Effects of Thinning on Transpiration by Riparian Buffer Trees in Response to Advection and Solar Radiation

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Abstract

Upwind advective energy occurring in edge environments may increase tree water use. In humid agricultural landscapes, advection-enhanced transpiration in riparian buffers may provide hydrologic regulation. The objectives of this study were to determine how water use by trees growing in a riparian buffer in central Iowa is influenced by 1) advective energy, 2) tree position, and 3) thinning (40% LAI reduction). We measured meteorological variables and sap flux density from July to September in 13 trees (2009) and 12 trees (2010) in one thinned plot (TP, treated in Aug 2010) and one untreated (control) plot (UP). The difference in Q_s between edge and interior trees (39% higher in 2009) was attributed to the advective energy at the buffer edge. After thinning, maximum Q_s increased was greater in TP compared to UP, explained primarily by solar radiation (R^2=0.7, $p<0.05$), since meteorological conditions were not optimal for advection. However, the LAI reduction counteracted the increase in whole tree Q_s, such that post-treatment plot transpiration per LAI measured from TP (0.4 mm day^{-1}) was less than for UP (0.5 mm day^{-1}).

INTRODUCTION

Agricultural production has greatly increased during the 20th century and this trend is expected to continue in the 21st century. Concurrently, hydrologic services have declined, representing a major threat to the well-being of human populations in many regions of the world (MEA, 2005). Riparian buffer systems are conservation practices for enhancing ecosystem services, particularly water quality and flow regulation, from intensively modified agricultural landscapes (Schultz et al., 2009). Transpiration by buffer trees is an important mechanism for restoring hydrological services through the removal of soil water excess, which should lead to increased soil water storage capacity, reduced runoff, improved sediment and nutrient retention, and greater streambank stabilization (Schultz et al., 2009).

Advection processes are caused by air currents transporting energy (sensible heat) and relatively high vapour pressure deficit, different to the surrounding environment. These energy differences can be occasioned by two adjacent different types of vegetation in terms of albedo, height, etc. which will condition their energy balance. For example, wind first contacts a surface with short vegetation (such as a crop field) and afterwards contacts taller vegetation (such as a tree buffer). Thus, advection processes can be expected to substantially influence water use by trees in this case. Due to the riparian buffer structure (2-3 rows of trees planted parallel to the stream), edge effects between crop fields and buffer systems can create unique microclimate conditions that directly influence their ecohydrological functions. However, data about water use by riparian buffer systems in humid temperate climates where large scale annual cropping systems are often concentrated, such as the Corn Belt region of the Midwestern U.S., are sorely lacking. This information would greatly assist policy and management decisions regarding effective buffer design.

We conducted a field study to determine how water use by trees growing in a riparian buffer in central Iowa is influenced by 1) tree position, 2) advective energy, and 3) thinning (40% LAI reduction). Our hypothesis was that tree water use would be greater for edge trees due to advection, and that this effect would be more pronounced at the south-east edge which receives the prevailing winds during the growing season. We further hypothesized that if advection enhances transpiration, widely spaced trees in single rows could maximize available advective energy and thereby buffer water useby allowing air flow to penetrate deeper into the interior of low density stands, rather than only affecting edge trees.

MATERIALS AND METHODS

Experimental Site

This study was conducted in a multi-species riparian buffer (42°11´N, 93°30´W) established in the spring of 1994 along Bear Creek (Iowa, USA). The Bear Creek watershed area is 76.6 km^2, of which nearly 90% is cultivated under a corn (*Zea mays* L.)-soybean (*Glycine max*) rotation system (Schultz et al., 1995).

The study was conducted over two years. In 2009 we assessed the advective effect on the riparian buffer located on both sides of Bear Creek, one orientated 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). The SE plot comprised 3 tree rows 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 shorter black walnut (*Juglans nigra* L.). The NW plot comprised only 2 rows of *A. saccharinum*. In 2010 we conducted a thinning treatment in August 24-29 (40% Leaf Area Index, LAI, reduction) in the SE plot (370 m^2). Trees for removal were selected with the goal of removing trees of poor quality first (i.e. damaged or low vigor) and to promote similar size and distribution of remaining trees (Lagergren et al., 2008).

In 2009 we monitored sap flux density in 3 *A. saccharinum* trees in each row (n=9) in theSE plot and 2 trees per row in the NW plot (n=4, no middle row) (Hernandez-Santana et al., 2011). In 2010 we measured sap flux density only in the SE area (July 13-September 18, DOY= 194-260) in 8 trees in a thinned plot (TP) and 4 trees in an untreated (control) plot (UP). LAI was determined on the 2nd of September, 2009, and before and after the thinning treatment in 2010 using a Plant Canopy Analyser (LAI-2000 Li-Cor Inc., Lincoln, NW, USA).

Meteorological Data

Five meteorological stations were installed in 2009 along a transect across the riparian buffer. Station 1 was located 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. In 2010 we kept station 1 and 2 at the same locations, and installed a new station 3 in the UP and a new station 4 in the TP. Wind speed (u) 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). In addition, station 1 also included a precipitation gauge (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. This sensor was also installed in station 4 in 2010. All sensor signals were recorded every 10 s on a datalogger (CR10X, Campbell Scientific, Inc., Logan, UT) and 15 min averages stored for analysis.

Sap Flux Measurements

Sap flux density (J_v, m^3 m^{-2} s^{-1}) was measured using the Heat Ratio Method

(HRM) as described by Burgess et al. (2001). A single heat-pulse probe consisted of one heater probe and two temperature probes, each of them with 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. Two probes per tree were installed at approximately 1.3 m height to account for radial variability, in 2009 with N and E orientation and in 2010 with N and S orientation. Each probe set was protected with aluminium insulation to minimize irradiation and ambient thermal gradients. Temperature probes were placed equidistant from the heater with a spacing of -0.6, 0, and 0.6 cm. Temperatures were averaged and stored every 15 min (Multiplexer AM 16/32B and datalogger CR1000, Campbell Scientific Inc., Logan, UT, USA) and calculations of sap flux density and corrections were made according to Burgess et al. (2001). Following completion of the sampling period in 2009, the reference (zero) flux density value was determined by cutting into the sapwood above and below the probes to cease sap flow in two *A. saccharinum* trees over 5 days (Burgess et al., 2001).

Whole tree sap flux, Q_s ($m^3 s^{-1}$), was calculated as the product of J_v (averaged from the 3 thermocouples and the band cross-sectional area) and sapwood cross-sectional area measured at the probe level for each monitored tree. At the end of the study, wood cores were obtained with a Pressler increment borer and sapwood thickness was determined based on wood translucency. These depths were compared with the sap flux density profiles. Cumulative sap flux (Q_s^c) (m^3 day^{-1}) was obtained by integrating Q_s over time. Plot transpiration (E) on a ground area basis (mm day^{-1}) was calculated by multiplying Q_s and tree density. E was also converted to a leaf area basis using the measured LAI (E_l=E/LAI).

Advection Effect

For large wet surfaces LE should be equal to R_n, and this is called equilibrium evaporation (Brutsaert, 1982). When additional energy enters the system through advection, LE exceeds R_n. We evaluated advection effects on transpiration by comparing LE to R_n. We used the LE/R_n ratio to determine the degree of influence of upwind advection on LE (Hernandez-Santana et al., 2011). Comparing LE/R_n, we will know if there is an extra source of energy so that the latent heat loss can significantly exceed any net radiative gain (Jones, 1992). In the absence of advection, this ratio is expected to equal 1.0 because LE will be limited by the energy available from R_n. Net radiation was not directly measured but calculated following ASCE-EWRI (2005).

RESULTS

Meteorological Variables

During the study period (July-September) cumulative rainfall was 127 mm in 2009, which was less than half of the mean cumulative rainfall of those months from 1971 to 2000 (about 300 mm; Midwestern Regional Climatic Center, mcc.sws.uiuc.edu), whereas cumulative rainfall was 30% greater in 2010 (447 mm) compared to the 30-year mean. The number of days with rainfall in 2009 and 2010 was 13 and 27, respectively.

The average temperature measured at microclimate station 1 (crops) considering the same period for the two years (July 14 to September 18, DOY=195-260) was significantly greater (t-test, $p < 0.05$) in 2010 (22.4°C) than in 2009 (19.3°C). Vapor pressure deficit (D) was also greater in 2010 (0.60 kPa) than in 2009 (0.57 kPa). However, u was greater in 2009 (1.5 m s^{-1}) than in 2010 (1.1 m s^{-1}), while wind direction did not change significantly (158°, SE).

Wind velocity differences between crops and trees were observed for both 2009 and 2010 ($p<0.01$) (0.5 m s^{-1} and 0.4 m s^{-1} in the trees in 2009 and 2010, respectively). Significant differences ($p<0.01$) were also found between tree and crop climate stations for both years, being these differences slightly higher in 2009 (air temperature being 18.3°C and 22.1°C in trees in 2009 and 2010, respectively). Among all the meteorological variables measured, only the ratio between R_s measured at crops and trees changed significantly in response to the thinning treatment (i.e. R_{strees}/R_{scrops}= 0.07 and 0.45, before and after thinning, respectively, p<0.01).

Whole Tree Sap Flux and Advective Effect on Transpiration Rates in 2009

Whole tree sap flux varied with position in the riparian buffer (i.e., edge versus inner/middle) for *A. saccharinum* (Fig. 1), with inner and middle stream-side trees having around 39% lower values than edge trees. The maximum difference was observed between edge trees at SE plot and inner trees at NW plot (69%). The least difference in Q_s occurred between edge *A. saccharinum* trees in the NW plot and edge trees in the SE plot (30%).

The LE/R_n ratio was significantly greater on average for *A. saccharinum* edge SE than for *A. saccharinum* edge NW (t-test, p<0.001) (Fig. 2). For *A. saccharinum* edge SE there were 12 days out of 31 analyzed that were > 1 (Fig. 2). Comparing only edge trees' Q_s at the SE plot, transpiration was 29% higher on days with advection relative to days without advective energy (p<0.05). Days with advection usually had prevailing winds from the SE (137º) whereas winds were from the S (191º) for non-advective days. No significant differences were found for *D*, *u* and temperature between advective and non-advective days. There were also significant differences comparing *u* between climate stations in the crop field (#1) and in the buffer interior (#3) for advective and non-advective days (p<0.05), with higher values recorded for advective days (2.1 m s^{-1}) compared to non-advective days (1.3 m s^{-1}).

Whole Tree Sap Flux and Advective Effect on Transpiration Rates in 2010

During the pre-thinning period, Q_s was significantly greater (p<0.05) on average for trees in UP (0.021 m^3 day^{-1}) than TP (0.014 m^3 day^{-1}) (Fig. 3a). However, after the thinning both plots showed similar Q_s (0.011 m^3 day^{-1} and 0.013 m^3 day^{-1}, TP and UP, respectively, p>0.05) (Fig. 3b). Q_s was in general lower in the post-thinning period than in the pre-thinning due to the difference in R_s between the two periods (average solar radiation 1.5 greater in the pre-thinning than in the post-thinning period, 17.5 vs. 14.7 light hours per day in the pre- and post-thinning periods, respectively).

Using the LE/R_n ratio we observed that no advective conditions occurred during 2010, not even after the thinning (data not shown). After the thinning we observed an increase in R_s in TP and no differences in the other micrometeorological variables. The relationship between R_s and Q_s (Fig. 4) was highly significant for both TP and UP, before and after the thinning (R^2>0.55, <0.0001, in all cases). The response of Q_s to R_s (R_s-Q_s regression slopes) was significantly different in the pre-thinning period between TP and UP, while there were no significant differences in the post-thinning period.

The upscaling of Q_s to obtain E_l (mm day^{-1}) in the post-thinning period using LAI showed average transpiration was lower in TP (0.4 mm day^{-1}; LAI = 2.40) compared to UP (0.5 mm day^{-1}; LAI=4.02).

DISCUSSION

A related previous work (Hernandez-Santana et al., 2011) documented significantly greater Q_s by *A. saccharinum* trees growing at the edge position compared to the interior positions at the SE, as well as compared to the NW edge trees, in 2009 (Fig. 1). The results were interpreted as indicative of advection effects. Support for the role of advection in explaining differences in Q_s across positions in 2009 was provided by LE/R_n (Fig. 2). Thus, estimated transpiration of the SE edge trees exceeded what would be attributed to R_n alone, lending support to our hypothesis that transpiration by SE edge trees adjacent to crops could be enhanced by advective energy transported by prevailing winds in 2009.

However, in 2010 we did not observe any advective effects on transpiration - either before or after the thinning treatment. This can be explained by the sharply contrasting meteorological conditions between the two study years (2010 was an extremely wet year and the *u* difference between the field and within-tree climate stations was lower in 2010 than in 2009). The prevailing SE wind direction both years likely allowed for continuous entry of unsaturated air from the cropped area to the trees. However, in 2010 due to fewer dry days and lower u and u differences between crops and trees, upwind air was probably more humid and therefore advection did not have a strong effect.

R_s measured at 3.5 m was the only meteorological variable of all those measured that responded to the clearing treatment in 2010, which probably resulted in a greater canopy exposure (Morikawa et al., 1986) and higher energy availability for individual trees (Breda et al., 1995). Thus, those new conditions may have caused the increased Q_s in TP after the thinning compared to UP (Fig. 3). Accordingly, the results showed a strong and positive relationship between Q_s and R_s. Previous studies typically report that after thinning trees benefit from less competition and more open conditions (more water and energy) (Breda et al., 1995) as in this work, but some works report no positive effects of thinning, possibly due to species differences in stress-coping mechanisms (Bladon et al., 2006).

Pervious work suggests that canopies with high LAI may limit transpiration, whereas in open canopies with a lower LAI, transpiration may be more dependent on climatic factors such as R_n, u and D since they are more coupled to atmosphere (Breda et al., 1995). The different behaviors of the TP and UP in 2010 can be interpreted then in terms of a better coupling to the atmosphere by more open canopy stands. It has also been reported in other works that following thinning, LAI eventually reaches full canopy closure after adapting to the openings (Aussenac, 2000), although canopy structure and LAI distribution between thinned and control plots may still be different (Breda et al., 1995). An increase in light as a result of a clearing leads to a rapid modification in the architecture of the tree (Aussenac, 2000). Thus, LAI is not necessarily proportional to stand density, and in some works (e.g., Shelburne et al., 1993) it has been also shown that a large amount of leaf area per unit sapwood area is a characteristic of low-density stands which could also counteract the LAI reduction after the thinning treatment. Although Q_s in TP increased compared to UP after thinning (not significant differences), since Q_s prior to thinning was greater ($p<0.05$) in UP vs. TP (likely do to coincidentally larger-sized trees in UP and different quantity of trees at different position), the overall treatment response on Qs is relevant. However, E_l decreased in TP, associated with the 40% LAI decrease following the thinning, an effect also observed in other works (Morikawa et al., 1986). However, the new conditions created with the thinning could, over time, enhance stand transpiration. Further, during periods when environmental conditions are favorable for advective energy, transpiration in thinned stands may be greater than in unthinned stands.

CONCLUSIONS

Whole tree sap flux varied according to (1) location relative to the forest edge (edge>middle/inner), (2) prevailing winds (SE >NW), and (3) canopy exposure after thinning. The edge and prevailing wind effect on Q_s was attributed to advection from the surrounding crops in 2009, and canopy exposure due to the available R_s increment in the TP in 2010. However, E_l decreased after thinning due to the reduction in LAI. These findings have practical implications for optimal riparian buffer design, since widely spaced trees should maximize water use by effectively utilizing available u and R_s.

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Figures

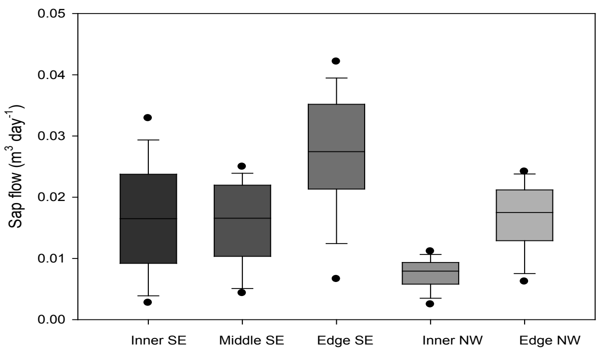

Fig. 1. Box plot with daily sap flow of *A. saccharinum* interior, middle, edge rows situated at SE, and interior and edge rows situated at NW. In each box: median, 10th, 25th 75th and 90th percentiles, the vertical lines are error bars, and the points the maximums and minimums. Modified from Hernandez-Santana et al. (2011).

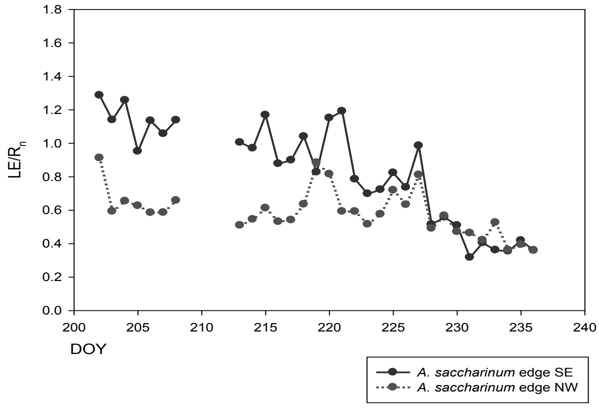

Fig. 2. LE/R_n ratio calculated on a daily basis for *A. saccharinum* at edge position at SE and NW plots.

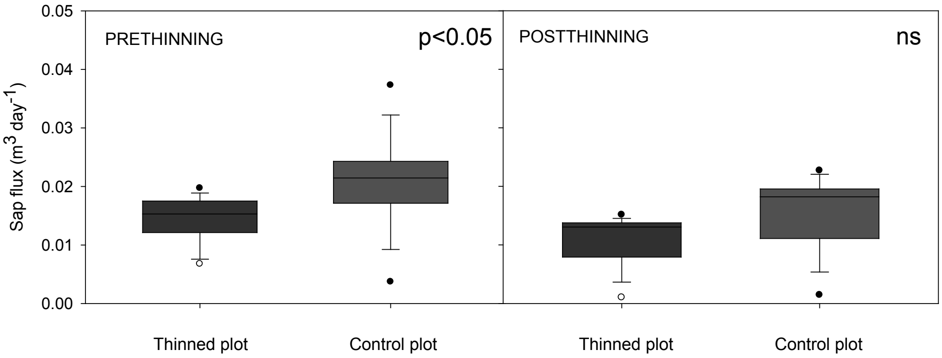

Fig. 3. Box plot with daily sap flow of *A. saccharinum* before and after the thinning for both plots the thinned and the unthinned.

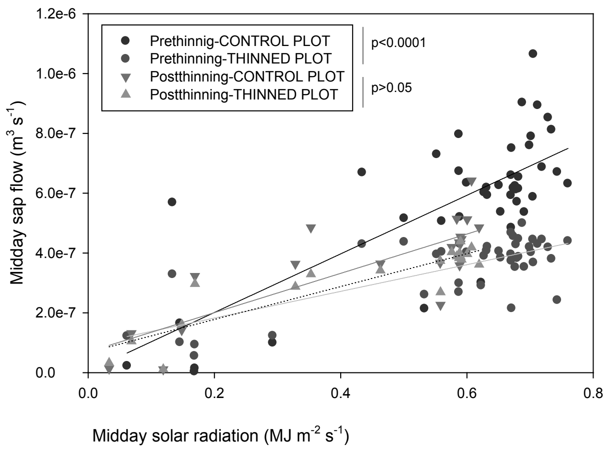

Fig. 4. Relationship between midday solar radiation and midday sap flow, for control and thinned plot, before and after the thinning.