

# Effect of Herbicides on Evapotranspiration of Willow Marshes in the Upper St. Johns River Basin, Florida

Yin Tang<sup>1</sup>; Danny Goodding<sup>2</sup>; Luz M. Castro Morales<sup>3</sup>; Dingbao Wang, A.M.ASCE<sup>4</sup>;  
Pedro F. Quintana-Ascencio<sup>5</sup>; Dianne L. Hall<sup>6</sup>; and John E. Fauth<sup>7</sup>

**Abstract:** During the last 40 years, Carolina willow (*Salix caroliniana Michx.*) expanded into areas previously dominated by herbaceous marshes in the Upper St. Johns River basin (USJRB) of east-central Florida, United States. This change in vegetation affects evapotranspiration (ET). To quantify changes in ET at the community level after willows were removed using herbicides, a two-year field experiment with a randomized complete block design was implemented. The design included an unsprayed control and two different aerially sprayed herbicide treatments and was replicated in four blocks along the Upper St. Johns River. Daily ET was estimated using the Penman-Monteith equation from July 1, 2014, to August 31, 2016. Cumulative ET difference between the control and treated plots increased substantially during the growing season after herbicide application. Mean annual evapotranspiration was  $1,368 \pm 51$  mm year<sup>-1</sup> on control plots,  $1,096 \pm 137$  mm year<sup>-1</sup> on plots treated with Aquasweep or Ecomazapyr herbicide, and  $968 \pm 117$  mm year<sup>-1</sup> on plots treated by Clearcast herbicide. A single-parameter annual ET model derived from a Budyko-type equation was applied to the study area, and the model parameter ( $\epsilon$ ) strongly correlated with willow fractional coverage in April. The empirical equation obtained from this study can be potentially used for evaluating the impacts of willow treatment and climate on long-term evapotranspiration in the study area. DOI: [10.1061/\(ASCE\)HE.1943-5584.0001685](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001685). © 2018 American Society of Civil Engineers.

**Author keywords:** Willow; Herbicide; Evapotranspiration; Penman-Monteith; Budyko.

## Introduction

Almost 80% of the world's human population lives in regions where water security and riparian biodiversity are threatened (Vörösmarty et al. 2010). East-central Florida is no exception. Rapid population growth and suburban sprawl are depleting groundwater supplies, making surface water more important for sustaining human activities (Hackney 2015). At the same time, vegetation changes along the state's largest river—the St. Johns—may send increasing amounts of water into the atmosphere, reducing the amount available both to humans and to the riparian ecosystem.

<sup>1</sup>Graduate Student, Dept. of Civil, Environmental and Construction Engineering, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816; Assistant Professor, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Rd., Chaoyang, Beijing 100101, China (corresponding author). ORCID: <https://orcid.org/0000-0002-4479-5074>. Email: [yin.tang@knights.ucf.edu](mailto:yin.tang@knights.ucf.edu); [tangyin@igsnr.ac.cn](mailto:tangyin@igsnr.ac.cn)

<sup>2</sup>Graduate Student, Dept. of Biology, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816.

<sup>3</sup>Undergraduate Student, Dept. of Biology, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816.

<sup>4</sup>Associate Professor, Dept. of Civil, Environmental and Construction Engineering, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816.

<sup>5</sup>Professor, Dept. of Biology, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816.

<sup>6</sup>Environmental Scientist, Bureau of Water Resources, St. Johns River Water Management District, 4049 Reid St., Palatka, FL 32177.

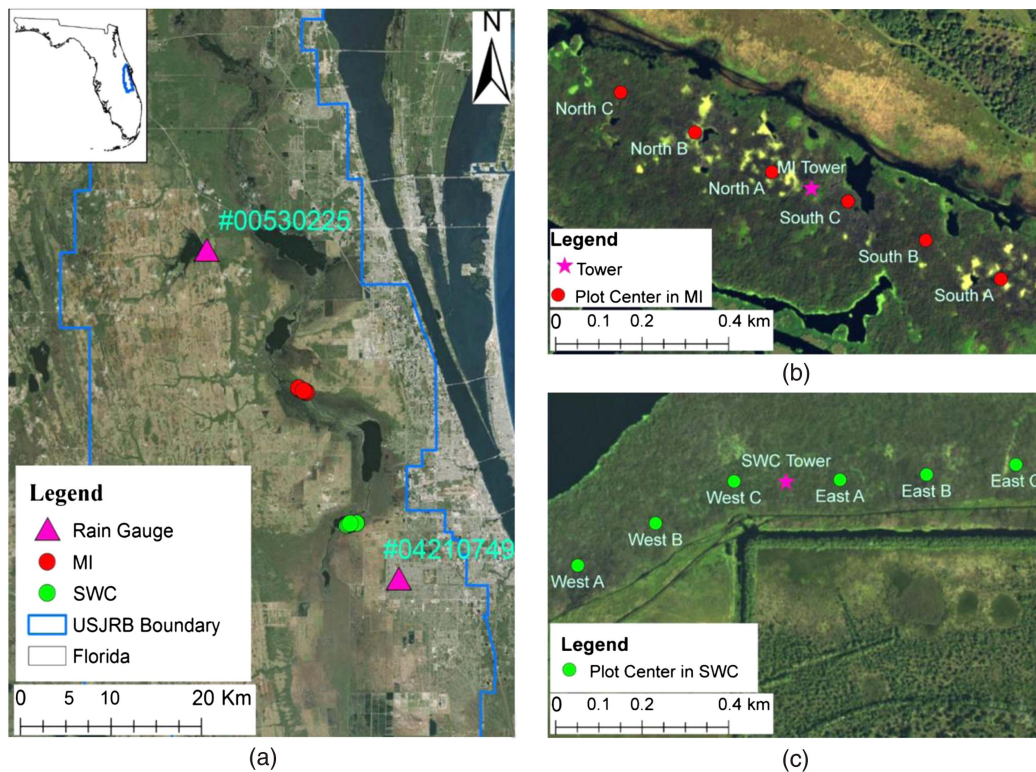
<sup>7</sup>Associate Professor, Dept. of Biology, Univ. of Central Florida, 4000 Central Florida Blvd., P.O. Box 162450, Orlando, FL 32816.

Note. This manuscript was submitted on August 15, 2017; approved on March 14, 2018; published online on June 18, 2018. Discussion period open until November 18, 2018; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Hydrologic Engineering*, © ASCE, ISSN 1084-0699.

Over the last 40 years, altered hydroperiods, reduced fire frequency, and other changes to the ecological disturbance regime allowed Carolina willow (*Salix caroliniana Michx.*), a native deciduous shrub or small tree, to invade areas that historically were herbaceous marshes in the Upper St. Johns River basin (USJRB) of east-central Florida, United States (Hall 1987; Ponzio et al. 2006; Quintana-Ascencio et al. 2013). Conversion of herbaceous marshes into willow swamps limits recreational activities like boating, fishing, and duck hunting, and reduces the fuel load needed to sustain prescribed burns. More alarming, however, is the potential for Carolina willow to reduce water availability through its high transpiration rate, which is about twice as high as the herbaceous vegetation it replaces (Doody et al. 2009).

To address the ecological and hydrological consequences of Carolina willow invasion, vegetation management such as mechanical removal, hydroperiod manipulation, and herbicide use may be required (Castro-Morales et al. 2014; Chee et al. 2016; Nicholson et al. 2012; Ponzio et al. 2006; Quintana-Ascencio et al. 2013; Wilkinson et al. 2013). Changes in vegetation may alter evapotranspiration (ET) by orders of magnitude (Bosch and Hewlett 1982). Previous studies evaluated effects of vegetation change on ET at different temporal and spatial scales (e.g., Donohue et al. 2007; Zhang et al. 2001). Correspondingly, methods have been developed to measure (e.g., eddy covariance measurements and lysimeters) or estimate (e.g., models) ET rates.

Several equations estimate the short-term ET rate (Bai et al. 2016; Choudhury 1997; Jensen et al. 1990; Monteith 1981; Zhang et al. 2016). The Penman-Monteith (PM) equation usually provides results consistent with direct ET measurements from flux towers and other field measurements, especially for well-watered and stressed canopies (Cleugh et al. 2007; Jensen et al. 1990; Leuning et al. 2008; Mu et al. 2007) such as willow swamps. The PM equation was introduced by Penman to estimate open water evaporation (Penman 1948) and extended by Monteith to include canopy



**Fig. 1.** (a) Locations of MI and SWC in the USJRIB; (b) plot centers in MI North and MI South blocks and the weather tower; and (c) plot centers in SWC East and SWC West blocks and the weather tower.

resistance to evaporation (Monteith 1965). It is an efficient tool for estimating ET from vegetation-covered surfaces (Stanhill 2002) and was recommended by the Food and Agriculture Organization to calculate the ET of crops (Allen et al. 1998).

On the long-term scale, annual ET at the catchment scale primarily depends on annual precipitation ( $P$ ) and atmospheric water demand (Oidekop 1911; Schreiber 1904). Atmospheric water demand can be computed by potential evaporation or energy supply represented by water equivalent of net radiation ( $R_n$ ) for a moist surface (Budyko 1958; Choudhury 1999). Various deterministic or parametric Budyko-type equations describe that relationship (e.g., Budyko 1958; Choudhury 1999; Dooge 1992; Yang et al. 2008; Zhang et al. 2004). Wang and Tang (2014) derived a one-parameter Budyko equation by applying a proportionality relationship, generalized from the Soil Conservation Services (SCS) curve number method (US Department of Agriculture SCS 1972), to the partitioning of annual precipitation. These parsimony models provide practical tools to quantify annual ET and evaluate its long-term responses to landscape change (e.g., deforestation and vegetation management).

The objectives of this case study were to (1) evaluate the effects of experimentally removing Carolina willow on daily ET, and (2) develop a single-parameter, annual ET model for quantifying the long-term response of ET to willow management. Results of this study compare the daily ET rates and seasonality of willow growth and ET, and estimate a parameter for an annual ET model.

## Field Experiment and Data Collection

### Field Experiment

A two-year experiment was implemented at two sites, Moccasin Island (MI) and Sweetwater Canal (SWC), along the USJR in

Florida [Fig. 1(a)] using a randomized complete block design (Clewer and Scarisbrick, 2001) with two blocks per site (i.e., four repeats in total). Each block contained three square ( $150 \times 150$  m) plots with a 50-m buffer between adjacent plots. Two plots within each block were selected at random and sprayed by helicopter with herbicides. The remaining plot was untreated and served as a control [Fig. 1(b)]. Herbicides were applied in two years: first in August 2014, and again in July 2015. Plots treated by Clearcast (BASF Corporation, Research Triangle Park, North Carolina) were sprayed in both years (denoted as “C-C-treated”) whereas the other herbicide treatment used Aquasweep (Nufarm Americas Inc., Burr Ridge, Illinois) in 2014 and Ecomazapyr (Alligare, LLC, Opelika, Alabama) in 2015 (“A-E-treated”); Table 1). Plots were sprayed in back-to-back years because willows resprouted the first spring after spraying, but not after the second herbicide treatment.

### Data Collection

One weather station (HOBO U30 USB Weather Station, Onset Computer Corporation, Bourne, Massachusetts) at  $\sim 2$ -m height was installed at the center of each plot, and one weather tower at  $\sim 7$ -m height was installed midway between blocks at each site [Figs. 1(b and c)]. Towers were installed atop a telescoping antenna mast sleeved inside a steel pipe anchored in 45.4 kg (100 lb) of concrete, and were guyed to the base of nearby willows. Weather towers remained operational during Hurricane Matthew, which made landfall on October 7, 2016, but the below-canopy weather stations were removed beforehand to prevent damage from downed willows.

Air temperature ( $T$ ), solar radiation ( $R_s$ ), relative humidity ( $R_h$ ), and wind speed ( $U$ ) were recorded at 30-minute intervals from July 1, 2014, to August 31, 2016, on each weather station and weather tower. Over the entire period, missing data for these meteorological variables due to sensor failure were less than 5%.

**Table 1.** Herbicides applied on treatment plots and dates of application

Plot type	Plot name	First treatment		Second treatment	
		Date	Herbicide	Date	Herbicide
A-E-treated	North A, South A, East B, West A	8/21/2014	Aquasweep	7/15/2016	Ecomazapyr
C-C-treated	North B, South C, East C, West C	8/21/2014	Clearcast	7/15/2016 or 7/21/2016	Clearcast

Note: See Fig. 1 for plot locations.

**Table 2.** Latitude ( $\varphi_i$ ) and height ( $z_{mi}$ ) of weather stations and towers, and the calibrated extinction coefficient ( $k$ ) of Eq. (4) for each plot along the St. Johns River

Name	$\varphi_i$ (°N)	$z_{mi}$ (m)	$k$
North A	28.20	1.88	0.30
North B	28.20	1.92	0.14
<b>North C</b>	28.20	1.87	0.18
South A	28.20	1.89	0.44
<b>South B</b>	28.20	1.89	0.31
South C	28.20	1.88	0.26
<b>East A</b>	28.07	1.82	0.39
East B	28.07	1.84	0.40
East C	28.07	1.93	0.50
West A	28.07	1.88	0.22
<b>West B</b>	28.07	1.89	0.29
West C	28.07	1.94	0.28
Tower in MI	28.20	7.00	—
Tower in SWC	28.07	7.94	—

Note: The four unsprayed control plots are highlighted in bold.

Linear interpolation was used to fill data gaps. Daily values of mean, maximum, and minimum  $T$ ,  $R_s$ ,  $U$ , and  $R_h$  were computed from the 30-minute sampling records. Latitude ( $\varphi_i$ ) and height ( $z_{mi}$ ) of each weather station and weather tower were measured during sensor installation (Table 2). Heights of willow stands within a 7-m radius of each plot center were measured with telescoping rods or retractable measuring tapes in September 2014. Mean willow height ( $h_c$ ) was 4.2 m for MI North, 4.6 m for MI South, 4.8 m for SWC East, and 5.1 m for SWC West. Canopy fractional coverage ( $C_w$ ) was measured with a spherical crown densiometer (Forestry Suppliers, Jackson, Mississippi) in six random locations within each subplot in April 2015 and 2016.

Daily potential evapotranspiration ( $E_p$ ) for 2014–2015 was obtained from the Caribbean-Florida Water Science Center at the U.S. Geological Survey (USGS). Daily  $E_p$  was computed by the Priestley-Taylor (PT) equation based on Geostationary Operational Environmental Satellites (GOES) with a spatial resolution of 2 km (Jacobs et al. 2008). The  $E_p$  data for pixels covering the four experimental blocks were extracted: pixel (28.20°N, 80.83°W) for MI North, pixel (28.20°N, 80.81°W) for MI South, pixel (28.08°N, 80.76°W) for SWC East, and pixel (28.08°N, 80.77°W) for SWC West. Daily precipitation from rain gauges #0530225 (near MI) and #04210749 (near SWC) were provided by the St. Johns River Water Management District [triangles in Fig. 1(a)]. The annual value of flux variable (e.g., precipitation) referred to a water year (September 1st to August 31st) and was aggregated from daily values. Means and standard deviations for each type of treatment (e.g., control plots) were calculated to quantify mean responses and their uncertainties, which are vital for ecological forecasting (Clark et al. 2001, Nilsson et al. 2003).

## Methods

Daily ET estimations were computed using the PM equation, and ET seasonality was analyzed based on monthly ET means from

daily values. A one-parameter Budyko equation was developed to model annual ET as a function of willow fractional coverage.

### Daily Evapotranspiration by the Penman-Monteith Equation

Daily evapotranspiration on each plot was computed by the Penman-Monteith equation (Allen et al. 1998; Monteith 1965) as follows:

$$\lambda ET = [\Delta(R_n - G) + \rho_a c_p (e_s - e_a) / r_a] / [\Delta + \gamma(1 + r_s / r_a)] \quad (1)$$

where ET = estimated daily actual evapotranspiration (mm day<sup>-1</sup>);  $\lambda$  = latent heat of vaporization (MJ kg<sup>-1</sup>), which depends on temperature;  $\Delta$  represents the slope of the relationship between saturation vapor pressure and air temperature (kPa °C<sup>-1</sup>);  $R_n$  = daily net radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), which is the difference between net longwave radiation and net shortwave radiation, and 0.17 is used for albedo considering willow land cover (Blanken and Rouse 1994);  $G$  = ground heat flux, which was assumed to be negligible for daily calculation;  $\rho_a$  = mean air density at constant pressure (kg m<sup>-3</sup>);  $c_p$  = specific heat of air at constant pressure, and the value of  $1.013 \times 10^{-3}$  (MJ kg<sup>-1</sup> °C<sup>-1</sup>) was recommended by Allen et al. (1998);  $e_s$  = saturation water vapor pressure at a given air temperature (kPa);  $e_a$  = actual water vapor pressure (kPa), which is derived from  $e_s$  and  $R_h$ ;  $\gamma$  = psychrometric constant (kPa °C<sup>-1</sup>);  $r_a$  = aerodynamic resistance (s m<sup>-1</sup>), which determines transfer of heat and water vapor from the evaporating surface into the air above the canopy; and  $r_s$  = bulk surface resistance for vapor flow through the land surface (s m<sup>-1</sup>).

### Aerodynamic Resistance

The aerodynamic resistance ( $r_a$ ) to heat transfer from the surface to the air above the canopy (e.g., at the towers) depends on wind speed and land surface roughness, which is affected by vegetation height and the amount of foliage. When vegetation height is more than 0.7 m, foliage roughness accounts for a small portion of surface roughness (Antonarakis et al. 2010; Järvelä 2004). Because Carolina willows were ~4- to 6.5-m tall, the effect of herbicides on surface roughness was assumed to be negligible. Therefore, the variable  $r_a$  was approximated under neutral stability conditions (Brutsaert and Stricker 1979; Garratt and Hicks 1973) as

$$r_a = \ln[(z_m - d) / z_{om}] \ln[(z_h - d) / z_{oh}] / k^2 / u_z \quad (2)$$

where  $z_m$  = height of wind measurements (m);  $z_h$  = height of humidity measurements (m), and both  $z_m$  and  $z_h$  are approximated to the height of wind speed measurement at the towers in this study;  $d$  = zero plane displacement height (m);  $z_{om}$  = roughness height governing momentum transfer (m);  $z_{oh}$  = roughness height governing transfer of heat and vapor (m);  $u_z$  = wind speed measured at the towers (m s<sup>-1</sup>); and  $k$  = von Karman's constant and equals 0.41 (dimensionless). According to Allen et al. (1989),  $z_{om}$  is ten times  $z_{oh}$ . The parameter  $z_{om}$  was estimated as 0.123 times  $h_c$ , which is mean vegetation height; therefore,  $z_{oh}$  was computed



as  $0.0123 h_c$ . Displacement height  $d$  is defined as the height at which mean wind velocity is zero due to large obstacles such as canopy and grass surface. The value of  $d$  was designated as 0.9 times the height of weather stations below canopy (i.e.,  $d = 0.9z_{m,below}$ ) since measured mean daily wind speed was  $1 \text{ m s}^{-1}$  at the towers and  $0.1 \text{ m/s}$  at the below-canopy weather stations.

### Surface Resistance

Surface resistance was estimated as the canopy resistance for well-watered, actively growing willow stands (Allen et al. 1989) as follows:

$$r_s = 2r_l/\text{LAI} \quad (3)$$

where  $r_l$  = mean value of minimum daytime stomatal resistance for a single leaf; and LAI = leaf area index ( $\text{m}^2$  of leaf area per  $\text{m}^2$  of soil surface). Minimum stomatal resistance of willow without water stress is about  $100 \text{ s m}^{-1}$  (Glenn et al. 2008), which is close to the value for alfalfa and some grasses (Monteith 1965, 1981). Szeicz and Long (1969) recommended one-half leaf area as effective in evapotranspiration because typically the upper half of dense vegetation surface receives the most net radiation. Allen et al. (1989) defined the half of LAI as the active (sunlit) leaf area index for estimating reference evapotranspiration.

The LAI for willow stands varied with time, vegetation height, and treatment. Therefore, daily LAI values were estimated for each experimental plot using measured solar radiation above and below the canopy. The LAI is based on the inverse of the expanded Beer-Lambert equation (Bréda 2003; Monsi and Saeki 1953) as follows:

$$\text{LAI} = -(1/k) \ln(I/I_0) \quad (4)$$

where  $I$  = solar radiation transmitted below canopy ( $\text{MJ m}^{-2} \text{ day}^{-1}$ );  $I_0$  = above-canopy solar radiation measured at the towers ( $\text{MJ m}^{-2} \text{ day}^{-1}$ ); and  $k$  is the extinction coefficient, which is dimensionless and can be calibrated based on direct measurements of LAI by allometry or litter fall (Burton et al. 1991; Smith et al. 1991; Vose and Swank 1990). The temporal variation of LAI was described by the ratio  $I:I_0$ , and  $k$  was calibrated by matching mean estimated daily LAI during July 1–31, 2014, from Eq. (4) to a reported value of LAI for July (Schaeffer et al. 2000, 3.2, p. 269, Fig. 10).

### Seasonal Variation in LAI and ET

Monthly ET and LAI were estimated by averaging daily values; then, the effects of willow removal on seasonality of LAI and ET were evaluated. Based on observed data for control plots and previous studies (Berghuijs et al. 2014; Li et al. 2017; Milly 1994), the intra-annual variability of ET and LAI follows a simple sine curve and can be modeled as follows:

$$\text{LAI}(t) = \overline{\text{LAI}}[1 + \delta_{\text{LAI}} \sin(2\pi(t - s_{\text{LAI}})/\tau_{\text{LAI}})] \quad (5)$$

$$\text{ET}(t) = \overline{\text{ET}}[1 + \delta_{\text{ET}} \sin(2\pi(t - s_{\text{ET}})/\tau_{\text{ET}})] \quad (6)$$

where  $\text{LAI}(t)$  = leaf area index as a function of  $t$ , with the time-mean value of  $\overline{\text{LAI}}$ ;  $\text{ET}(t)$  = evapotranspiration as a function of  $t$ , with the time-mean value of  $\overline{\text{ET}}$ ;  $\delta$  = dimensionless seasonal amplitude;  $t$  = time (days);  $s$  = phase shift (days) for LAI or ET; and  $\tau$  = duration of the seasonal cycle (days). Duration of the seasonal cycle is 1 year (i.e.,  $\tau_{\text{LAI}} = \tau_{\text{ET}} = 365$ ). The variables  $\tau$  and  $\delta$  were estimated by minimizing the squared errors between observed and modeled values from Eqs. (5) and (6). The coefficient of determination ( $R^2$ ), which reflects the goodness of the model, was

computed by comparison with the observed monthly time series. Additionally, to understand the controlling factors on the seasonality of ET, the correlation coefficients ( $r$ ) between mean monthly ET and mean monthly LAI,  $R_n$ , and  $P$  were calculated.

### Comparing Evapotranspiration among Treatments

The cumulative ET difference between control and treated plots was calculated. The entire study period was divided into five sections: (1) pretreatment, July 1, 2014, to August 21, 2014; (2) the first nongrowing season after the first herbicide application, which spanned November 1, 2014, to March 31, 2015; (3) the first growing season, April 1, 2015, to October 31, 2015, when willows re-leafed after herbicide application; (4) the second nongrowing season, November 1, 2015, to March 31, 2016; and (5) the second growing season, April 1, 2016, until August 31, 2016, when willows did not recover from herbicide treatments. The cumulative ET differences among five time sections were compared.

### Annual Evapotranspiration Model

The annual ET model is based on a one-parameter Budyko equation derived by Wang and Tang (2014). Annual  $E_p$  in their model was estimated by the water equivalent of net radiation (Budyko 1958; Choudhury 1999) as follows:

$$\text{ET} = \left[ P + R_n - \sqrt{(P + R_n)^2 - 4\varepsilon(2 - \varepsilon)P \times R_n} \right] / [2\varepsilon(2 - \varepsilon)] \quad (7)$$

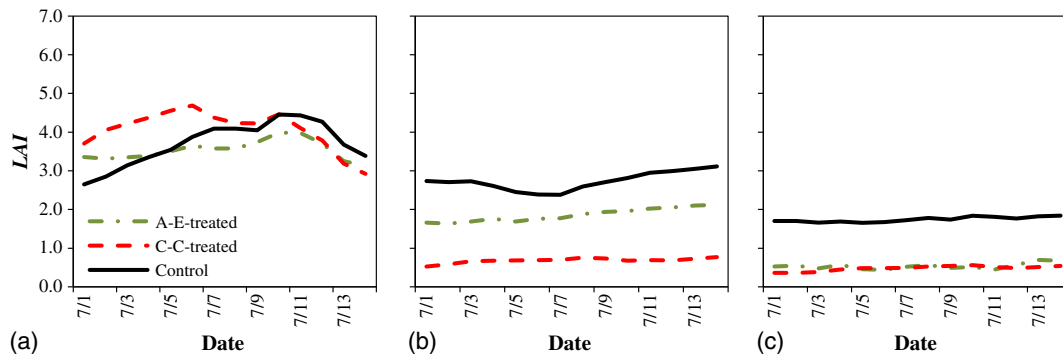
where ET = annual evapotranspiration;  $P$  = annual rainfall;  $R_n$  = water equivalent of annual net radiation; and  $\varepsilon$  = model parameter that represents the control of landscape characteristics on ET. The parameter  $\varepsilon$  ranges from 0 to 1, with  $\varepsilon = 0$  corresponding to the lower bound of ET and  $\varepsilon = 1$  to the upper bound of ET. The value of  $\varepsilon$  can be calculated by substituting annual  $P$ ,  $R_n$ , and ET during the study period into Eq. (7). Annual  $P$  was obtained from daily data measured at rain gauges [Fig. 1(a)]. Annual  $R_n$  is the annual value of the water equivalent of net radiation. Daily ET estimations by the Penman-Monteith equation were aggregated to produce annual ET.

## Results

### Daily Evapotranspiration by the Penman-Monteith Equation

#### Leaf Area Index

The calibrated extinction coefficient  $k$  [Eq. (4)] varied among the twelve plots from 0.14 in North B to 0.50 in East C; the mean value was 0.31 (Table 2). During the pretreatment period (July 1–14, 2014), differences in daily LAI among plots were small [Fig. 2(a)]. After the first herbicide application, the July 1–14, 2015, LAI in control plots, which were not sprayed with herbicide, was larger than in treated plots, especially those sprayed with Clearcast [C-C-treated plots, Fig. 2(b)]. After the second herbicide treatment in 2016, July 1–14 LAI was still the largest in control plots, but differences between treated plots were smaller [Fig. 2(c)]. Mean daily LAI values with uncertainties (standard deviation) from September 1, 2014, to August 31, 2016, were  $2.1 \pm 0.6$  for control plots,  $1.3 \pm 0.5$  for the A-E-treated plots, and  $1.0 \pm 0.4$  for the C-C-treated plots. Mean daily LAI values during the growing season were  $2.4 \pm 0.4$  for control plots,  $1.4 \pm 0.3$  for the A-E treatment, and  $1.0 \pm 0.2$  for the C-C-treated plots. Mean daily



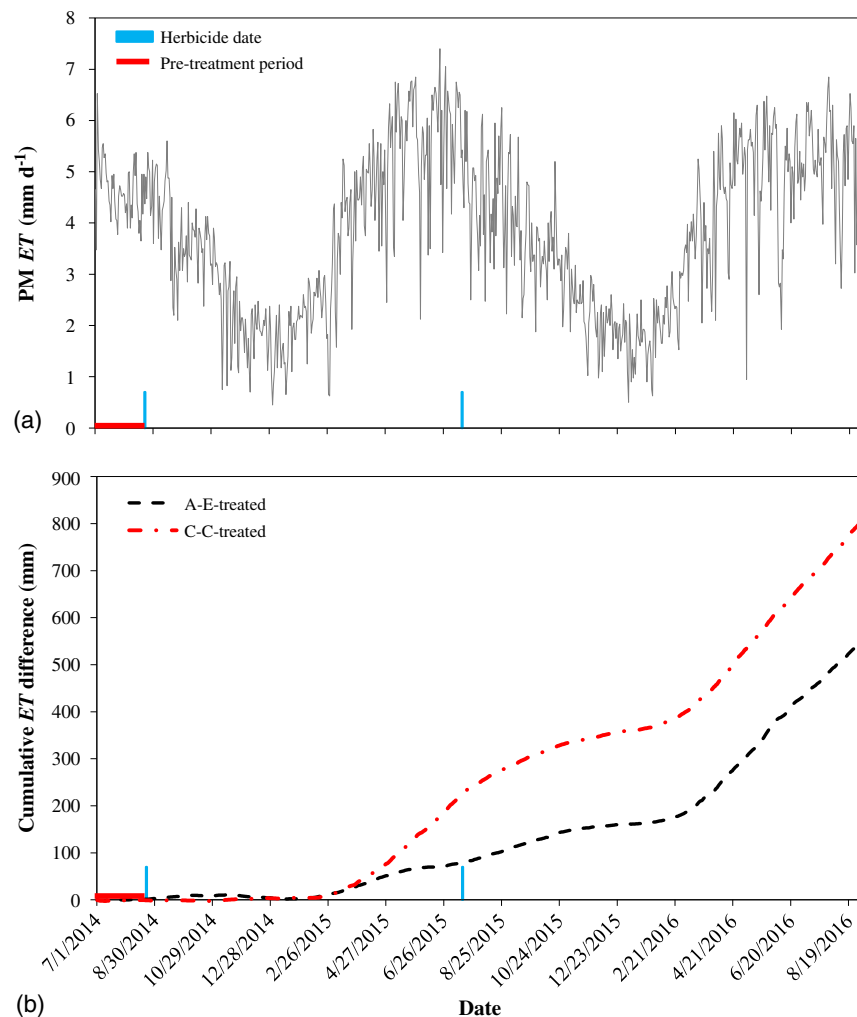
**Fig. 2.** Estimated daily leaf area index averaged over the control plots and plots treated by A-E and C-C during July 1–14 in (a) 2014 (pretreatment); (b) 2015 (after the first treatment); and (c) 2016 (after the second treatment).

LAI values during the nongrowing season were  $1.6 \pm 0.3$  for control plots,  $1.3 \pm 0.4$  for the A-E treatment, and  $1.0 \pm 0.3$  for the C-C-treated plots.

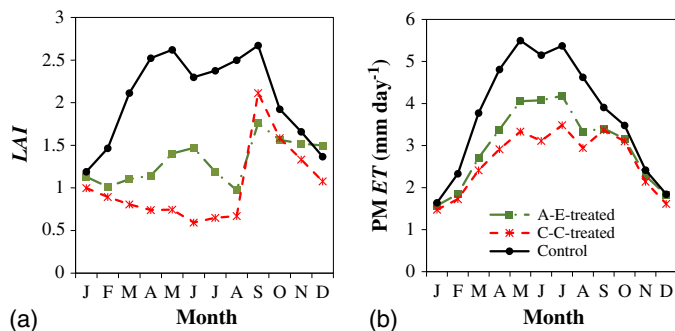
### Aerodynamic Resistance and Surface Resistance

Heights (e.g.,  $z_m$ ,  $z_h$ , and  $d$ ) can be considered constant for each plot, and differences among plots were less than 0.9 m [Eq. (2)].

The spatial variation of wind speed above canopy was relative small; mean wind speed was  $1.0 \text{ m s}^{-1}$  at both the MI and SWC towers. Thus, temporal variation of  $r_a$  was mainly driven by variation of wind speed above canopy, and the spatial variation of  $r_a$  can be negligible. Mean wind speed in the growing season (April to October) (i.e.,  $0.8 \text{ m s}^{-1}$ ) was lower than in the nongrowing season ( $1.2 \text{ m s}^{-1}$ ). Correspondingly,  $r_a$  was larger in the growing season



**Fig. 3.** (a) Computed daily Penman-Monteith ET averaged over the control plots; and (b) averaged cumulative difference (control minus treated) of daily ET during July 1, 2014, to August 31, 2016, over A-E-treated and C-C-treated plots. Vertical lines indicate herbicide application dates. Horizontal lines indicate the pretreatment period.



**Fig. 4.** (a) Mean monthly leaf area index; and (b) mean monthly ET computed by PM equation during September 1, 2014, to August 31, 2016, over the control plots and A-E-treated and C-C-treated plots.

**Table 3.** Correlation coefficients between mean monthly evapotranspiration and mean monthly leaf area index, mean monthly net radiation, and mean monthly precipitation

Plot type	LAI	Net radiation ( $R_n$ )	Precipitation ( $P$ )
Control	<b>0.91</b>	<b>0.99</b>	0.47
A-E-treated	0.17	<b>0.95</b>	0.44
C-C-treated	0.04	<b>0.87</b>	0.41

Note: The correlation coefficients with  $p$ -values less than 0.05 are highlighted in bold.

than in the nongrowing season. Minimum wind speed at the towers was  $0.7 \text{ m s}^{-1}$  in September, and the maximum wind speed was  $1.5 \text{ m s}^{-1}$  in February. Estimated  $r_a$  ranged from  $56 \text{ s m}^{-1}$  in February to  $110 \text{ s m}^{-1}$  in September. The typical  $r_a$  value for willow canopy is about  $50 \text{ s m}^{-1}$  at a wind speed of  $1 \text{ m s}^{-1}$  and about  $150 \text{ s m}^{-1}$  at a wind speed of  $0.7 \text{ m s}^{-1}$  (Lindroth 1993).

Willow surface resistance for each plot was computed by substituting the daily LAI in Eq. (3). Variability of  $r_s$  among plots was mainly due to variation in LAI. For control plots, mean monthly  $r_s$  over blocks ranged from  $83 \text{ s m}^{-1}$  in September to  $200 \text{ s m}^{-1}$  in January. In the A-E treatment,  $r_s$  ranged from  $149 \text{ s m}^{-1}$  in September to  $283 \text{ s m}^{-1}$  in August; in the C-C treatment,  $r_s$  ranged from  $182 \text{ s m}^{-1}$  in September to  $438 \text{ s m}^{-1}$  in June. The reported  $r_s$  for willow from Bowen ratio measurements ranged from 40 to  $1,000 \text{ s m}^{-1}$ , which corresponds to variation in LAI from 6 to 0.2 (Lindroth 1993). The recommended  $r_s$  value for 95% coverage of herbaceous marsh in the Everglades of Florida, United States, is  $52 \text{ s m}^{-1}$  (Jacobs et al. 2008).

#### Daily Evapotranspiration by the Penman-Monteith Equation

Daily ET values from July 1, 2014, to August 31, 2016, computed by the PM equation varied from  $0.3$  to  $7.4 \text{ mm day}^{-1}$ . Mean daily ET was  $3.7 \pm 0.1 \text{ mm day}^{-1}$  for control plots, with maximum values of  $5.5 \pm 0.6 \text{ mm day}^{-1}$  in May [Fig. 3(a)]. In comparison, mean daily ET for herbaceous marsh in the Everglades of south Florida

was  $3.9 \pm 0.1 \text{ mm day}^{-1}$  (Jacobs et al. 2008). The reported transpiration rate of willow in riparian regions was  $6.0 \pm 0.5 \text{ mm day}^{-1}$  during the growing season (Hall et al. 1998).

#### Comparing Evapotranspiration among Treatments

The difference among treatments in daily ET rate was close to zero during the pretreatment period. Treatments also had similar daily ET rates during the nongrowing season after the first herbicide application. Starting from the first growing season, the daily ET difference increased substantially for C-C-treated plots but increased relatively less for A-E-treated plots. During the second nongrowing and growing seasons, the ET change rates were similar for both A-E-treated and C-C-treated plots. Compared with the first growing season, the ET difference for A-E-treated plots increased substantially during the second growing season.

#### Seasonal Variations of LAI and ET

Consequently, seasonal variation in LAI in treated plots, especially the C-C treatment, differed from the control plot [Fig. 4(a)]. The  $R^2$  between observed monthly LAI and values predicted by the sine model [Eq. (5)] was 0.78 for control plots, 0.29 for the A-E treatment, and 0.53 for the C-C treatment. The small values of  $R^2$  indicate that the simple sine model [Eq. (5)] had poor performance predicting the intra-annual variability of LAI in treated plots. The seasonal variations in ET were similar in both the control and treated plots [Fig. 4(b)]. The  $R^2$  between observed and modeled monthly ET [Eq. (6)] for all treatments was higher than 0.80.

The correlation coefficients ( $r$ ) between mean monthly ET and LAI was 0.91 in control plots, 0.17 for A-E-treated plots, and 0.04 for C-C-treated plots. The values of  $r$  between mean monthly ET and  $R_n$  for all treatments was higher than 0.85, and the values of  $r$  between mean monthly ET and  $P$  for all treatments was around 0.4 (Table 3).

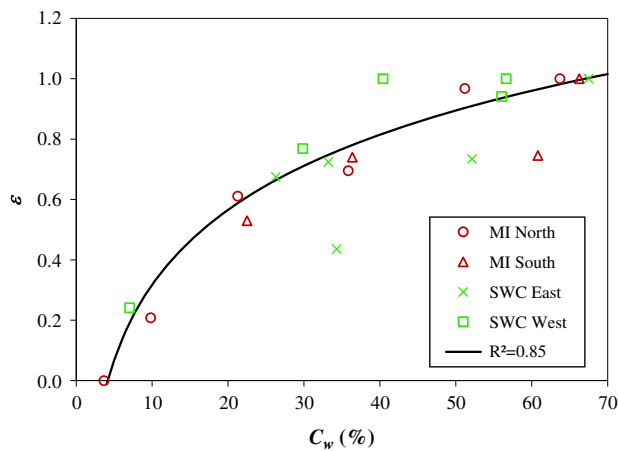
#### Estimated Parameter of Annual Evapotranspiration Model

The aggregated annual ET from the 12 plots in the two years of the study varied from  $575 \text{ mm year}^{-1}$  to  $1,519 \text{ mm year}^{-1}$ . The mean annual ET rate was  $1,368 \pm 51 \text{ mm year}^{-1}$  for control plots,  $1,096 \pm 137 \text{ mm year}^{-1}$  for the A-E-treated plots, and  $968 \pm 117 \text{ mm year}^{-1}$  for the C-C-treated plots. Based on annual ET, the parameter ( $\varepsilon$ ) of the annual ET model [Eq. (7)] was computed, and a strongly positive linear correlation (i.e.,  $r = 0.85$ ,  $p < 0.01$ ) existed between  $\varepsilon$  and  $C_w$ . A natural-logarithm curve was fit to the scatters in the  $\varepsilon$  and  $C_w$  space (Fig. 5) as follows:

$$\varepsilon = 0.34 \ln(C_w) - 0.48 \quad (8)$$

The  $R^2$  of the fitted curve (i.e., the solid line in Fig. 5) was 0.85, which indicated that the  $\varepsilon$  predicted by Eq. (8) explained 85% of the variation in the estimated  $\varepsilon$  among the 12 plots. Substituting Eq. (8) into Eq. (7), an empirical annual ET model can be obtained as follows:

$$ET = \left\{ P + R_n - \sqrt{(P + R_n)^2 - 4[0.34 \ln(C_w) - 0.48][2.48 - 0.34 \ln(C_w)]P \times R_n} \right\} / \{2[0.34 \ln(C_w) - 0.48][2.48 - 0.34 \ln(C_w)]\} \quad (9)$$



**Fig. 5.** The relationship between parameter  $\varepsilon$  of the Budyko model [Eq. (7)] and the willow fractional coverage in April ( $C_w$ ) in 2015 and 2016 was fitted by  $\varepsilon = 0.34 \ln(C_w) - 0.48$  [Eq. (8)].  $R^2$  evaluates the goodness of the fitted curve to the individual data points.

## Discussion

### Uncertainties and Performance of Daily ET Estimation

The Penman-Monteith equation captured the detailed physical processes of ET (Cleugh et al. 2007; Leuning et al. 2008); however, a large number of parameters and inputs were required to accurately estimate daily ET (Beven 1979; Jacobs et al. 2008). Although the empirical equations used to estimate parameters and their applicability to local sites may bring uncertainties (Mu et al. 2007), some parameters commonly assumed to be constant (e.g., roughness height and albedo) were also sensitive to changes in land surface, such as defoliation and death of willows (Lindroth 1993). Additionally, the “big leaf” assumption of the PM equation, which applies to uniform and dense vegetation surfaces (Monteith 1965), was undermined by treatments that cause sparse surfaces, such as herbiciding and mechanical removal. Few herbicides might reach the control plots due to the aerial spray, which may cause the differences in ET between the control and treated plots to be underestimated. The daily ET estimates in this study were similar to the USGS satellite-based  $E_p$  by the PT equation in corresponding pixels with a correlation coefficient of 0.91 ( $r = 0.91$ ,  $p$ -value < 0.05).

### Impact of Willow Removal on ET

In this study, the effect of vegetation change on ET was quantified using the randomized complete block design of the field experiment, which minimized and accounted for nonvegetation factors. After the herbicide application, woody vegetation growth was inhibited, and the leaf area index decreased substantially, especially during the growing season (Fig. 2). The lowest ET was in C-C-treated plots ( $2.7 \pm 0.3 \text{ mm day}^{-1}$ ) because willows re-leaved slowly after spraying the first year and suffered near-complete mortality after herbiciding the second year. Estimated ET was moderate in the A-E-treated plots ( $3.0 \pm 0.4 \text{ mm day}^{-1}$ ), where willows regenerated strongly after the initial spraying with Aquasweep but were killed after treatment with Ecomazapyr in the second year. The highest ET was in the control ( $3.7 \pm 0.1 \text{ mm day}^{-1}$ ). Moreover, during the growing season when LAI was relatively large, differences in ET among herbicide treatments and controls were more substantial. ET estimates for Carolina willows obtained in this study were higher than the ET rates previously reported for

herbaceous vegetation such as sawgrass, cattail, and mixed marsh in pasture by as much as 20% (Budny and Benschoter 2016; Jacobs et al. 2008; Mao et al. 2002; McLaughlin et al. 2012).

Seasonality of ET is widely used in the management of irrigation and groundwater pumping in water-deficient regions (Zhang and Oweis 1999). Removing willows affected the magnitude of ET but not its seasonality. The simple sine models [Eqs. (5) and (6)] had poor performances of predicting the intra-annual variability of LAI in treated plots but good performances of predicting ET. The correlation coefficients between monthly ET and LAI for the treated plots were much smaller than those for  $R_n$  and  $P$  (Table 3). These results indicated that the seasonal pattern of ET depended on the seasonality of  $R_n$  and  $P$ , but not LAI.

### Tool for Evaluating the Impacts of Herbicides and Climate on Long-Term ET

By dividing the  $P$  on both sides of Eq. (9), a one-parameter Budyko-type equation is obtained. This Budyko framework describes climate ( $R_n/P$ ) control on long-term water balance (Tang and Wang 2017). One-parameter Budyko equations have been used for quantifying the contribution of climate change and land-use change to evapotranspiration changes and long-term stream flow (e.g., Jiang et al. 2015; Roderick and Farquhar 2011; Wang and Hejazi 2011). Therefore, Eq. (9) can be potentially used to evaluate the effect of climate on long-term ET. Other than climate, the controlling factors in this study were mainly restricted to variability in vegetation caused by herbicides. As a result, the correlation was strong between parameter  $\varepsilon$  of the Budyko equation and willow fractional coverage ( $C_w$ ), which quantifies variation in willow leaf area due to herbicides [Eq. (8)]. Therefore, Eq. (9) also can be used to evaluate how herbiciding willows affects long-term ET.

## Conclusion

Changes in ET associated with removing invasive Carolina willows using herbicides were calculated in the USJRB in east-central Florida. Daily ET and annual ET were estimated by the PM equation and Budyko equation, respectively. Herbicide application significantly decreased LAI and ET. Evapotranspiration was higher in control plots than in treatment plots, and differences increased during the growing season. The parameter  $\varepsilon$  of the annual evapotranspiration model derived from a Budyko-type equation strongly correlated with willow fractional coverage in April. Based on this correlation, an empirical Budyko-type relationship was proposed that may provide a useful tool to predict the impact of willow herbicide treatments on long-term annual evapotranspiration in the USJRB, and these results are relevant for riparian zones in other areas invaded by willows across the world.

## Acknowledgments

This research was funded by the St. Johns River Water Management District (SJRWMD). The authors thank Kimberli Ponzio, Cecil Slaughter, Ken Snyder, Randy Snyder, Tim Miller, Dean Dobberfuhl, and many others from the SJRWMD for sharing their experiences and advice. The opinions, findings, and conclusions expressed in this manuscript are those of the authors and not necessarily those of the SJRWMD. The authors also recognize the editor and reviewers for their constructive comments.



## References

- Allen, R. G., M. E. Jensen, J. L. Wright, and R. D. Burman. 1989. "Operational estimates of reference evapotranspiration." *Agron. J.* 81 (4): 650–662. <https://doi.org/10.2134/agronj1989.00021962008100040019x>.
- Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements: FAO irrigation and drainage paper 56*. Rome, Italy: FAO.
- Antonarakis, A. S., K. S. Richards, J. Brasington, and E. Muller. 2010. "Determining leaf area index and leafy tree roughness using terrestrial laser scanning." *Water Resour. Res.* 46 (6): W06510. <https://doi.org/10.1029/2009WR008318>.
- Bai, P., X. Liu, T. Yang, F. Li, K. Liang, S. Hu, and C. Liu. 2016. "Assessment of the influences of different potential evapotranspiration inputs on the performance of monthly hydrological models under different climatic conditions." *J. Hydrometeorol.* 17 (8): 2259–2274. <https://doi.org/10.1175/JHM-D-15-0202.1>.
- Berghuijs, W. R., M. Sivapalan, R. A. Woods, and H. H. G. Savenije. 2014. "Patterns of similarity of seasonal water balances: A window into streamflow variability over a range of time scales." *Water Resour. Res.* 50 (7): 5638–5661. <https://doi.org/10.1002/2014WR015692>.
- Beven, K. 1979. "A sensitivity analysis of the Penman-Monteith actual evapotranspiration estimates." *J. Hydrol.* 44 (3–4): 169–190. [https://doi.org/10.1016/0022-1694\(79\)90130-6](https://doi.org/10.1016/0022-1694(79)90130-6).
- Blanken, P. D., and W. R. Rouse. 1994. "The role of willow-birch forest in the surface energy balance at Arctic treeline." *Arct. Alp. Res.* 26 (4): 403–411. <https://doi.org/10.2307/1551802>.
- Bosch, J. M., and J. D. Hewlett. 1982. "A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration." *J. Hydrol.* 55 (1–4): 3–23. [https://doi.org/10.1016/0022-1694\(82\)90117-2](https://doi.org/10.1016/0022-1694(82)90117-2).
- Bréda, N. J. 2003. "Ground-based measurements of leaf area index: A review of methods, instruments and current controversies." *J. Exp. Bot.* 54 (392): 2403–2417.
- Brutsaert, W., and H. Stricker. 1979. "An advection-aridity approach to estimate actual regional evapotranspiration." *Water Resour. Res.* 15 (2): 443–450. <https://doi.org/10.1029/WR015i002p00443>.
- Budny, M. L., and B. W. Benscoter. 2016. "Shrub encroachment increases transpiration water loss from a subtropical wetland." *Wetlands* 36 (4): 631–638. <https://doi.org/10.1007/s13157-016-0772-5>.
- Budyko, M. I. 1958. *The heat balance of the earth's surface*. Washington, DC: U.S. Dept. of Commerce.
- Burton, A. J., K. S. Pregitzer, and D. D. Reed. 1991. "Leaf area and foliar biomass relationships in northern hardwood forests located along an 800 km acid deposition gradient." *For. Sci.* 37 (4): 1041–1059.
- Castro-Morales, L. M., P. F. Quintana-Ascencio, J. E. Fauth, K. J. Pozzio, and D. L. Hall. 2014. "Environmental factors affecting germination and seedling survival of Carolina willow (*Salix caroliniana*)." *Wetlands* 34 (3): 469–478. <https://doi.org/10.1007/s13157-014-0513-6>.
- Chee, Y. E., L. Wilkinson, A. E. Nicholson, P. F. Quintana-Ascencio, J. E. Fauth, D. Hall, and L. Rumpff. 2016. "Modelling spatial and temporal changes with GIS and spatial and dynamic Bayesian networks." *Environ. Modell. Software* 82: 108–120. <https://doi.org/10.1016/j.envsoft.2016.04.012>.
- Choudhury, B. J. 1997. "Global pattern of potential evaporation calculated from the Penman-Monteith equation using satellite and assimilated data." *Remote Sens. Environ.* 61 (1): 64–81. [https://doi.org/10.1016/S0034-4257\(96\)00241-6](https://doi.org/10.1016/S0034-4257(96)00241-6).
- Choudhury, B. J. 1999. "Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model." *J. Hydrol.* 216 (1): 99–110. [https://doi.org/10.1016/S0022-1694\(98\)00293-5](https://doi.org/10.1016/S0022-1694(98)00293-5).
- Clark, J. S., et al. 2001. "Ecological forecasts: An emerging imperative." *Science* 293 (5530): 657–660. <https://doi.org/10.1126/science.293.5530.657>.
- Cleugh, H. A., R. Leuning, Q. Z. Mu, and S. W. Running. 2007. "Regional evaporation estimates from flux tower and MODIS satellite data." *Remote Sens. Environ.* 106 (3): 285–304. <https://doi.org/10.1016/j.rse.2006.07.007>.
- Clewer, A. G., and D. H. Scarisbrick. 2001. *Practical statistics and experimental design for plant and crop science*, 159–181. New York, NY: Wiley.
- Donohue, R. J., M. L. Roderick, and T. R. McVicar. 2007. "On the importance of including vegetation dynamics in Budyko's hydrological model." *Hydrol. Earth Syst. Sci.* 11 (2): 983–995. <https://doi.org/10.5194/hess-11-983-2007>.
- Doody, T. M., R. G. Benyon, and T. Theiveyanathan. 2009. "Quantifying water savings from willow removal in creeks in south central NSW." Accessed August 26, 2013. [http://www.weeds.org.au/WoNS/willows/docs/Quantifying\\_water\\_savings.pdf](http://www.weeds.org.au/WoNS/willows/docs/Quantifying_water_savings.pdf).
- Dooge, J. C. I. 1992. "Sensitivity of runoff to climate change: A Hortonian approach." *Bull. Am. Meteorol. Soc.* 73 (12): 2013–2024. [https://doi.org/10.1175/1520-0477\(1992\)073<2013:SORTCC>2.0.CO;2](https://doi.org/10.1175/1520-0477(1992)073<2013:SORTCC>2.0.CO;2).
- Garratt, J. R., and B. B. Hicks. 1973. "Momentum, heat and water vapor transfer to and from natural and artificial surfaces." *Q. J. R. Meteorol. Soc.* 99 (422): 680–687. <https://doi.org/10.1002/qj.49709942209>.
- Glenn, E. P., A. R. Huete, P. L. Nagler, and S. G. Nelson. 2008. "Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape." *Sensors* 8 (4): 2136–2160. <https://doi.org/10.3390/s8042136>.
- Hackney, C. T., ed. 2015. *St. Johns river economic study*, 284. Jacksonville, FL: Univ. of North Florida.
- Hall, G. B. 1987. *Establishment of minimum surface water requirements for the greater Lake Washington Basin*, 85. Technical Publication SJ87-3. Palatka, FL: St. Johns River Water Management District.
- Hall, R. L., S. J. Allen, P. T. Rosier, and R. Hopkins. 1998. "Transpiration from coppiced poplar and willow measured using sap-flow methods." *Agric. For. Meteorol.* 90 (4): 275–290. [https://doi.org/10.1016/S0168-1923\(98\)00059-8](https://doi.org/10.1016/S0168-1923(98)00059-8).
- Jacobs, J., J. Mecikalski, and S. Paech. 2008. *Satellite-based solar radiation, net radiation, and potential and reference evapotranspiration estimates over Florida*, 138. Report. South Florida Water Management District.
- Järvelä, J. 2004. "Determination of flow resistance caused by nonsubmerged woody vegetation." *Int. J. River Basin Manage.* 2 (1): 61–70.
- Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. *Evaporation and irrigation water requirement: ASCE manual no. 70*, 332. New York, NY: ASCE.
- Jiang, C., L. Xiong, D. Wang, P. Liu, S. Guo, and C. Y. Xu. 2015. "Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters." *J. Hydrol.* 522: 326–338. <https://doi.org/10.1016/j.jhydrol.2014.12.060>.
- Leuning, R., Y. Q. Zhang, A. Rajaud, H. Cleugh, and K. Tu. 2008. "A simple surface conductance model to estimate regional evaporation using MODIS leaf area index and the Penman-Monteith equation." *Water Resour. Res.* 44 (10): W10419. <https://doi.org/10.1029/2007WR006562>.
- Li, Q., X. Wei, M. Zhang, W. Liu, H. Fan, G. Zhou, K. Giles-Hansen, S. Liu, and Y. Wang. 2017. "Forest cover change and water yield in large forested watersheds: A global synthetic assessment." *Ecohydrology* 10 (4): e1838. <https://doi.org/10.1002/eco.1838>.
- Lindroth, A. 1993. "Aerodynamic and canopy resistance of short-rotation forest in relation to leaf area index and climate." *Bound.-Layer Meteorol.* 66 (3): 265–279. <https://doi.org/10.1007/BF00705478>.
- Mao, L. M., M. G. Bergman, and C. C. Tai. 2002. "Evapotranspiration measurement and estimation of three wetland environments in the upper St. Johns River basin, Florida." *J. Am. Water Resour. Assoc.* 38 (5): 1271–1285. <https://doi.org/10.1111/j.1752-1688.2002.tb04347.x>.
- McLaughlin, D. L., M. T. Brown, and M. J. Cohen. 2012. "The ecology of a pioneer wetland species and a drastically altered landscape." *Ecohydrology* 5: 656–667.
- Milly, P. C. D. 1994. "Climate, soil water storage, and the mean annual water balance." *Water Resour. Res.* 30 (7): 2143–2156. <https://doi.org/10.1029/94WR00586>.
- Monsi, M., and T. Saeki. 1953. "The light factor in plant communities and its significance for dry matter production." *Jpn. J. Bot.* 14 (1): 22–52.
- Monteith, J. L. 1965. "Evaporation and environment." *Symp. Soc. Exp. Biol.* 19 (205–223): 205–234.



- Monteith, J. L. 1981. "Evaporation and surface temperature." *Q. J. R. Meteorol. Soc.* 107 (451): 1–27. <https://doi.org/10.1002/qj.49710745102>.
- Mu, Q., F. A. Heinsch, M. Zhao, and S. W. Running. 2007. "Development of a global evapotranspiration algorithm based on MODIS and global meteorology data." *Remote Sens. Environ.* 111 (4): 519–536. <https://doi.org/10.1016/j.rse.2007.04.015>.
- Nicholson, A. E., Y. En Chee, and P. F. Quintana-Ascencio. 2012. "A state-transition DBN for management of willow in an American Heritage River catchment." In *Proc., 9th Bayesian Modeling Applications Workshop at the Conference of Uncertainty in Artificial Intelligence*, edited by A. Nicholson, J. M. Agosta, and J. Flores, 55–64. Catalina Island, CA.
- Nilsson, C., J. E. Pizzuto, G. E. Moglen, M. A. Palmer, E. H. Stanley, N. E. Bockstael, and L. C. Thompson. 2003. "Ecological forecasting and the urbanization of stream ecosystems: Challenges for economists, hydrologists, geomorphologists, and ecologists." *Ecosystems* 6 (7): 659–674. <https://doi.org/10.1007/s10021-002-0217-2>.
- Ol'dekop, E. M. 1911. "On evaporation from the surface of river basins." *Trans. Meteorol. Obs.* 4: 200.
- Penman, H. L. 1948. "Natural evaporation from open water, bare soil and grass." *Proc. R. Soc. London A: Math. Phys. Eng. Sci.* 193 (1032): 120–145. <https://doi.org/10.1098/rspa.1948.0037>.
- Ponzio, K. J., S. J. Miller, E. Underwood, S. P. Rowe, D. J. Voltolina, and T. D. Miller. 2006. "Responses of a willow (*Salix caroliniana* Michx.) community to roller-chopping." *Nat. Areas J.* 26 (1): 53–60. [https://doi.org/10.3375/0885-8608\(2006\)26\[53:ROAWSC\]2.0.CO;2](https://doi.org/10.3375/0885-8608(2006)26[53:ROAWSC]2.0.CO;2).
- Quintana-Ascencio, P. F., J. E. Fauth, L. M. Castro Morales, K. J. Ponzio, D. Hall, and K. Snyder. 2013. "Taming the beast: Managing hydrology to control Carolina willow (*Salix caroliniana*) seedlings and cuttings." *Restor. Ecol.* 21 (5): 639–647.
- Roderick, M. L., and G. D. Farquhar. 2011. "A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties." *Water Resour. Res.* 47 (12): W00G07. <https://doi.org/10.1029/2010WR009826>.
- Schaeffer, S. M., G. W. David, and D. C. Goodrich. 2000. "Transpiration of cottonwood/willow forest estimated from sap flux." *Agric. For. Meteorol.* 105 (1): 257–270. [https://doi.org/10.1016/S0168-1923\(00\)00186-6](https://doi.org/10.1016/S0168-1923(00)00186-6).
- Schreiber, P. 1904. "Über die Beziehungen zwischen dem Niederchlagund der Wasserführung der Flüsse in Mitteleuropa." *Meteorol. Z.* 21: 441–452.
- Smith, F. W., A. D. Sampson, and N. J. Long. 1991. "Comparison of leaf area index estimates from tree allometrics and measured light interception." *For. Sci.* 37 (6): 1682–1688.
- Stanhill, G. 2002. "Is the Class A evaporation pan still the most practical and accurate meteorological method for determining irrigation water requirements?" *Agric. For. Meteorol.* 112 (3–4): 233–236. [https://doi.org/10.1016/S0168-1923\(02\)00132-6](https://doi.org/10.1016/S0168-1923(02)00132-6).
- Szeicz, G., and I. F. Long. 1969. "Surface resistance of crop canopies." *Water Resour. Res.* 5 (3): 622–633. <https://doi.org/10.1029/WR005i003p00622>.
- Tang, Y., and D. Wang. 2017. "Evaluating the roles of watershed properties on long-term water balance through a four-parameter Budyko equation." *Water Resour. Res.* 53 (5): 4142–4157. <https://doi.org/10.1002/2016WR019920>.
- U.S. Department of Agriculture SCS (U.S. Department of Agriculture Soil Conservation Service). 1972. *National engineering handbook, section 4, hydrology*. Washington, DC: U.S. Government Printing Office.
- Vörösmarty, C. J., et al. 2010. "Global threats to human water security and river biodiversity." *Nature* 467 (7315): 555–561. <https://doi.org/10.1038/nature09440>.
- Vose, J. M., and W. T. Swank. 1990. "Assessing seasonal leaf area dynamics and vertical leaf distribution in eastern white pine (*Pinus strobus* L.) with a portable light meter." *Tree Physiol.* 7 (1-2-3-4): 125–134. <https://doi.org/10.1093/treephys/7.1-2-3-4.125>.
- Wang, D., and M. Hejazi. 2011. "Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States." *Water Resour. Res.* 47 (10): W00J12. <https://doi.org/10.1029/2010WR010283>.
- Wang, D., and Y. Tang. 2014. "A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models." *Geophys. Res. Lett.* 41 (13): 4569–4577. <https://doi.org/10.1002/2014GL060509>.
- Wilkinson, L., Y. E. Chee, A. E. Nicholson, and P. Quintana-Ascencio. 2013. "An object-oriented spatial and temporal Bayesian network for managing willows in an American heritage river catchment." In Vol. 1024 of *Proc., 2013 UAI Conf. on Application Workshops: Big Data Meet Complex Models and Models for Spatial, Temporal and Network Data*, 77–86. Washington, DC.
- Yang, H., D. Yang, Z. Lei, and F. Sun. 2008. "New analytical derivation of the mean annual water-energy balance equation." *Water Resour. Res.* 44 (3): W03410. <https://doi.org/10.1029/2007WR006135>.
- Zhang, H., and T. Oweis. 1999. "Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region." *Agric. Water Manage.* 38 (3): 195–211. [https://doi.org/10.1016/S0378-3774\(98\)00069-9](https://doi.org/10.1016/S0378-3774(98)00069-9).
- Zhang, K., J. S. Kimball, and S. W. Running. 2016. "A review of remote sensing based actual evapotranspiration estimation." *Wiley Interdiscip. Rev. Water* 3 (6): 834–853. <https://doi.org/10.1002/wat2.1168>.
- Zhang, L., W. R. Dawes, and G. R. Walker. 2001. "Response of mean annual evapotranspiration to vegetation changes at catchment scale." *Water Resour. Res.* 37 (3): 701–708. <https://doi.org/10.1029/2000WR900325>.
- Zhang, L., K. Hickel, W. R. Dawes, F. H. S. Chiew, A. W. Western, and P. R. Briggs. 2004. "A rational function approach for estimating mean annual evapotranspiration." *Water Resour. Res.* 40 (2): W02502. <https://doi.org/10.1029/2003WR002710>.