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Abstract

Riparian buffers are designed as management practices to increase infiltration and reduce surface runoff and transport of sediment and nonpoint source pollutants from crop fields to adjacent streams. Achieving these ecosystem service goals depends, in part, on their ability to remove water from the soil via transpiration. In these systems, edges between crop fields and trees of the buffer systems can create advection processes, which could influence water use by trees. We conducted a field study in a riparian buffer system established in 1994 under a humid temperate climate, located in the Corn Belt region of the Midwestern U.S. (Iowa). The goals were to estimate stand level transpiration by the riparian buffer, quantify the controls on water use by the buffer system, and determine to what extent advective energy and tree position within the buffer system influence individual tree transpiration rates. We primarily focused on the water use response (determined with the Heat Ratio Method) of one of the dominant species (*Acer saccharinum*) and a subdominant (*Juglans nigra*). A few individuals of three additional species (*Quercus bicolor, Betula nigra, Platanus occidentalis*) were monitored over a shorter time period to assess the generality of responses. Meteorological stations were installed along a transect across the riparian buffer to determine the microclimate conditions. The differences found among individuals were attributed to differences in species sap velocities and sapwood depths, location relative to the forest edge and prevailing winds and canopy exposure and dominance. Sapflow rates for *A. saccharinum* trees growing at the SE edge (prevailing winds) were 39% greater than SE *interior* trees and 30% and 69% greater than NW *interior* and *edge* trees, respectively. No transpiration enhancement due to edge effect was detected in the subdominant *J. nigra*. The results were interpreted as indicative of advection effects from the surrounding crops. Further, significant differences were document in sapflow rates between the five study species, suggesting that selection of species is important for enhancing specific riparian buffer functions. However, more information is needed on water use patterns among diverse species growing under different climatic and biophysical conditions to assist policy and management decisions regarding effective buffer design.

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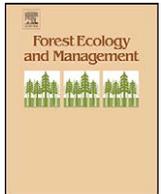
Enhanced transpiration by riparian buffer trees in response to advection in a humid temperate agricultural landscape

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ABSTRACT

Riparian buffers are designed as management practices to increase infiltration and reduce surface runoff and transport of sediment and nonpoint source pollutants from crop fields to adjacent streams. Achieving these ecosystem service goals depends, in part, on their ability to remove water from the soil via transpiration. In these systems, edges between crop fields and trees of the buffer systems can create advection processes, which could influence water use by trees. We conducted a field study in a riparian buffer system established in 1994 under a humid temperate climate, located in the Corn Belt region of the Midwestern U.S. (Iowa). The goals were to estimate stand level transpiration by the riparian buffer, quantify the controls on water use by the buffer system, and determine to what extent advective energy and tree position within the buffer system influence individual tree transpiration rates. We primarily focused on the water use response (determined with the Heat Ratio Method) of one of the dominant species (*Acer saccharinum*) and a subdominant (*Juglans nigra*). A few individuals of three additional species (*Quercus bicolor, Betula nigra, Platanus occidentalis*) were monitored over a shorter time period to assess the generality of responses. Meteorological stations were installed along a transect across the riparian buffer to determine the microclimate conditions. The differences found among individuals were attributed to differences in species sap velocities and sapwood depths, location relative to the forest edge and prevailing winds and canopy exposure and dominance. Sapflow rates for *A. saccharinum* trees growing at the SE edge (prevailing winds) were 39% greater than SE *interior* trees and 30% and 69% greater than NW *interior* and *edge* trees, respectively. No transpiration enhancement due to edge effect was detected in the subdominant *J. nigra*. The results were interpreted as indicative of advection effects from the surrounding crops. Further, significant differences were document in sapflow rates between the five study species, suggesting that selection of species is important for enhancing specific riparian buffer functions. However, more information is needed on water use patterns among diverse species growing under different climatic and biophysical conditions to assist policy and management decisions regarding effective buffer design.

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1. Introduction

Landscape scale conversion of native vegetation to intensive production of annual crops in many parts of the world has resulted in unprecedented environmental change (Rockstrom et al., 2009). In particular, one of the most dramatic consequences of agricultural conversion has been the alteration of hydrologic cycles. For example, in the Upper Mississippi River basin and its tributaries in the Midwestern USA, historical land use and land cover change has resulted in increased baseflow and peak discharge (Schilling and Libra, 2003; Zhang and Schilling, 2006). Additionally, these hydro-logical changes are having far-reaching implications for water quality and biodiversity by increasing sediment and nutrient delivery to streams and ultimately to the Gulf of Mexico, where the formation of hypoxic zones threatens both the marine biota as well as livelihood systems of human societies (Alexander et al., 2008; Schilling et al., 2008; Rabalais et al., 2010).

Riparian buffers are increasingly promoted as best management practices to reduce the transport of nonpoint source pollutants in agricultural runoff before they enter surface waters (Dosskey, 2001; Herring et al., 2006; Baker et al., 2007). The Millenium Ecosystem Assessment (2005) emphasized the value of ecosystems such as riparian buffers for enhancing multiple ecosystem services from agricultural landscapes, including water flow regulation, clean water provisioning, habitat quality improvement, biodiversity enhancement, and other environmental amenities. Extensive

research on riparian buffer systems has documented their capacity to increase infiltration and reduce surface runoff and mass transport of sediment and nutrients from crop fields to adjacent streams (e.g. Lee et al., 2000, 2003; Tufekcioglu et al., 2003; Schultz et al., 2004; Zaimes et al., 2006). Achieving these ecosystem service goals of riparian buffer systems depends, in part, on their ability to dewater and stabilize streambanks (Schultz et al., 2009), and thus, their efficiency of removing water from the soil via transpiration (Taylor et al., 2001). However, data about the rates and amounts of water use by different tree species and riparian buffer systems are sorely lacking, especially in humid temperate climates where large scale annual cropping systems are often concentrated, such as the Corn Belt region of the Midwestern U.S. This information would greatly assist policy and management decisions regarding effective buffer design.

Most studies examining ecohydrological functions of streamside vegetation have been conducted in semiarid climates, and have documented exceedingly high plant transpiration rates due to a combination of advective energy and access by trees to groundwater (e.g. Hall et al., 1998; Nagler et al., 2003; Gazal et al., 2006; Yepez et al., 2007). Increased water use by riparian vegetation has also been linked to decreased streamflow and groundwater levels, especially in arid to semi-arid climates (Dye and Versfeld, 2007). In more humid climates, tree planting on large scales such as plantations (Buytaert et al., 2007; Almeida et al., 2007), reforestations (Dierick and Hoelscher, 2009), or afforestations (Vertessy et al., 1995) has also shown to increase evaporative water losses and, in turn, reduce runoff and stream flow. However, to the best of our knowledge no studies have quantified transpiration by riparian buffer systems within agricultural landscapes in humid temperate climates, where edges between crop fields and buffer systems can create unique microclimate conditions due to advective energy that can directly influence their ecohydrological functions.

Moreover, only a few previous works on transpiration have explicitly compared water use by trees located at the edge compared to interior positions (Taylor et al., 2001; Cienciala et al., 2002; Giambelluca et al., 2003; Herbst et al., 2007). These earlier studies generally observed much higher transpiration rates by forest edge trees compared to interior trees. Due to the riparian buffer structure (2–3 rows of trees planted parallel to the stream) water use would be affected not only by species differences but also by the particular position of individual trees within the riparian buffer system (Taylor et al., 2001). Advection processes are caused by air currents transporting energy in the form of sensible heat and having a relatively high vapour pressure deficit over a surface with short vegetation (such as a crop field) which contacts taller vegetation (such as a tree buffer). Advection can therefore be expected to substantially influence water use by trees (Smith et al., 1997) as air entering a forest edge is relatively warm, dry and turbulent, thus increasing evaporative potential (Giambelluca et al., 2003). This impact of advection would depend on the coupling of the canopies to the atmosphere (McNaughton and Jarvis, 1983). The degree of coupling of the evaporating surface (leaf) to the environment determines the relative importance of the two evaporative components determined by McNaughton and Jarvis (1983): equilibrium evaporation rate (E_{eq}) that depends only on the energy supply (radiation), and imposed evaporation rate (E_{imp}) which depends mainly on atmospheric conditions. The Ω, or decoupling coefficient, is a measure of the coupling and can vary between 0 (for perfect coupling) and 1 (for complete isolation) (Jones, 1992).

Species selection has been put forward as a measure to control tree water use of reforested stands to achieve management objectives, yet species-specific information is presently very limited (Dierick and Hoelscher, 2009). Moreover, in ecosystems where advection may occur, it may lead to increased evaporative demand and, given sufficiently high saturation deficit, conditions of atmo-

spheric drought that could promote increased tree water use. However, different tree species can vary significantly in their response to evaporative demand (Bladon et al., 2006) and atmospheric drought (Guehl et al., 1991). This variation is frequently associated with differences in tree species' xylem conductivity, as only species with high twig or root xylem conductivity were found to respond positively to higher evaporative demand (Bladon et al., 2006). Knowledge about how interactions between species composition and stand structure influence water use patterns in response to local microclimate conditions is a prerequisite for designing management practices to optimally utilize available resources. For example, in agricultural landscapes in humid climates where excess soil water and subsequently low soil water storage capacity are common problems, increased tree water use in response to advection would suggest a strategy of widely spaced trees in single rows in order to maximize available advective energy and, thus, water use by all trees. Advective energy could penetrate deeper into the interior of low density stands, rather than only affecting edge trees. Conversely, if the influence of advection on transpiration is low, then denser, multi-row belts would better optimize water use and simplify plantation design and management (Taylor et al., 2001). Further, understanding how edge zones and associated landscape fragmentation affect water use patterns may have important implications for scaling carbon and water fluxes from trees to stands, since models are generally parameterized with data representing interior conditions (Cienciala et al., 2002).

We conducted a field study in a riparian buffer system located in Central Iowa with the following objectives: (1) estimate stand level transpiration by the riparian buffer, (2) quantify microclimate and stand structural controls on water use by the buffer system, (3) determine to what extent advective energy and tree position within the buffer system influence individual tree transpiration rates, and (4) assess differences in environmental responses between species. Our hypothesis was that transpiration rates would be higher for edge trees because of advection, and that this effect would be more pronounced at the south-east edge which receives the prevailing winds during the growing season. Additionally, we hypothesized that tree species with high transpiration rates should be more responsive (sensitive) to advection conditions.

2. Methodology

2.1. Experimental site

This study was conducted in a multi-species riparian buffer established in the spring of 1994 on a private farm along Bear Creek (Iowa, USA). The buffer conforms to the Code 393 grass filter and the Code 391 riparian forest buffer standards (USDA-NRCS, 1999a,b), with the key objective of reducing nonpoint source pollution (Lee et al., 2003). The Bear Creek watershed lies on the most recently glaciated landform of Iowa (12,000–14,000 years), the Des Moines Lobe, in Story and Hamilton Counties in central Iowa (latitude 42°11′N, longitude 93°30′W). The area is flat with a poorly integrated natural drainage system. The Des Moines Lobe is a subregion of the western corn belt plains ecoregion (Lowrance et al., 2006). Soils in the region developed from glacial till and alluvial or lacustrine deposits. Bear Creek is a third-order stream, draining an area of 76.6 km². Nearly 90% of the land within the Bear Creek watershed is in a corn (*Zea mays* L.)–soybean (*Glycine max*) rotation, on a soil that had been cultivated or grazed for more than 75 years (Lowrance et al., 2006). Details of the multi-species riparian buffer design, placement, and plant species are given in Schultz et al. (1995).

The study was carried out at three different locations. We first assessed the advective effect on both sides of Bear Creek, one ori-

Table 1
Comparison of the features plots studied in a riparian buffer system in Central Iowa.

Sites	SE plot	NW plot	MS plot
Tree density (tree m^{-2})	0.058	0.066	0.046
LAI[a] (m^{-2} m^{-2})	2.57	1.48	1.13
Species	*A. saccharinum, J. nigra*	*A. saccharinum*	*A. saccharinum, Q. bicolour, B. nigra, P. occidentalies*
Measurement period (DOY)	196–238 (9 *A. saccharinum* and 3 *J. nigra*)/244–260 (2 *A. saccharinum*, 2 *J. nigra*)	202–238/244–260	244–260

[a] LAI: leaf area index; DOY: day of year.

entated south-east (SE) (July 15–August 26 2009, DOY = 196–238) and the other north-west (NW) (July 21–August 26 2009, DOY = 202–238). At the SE plot there were 3 tree rows composed of silver maple (*Acer saccharinum* L.): *edge* (closest to the crop field), *middle* (between edge and interior row) and *interior* (adjacent to the creek) and one edge row of black walnut (*Juglans nigra* L.) (Fig. 1). We monitored 3 *A. saccharinum* trees in each row (n = 9) and 3 *J. nigra* trees for the edge row only (n = 3). We also monitored sap flow of *A. saccharinum* at the more sheltered NW plot for comparative purposes; however, there was no middle row in this plot, so only edge and interior trees were measured. In this NW plot only two individuals were measured per row (n = 4). Additionally, we assessed water use patterns in a nearby multi-species plot (MS) for two individuals each of three additional species (September 1–15, 2009): swamp white oak (*Quercus bicolor* Willd.), river birch (*Betula nigra* L.) and American sycamore (*Platanus occidentalis* L.), as well as for two additional *A. saccharinum* trees. All trees in the SE and NW plots were 16 years old, while trees in the MS plot were 14 years old. The understory in the three sites was sparse, and was dominated by bare soil covered by a thin litter layer on the ground surface. Details of the plots are shown in Table 1 and the characteristics of the monitored trees in Table 2. Leaf area index (LAI) was determined mid-way through the study (on 2nd September 2009) using a Plant Canopy Analyser (LAI-2000 Li-Cor Inc., Lincoln, NW, USA). We used view caps for the lens which provides azimuthal masking of view into quadrants of 10° to account for the edge effects of the study plot.

2.2. Meteorological data and soil water content

Five meteorological stations were installed along a transect across the riparian buffer (DOY = 194) (Fig. 1). Station 1 was located

Fig. 1. Diagram with tree and meteorological station location.

approximately 50 m into the soybean field, station 2 was located just outside the first *A. saccharinum* tree row (*edge*), station 3 was located in the *middle* tree row, station 4 was located between the two *A. saccharinum* rows on the NW plot, and station 5 was located at the NW buffer/field boundary. Wind speed at 3.5 m above the soil was measured with a Wind Sentry cup anemometer (R.M. Young Co., Traverse City, MI) and air temperature and relative humidity at 3.5 m were measured with a Vaisala HMP45 sensor (Vaisala, Woburn, MA) (tree canopy extended from 1.9 m height on average). In addition, the two stations west of the trees were equipped to measure wind direction with a Wind Sentry vane (R.M. Young Co., Traverse City, MI) and station 1 also included a precipitation gage (TE525 Texas Electronics Inc., Dallas, TX) and a quantum sensor to measure photosynthetically active radiation (PAR μmol m^{-2} s^{-1}; LI-190, LI-COR Bioscience, Lincoln, NE), from which solar radiation (R_s W m^{-2}) was derived (Weiss and Norman, 1985). All sensor signals were recorded every 10 s on a datalogger (CR10X, Campbell Scientific, Inc., Logan, UT) and 15 min averages stored for analysis. On Day 237 two additional stations were deployed at the second sap flow measurement location (MS plot). Station 6 was located approximately 50 m from the tree rows and station 7 was located within the tree rows. Both stations had sensors for wind speed, air temperature, and relative humidity and station 6 also included a wind vane to record wind direction.

Although groundwater depths were not measured in this study previous work at the Bear Creek riparian buffer site established that the water table is shallow (1–2 m) with an average horizontal gradient of 0.05 (Andress, 1999; Cheng, 2005). Capillary rise in silt-loam soils found in the riparian zone may extend upwards 1–2 m (Gillham, 1984) and place groundwater within the root zone of the vegetation. Hence, we can assume that the trees evaluated in this study were not under water stress during the monitoring period.

2.3. Sap flow measurements

Sap flux density (u_i, cm^3 cm^{-2} h^{-1}) was measured using the Heat Ratio Method (HRM) as described by Burgess et al. (2001). This method uses probe sets with thermocouples and heat pulses to measure sap velocity. A single heat-pulse probe consisted of two temperature probes and one heater probe each attached to a cable of up to 10 m in length. Each of the two temperature probes had three thermocouples, situated at 1.2 cm (outer), 2.4 cm (middle) and 3.7 cm (interior) from the needle tip, to obtain a radial sap flux density profile (Gebauer et al., 2008).

In the first period of the research, we monitored a total of 13 *A. saccharinum* trees and 3 *J. nigra* trees (Fig. 1). Two probes per tree were installed to account for circumferential variability (one with N-S orientation and the other with E-W orientation).

Probes were inserted into the trees by first drilling 1.3 mm diameter holes, 4.2 cm deep into the xylem tissue. A steel drilling square guide was strapped to the tree to ensure that holes were drilled parallel at fixed spacing along the plant stem–root axis (Burgess et al., 2001). The fibrous layers of the outer bark were first shaved to obtain an even surface for drilling, taking care to leave the cambium layer intact (Bleby et al., 2004). Temperature probes were
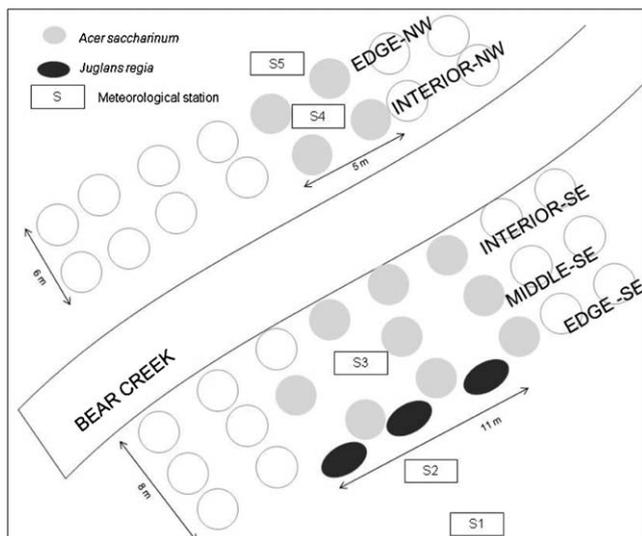
Table 2
Size of the studied tree individuals of the 3 plots located in the Bear Creek riparian buffer system. Mean ± SD.

Sites	SE plot				NW plot		MS PLOT			
	A. saccharinum			J. nigra	A. saccharinum		A. saccharinum	Q. bicolor	B. nigra	P. occidentalis
	Edge	Middle	Creek		Edge	Creek				
Sample number	3	3	3	3	2	2	2	2	2	2
DBH[a] (cm)	18.49 (±4.16)	17.19 (±2.21)	17.29 (±5.34)	10.53 (±0.74)	13.41 (±3.84)	11.17 (±3.78)	12.43(±0.69)	13.05 (±0.29)	14.61(±1.75)	12.25(±0.17)
Height (m)	14.34 (±1.97)	11.37 (±0.56)	12.19 (±3.4)	8.34 (±0.40)	9.23 (±1.51)	8.96 (±0.85)	9.02 (±0.93)	8.86 (±1.79)	9.56 (±2.08)	9.03 (±0.73)
Species density (tree m^{-2})		0.046		0.003		0.053	0.011	0.002	0.005	0.005

[a] DBH: diameter at breast height.

placed equidistant from the heater with a spacing of −0.6, 0, and 0.6 cm (Bleby et al., 2004). We used petroleum jelly as suggested by Burgess et al. (2001) to make probe insertion easier and improve the thermal contact between the sap flow probes and tree wood tissue. Two sets of probes were installed in the stem at approximately 1.3 m at the north and east faces to avoid irradiation effects. Each probe set was insulated with aluminium foil to minimize irradiation and ambient thermal gradients.

Individual thermocouple circuits were connected to a 64-channel multiplexer (Model AM 16/32B, Campbell Scientific Inc., Logan, UT, USA), which in turn was connected to a datalogger (Model CR1000. Campbell Scientific Inc.). Temperatures were averaged and stored every 10 min and calculations of sap flux density were made according to Burgess et al. (2001).

The wounding effect was corrected for as described in Burgess et al. (2001). Thermal diffusivity of green wood, wood density and water content of the sapwood were measured in sapwood cores taken at the end of the experiment (see sapwood depth section). The cores were oven-dried for 4 days at 60 °C to obtain the dry weight. The empirical measurement of the thermal diffusivity of green wood was determined as suggested by Burgess et al. (2001).

Following completion of the sampling period, the reference velocity (zero) flow value was determined by making cuts into the sapwood above and below the probes to stop sap flow in two A. saccharinum and one J. nigra over 5 days (Burgess et al., 2001; Dawson et al., 2007).

2.4. Estimation of whole tree sap flow and stand transpiration

Whole tree sap flow, F (m^3 s^{-1}), was calculated as the product of sap flux density, u_i, and sapwood cross-sectional area measured at the probe level for each monitored tree. At the end of the experiment, wood cores were obtained with a Pressler increment borer and sapwood thickness was determined based on color of the wood cores (J. nigra) and by the wood translucency (A. saccharinum, Q. bicolor, P. occidentalis, B. nigra) (Vertessy et al., 1995). These depths were compared with the sap velocity profiles. Thus, sap flow was obtained as the product of averaged sap velocity described by the thermocouple location and the band cross-sectional area. For each of the three plots (SE, NW, MS), stand transpiration (E) on a ground area basis (kg m^{-2} s^{-1} or mm day^{-1}) was calculated by multiplying average tree sap flow for each species by its stem density and summing over all species (Wullschleger et al., 2001). E could be converted to a leaf area basis by dividing by LAI.

Ground-projected canopy area, an index of competition between trees, was calculated from the canopy diameter measured with a tape measure under the canopy in North-South and East-West directions. Area was calculated by the formula of an ellipse (Nagler et al., 2007).

2.5. Calculation of canopy conductance and the decoupling coefficient

Canopy conductance (g_c, m s^{-1}) was estimated by inverting the Penman–Monteith equation (Jones, 1992):

$$E = \frac{s(R_n - G) + \rho_a C_p D g_a}{\lambda[s + (\gamma(g_a/g_c))]} \tag{1}$$

where λ is the latent heat of water vaporization (J kg^{-1}), E is the canopy transpiration (kg m^{-2} s^{-1}), s (kPa K^{-1}) is equal to the slope of the saturation vapour pressure vs. temperature curve evaluated at the air temperature, (R_n–G) is the available energy at the canopy level (W m^{-2}), ρ_a (kg m^{-3}) is the density of dry air, C_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}), D (kPa) is the vapor pressure deficit, g_a (m s^{-1}) is the aerodynamic conductance calculated from wind speed using the empirical equation of Thom and

Oliver (1977), and γ (kPa K^{-1}) is the psychometric constant. Net radiation (R_n) and soil heat flux (G) were not directly measured. R_n was calculated using solar radiation data following Shaw (1956) and G was estimated as a fraction of R_n following Sauer and Horton (2005). Canopy conductance was calculated on a species-specific basis and on the tree position and orientation (edge, middle, inner, SE and NW). To achieve that, E was based on the row density which is the same for each row and species (0.02 tree m^{-2}, *J. nigra* and *A. saccharinum*). Thirty-minute estimates of g_c were calculated using all the variables specific to those time steps, whereas daily g_c values were based on daily averages of the relevant variables. Values were converted to mmol m^{-2} s^{-1} according to Pearcy et al. (1989).

The response of g_c to D was analyzed using the following relationship described in Oren et al. (1999):

$$g_c = g_{cref} - \delta \ln D \tag{2}$$

where $-\delta$ is the sensitivity of the g_c response to $\ln D$ or the slope of g_c vs. $\ln D$ ($-dg_c/d \ln D$) and g_{cref} is g_c at $D = 1$ kPa. Regardless of species, $-\delta$ is considered by Oren et al. (1999) to be highly correlated with g_{cref} with a slope of approximately 0.6 at low D. Thus, species with high g_c at low D show a greater sensitivity to D, as required by the role of stomata in regulating leaf water potential (Oren et al., 1999).

We used the Penman–Monteith equation reformulated by McNaughton and Jarvis (1983) to explain the different water use patterns by *A. saccharinum* and *J. nigra*:

$$E = \Omega E_{eq} + (1 - \Omega) E_{imp} \tag{3}$$

which makes use of the so-called decoupling factor Ω ($0 < \Omega < 1$) and distinguishes two components of evaporation: E_{eq}, the 'equilibrium evaporation' which depends mainly on radiation, and E_{imp}, the 'imposed evaporation' which depends mainly on atmospheric conditions. For hypostomateous leaves, the following expressions hold (Jarvis and McNaughton, 1986):

$$E_{eq} = \frac{s}{s+\gamma} \frac{R_n - G}{\lambda} \tag{4}$$

$$E_{imp} = \frac{\rho_a c_p D}{\lambda \gamma r_c} \tag{5}$$

where r_c is canopy resistance (s m^{-1}).

2.6. Advection effect

We evaluated advection effects among edge orientations (SE-NW) and species (*A. saccharinum* and *J. nigra*) by comparing the latent heat flux (LE) to R_n. Based on the Priestley–Taylor equation (Priestley and Taylor, 1972):

$$LE = \alpha \frac{s}{a+\gamma} (R_n - G) \tag{6}$$

From Eq. (6), α can be defined as:

$$\alpha = \frac{s+\gamma}{\gamma} \frac{LE}{(R_n - G)} \tag{7}$$

Assuming G to be small ($<5\%$ or R_n) and differences in G between sites to be neglible and because we are interested in determine the degree of influence of positive heat advection, we will compare the ratio LE/R_n among sites. Comparing LE/R_n, we will know if there is an extra source of energy so that the latent heat loss significantly exceeds any gain in net radiation (Jones, 1992). In the absence of advection, this ratio is expected to approach 1.0 because LE will be limited by the energy available from R_n. This ratio could be less than 1 if the trees are limited by atmospheric drought. The impact of local advection was also investigated by comparing the magnitude of the differences between *A. saccharinum* E_{imp} at the NW and SE plot (Tolk et al., 2006), and *J. nigra* E_{imp}.

2.7. Data analysis

Values of F, E_{imp}, E_{eq}, and the ratio LE/R_n among species were compared using a t-test for independent samples and corrected for multiple comparisons with Tukey's HSD. Relationships between the variables studied were evaluated using simple and non-linear regression analyses. All statistical analyses were conducted with Statistica (Version 7. Statsoft, OK, USA).

3. Results

3.1. Meteorological variables and soil water content

During the study period (July–September) cumulative rainfall was 127 mm (Fig. 2a) which was less than half of the mean cumulative rainfall of those months from 1971 to 2000 (about 300 mm according to the Midwestern Regional Climatic Center, mcc.sws.uiuc.edu). Mean solar radiation was 139.1 W m^{-2} in the first period (DOY = 196–238) and 202.4 W m^{-2} in the second period (DOY = 244–260) (Fig. 2b). Air temperature was on average 0.8 °C higher in the first period than in the second and varied only slightly between stations (maximum variation 0.25 °C and 0.48 °C in the first and second measurement period, respectively). Vapor pressure deficit (D) was slightly higher in the second period (0.6 kPa) than in the first (0.5 kPa). All means were calculated for all time periods. The average difference between stations was also higher, because in the second period there were two additional stations installed at the MS plot (15.3% and 17.5% in the first and second sampling period, respectively) (Fig. 2c and f). The mean maximum D was registered in the station located at the crop site with SE orientation (0.6 kPa) in both periods and the minimum in the stations located in the woodland sites (0.5 kPa). The greatest variation among the meteorological stations was observed for wind velocity (coefficient of variation for the first period 44% and for the second period 50%). Wind speed was not very high on a daily basis, peaking at 1.6 m s^{-1} in the first period at the crop station (SE plot), and in the second period at the NW plot (1.1 m s^{-1}) (Fig. 2d and g). Wind direction averaged 173° and 147° from the stations located in the crop field (1 and 5) during the first measurement period, and thus likely allowed for continuous entry of unsaturated air from the cropped area to the northwest (Fig. 2e). Due to instrumentation failure of station 2 we did not use the data of this period of DOY 217–229 in the aforementioned comparisons.

3.2. Stand transpiration

3.2.1. Radial patterns of sap flow density

Across all species, u_i was generally highest at the middle thermocouple (2.4 cm) and lowest at the inner thermocouple (3.7 cm). The exceptions were for instances where u_i was greater for the inner thermocouple, which occurred in two individuals of *A. saccharinum* and one individual each of *P. occidentalis* and *J. nigra*. The results of the sapwood depth measurements corroborate that all sensors were generally in contact only with sapwood and not with heartwood. Only three individuals had slightly narrower sapwood depth (Table 3) than the inner thermocouple, but as sap flow velocities were actually recorded by these thermocouples (likely reflecting the small difference between measured sapwood depth and the inner thermocouple position), we did not apply any correction factor. Overall, the thermocouple positions effectively captured the range of sapwood depths recorded for the study species (Table 3). Among species, higher sapwood depths were recorded for diffuse-porous species (4.1–7.3 cm) compared to ring-porous species (3.3–4.6 cm) (Table 3). The magnitude of the observed u_i also differed considerably among species (Table 3). On
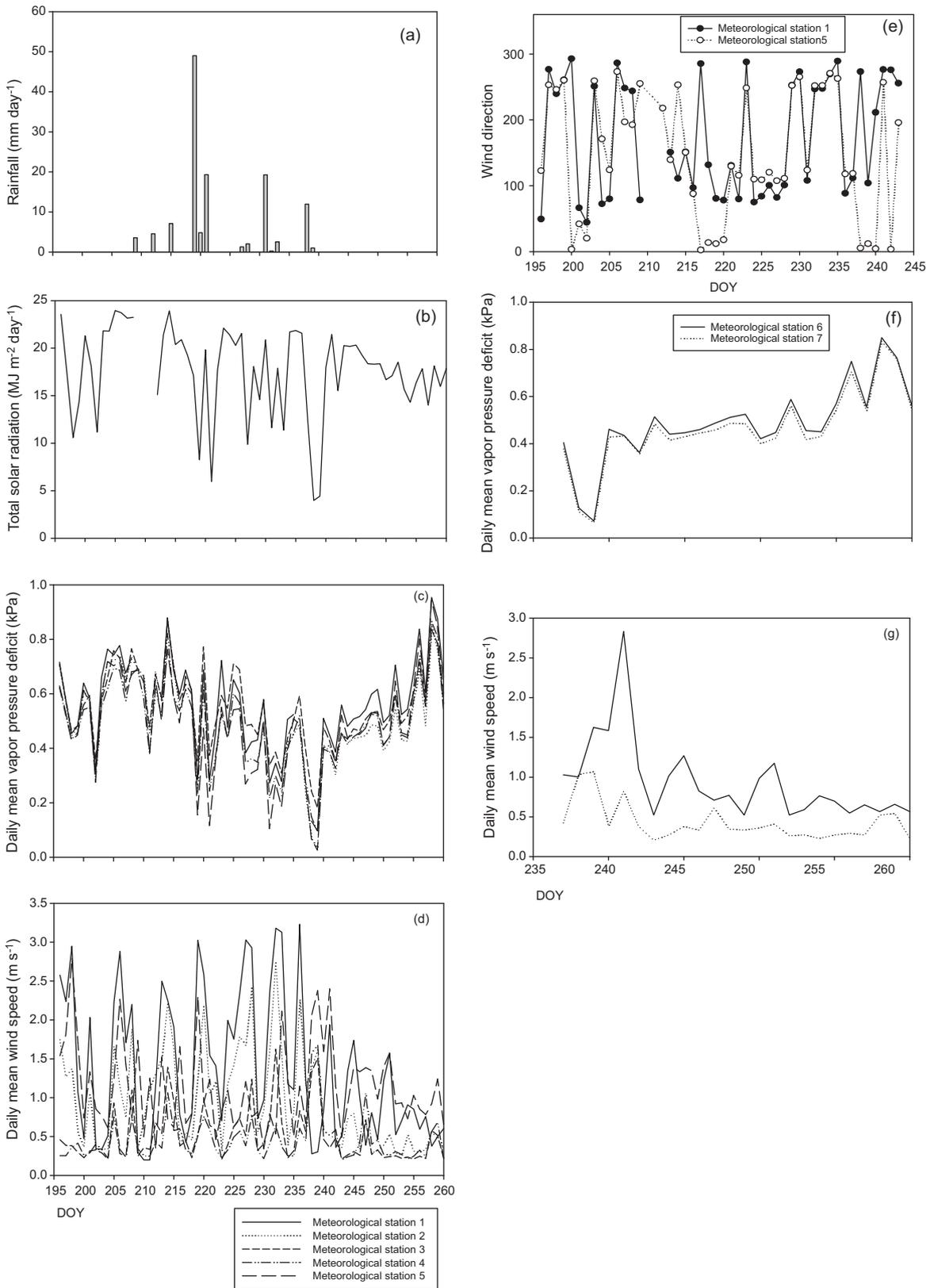
Fig. 2. Time evolution for the whole study period of daily (a) total rainfall, (b) total solar radiation, (c) mean air vapour pressure deficit at SE and NW plot, (d) daily mean wind speed at SE and NW, (e) wind direction in meteorological stations 1 and 5 (f) mean air vapour pressure deficit at MS plot and (g) daily mean wind speed at MS plot.

average, u_i was higher in ring-porous species (*J. nigra*, *Q. bicolor*) than in diffuse-porous species (*A. saccharinum*, *B. nigra*, *P. occidentalis*); however, a clear pattern did not emerge between these two groups.

Mean F calculated for the whole study period and DBH were positively correlated for *A. saccharinum* ($R^2 = 0.77$, $p < 0.001$). Due to the small sample size for the other trees species (2–3 trees per species), regression analyses were not possible.

Table 3
Comparing sap flux density (u_i, cm^3 cm^{-2} h^{-1}) and sapwood depth (cm) among species growing in the Bear Creek riparian buffer system (Iowa, US). Mean ± SD. The statistics are only for the first period (*A. saccharinum* 3–9, *J. nigra* 2), only for the second period (*Q. bicolour* 1–2, *B. nigra* 1–2, *P. occidentalis* 1–2, *A. saccharinum* 14–15) and for the whole study period (*A. saccharinum* 1–2, 10–13, *J. nigra* 1,3).

	u_i	Sapwood depth		u_i	Sapwood depth
Edge-SE			Edge-SE		
A. saccharinum 1	4.0 ± 1.2	6.2 ± 0.2	*J. nigra1-SE*	4.1 ± 0.8	4.4 ± 0.9
A. saccharinum2	4.0 ± 0.5	6.0 ± 0.1	*J. nigra2-SE*	5.5 ± 0.6	4.6 ± 0.3
A. saccharinum3	4.9 ± 0.8	5.2 ± 0.1	*J. nigra3-SE*	6.7 ± 0.1	4.6 ± 0.0
Middle-SE			MS plot		
A. saccharinum4	2.9 ± 0.5	5.1 ± 0.4	*Q. bicolor1*	12.3 ± 0.4	3.5 ± 0.0
A. saccharinum5	3.3 ± 0.3	7.2 ± 0.0	*Q. bicolor2*	10.8 ± 0.2	3.3 ± 0.3
A. saccharinum6	2.5 ± 0.8	6.1 ± 0.3	*B. nigra1*	2.8 ± 0.8	4.5 ± 0.0
Interior-SE			*B. nigra2*	3.1 ± 0.3	5.8 ± 0.2
A. saccharinum7	2.4 ± 0.4	4.7 ± 0.6	*P. occidentalis1*	9.7 ± 0.6	4.6 ± 0.1
A. saccharinum8	3.6 ± 0.7	7.3 ± 0.2	*P. occidentalis2*	8.2 ± 0.1	4.8 ± 0.0
A. saccharinum9	2.2 ± 0.5	6.2 ± 0.2	*A. saccharinum14*	5.1 ± 0.5	5.2 ± 0.2
Edge-NW			*A. saccharinum15*	4.7 ± 0.3	5.3 ± 0.4
A. saccharinum10	2.9 ± 0.5	4.1 ± 0.7			
A. saccharinum11	2.7 ± 0.2	5.0 ± 0.3			
Interior-NW					
A. saccharinum12	3.8 ± 1.1	4.9 ± 0.1			
A. saccharinum13	4.3 ± 0.7	3.6 ± 0.6			

3.2.2. Whole tree sap flow

The maximum F was usually observed around midday, while the minimum F usually occurred at night. Since variability in DBH among all species was relatively small (the maximum difference was about 7 cm in *A. saccharinum*) (Table 2), differences in F among species can be directly compared. Comparing among species during the first sampling period (DOY 196–238), F was higher for *A. saccharinum* than for *J. nigra*, except for the *interior* NW individuals (Fig. 3a). Average whole tree F (m^3 s^{-1}) ranged from 9.4×10^{-8} m^3 s^{-1} (minimum) to 3.1×10^{-7} m^3 s^{-1} (maximum) in *middle* and *edge* SE *A. saccharinum*, respectively. Average F for *J. nigra* was 8.2×10^{-8} m^3 s^{-1}.

The results from the second period demonstrated that *A. saccharinum F* for the two plots (MS and NW) were similar. Regarding the second sampling period (DOY 244–260), the maximum daily F was observed in *Q. bicolor* and *P. occidentalis*, while the minimum occurred in *B. nigra* (Fig. 3d). There were significant differences ($p < 0.01$) in u_i among species except between *A. saccharinum* (NW plot) and *J. nigra* (SE plot). However, comparing F, significant differences ($p < 0.01$) were observed across all species. The average whole tree sap flow was significantly related to D ($p < 0.0001$) in all species and the response to D was similar in all cases (Fig. 5). There was no significant relationship between mean daily F and projected canopy area, nor for projected canopy area between *edge* and *interior* trees.

3.2.3. Advective effects on transpiration rates in A. saccharinum and J. nigra

Comparing *A. saccharinum* and *J. nigra* at the same position (*edge*, SE plot), F in *A. saccharinum* was significantly correlated (exponential relationship, $p < 0.001$) with R_s ($R^2 = 0.63$) and D ($R^2 = 0.64$), and was linearly related to the estimated PET using the Priestley–Taylor equation ($R^2 = 0.55$ $p < 0.001$). The regressions between daily F and meteorological variables for *J. nigra* were much weaker than for *A. saccharinum* but significant ($p < 0.0064$), both for R_s ($R^2 = 0.18$) and D ($R^2 = 0.25$). *Juglans nigra* exhibited relatively stable and consistent F throughout the measurement period, whereas *A. saccharinum F* displayed greater sensitivity to environmental conditions, and therefore greater day-to day variability.

Canopy conductance, g_c (kg m^{-2} s^{-1}) was estimated from sap flow and other variables measured specified in Eq. (1) for *A. saccharinum* at edge positions (SE and NW plots) and for *J. nigra*. In order to isolate the response of g_c to D, Fig. 4 shows the data after using a series of filters following Ewers et al. (2005) (photosynthetically

active radiation >1.0 mmol m^{-2} s^{-1} and boundary analysis to select the highest values of g_c within each 0.2 kPa grouping of D-values). All the relationships were significant ($p < 0.0001$). Canopy conductance declined with increasing D in the three cases analyzed, but
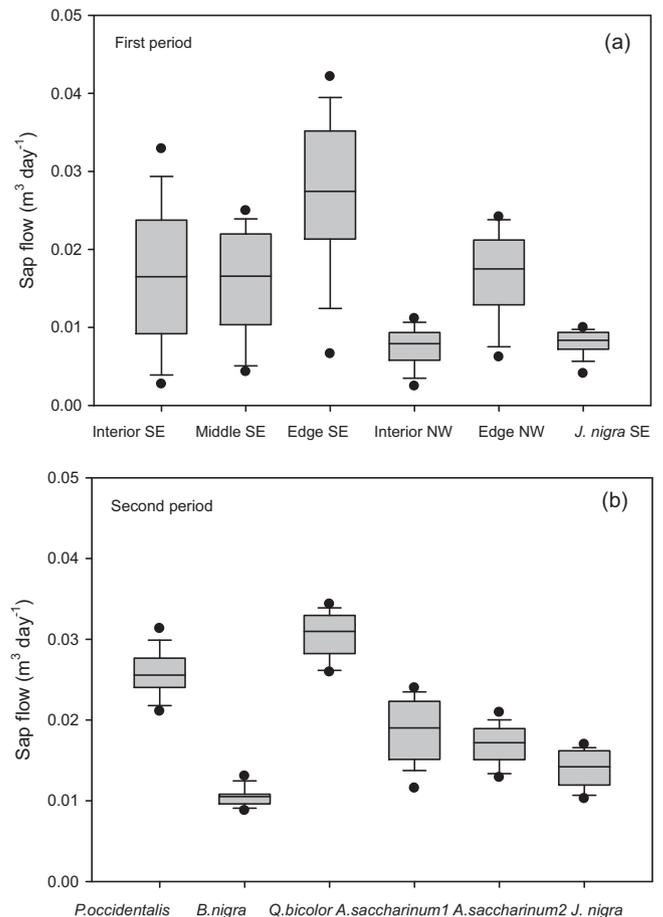
Fig. 3. Box plot with daily sap flow of (a) *A. saccharinum* interior, middle, edge rows situated at SE, *A. saccharinum* interior and edge rows situated at NW, and *J. nigra* situated at SE; (b) *P. occidentalis*, *B. nigra*, *Q. bicolor*, *A. saccharinum* 1 (situated at MS plot) and *A. saccharinum* 2 (situated at NW plot) and *J. nigra*. In each box it is plotted median, 10th, 25th 75th and 90th percentiles, the vertical lines are error bars, and the points the maximums and minimums. Data are from the (a) first and (b) second measurement period.
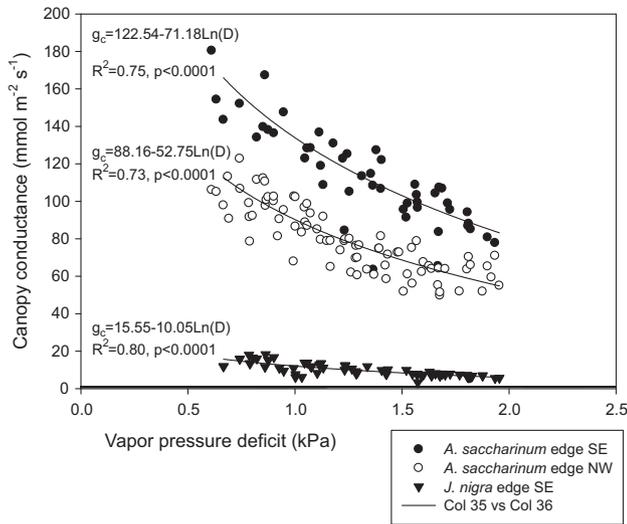
Fig. 4. Relationship between canopy conductance and vapor pressure deficit at midday, for *A. saccharinum* at edge position at SE plot, at NW plot and *J. nigra* at edge position at SE plot, for the first measurement period.

the rate of decline in g_c was lower in *J. nigra* than in *A. saccharinum*. Comparing among species at the SE edge plot, *A. saccharinum* consistently had greater g_c than *J. nigra*. To quantify the changes in the rate of g_c decline with D, the relationship between $-\delta$ and g_{cref} (Eq. (2)) was determined using the data shown in Fig. 4. There was no significant difference between the hypothesized 0.6 proportion between $-\delta$ and g_{cref} (0.58, 0.59 and 0.64 for *A. saccharinum* at SE, *A. saccharinum* at NW and *J. nigra*, respectively) (Fig. 5).

Equilibrium evapotranspiration (E_{eq}) and imposed evapotranspiration (E_{imp}) as calculated using Eqs. (4) and (5) help us to clarify the differences in water use patterns observed for edge trees of *A. saccharinum* and *J. nigra* in relation to microclimate. E_{eq} calculated for *J. nigra* and *A. saccharinum* at the edge position (SE and NW) were not significantly different. Edge effects are assumed to be negligible if the ratio of E_{imp} to E_{imp} between pairs of tree positions (*edge-interior*) is constant and equal to unity. Also, comparing the ratio of E_{imp} to E_{imp} of different tree species (*A. saccharinum–J. nigra*) we can determine if both species situated at the same position were affected by this edge location. Although the ratio between
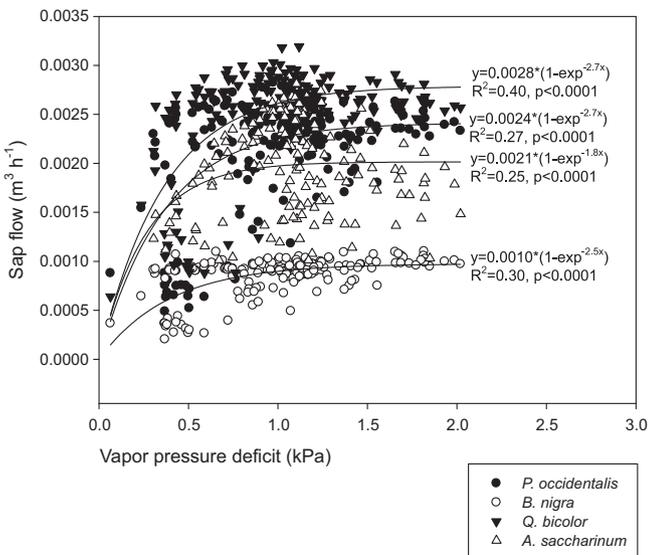

Fig. 5. Tree sap flow response to vapor pressure deficit measured in the second study period in trees at MS plot.
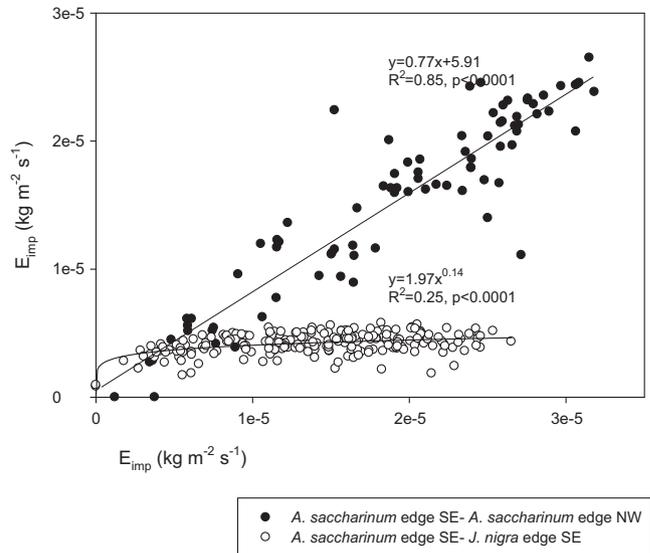

Fig. 6. Relationship between hourly imposed transpiration (E_{imp}) *A. saccharinum* at edge position at SE plot (X axis) and *A. saccharinum* at edge position but at NW plot and *J. nigra* at edge position at SE plot (Y axis), for the first measurement period.

SE E_{imp} and NW E_{imp} for *A. saccharinum* edge trees was not equal to unity (Fig. 6), it was linear and constant, and the E_{imp} values were not significantly different between *A. Saccharinum* edge trees at SE E_{imp} and NW E_{imp} (based on t-test for independent samples). The relationship between *A. saccharinum edge* SE E_{imp} and *A. saccharinum edge* NW E_{imp} was strong ($R^2 = 0.85$, $p < 0.0001$) and linear. This means that E_{imp} measured at both positions was similarly responsive (linear relationship) but with different intensity (relationship slope different to unity) to the environmental conditions. However, significant differences were observed when comparing *A. saccharinum* SE E_{imp} with *J. nigra* SE E_{imp}. The best fit curve between *A. saccharinum edge* SE E_{imp} and *J. nigra* E_{imp} was exponential and weaker although significant ($R^2 = 0.25$, $p < 0.0001$), with an evident E_{imp} upper limit of about 6×10^{-5} kg m^{-2} s^{-1} (Fig. 6).

As can be seen in Fig. 3a, F varied with position in the riparian buffer (i.e., *edge vs. interior/middle*) for *A. saccharinum*. These and other calculations utilize a single estimate of R_n for the site under the prevailing conditions. While under non-advective conditions the assumption of a uniform R_n is reasonable, under advective condtions warming of the canopy in the upwind trees could produce a reduced R_n due to greater upwelling longwave radiation. Direct measurement of this effect on R_n would be very difficult and the magnitude of the difference is believed to be small. Advective effects on transpiration in *A. saccharinum* were analyzed by comparing daily E of the *edge* trees with the trees adjacent to the stream in the SE plot (*interior*). Despite the strong relationship between *A. saccharinum* transpiration measured at *edge* and *interior* trees ($R^2 = 0.76$ $p < 0.0001$), the transpiration was 39% lower for the *interior* stream-side trees than for the *edge* trees (Fig. 7) and this regression (*edge-interior* transpiration) was significantly different from the 1:1 line ($p < 0.001$). As mentioned before, the edge effect was observed when the ratio of the two flows is not constant and equal to unity, because this would mean that trees in two different positions would be responding to environmental conditions in a similar and proportional manner. This 39% difference in transpiration was similar with the *middle* trees of SE plot, maximum for *interior* trees at NW plot (69%) and lowest for *edge* *A. saccharinum* trees at the NW plot (30%). Using the ratio LE/R_n we compared the fraction of R_n used for evaporation of the same species (*A. saccharinum*) at the same position (*edge*) with different orientation (SE and NW) and between the two species (*A. saccha-*
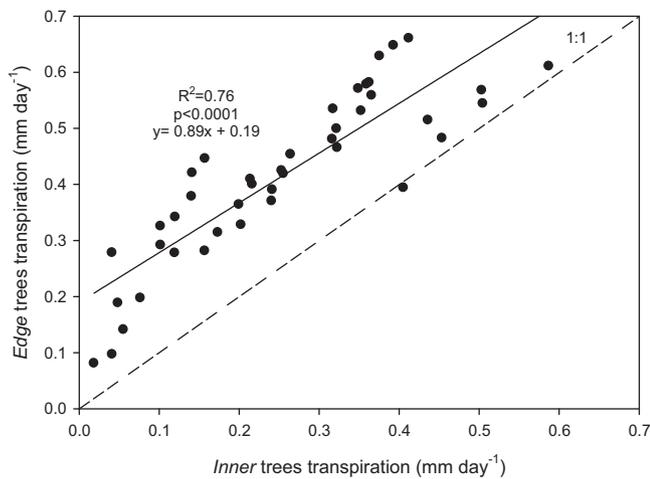
Fig. 7. Comparison of daily transpiration measured simultaneously in edge and interior trees at SE plot for the first study period.

rinum and *J. nigra*) with the same orientation and position (*edge* SE) (Fig. 7). This ratio was significantly higher on average for *A. saccharinum edge* SE than for *A. saccharinum edge* NW and *J. nigra* ($p < 0.001$, Fig. 8). For *A. saccharinum edge* SE there were 8 days out of 25 analyzed that were higher than 1 whereas only 2 days for *A. saccharinum* edge NW (although there were fewer measurements, 16, coinciding with advective conditions) and none for *J. nigra* (Fig. 8). As stated earlier, if the ratio LE/R_n is greater than 1, then plants are getting energy from the surrounding environment (advection), which in this case happens with the *A. saccharinum* at the edge SE. Comparing only *edge* trees' *F* at the SE plot, for those days with advection, transpiration was 27% higher for days without advective energy ($p = 0.044$). Days with advection had prevailing winds from SE on average (137°) whereas winds were from the S (191°) for non-advective days. No significant differences were found for *D*, wind speed and temperature between advective and non-advective days, although values were generally higher for the advective days. There were also significant differences comparing wind velocity differences between stations in the crop field (#1) and in the buffer interior (#3) for advective and non-advective days ($p = 0.043$), with higher values recorded for advective days (2.1 m s^{-1}) compared to non-advective days (1.3 m s^{-1}).
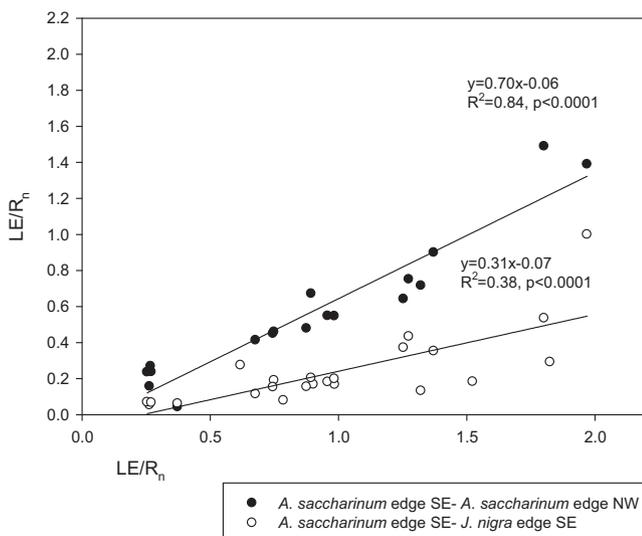

Fig. 8. LE/R_n calculated on a daily basis for *A. saccharinum* at edge position at SE and NW plots, and *J. nigra* located at edge position at SE plot.

3.2.4. Stand transpiration

Cumulative E for the riparian buffer system considering every species for the whole study period reached 84 mm, which represents a mean of 1.4 mm day^{-1} and accounts for approximately 66% of the cumulative rainfall for the same period (127 mm). Daily *E* was also calculated for each of the tree plots separately, since tree species and densities were very different. For the first period, mean daily *E* in the SE plot was 0.89 mm day^{-1} and 0.53 mm day^{-1} for NW plot. In the second measurement period mean transpiration in MS plot was 0.52 mm day^{-1} and 0.80 mm day^{-1} in the NW plot. The canopy transpiration for the first period considering only the *middle* trees would be about 1.6 mm day^{-1} while it would be 2.6 mm day^{-1} considering only the individuals at the *edge* position. For the second period considering the MS plot as a monoculture of each species, transpiration would be maximum with a pure *Q. bicolor* stand (0.7 mm day^{-1}) and minimum with a pure stand of *B. nigra* (0.2 mm day^{-1}).

4. Discussion

In this study, we assessed water use by trees located within a riparian buffer system at varying positions (edge *vs.* interior) and for different species (*A. saccharinum* and *J. nigra*), to test our hypothesis that advective energy would lead to high transpiration rates by edge trees and on aspects exposed to prevailing winds (SE), and that species with higher transpiration rates should exhibit greater sensitivity to advective conditions. As predicted, our results documented significantly greater sapflow rates by *A. saccharinum* trees growing at the edge position compared to the interior positions at the SE (Figs. 3a and 6). Additionally, sapflow was higher for SE edge trees compared to NW edge trees (Fig. 3a). The results were interpreted as indicative of advection effects. Support for the role of advection in explaining differences in F across positions was provided by the Priestley–Taylor coefficient, which was significantly higher for trees at the SE *edge* (prevailing winds) compared with the NW edge. Thus, estimated transpiration of the SE *edge* trees exceeded what would be attributed to net radiation alone (Jordan et al., 2009), lending support to our hypothesis that transpiration by SE edge trees adjacent to crops could be enhanced by advective energy transported by prevailing winds (Fig. 2e). The lack of significant differences between *D*, wind speed and temperature for advective and non-advective days, despite a trend of higher values for advective days, was probably due to the small sample size (only 8 days with advection). Giambelluca et al. (2003), working in a tropical forest fragment in Vietnam, also documented enhanced transpiration during relatively clear, sunny periods when the crop field was dry and hot, and conditions were conducive to high positive heat advection. In our study, days with advective conditions also corresponded with SE winds and higher wind velocities in the crops relative to within the riparian buffer.

Overall, our results indicate that sapflow rates for *A. saccharinum* trees growing at the SE edge were 39% greater than SE interior and middle trees (SE *middle* and *inner*) and 30% and 69% greater than NW *inner* and *edge* trees, respectively. These values are in the range of other studies conducted to detect edge effects on plant transpiration. Giambelluca et al. (2003), working in a tropical forest fragment in Vietnam, reported that sap flow rates of edge trees were on average 16% greater than interior trees, and as much as 56% greater for "well-exposed" trees. Similarly, Herbst et al. (2007), working in a temperate mixed deciduous forest in the U.K., reported a similar increase in sapflow for dominant *Fraxinus excelsior* trees, edge *vs.* interior, while the two subdominant species, *Crataegus monogyna* and *Acer campestre,* exhibited a difference closer to 16%, when comparing edge *vs.* interior trees (Herbst et al., 2007). However, no significant effect was found between edge and inner trees of

the other codominant species (*Quercus robur*) in this same study. Taylor et al. (2001) reported greater (64% and 52% for two different periods) differences between edge and inner trees for a *Eucalyptus globulus* plantation. Cienciala et al. (2002) reported that transpiration rates of *Pinus sylvestris* trees growing in the interior forest were about 64% lower than for edge trees in a boreal coniferous forest. Thus, edge effects on increasing transpiration rates have clearly been demonstrated across different species and climates. However, while some studies explicitly attributed these edge effects to advection (Taylor et al., 2001; Giambelluca et al., 2003; Herbst et al., 2007, this study), other works implicated other variables as the predominant explanation for observed edge effects, including soil moisture conditions (Cienciala et al., 2002) and basal area (Herbst et al., 2007). Thus, our study in a riparian buffer system contributes to the past edge effect work, and establish more conclusively the importance of advection effect in humid temperate regions.

At the tree scale, there are many other factors besides advection and species that affect transpiration rates and which could potentially explain the differences observed in our study between edge and interior trees, including water table depth, tree size, and canopy dominance (Herbst et al., 2007). However, differences in water source availability among the sites was not a likely factor in our study, since groundwater depths in the buffer are uniformly shallow under a flat horizontal gradient (Simpkins et al., 2002). Further, water stress did not appear to affect sap flow rates in any of the species, since rates remained stable over time. Trees were likely tapping soil water and capillary water below 25 cm. Potential errors in sap flow measurements due to radial variability (Gebauer et al., 2008) were addressed by assessing radial profiles of sap velocity with 3 thermocouples located at different sapwood depths. Further, visual estimation of sapwood depths was not difficult in the study species, and generally agreed with the results obtained from the radial sap velocity profiles. The sample size of *A. saccharinum* was robust enough to derive reliable conclusions, but we acknowledge that the relatively small sample size of the other species only allows for identification of general trends that require further research to verify. Nevertheless, the similar response of *F* to *D* among species and between the different species and *A. saccharinum* (Fig. 5) suggest that the observed trends are meaningful.

There was a significant positive relationship between DBH and *F* for *A. saccharinum* individuals ($R^2 = 0.77$, $p < 0.001$), which was not surprising, considering that sapwood area was also greater for larger individuals. Because edge trees were generally larger than interior trees and are the same age, these results suggest that greater water use by edge trees affected by advection resulted in greater CO_2 assimilation and growth rates (Table 2). Although it is also reasonable to assume that edge trees will exhibit faster growth rates than non-edge trees because they are subject to less competition for light and soil resources (Taylor et al., 2001), SE edge trees were larger than NW edge trees (Table 2), likely reflecting the stronger advective effects on the SE which receives the prevailing winds. Moreover, tree canopy area, used here as a competition index, did not show any relationship with tree sap flow or tree position. As demonstrated by Waring (1983), canopy leaf area can be related to competition for light because growth efficiency is responsive to canopy leaf area and other environmental factors, and maximum canopy leaf area is related to potential productivity. However, other works (Loranty et al., 2010a,b) show an explicit relationship between competition for light and transpiration by trees in the interior of forests, suggesting that trees subject to photosynthetic limitation as a result of competitive shading exhibit a dynamic stomatal response resulting in a more conservative strategy for managing hydrologic resources. In order to test whether the higher transpiration recorded for edge trees in our study was due to enhanced stomatal opening in response to greater light in the edge environment (i.e. not just due to the radiation

driving transpiration itself), we analyzed the response of g_c to photosynthetically active radiation. However, this relationship was not significant ($p = 0.47$), thereby corroborating our earlier interpretation that advective energy was likely the driving factor explaining the different transpiration rates observed for edge and interior trees.

Comparing edge effects on *F* across species *Acer saccharinum* trees were larger than *J. nigra* trees despite their same age, which was likely a consequence of slower growth rates (and associated lower transpiration rates) in the latter. The results indicated that *J. nigra E* is more strongly controlled by available energy (E_{eq}). In contrast, the results of *A. saccharinum* indicated that imposed evaporation (E_{imp}), which depends mainly on atmospheric conditions (including advection), is a strong driver of *E* in this species. This occurs where the boundary layer conductance is large, heat and mass transfer are very efficient so that leaf temperatures approach air temperature irrespective of the input radiation, and the surface is well coupled to the environment (Jones, 1992). Although *J. nigra* was also located at the SE edge, it occupied a sub-canopy position (6 m of height difference on average with *A. saccharinum*), and therefore received shelter from the wind by the taller *A. saccharinum* canopy. Matlack (1993) found that exclusion of light by closure of the side canopy curtailed edge effects in the variables dependent on direct beam radiation (*D*, temperature, and litter moisture).

We found reported sap flow results in the scientific literature for only 2 species out of the 5 species examined in our study. For *J. nigra* there were two studies with differing results: Frak et al. (2002) reported lower sap flow rates (0.0024 m³ day⁻¹), whereas Jose et al. (2000) reported slightly higher rates (0.03 m³ day⁻¹) compared to our study. The differences with the first study (Frak et al., 2002) may be attributed to the experimental design (sampled trees were only 2 years old) and their growth conditions (planted in pots with sand). In the second study, the trees had more comparable DBH to our trees (9–9.6 cm) (Jose et al., 2000). Another study conducted by Bartens et al. (2009) for *Q. bicolor* reported much lower *F* (0.0015 m³ day⁻¹) compared to our values for this same species (0.03 m³ day⁻¹), which may be due to the young age of the trees (2 years) in the former study. To the best of our knowledge, there are no published sap flow data for *A. saccharinum*. Overall, ecophysiological assessments of *A. saccharinum* suggest that its hydraulic properties are consistent with adaptive and exploitive behavior typical of early successional species, such as low whole-tree resistance, which assures high transpiration rates in the presence of sufficient water (Tsuda and Tyree, 1997). Concordantly, we found higher g_c and g_{cref} for *A. saccharinum* than for *J. nigra*. This is in agreement with the findings of Oren et al. (1999), where highest g_{cref} values were recorded in diffuse-porous species. We also found higher $-\delta$ for *A. saccharinum* than for *J. nigra*, which also agrees with Oren et al.'s (1999) results (i.e., lowest $-\delta$ found in ring-porous species). Although this higher $-\delta$ indicates a greater absolute reduction in g_c with increasing *D*, in our *D* range this decrease was not sufficient to cause *A. saccharinum* to have lower g_c than *J. nigra*. Therefore, having a higher g_c in these study conditions (e.g., no soil water deficit and low *D*) represents an advantage for *A. saccharinum*, and also supports our original hypothesis that tree species with high transpiration rates are more responsive to advective conditions.

Assessing the water use among the 5 species studied, there were significant differences between the species although a clear pattern between ring-porous and diffuse-porous species did not emerge (Table 3). Highest F was recorded in *Q. bicolor*, a ring-porous species, and the minimum was recorded in *B. nigra*, a diffuse-porous species. However, between these two extremes there were no clear patterns in relation to wood properties (Fig. 3b), although these results could be limited by the small sample size (Table 3). Other authors, such

as Phillips et al. (1996) found similar sap flux densities between a diffuse- and a ring-porous species (*Liquidambar siyraciflua* and *Quercus alba*, respectively) and no significant differences between sap flux density at different sapwood depths in either species. Studies comparing hydraulic conductivity (Steppe and Lemeur, 2007; McCulloh et al., 2009) and sapwood depths (Gebauer et al., 2008) among different diffuse and ring porous species can help interpret our results as F is directly related to hydraulic conductance (Wullschleger et al., 1998). The hydro-active sapwood was found to occupy 70–90% of the stem cross-sectional area in mature trees of diffuse porous species, whereas it occupied only about 21% in ring-porous species (Gebauer et al., 2008). Further, ring-porous species generally have a higher number of vessels with larger diameters, which contribute more to the total hydraulic conductivity than small vessels (Steppe and Lemeur, 2007). *A metanalysis conducted* by McCulloh et al. (2009) further suggests a large degree of variability in wood property–water use relationships among species with respect to environmental conditions. Our work further corroborates this high variability and lack of consistent pattern. Thus, the differences found in F among our study species together with the lack of strong pattern between ring- and diffuse-porous species F likely reflects compromise between the number and size of vessels, sapwood depths and individual species adaptations to particular site conditions.

Stand level E was strongly influenced by differing densities among the study species, with *A. saccharinum* having a much higher density than the other species. This would explain the higher transpiration (0.8 mm day^{-1}) in NW plot (total tree density = 0.053 trees m^{-2}) compared to the MS plot (0.52 mm day^{-1}, 0.023 tree m^{-2}). Additionally, tree position (especially edge *vs.* interior) was shown to strongly affect F in this species, which would explain the higher transpiration in the SE plot (0.89 mm day^{-1}) compared to NW plot although in this last plot a slightly higher density was found than in the SE plot (0.049 tree m^{-2}). It was demonstrated that the stand water use determined, 66% of the accumulated rainfall for this period was important for the achievement of the riparian goals. To compare the tree transpiration results obtained here with the surrounding crops (corn and soybean) we used the results of a study by Hernandez-Ramirez et al. (2009) conducted near our study plot, which reported mean daily E for *Z. mays* of 1.6 mm day^{-1}, and slightly lower values for *G. max*. This value is slightly higher than our mean daily E estimated for the buffer system (1.4 mm day^{-1}), but much lower than the estimated E for SE *edge* trees (2.6 mm day^{-1}) during peak growing season. Considering that the growing season of the crops is shorter than for the trees, and that trees are active early in the growing season before crop establishment when rainfall is also the highest, the buffer system is apparently capable of achieving high rates of water removal and thus soil dewatering potential in agricultural landscapes.

A sound understanding of tree species' water use differences play a decisive role in the hydrology of planted forests (Almeida et al., 2007; Buytaert et al., 2007; Dye and Versfeld, 2007; Dierick and Hoelscher, 2009; Vertessy et al., 1995), thus appropriate tree species selection is a key point in agricultural conservation practices involving riparian buffers. However, to date, the practical applications of this approach are largely theoretical because information on growth and water use rates exists for only a limited number of species (Dierick and Hoelscher, 2009). In this study, we found strong differences among 5 common riparian buffer species, suggesting that more research is needed to understand water use pattern among different species as a basis for improving management and conservation decisions. For example, as a central objective of riparian buffer systems is to improve water quality and flow regulation, based on our results the best species to achieve that goal would be to incorporate proportionally higher densities of Q.

bicolor (Fig. 4). Further, the increased transpiration rates reported for edge trees compared to interior trees in our study suggest that the design of riparian buffers for enhancing ecohydrological functions can be maximized by planting lower densities facing prevailing winds (or thinning existing dense stands) to increase total water use on a per tree basis. In other words, even though stand leaf area may remain similar, the amount of leaf surface area exposed to advective energy should increase. As demonstrated here and in other studies (Giambelluca et al., 2003; Herbst et al., 2007), fragmentation increases transpiration due to advective effects that are maximized with increasing edge environment and orientation to prevailing winds.

5. Conclusions

Our findings suggest that the variation in tree transpiration among individuals within the riparian buffer system was attributed to: (1) differences in species due to u_i and sapwood depth (*Q. bicolor* F > *P. occidentalis* F > *A. saccharinum* F > *J. nigra* F > *B. nigra* F), (2) location relative to the forest edge (*edge* F > *middle/inner* F), (3) prevailing winds (SE F > NW F), and (4) canopy exposure and dominance (*A. saccharinum* F > *J. nigra* F). The edge effect on transpiration in *A. saccharinum* was attributed to advection from the surrounding crops.

These findings have practical implications for optimal riparian buffer design. Widely spaced trees should maximize water use by effectively utilizing available wind energy. Further, selection of species with high transpiration rates under conditions of high water availability, such as *Q. bicolor* and *P. occidentalis*, should also enhance total water use by the riparian buffer system. High rates of transpiration by riparian buffer trees can contribute to regulating hydrologic flows in agricultural landscapes by removing excess soil water and thereby dewatering streambanks, which should lead to increased soil water storage capacity, reduced runoff, improved sediment and nutrient retention, and greater streambank stabilization (Lee et al., 2003).

More detailed studies are needed to better understand the relationships between water use of these riparian buffers with runoff, water table depth and other hydrological processes. Additionally, particularly relevant for buffer design would be studies assessing edge effects in different species, as well as the potential for enhancing total water use by buffer systems by implementing thinning treatments once stands reach high densities.

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