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Evapotranspiration differences between agroforestry and grass buffer systems

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ABSTRACT

Improved soil and water quality, and carbon sequestration are notable benefits of agroforestry practices compared to row-crop agriculture. Over an agricultural watershed with two buffer cropping systems (agroforestry buffers and grass buffers) soybean crop evapotranspiration was calculated from the Penman-Monteith equation using 10-min averages of meteorological measurements within crop alleys for 54 days in summer 2007. Wind speeds were consistently lower over the agroforestry buffer portion of the watershed by an average of 0.42 m s^{-1}. For calculated evapotranspiration assuming water-stressed conditions, this decrease in wind speed from the presence of agroforestry buffers was offset almost entirely by an increase in net radiation. Net radiation differences between the two systems were highest during the morning (~40 W m^{-2}) and were likely the result of solar radiation scattered from the agroforestry buffers. Wind speed reduction over the crop portion surrounded by agroforestry buffers varied by wind direction with daytime winds ≥0.6 m s^{-1} greater over the grass buffer portion of the crop for northerly and southerly winds (nearly perpendicular to the agroforestry buffers). Therefore, buffer orientation relative to the prevailing wind is important for reducing evapotranspiration. Changes in crop alley width would be expected to impact the portion of the crop within wind-sheltered zones and the portion receiving scattered radiation from trees. The sensitivity of evapotranspiration to agroforestry buffer orientation and crop alley width should be a focus of future investigations.

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1. Introduction

Carbon sequestration and improvements in soil and water quality are among the potential benefits of agroforestry practices compared to row-crop agriculture (Quinkenstein et al., 2009; Udawatta et al., 2011; Udawatta and Jose, 2012). Agroforestry and grass buffers have been found to reduce non-point source pollution in runoff while improving soil properties (Seobi et al., 2005; Udawatta et al., 2006; Kumar et al., 2008). Such improvements have been attributed to the addition of organic matter, roots of the permanent vegetation, nutrient uptake, and water use (Kumar et al., 2011; Udawatta et al., 2014; Chendev et al., 2015).

Changes in microclimate from the permanent vegetation in buffers may influence evapotranspiration, soil water dynamics, carbon sequestration, nutrient dynamics, and soil enzyme activities. Larger trees act as a barrier to wind speed, reducing crop damage (Brandle et al., 2004) and influencing evapotranspiration and other energy fluxes in the adjacent areas (Campi et al., 2009; Tamang et al., 2010). Reduced energy levels under buffers and adjacent areas should promote less evapotranspiration and greater soil moisture storage. Increased crop quality and yields have been found on the leeward side of windbreaks (Huth et al., 2002; Campi et al., 2009). The potential for increased frost damage in the leeside of windbreaks has also been noted (Tamang et al., 2010). The wind break effect varies by crop, windbreak type, geographic location, moisture condition, and soil properties (Brandle et al., 2004). For example, in the drier regions of Australia, long-term benefits of forest buffers to improve soil quality may be offset by competition from the trees for soil moisture (Cleugh et al., 2002; Huth et al., 2002). Lopez-Bravo et al. (2012) found reductions in coffee yields near shade trees in Costa Rica.

Turbulence generated by windbreaks increases vertical mixing of heat and moisture downwind of the break (Cleugh, 1998). Less vertical mixing would be expected in the 'quiet zone,' resulting in warmer and moister daytime conditions compared to those in the 'wake zone.' One would expect the 'wake zone' to experience greater evapotranspiration in response (Cleugh, 1998). Campi et al. (2009) show a peak in evapotranspiration 10 tree heights down-

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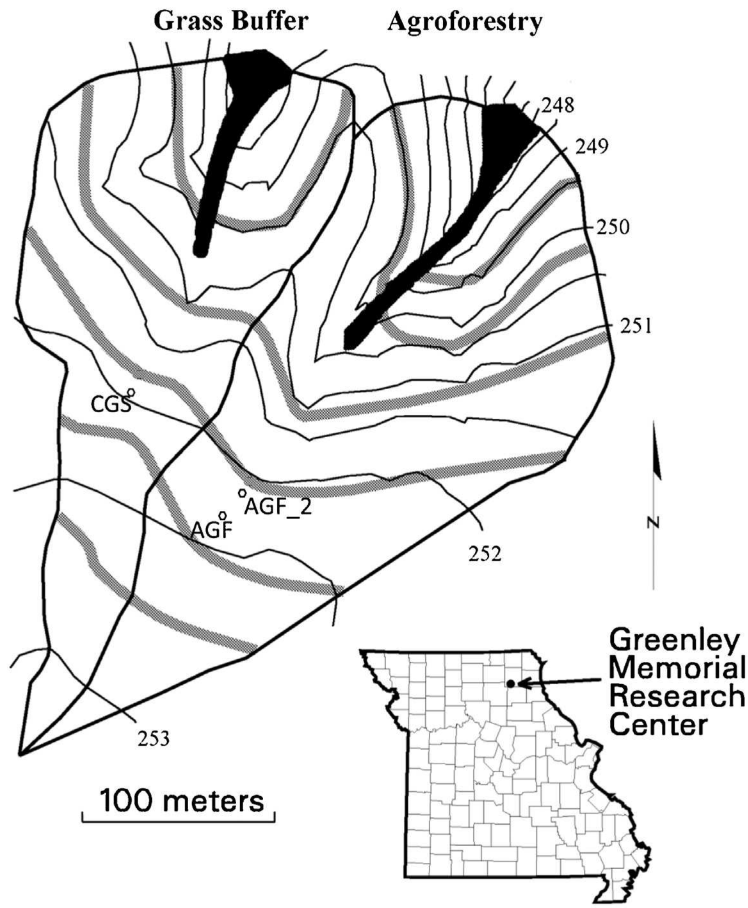

Fig. 1. Contour grass strip (grass only; CGS) buffer and agroforestry (grass and trees; AGF) buffer watersheds at the Greenley Memorial Research Center, Knox County, Missouri. Elevation contour intervals are 0.5 m (black). Buffers (gray), grass waterways (wide black) and microclimate station locations (circles) are also displayed.

wind of a windbreak. The repeated linear structure of the forest buffers in alley cropping systems adds complexity. For example, a greater proportion of the crop in the sheltered 'quiet zone', compared to that in the turbulent 'wake zone', is to be expected for alley cropping systems compared to a single extended windbreak. Exact extents of the quiet zone and wake zones are sensitive to the turbulent structure of the incident wind, related to the site's upwind surface roughness, as well as the porosity of the windbreak and wind direction. The radiation budget in crop alleys may also be influenced by the tree buffers through emitted longwave and scattered shortwave radiation (Brandle et al., 2004).

In this investigation, differences in microclimate and calculated evapotranspiration between agroforestry and grass buffered areas of a soybean [Glycine max (L.) Merr.] crop are examined. Although dependent on the permeability of the buffer, the 'quiet zone' will generally extend downwind of the windbreak for a distance equal to a number of tree height multiples (H). In this investigation, the distance between agroforestry buffer strips is approximately 10H, therefore, we expect a clear effect of agroforestry buffers on the microclimate within crop alleys.

2. Materials and methods

2.1. Experimental site and management

The study site is a north aspect watershed located at the University of Missouri, Greenley Memorial Research Center near Novelty, Missouri (40° 01′ N, 92° 11′ W; Fig. 1). A corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation, with contour planting and no-till land preparation has been implemented on the watershed since 1991 (Udawatta et al., 2002). The contour grass strip (CGS) buffer portion of the watershed is 3.16 ha with grass only buffers and the agroforestry buffer portion (AGF) is 4.44 ha with grass and tree buffers. The buffer strips (Fig. 1) are 4.5 m wide and spaced 36.5 m apart (22.8 m at lower slope positions). A grass and legume combination was established in 1997 in the buffer strips and included brome grass (*Bromus* spp.), birdsfoot trefoil (*Lotus corniculatus* L.) and redtop (*Agrostis gigantea* Roth). The agroforestry buffers consisted of Pin oak trees (*Quercus palustris* Muenchh.) planted in the center of the buffer strips at 3-m spacing. Average tree heights in the AGF area were 3.9 m in 2007. In both areas, grass waterways consisted of Kentucky 31 fescue [*Schedonorus phoenix* (Scop.) Holub]. Further details on watershed management and general experimental design, as well as parent material, soils, and climatic data can be found elsewhere (Udawatta et al., 2002, 2006).

In 2006, corn was planted and harvested over both the AGF and CGS areas on 14 April and 27 September respectively, with a mean yield of 11.06 Mg ha^{-1}. In 2007, soybeans were seeded on both the AGF and CGS areas at 444,600 seeds ha^{-1} on 8 June and harvested on 26 October with a mean yield of 3.4 Mg ha^{-1} (Senaviratne et al., 2012).

2.2. Microclimate stations and data collection

Net radiometers, anemometers, humidity and temperature sensors were installed on masts above the crops at 3 m above ground level. Data were recorded at 10 min intervals with a CR23X data logger. The microclimate stations are 12 m south of the third buffers in

Table 1
Daily averages of meteorological variables, and total calculated evapotranspiration, from the 54 day period in 2007 (21 June–13 August) for the agroforestry buffer portion of the crop (AGF) and the contour grass strip buffer portion of the crop (CGS). Asterisks (*) indicate that AGF to CGS differences are significant with 95% confidence.

	u_z(m s^{-1})*	T(°C)*	RH(%)	R_n(W m^{-2})*	ET_{WW}(mm)*	ET_{WS}(mm)
AGF	1.52	24.46	74.87	161.91	278.74	229.81
CGS	1.94	24.64	74.85	157.74	286.84	230.22

Table 2
Daytime (1000-1600 LST) averages of the 10-min values (totals for calculated evapotranspiration) for the AGF location and the difference between the AGF and CGS locations (DIFF = AGF − CGS) for eight wind direction categories. For each wind direction, n refers to the number of 10-minute periods over the 54 day period (21 June–13 August 2007) with average wind direction within 22.5° of the given direction. Asterisks (*) indicate that differences are significant with 95% confidence.

	u_z(m s^{-1})		T(°C)		RH(%)		R_n(W m^{-2})		ET_{WW}(mm)		ET_{WS}(mm)	
	AGF	DIFF	AGF	DIFF	AGF	DIFF	AGF	DIFF	AGF	DIFF	AGF	DIFF
N (0°) (n = 199)	1.53	-0.90*	26.65	0.28*	63.66	-0.86	371.04	1.83	13.7	-0.5	11.9	0.3
NE (45°) (n = 197)	2.56	-0.29*	25.32	0.15	58.14	-0.94*	465.23	4.33	17.2	0	13.8	0.2
E (90°) (n = 279)	2.16	-0.25*	27.99	-0.10*	53.78	-0.5	498.36	-5.07	26.7	-0.6	22.3	-0.1
SE (135°) (n = 338)	2.36	-0.65*	29.84	0.03	55.91	-1.02*	488.59	-6.84	33.2	-1.2*	27.6	0.1
S (180°) (n = 489)	3.09	-0.50*	30.98	-0.06	54.7	-0.78*	482.97	-6.26	51.4	-1.6*	41.1	-0.2
SW (225°) (n = 141)	2.14	-0.06	28.95	-0.05	58.28	-0.95	458.04	5.66	12.7	0.2	10.6	0.2
W (270°) (n = 195)	2.29	-0.27*	27.98	0.06	60.44	-0.58	430.82	10.17*	16.3	0.2	13.5	0.4*
NW (315°) (n = 160)	1.82	-0.80*	29.09	0.20*	58.69	-1.01	463.18	11.05	14.3	-0.2	12.2	0.4

both watersheds (Fig. 1). An additional microclimate station (AGF_2 in Fig. 1) recorded data in 2006, but not 2007, on the agroforestry watershed approximately 3 m south from the third buffer. During the soybean year in 2007, periods of continuous data records for all variables required for evapotranspiration calculation at both sites were 18 March–3 May, 25 May–15 June, 21 June–13 Aug, and 7 Sep-21 Oct. As soybeans were planted on 8 June 2007, the period 21 June–13 August, 2007 will be the focus of this investigation and this 54 day period will be referred to as summer for the remainder of this paper. Crop management was identical on both the CGS and AGF portions of the watershed, and soybean heights were more than 2 m below instrumentation height through the growing season. Therefore, it is assumed that differences between treatments in surface characteristics affecting net radiation, wind speed, etc. are negligible for the 54 day study period.

2.3. Soybean crop evapotranspiration

The Penman-Monteith equation was used to calculate soybean crop evapotranspiration (Allen et al., 1998):

$$ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{L_v\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)} \quad (1)$$

where ET is the crop evapotranspiration (mm s^{-1}), R_n is net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), Δ is the slope of the saturation vapor pressure curve (kPa/°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), ρ_a is the air density (kg m^{-3}), c_p is the specific heat of air at constant pressure (1005 J kg^{-1} K^{-1}), r_a is the aerodynamic resistance (s m^{-1}), r_s is the bulk surface resistance (s m^{-1}), γ is the psychrometric constant (kPa/°C), and L_v is the latent heat of vaporization for water (2.453·10^6 J kg^{-1}). The aerodynamic resistance (r_a) is given by (Allen et al., 1998):

$$r_a = \frac{\ln\left[\frac{Z_m - d}{Z_{om}}\right]\ln\left[\frac{Z_h - d}{Z_{oh}}\right]}{k^2 u_z} \quad (2)$$

where Z_m and Z_h are the heights (3 m) of wind and humidity measurements respectively, d is the zero plane displacement height (m), Z_{om} and Z_{oh} are the roughness lengths (m) governing momentum and heat transfer respectively, k is von Karman's constant (0.41, unitless), and u_z is the wind speed (m s^{-1}) at height Z_m.

For a soybean crop, aerodynamic properties can be calculated as $d = 0.67\,h_c$, $Z_{om} = 0.10\,h_c$, $Z_{oh} = 0.014\,h_c$, where h_c is the crop height (Ortega-Farias et al., 2004). Soil heat flux (G) was quantified as $0.1R_n$ during the daytime hours, and $0.5R_n$ during the nighttime hours (Allen et al., 1998). Procedures to calculate the psychrometric constant (γ), slope of the saturation vapor pressure curve (Δ), actual vapor pressure (e_a), and saturation vapor pressure (e_s) from the meteorological data measured in this study are given by Allen et al. (1998).

Quantifying the aerodynamic properties in Eq. (2) and the bulk surface resistance through the growing season requires sub-seasonal measurements of crop height (h_c), leaf area index, and stomatal resistance (Allen et al., 1998; Ortega-Farias et al., 2004). Unfortunately, this information is lacking from our study. Therefore, we assume constant properties of the soybean crop through the growing season to isolate the effects of meteorological differences on evapotranspiration from a fully developed soybean crop canopy. Ortega-Farias et al. (2004) report that for a soybean crop with 55 plants m^{-2}, a fully developed canopy has an average h_c of 0.65 m with a leaf area index of nearly 4 m^2 m^{-2}. Using the Penman-Monteith model and excluding times of day with low solar irradiance, Baldocchi et al. (1987) calculated bulk surface resistance (r_s) for a soybean crop with a leaf area index of 3.8 in Mead, Nebraska USA for conditions ranging from well-watered to water-stressed (Kelliher et al., 1995; Baldocchi et al., 1985; 1987). From Fig. 7 in Baldocchi et al. (1987), it appears that $r_s \sim 40$ s m^{-1} broadly represents bulk surface resistance during well-watered periods, and $r_s \sim 100$ s m^{-1} during periods with some water stress. We calculate evapotranspiration from Eqs. (1) and (2) with $h_c = 0.65$ m assuming well-watered conditions (ET_{WW}, $r_s = 40$ s m^{-1}) and water-stressed conditions (ET_{WS}, $r_s = 100$ s m^{-1}).

3. Results

During summer 2007, the mean daily (0000–2350 Local Standard Time [LST]) wind speed over the contour grass strip buffer portion of the crop (CGS) was 1.94 m s^{-1}, and 1.52 m s^{-1} over the agroforestry buffer (AGF) portion of the crop (Table 1). Using a two-sided paired t test on the daily averages, this 0.42 m s^{-1} difference was statistically significant ($p < 0.05$). Other significant differences in daily average values were observed for air temperature (0.18 °C hotter at CGS) and net radiation, with the AGF crop receiving on

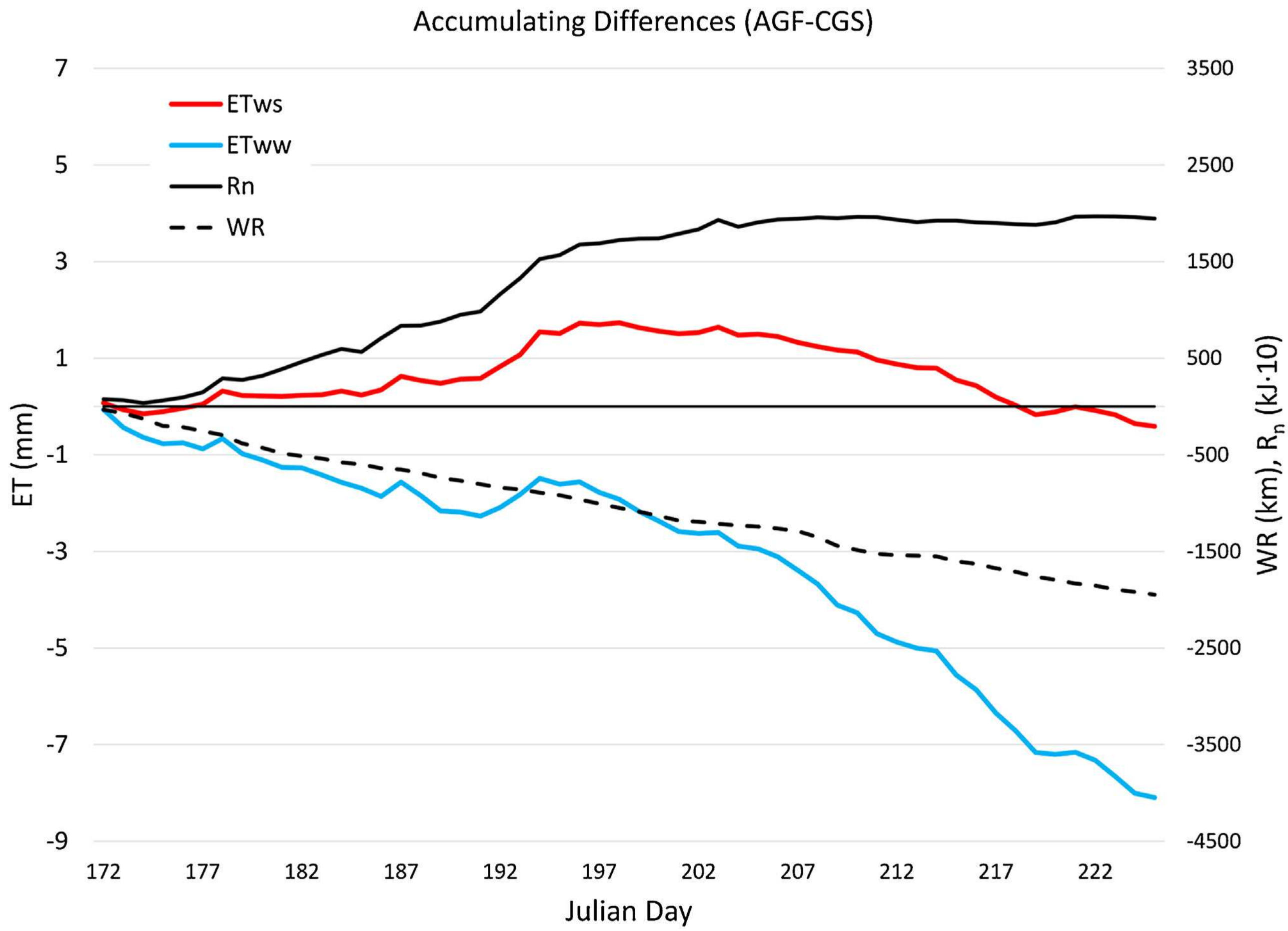

Fig. 2. Accumulating differences between the agroforestry buffer portion of the crop (AGF) and the contour grass strip buffer portion of the crop (CGS), see Fig. 1, in 2007 for calculated soybean crop evapotranspiration (red and blue lines), net radiation (black solid line), and wind run (dashed black line).

average 4.17 W m^{-2} more radiation than the CGS crop (Table 1). Differences in calculated evapotranspiration vary from well-watered (ET_{WW}) to water-stressed conditions (ET_{WS}), with 8.1 mm more ET_{WW} over the CGS crop than the AGF crop, and negligible differences for ET_{WS} (Table 1).

Daytime (1000–1600 LST) averages by wind direction (as measured at the CGS crop) are displayed in Table 2. Southerly winds were most common, with 489 ten-minute averages displaying a wind direction between 157.5° and 202.5° over the 54 day period (Table 2). Daytime southwesterly winds (202.5°–247.5°) were least common, recorded only 141 times over the 54 day period.

The CGS crop displayed higher winds speeds than the AGF crop for all directions, significant with 95% confidence for all but southwesterly winds (Table 2). Here, statistical significance is determined with a two-sided paired *t* test on daily averages of 10-min values between 1000 and 1600 LST. The largest wind speed differences (≥0.8 m s^{-1}) correspond to north (337.5°–22.5°) and northwesterly (292.5°–337.5°) winds (Table 2). Other large differences are seen for southerly and southeasterly winds. The buffers are generally oriented east-west (Fig. 1), so it is not surprising that winds with strong northerly or southerly components display the largest differences in wind speed between the two locations (Brandle et al., 2004).

While the average temperature through the summer period was warmer at the CGS site (Table 1), the largest daytime temperature differences corresponded to hotter conditions at the AGF crop (≥0.20 °C) and were coincident with the large wind differences of the northerly winds (Table 2). Daytime relative humidity was consistently lower at the AGF crop (Table 2), even for wind directions corresponding to roughly the same temperature between the sites (e.g., southeasterly). Other investigators have noted warmer and less humid daytime conditions in sheltered areas adjacent to wind breaks (Campi et al., 2009).

Despite the consistently higher wind speeds at CGS, ET_{WS} was only lower at AGF when average daytime net radiation was lower at AGF (Table 2). Daytime net radiation was higher at AGF for all wind directions except easterly to southerly (Table 2). For westerly winds, wind speeds are significantly higher at CGS, yet both net radiation and ET_{WS} are significantly higher at AGF. Therefore, there is evidence (Tables 1 and 2) that the greater net radiation at AGF overcomes the impacts of the reduced wind speed, especially for evapotranspiration assuming water-stressed conditions (r_s = 100 s m^{-1} in Eq. (1)).

Through the entire summer, wind speeds were greater at CGS, as seen by the accumulating differences in wind run (Acock and Pachepsky, 2000), the product of speed and time, at the two sites (Fig. 2). Net radiation, however, was consistently higher at the AGF site until around 23 July (Julian day 204), whereafter it remained nearly equal at the two sites. Between 21 June (Julian day 172) and 15 July (Julian day 196), total ET_{WS} at the AGF crop location exceeded the CGS location by more than 1.7 mm, with ~16,767 kJ m^{-2} more net radiation (Fig. 2). After 15 July, ET_{WS} at the CGS site was greater, with the lesser net radiation differences not overcoming the wind speed differences (Fig. 2). The primary difference between the summer evolution of ET_{WS} and ET_{WW} is that

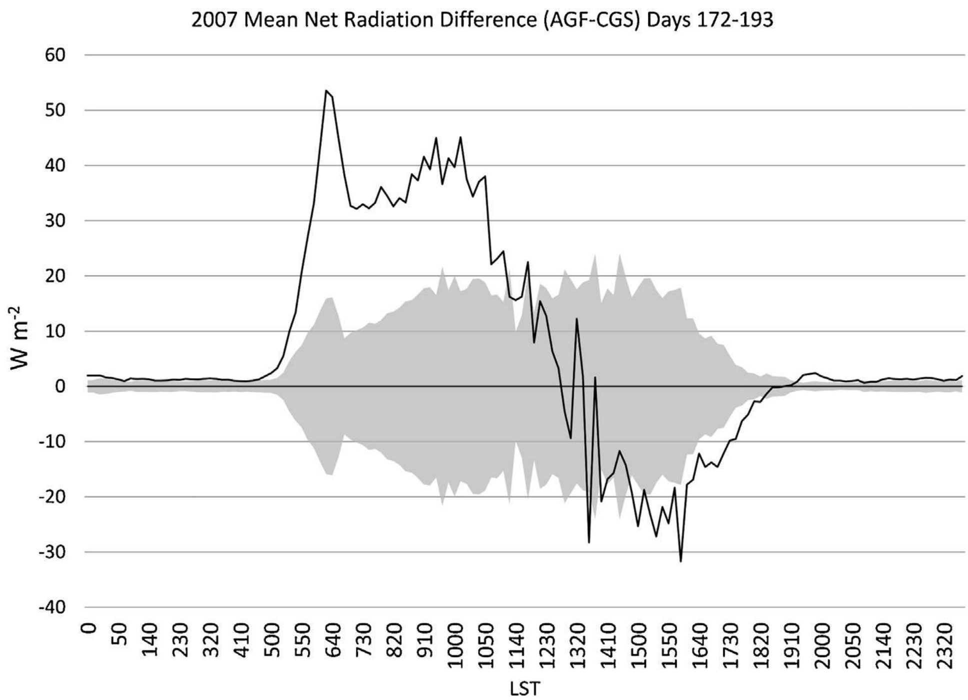

Fig. 3. The mean net radiation difference (black line) between the agroforestry buffer portion of the crop (AGF) and the contour grass strip buffer portion of the crop (CGS), see Fig. 1, for each 10-min interval during Julian days 172–193 2007. The gray shading represents the 95% confidence interval centered on zero $W\,m^{-2}$ as determined by paired *t* tests (sample sizes = 22).

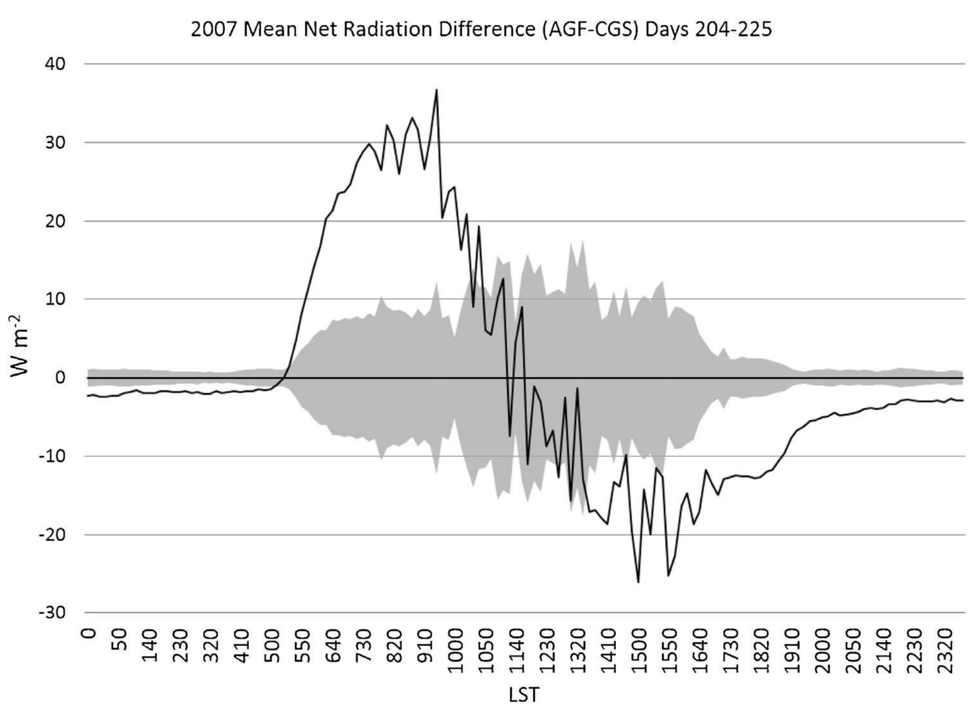

Fig. 4. The mean net radiation difference (black line) between the agroforestry buffer portion of the crop (AGF) and the contour grass strip buffer portion of the crop (CGS), see Fig. 1, for each 10-min interval during Julian days 204–225 2007. The gray shading represents the 95% confidence interval centered on zero $W\,m^{-2}$ as determined by paired *t* tests (sample sizes = 22).

the higher net radiation at the AGF site before 15 July almost balances the higher wind speeds at the CGS throughout the summer for ET_{WS}, while the wind speed differences overcome the radiation differences for nearly the entire summer for ET_{WW} (Fig. 2). The denominator of Eq. (1) decreases evapotranspiration with increasing wind speed and the impact of this component increases with increasing r_s.

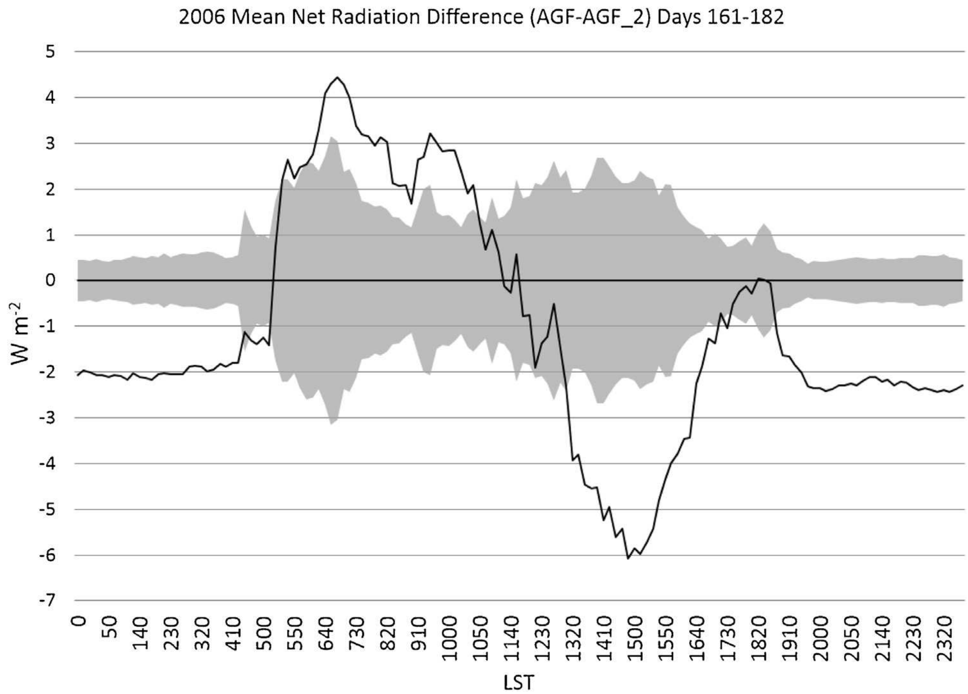

Fig. 5. The mean net radiation difference (black line) between the agroforestry buffer portion of the crop 12 m from the north agroforestry buffer (AGF) and the area 3 m from the north buffer (AGF_2), see Fig. 1, for each 10-min interval during Julian days 161–182 2006. The gray shading represents the 95% confidence interval centered on zero W m^{-2} as determined by paired *t* tests (sample sizes = 22).

4. Discussion

Calculated ET_{WS} for summer 2007 was nearly equal between the agroforestry (AGF) and contour grass strip (CGS) buffer portions of the crop despite the higher wind speeds over the CGS buffer portion. This is likely due to higher net radiation at the agroforestry portion (AGF) of the crop (Table 1 and Fig. 2). Brandle et al. (2004) note that emitted longwave and scattered shortwave radiation from trees may increase net radiation in crop alleys compared to open areas. Fig. 3 displays the daily cycle of the net radiation difference between the two locations, averaged over Julian days 172–193 (21 June–12 July). Statistical significance for all differences (i.e., all 10-min periods) were determined with 144 paired *t* tests, each with a sample size of 22 corresponding to the number of days between 21 June–12 July. The AGF site experienced about 13,289 kJ m^{-2} (an average of 6.99 W m^{-2}) more net radiation than the CGS site during this period.

On Julian day 183, sunrise and sunset were approximately 0445 and 1940 LST respectively. Thus, large and statistically significant differences in net radiation between the two sites were only evident during the daytime hours (Fig. 3). This suggests that the shortwave radiation budget is more important to net radiation differences than the longwave radiation budget. Higher net radiation at the AGF site was restricted to the morning and early afternoon hours (Fig. 3). From 620–1020 LST, net radiation at the AGF site was about 40 W m^{-2} greater than the CGS site (Fig. 3). After ∼1300 LST, the CGS site displayed more net radiation, with about 20 W m^{-2} greater flux between 1400 and 1620 LST. After 1620 LST, the difference between the two sites began to disappear as the sun set (Fig. 3).

Assuming simple isotropic scattering of incoming shortwave solar radiation from a linear barrier of trees of average albedo of the order of 0.2, then the ratio of direct to diffuse solar radiation at a distance of about 10 m from the barrier that extends 3 m above the height of the instruments is of the order of 0.05. This is in agreement with the models of Kuusk et al. (2014), for example and suggests that for 500 W m^{-2} of insolation an additional 25 W m^{-2} will impact the instruments. However, as leaves which comprise the majority of the scattering surface will not scatter isotropically this is likely an overestimate, but it can be seen that it is possible that scattered radiation from both AGF buffers can account for the additional net radiation.

With buffers oriented east-west (Fig. 1), morning radiation (solar azimuth angle due east) is scattered nearly equally off both north and south agroforestry buffers surrounding the crop. As the solar azimuth angle transitions to the south, one would expect scattered radiation from the south buffer to decrease, especially for lower solar altitude angles. However, the solar altitude angle at solar noon on Julian day 183 was ∼73.0°, which may explain why the minimum of AGF-CGS did not occur until around 1500 LST (Fig. 3), when the solar altitude angle was lower (<51°) and the solar azimuth angle was ∼257°, approximately perpendicular to the southeast-northwest oriented agroforestry buffers (Fig. 1). At this time, one would expect the south buffer strip to be intercepting diffuse radiation from the sky and not contributing scattered radiation from the trees to the instruments.

Fig. 2 suggests that the higher net radiation at the AGF site was not apparent in the later part of the summer period. While the increased morning net radiation over the AGF site was evident over the period 23 July–13 August (Fig. 4), it was not apparent at solar noon as it was earlier in the summer. This may be due to the lower solar altitude angle at noon (e.g., ∼67°on August 3), resulting in little scattering off the south buffer. Without higher net radiation over the AGF crop sustained beyond solar noon, the lower radiation in the afternoon hours offset the increased radiation in the morning hours in August (Figs. 2 and 4).

To further explore the potential importance of scattered radiation from both agroforestry buffers, the daily cycle of net radiation differences between the AGF site (12 m from the north buffer) and a site closer (3 m) to the north buffer, AGF_2 in Fig. 1, were compared for the period 10 June–1 July 2006. Corn was the crop in 2006 and later dates in July 2006 were excluded because of the expected influence of the corn height approaching the radiometer height. Note, data from AGF_2 were not available for 2007, the soybean year. It is not surprising that the magnitudes of the differences in net radiation between AGF and AGF_2 were small, <6 W m^{-2} (Fig. 5), as both sites may have received scattered radiation from the agroforestry buffers. It was very evident that differences, despite being small, had a clear diurnal cycle, and were statistically significant at all times except near solar noon, and for brief periods near sunrise and sunset.

At night, net radiation was greater at the site nearer to the north buffer (AGF_2), likely due to longwave radiation from the trees (Fig. 5). Soon after sunrise, however, the difference reversed, with AGF receiving nearly 4.5 W m^{-2} more net radiation at 0700 LST. At this time, the solar azimuth was ~79° with a ~24° solar altitude angle. One would expect more radiation to be scattered from the south buffer than the north buffer at this time, and with AGF being closer to the south buffer than AGF_2, it received more radiation. As the solar azimuth approached the south during the late morning, the altitude angle increased with significantly greater ($p < 0.05$) radiation at the AGF site until 1050 LST (Fig. 5). At this time, the azimuth was approximately 128°, yet the solar altitude angle was greater than 66°. It is possible that the AGF site was receiving a substantial contribution of scattered radiation from both buffers at this time (Figs. 1 and 5). With a solar azimuth of nearly 227° at 1320 LST, the direct radiation was nearly perpendicular to the south buffer that is oriented southeast-northwest (Fig. 1), with AGF_2 receiving significantly ($p < 0.05$) more radiation than AGF (Fig. 5). At this time and through the late afternoon, as the solar altitude angle lowers one would expect a lesser contribution of scattered radiation from the south buffer compared to the north buffer, the buffer closer to AGF_2 (Fig. 1). At 1850 LST, the altitude angle was less than 8°, and as expected, longwave radiation differences began to be prominent (Fig. 5).

Terrain is very gently sloping to the north-northeast in both the CGS and AGF portions of the crop (Fig. 1). Therefore, differences in slope and aspect between the two areas are unlikely to have contributed to the measured net radiation differences between the two sites. Another possible explanation for the diurnal net radiation difference patterns seen in Figs. 3 and 4 is tilt of the net radiometers. If the AGF net radiometer was tilted slightly to the east, then this could explain the disparity with the CGS location. This is unlikely, given that the magnitude of the differences between AGF and AGF_2 are much smaller than the difference from CGS (e.g., Figs. 4 and 5). Similarly, the CGS net radiometer tilted slightly to the west could explain the differences from AGF displayed in Fig. 3 and 4. To explore this possibility, data in 2007 from a net radiometer over the grass strip buffer itself was compared to the AGF net radiation data. Although the surfaces are different (e.g., soybean vs grass), the AGF site had increased net radiation during the morning hours relative to the net radiation over the grass strip buffer itself (not shown) of similar magnitudes as those seen in Figs. 3 and 4. Therefore, it is unlikely that the disparities in net radiation between the AGF and CGS locations were due to the net radiometer at the CGS location being tilted to the west.

5. Conclusions

For a 54 day period in summer 2007, evapotranspiration from a soybean crop using the Penman-Monteith equation was calculated using 10-min averages of meteorological measurements over an agricultural watershed within the alleys of two buffer cropping systems in northeastern Missouri, agroforestry buffers (AGF) and grass only buffers (CGS). The width of the crop alleys were approximately ten times the height of the agroforestry buffers and wind speed was consistently lower at the AGF site, especially when winds were nearly perpendicular to the buffer extents.

Despite the consistently lower wind speeds through the entire period, calculated evapotranspiration was nearly equal at both locations for water-stressed conditions (represented by a bulk surface resistance of 100 s m^{-1}). From 21 June to 15 July, ~1.7 mm more evapotranspiration was calculated at the AGF site compared to the CGS site for water-stressed conditions. This coincided with about ~16,767 kJ m^{-2} more net radiation at the AGF site. The difference in net radiation between the two sites became negligible approaching the end of the summer period, 13 August 2007, and total evapotranspiration at the CGS site from 15 July to 13 August exceeded the AGF site by 2.1 mm for water-stressed conditions and 6.45 mm for well-watered conditions (represented by a bulk surface resistance of 40 s m^{-1}).

There was a clear daily cycle in the net radiation difference between the two sites, with greater net radiation at the AGF site in the morning (~40 W m^{-2}) and less in the afternoon. The agroforestry buffers extend east-west to the east of the AGF monitoring site, and southeast-northwest to the west of the site. Therefore, it is likely that easterly solar azimuths resulted in additional scattered radiation from the two adjacent agroforestry buffers.

In short, for total calculated evapotranspiration over the 54 day period, the average 0.42 m s^{-1} reduction in wind speed observed in the crop area surrounded by the agroforestry buffer was overcome by scattered radiation from the trees for water-stressed conditions. This result may be unique to humid climates due to the small vapor pressure deficits. Daytime winds were observed to be ≥0.6 m s^{-1} greater over the grass buffer portion of the crop when winds were nearly perpendicular to the buffers. Therefore, the orientation of agroforestry buffers relative to the prevailing wind appears to be important in reducing evapotranspiration. While widening crop alleys may decrease the percentage of the crop receiving scattered radiation from trees, it may increase the portion of the crop outside of the wind-sheltered zones extending downwind from the agroforestry buffers. Future investigations should focus on the sensitivity of net radiation and wind speed to buffer orientations and crop alley width.

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