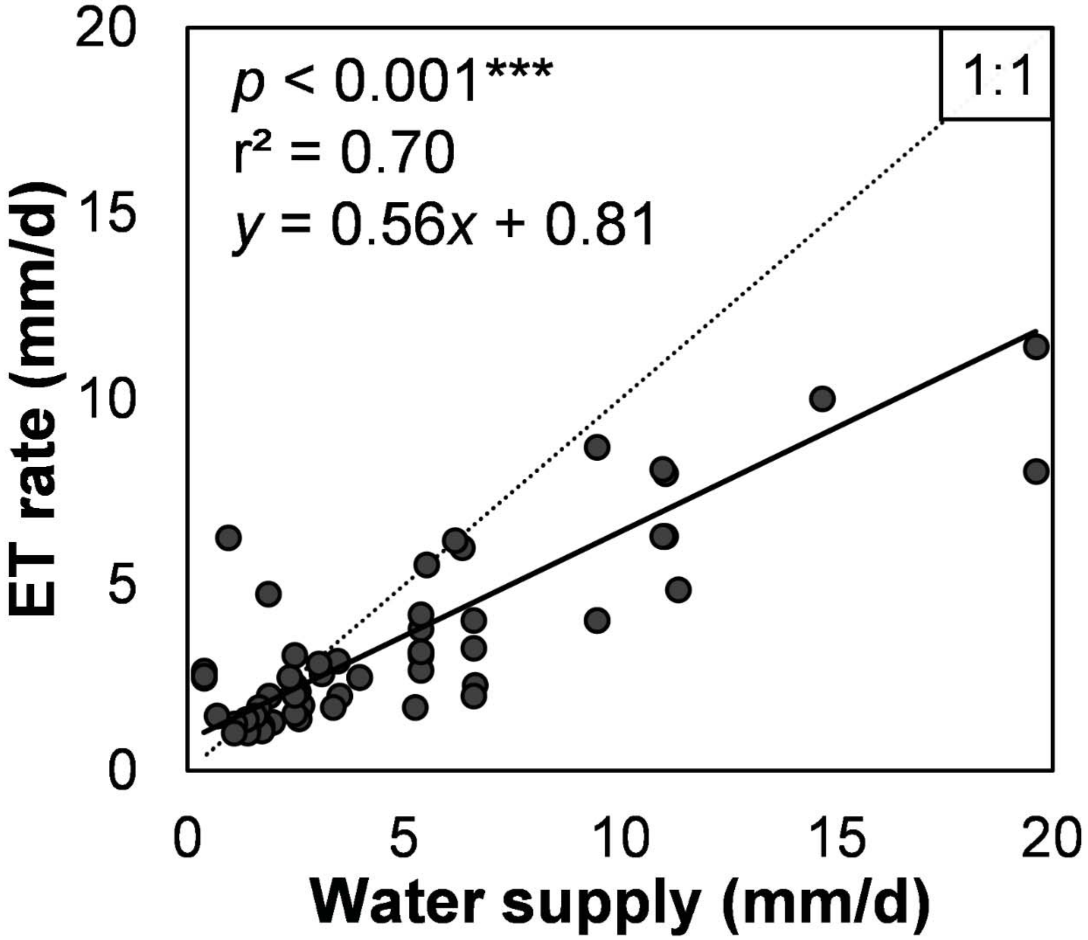

Figure 4. Summary of the linear regression between mean daily evapotranspiration rate of willows reported in scientific literature and the amount of water supplied daily, either by precipitation or irrigation (*n* = *63*). Reference articles included in this analysis are detailed in Table 2 of the present article, and are comprised of studies of open systems with water table low enough to allow drainage.

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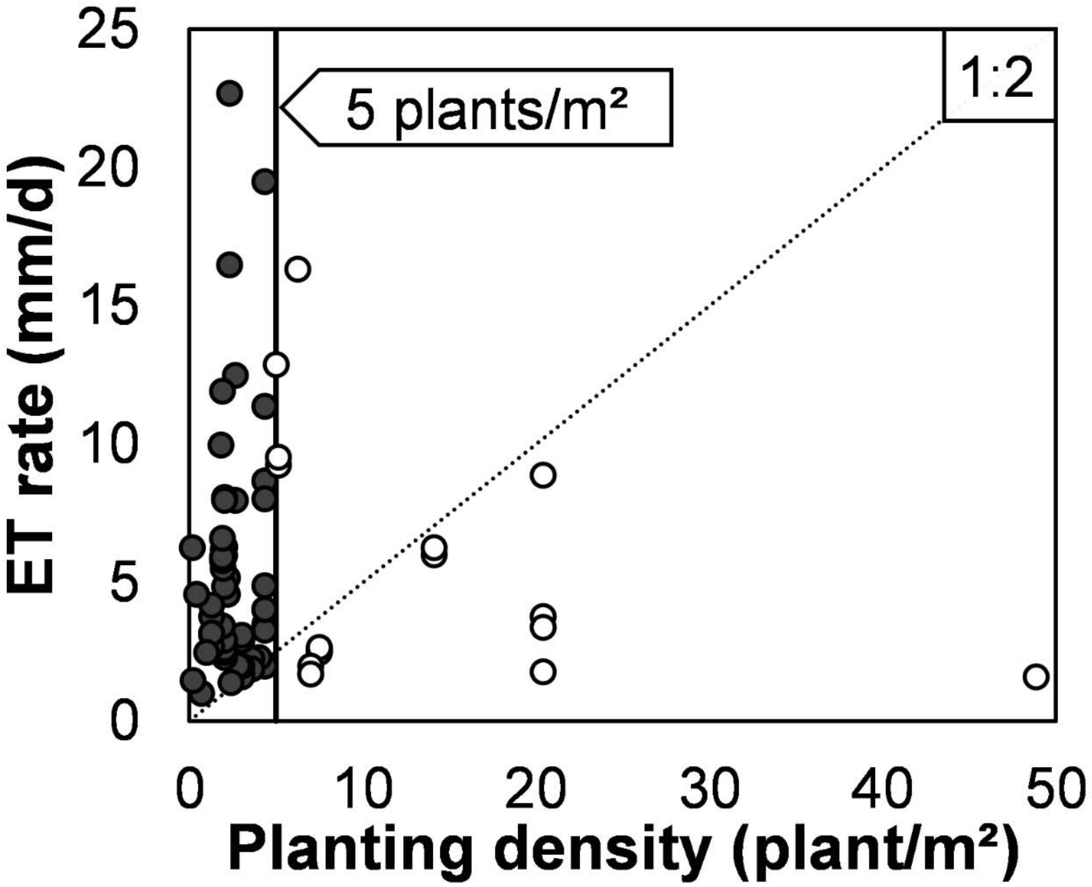

Figure 5. Mean daily evapotranspiration rate of willows reported in scientific literature in relation to planting density (*n* = *75*). Reference articles included in this analysis are detailed in Table 2 of the present article. An arbitrary threshold (dashed line) for ET was drawn at a planting density of 5 trees per m^2.

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Table 1. Summary of ten variables selected to categorize, compare and identify driving factors of willow (*Salix* sp.) evapotranspiration rates results found in the scientific literature.

Type	Variable	Levels	Description	Code
Plant variables	Willow species	19 species (see Table 2 for species listing and codes)		
	Age of plantation	First year	Establishment year	F
		Young	2 to 5 years old roots	Y
		Mature	> 5 years old roots	M
Environmental/management variables	Experimental context	Flood plain	Natural stands in wet habitat	F
		Plantation	Mand made plantation or natural stand in mesic to dry habitat	P
		Treatment wetland	Pilot and full-scale	T
		Mesocosm	Lysimeters and pots	M
	Water supply	Low	> 10 mm/d or saturated root zone	L
		Medium	5 to 10 mm/d or field capacity	M
		High	< 5mm/d or water deficit	H
	Planting density	Low	≤ 1 plants/m^2	L
		Medium	1 to 4 plants/m^2	M
		High	> 4 plants/m^2	H
	Dominant soil type	Organic	Significant organic matter content	O
		Clay	> 50% clay particles	C
		Sand	> 50% sand particles	S
		Gravel	> 50% gravel content	G
	Fertilization	Yes	Fertilizer, soil amendment or nutrient rich wastewaters	Y
		No		N
	Contamination	Yes	Soil or water contamination	Y
		No		N

Table 2

Table 2. Range of evapotranspiration rates (mm/d) reported in 57 articles for 19 different willow species (and various cultivars) in 16 countries, along with the corresponding information about plants, experimental and methodological variables. Results of transpiration only are indicated in parenthesis (T). Information missing about some variables is due either to non-reported information or to values that did not fitted the selected levels of a variable. Numerical value of water supply and planting density are detailed in parenthesis when available. The codes used for variables levels are detailed in table 1 of the present article. Each article tested one to nine experimental treatments (n), for a total of 110 mean results considered for comparative analysis.

Species ‘cultivar’	**Code**	**ET range (mm/d)**	**Age**	**Context**	**Water (mm/d)**	**Density (plant/m^2)**	**Soil**	**Fert.**	**Cont.**	**n**	**Country**	**Ref.**
S. alba ‘SI62-059’	SAAL	3.4-11.9	F, Y	M	M	M (1.9)	S	Y, N	N	4	Italy	1
S. alba ‘SI62-059’	SAAL	4.6-7.0	Y	M	M	M (1.9)	S	Y	N	1	Italy	2
S. amygdalina	SAAM	0.6-2.3	F	M	H	H (48.8)	G	Y	Y	1	Poland	3
S. amygdalina	SAAM	1.0-3.0	F, Y	M	L, M (3.4-5.3)	H (7)	S	Y	Y	3	Poland	4
S. amygdaloïdes	SAAG	3.6-5.2	-	F	H, M	-	S	N	N	2	U.S.	5
S. amygdaloïdes	SAAG	3.5 (T)	-	F	H	-	S	N	N	1	U.S.	6
S. babylonica	SABA	1.5-6.6	-	F	H, M	-	-	N	N	2	Australia	7
S. babylonica	SABA	2.4	F	T	H	-	G	Y	N	1	China	8
S. babylonica	SABA	9.3-9.6	F	M	H	H (5.1)	C	Y, N	Y,N	2	Canada	9
S. babylonica	SABA	16.4	-	M	H	H (6.25)	C	N	N	1	U.S.	10
S. bujartica ‘Germany’	SABU	4.8 (T)	Y	P	L (1.9)	-	C	N	N	1	Sweden	11

S. caroliniana	SACA	3.8	M	F	H	-	-	N	Y	1	U.S.	12
S. cinerea	SACI	21.6	-	T	H	-	S	Y	N	1	Belgium	13
S. cinerea	SACI	3.0	-	F	H	H	C	N	N	1	Czechoslovakia	14
S. exigua	SAEX	0.7-1.6	M	P	L (1.1)	L (0.7)	S	N	N	1	U.S.	15
S. fragilis	SAFR	3.5	-	F	H	-	-	N	N	1	Australia	16
S. fragilis	SAFR	0.7	-	F	H	-	G	N	N	1	New-Zeland	17
S. gooddingii	SAGO	2.5-8.9 (T)	F	M	M	H (20.4)	S	Y	Y, N	2	U.S.	18
S. gooddingii	SAGO	12.9 (T)	Y	M	H	H (5.0)	S	N	N	1	U.S.	19
S. gordejevii	SAGR	1.9 (T)	-	P	L	H (3.6)	S	N	N	1	China	20
S. kinuyanagi ‘Kimura’	SAKI	4.6-5.4	F	M	H	M (2.2)	S	Y, N	Y, N	2	New-Zealand	21
S. kinuyanagi ‘Kimura’	SAKI	4.6	Y	M	H	L (0.4)	S	Y	Y	1	New-Zealand	22
S. matsudana	SAMA	2.1	M	P	L (2.6)	L	S	N	N	1	China	23
S. matsudana	SAMA	1.8	M	P	L (2.7)	L	S	N	N	1	China	24
S. matsudana	SAMA	6.3	M	P	L (0.9)	L (0.2)	S	N	N	1	China	25
S. matsudana	SAMA	1.2-5.3 (T)	M	P	L (3.0)	-	S	N	N	1	China	26
S. miyabeana ‘SX67’	SAMI	16.5-22.7	M	T	H	M (2.3)	O	Y	Y	2	Canada	27
S. miyabeana ‘SX67’	SAMI	5.5-6.2	F, Y	P	M (5.5-6.2)	M (2.0)	O	N	N	2	Canada	28
S. miyabeana ‘SX64’	SAMI	2.5-2.7 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. miyabeana ‘SX64’	SAMI	2.7-3.9	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. nigra	SANI	6.0-13.0	Y	P	L, M	M (2.6)	C	N	Y	2	U.S.	31

		(T)										
S. psammophila	SAPS	1.5 (T)	-	P	L (1.6)	-	S	N	N	1	China	32
S. psammophila	SAPS	1.4	-	P	L	L (0.2)	S	N	N	1	China	33
S. purpurea ‘9882-34’	SAPU	3.1-3.8	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. purpurea ‘9882-34’	SAPU	2.6 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. sachalinensis ‘SX61’	SASA	2.5 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. sachalinensis x S. miyabeana ‘9870-40’	SSSM	3.2-4.2	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. sachalinensis x S. miyabeana ‘9870-23’	SSSM	2.7 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. viminalis	SAVI	10.0	-	P	H (14.7)	M (1.79)	S	N	N	1	Switzerland	34
S. viminalis ‘1023’ ‘1047’ ‘1052’ ‘1054’	SAVI	1.4-1.7	-	P	L (1.4-1.7)	-	C, S	N	N	2	Poland	35
S. viminalis ‘Inger’ ‘Sven’ ‘Tordis’ ‘Torhild’	SAVI	1.9-7.6	Y	M	H	H (4.35)	O	Y, N	N	2	Ireland	36
S. viminalis	SAVI	1.5-2.9	F, Y	T	L, H	M (3.0)	O	Y, N	N	4	Ireland	37
S. viminalis ’78-183’	SAVI	6.3-8.3	Y	M	H (11.0)	M (2.0)	C, S	Y	N	2	Sweden	38
S. viminalis ‘Tora’	SAVI	2.2-7.5	F, Y	M	M, H (6.4-11.4)	M (2.0)	C	Y	Y	3	Sweden	39
S. viminalis ‘Tora’	SAVI	2.3-8.3	Y	M	L, H (4.0-11.0)	M (2.0)	C, S	Y	N	4	Sweden	40
S. viminalis ‘Bjorn’ ‘Tora’ ‘Jorr’	SAVI	2.7-5.7	F, Y	T	H	L	O	Y	N	2	Denmark	41
S. viminalis ‘77683’ ‘77666’	SAVI	3.0	Y	M	L	-	S	N	N	1	Sweden	42
S. viminalis ‘SQV 5027’	SAVI	6.0-6.3	F	M	M, H	H (14.1)	O	Y	N	2	Canada	43
S. viminalis	SAVI	2.6	Y	P	L (3.1)	M (2.0)	C	Y	N	1	Sweden	44
S. viminalis ‘L78183’ ‘Loden’ ‘Jorr’ ‘Rapp’ ‘Tora’	SAVI	0.7-2.1 (T)	Y	P	L (2.6)	M (2.4)	C	N	N	1	Sweden	45

S. viminalis	SAVI	2.9-3.0	Y	P	L (3.5)	M (2.0)	C	Y	N	1	Sweden	46
S. viminalis 'Jorr'	SAVI	2.0-19.5	F, Y	M	L, M, H (6.6-19.6)	H (4.4)	C, S	Y, N	N	9	U.K.	47
S. viminalis '77075' '77077' '77082' '77083' '77683' '82007'	SAVI	2.0-3.7	Y, M	P	L (2.5)	M, H (3.0-4.0)	C, S, O	Y	N	5	Sweden	48
S. viminalis	SAVI	1.6-2.3	-	P	L (1.9)	-	C	N	N	1	Sweden	49
S. viminalis 'Régalis'	SAVI	1.0-1.2	-	P	L (1.4-1.7)	-	S	N	Y, N	6	Germany	50
S. viminalis	SAVI	1.2 (T)	M	P	L (1.0)	-	-	N	Y	1	Belgium	51
S. viminalis 'Tora'	SAVI	1.3-1.5	Y, M	P	L (0.7-1.1)	M	C, S	N	N	1	Germany	52
S. viminalis 'Q683'	SAVI	1.8-3.4	1	M	H	H (20.4)	S	N	Y, N	2	U.K.	53
S. viminalis 'Jorunn'	SAVI	2.5 (T)	-	P	L (2.4)	L (1.0)	-	N	N	1	U.K.	54
Salix sp.	SASP	3.1	-	P	L	-	C	N	N	1	Sweden	55
Salix sp.	SASP	3.1 (T)	-	F	H	-	-	N	N	1	U.S.	56
Salix sp.	SASP	1.1-1.4	-	P	L (2.0)	-	-	N	N	1	Germany	57

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