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Evapotranspiration crop coefficients for mixed riparian plant community and transpiration crop coefficients for Common reed, Cottonwood and Peach-leaf willow in the Platte River Basin, Nebraska-USA

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SUMMARY

Application of two-step approach of evapotranspiration (*ET*) crop coefficients (*Kc*) to "approximate" a very complex process of actual evapotranspiration (*ETa*) for field crops has been practiced by water management community. However, the use of *Kc*, and in particular the concept of growing degree days (GDD) to estimate *Kc*, have not been sufficiently studied for estimation of evaporative losses from riparian vegetation. Our study is one of the first to develop evapotranspiration crop coefficient (Kc_{ET}) curves for mixed riparian vegetation and transpiration (*TRP*) crop coefficients (Kc_{TRP}) for individual riparian species as a function GDD through extensive field campaigns conducted in 2009 and 2010 in the Platte River Basin in central Nebraska, USA. Kc_{TRP} values for individual riparian vegetation species [Common reed (Phragmites australis), Cottonwood (Populus deltoids) and Peach-leaf willow (Salix amygdaloides)] were quantified from the *TRP* rates obtained using scaled-up canopy resistance from measured leaf-level stomatal resistance and reference evapotranspiration. The Kc_{ET} and Kc_{TRP} curves were developed for alfalfa-reference (Kcr_{ET} and Kcr_{TRP}) surface. The seasonal average mixed riparian plant community Kcr_{ET} was 0.89 in 2009 and 1.27 in 2010. In 2009, the seasonal average Kcr_{TRP} values for Common reed, Cottonwood and Peach-leaf willow were 0.57, 0.51 and 0.62, respectively. In 2010, the seasonal average Kcr_{TRP} were 0.69, 0.62 and 0.83 for the same species, respectively. In general, *TRP* crop coefficients had less interannual variability than the Kcr_{ET}. Response of the vegetation to flooding in 2010 played an important role on the interannual variability of Kcr_{ET} values. We demonstrated good performance and reliability of developed GDD-based Kcr_{TRP} curves by using the curves developed for 2009 to predict *TRP* rates of individual species in 2010. Using the Kcr_{TRP} curves developed during the 2009 season, we were able to predict the *TRP* rates for Common reed, Cottonwood and Peach-leaf willow in 2010 within 7%, 8% and 13% accuracy, indicating a good performance of the two-step approach proposed in this study for estimating *TRP* for riparian vegetation. The surface conditions of the riparian ecosystem need to be considered when using the two-step approach to estimate *ETa* or *TRP* rates of riparian plant communities. The results of this study provide important water use information and data for riparian vegetation that can be used for more robust hydrologic/water balance analyses.

1. Introduction

Direct measurement of actual evapotranspiration (*ETa*) for riparian vegetation is an extremely challenging and expensive task and there is not a simple and robust method to estimate *ETa* for riparian zones that comprises of very complex biophysical and environmental attributes. Also, direct measurements of *ETa* involving advanced instrumentation and methods such as Bowen ratio energy balance system, eddy covariance system, lysimeters, and surface renewal, require substantial maintenance and skilled personnel. Another approach of quantifying *ETa* for riparian systems is a two-step empirical approach that uses reference evapotranspiration (ET_{ref}) and crop-specific evapotranspiration coefficients (*Kc*). However, there is a lack of information and data on *Kc* values for riparian systems and the accuracy of the two-step approach in estimating *ETa* for riparian ecosystems is essentially not known. In many cases, riparian systems are complex and comprise of

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Nomenclature

BREBS	Bowen ratio energy balance system	Rs	incoming shortwave radiation (MJ m^{-2} d^{-1})
ET_{ref}	reference evapotranspiration (mm/day)	Rn	net radiation (MJ m^{-2} d^{-1})
ETr	alfalfa-reference evapotranspiration (mm/day)	G	soil heat flux (zero for daily time step)
ET	evapotranspiration (mm/day)	Δ	slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1})
ETa	actual evapotranspiration (mm/day)	U_2	average daily wind speed at 2 m height (m s^{-1})
ET_{BREBS}	BREBS-measured actual evapotranspiration (mm/day)	e_s	saturation vapor pressure (kPa)
Kc	crop coefficient (applies to both grass- and alfalfa-reference surfaces)(unitless)	e_a	actual vapor pressure (kPa)
Kc_{ET}	evapotranspiration crop coefficient (unitless)	γ	psychrometric constant (0.0671 kPa °C^{-1})
Kcr_{ET}	alfalfa-reference evapotranspiration crop coefficient (unitless)	$e_s - e_a$	vapor pressure deficit (VPD, kPa)
Kc_{TRP}	transpiration crop coefficient (applies to both grass- and alfalfa-reference surfaces) (unitless)	ρ_a	density of dry air (kg m^{-3})
Kcr_{TRP}	alfalfa-reference transpiration crop coefficient (unitless)	C_p	specific heat of dry air at constant pressure (J kg^{-1} °C^{-1})
$RMSD$	root mean square difference (mm/day)	g_T	total conductance (1/canopy resistance, m s^{-1})
E	Nash–Sutcliffe modeling efficiency coefficient (unitless)	r_a	aerodynamic resistance (s m^{-1})
TRP	transpiration (mm/day or kg m^{-2} s^{-1})	r_c	canopy resistance (s m^{-1})
T	average daily air temperature (°C)	z_m	height of wind measurement (m)
T_{max}	daily maximum air temperature (°C)	z_h	height of humidity measurement (m)
T_{min}	daily minimum air temperature (°C)	d	zero plane displacement height (m)
T_{base}	base temperature (7 °C for Common reed and Peach-leaf willow; 8 °C for Cottonwood)	z_{oh}	roughness length governing transfer of heat and water vapor (m)
GDD	growing degree days (°C)	z_{om}	roughness length governing transfer of momentum (m)
TU	thermal unit (°C)	κ	von Karman's constant (0.41)
RH	relative humidity (%)	u_z	wind speed at height z (m s^{-1})
		LAI	leaf area index (unitless)
		Est	estimated

variety of species, various hydrologic characteristics and the sites may have dry soil surface or open water surface, which makes it further challenging to apply the two-step approach. Thus, there has been a limited application of the two-step approach for estimating riparian zone evaporative fluxes. Further research to measure such coefficients and assess the accuracy of two-step approach in estimating *ETa* for riparian systems is necessary given the great diversity in riparian vegetation species composition and hydrological and environmental conditions. Furthermore, in some cases, rather than the average or total evaporative losses from the mixed riparian zone, it is necessary to quantify the transpiration (*TRP*) rates of individual species in a mixed riparian plant community. Therefore, developing transpiration crop coefficients, rather than using evapotranspiration crop coefficients for riparian vegetation could be a viable approach for quantifying evaporative losses of individual plant species within the complex riparian systems.

Crop coefficients have been used to estimate *ETa* for particular crops from estimates or measurements of ET_{ref} (i.e., $ETa = ET_{ref} \times Kc \times Ks$) [$Ks$ is the soil water stress coefficient, ranging from 0 (maximum stress) to 1 (minimum or no stress)]. ET_{ref} is adjusted by the *Kc* values to obtain an approximation of *ETa* from a given vegetation surface (van Wijk and de Vries, 1954; Jensen et al., 1971; Doorenbos and Pruitt, 1977; Irmak, 2005; Irmak et al., 2008b). ET_{ref} is quantified from models based on measured meteorological observations and is a simplified concept of surface energy balance to represents the atmospheric evaporative demand over a defined reference vegetation surface (Doorenbos and Pruitt, 1977; Irmak et al., 2012). While it has been used in agricultural settings because of its simplicity, the two-step approach is not a physically-based approach that can utterly represents the very complex physics of the evaporative losses from a given surface. Most ET_{ref} equations, including the ASCE-EWRI and FAO-56 equations, are all simplified forms or derivatives of the original work of combination-based energy balance equations that were derived by Penman (1948, 1963) and Monteith (1965). Nevertheless, in many practical applications, the water resources management agencies, planners, and decision-makers need practical approaches that can provide rational data in quantifying water losses from riparian systems.

The crop coefficient curves can be expressed as a function of time (usually date or day of year), plant growth stage, percent effective cover, thermal unit, etc. Plant development is generally dependent on heat units and a physiological growth rate could be developed based on thermal units (*TU*) [(or growing degree-days (*GDD*)] (Sammis et al., 1985; Amos et al., 1989; Irmak, 2005). The concept of *GDD* can improve the description and prediction of plant phenology and development stage as compared with other approaches such as time of the year or number of days (Frank and Hofmann, 1989; McMaster and Wilhelm, 1997). *GDD* is intended to describe the heat energy received/observed by the plant over a given period of time. This is equivalent to integrating the area under the diurnal temperature curve, summing the daily heat energy over an interval of time, and then relating the accumulation of heat energy to progress in plant development. Crop coefficients that are based on *GDD* have been shown to be able to adjust for differences in growth rate due to non-average weather conditions and generally used for agronomic plants (Amos et al., 1989). Sammis et al. (1985) suggested that a *Kc* curves developed for a given location using *GDD* should be applicable in locations with different climatic conditions because *GDD* accounts for differences in plant development rate associated with temperature differences.

While the application of *Kc* to approximate a complex process of *ETa* for field crops has been practiced by irrigation community since early 1960s–1970s, the use of *Kc*, and the concept of *GDD*, in particular, to estimate *Kc* have not been studied for estimation of evaporative losses from riparian vegetation. The objectives of this research were to: (i) measure total evaporative losses from a mixed riparian plant community for two consecutive years (2009 and 2010), (ii) develop "average" alfalfa-reference evapotranspiration crop coefficients (Kcr_{ET}) for a Common reed-dominated, Cottonwood and Peach-leaf willow "mixed" riparian plant community using Bowen ratio energy balance system-measured *ETa* and estimated alfalfa-reference evapotranspiration (*ETr*), (iii) develop alfalfa-reference *TRP* crop coefficients (Kcr_{TRP}) for Common reed, Cottonwood and Peach-leaf willow separately to be able to estimate *TRP* rates for "individual" riparian species, and (iv) evaluate the performance of *TRP* crop coefficient curves developed in 2009 for estimating *TRP* rates of individual riparian species in 2010.

2. Materials and methods

2.1. Research site description

The research site (Figs. 1 and 2) is located in the Platte River Basin in central Nebraska near Central City, in Merrick County, Nebraska. The coordinates of the water and energy flux measurement tower are 41°7.939′N 97°55.52′W with a 507 m above mean sea level. Based on the plant species composition of the experimental site and percent cover identification measurements conducted in 2010, Common reed (*Phragmites australis*) was the dominant species with 55.2% cover. Peach-leaf willow (*Salix amygdaloides*) and Cottonwood (*Populus deltoides*) had 29.3% and 6.7% cover, respectively. Some other plant species such as Purple loosestrife (*Lythrum salicaria*), Sedge (*Carex sp.*), Reed canary (*Phalaris arundinacea*), Swamp smartweed (*Polygonum amphibium*), Wild-indigo (*Amorpha fruticosa*), Annual sunflower (*Helianthus annuus*), and Common cattail (*Typha latifolia*) occupied the remaining 8.8% of the experimental site with each individual species having a minor percent cover. The experimental site is a sand-bar island measuring 508 m long and 120–130 m wide with a northeast orientation in the Platte River formed at a braided area. The two experimental years (2009 and 2010) were contrasted in terms of climatic conditions and surface characteristics. In 2009, there was no standing water on the island and the soil surface was dry for the majority of the season, except on rainy days. However, several flooding events occurred in 2010 causing presence of standing water on a large portion (close to 90%) of the island surface for the substantial portion of the growing season (mid-June to October). The ponding water level on the island varied from 0.10 to 0.20 m to as high as 0.90 m during the 2010 growing season. The soil at the site is loamy sand (Gothenburg mixed, mesic typic psammaquents) with a particle size distribution of 87.5% sand, 10.3% silt and 2.2% clay with 0.064 $m^3\ m^{-3}$ (vol.%) field capacity, 0.016 $m^3\ m^{-3}$ permanent wilting point and 0.27 $m^3\ m^{-3}$ saturation point. The bulk density is 1.82 g/cm^3 with negligible organic matter content (Irmak, 2010). Below the top 0.10–0.20 m depth, the soil usually remains saturated due to a high water table. The soil at the experimental site was washed into the site by the Platte River flow over time. The river is wide, braided and shallow with low-gradient sand-bed covering a draining area of approximately 137,000 km^2 from the states of Colorado, Wyoming and Nebraska. Average monthly river flows range from nearly bank full in May–June (72 $m^3\ s^{-1}$) to usually low flows in July–August (18 $m^3\ s^{-1}$) exposing substantial area of the river bed (Henszey et al., 2004). The flow of the Platte River is controlled to provide a regulated flow rate to maintain the health of the ecological habitat for endangered birds, fish and other wildlife species in the Platter River ecosystems.

Fig. 2. Overall view of experimental site with mixed riparian plant species (Common reed, Peach-leaf willow, and Cottonwood).

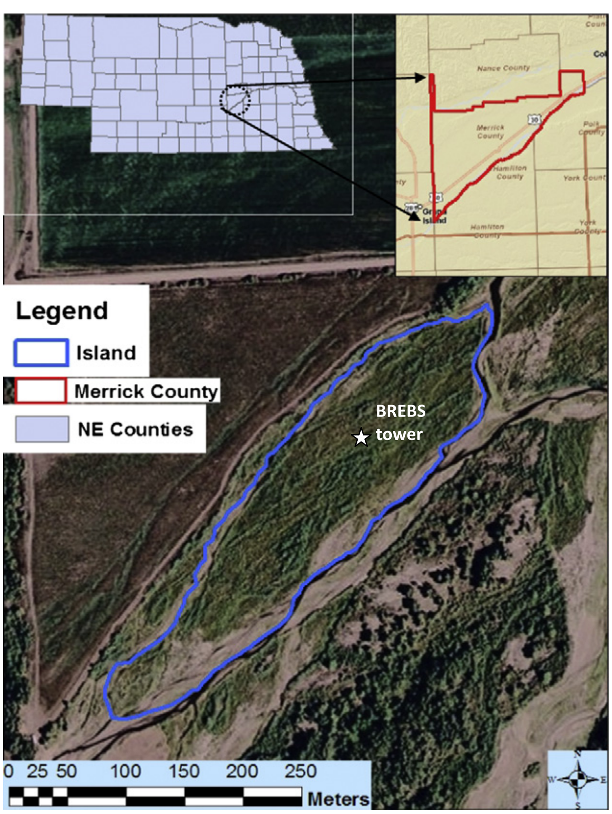

Fig. 1. Location of the Bowen ratio energy balance system (BREBS) at the Common reed-dominated Cottonwood and Peach-leaf willow riparian plant community in the Platte River Basin in central Nebraska, USA.

2.2. Measurement of evapotranspiration and climatic variables

The Bowen ratio energy balance system (BREBS)-measured surface energy flux data, including actual evapotranspiration (ET_{BREBS})

and other datasets used in this study are part of the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX; Irmak, 2010) that operates eleven BREBSs and eddy covariance systems over various vegetation surfaces ranging from irrigated and rainfed grasslands; irrigated alfalfa; rainfed switchgrass; irrigated seed maize/cover crop rotation; to other irrigated and rainfed croplands, including maize, soybean, seed maize and cover crop rotation, and winter wheat under different tillage, irrigation [center pivot irrigation, subsurface drip irrigation, and gravity (furrow) irrigation], and management practices. The integrated surface energy fluxes, including *ETa*, and meteorological variables, including air temperature, relative humidity, incoming shortwave radiation, wind speed and direction, and precipitation were measured using a BREBS installed in the middle of the experimental island. Air temperature (*T*) and relative humidity (*RH*) gradients were measured using two platinum resistance thermometers and monolithic capacitive humidity sensors (REBS Models THP04015 and THP04016, respectively). The BREBS used an automatic exchange mechanism that physically exchanged the *T* and *RH* sensors between two heights above the canopy. The lower exchanger sensors level was maintained at an average height of 1 m above the canopy throughout the season and the distance between the upper and lower exchanger sensors was kept at a constant distance of 1 m. Incoming and outgoing shortwave radiation were measured simultaneously using REBS model THRDS7.1 double sided total hemispherical radiometer. Net radiation (*Rn)* was measured using a REBS Q∗7.1 net radiometer. Ground heat flux (*G*) was measured using three REBS HFT-3.1 heat flux plates and three REBS STP-1 soil thermocouple probes. Each set of soil heat flux plate, surface soil moisture sensor and soil thermocouple was placed at a depth of 0.06–0.08 m below the soil surface in close proximity to each other. In addition, the soil profile moisture content was measured using CS616 water content reflectometers at 0–0.30 and 0.30–0.60 m depth on an hourly basis throughout the year. Three CS616 sensors were installed in each depth. The BREBS was installed on April 28, 2009 and was vigorously maintained and monitored on a weekly basis (Irmak, 2010).

2.3. Reference evapotranspiration (ET_{ref})

The Penman–Monteith *ET* equation with a fixed canopy resistance (70 s m^{-1} for grass- and 45 s m^{-1} for alfalfa-reference surface) was used to calculate the alfalfa-reference evapotranspiration on a daily time step (Penman, 1948, 1963; Monteith, 1965; Irmak et al., 2012):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} U_2(e_s - e_a)}{[\Delta + \gamma(1 + C_d U_2)]} \tag{1}$$

where ET_{ref} = reference *ET* (mm day^{-1}); Δ = slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}); *Rn* = net radiation at the canopy surface (MJ m^{-2} day^{-1}); *G* = heat flux density at the soil surface [(MJ m^{-2} day^{-1}) equal to zero for daily time step)]; *T* = average daily air temperature [$T = (T_{max} + T_{min})/2$] (°C); T_{max} = daily maximum air temperature (°C); T_{min} = daily minimum air temperature (°C); U_2 = average daily wind speed at 2 m height (m s^{-1}); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); γ = psychrometric constant (0.0671 kPa °C^{-1}); $e_s - e_a$ = vapor pressure deficit (kPa); C_n and C_d = numerator and denominator constants that change with reference surface and calculation time step (on a daily time step C_n = 900 and C_d = 0.34 for grass-reference surface and C_n = 1600 and C_d = 0.38 for alfalfa-reference surface); and 0.408 is $1/\lambda$, where λ = 2.45 MJ m^{-2} mm^{-1}. Because of this constant, both *Rn* and *G* are in MJ m^{-2} d^{-1} for daily and MJ m^{-2} h^{-1} for hourly calculations. The BREBS-measured climate variables were used as the input data to estimate ET_{ref}. In addition, because the experimental site did not represent "reference" conditions, climate dataset from a nearby High Plains Regional Climate Center automatic weather station (Central City weather station; Latitude: 41°12′N; Longitude: 98°01′W; elevation: 517 m) were used to compare the *ETr* estimates using the data from the BREBS vs. weather station to evaluate any potential differences in calculated *ETr* values using the two datasets. The weather station was approximately 10 km west of the experimental site.

2.4. Mixed riparian plant community ET crop coefficients

The "average" evapotranspiration crop coefficients for the Common reed-dominated Cottonwood and Peach-leaf willow mixed riparian plant community were developed as the ratio of BREBS-measured *ET* (ET_{BREBS}) and estimated *ETr*. The alfalfa-reference evapotranspiration crop coefficients (Kcr_{ET}) were developed (i.e., $Kcr_{ET} = ET_{\text{BREBS}}/ETr$) on a daily basis for two years. The coefficients were developed from early season through complete physiological maturity, which usually occurred in early to mid- or late-October. In developing the evapotranspiration and transpiration crop coefficients, the *Ks* stress factor was taken as 1.0 because the roots of all three riparian plant species had unlimited access to water in both years resulting in no plant water stress conditions. This approach assumes that the developed or estimated Kcr_{ET} values for the same riparian species would be very similar between the years. However, this assumption does not fully take into account the potential contribution of soil evaporation when developing or estimating Kcr_{ET} values. Our hypothesis was that while the Kcr_{ET} values can potentially be different for the same species between the years (depending on the surface conditions; e.g., flooded vs. non-flooded) the transpiration crop coefficients (Kcr_{TRP}) will vary much less between the years in a riparian site similar to the one studied in this experiment where plant roots have continuous access to water.

2.5. Transpiration crop coefficients for individual riparian vegetation species

The Kcr_{TRP} values were calculated as the ratio of the absolute daytime *TRP* of each vegetation species to *ETr*. The *TRP* values were quantified using the canopy resistance values which were scaled up from measured leaf-level stomatal resistance using photosynthetic photon flux density, light interception by sunlit and shaded leaves, zenith angle, above- and within-canopy radiation physics parameters, leaf area index for sunlit and shaded leaves, and other climatic variables. The *TRP* data and detailed descriptions are presented in Kabenge and Irmak (2012). The scaled up canopy resistance values were used in quantifying the *TRP* crop coefficients on an hourly time step and summed for a 24-h time step. The *TRP* crop coefficients on a daily basis were regressed against the daily cumulative *GDD* during the 2009 season. *GDD*-based scale regression was fitted to the *TRP* crop coefficient curves in 2009. The fitted relationship for 2009 was then used to estimate the *TRP* crop coefficients and *TRP* rates in 2010 using cumulative *GDD* as the base scale. The *GDD* equation used in this study is:

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \tag{2}$$

where, T_{max}, T_{min}, and T_{base} is in °C. T_{base} is the temperature below which the plant physiological process does not resume (McMaster and Wilhelm, 1997). The *TRP* would be minimal or zero below the base temperature. *Tbase* varies among vegetation species and likely varies with growth stage or process being considered (Wang, 1960; Sammis et al., 1985; Yang et al., 1995; McMaster and Wilhelm, 1997). Kalischuk et al. (2001) and Berg et al. (2007) used a base temperature value of 5 °C for black Cottonwood (*Populus trichocarpa*) whereas Gregg et al. (2006) used 10 °C for cloned Cottonwood saplings (*Populus deltoides*) when calculating *GDD*. Martin and Stephens (2008) used base temperatures between 2.0 and 7.6 °C when examining water uptake and shoot extension growth for Willow (*Salix viminalis* L.). When modeling growth and carbon allocation of *Phragmites australis* in the Scheldt estuary in Netherlands, Soetaert et al. (2004) considered 4.0 °C as the threshold temperature that triggers growth. Jones (1992a,b) suggested that a minimum temperature of 5.0 °C or 6.0 °C for plant growth is usually assumed for temperate crops and about 10 °C for agronomic crops such as maize. In this study, we used 7.0 °C as the base temperatures for Common reed and Peach-leaf willow and 8 °C for Cottonwood.

2.6. Modeling transpiration for individual plant species

The time-averaged *TRP* for individual riparian species was estimated as a function of total conductance and average vapor pressure deficit (Tan et al., 1978; Spittlehouse and Black, 1980; Barradas et al., 2005; Nicolás et al., 2008) as:

$$TRP = (\rho_a C_p/\gamma\delta) g_T \cdot VPD \tag{3}$$

where *TRP* is transpiration rate (kg m^{-2} s^{-1}), ρ_a is the density of dry air (kg m^{-3}), C_p is the specific heat of dry air at constant pressure (J kg^{-1} °C^{-1}), γ is the psychrometric constant (Pa °C^{-1}), λ is the latent heat of evaporation of water (J kg^{-1}), g_T is the total conductance [1/canopy resistance (r_c), m s^{-1}], *VPD* is the average vapor pressure deficit (Pa), calculated using BREBS-measured air temperature (Irmak et al., 2012). Total conductance was calculated based on the electrical analogue of a parallel circuit from canopy resistance (r_c, s m^{-1}) and aerodynamic resistance (r_a, s m^{-1}) (Monteith, 1965; Monteith and Unsworth, 1990):

$$1/g_T = r_c + r_a \tag{4}$$

The canopy resistance (r_c) values used in Eq. (4) were those scaled up from measured leaf stomatal resistance for each riparian species using the approach proposed by Irmak et al. (2008a); Irmak and Mutiibwa, (2010) who developed an integrated approach of coupling a number of microclimatic and in-canopy radiation transfer parameters to scale up measured leaf-level stomatal resistance to r_c. With the espousal of plant and environmental factors such as leaf area index for sunlit and shaded leaves, plant height, light interception above and within the canopy, solar zenith angle, direct and diffuse solar radiation, they scaled up leaf stomatal resistance to r_c as a primary function of measured photosynthetic photon flux density. Detailed description of the integrated scaling up process for other vegetation types is outlined in Irmak et al. (2008a) and Mutiibwa and Irmak (2011) and their integrated approach and the equations that were used in this study will not be repeated here. The computation of r_a is based on the assumption of a logarithmic wind profile (de Wit et al., 1978):

$$r_a = \frac{\ln[(z_m - d)/z_{om}]\ln[(z_h - d)/z_{oh}]}{\kappa^2 u_z} \tag{5}$$

where z_m is height of wind measurement (m), z_h is height of humidity measurement (m), d is the zero plane displacement height (m), z_{oh} is the roughness length governing transfer of heat and water vapor (m), z_{om} is the roughness length governing transfer of momentum (m), κ is von Karman's constant (0.41), u_z is wind speed at height z (m s^{-1}). The values of d, z_{om}, and z_{oh} were calculated after de Wit et al. (1978) and Brutsaert (1982):

$$d = 0.67h \tag{6}$$

$$z_{om} = 0.123h \tag{7}$$

where h is crop height measured during the growing season.

$$z_{oh} = 0.1 z_{om} \tag{8}$$

We used the scaled up canopy resistance as one of the inputs to Eq. (3) and calculated hourly *TRP* rates for individual species. The daytime total *TRP* values were estimated as the sum of the hourly values with a corresponding positive *Rn* such that the daytime was defined as when $Rn > 10$ W m^{-2}.

2.7. Leaf area index and plant height measurements

Leaf area index (*LAI*) was measured using a model *LAI*-2000 plant canopy analyzer (Li-COR Biosciences, Lincoln, Nebraska, USA). For each *LAI* value recorded, one reading above the canopy was taken and four other readings at different points within 1 m of each other were taken at the base of the canopy to sample variability within the canopy. *LAI* was measured at five locations on the island on a weekly basis. Two of the areas located south and northwest of the BREBS were dominated by Common reed (Figs. 1 and 2). One area that was dominated by Peach-leaf willow and the other two areas dominated by Cottonwood species were located on the east, northeast and northwest of BREBS, respectively. On average, a total of sixteen *LAI* measurements were taken from each location on each measurement day and averaged for the day. The measurements started when *LAI* was approximately 0.5–1.0.

To determine the height for each vegetation species during the growing season, ten Common reed plants, three Cottonwood trees and eight Peach-leaf willow trees were marked and their height was measured every week through the growing season in both years. The marked plants/trees were distributed around the BREBS tower and the height was measured using a telescopic surveyor's ranging gauge. On each measurement day a total of 21 height measurements were taken (ten for Common reed, three for each Cottonwood trees and eight for Peach-leaf willow trees). The height measurements from each of the plants were averaged into one value for each species for the measurement day's record.

The Kcr_{ET} and Kcr_{TRP} coefficients were developed for both years. Also, for evaluation of the transferability of *TRP* crop coefficients between the years, the *TRP* crop coefficients using the *GDD* vs. Kcr_{TRP} relationships that were developed in 2009 for Common reed, Cottonwood and Peach-leaf willow were used to estimate Kcr_{TRP} values in 2010 and the *TRP* rates of individual species were calculated using estimated Kcr_{TRP} and *ETr* in 2010 (i.e., $TRP = Kcr_{TRP} \times ETr$). The root mean square difference (*RMSD*) between the *TRP* rates modeled (observed) from scaled up measured stomatal resistance to canopy resistance and estimated using $Kcr_{TRP} \times ETr$ approach and coefficient of determination (r^2) were used to judge the accuracy and performance of the *TRP* rates estimated using the *TRP* crop coefficients developed for each species. The *RMSD* was calculated using the following equation:

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i^e - y_i^m)^2} \tag{9}$$

where n is the number of observations, y_i^m is the modeled (from scaled up measured stomatal resistance to canopy resistance) transpiration (mm/day), and y_i^e is the estimated transpiration using the $TRP = Kcr_{TRP} \times ETr$ approach developed in this study. In addition to *RMSD*, the Nash–Sutcliffe model efficiency coefficient (*E*) (Nash and Sutcliffe, 1970) was used to assess the predictive power of the $Kcr_{TRP} \times ETr$ two-step approach in estimating transpiration rates of individual species:

$$E = 1 - \frac{\sum_{n=1}^{T}(TRP_{obs} - TRP_{mod})^2}{\sum_{n=1}^{T}(TRP_{obs} - \overline{TRP}_{obs})^2} \tag{10}$$

where TRP_{obs} is observed transpiration rate (mm/day) and TRP_{mod} is the modeled transpiration rate (mm/day). The Nash and Sutcliffe efficiency coefficients can range from $-\infty$ to 1 and an efficiency

Table 1
Daily average meteorological parameters measured during May–October at the experimental site [wind speed at 3-m (U_3), maximum and minimum air temperature (T_{max} and T_{min}), relative humidity (RH), incoming shortwave radiation (Rs), net radiation (Rn), and precipitation].

Period	Meteorological variable	May	June	July	August	September	October
2009	U_3 (m s^{-1})	2.3	1.5	1.2	1.3	1.1	1.9
	$Tmax$ (°C)	22.8	24.9	26.4	25.9	22.5	11.6
	$Tmin$ (°C)	10.5	15.4	15.0	14.7	10.8	2.2
	RH (%)	66	80	80	81	78	79
	Rs (W m^{-2})	257	242	273	259	168	98
	Rn (W°m^{-2})	152	155	176	167	106	53
	VPD (kPa)	0.95	0.68	0.68	0.65	0.59	0.31
	Precipitation (mm)	27	178	29	38	0	8
2010	U_3 (m s^{-1})	1.9	1.4	1.1	1.1	1.4	1.3
	$Tmax$ (°C)	20.7	27.0	28.3	28.9	24.3	20.2
	$Tmin$ (°C)	10.0	17.3	19.5	18.0	11.0	4.9
	RH (%)	72	80	84	81	78	69
	Rs (W m^{-2})	243	276	268	262	183	161
	Rn (W m^{-2})	153	179	173	163	106	71
	VPD (kPa)	0.73	0.75	0.63	0.75	0.70	0.76
	Precipitation (mm)	81	163	120	96	34	14
Long-term (1987–2008)	U_3 (m s^{-1})	3.1	2.6	2.0	1.9	2.3	2.5
	T_{max} (°C)	23.8	28.6	30.6	29.7	26.2	19.8
	T_{min} (°C)	10.9	16.2	18.7	17.7	12.4	5.4
	RH (%)	68	70	76	76	68	65
	Rs (W m^{-2})	220	256	254	220	182	129
	Rn (W m^{-2})	131	156	155	130	95	54
	VPD (kPa)	0.94	1.15	1.04	0.97	1.07	0.81
	Precipitation (mm)	120	94	91	70	72	50

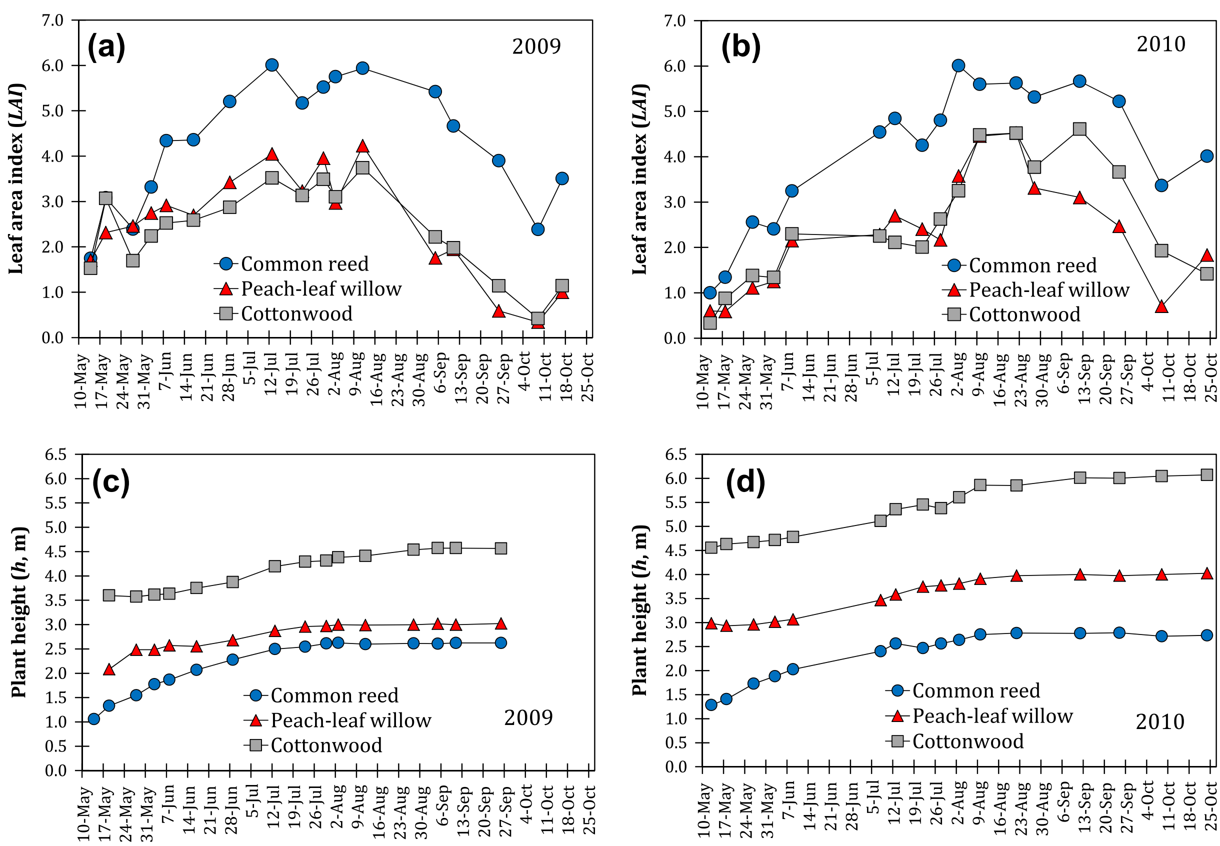

Fig. 3. Seasonal trends of measured leaf area index (LAI) for Common reed, Peach-leaf willow, and Cottonwood in 2009 (a) and 2010 (b) and plant height (h) for the same species in 2009 (c) and 2010 (d). Each data point represents an average of 8, 4, and 8 measurements for Common reed, Peach-leaf willow, and Cottonwood, respectively.

of 1 ($E = 1$) indicate a perfect match of modeled transpiration rates to the observed (transpiration from scaled up canopy resistance using measured leaf level stomatal resistance) data. An efficiency of 0 ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas a negative efficiency ($E < 0$) occurs when the observed mean is a better predictor than the model or when the residual variance (numerator, is larger than the data variance (denominator).

3. Results and discussion

3.1. Meteorological conditions, Leaf area index (LAI), and plant height (h)

Monthly average BREBS-measured meteorological variables, including wind speed, *Tmax*, *Tmin*, incoming shortwave radiation (*Rs*), *Rn*, precipitation, *RH*, and *VPD* in 2009 and 2010 are presented in Table 1. For comparison, long-term (1987–2008) monthly average values of climate data for Central City are included. The wind speed is usually greatest during spring months and in the fall of both growing seasons. On a seasonal average basis, 2010 was warmer, had greater *Rs*, and lower wind speeds than 2009. The long-term average precipitation from May through October is 497 mm. Conditions in 2009 were much drier than long-term average conditions with only 280 mm precipitation, which also made it drier than 2010 that had 508 mm of precipitation. The site was flooded in 2010 with the water on the surface rising up to 0.90 m.

The progression of measured *LAI* and plant height (*h*) for each plant species in both years is presented in Fig. 3. Common reed had greatest *LAI* in both years and had very similar peak *LAI* values (6.0) in 2009 and 2010. In 2009, Peach-leaf willow and Cottonwood had very similar *LAI* and peaked at about 4.0. In 2010, both species also had similar *LAI* from early season until end of August. Cottonwood trees reached a height of 6 m in 2010 and Peach-leaf willow maximum height was about 4.0 m. In both years, the maximum height of Common reed was about 2.5 m. The plant height and *LAI* values in both years were not impacted by water-limiting or water stress conditions. While the surface conditions were dry in 2009, the soil water status below the topsoil was never less than 15 vol.% (0.15 $m^3\ m^{-3}$) (Fig. 4a). The measured soil water content in the 0.30–0.60 m profile was always above 25 vol.% and it was never below 22 vol.% in the 0–0.30 m soil profile in 2010 (Fig. 4b). The soil water content never dropped below 26 vol.% at 0.30–0.60 m soil layer. Thus, in both years, the roots of all plant species had unlimited access to water. This was the primary reason for using stress factor *Ks* = 1.0 in the evapotranspiration and *TRP* crop coefficient calculations.

3.2. Seasonal distribution of ET_{BREBS} and ETr

In 2009, ET_{BREBS} was mostly less than *ETr* from the start of the season until late May and from late September to the end of the season (Fig. 5a). ET_{BREBS} ranged from near zero to 8.5 mm/day on August 8 with a seasonal average of 3.8 mm/day. *ETr* ranged from 0.34 mm/day to 11 mm/day with a seasonal average of 4.2 mm/day. The maximum *ETr* occurred on May 20 as 11 mm/day. Earlier in the season ET_{BREBS} was about 54% of *ETr*. During mid-season, daily ET_{BREBS} values were higher than *ETr* by about 5.3%. Toward the end of the season ET_{BREBS} was about 60% of *ETr*. In 2010, ET_{BREBS} ranged from near zero to 10.6 mm/day with a seasonal average of 5.5 mm/day. *ETr* ranged from 0.5 mm/day to 8.4 mm/day with a seasonal average of 4.4 mm/day. The maximum *ETr* also occurred on May 20 as 8.4 mm/day. Although the maximum and minimum *ETr* ranges were different, the seasonal average *ETr* showed very similar evaporation demand between the years (average of 4.2 and 4.4 mm/day for 2009 and 2010, respectively) suggesting that the evaporative forcing averaged over the season did not vary significantly between the two years. ET_{BREBS} data on the other hand increased more than 40% from 2009 to 2010 due to increased free water evaporation. The duration of the flooding conditions, in addition to warmer air temperatures

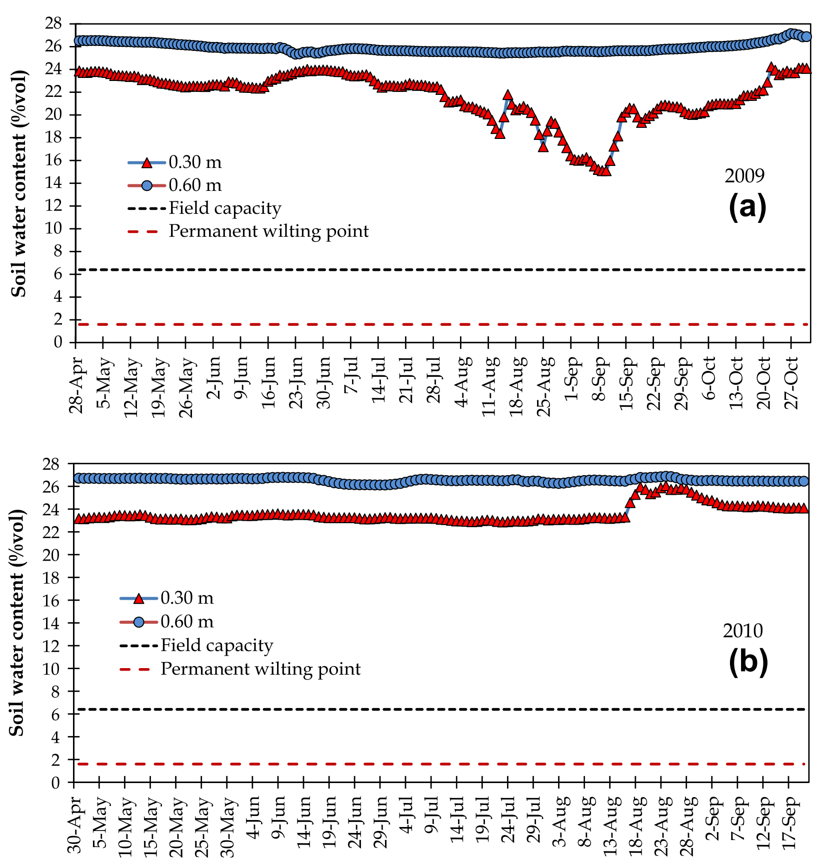

Fig. 4. Seasonal trend in measured soil water content in the 0–0.30 and 0.30–0.60 m soil profile in 2009 (a) and 2010 (b) season.

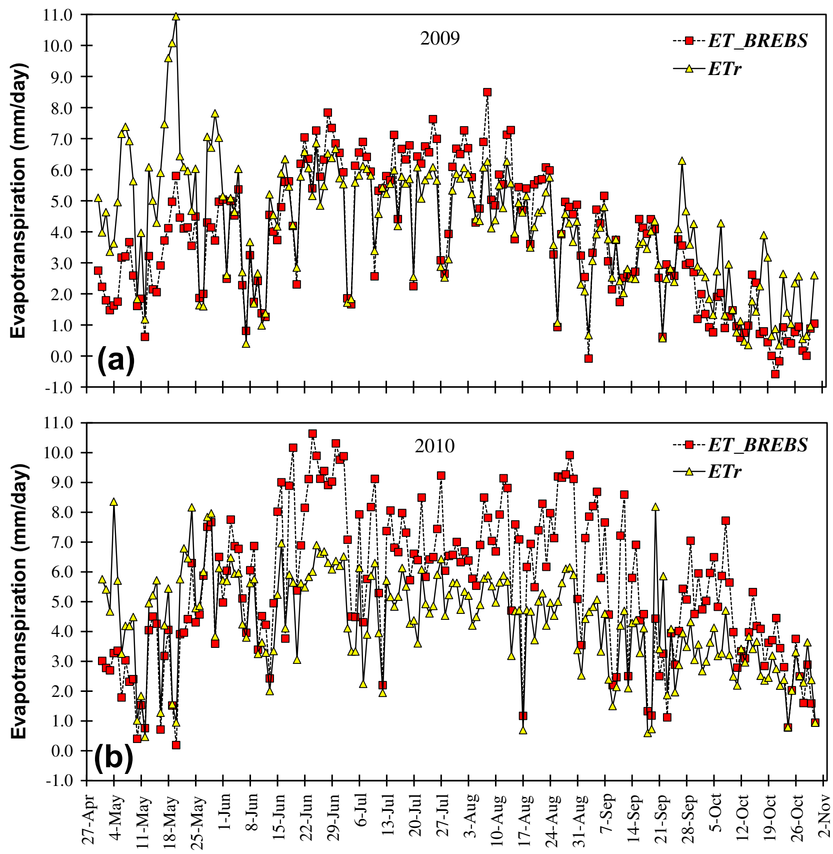

Fig. 5. Seasonal trends of Bowen ratio energy balance-measured daily actual evapotranspiration (ET_{BREBS}) and Penman–Monteith–estimated alfalfa-reference evapotranspiration (*ETr*) during 2009 (a) and 2010 (b) seasons.

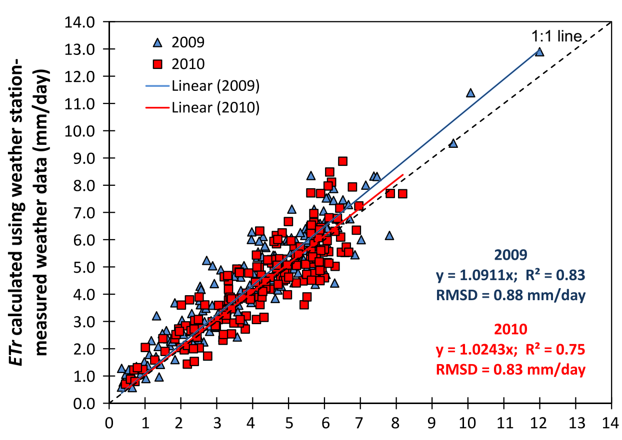

Fig. 6. Regression between alfalfa-reference evapotranspiration (*ETr*) calculated using climate data measured with the Bowen ratio energy balance system (BREBS) at the research site vs. *ETr* calculated using climate data measured at a nearby weather station in 2009 and 2010 seasons.

and greater *Rs*, is the dominant driver of this increase in ET_{BREBS}. The duration of the flooding in 2010 was from mid-June through October. Kabenge and Irmak (2012) reported that for the same study site the average surface evaporation rate of the riparian zone was 0.81 mm/day in 2009 and 1.70 mm/day in 2010. Seasonal evaporation was 160 mm in 2009 and 312 mm in 2010. Earlier in the season, ET_{BREBS} was about 74% of *ETr*. For the rest of the season daily ET_{BREBS} exceeded *ETr* substantially and ET_{BREBS} was 139% of *ETr*. The seasonal total for *ETr* for 2010 was 5% higher than the *ETr* in 2009, while ET_{BREBS} had a much higher increase of 45% as compared with the 2009 season. The high values of ET_{BREBS} measured in 2010 is due to a higher proportion of evaporation from the flood water covering the surface during 2010 as well as greater air temperatures and *Rs* in 2010 than in 2009.

High deviations between ET_{BREBS} and *ETr* noted in Fig. 5 can be explained by the low *LAI* values at that period which resulted in some of the available energy being portioned to sensible heat to warm up the land/vegetation surface as well as surrounding boundary layer/microclimate. In addition, higher temperatures and *VPD* were recorded on many days that had ET_{BREBS} much less than *ETr*. Data measured during such dry settings may cause overestimation of *ETr* due to air temperature measurements that are too high and humidity measurements that are too low relative to the "reference" conditions assumed by the Penman–Monteith equation. Under dry conditions, the *ETr* calculations may reflect *ET* demand of the "actual ambient" conditions (experimental site) rather than "reference" environment.

To evaluate the potential impact of using BREBS vs. weather station-measured climate data to estimate *ETr* between near-reference (closest weather station approximately 10 km from the experimental site) and non-reference (experimental island) sites, the *ETr* values were calculated using two different climatic data and presented in Fig. 6. The *ETr* values calculated using BREBS vs. weather station data were within 9% and 2% in 2009 and 2010, respectively, with a relatively low *RMSD* of 0.88 mm/day in 2009 and 0.83 mm/day in 2010. In both years the scatter in the data is larger at higher *ETr* rates. Overall, although the riparian zone had significantly different surface characteristics, the *ETr* values that were calculated using the data collected in this zone were very similar to the values calculated using a reference weather station

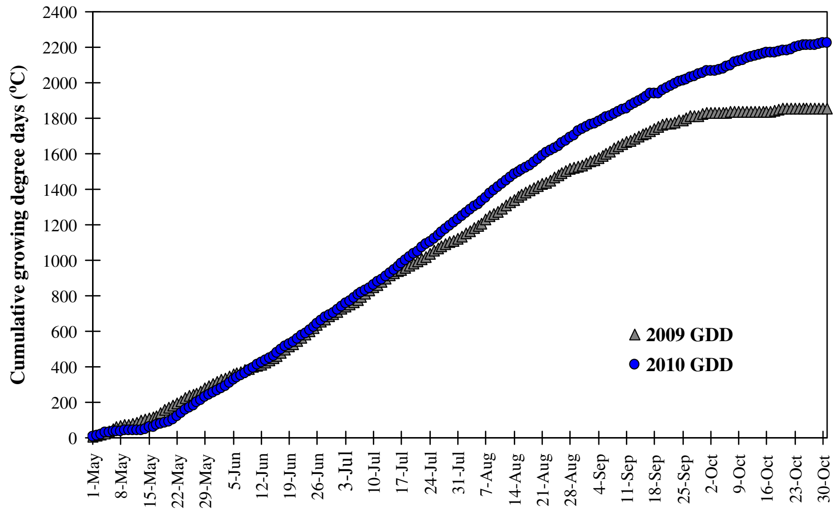

Fig. 7. Cumulative growing degree days, *GDD* (average base temperature of 7 °C) for the riparian zone in 2009 and 2010 growing seasons.

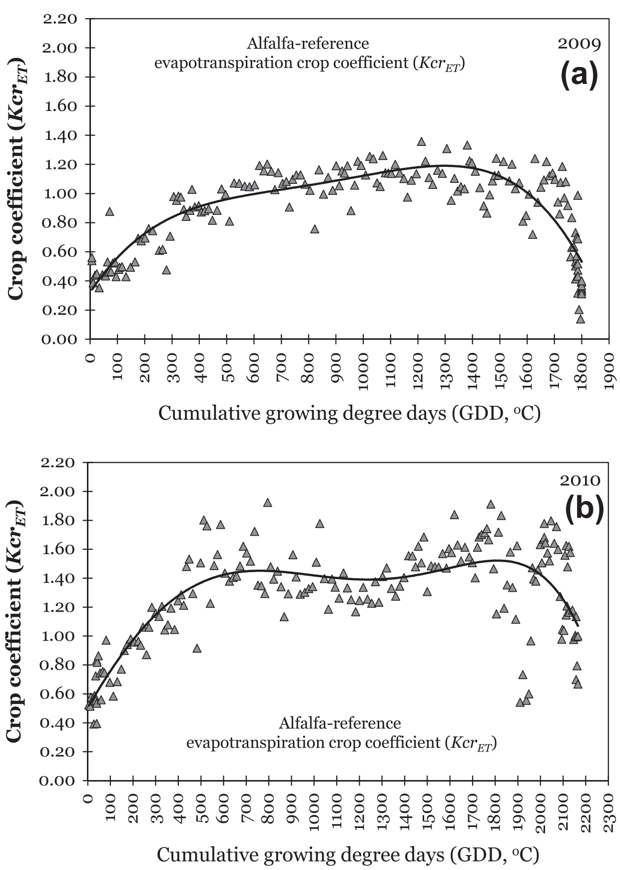

Fig. 8. Seasonal trends of alfalfa-reference evapotranspiration crop coefficients (Kcr_{ET}) for mixed riparian plant community in 2009 (a) 2010 (b) as a function of cumulative growing degree days (*GDD*).

data. Thus, in practical applications, the evapotranspiration and *TRP* crop coefficients that were calculated using BREBS-measured climatic data vs. weather station-measured data should result in similar values.

3.3. Mixed riparian vegetation evapotranspiration crop coefficients

The Kcr_{ET} curves for the mixed riparian plant community were developed as a function of cumulative *GDD*. Cumulative *GDD* values for 2009 and 2010 were presented in Fig. 7. In 2009, the cumulative *GDD* at the end of the season (October 7–8) was about 1800 °C whereas the *GDD* was 2220 °C at the end of the season (end of October) in 2010. The *GDD* value at the end of October in 2009 was 1850 °C. The Kcr_{ET} curves for the mixed vegetation for 2009 and 2010 are presented in Fig. 8a and b. The Kcr_{ET} showed day-to-day variations in both seasons. Daily Kcr_{ET} values in 2009 ranged from 0.14 at the end of the season in early October when the cumulative *GDD* was 1800 °C to 1.36 in early August when *GDD* was about 1200 °C, but the Kcr_{ET} were usually above 0.30 throughout the season. The peak Kcr_{ET} value (1.36) remained similar between the 1200–1400 °C cumulative *GDD* range. The average seasonal Kcr_{ET} in 2009 was 0.89. There was a rather sharp decrease in Kcr_{ET} in early October (1800 °C *GDD*) due to plant senescence. Similar decline in Kcr_{ET} was observed in 2010, but at a later period at the end of October when the cumulative *GDD* was about 2150–2200 °C. The growing season was about 25 days longer in 2010 than in 2009. The Kcr_{ET} values continued to decline slightly in early October while the *GDD* remained relatively constant at around 1800 °C because of negative air temperatures. Decline in Kcr_{ET} is due to low ET_{BREBS} values during that period.

While the Kcr_{ET} curve had a relatively uniform parabolic distribution in 2009, the values were fluctuated more (cyclic distribution) in 2010. Daily Kcr_{ET} in 2010 ranged from 0.39 in the beginning of the season and peaked at 1.92 (1780 °C *GDD*) and were usually above 0.40 throughout the season. The 2010 peak Kcr_{ET} value was a very similar observation to the *GDD* value at which the peak Kcr_{ET} occurred in 2009 (1800 °C *GDD*). As a result of flooding and fluctuating water level on the island site, the Kcr_{ET} values had two peaks: one from mid-June through late-July (510–1025 °C *GDD* range) and the other one from late-August to late-October (1020–2050 °C *GDD* range). During the mid-season from mid-July to mid-August, the Kcr_{ET} values declined as a result of flooding impact on plant physiology (reduced *LAI* and declined transpiration rates, and therefore, reduced ET_{BREBS}). The average seasonal Kcr_{ET} in 2010 was 1.27. Again, the greater Kcr_{ET} values as well as cyclic distribution in 2010 were due to the increased rate of surface evaporation due to flooding that was reflected in the greater ET_{BREBS} values observed in 2010. Thus, the ET_{BREBS} values included a much higher rate of surface evaporation as compared with the rates in 2009 (but decreased transpiration between mid-July and mi-August), resulting in greater ET_{BREBS} and greater, but fluctuating, Kcr_{ET} values in 2010. The Kcr_{ET} values developed in 2010 represent flooded surface conditions, therefore, may not be applicable

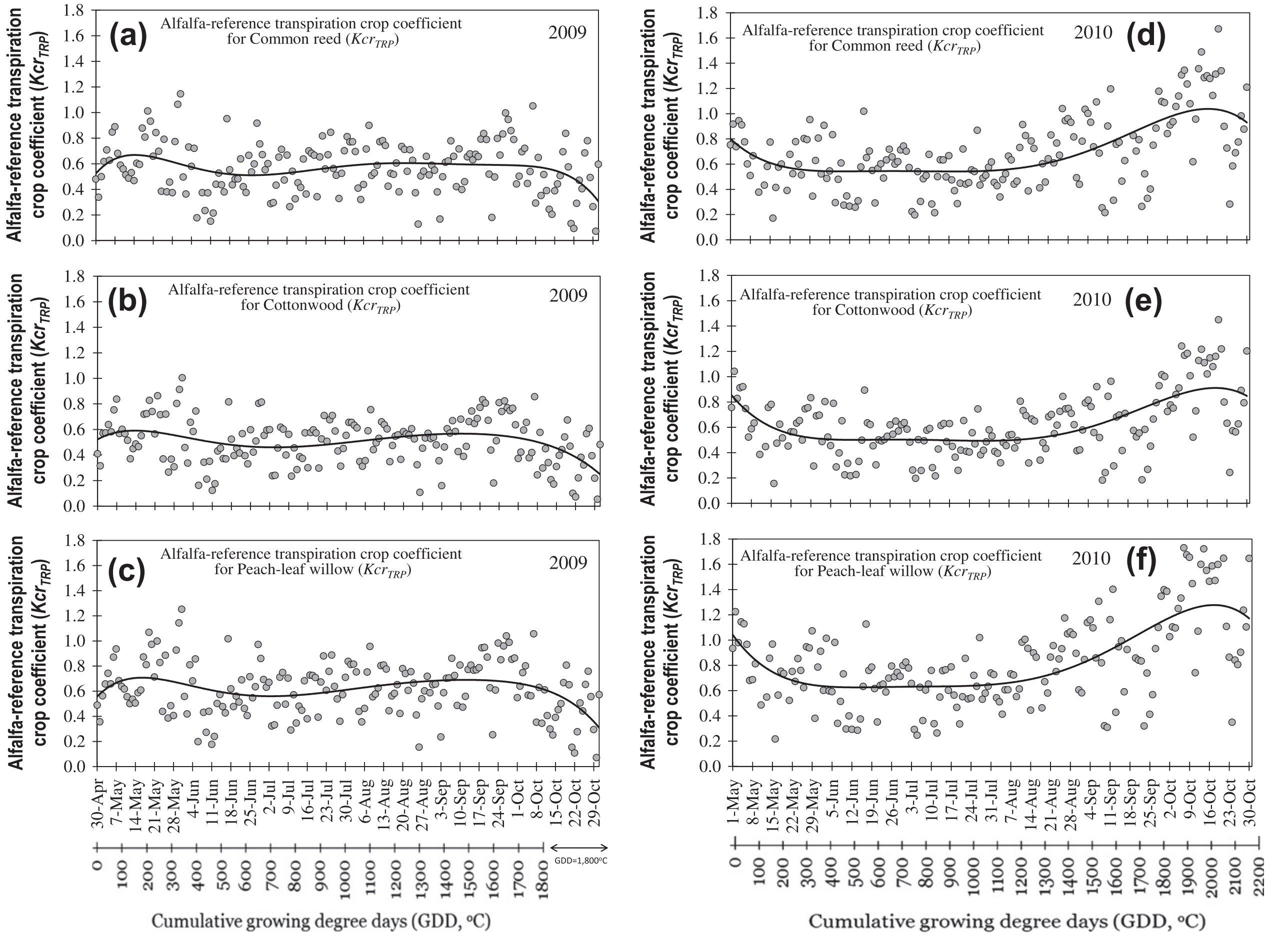

Fig. 9. Seasonal trends of daily alfalfa-reference transpiration (*TRP*) crop coefficients (Kcr_{TRP}) in 2009 for Common reed (a), Cottonwood (b), and Peach-leaf willow (c); and in 2010 for Common reed (d), Cottonwood (e), and Peach-leaf willow (f).

to estimate the actual *ET* in riparian conditions where the soil surface is dry as it was the case in 2009. Similarly, the Kcr_{ET} values developed using 2009 ET_{BREBS} data that were measured over mixed riparian plant community may not accurately represent the conditions in 2010 and thus, may not be applicable to estimate *ETa* when the mixed riparian plant community is under flood water. This also suggests that the variation in *ETa* and crop coefficients among the years in the riparian areas may be greater than those observed in agricultural settings due to the hydrologic and surface characteristics of the surrounding river. For example, Sharma and Irmak (2012) reported monthly average Kcr_{ET} values ranging from 0.24 in May to 1.05 in July for maize and from 0.31 in May to 0.93 in July for soybean. The Kcr_{ET} values reported in study for riparian vegetation are, on average, about 30–50% greater under flood conditions than those in agricultural fields. Thus, the surface conditions of the riparian ecosystem need to be considered when using the two-step approach to estimate *ETa* or *TRP* rates of riparian plant communities by properly quantifying Kc_{ET} or Kc_{TRP} values based on the surface conditions (i.e., flooded vs. non-flooded).

3.4. Transpiration crop coefficients for individual riparian vegetation species

One significant advantage of *TRP* crop coefficients over the evapotranspiration crop coefficients is that they provide more robust water use rates of individual species and also they are less impacted by the surface characteristics (e.g., flooding), making them more transferable between the locations with different surface characteristics. The *TRP* crop coefficients were obtained through dividing the *TRP* rates of individual plant species by *ETr* rates (e.g., $Kcr_{TRP} = TRP_{\text{Common reed}}/ETr$). The distribution of alfalfa-reference based *TRP* crop coefficients as a function of *GDD* for three species for 2009 and 2010 are presented in Fig. 9. In Fig. 9, both the date and the *GDD* scales were included in the *X*-axis. The *GDD* scale for 2009 (Fig. 9a–c) ranged from 0 (beginning of the season) to 1800 °C (end season). After *GDD* value of 1800 °C the *X*-axis (*GDD*) remains the same until end of October and *GDD* does not increase due to negative values of air temperature. In 2009, the maximum *GDD* of 1800 °C was reached on October 7. In 2009, the distribution of Kcr_{TRP} generally showed lower coefficients at the beginning and end of the season for all species, periods that are also associated with low *LAI*. The Kcr_{TRP} values ranged between 0.07–1.15, 0.05–1.01 and 0.07–1.25 for Common reed, Cottonwood and Peach-leaf willow (Fig. 9a–c), respectively. The seasonal average Kcr_{TRP} values were 0.57, 0.51 and 0.62, for the same species, respectively. For all species, the greatest Kcr_{TRP} values were observed at the end of May-early June before the flooding occurred.

In 2010, Kcr_{TRP} ranged between 0.17–1.67, 0.16–1.45, and 0.22–1.98 (Fig. 9d–f) for Common reed, Cottonwood and Peach-leaf willow, respectively. The seasonal average Kcr_{TRP} values were 0.69, 0.62 and 0.83, for the same species. The Kcr_{TRP} curves had different shapes in both years than those developed for Kcr_{ET}. This is expected because *ETa* has more gradual increase and decrease trend than *TRP* because it includes surface evaporation and, therefore, there is more chance to have some degree of *ETa* even under low atmospheric demand conditions. However, *TRP* is more sensitive

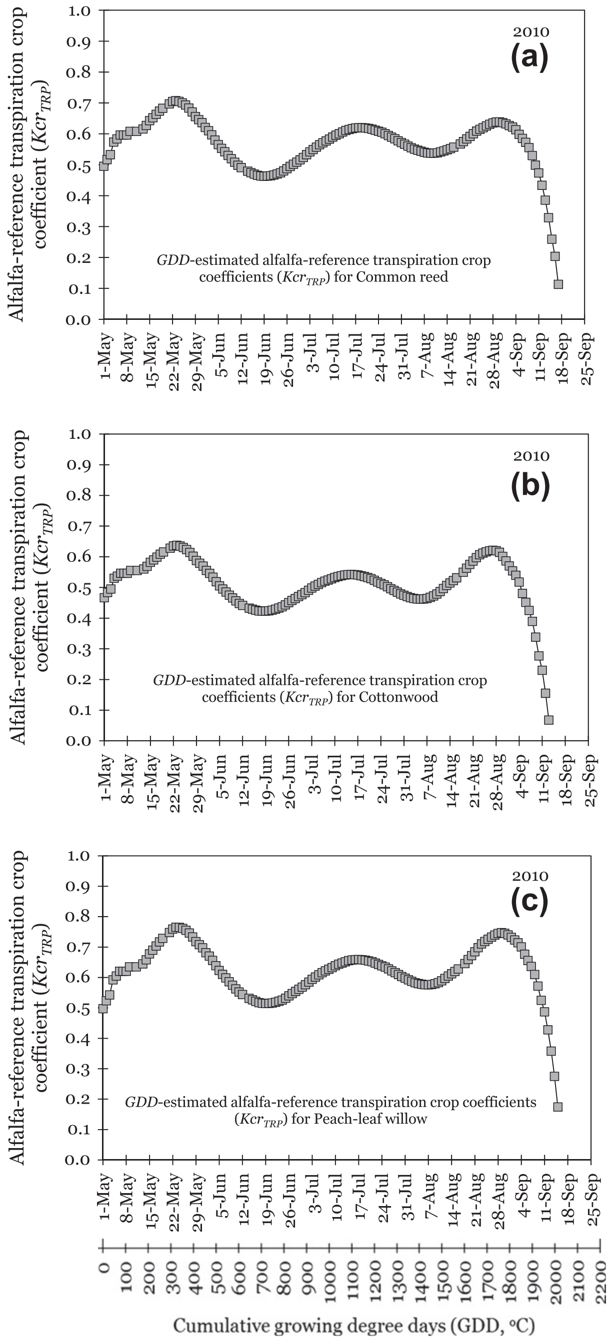

Fig. 10. Growing degree days (*GDD*)-estimated alfalfa-reference transpiration crop coefficients (Kcr_{TRP}) for Common reed (a), Cottonwood (b) and Peach-leaf willow (c) during 2010 season. These three curves were developed using the relationship developed between *GDD* and Kcr_{TRP} using 2009 data to assess the transferability of the Kcr_{TRP} curves between the years.

to climatic conditions and surface characteristics than *ETa* and fluctuates more with time as a function of plant response to environmental variables, including flooding, water level changes, water temperatures, etc., in addition to the microclimatic variables. The Kcr_{TRP} may not have a uniform and gradual increasing and decreasing shape as Kcr_{ET} curves due to rapid fluctuations in *TRP* rates. While we showed that there was a general increasing trend in *Kcr* curves towards the mid-season and decreasing trend towards the end-season, the Kcr_{TRP} curves had a fluctuation trend throughout the season as a result of changes in plant physiological functions (stomatal behavior) and *TRP* rates rather than evapotranspiration rates of individual species, which can fluctuate in a narrower range than total *ETa* flux, resulting in a narrower range of Kcr_{TRP} values than Kcr_{ET}. Thus, the Kcr_{ET} values developed in 2009 should be used when there is no standing water on the surface. In most riparian corridors it is common to have backed-up standing water from the river. In such cases the Kcr_{ET} values developed in 2010 should be used. In general, *TRP* crop coefficients had less variability between the years than the evapotranspiration crop coefficients.

3.5. Transferability of GDD-based transpiration crop coefficients between the years

The relationships measured between *GDD* and Kcr_{TRP} for individual species in 2009 were used to estimate individual species Kcr_{TRP} curves in 2010 to evaluate their performances in estimating *TRP* rates and their transferability between the years. The estimated Kcr_{TRP} curves for each individual species are presented in Fig. 10. A 5th or 6th order polynomial equation was fitted to the *TRP* crop coefficients vs. *GDD* relationships and the coefficients for the polynomial relationships as a function of *GDD* are presented in Table 2. The primary objective of fitting high order polynomials is to capture the subtle variability in time and to develop relationships that can be used in other sites. The results of the *TRP* crop coefficients for the individual vegetation species represent the period between mid-May and mid-September. The seasonal total average *GDD* for Common reed and Peach-leaf willow were 1825 °C while for Cottonwood it was 1694 °C in 2009. The corresponding values for 2010 were 2223 °C and 2050 °C, respectively. The predicted Common reed Kcr_{TRP} varied between 0.11 and 0.71 with a seasonal average of 0.58 (Fig. 10a). The predicted Kcr_{TRP} for Cottonwood (Fig. 10b) varied between 0.07 and 0.64 with an average of 0.51. The Peach-leaf willow had higher Kcr_{TRP} values than other species, indicating higher rate of *TRP*, and the values varied between 0.18 and 0.77 with a seasonal average of 0.63. Overall, the relationships developed between *GDD* and Kcr_{TRP} in 2009 were able to mimic the measured Kcr_{TRP} values in 2010, indicating that the Kcr_{TRP} values were less impacted by the surface conditions (flooding) and have less variability between the years than the Kcr_{ET} values, suggesting that the Kcr_{TRP} approach is a more robust approach for quantifying water use rates of riparian vegetation.

3.6. Performance of developed growing degree days-based transpiration crop coefficients

The transpiration data used to assess the performance of the two-step approach developed in this study to estimate *TRP* rates of individual species are presented in Fig. 11a for 2009 and in Fig. 11b for 2010. The *TRP* data (from scaled up canopy resistance using measured leaf stomatal resistance) were obtained from Kabenge and Irmak (2012). The *TRP* rates in both years exhibited considerable day-to-day fluctuation as a function of response of plant physiological parameters to changes in environmental variables, including flooding. These datasets align with the fluctuations observed earlier in Kcr_{ET} (Fig. 8) and, especially in Kcr_{TRP} (Figs. 9 and 10) and explain the reasons for the fluctuations in Kcr_{ET} and Kcr_{TRP} (as a result of fluctuations in daily *TRP* rates). In 2009, *TRP* rates ranged from 0 to 10.2 mm/day with a seasonal average of 2.6 mm/day for Common reed; from 0 to 8.3 mm/day with a seasonal average of 2.3 mm/day for Cottonwood; and from 0 to 10.8 mm/day with a seasonal average of 2.8 mm/day for Peach-leaf willow. In 2010, *TRP* values were lower than those observed in 2009 and ranged from 0 to 7.9 mm/day with a seasonal average of 3.0 mm/day for Common reed; from 0 to 7.6 mm/day with a seasonal average of 2.7 mm/day for Cottonwood; and from 0 to

Table 2
Coefficients for five- or six-order polynomial equation (i.e., $Kcr = a_0\ GDD^5 + a_1\ GDD^4 - a_2\ GDD^3 + a_3\ GDD^2 + a_4\ GDD + a_5$) relating alfalfa-reference evapotranspiration crop coefficients (Kcr_{ET}) and transpiration (TRP) crop coefficients (Kcr_{TRP}) to growing degree days (GDD) for mixed riparian vegetation (5th order polynomial) and individual plant species (6th order polynomial) in 2009.

Coefficients for alfalfa-reference Kcr_{ET} and GDD relationships in 2009				
Polynomial coefficient	Mixed vegetation *ETa*	Common reed *TRP*	Peach-leaf willow *TRP*	Cottonwood *TRP*
a_0	4.80E−01	4.73E−01	4.71E−01	4.50E−01
a_1	−3.04E−04	4.14E−03	4.99E−03	3.84E−03
a_2	7.43E−06	−2.37E−05	−2.78E−05	2.54E−05
a_3	−1.36E−08	5.03E−08	5.88E−08	6.11E−08
a_4	9.20E−12	−4.91E−11	−5.81E−11	−6.77E−11
a_5	−2.16E−15	2.25E−14	2.70E−14	3.51E−14
a_6		−3.91E−18	−4.78E−18	−6.87E−18

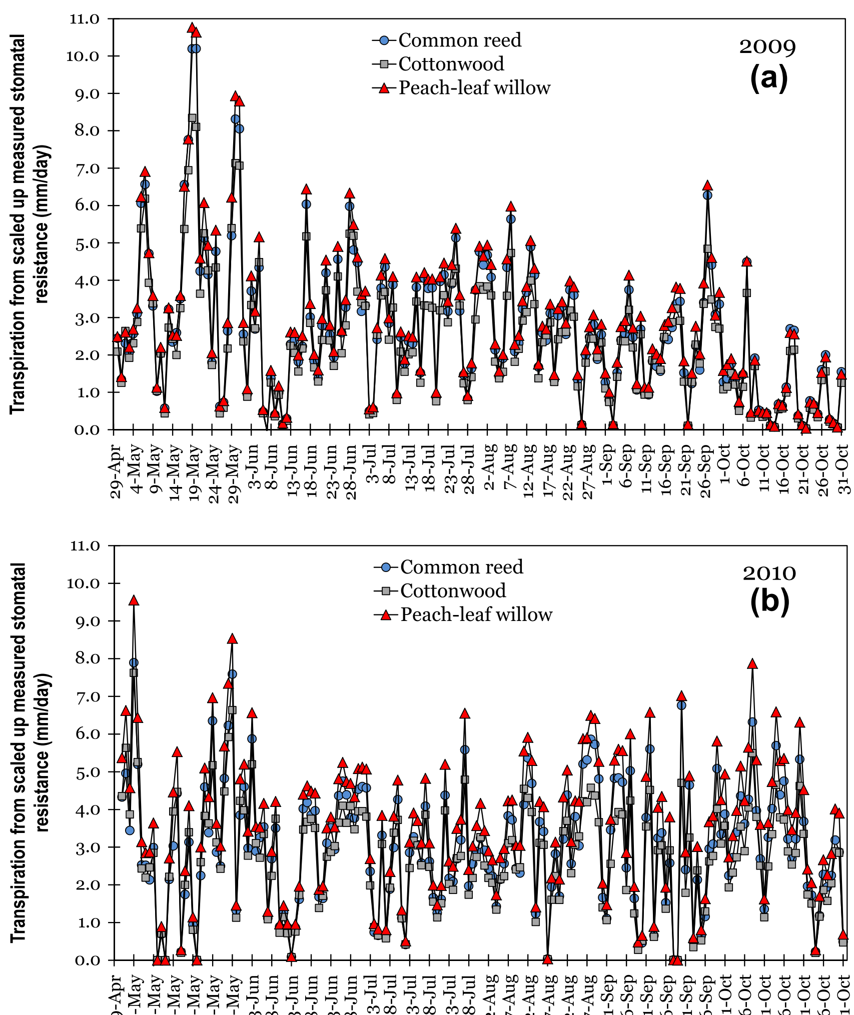

Fig. 11. Seasonal trends of daily plant transpiration (*TRP*) for Common reed, Cottonwood and Peach-leaf willow in 2009 (a) and 2010 (b). Transpiration values were obtained from scaled up canopy resistance from measured leaf-level stomatal resistance for individual species (data from Kabenge and Irmak, 2012).

9.6 mm/day with a seasonal average of 3.6 mm/day for Peach-leaf willow (Kabenge and Irmak, 2012). In both years, Peach-leaf willow had greater peak and seasonal average *TRP* rates than Common reed and Cottonwood.

To evaluate the performance of Kcr_{TRP} curves developed in 2009 for individual species by analyzing their estimates of *TRP* rates in 2010, the regression between modeled (observed) *TRP* and estimated *TRP* rates using $TRP = Kcr_{TRP} \times ETr$ approach for Common reed, Cottonwood and Peach-leaf willow for 2010 were performed (Fig. 12). The cumulative seasonal modeled and estimated (two-step approach developed in this study) *TRP* values for the three species are presented in Table 3. The Kcr_{TRP}-based seasonal *TRP* values were calculated from May 1 to August 31, May 1 to August 31 and from May 1 to September 6 for Common reed, Cottonwood and Peach-leaf willow, respectively (Table 3). In general, *TRP* rates estimated using the $Kcr_{TRP} \times ETr$ approach with the *TRP* coefficients developed in this study for all the vegetation species resulted in good estimates relative to the *TRP* data obtained by the scaling up approach. However, the approach with the *TRP* crop coefficients developed in this study using the *GDD* as the base scale tended to overestimate the *TRP* rates for lower values and underestimate for higher values. For all species, the *GDD*-based two-step approach, in

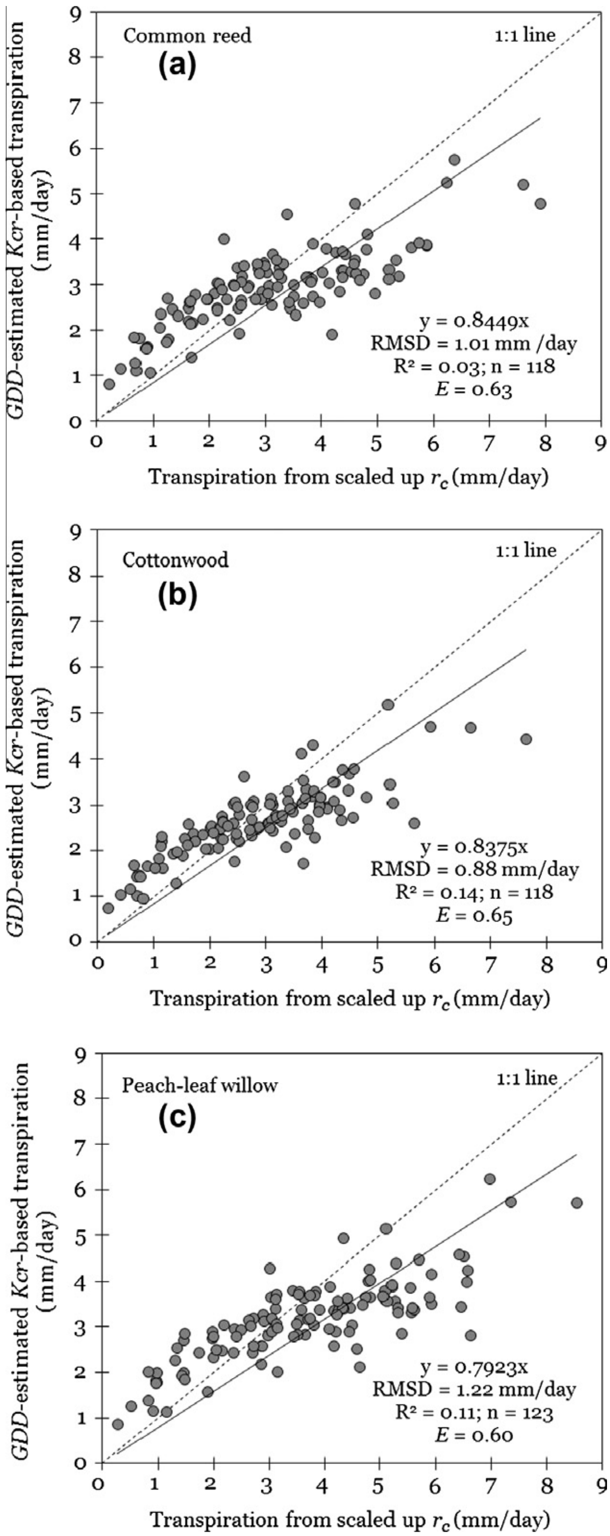

Fig. 12. Regression between modeled transpiration (*TRP*) rates based on two-step $TRP = Kcr_{TRP} \times ETr$ approach vs. *TRP* rates observed from scaled up canopy resistance from measured leaf-level stomatal resistance for individual species (data from Kabenge and Irmak, 2012) for Common reed (a), Cottonwood (b) and Peach-leaf willow (c) during the 2010 season. *RMSD* = root mean square difference; *n* = number of observations; *E* = Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970).

general, overestimated the modeled *TRP* rates for values lower than approximately 3.5–4.0 mm/day and underestimated the rates above that value. Although the R^2 values were low for all species, the *RMSD* values between the modeled and $Kcr_{TRP} \times ETr$ approach-estimated *TRP* were reasonable when considering the difficulties in modeling riparian vegetation transpiration rates (*RMSD* = 1.01, 0.88 and 1.22 mm/day for Common reed, Cottonwood and Peach-leaf willow, respectively; Fig. 12a–c). The Nash and Sutcliffe modeling efficiency (*E*) values were 0.63, 0.65 and 0.60 for Common reed, Cottonwood and Peach-leaf willow, respectively, indicating moderate/good performance. The two-step *TRP* modeling approach worked better for Cottonwood (lower *RMSD* and greater modeling efficiency) than Common reed and Peach-leaf willow.

The modeled 2010 seasonal cumulative (from May 1 through October) *TRP* values were 292, 316 and 409 mm for Common reed, Cottonwood and Peach-leaf willow, respectively. The associated $Kcr_{TRP} \times ETr$-based approach estimated seasonal cumulative *TRP* values were 345, 315 and 392 mm and the associated time period (May 1–August 31) modeled *TRP* values were 370, 342 and 452 mm for the Common reed, Cottonwood and Peach-leaf willow, respectively (Table 3). Similarly, the *TRP* rates estimated using the Kcr_{TRP} were close to the modeled *TRP* for all species with the largest difference (60 mm) occurring for the Peach-leaf willow. The two-step approach-estimated seasonal *TRP* values were within 7%, 8% and 13% of the modeled *TRP* values for the Common reed, Cottonwood and Peach-leaf willow, respectively, indicating a good performance of the two-step approach proposed in this for estimating *TRP* for riparian vegetation.

4. Summary and conclusions

Evapotranspiration crop coefficients (Kcr_{ET}) for a mixed riparian system and transpiration (*TRP*) crop coefficients (Kcr_{TRP}) for individual riparian plant species (Common reed, Cottonwood and Peach-leaf willow) were measured in two contrasting years in the Platte River Basin in central Nebraska, USA. This study is the first to develop and utilize *TRP* crop coefficient concept for estimating evaporative losses for riparian vegetation. Kcr_{ET} values showed considerable variation between the two years due to the differences in plant response to flooding in 2010. *TRP* crop coefficients for individual vegetation species were quantified from the *TRP* rates obtained using scaled up canopy resistance from measured leaf-level stomatal resistance for individual species. Kcr_{TRP} coefficients had less interannual variability than the Kcr_{ET} coefficients.

The *GDD*-based crop coefficients curves that were developed in 2009 were able to estimate *TRP* rates in 2010 with a reasonable accuracy. Using the *GDD* approach, the total *TRP* for Common reed, Cottonwood and Peach-leaf willow was estimated within 7%, 8% and 13% accuracy, respectively, using Kcr_{TRP}. The root mean square difference (*RMSD*) between $Kcr_{TRP} \times ETr$ approach-estimated and modeled (observed from scaled-up canopy resistance) *TRP* were 1.01, 0.88 and 1.22 mm/day for Common reed, Cottonwood and Peach-leaf willow, respectively. The Nash and Sutcliffe modeling efficiency (*E*) values were 0.63, 0.65 and 0.60 for Common reed, Cottonwood and Peach-leaf willow, respectively, indicating moderate/good performance. Generally, the Kcr_{ET} values of the mixed riparian vegetation were influenced by climatic variables and more so by surface characteristics to varying proportions in the 2009 and 2010 growing seasons. Response of the vegetation to flooding in 2010 was an important factor in interannual variability in Kcr_{ET} values. One significant advantage of *TRP* crop coefficients over the evapotranspiration crop coefficients is that they provide water use rate of individual species and also they are less impacted by the surface characteristics (e.g., flooding), making them more robust and transferable than the evapotranspiration crop coefficients between the locations with different surface characteristics.

Table 3
Modeled (from scaled up canopy resistance from measured leaf-level stomatal resistance for individual species) and transpiration crop coefficient-estimated cumulative seasonal transpiration for Common reed, Cottonwood, and Peach-leaf willow riparian species in 2010 in the Platte River Basin, Nebraska, USA.

Transpiration method	Riparian vegetation transpiration (mm)					
	Period	Common reed transpiration	Period	Cottonwood transpiration	Period	Peach-leaf willow transpiration
Modeled	May 1–August 31	370	May 1–August 31	342	May 1–September 6	452
$TRP = Kcr_{TRP} \times ETr$	May 1–August 31	345	May 1–August 31	315	May 1–September 6	392

The information presented in this study can be useful to enable water management agencies to estimate water use rates of riparian ecosystems which will also enable including riparian systems water use information in local and regional water balance analyses for more accurate and complete assessments of hydrologic water balances. Given the extremely complex nature of *TRP* rates of riparian species, the two-step approach of modeling of *TRP* developed and presented in this study performed well. The approach only needs *GDD* data to develop crop coefficients curves. Future research on the optimum base temperature for various vegetation species will improve application of the *GDD* approach to predict *TRP* crop coefficients and *TRP* rates. Further research is needed to assess the performance and applicability of the developed Kcr_{ET} and Kcr_{TRP} coefficient to estimate riparian vegetation water use in other regions.

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