2013

Evapotranspiration and surface energy balance of a common reed-dominated riparian system in the Platte River basin, central Nebraska

Isa Kabenge
Makerere University

Suat Irmak
University of Nebraska-Lincoln, suat.irmak@unl.edu

John E. Gilley
University of Nebraska-Lincoln, john.gilley@ars.usda.gov

George E. Meyer
University of Nebraska-Lincoln, gmeyer1@unl.edu

Stevan Z. Knezevic
University of Nebraska-Lincoln, sknezevic2@unl.edu

Authors

Isa Kabenge, Suat Irmak, John E. Gilley, George E. Meyer, Stevan Z. Knezevic, Timothy J. Arkebauer, Duane Woodward, and Milton Moravek

Evapotranspiration and Surface Energy Balance of a Common Reed-Dominated Riparian System in the Platte River Basin, Central Nebraska

I. Kabenge, S. Irmak, G. E. Meyer, J. E. Gilley, S. Knezevic,
T. J. Arkebauer, D. Woodward, M. Moravek

ABSTRACT. *Quantifying actual evapotranspiration (ET_a) of riparian zones is important for more robust water balance analyses that will enable better planning, managing, and allocating of water resources as well as developing strategies to protect delicate riparian ecosystem functions. The ET_a, sensible heat flux (H), net radiation (R_n), soil heat flux (G), meteorological variables (air temperature, T_a; incoming shortwave radiation, R_s; wind speed, u_3; relative humidity, RH; vapor pressure deficit, VPD; precipitation, etc.), and albedo were measured on an hourly time step, and leaf area index (LAI) and plant height were measured on a weekly basis for a common reed (*Phragmites australis*) dominated cottonwood (*Populus deltoides*) and peach-leaf willow (*Salix amygdaloides*) riparian plant community in 2009 and 2010 through extensive field campaigns conducted in the Platte River basin in central Nebraska. The two growing seasons were contrasted by warmer air temperatures, higher precipitation, and presence of flood water on the surface during the 2010 season. The seasonal variations of daily average ET_a were mainly controlled by R_n and air temperature. In 2009, total ET_a and precipitation were 679 mm and 280 mm, respectively, and the values were substantially greater in 2010 (982 mm and 508 mm, respectively). The seasonal daily ET_a for the mixed plant community ranged from 0.5 to 8.5 mm d^{-1} with a seasonal average of 3.7 mm d^{-1} in 2009 and from 0.5 to 11 mm d^{-1} with a seasonal average of 5.5 mm d^{-1} in 2010. In 2010, ET_a varied widely with meteorological conditions and in response to variations in phenology of the vegetation to flooding. In 2009, on a seasonal average basis, a total of 77% and 14% of the available energy was partitioned into ET_a and H, respectively. In 2010, over 90% and -12% (negative due to flooding) of the available energy was partitioned into ET_a and H, respectively. The research results presented here provide valuable ET_a data and information for enhancing the understanding of the interactions between the surface/vegetation conditions and the surrounding microclimate and surface energy balance for mixed riparian vegetation. The results of this research should aid water managers and decision/policy makers in accounting for water use rates of phragmites-dominated cottonwood and peach-leaf willow riparian plant communities in water balance analyses to make better-informed water resources planning and management decisions.*

Keywords. *Bowen ratio, Common reed, Cottonwood, Energy balance, Evapotranspiration, Peach-leaf willow, Riparian vegetation.*

T he amount of water used by riparian zones is among the top third of water depletions (Cleverly et al., 2006) of various ecosystems. Actual evapotrans-

The authors are **Isa Kabenge, ASABE Member,** Lecturer, College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda; **Suat Irmak, ASABE Member,** Professor, **George E. Meyer, ASABE Member,** Professor, and **John E. Gilley, ASABE Member,** Professor, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska; **Steven Knezevic,** Professor, and **Timothy J. Arkebauer,** Professor, Department of Agronomy, University of Nebraska-Lincoln, Lincoln, Nebraska; **Duane Woodward, ASABE Member,** Hydrologist, and **Milton Moravek,** Assistant Manager, Central Platte Natural Resources District, Grand Island, Nebraska. **Corresponding author:** Suat Irmak, 239 L.W. Chase Hall, University of Nebraska-Lincoln, Lincoln, NE 68583; phone: 402-472-4865; e-mail: sirmak2@unl.edu.

piration (ET_a) from riparian zones can be a significant component of an overall water balance of the ecosystem in a given watershed, and its accurate quantification is essential to properly evaluate the potential distribution and use of water in rivers, lakes, and wetlands for human and environmental needs (Nagler et al., 2005). Quantifying riparian zone ET_a is also important for more accurate planning, managing, and allocating of water resources for agricultural and other uses, as well as for developing strategies to meet the water demands of the ecosystems themselves to protect delicate ecosystem functions. Depending on the ecosystem and watershed functions and roles in a region, in some cases, the amount of transpiration by riparian vegetation is considered water that would otherwise be used for irrigation of agricultural crops or for domestic, industrial, mining, and other uses (Drexler et al., 2004). However, riparian zones also serve many fundamental functions of ecosystems and provide benefits to the health of such systems, including providing quality habitat to aquatic flora and fauna, recharging groundwater, storing

flood waters, nutrient filtering, buffering, and recycling, as well as economic benefits in some regions. Riparian zones also support a diverse group of wildlife species, including migrating endangered species of birds, reptiles, amphibians, insects, and mammals (Blossey et al., 2002; Lafleur, 2008) and support rich, diverse, and often rare vegetation assemblies and are areas of high biodiversity. They are, thus, a critical habitat for the survival of a variety of species, many of which are of significant conservation value for the ecosystems.

Riparian systems in the Platte River valley in Nebraska and elsewhere in the U.S. have been invaded by non-native plant species such as common reed, peach-leaf willow, and cottonwood that outcompete most of the native plants, change wetland hydrology, alter wildlife habitat, and increase fire danger (Blossey, 1999; Amsberry et al., 2000; Blossey et al., 2002; Mal and Narine, 2004; Knezevic et al., 2008). The state of Nebraska designated common reed as a noxious weed, legally defined as "a destructive or harmful pest." Concerns about increasingly limited availability of water resources for agricultural and other demands, especially due to recent drought conditions coupled with extensive water withdrawals in agricultural states such as Nebraska, prompted policy and decision makers as well as water managers and users to study water use rates of various riparian systems to better quantify the water balances for short-term and long-term planning, allocation, and management. Riparian zones are one of the key vegetation surfaces where water use information is lacking in such evaluations. While Nebraska has over 3.5 million ha of irrigated croplands, and water balance analyses have historically focused on irrigated agricultural crops, over 600,000 ha of riparian zones also play an important role in the water balance of the state, and their water use rates have to be accounted for in such analyses.

While evapotranspiration by riparian vegetation is an important component in determining regional water budgets, in most cases it is poorly quantified (Nagler et al., 2007), and interactions between water loss from the riparian zone vs. plant physiological functions and meteorological conditions are complex and not well understood (Peacock and Hess, 2004). Based on water use results reported in the scientific literature, there is uncertainty in terms of the amount of water used by various riparian zones (Goodrich et al., 2000) in various climates, as well as for the same riparian species in the same climatic conditions. Differences in water use amounts among studies can be partially attributed to the difficulty in accurately estimating ET_a over riparian ecosystems, which are mosaics of complex systems usually comprised of mixed vegetation communities that have significantly different canopy structures and different amounts of bare soil and open water. In addition, Peacock and Hess (2004) suggested that the variability in wetland and riparian ET_a findings may be attributed to the lack of recognition of the role of transpiration of mixed and complex vegetation. The range of measurement scales, varying from leaf level to stand level, also contributes to some of the differences in the reported results. Method used to quantify water use and differences in location characteristics (e.g., climate, soil,

water level, and other hydrological differences in riparian ecosystems) can also cause differences in the amount of water use reported for the same species. Riparian zones, by their nature, are a challenging environment in which to measure ET_a because they are not easily accessed, and in most cases such zones have non-uniform shapes, hydrology, topography, and species composition.

Various methods have been used to quantify riparian vegetation ET_a, including the water balance approach and sap flow measurement (Mac Nish et al., 2000; Goodrich et al., 2000; Schaeffer et al., 2000; Nagler et al., 2003, 2005, 2007), the eddy covariance system (Nagler et al., 2005; Cleverly et al., 2006), and the Bowen ratio energy balance system (BREBS) (Drexler et al., 2004; Peacock and Hess, 2004; Nagler et al., 2005; Irmak et al., 2012). The Bowen ratio method is regarded as one of the most accurate methods of estimating ET_a (Peacock and Hess, 2004). The method is reliable and provides robust ET_a values for riparian areas with small values of Bowen ratio (Angus and Watts, 1984; Drexler et al., 2004). BREBS has been developed from the principle of energy balance, as described by Bowen (1926). Given the fact that there are very limited data and information on the measurement of riparian ET_a, there is an imperative need for these kinds of measurements to increase in number and intensity due to the great diversity among riparian ecosystems in terms of species composition, physiological properties, physical structure, hydrology, topography, soil characteristics, microclimatic and climatic conditions, and the great diversity in management practices. The overall objective of this research was to quantify ET_a and other surface energy fluxes, including net radiation, soil heat flux, and sensible heat flux, in a phragmites (common reed) dominated peach-leaf willow and cottonwood riparian plant community in the Platte River basin in central Nebraska. We also investigated the interaction of the energy balance components with the riparian vegetation leaf area index (LAI) and examined seasonal variations of energy components and their interactions with meteorological variables. Partitioning of available energy into latent and sensible heat flux was also quantified for two years.

MATERIALS AND METHODS

RESEARCH SITE

Extensive field measurement campaigns were conducted in 2009 and 2010. This research is a subcomponent of a large water and energy flux measurement project, the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX; Irmak, 2010). The research site is located on an island in the Platte River basin in central Nebraska near Central City, in Merrick County, Nebraska (fig. 1). The coordinates of the experimental site where the flux tower was installed are 41° 7.939′ N and 97° 55.52′ W at an elevation of 507 m above mean sea level. The experimental site is a sandbar island measuring 508 m long and 120 to 140 m wide with a northeast-southwest orientation in the Platte River and formed at a braided area. Common reed started to infest and invade the island in
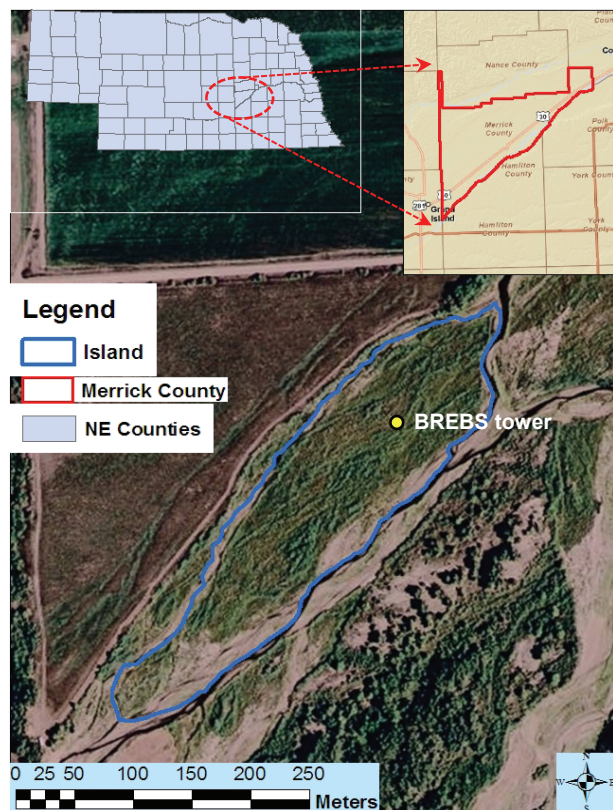
Figure 1. Location of the Bowen ratio energy balance system (BREBS) at the phragmites-dominated cottonwood and peach-leaf willow riparian plant community in the Platte River basin near Central City, Nebraska.

early 2006 and became the dominant species at the site by late 2008. The cottonwood and peach-leaf willow trees varied between four and six years old. The soil at the site is loamy sand (Gothenburg mixed, mesic Typic Psamma-quents) with a particle size distribution of 87.5% sand, 10.3% silt, and 2.2% clay (Irmak, 2010). The soil was washed onto the site by the Platte River flow over time and created the sandbar. Over time, however, the soils are gaining some organic matter as a result of decaying plant material during and at the end of each growing season. Below the top 0.20 to 0.30 m depth, the soil usually remains wet or saturated due to a high water table on the island. The Platte River in central Nebraska lies within the Central Great Plains ecoregion, and it is wide, braided, and shallow with a low-gradient sand bed draining approximately 137,000 km^2 from Colorado, Wyoming, and Nebraska. Mean monthly river flows range from nearly bank full in June (72 m^3 s^{-1}) to usually low flows in August (18 m^3 s^{-1}), exposing a substantial area of the river bed (Henszey et al., 2004).

For a 116-year period (1893-2008) around the study area, the highest recorded daily maximum temperature was 46.7°C in 1936, while the lowest daily maximum temperature was -24.6°C recorded in 1899 (Irmak et al., 2012). The highest recorded daily minimum temperature was 26.7°C in 1934, while the lowest daily minimum temperature was -38.0°C, recorded in 1912. The long-term

daily average temperature for the 116-year period is 10.5°C. The maximum annual precipitation of 1,000 mm was recorded in 2008, and a minimum of 356 mm was recorded in 1966, while the long-term average annual precipitation is 649 mm. The daily maximum precipitation value was recorded as 123 mm in 1967. Observed long-term average daily maximum, minimum, and average wind speed (u_3) values during 1987-2008 were 5.9, 0.59, and 2.7 m s^{-1}, respectively (Irmak et al., 2012).

MODIFIED STEP-POINT METHOD TO DETERMINE SPECIES COMPOSITION AND DAUBENMIRE COVER CLASS METHOD TO DETERMINE VEGETATION COVER

Composition of each plant species found on the experimental site was determined on 30 July 2010 using a basal-hit species composition method. The modified step-point sampling procedure described by Owensby (1973) was followed to determine the species composition. Two hundred sampling points (about 10 m apart) were placed on randomized transects throughout the experimental site. Despite being random, the transects were systematically controlled to be in the northwest-southeast direction, perpendicular to the general orientation of the island. The modified step-point frame was lowered perpendicularly to the soil surface in front of the sampler's boot. The sampling point was offset from the initial ground contact of the frame to alleviate subconscious placement of the sampler. Species recorded were those whose bases were in contact with the sampling point.

The Daubenmire cover class method is a widely used measure of percent cover of plant species because it is not biased by the size or distribution of individual species (Floyd and Anderson, 1987). The canopy coverage technique described by Daubenmire (1959) was used to estimate cover of each plant species on the island. A 0.20 × 0.50 m quadrant was used to outline 200 sampling plot placements about 10 m apart along randomized transects throughout the island. The coverage, interpreted as a vertical projection of a polygon drawn along the edges of the undisturbed canopy, was estimated separately for each species in each plot. Percentage of the quadrant's area covered by each plant species' canopy was assigned to one of six classes; 0% to 5%, 5% to 25%, 25% to 50%, 50% to 75%, 75% to 95%, and 95% to 100% in the field. It was assumed that a plant species covered all area within the horizontal boundary (outline) coverage of its canopy. Subsequently, midpoints of the cover classes (2.5%, 15%, 37.5%, 62.5%, 85%, and 97.5%) were used to calculate the mean coverage using the assumption that actual cover values are uniformly distributed about the midpoints of each cover class. Although Daubenmire (1959) suggested that the technique is applicable to plants that are not much more than 1 m tall, Floyd and Anderson (1987) successfully applied the method to sample cover in sagebrush with plants that could grow as high as 3 m. The percent coverage relates individual plant species to the total area of the island. If the sum of percent coverage of different plant species is greater than 100%, then the canopy is composed of overlapping strata for the individual plant species.

BOWEN RATIO ENERGY BALANCE METHOD TO MEASURE WATER VAPOR AND ENERGY FLUXES

The Bowen ratio energy balance (BREB) method is a robust method to quantify latent heat flux (ET_a) in which the temperature and humidity gradients between the two vertical points are measured to determine the Bowen ratio (β). The Bowen ratio (Bowen, 1926) is defined as the ratio of H of a surface to ET_a (Bowen 1926; Fritschen, 1965; Perez et al., 1999; Drexler et al., 2004). This approach was first proposed by Bowen (1926) as a method to determine evaporation from any water surface in terms of the net radiant energy absorbed by the water and the heat energy stored in the water. In general, if $\beta > 1$, more turbulent energy is returned to the atmosphere as sensible heat, usually indicating a dry climate, except in extensively irrigated areas, while $\beta < 1$ is usually an indication of a more humid climate. The general energy balance equation is:

$$R_n = G + H + ET + M + S \qquad (1)$$

where R_n is net radiation (W m^{-2}), G is heat flux to and from the soil and/or water (W m^{-2}), H is sensible heat flux density (W m^{-2}), ET is latent heat flux (W m^{-2}), M is energy flux used in photosynthesis and respiration (W m^{-2}), and S is energy transfer (storage) into and out of plant tissue (W m^{-2}). Depending on the vegetation surface characteristics and other factors, M and S are generally small and assumed not to have much contribution to the energy balance. By rearranging the summarized energy balance equation (eq. 1), ET can be expressed using the BREB method as:

$$ET = (R_n - G) / (1 + \beta) \qquad (2)$$

and sensible heat flux can be expressed as:

$$H = \beta[(R_n - G) / (1 + \beta)] \qquad (3)$$

where β is the Bowen ratio, which is defined as:

$$\beta = H / ET \qquad (4)$$

Using the flux gradient theory, ET and H can be expressed as functions of the turbulent transfer coefficient and the gradient of a relevant property. Generally, values of turbulent transfer coefficients for heat and vapor (K_h and K_v) are not easily obtainable, but BREB theory assumes equality of the eddy transfer coefficients for sensible heat and water vapor (Kanemasu, 1979; Peacock and Hess, 2004). Earlier studies confirmed this equality under a wide variety of conditions (Tanner, 1960; Dyer, 1974; Yaglom, 1977). Substituting the expressions for H and ET, β can be expressed as:

$$\beta = ([(T_2 - T_1) / (e_2 - e_1)] \qquad (5)$$

where $(T_2 - T_1)$ is the temperature difference between the two heights in a vertical direction (°C), and $(e_2 - e_1)$ is the difference in actual vapor pressure of the air between the two heights in a vertical direction (kPa). Drexler et al. (2004) pointed out that near sunrise and sunset, errors in BREB-measured ET may occur as β tends to approach -1 and the denominator in equation 2 approaches zero, and the BREB method can provide unreasonable flux data. In such cases, ET can be estimated from alternative methods, such as an aerodynamic method. However, it is worth noting that the sunrise and sunset duration is a very small fraction of the day and the energy fluxes are very small; thus, the error introduced in daily totals of ET is also quite small (Angus and Watts, 1984). The BREB method is more accurate when β is close to zero, but the relative error in ET grows as the absolute magnitude of β increases.

Although the BREB method has been successfully applied in riparian areas, energy balance estimates can be confounded by sensible heat advection, which is the horizontal movement of momentum, energy, or other scalar quantities across a heterogeneous landscape (Brutsaert, 1982; Cleverly et al., 2006). Advection in riparian zones occurs when wet surfaces in the riparian ecosystems are located adjacent to dry surfaces and is most easily identified when the evaporative fraction, given by the ratio of latent heat flux to net radiation, is greater than unity. Since ET tends to be high in riparian ecosystems, upward positive H values are likely to be small most of the time; thus, small β values can be expected.

MEASUREMENT OF SURFACE ENERGY FLUXES AND METEOROLOGICAL VARIABLES

The flux data measured with the BREB system (Radiation and Energy Balance Systems, Inc., Bellevue, Wash.) 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 ten deluxe-version BREB systems and one eddy covariance system over various vegetation. NEBFLUX measures all surface energy flux variables, meteorological variables, plant physiological parameters, soil water content (every 0.30 m up to 1.80 m on an hourly basis), soil characteristics, and agronomical components, including biomass production and/or yield, for a significant number of different vegetation surfaces. All NEBFLUX towers operate on an hourly basis throughout the year. The integrated surface energy fluxes, including evapotranspiration, and meteorological variables, including air temperature, relative humidity, incoming shortwave radiation, wind speed and direction, and precipitation, for plant communities on the island were measured using the BREB system. Measurement procedures used for the other required variables in the energy balance equation (eq. 1) are described in the following sections.

A model REBS Q*7.1 net radiometer (Radiation and Energy Balance Systems, Inc., Bellevue, Wash.) was used to measure net radiation. Incoming and outgoing shortwave and longwave radiation were measured simultaneously using a REBS model THRDS7.1 double-sided total hemispherical radiometer that is sensitive to wavelengths from 0.25 to 60 μm (Irmak, 2010). Surface albedo was calculated from these measurements as the ratio of outgoing reflected shortwave to incoming shortwave radiation. The radiometers were mounted sufficiently high to obtain a clear view of the underlying surface being measured with minimal influence from the mounting tower, other objects, or surrounding canopy surfaces that might

affect albedo or longwave radiation from the surface that was measured. Proper leveling of the radiometer domes was maintained to ensure accuracy. Soil heat flux was measured using REBS HFT-3.1 heat flux plates and REBS STP-1 soil thermocouples. Three soil heat flux plates were placed at depths between 0.05 and 0.06 m below the soil surface. Three soil thermocouples were installed near soil heat flux plates at depths 0.05 to 0.06 m below the soil surface. Soil heat flux measurements were adjusted for soil temperature and moisture, as measured by three REBS SMP1R soil moisture probes installed in the same location as the soil temperature sensors and soil heat flux plates (Irmak, 2010).

Air temperature and relative humidity gradients were measured using two platinum resistance thermometers and monolithic capacitive humidity sensors (REBS models THP04015 and THP04016, respectively) with resolutions of 0.0055°C for temperature and 0.033% for relative humidity. Measured temperature and relative humidity gradients were used to calculate sensible heat flux density, Bowen ratio, and vapor pressure deficit. The BREB system included a barometric pressure sensor (model 276, Setra Systems, Inc., Boxborough, Mass.) for measuring barometric pressure. Precipitation was recorded using a tipping-bucket rain gauge (model TR-525, Texas Electronics, Inc., Dallas, Tex.). Wind speed and direction above the canopy were measured using a cup anemometer (model 034B, Met One Instruments, Grant Pass, Ore.) that had a wind speed range of 0 to 44.7 m s^{-1} and threshold wind velocity of 0.28 m s^{-1}. The BREB system used an automatic exchange mechanism that physically exchanged the temperature and humidity sensors every 15 min at two heights above the canopy to minimize the impact of any bias in the top and bottom temperature and humidity sensors on the Bowen ratio calculations. All variables were sampled every 60 s, averaged and recorded on an hourly basis using a model CR10X datalogger and AM416 relay multiplexer (Campbell Scientific, Inc., Logan, Utah) (Irmak, 2010; Irmak and Mutiibwa, 2010). Extensive maintenance procedures that were described by Irmak (2010) were followed weekly to ensure continuous and good-quality data collection throughout the year.

LEAF AREA INDEX

A plant canopy analyzer (model LAI 2000, Li-Cor Biosciences, Lincoln, Neb.) was used to measure leaf area index (LAI). The instrument measures how much light is attenuated at several angles as it passes through the canopy and calculates LAI according to the Beer-Lamberts law. According to the Beer-Lamberts law, light transmittance through a canopy depends on foliage orientation (which affects the light extinction coefficient), foliage density (which affects the absorber concentration), and path length (Li-Cor, 2010; Irmak and Mutiibwa, 2008). Measurements were made above and below the canopy to determine canopy light interception at five angles, from which LAI is computed using a model of radiative transfer in vegetative canopies. For each LAI value recorded, one reading above the canopy was taken and four other readings at different locations in the experimental site 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. On each measurement day, a total of 24 to 30 LAI measurements were made from various locations on the island to represent an average LAI of the mixed plant community, and values were averaged for the day.

RESULTS AND DISCUSSION
SPECIES COMPOSITION AND COVERAGE

Table 1 presents species composition and coverage measured on 30 July 2010. Plant species identified on the island included common reed (*Phragmites australis*), purple loosestrife (*Lythrum salicaria*), sandbar willow (*Salix exigua* subsp. *interior*), sedge (*Carex* sp.), cottonwood (*Populus deltoides*), reed canarygrass (*Phalaris arundinacea*), peach-leaf willow (*Salix amygdaloides*), swamp smartweed (*Polygonum amphibium*), wild indigo (*Amorpha fruticosa*), annual sunflower (*Helianthus annuus*), and common cattail (*Typha latifolia*). Common reed established continuous monoculture and dominant stands on over 1/3 of the island area, especially in the southern part and along the edges. Other parts of the island were dominated by willow stands, while the rest of the island area was a mixture of cottonwood, common reed, willow, purple loosestrife, and other plant species. Purple loosestrife formed the undergrowth throughout most of the island, especially during the second half of the 2010 growing season. Willow species had a small composition but large coverage because they have a horizontal growth habit, meaning that a single tree has a large canopy cover per unit area. Because the canopy of different plant species form overlapping strata, the sum of percentage coverage was greater than 100%.

METEOROLOGICAL CONDITIONS

Table 2 shows measured monthly average meteorological variables. For comparison, long-term (1987-2008) monthly average values of climate data for Central City were also included. The research site was flooded during the 2010 season with the water on the surface rising up to 0.70 to 0.90 m in June and July. The site was characterized by strong seasonal variation in air

Table 1. Measured vegetation percent composition and canopy cover (30 July 2010).

Vegetation	Species Composition (%)	Canopy Cover (%)
Common reed (*Phragmites australis*)	56.5	55.2
Purple loosestrife (*Lythrum salicaria*)	28.0	24.6
Sandbar willow (*Salix exigua* subsp. *interior*)	6.0	17.7
Sedge (*Carex* sp.)	5.0	1.1
Cottonwood (*Populus deltoides*)	6.0	6.6
Reed canarygrass (*Phalaris arundinacea*)	2.5	2.0
Peach-leaf willow (*Salix amygdaloides*)	0.5	11.7
Swamp smartweed (*Polygonum amphibium*)	0.5	0.01
Wild indigo (*Amorpha fruticosa*)	0.0	0.8
Annual sunflower (*Helianthus annuus*)	0.0	3.2
Common cattail (*Typha latifolia*)	0.0	1.0

Table 2. Meteorological variables measured between May and October in 2009 and 2010 at the experimental site.[a]

Meteorological Variable	Month					
	May	June	July	Aug.	Sept.	Oct.
2009						
u_3 (m s^{-1})	2.3	1.5	1.2	1.3	1.1	1.9
T_{a_max} (°C)	22.8	24.9	26.4	25.9	22.5	11.6
T_{a_min} (°C)	10.5	15.4	15.0	14.7	10.8	2.2
RH_{avg} (%)	66	80	80	81	78	79
R_s (W m^{-2})	257	242	273	259	168	98
R_n (W m^{-2})	152	155	176	167	106	53
VPD (kPa)	0.95	0.68	0.68	0.65	0.59	0.31
Precip. (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
T_{a_max} (°C)	20.7	27.0	28.3	28.9	24.3	20.2
T_{a_min} (°C)	10.0	17.3	19.5	18.0	11.0	4.9
RH_{avg} (%)	72	80	84	81	78	69
R_s (W m^{-2})	243	276	268	262	183	161
R_n (W m^{-2})	153	179	173	163	106	71
VPD (kPa)	0.73	0.75	0.63	0.75	0.70	0.76
Precip. (mm)	81	163	120	96	34	14
Long-term average (1987-2008)						
u_3 (m s^{-1})	3.1	2.6	2.0	1.9	2.3	2.5
T_{a_max} (°C)	23.8	28.6	30.6	29.7	26.2	19.8
T_{a_min} (°C)	10.9	16.2	18.7	17.7	12.4	5.4
RH_{avg} (%)	68	70	76	76	68	65
R_s (W m^{-2})	220	256	254	220	182	129
R_n (W m^{-2})	131	156	155	130	95	54
VPD (kPa)	0.94	1.15	1.04	0.97	1.07	0.81
Precip. (mm)	120	94	91	70	72	50

[a] u_3 = wind speed at 3 m, T_{a_max} = maximum air temperature, T_{a_min} = minimum air temperature, RH_{avg} = average relative humidity, R_s = incoming shortwave radiation, and R_n = net radiation.

temperature. Mean daily temperature during the 2009 season was 16.9°C, which was substantially higher than the long-term daily average value of 10.5°C. The 2010 growing season was warmer than the average, with a seasonal mean daily temperature of 19.2°C. Overall, the 2010 season was warmer than the 2009 season. In 2009, the mean daily relative humidity varied from 46.4% to 100%, with a seasonal average of 77.9%, but most days of the season had mean values between 60% and 85%. In 2010, the seasonal average relative humidity was 77.4%, but most days of the season had mean values between 70% and 90%. Vapor pressure deficit (VPD) generally had a decreasing trend during the 2009 season, ranging from near 0 to 1.91 kPa, with a seasonal average of 0.64 kPa. In 2010, VPD ranged from 0 to 1.77 kPa, with a seasonal average of 0.72 kPa, which was higher than 2009 due to warmer temperatures. In 2009, daily average maximum and minimum recorded wind speed were 4.1 and 0.4 m s^{-1}, respectively, and the seasonal average (1.6 m s^{-1}) was lower than the long-term average (2.7 m s^{-1}). In 2010, daily average maximum and minimum wind speed were 3.9 and 0.4 m s^{-1}, respectively, with a lower seasonal average of 1.4 m s^{-1}.

The study site received approximately 280 mm of precipitation during the period of May to October 2009 (fig. 2a). The growing season was drier than the average, and accumulated precipitation was 43% less than the long-term (1987-2008) average value of 490 mm for the same period. Although most of the precipitation was received between mid-May and mid-August, June accumulated 63% of the total precipitation received during the season due to larger precipitation events that occurred more frequently.

From May to October 2010, the site received approximately 510 mm of precipitation (fig. 2b). The 2010 growing season accumulated 4% more precipitation than the long-term (1987-2008) average (490 mm) for the same period. Precipitation in 2010 was more evenly distributed as compared with the 2009 season.

LEAF AREA INDEX

Measured LAI values for individual species are presented in figure 3, and the average mixed plant community LAI values are presented in figure 4. Common reed had the greatest LAI in both years, with a maximum value of 6.0, occurring from mid-July to early August in both years. For all species, LAI was greater in the drier year (2009) until early August and was greater in 2010 after late July and early August as flooding increased the LAI for all species. Seasonal average LAI for common reed, cottonwood, and peach-leaf willow were 4.3, 2.4, and 2.5, respectively, in 2009 and 4.2, 2.5, and 2.4, respectively, in 2010. The seasonal average LAI values were very similar for each species between the two years, and the standard deviations were usually greater in mid-season than in the early and late season. Average LAI (fig. 4) was 1.6 in the early season (mid-May), peaked in mid-August as close to 5.0, decreased steadily to a minimum of 1.2 in early October, and the last recorded value was 2.10 in mid-October. Our results are comparable with those measured by Burba et al. (1999), who reported mid-August peak LAI of 2.6 to 3.9 for different wetlands dominated by common reed. Based on our visual observations, the canopy structure, and in turn LAI, in our experiments was affected by strong wind gusts during the season, causing lodging and bending primarily of common reed and other plant species in some parts of the experimental site. For example, between 19 and 28 May and after 9 October, the lodging of the vegetation due to very high wind gusts may explain the spikes in LAI (figs. 3 and 4) measured during those periods. The impact of flooding on LAI in 2010 seems to be associated with a general decrease in LAI in mid-July followed by a steady increase toward end of the season. The vegetation generally seems to have undergone a slow development stage due to waterlogging and, as a result, a reduced amount of root zone O_2 content (Hook, 1984; Kozlowski, 1997; Kozlowski and Pallardy, 2002) from mid-June to late August, which resulted in strain on the vegetation.

SURFACE ALBEDO

Most of the 2009 growing season albedo values were below 0.20, and only four days had values greater than 0.20 (fig. 5). All four days with $\alpha > 0.20$ had average relative humidity of 75% or greater, and they occurred in the early season in May with partial canopy cover and after senescence in October. Lafleur (2008) noted that reed marshes tend to have lower albedo values because they have taller vegetation that intercepts a higher proportion of radiation. Although albedo was generally gradually decreasing toward the end of October, an early snow event that occurred on 9 October 2009 was the cause for the spike in albedo to 0.22 on that day (fig. 5). Albedo was affected
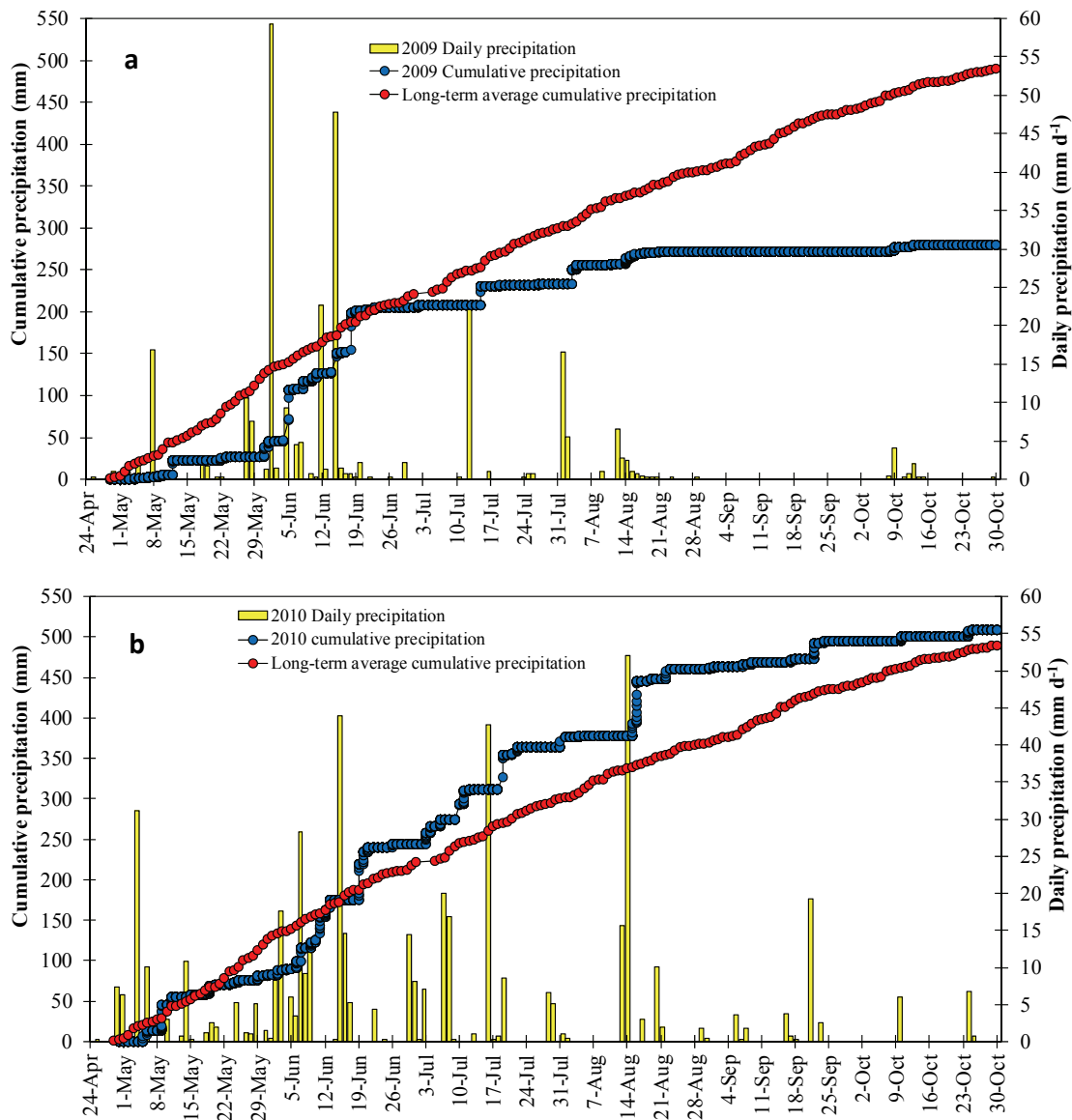
Figure 2. Long-term average and (a) 2009 and (b) 2010 growing season cumulative precipitation and daily precipitation.

by flooding events in 2010. There was a noticeable decrease in albedo during the second half of June due to the presence of ponding water on the surface. Albedo stayed relatively constant in July, varying between 0.14 and 0.19. Unlike the 2009 season, albedo continued to increase during August until the end of the season. Thus, on average, the 2010 albedo values were lower than the 2009 values until the end of July, when the effect of water on the surface was reduced by the increased fraction of ground cover by the vegetation. Seasonal average albedo for 2009 and 2010 was 0.16. Lafleur et al. (1987) reported average albedo of 0.18 to 0.20 for sedge-dominated wetland with a dry surface, 0.11 to 0.19 for sedge-dominated wetland with a wet surface, and 0.11 to 0.18 for willow-dominated wetland forest. Burba et al. (1999) reported albedo of 0.12 to 0.16 for common reed. Lafleur (2008) reported a general range of 0.10 to 0.18 for mid-summer albedo with an overall mean of 0.15, almost the same value as the seasonal average value measured in this study.

SOIL HEAT FLUX AND SENSIBLE HEAT FLUX

Daily soil heat flux showed a high degree of fluctuation at the beginning of the 2009 season from early May until about mid-June. Fluctuation gradually decreased as the season progressed (fig. 6a) due to increasing shading of the soil surface by the vegetation canopy, normalizing and stabilizing G, resulting in reduction of energy exchange between soil and surface. Since G is primarily a function of R_n, large magnitudes of G are expected for the low vegetation cover periods of the season due to effective penetration of radiation (Rose, 2004). Implicitly, G is also controlled by the albedo. Toward the end of the season G was reduced by lower values of R_n, resulting from the shorter day length. Negative values of G occurred typically from 19:00-20:00 to 08:00-09:00, indicating that G was an important source of energy for the nocturnal energy balance (Irmak, 2011; Skaggs and Irmak, 2011). Negative G values during nighttime can be explained by the transport of stored heat from the ground to the cooler surrounding surface
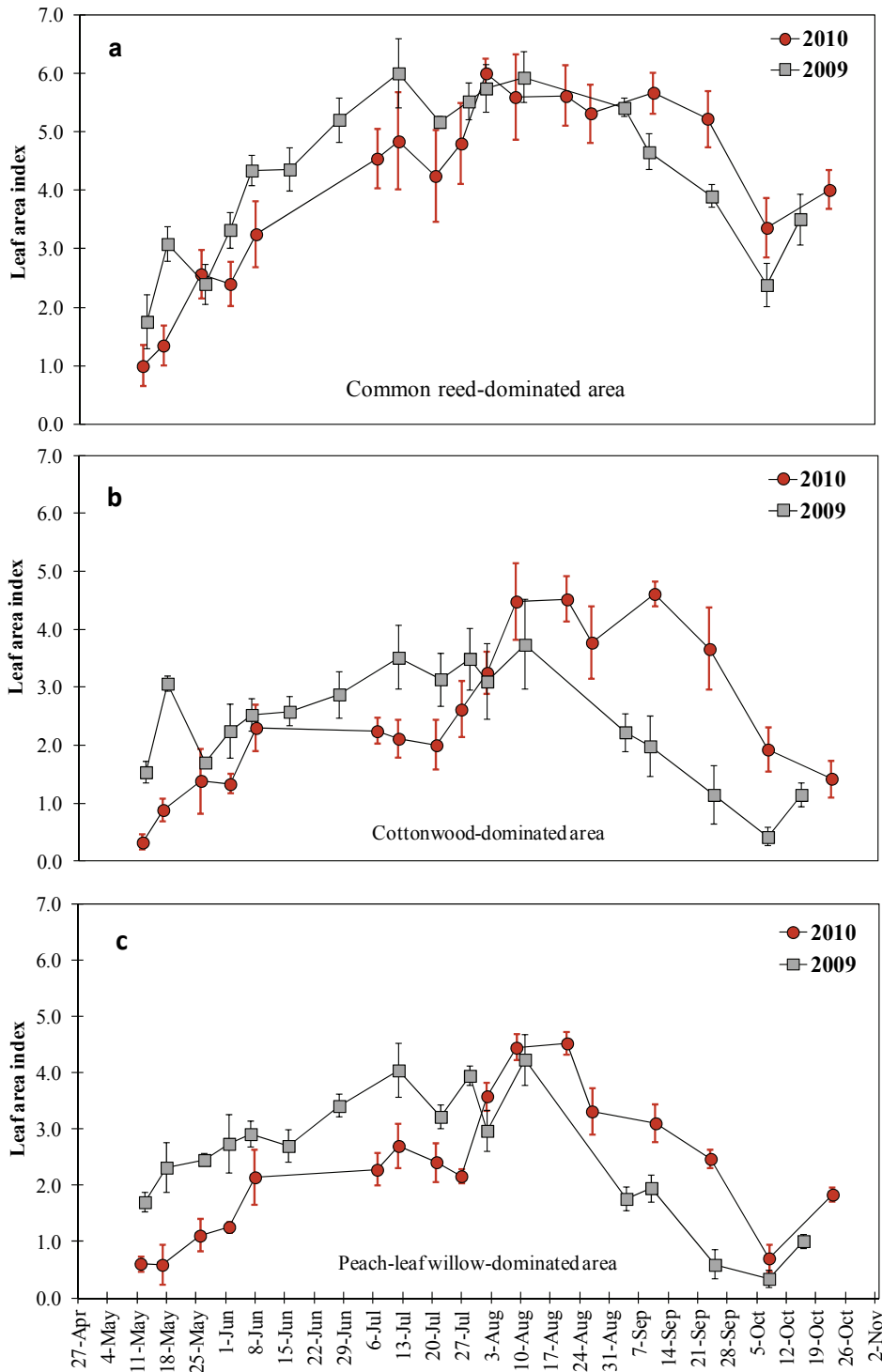
Figure 3. Leaf area index (LAI) for areas dominated by (a) common reed, (b) cottonwood, and (c) and peach-leaf willow at the experimental site in the 2009 and 2010 growing seasons. Each data point for each species represents an average of 24 to 30 LAI measurements. Vertical bars indicate standard deviations.

(Rott and Obleitner, 1992; Rose, 2004; Irmak, 2011). For the portion of the day when G was positive, soil acts as a considerable sink for energy. Since loss of heat at night was comparable to heat gain during daytime, daily G was small in comparison with R_n, ET_a, and H.

In 2010, daily average G values ranged between -13 and 46 W m^{-2} before flooding, and the range decreased to -18 and 19 W m^{-2} during the rest of the season (fig. 6b) due to

standing water on the surface. Lower values of G after flooding could be explained by the reduced capacity of water to store energy because some of the available energy is used as latent heat for evaporation (Rose, 2004). In addition, wet or saturated conditions result in a lower thermal diffusivity (ratio of conductivity to thermal capacity), which is a key factor in determining changes in G. Large fluctuations in G in the early season in both years
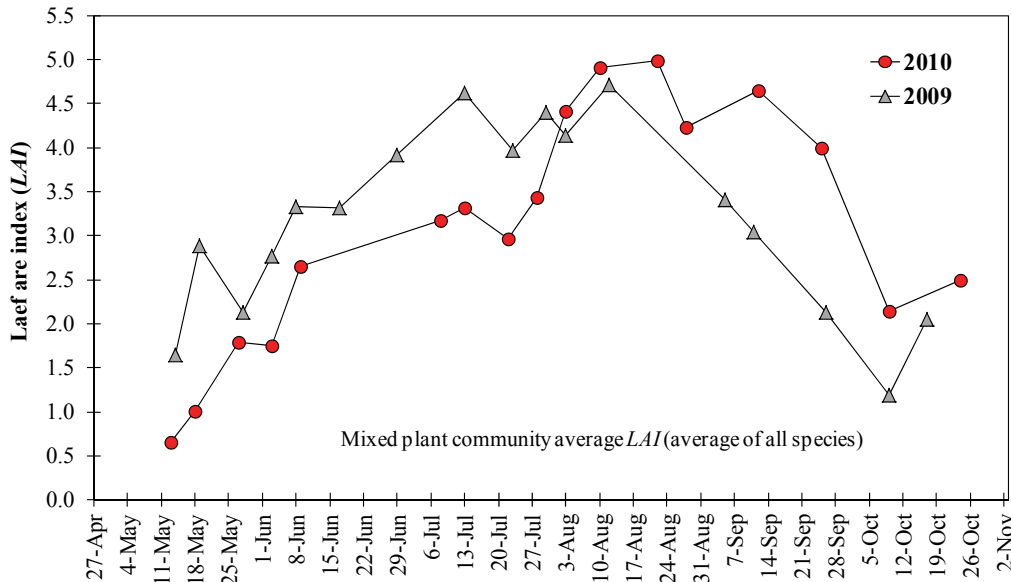
TRANSACTIONS OF THE ASABE

Figure 4. Leaf area index (LAI) for the mixed plant community (average LAI of common reed, cottonwood, and peach-leaf willow) in the 2009 and 2010 growing seasons. Each data point represents an average of 72 to 90 LAI measurements.
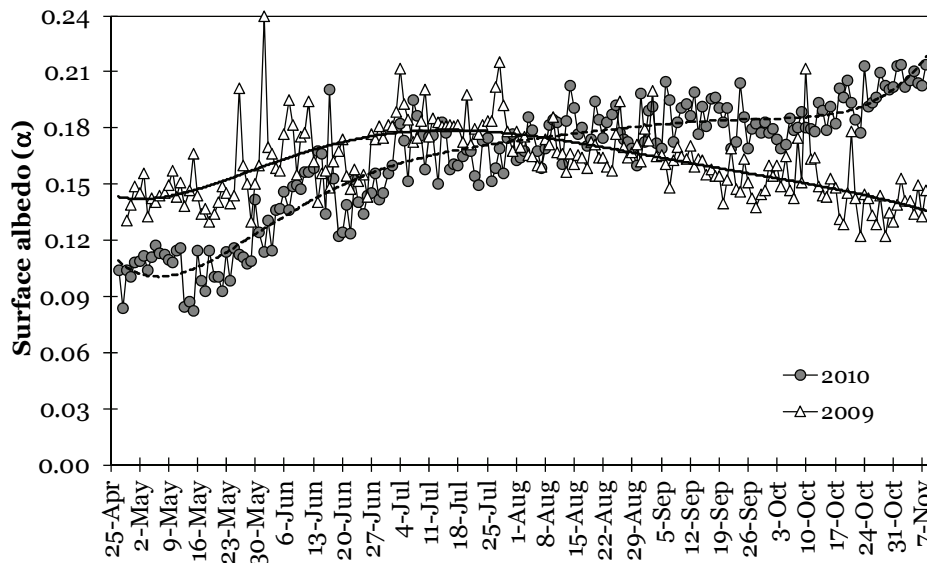

Figure 5. Daily surface albedo during the 2009 and 2010 growing seasons.

could be explained by non-uniform distribution of radiant energy on the surface because of the heterogeneous canopy architecture of the mixed riparian vegetation and the turbulent structure of varying temperatures traveling over the surface during the partial or incomplete canopy cover conditions. In the presence of water on the surface, complications in quantifying G arise because of spatial variation due to microtopography and non-homogenous canopy structure (Lafleur (2008), variations in the water level, and water advection, which carries heat in and out of the wetland. During May 2010, when the surface was dry, negative values of G were typical at nighttime from 19:00-20:00 to 08:00-09:00. The presence of flood water on the surface for the rest of the growing season resulted in an increase in the number of days with positive G at night. In addition, the absolute range of G during these days

decreased relative to the 2009 season. It was likely that a considerable amount of G was used for evaporation of water on the surface (Rott and Obleitner, 1992). Seasonal average daily G values for 2009 and 2010 were very small, 7.0 and 5.5 W m^{-2}, respectively.

In 2009, daily average H values ranged between -58 and 92 W m^{-2} (fig. 7a). Monthly average H values were 41, 7, 2, 2, 13, and 26 W m^{-2} for May, June, July, August, September, and October, respectively. In 2010, daily H values ranged between -148 and 101 W m^{-2} (fig. 7b), much greater values than those observed in 2009 due to the presence of flood water. Monthly average H values were 35, 6, -5, -41, -35, and -34 W m^{-2} in May, June, July, August, September, and October, respectively. The trend in H was inverse to that of LAI in both years because, as the canopy developed, the leaves intercepted more radiation
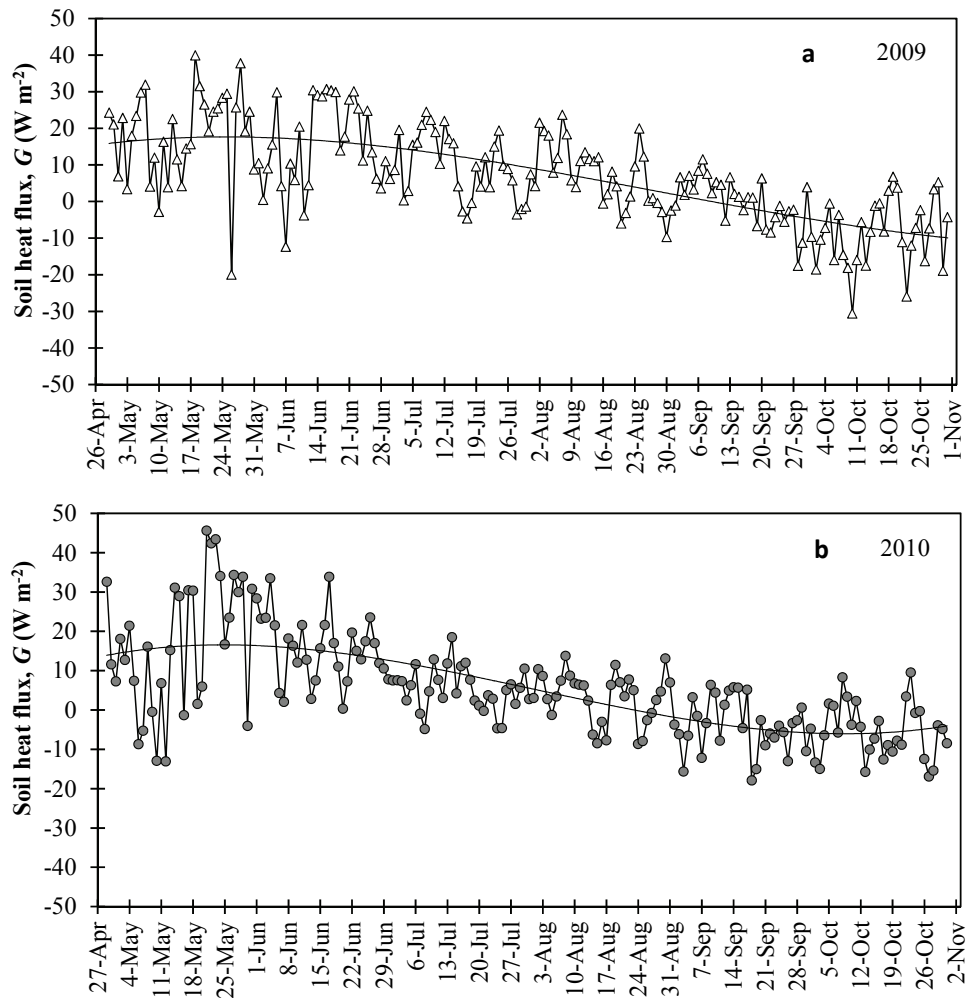
Figure 6. Distribution of daily average soil heat flux (*G*) during the (a) 2009 and (b) 2010 growing seasons.

that would be available as *H* and dissipated the energy through evaporating water on the surface. Thus, as LAI increased (especially when ET_a became prominent), *H* decreased, and vice versa. In 2010, the presence of water on the surface might have resulted in a cooler vegetation environment relative to the air, which explains the greater negative *H* (fig. 7b) from air to vegetation and water surface (Rose, 2004). Seasonal average values of *H* for 2009 and 2010 were 15 and -12 W m^{-2}, respectively.

HOURLY, DAILY, AND SEASONAL EVAPOTRANSPIRATION

BREBS-measured hourly and daily ET_a in 2009 and 2010 seasons are presented in figure 8. All ET_a data presented in this study represent the total evaporative losses from the mixed plant community at the experimental site, including the losses from common reed, cottonwood, and peach-leaf willow, as well as other vegetation surfaces presented in table 1 that had minor canopy coverage. However, since the first three species have the dominant coverage (91.1%), the majority of the measured ET_a data represent evaporative losses from these three main species. Purple loosestrife (*Lythrum salicaria*) did not have any considerable coverage until after mid-summer in 2010. Hourly ET_a in 2009 ranged from -0.1 to 1.0 mm h^{-1}, and the trend was generally in synchrony with the LAI during the season. However, the

peak hourly ET_a occurred on 22 June, before the peak LAI in mid-August. This period, during which ET_a was high with less than maximum LAI, was associated with observed elevated air temperatures and VPD. ET_a generally showed a decreasing trend from mid-August until mid-October; thereafter, a spike in ET_a was recorded. The late-season spike in ET_a was in agreement with a corresponding spike in observed LAI during the same period. These spikes may be explained by the enhanced transpiration rate of the lodged plant canopy that resulted from the observed high wind speeds in early October. In 2010, hourly ET_a ranged from -0.1 to 1.3 mm h^{-1}. In figure 8b, relatively higher ET_a in May and June, when LAI was not at its peak, might be explained by a combination of evaporation of flood water on the surface and evaporation of the intercepted precipitation from the wet canopy, as well as high wind speeds and VPD.

In 2009, daily average ET_a (fig. 9a) ranged from -0.6 to 8.5 mm d^{-1}, and the maximum value occurred on 8 August 2009. The seasonal average daily ET_a (May to October) was 3.7 mm d^{-1}. The monthly total ET_a values were 96, 137, 169, 165, 93, and 29 mm for May, June, July, August, September, and October, respectively. July had the highest total ET_a, comprising of 25% of the seasonal total ET_a, while the combined ET_a for June, July, and August was about 68% of the total growing season ET_a (520 mm).
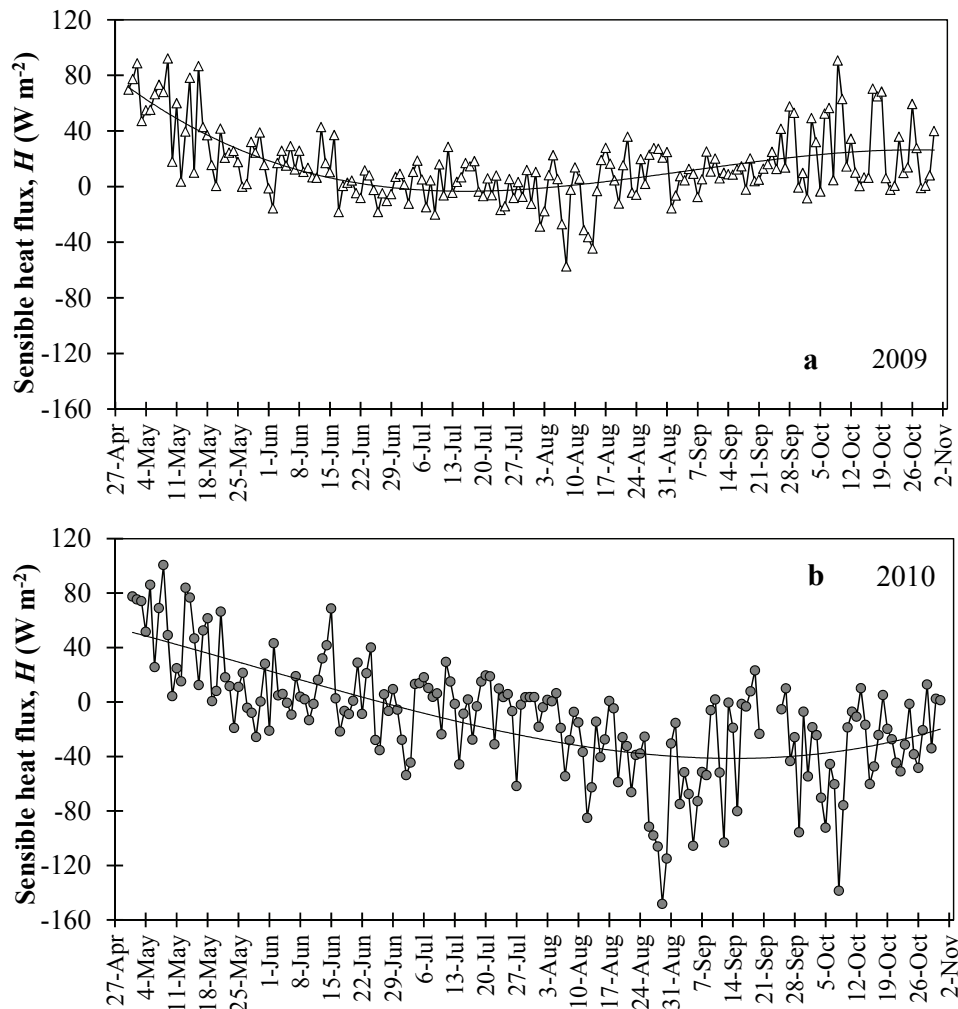
Figure 7. Daily average sensible heat flux (*H*) during the (a) 2009 and (b) 2010 growing seasons.

During the growing season, negative ET_a values were observed as a result of fog and/or dew formation on the leaf surface during late night and early morning hours.

Daily average ET_a ranged from 0.2 to 10.6 mm d^{-1} in 2010, and the maximum value occurred on 24 June (fig. 9b). Seasonal average daily ET_a (May to October) was 5.5 mm d^{-1}. High negative *H* values recorded in the 2010 season probably supplied energy for evaporation of flood water on the surface, as was also observed by Humphreys et al. (2003), which resulted in the high ET_a values. Monthly total ET_a was 108, 210, 211, 221, 145, and 120 mm for May, June, July, August, September, and October, respectively. The month of August had the greatest total ET_a, contributing 22% of the total, while the combined ET_a for other months of the growing season had 63% of the total growing season ET_a (794 mm). From July until mid-August, ET_a decreased to an average of about 7 mm d^{-1} and thereafter decreased gradually until end of the season.

Seasonal cumulative ET_a values for both seasons are presented in figure 10. In 2009, cumulative ET_a was 679 mm. ET_a accumulation rates of about 3, 5, 3, and 1 mm d^{-1} were measured during the periods of 30 April to 13 June, 13 June to 24 August, 24 August to 30 September,

and 30 September to 31 October, respectively. The greatest ET_a accumulation rate occurred when the LAI was above 2.5 to 3.0, indicating full canopy cover with a vegetation canopy transpiring at a potential (maximum) rate. The rates of ET_a accumulation generally mimicked canopy growth as depicted by LAI. Throughout the growing season, cumulative ET_a was higher than the cumulative precipitation, except during 19 to 26 June, a period that followed the most frequent large precipitation events of the season. In 2010, the cumulative ET_a was measured as 982 mm (45% greater than the value measured in 2009). ET_a accumulation rates of about 2, 6, 7, and 4 mm d^{-1} were measured during the periods of 1 May to 20 May, 20 May to 29 June, 29 June to 13 September, and 13 September to 31 October, respectively. Cumulative ET_a was higher than the cumulative precipitation for most of the growing season, except during 10 to 27 May and 20 to 26 June when the site received 62 and 64 mm of precipitation, respectively.

Species composition of riparian zones usually varies depending on the conditions of the site, and various values of ET_a were reported in previous studies. However, our results, in general, are in the range of those reported for various riparian vegetation communities. It is worth noting
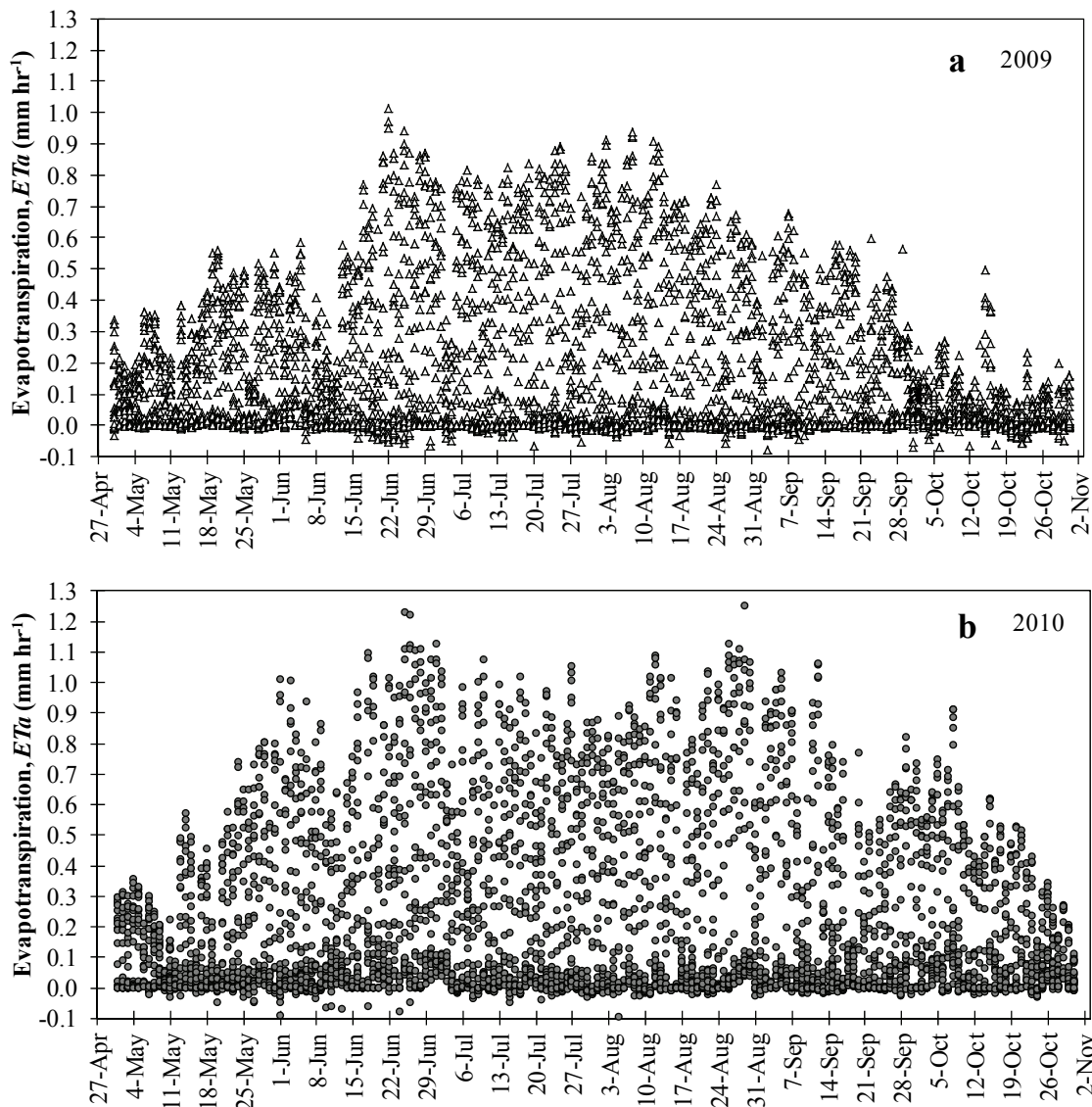
Figure 8. Distribution of measured hourly actual evapotranspiration (ET$_a$) during the (a) 2009 and (b) 2010 growing seasons.

that most studies focus on one species rather than estimating ET$_a$ of the mixed plant communities. For example, several studies have measured common reed ET$_a$, with results varying from 1.4 to 13 mm d^{-1} depending on the method used, season of the year, climatic regime (Crundwell, 1986), ecosystem hydrology, species characteristics, and other factors. Fermor et al. (2001) used plastic phytometers planted with common reed and sunk within a stand of reed and estimated ET$_a$ to range between 0.2 and 6.3 mm d^{-1} in a maritime climate in the U.K. Peacock and Hess (2004) used a BREB system to measure ET$_a$ from common reed in the U.K. and found values ranging between 0.5 and 5.0 mm d^{-1}. Burgoon et al. (1997) applied a water balance approach to common reed beds in the arid northwestern U.S. and determined average ET$_a$ from May to June to be 6 mm d^{-1}. Zhou and Zhou (2009) used the eddy covariance technique to measure the magnitude and dynamics of ET$_a$ over a reed marsh in the Liaohe Delta in northeast China and reported ET$_a$ values ranging between 0.1 and 5.8 mm d^{-1} during the growing

season (May to October). They calculated the growing season total ET$_a$ as 376 mm. Irrigated cottonwood water use was measured to range between 1 and 6 mm d^{-1} during the peak of the growing season (Nagler et al., 2007). Natural cottonwood stands have been reported to have summer ET$_a$ rates between 3.1 and 12 mm d^{-1} (Hartwell et al., 2010). From a mixed species study, transpiration for cottonwood/willow forests along the San Pedro River in southeastern Arizona, an arid area in the American Southwest, was found to range between 2.5 and 6.3 mm d^{-1} using a sapflow technique (Schaeffer et al., 2000). In the same area, transpiration from cottonwood contributed proportionally more (on average 85%) of the total water flux from the stand than willow.

RELATIONSHIP BETWEEN ET$_a$ AND PRIMARY METEOROLOGICAL VARIABLES

To investigate the primary forces driving ET$_a$ for the mixed riparian vegetation under these experimental conditions, the relationships between ET$_a$ vs. R_n, VPD, u_3, T_a, and R_s for the 2009 season are presented in figure 11.
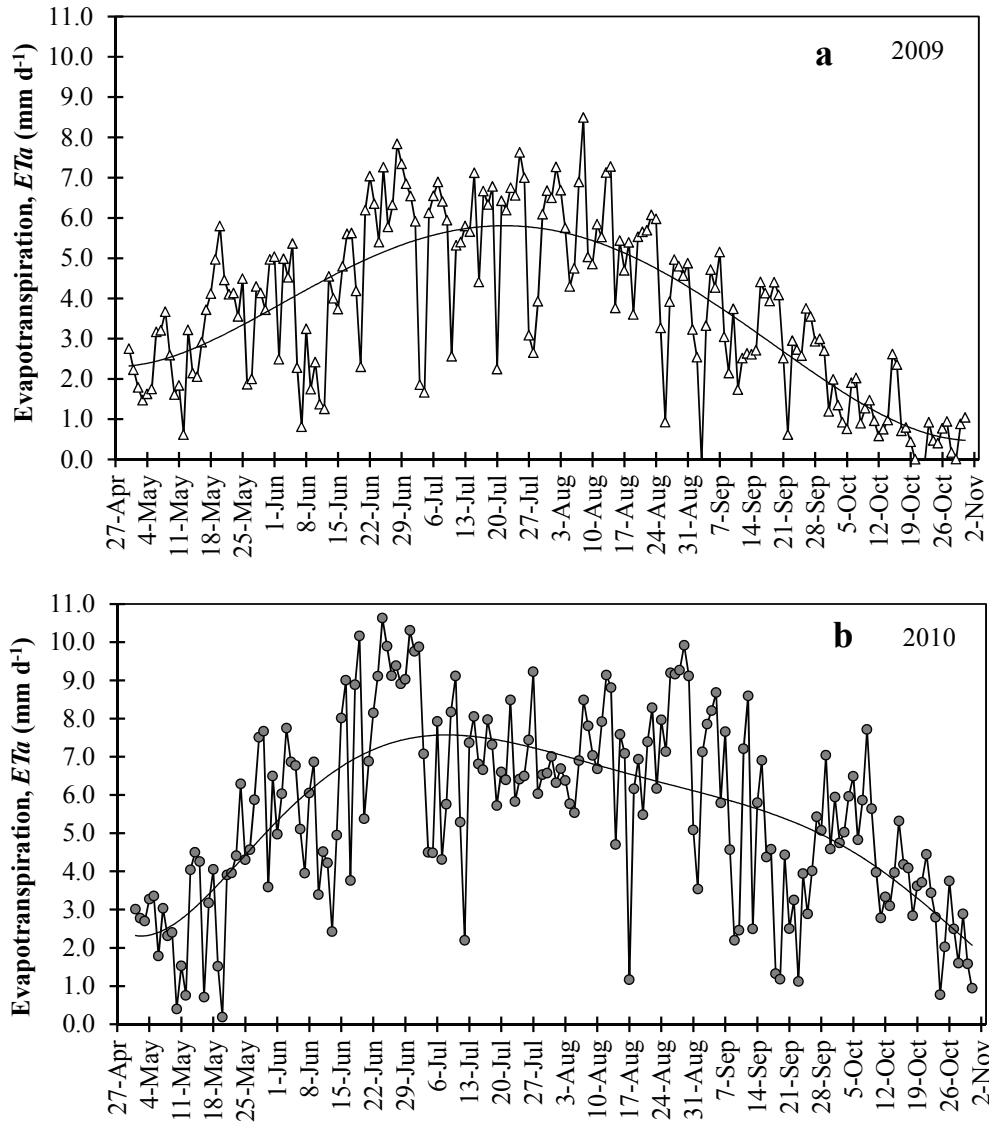
Figure 9. Distribution of measured daily actual evapotranspiration (ET$_a$) during the (a) 2009 and (b) 2010 growing seasons.
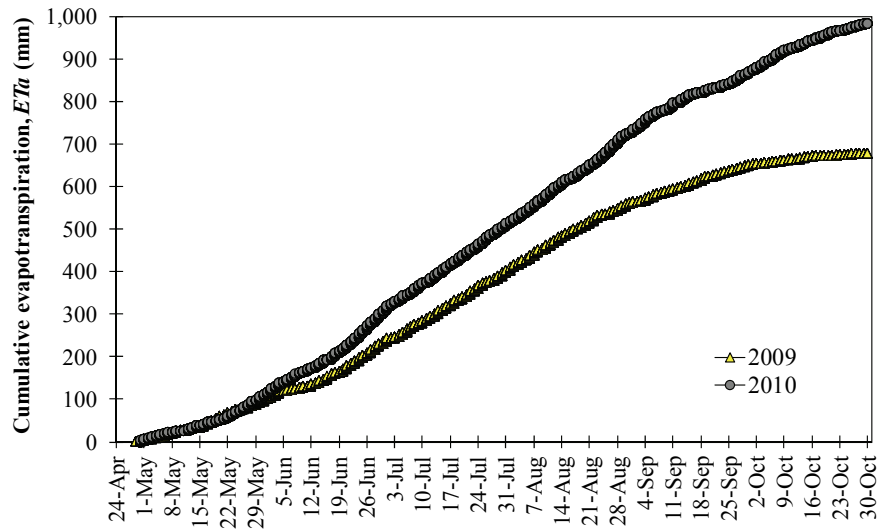

Figure 10. Cumulative actual evapotranspiration (ET$_a$) trends during the 2009 and 2010 growing seasons.
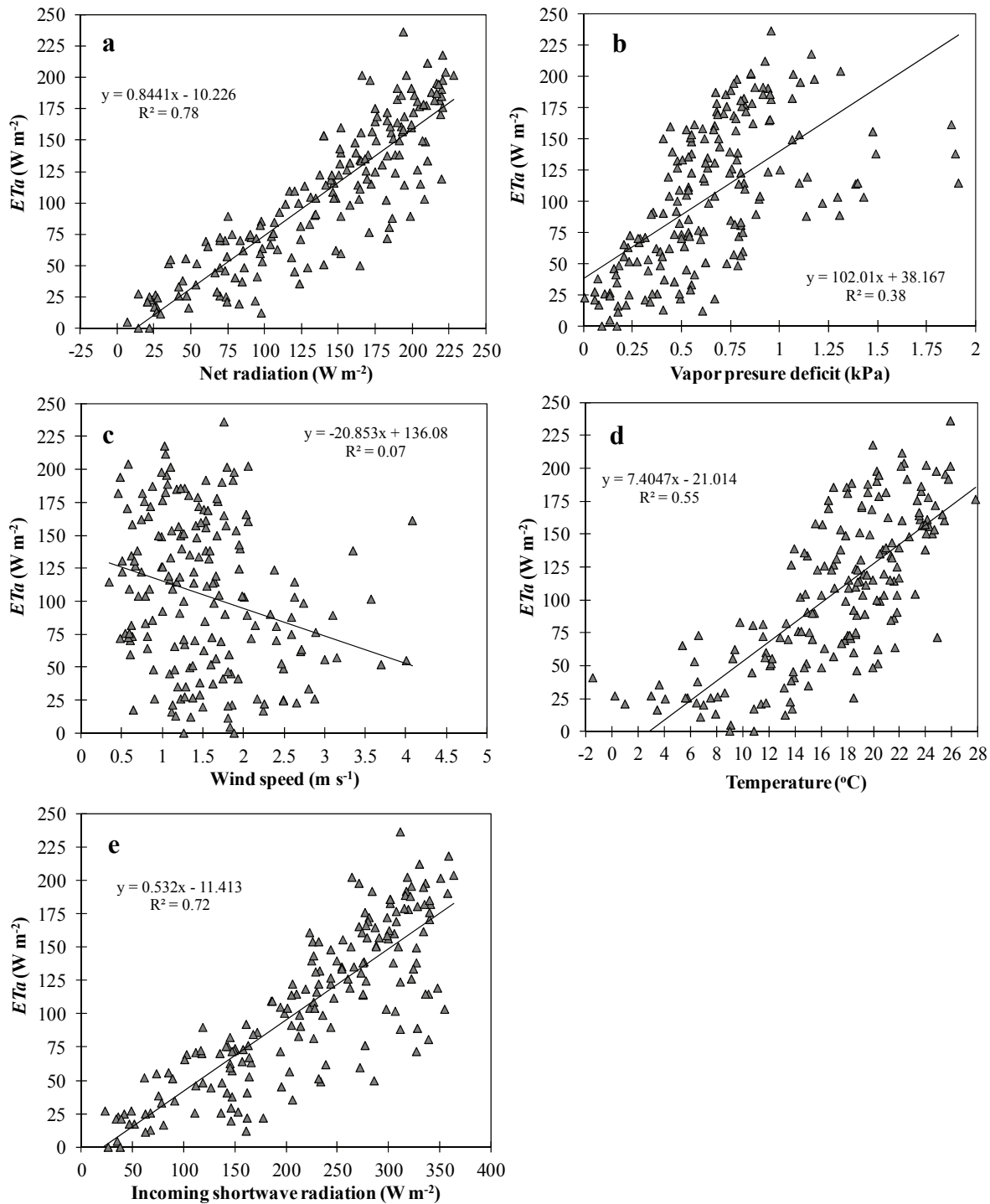
Figure 11. Relationship between measured daily actual evapotranspiration (ET$_a$) and (a) net radiation (R_n), (b) vapor pressure deficit (VPD), (c) wind speed (u_3), (d) daily average air temperature, and (e) incoming shortwave radiation (R_s) in 2009.

The main reason for correlating both R_n and R_s to ET$_a$ was that the measured R_n data in combination with G and the gradients of T_a and actual vapor pressure (ea) are used to determine ET$_a$ using the BREB method. Thus, R_n and ET$_a$ are not completely independent, and a strong correlation was expected between the two variables. However, R_s is independent of ET$_a$ in the BREB method and is not used directly in the energy balance equation when calculating β or ET$_a$. Net radiation, VPD, T_a, and R_s showed a positive correlation with ET$_a$, with varying r^2 values. We observed

that the relationship between ET$_a$ and climatic variables was affected by the phenology of the vegetation, albeit in a different way for each variable (table 3). Three days (18, 19, and 20 May) had extreme average air temperatures and low relative humidity that resulted in very high VPD (about 2.0 kPa). These high VPD values lowered the seasonal r^2 of VPD vs. ET$_a$ correlation. Wind speed had a very weak correlation (r$^2 = 0.07$) with ET$_a$. Theoretically, wind serves as a driving force for evaporative losses by replacing air saturated with water vapor with drier air over the canopy.

	2009			2010		
	May	June to Oct.	All Season	May	June to Oct.	All Season
R_n	0.57	0.88	0.78	0.68	0.73	0.56
VPD	0.71	0.61	0.38	0.60	0.004	0.26
T_a	0.65	0.56	0.55	0.38	0.55	0.45
R_s	0.53	0.87	0.72	0.58	0.77	0.58

However, the research site generally experienced higher wind speed early and late in the season; during these periods of the growing season, lower ET$_a$ values are expected because of low LAI and reduced R_n. In addition, the research site was surrounded by the braided Platte River from which water vapor evaporates, increasing the water vapor content of the wind and ultimately reducing the correlation between wind speed and ET$_a$. Thus, at our experimental site, the air above the canopy was most likely
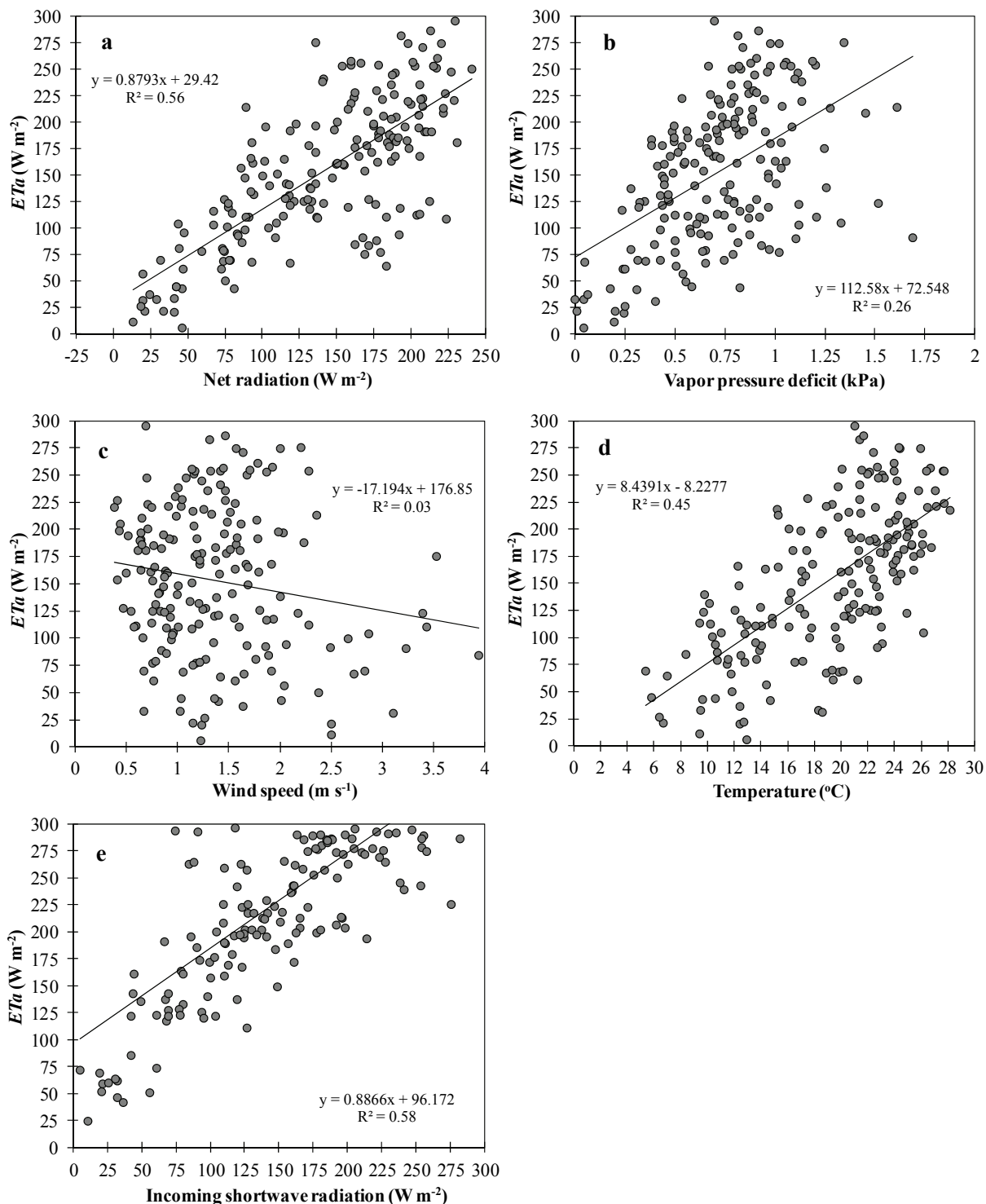

Figure 12. Relationship between measured daily actual evapotranspiration (ET$_a$) and (a) net radiation (R_n), (b) vapor pressure deficit (VPD), (c) wind speed (u_3), (d) daily average air temperature, and (e) and incoming shortwave radiation (R_s) in 2010.
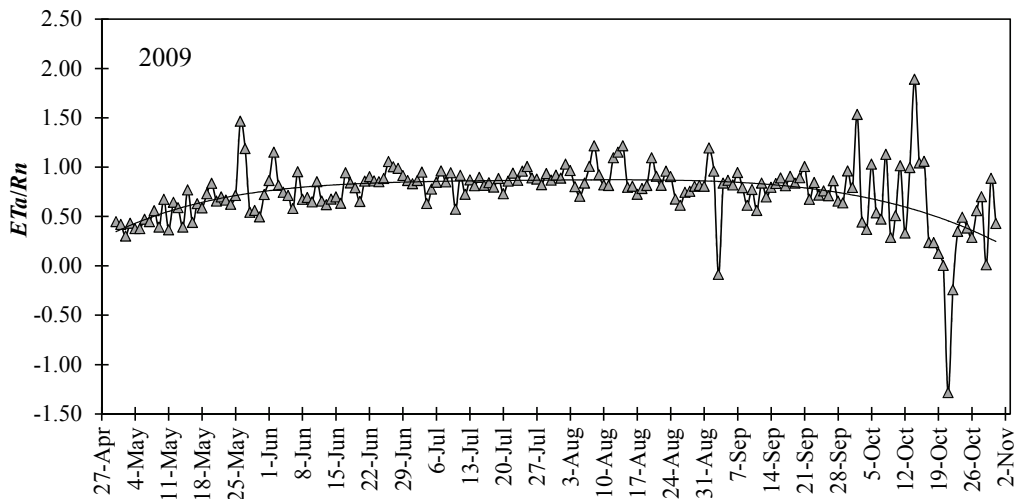
Figure 13. Evaporative flux ratio (ET$_a$/R$_n$) in 2009.

replaced with either similar or more saturated (humid) air that passed over the canopy, having minimal impact on elevating ET$_a$. Monteith (1973) suggested that the relationship between wind speed and ET$_a$ depends on the ratio of H to ET$_a$. Whenever the wind speed increases H, at the expense of latent heat, a negative correlation between wind speed and latent heat flux is observed. Irmak and Mutiibwa (2010) reported a weak positive relationship between wind speed and canopy resistance (a major controller or regulator of ET$_a$) of a non-stressed maize canopy. Thus, an increase in canopy resistance due to increased wind speed, might also explain the decreasing ET$_a$ with increase in wind speed as observed in figure 11c.

Figure 12 shows the relationships between measured ET$_a$ vs. R$_n$, VPD, wind speed, T$_a$, and R$_s$ during the 2010 season. Generally, ET$_a$ had a stronger relationship with the same climatic parameters in 2009 as compared with the 2010 season. As indicated earlier, this was probably due to the influence of the wet surface conditions on the impact of meteorological variables on ET$_a$. For example, the correlation between ET$_a$ and R$_s$ in the 2010 season ($r^2 = 0.56$) was not as strong as the 2009 correlation (0.72). The weak correlation between ET$_a$ and climatic variables (R$_n$, VPD, wind speed, and T$_a$) may suggest that the degree to which these variables interact with the vegetation is dependent on how coupled, or decoupled, the vegetation is with the atmosphere within the boundary layer. Vegetation in wetter conditions may be more decoupled with the atmosphere than vegetation at drier sites. In addition, in our study, the reduced correlation between ET$_a$ and R$_s$ might be due to the counter-effect of cooling due to evaporation of the flood water on the surface in 2010. Net radiation, T$_a$, VPD, and R$_s$ showed a positive correlation to ET$_a$, with r^2 values of 0.56, 0.45, 0.26, and 0.10, respectively.

PARTITIONING OF AVAILABLE ENERGY

In 2009, ET$_a$ resulted in the dominant sink for the available energy, with ratios of evaporative flux (ET$_a$/R$_n$), ranging from -1.3 to 1.9 during the 2009 growing season (fig. 13). Until the end of September, most days had ET$_a$/R$_n$

ratios within 0.30 to 1.2, followed by a wider variation during October. The seasonal average ET$_a$/R$_n$ ratio was 0.70, which was very similar to the value (0.74) obtained by Burba et al. (1999) for a common reed-dominated wetland in the Sandhills region of Nebraska and comparable to the range of 0.65 to 0.74 for a peat bog in eastern Canada reported by Admiral et al. (2006). Zhao et al. (2008) reported ET$_a$/R$_n$ ratios ranging between 0.30 and 0.6 for marshland dominated by woolly fruit sedge (*Carex lasiocarpa*) in northeastern China. The ET$_a$/R$_n$ ratios were larger in 2010, ranging from 0.11 to 2.81 (fig. 14). The evaporative flux ratio increased steadily from 0.5 to 1.0 in mid-June. July, August, September, and October, and these months also had gradually increasing average evaporative ratios of 1.10, 1.22, 1.26, and 1.55, respectively. High evaporative flux ratios are due to evaporation of the flood water on the surface, enhanced by greater negative H values measured during July to October 2010. Humphreys et al. (2003) pointed out that when H was directed downward (negative H), it could supply substantial energy for evaporation of available water. The 2010 growing season average ET$_a$/R$_n$ ratio of 1.14 was 60% greater than the 2009 value (0.70).

Available energy during the 2009 season was partitioned into ET$_a$ and H (fig. 15). Sensible heat was the main consumer of available energy at the beginning (due to partial canopy cover and low LAI) and toward the end of the growing season (due to leaf aging and senescence). On the other hand, ET$_a$ was the main consumer of available energy during the peak growing season, when the LAI range was about 2.5 to 5.0. Excluding extreme days, most of the sensible heat fraction [$H/(R_n - G)$] values were 0.40 to 0.50, -0.40 to 0.41, and -0.30 to 0.60 at the beginning, peak, and toward end of the season, respectively. Corresponding ratios of the evaporative fraction [ET$_a$/(R$_n$ - G)] for the same periods were similar. The LAI and surface conditions at the site played an important role in partitioning of the available energy. In 2009, on a seasonal average, a total of 77% and 14% of the available energy was partitioned into ET$_a$ and H, respectively.
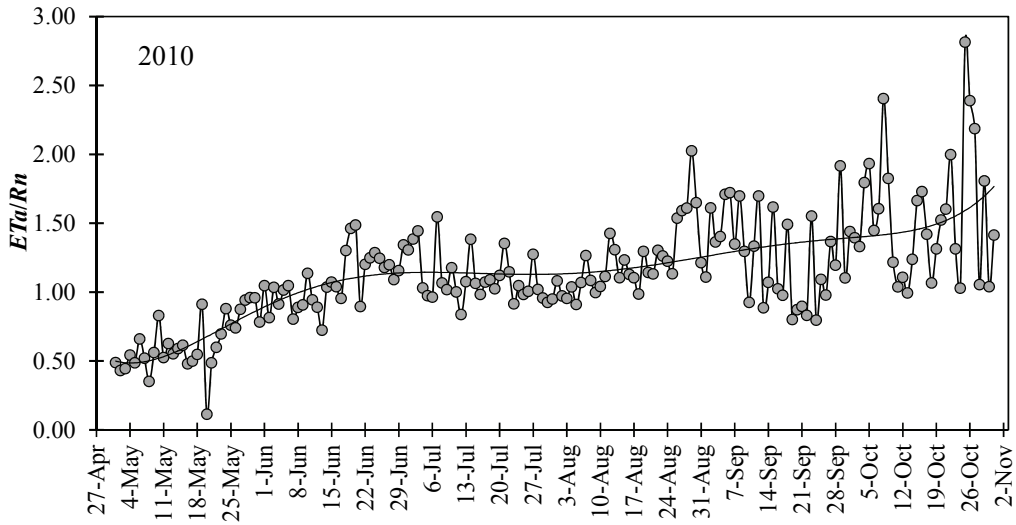
Figure 14. Evaporative flux ratio (ET_a/R_n) in 2010.
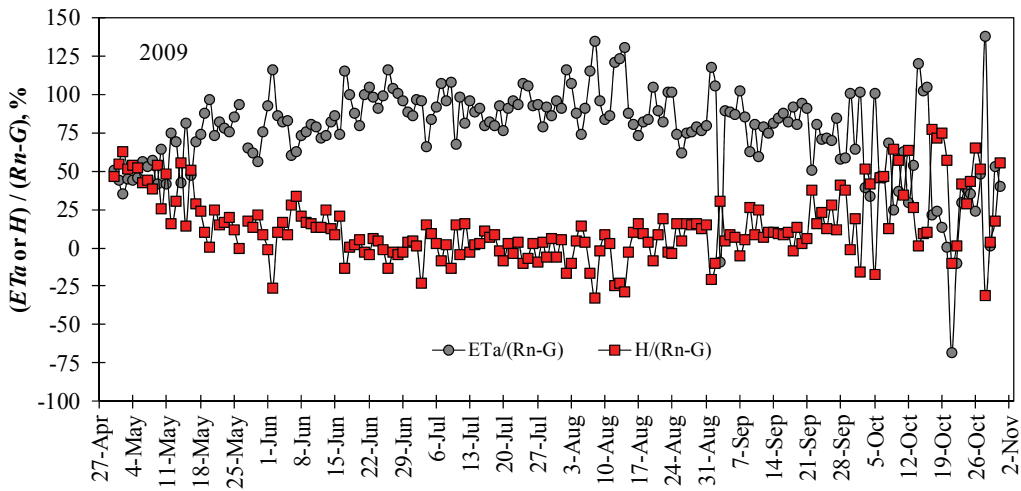

Figure 15. Partitioning of available energy ($R_n - G$) to actual evapotranspiration (ET_a) and sensible heat flux (H) in 2009.
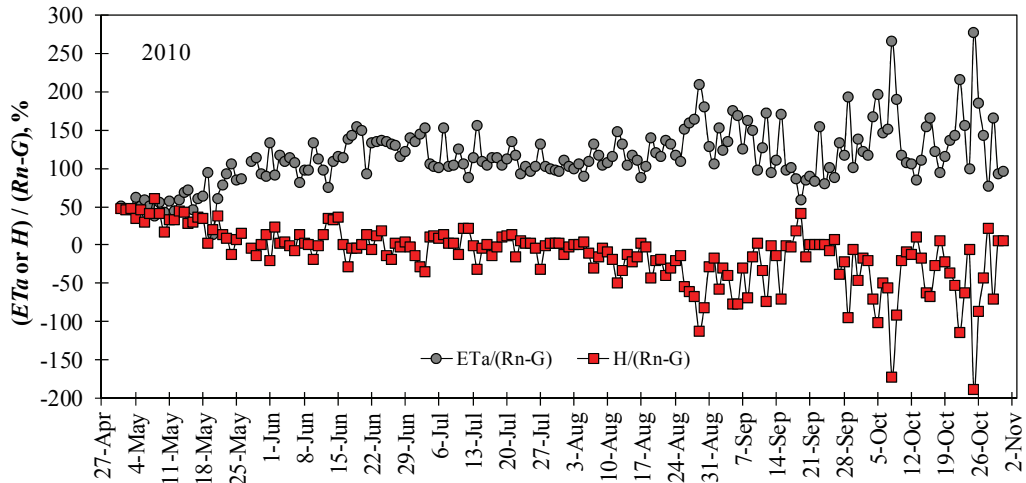

Figure 16. Partitioning of available energy ($R_n - G$) to actual evapotranspiration (ET_a) and sensible heat flux (H) in 2010.

Partitioning of available energy into ET_a and H in the 2010 season is presented in figure 16. The $H/(R_n - G)$ ratios were between 0.40 and 0.50 at the beginning of the season and generally decreased throughout the season, with monthly averages of 0.26, 0.03, -0.02, -0.26, -0.24, and -0.48 for May, June, July, August, September, and October, respectively. Corresponding monthly average ratios of $ET_a/(R_n - G)$ for May, June, July, August, September, and October were 0.67, 1.19, 1.13, 1.24, 1.21, and 1.43, respectively. High negative H values observed in 2010 might have supplied additional energy for evaporation of the intercepted precipitation and flood water on the surface, leading to higher ET_a values as compared with those observed in 2009. On a seasonal average, over 90% and -12% of the available energy was partitioned into ET_a and H, respectively.

SUMMARY AND CONCLUSIONS

Surface energy fluxes, including latent heat flux (actual evapotranspiration, ET_a), sensible heat flux (H), soil heat flux (G), net radiation (R_n), and meteorological variables (air temperature, relative humidity, wind speed, incoming shortwave radiation, and precipitation), and leaf area index (LAI) were measured for a common reed-dominated cottonwood and peach-leaf willow riparian zone on a sand island in the Platte River basin in central Nebraska through extensive field campaigns conducted in the 2009 and 2010 growing seasons. Energy fluxes were measured using a deluxe version of a Bowen ratio energy balance system. The two growing seasons were contrasted by warmer air temperatures, higher precipitation, and the presence of flood water on the surface during the 2010 season. Variation in relative fluxes of ET_a, H, and G were observed between the two seasons. In 2009, total ET_a and precipitation were 679 and 280 mm, respectively, and the values were substantially greater in 2010 (982 and 508 mm, respectively). Seasonal daily average ET_a was 3.7 mm d^{-1} in 2009 and 5.5 mm d^{-1} in 2010. In both seasons, ET_a was the dominant flux through which the available energy was partitioned. For this mixed riparian ecosystem, ET_a resulted in the dominant sink for available energy, with ratios of evaporative flux (ET_a/R_n) ranging from -1.3 to 1.9 during the 2009 growing season and from 0.11 to 2.81 in 2010. The seasonal average ET_a/R_n ratio was 0.70 and 1.14 for 2009 and 2010, respectively. In 2009, on a seasonal average, a total of 77% and 14% of the available energy was partitioned into ET_a and H, respectively. In 2010, on a seasonal average, over 90% and -12% of the available energy was partitioned into ET_a and H, respectively. ET_a varied widely with meteorological and surface conditions and in response to variations in phenology of the vegetation. ET_a increased with increasing LAI and peaked around the same period when LAI was at maximum during both seasons. Soil heat flux was an important source of energy at night but was a smaller fraction of R_n in 2010. High negative values of H were observed during the 2010 season due to the cooling effect on the vegetation canopy as a result of the evaporation of flood water. Partitioning of R_n

into convective surface energy fluxes from the riparian vegetation was strongly influenced by LAI, especially in the early season during partial canopy and in the late season due to leaf aging and senescence. This research provides valuable ET_a data and information for understanding the interactions between surface/vegetation conditions and the surrounding microclimate and surface energy balance variables for mixed riparian vegetation that should aid water managers and decision/policy makers in accounting for the water use rates of phragmites-dominated cottonwood and peach-leaf willow riparian plant communities in water balance analyses to make better-informed water resources planning and management decisions.

REFERENCES

Admiral, S. W., P. M. Lafleur, and N. T. Roulet. 2006. Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. *Agric. Forest Meteorol.* 140(1-4): 308-321.

Amsberry, L., M. A. Baker, P. J. Ewanchuk, and M. D. Bertness. 2000. Clonal integration and the expansion of *Phragmites australis*. *Ecol. Applications* 10(4): 1110-1118.

Angus, D. E., and P. J. Watts. 1984. Evapotranspiration: How good is the Bowen ratio method? *Agric. Water Mgmt.* 8(1-3): 133-150.

Blossey, B. 1999. Before, during, and after: The need for long-term monitoring in invasive plant species management. *Biol. Invasions* 1(2-3): 301-311.

Blossey, B., P. M. Schwarzländer, P. Häfliger, R. Casagrande, and L. Tewksbury. 2002. Common reed. In *Biological Control of Invasive Plants in the Eastern United States*, 131-138. R. G. Van Driesche, S. Lyon, B. Blossey, M. Hoddle, and R. Reardon, eds. Publication FHTET-2002-04. Morgantown, W.V.: USDA Forest Service.

Bowen, I. S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physical Review* 27(6): 779-787.

Brutsaert, W. 1982. *Evaporation into the Atmosphere: Theory, History, and Applications*. Boston, Mass.: D. Reidel.

Burba, G. G., S. B. Verma, and J. Kim. 1999. Surface energy fluxes of *Phragmites australis* in a prairie wetland. *Agric. Forest Meteorol.* 94(1): 31-51.

Burgoon, P. S., K. F. Kirkbride, M. Henderson, and E. Landon. 1997. Reedbeds for biosolids drying in the arid northwestern United States. *Water Sci. and Tech.* 35(5): 287-292.

Cleverly, J., C. Dahm, J. Thibault, D. McDonnell, and J. Coonrod. 2006. Riparian ecohydrology: Regulation of water flux from the ground to the atmosphere in the middle Rio Grande, New Mexico. *Hydrol. Proc.* 20(15): 3207-3225.

Crundwell, M. W. 1986. A review of hydrophyte evapotranspiration. *Revue Hydrobiologie Tropicale* 19(2-4): 215-232.

Daubenmire, R. F. 1959. A canopy-coverage method of vegetational analysis. *Northwest Sci.* 33(1): 43-64.

Drexler, J., R. Snyder, D. Spano, K. Ta, and U. Paw. 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. *Hydrol. Proc.* 18(11): 2071-2101.

Dyer, A. J. 1974. A review of flux-profile relationships. *Boundary Layer Meteorol.* 7(3): 363-372.

Fermor, P. M., P. D. Hedges, J. C. Gilbert, and D. J. G. Gowing. 2001. Reedbed evapotranspiration rates in England. *Hydrol. Proc.* 15(4): 621-631.

Floyd, D. A., and J. E. Anderson. 1987. A comparison of three methods for estimating plant cover. *J. Ecol.* 75(1): 221-228.

Fritschen, L. J. 1965. Accuracy of evapotranspiration determinations by the Bowen ratio method. *Bull. Intl. Assoc. Sci. and Hydrol.* 10(2): 38-48.

Goodrich, D. C., R. Scott, J. Qi, B. Goff, C. L. Unkrich, M. S. Moran, D. Williams, S. Schaeffer, K. Snyder, R. Mac Nish, T. Maddock, D. Pool, A. Chehbouni, D. Cooper, W. Eichinger, W. Shuttleworth, Y. Kerr, W. Marsett, and W. Ni. 2000. Seasonal estimates of riparian evapotranspiration using remote and *in situ* measurements. *Agric. Forest Meteorol.* 105(1-3): 281-309.

Hartwell, S., K. Morino, P. L. Nagler, and E. P. Glenn. 2010. On the irrigation requirements of cottonwood (*Populus fremontii* and *Populus deltoides* var. *wislizenii*) and willow (*Salix gooddingii*) grown in a desert environment. *J. Arid Environ.* 74(6): 667-674.

Henszey, R. J., K. Pfeiffer, and J. R. Keough. 2004. Linking surface and ground water levels to riparian grassland species along the Platte River in central Nebraska. *Wetlands* 24(3): 665-687.

Hook, D. D. 1984. Adaptations to flooding with fresh water. In *Flooding and Plant Growth*, 265-294. T. T. Kozlowski, ed. Orlando, Fla.: Academic Press.

Humphreys, E. R., T. A. Black, G. J. Ethier, G. B. Drewitt, D. L. Spittlehouse, E. M. Jork, Z. Nesic, and N. J. Livingston. 2003. Annual and seasonal variability of sensible and latent heat fluxes above a coastal Douglas-fir forest, British Columbia, Canada. *Agric. Forest Meteorol.* 115(1-2): 109-125.

Irmak, S. 2010. Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX). *Trans. ASABE* 53(4): 1097-1115.

Irmak, S. 2011. On the dynamics of nocturnal, day-time, and sum-of-hourly evapotranspiration and other surface energy fluxes over a non-stressed maize canopy. *J. Irrig. and Drain. Eng.* 137(8): 475-490.

Irmak, S., and D. Mutiibwa. 2008. Dynamics of photosynthetic photon flux density and light extinction coefficient for assessing some radiant energy interactions for maize canopy. *Trans. ASABE* 51(5): 1663-1673.

Irmak, S., and D. Mutiibwa. 2010. On the dynamics of stomatal resistance: Generalized linear estimation and relationships with primary micrometeorological variables. *Water Resour. Res.* 46(8): WO8526, doi: 10.1029/2009WR008484.

Irmak, S., I. Kabenge, K. E. Skagss, and D. Mutiibwa. 2012. Trend and magnitude of changes in climate variables and reference evapotranspiration over 116-year period in the Platte River valley, central Nebraska, USA. *J. Hydrol.* 420-421: 228-244.

Kanemasu, E. T. 1979. Techniques for calculating energy and mass fluxes. In *Modification of the Aerial Environment of Crops*, 156-182. ASAE Monograph No. 2 B. J. Barfield and J. F. Gerber, eds. St. Joseph, Mich.: ASAE.

Knezevic, S. Z., A. Data, and R. E. Rapp. 2008. Noxious weeds of Nebraska: Common reed. Extension Circular EC166. Lincoln, Neb.: University of Nebraska-Lincoln.

Kozlowski, T. T. 1997. Responses of woody plants to flooding and salinity. Tree Physiology Monograph No. 1. Victoria, British Columbia, Canada: Heron Publishing.

Kozlowski, T. T., and S. G. Pallardy. 2002. Acclimation and adaptive responses of woody plants to environmental stresses. *Botanical Review* 68(2): 270-334.

Lafleur, P. M. 2008. Connecting atmosphere and wetland: Energy and water vapor exchange. *Geography Compass* 2(4): 1027-1057.

Lafleur, P., W. R. Rouse, and S. G. Hardill. 1987. Components of the surface radiation balance of subarctic wetland terrain units during the snow-free season. *Arctic and Alpine Res.* 19(1): 53-63.

Li-Cor. 2010. LAI-2000 Plant Canopy Analyzer. Lincoln, Neb.: Li-Cor Biosciences.

Mac Nish, R. D., C. L. Unkrich, E. Smythe, D. C. Goodrich, and T. Maddock III. 2000. Comparison of riparian evapotranspiration estimates based on a water balance approach and sap flow measurements. *Agric. Forest Meteorol.* 105(103): 271-279.

Mal, T. K., and L. Narine. 2004. The biology of Canadian weeds. 129. *Phragmites australis* (Cav.) Trin. ex Steud. *Canadian J. Plant Sci.* 84(2): 365-396.

Monteith, J. L. 1973. *Principles of Environmental Physics.* London, U.K.: Arnold.

Nagler, P., E. Glenn, and T. L. Thompson. 2003. Comparison of transpiration rates among saltcedar, cottonwood, and willow trees by sap flow and canopy temperature methods. *Agric. Forest Meteorol.* 116(1-2): 73-89.

Nagler, P. L., R. L. Scott, C. Westenburg, J. R. Cleverly, E. P. Glenn, and A. R. Huete. 2005. Evapotranspiration on western U.S. rivers estimated using the enhanced vegetation index from MODIS and data from eddy covariance and Bowen ratio flux towers. *Remote Sensing Environ.* 97(3): 337-351.

Nagler, P., A. Jetton, J. Fleming, K. Didan, E. Glenn, J. Erker, K. Morino, J. Milliken, and S. Gloss. 2007. Evapotranspiration in a cottonwood (*Populus fremontii*) restoration plantation estimated by sap flow and remote sensing methods. *Agric. Forest Meteorol.* 144(1-2): 95-110.

Owensby, C. E. 1973. Modified step-point system for botanical composition and basal cover estimates. *J. Range Mgmt.* 26(4): 302-303.

Peacock, C. E., and T. M. Hess. 2004. Estimating evapotranspiration from a reed bed using the Bowen ratio energy balance method. *Hydrol. Proc.* 18(2): 247-260.

Perez, P. J., F. Castellvi, M. Ibanez, and J. I. Rosell. 1999. Assessment of reliability of Bowen ratio method for partitioning fluxes. *Agric. Forest Meteorol.* 97(3): 141-150.

Rose, C. W. 2004. Evapotranspiration and exchange of energy at the earth's surface. In *An Introduction to the Environmental Physics of Soil, Water, and Watersheds*, 153-189. Cambridge, U.K.: Cambridge University Press.

Rott, H., and F. Obleitner. 1992. The energy-balance of dry tundra in west Greenland. *Arctic and Alpine Res.* 24(4): 352-362.

Schaeffer, S. M., D. G. Williams, and D. C. Goodrich. 2000. Transpiration of cottonwood/willow forest estimated from sap flux. *Agric. Forest Meteorol.* 105(1-3): 257-270.

Skaggs, K. E., and S. Irmak. 2011. Characterization of nighttime evapotranspiration and other surface energy fluxes and interactions with microclimate variables in subsurface drip and center-pivot irrigated soybean fields. *Trans. ASABE* 54(3): 941-952.

Tanner, C. B. 1960. Energy balance approach to evapotranspiration from crops. *SSSA Proc.* 24(1): 1-9.

Yaglom, A. M. 1977. Comments on wind and temperature flux-profile relationships. *Boundary Layer Meteorol.* 11(1): 89-102.

Zhao, X. S., Y. Huang, Z. J. Jia, H. Liu, T. Song, Y. Wang, L. Shi, C. Song, and Y. Wang. 2008. Effects of the conversion of marshland to cropland on water and energy exchanges in northeastern China. *J. Hydrol.* 355(1-4): 181-191.

Zhou, L., and G. Zhou. 2009. Measurement and modeling of evapotranspiration over a reed (*Phragmites australis*) marsh in northeast China. *J. Hydrol.* 372(1-4): 41-47.