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Evaporative loss from irrigated interrows in a highly advective semi-arid agricultural area ☆

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ABSTRACT

Agricultural productivity has increased in the Texas High Plains at the cost of declining water tables, putting at risk the sustainability of the Ogallala Aquifer as a principal source of water for irrigated agriculture. This has led area producers to seek alternative practices that can increase water use efficiency (WUE) through more careful management of water. One potential way of improving WUE is by reducing soil evaporation (*E*), thus reducing overall evapotranspiration (ET). Before searching for ways to reduce *E*, it is first important to quantify *E* and understand the factors that determine its magnitude. The objectives of this study were (1) to quantify *E* throughout part of the growing season for irrigated cotton in a strongly advective semi-arid region; (2) to study the effects of LAI, days after irrigation, and measurement location within the row on the *E*/ET fraction; and (3) to study the ability of microlysimeter (ML) measures of *E* combined with sap flow gage measures of transpiration (*T*) to accurately estimate ET when compared with weighing lysimeter ET data and to assess the *E*/*T* ratio. The research was conducted in an irrigated cotton field at the Conservation & Production Research Laboratory of the USDA-ARS, Bushland, TX. ET was measured by a large weighing lysimeter, and *E* was measured by 10 microlysimeters that were deployed in two sets of 5 across the interrow. In addition, 10 heat balance sap flow gages were used to determine *T*. A moderately good agreement was found between the sum $E + T$ and ET (SE = 1 mm or ~10% of ET). It was found that *E* may account for >50% of ET during early stages of the growing season (LAI < 0.2), significantly decreasing with increase in LAI to values near 20% at peak LAI of three. Measurement location within the north-south interrows had a distinct effect on the diurnal pattern of *E*, with a shift in time of peak *E* from west to east, a pattern that was governed by the solar radiation reaching the soil surface. However, total daily *E* was unaffected by position in the interrow. Under wet soil conditions, wind speed and direction affected soil evaporation. Row orientation interacted with wind direction in this study such that aerodynamic resistance to *E* usually increased when wind direction was perpendicular to row direction; but this interaction needs further study because it appeared to be lessened under higher wind speeds.

1. Introduction

Use of groundwater from the Ogallala aquifer as a source of irrigation water has transformed the High Plains into one of the largest and most productive agricultural regions in the United States [1], earning it the nickname "breadbasket of the world" [2]. Unfortunately, the agricultural productivity of the region has come at the cost of declining water tables, putting at risk the sustainability of the aquifer as a principle source of water for irrigated agriculture and other public requirements [3]. Groundwater depletion has increased pumping costs and reduced well flow rates. The decrease in profits of agricultural crop production in the region has led producers to seek alternative practices that can increase water use

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efficiency (WUE = economic yield per unit of water used) and thus increase the profitability of production systems. Some of these alternatives include increasing the portion of dryland (non-irrigated) farming, converting back to rangelands, applying conservation tillage, utilizing precision irrigation systems, and selecting different crops [4].

In terms of precision irrigation systems, increasing WUE is aimed at increasing the crop's use of applied water for growth and production, with minimum non-productive losses. This can be achieved by more careful consideration of the timing, frequencies, amounts and application methods of water. Water losses in agricultural systems can be attributed to runoff, deep drainage, or evaporation from the soil. Runoff occurs when irrigation or precipitation intensity is greater than the infiltration rate of the soil and ponded water exceeds surface storage capacity. Deep drainage occurs when irrigation amounts exceed ET for a long enough time to move water below the root zone. Both runoff and deep drainage are relatively easy to manage since irrigation intensity and amounts are controllable.

A third form of water loss is evaporation from the soil surface (E). Management (i.e., minimization) of E has been reported by many to potentially be an effective measure to conserve soil water and improve crop WUE e.g. [5–7]. There is controversy regarding the definition of E as a water loss. While many consider E as a water loss that does not directly contribute to the production process [5–10], some claim that E may indirectly benefit crop growth by maintaining a micro-climate within the canopy favorable to the growth and productivity of the plants e.g. [11–13]. Whether E is a loss or a micro-climate moderator, it is agreed that in sparse canopies and row crops, especially under arid and semi-arid conditions, it is a significant component of the water balance that may account for 30–60% of seasonal total ET e.g. [14–16]. Nevertheless, quantification of E remains a challenge.

An additional source of water loss is nocturnal transpiration (T). While during the day T is inevitable, at night, when little to no carbon uptake occurs in C3 and C4 plants, transpiration can be considered as water loss. Historically, nocturnal transpiration was assumed negligible [17], although some reports of nocturnal water loss were already published in the mid and late 1900s [18–21]. Recently, increasing evidence suggest that nighttime transpiration can be quite substantial, ranging from 5 to 30% of the total daily flux [22–25]. Greater rates have been reported in some extreme cases [26]. Nevertheless, studies providing evidence of nighttime water loss by crop canopies under field conditions are rare [24].

Numerous studies treat E and T as one combined entity referred to as evapotranspiration (ET). The number of studies aiming at quantifying and/or modeling ET is large enough to lead researchers to suggest rules and recommendations on the types of documentation that should accompany ET datasets and associated products when published [27]. Although combining E and T is expedient for some applications, doing so obscures biological and physical processes, which play a significant role in regulating the hydrological cycle and obscures the potential for reducing E to improve water utility. This realization has led to specifying the partitioning of ET into E and T as one of six scientific challenges deemed central to a better understanding of the ecohydrology, as well as agrohydrology, of water-limited environments [28]. Separation of E and T is essential for evaluating crop growth and water use models that attempt to model WUE [29]; such models are increasingly needed to discriminate between alternative management schemes for increasing WUE. Measurement of E from the soil surface of irrigated crops with micro-lysimeters [30–33] and estimation of T using heat balance sap flow gages [34–36] have both been shown to be successful. Rarely, all three components, i.e., ET, E and T were concurrently measured. The number of studies devoted to the partitioning of ET into E and T is relatively small, and suitable and appropriate field data to experimentally validate and verify models partitioning ET into E and T are lacking [37].

The present report describes a sub-study, part of the Bushland Evapotranspiration And Remote sensing EXperiment 2008 (BEAREX08) campaign [38]. The objectives of this study were (1) to quantify E throughout the rapid vegetative growth phase of irrigated cotton in a strongly advective semi-arid area; (2) to study the effects of LAI, days after irrigation, and measurement location within the row on the E/ET fraction; and (3) to study the ability of microlysimeter (ML) measures of E combined with sap flow gage measures of T to accurately estimate ET, compared with weighing lysimeter ET data.

2. Materials and Methods

2.1. Site description

The research was conducted at the USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas (35° 11′ N – 102° 06′ E, 1170 m above sea level), in the US Southern High Plains. Measurements were concentrated in one of four lysimeter fields, where irrigated cotton was planted on May 21, day of year (DOY) 142, 2008, with rows oriented north–south (N–S) and row spacing of 0.76 m. Data were collected before and during the 2nd Intensive Observation Period (IOP, July 16 to August 3, DOY 198-216, 2008) of BEAREX08 campaign [38]). Measurements began on June 26 and covered DOY 178-216. Measurements were spanned over a period including crop leaf area indices ranging from <0.5 to 3 and corresponding cover fractions of 0.16–0.58.

2.2. Measurements

ET was measured by a large weighing lysimeter (nominally 3 × 3 × 2.4-m deep) called the NE lysimeter. Detailed descriptions of the lysimeter are given by Marek et al. [39], and its location within the larger BEAREX08 campaign is described in [38]. The lysimeter was calibrated to an accuracy of 0.04 mm in January 2008 [40]. The change in lysimeter water storage (ΔS, mm) was calculated using 15-min means of the lysimeter mass converted to storage of water in mm, referenced to an arbitrary zero storage value. To synchronize ΔS with ML measurements (see below), ΔS was determined from ∼sunrise (∼07:00) to ∼sunset (∼21:00) and again to the next morning. ET was equal to ΔS, adjusted for precipitation and irrigation events, since runoff and drainage losses

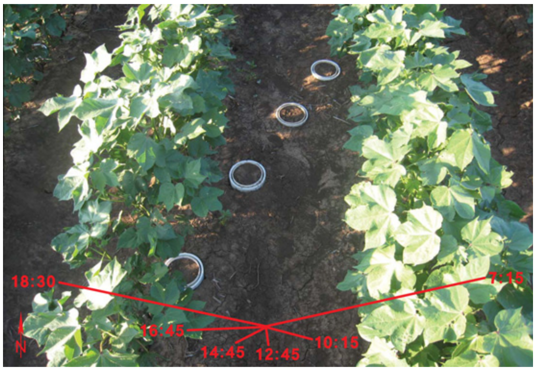

Fig. 1. The cotton field on July 24, 2008, overlaid by an illustration of the sun zenith and azimuth angles at the times of microlysimeter (ML) weighing. The direction of the lines represents the azimuth, and the length of the lines is proportional to the zenith angle, such that the higher the sun is the shorter is the line (mimicking the length of the shadow formed by an object with a given unit height). Note that only 4 MLs are apparent in the photo, the fifth ML of this set is behind the leaves at the upper part of the photo.

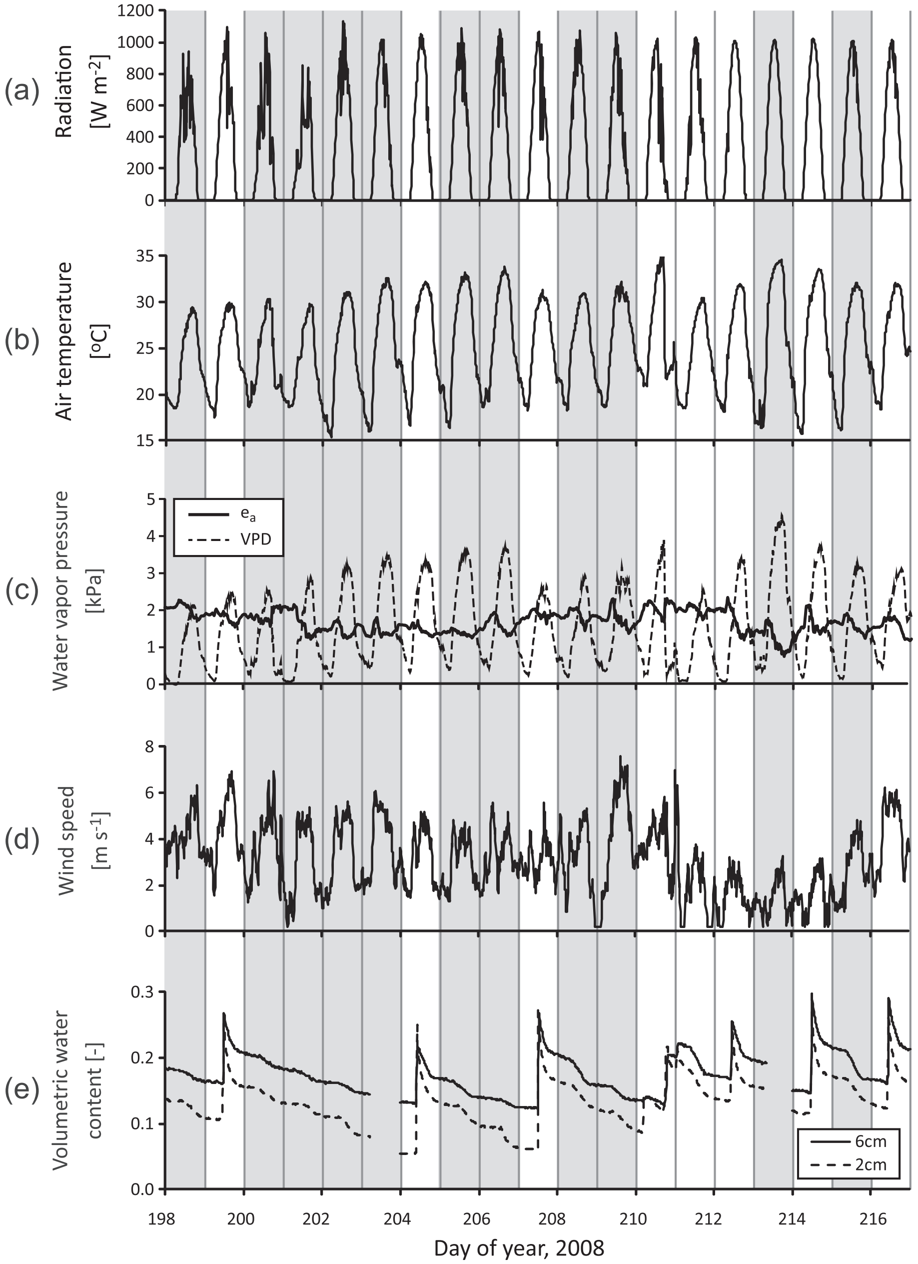

Fig. 2. Meteorological conditions during the intensive observation period (IOP). Grayed areas represent days during which soil evaporation measurements were conducted. Soil water content at depths of 2 and 6 cm are an average of the 10 locations.

were zero (see [40]). Irrigation depths of 15–25 mm were applied every 2–4 days using mid elevation spray heads spaced at 1.5 m on a lateral move irrigation system. The peak application rate was approximately 50 mm h^{-1}; and the irrigation application at any one point in the field was 15–25 min in duration.

In addition to the lysimeter measurements, ET was derived from a water balance approach using neutron probe measurements according to methods described by Evett [41] and Evett et al. [40] where discrepancies between the two ET measurement methods are described. In general, it was concluded that the lysimeter tended to slightly overestimate field ET, largely due to somewhat greater LAI and cover fraction on the lysimeter compared to the surrounding field. This bias in lysimeter ET was also confirmed by Alfieri et al. [42] based on an analysis of leaf area maps generated from aircraft observations and source area footprint estimates from eddy covariance towers sampling areas in the same field. However, since measurements of *E* and *T* were conducted in the immediate vicinity of the NE lysimeter, ET values from the lysimeter were used for this local scale comparison.

Evaporation was measured using 10 MLs made of 8-mm thick rigid white polyvinyl chloride (PVC) tubes with 105-mm inside diameter, 88-mm depth and metal bottoms. The low thermal conductivity and white color of the plastic wall material minimizes heat conduction by the walls, and the metal bottoms avoid impedance of vertical heat transfer. These design features were proven to improve ML accuracy [43]. Undisturbed soil cores were replaced daily immediately after weighing at sunset. Two replicates of five MLs each were deployed level with the soil surface along a cross section of the interrow at distances from the row center of 0.075, 0.225, 0.375, 0.525, and 0.675 m from west to east (Fig. 1). To obtain daytime and nighttime *E*, the MLs were manually weighed at sunrise (~07:00) and sunset (~21:00) using an electronic scale with a precision of 0.1 g (equivalent to 0.01 mm water) enclosed in a covered box to avoid wind effects on the measurements. During two days (DOY 213 and 215), both after irrigation on the previous day, the MLs were weighed every two hours from sunrise to sunset to obtain a diurnal course of soil evaporation.

Transpiration from plants in an adjacent row in the field was measured using heat balance sap flow gages [44]. Ten representative plants were selected and instrumented with sap flow gages (models[1] SGA-5, SGA-9, Dynamax, Inc., Houston, TX). The gages were placed on the stem at least 0.05 m above the soil surface and below any leaves and were covered with several layers of insulation and aluminum foil to shield the gage from external heating. Approximately 0.1 W of power was applied to the gage heat strips. The gage outputs were sampled at 0.2 Hz, averaged for 30-min, and logged on a datalogger (model CR-7, Campbell Scientific, Logan, UT). Transpiration was estimated from the sap flow of five to ten plants during the time period of 7:00–22:00. Data from identical periods were summed when comparing E and T. Sap flow gages must fit the plant stem tightly for successful operation, and some gage data had to be rejected early in the experiment because of poor sensor contact with the plant stem, which produced erroneous readings. The number of gage data used in calculating T increased during the experiment as plant stem diameter increased so that good sensor contact with the stem was achieved. Transpiration was computed using an area-based approach, i.e., the average of the selected gage outputs was multiplied by the number of plants per sample area.

The LAI was measured periodically by taking whole plant samples from 1 m^2 areas (three replicates in each field), stripping the leaves and measuring their area with a leaf area meter (model 3100, LI-COR Environmental, Lincoln, NE). Plant height and width were measured in three replicates in the NE field and one replicate in the NE lysimeter.

Meteorological data (solar radiation, wind speed and direction, air temperature and relative humidity) were acquired from a standard meteorological station over a well-watered short grass plot adjacent to the field. Alfalfa reference evapotranspiration, ET_r, was calculated using the ASCE 2005 Penman–Monteith standardized reference evapotranspiration method [45]. Soil water content was determined using conventional TDR [46] with trifilar probes (10 replicates) inserted horizontally into the side of a soil pit adjacent to the MLs at 20 and 60 mm depths after which the pit was backfilled.

Aerodynamic resistance (r_a) was computed for the NE and the SE fields from eddy-covariance tower measurements described by Alfieri et al. [42]. The value of r_a was computed using measurements of mean wind speed (u) and friction velocity ($u*$) from the three-dimensional sonic anemometer using the expression $r_a = u/u*^2$. Mean daily r_a values were determined as the average of hourly aerodynamic resistance estimates from sunrise to sunset, excluding data when friction velocity was smaller than 0.2 m s^{-1} since very low $u*$ values are indicative of poor turbulent mixing and may result in an under-measurement of the moisture flux.

3. Results and discussion

3.1. Meteorological and plant parameters

Solar radiation at the site during the IOP reached a maximum of ~1000 W m^{-2}; the first days were partly cloudy and skies cleared towards the end of the IOP (Fig. 2a). Daily maximum and minimum temperatures were ~29 °C and ~18 °C, respectively, at the beginning of the IOP, and ~32 °C and 17 °C, towards the end. The clearing skies resulted in daily fluctuations ~4 °C larger towards the end of the study period (Fig. 2b). Water vapor pressure fluctuated most of the time between ~1.3 kPa and 2.2 kPa, with diel patterns often being obscured by weather fronts. Water vapor pressure deficit (VPD) showed a clear diel pattern with daily nighttime minimum ranging 0–0.6 kPa and daily maximum (~noon) of 2.2–4.3 kPa. Water vapor pressure was lowest on DOY 213, reaching a minimum of 0.85 kPa at 16:45 (Fig. 2c). Wind speed at 2-m height showed a distinct diel pattern, with calmer winds during the night, increasing in the morning, and decreasing around sunset (Fig. 2d). This pattern is opposite to that of diel wind speeds observed at greater heights above the surface where nighttime wind speeds are typically greater than daytime speeds due to better coupling with the jet stream at night after heat-driven buoyant turbulence has subsided [47,48]. During the IOP, winds were greater on DOY 209 and 210, followed by four days of particularly light winds. Irrigation and precipitation events were reflected by increases in the soil water content (Fig. 2e). The only precipitation event during the IOP (on DOY 210) was detected by the increase in soil water content. The cotton was in the vegetative growth stage during

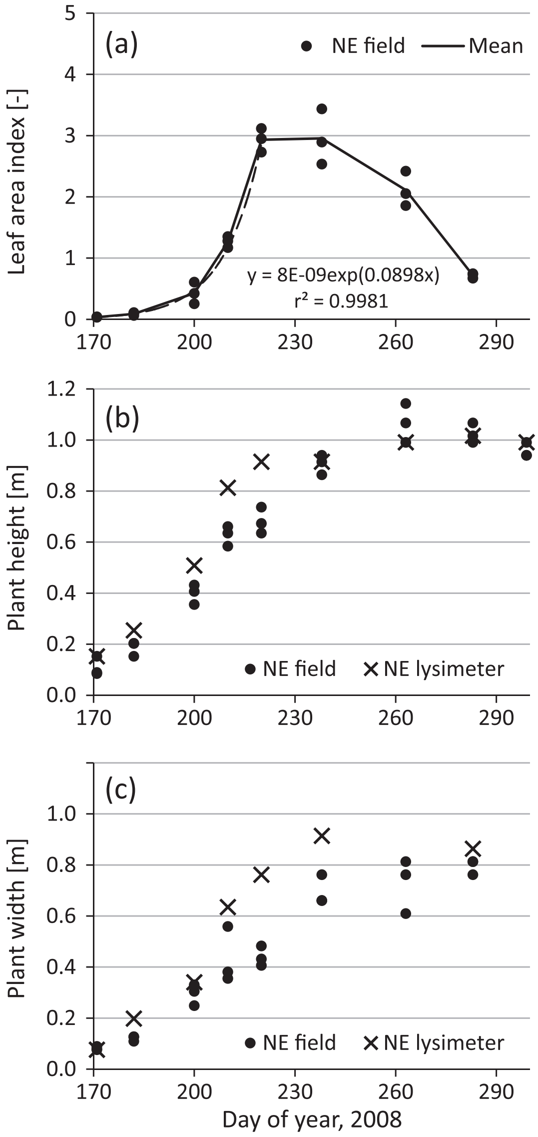

Fig. 3. Progression of measured (a) leaf area index (LAI), (b) plant height and (c) plant width in the NE lysimeter field during the 2008 cotton growing season.

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Table 1
Means and standard deviations (in parentheses) of daytime and nighttime evaporation (E) as measured by microlysimeters, daytime and nighttime evapotranspiration (ET) as measured by the NE large weighing lysimeter (Lys), ratios of daytime and nighttime E/ET, and daytime transpiration (T) as measured using sap flow gages on four days. Also shown are the sum of E and T for the four daytime periods during which T was measured without interference from irrigation or precipitation events, and the daytime values of lysimeter-measured ET for comparison. Daily alfalfa reference ET (ET_r) is also provided. All values of E, T, ET, and ET_r are in mm; DOY means day of year; and times are in Central Standard Time.

Date (2008)	DOY	Daytime E	Nighttime E	Daytime Lys ET	Nighttime Lys ET	Daytime E/ ET	Nighttime E/ ET	Daytime T	Daytime E + T	E + T-Lys ET	ET_r
6/26	178	2.02 (0.17)	0.13 (0.06)	3.76	0.17	0.54	0.73				8.36
6/27	179	1.57 (0.16)	0.06 (0.02)	3.34	0.12	0.47	0.49				7.53
7/15	197		0.08 (0.04)		0.23		0.36				5.33
7/16	198	1.40 (0.09)	0.12 (0.03)	5.61	0.38	0.25	0.31				5.82
7/18	200	2.69 (0.80)		6.81		0.39					7.35
7/19	201	1.90 (0.39)	0.17 (0.03)	6.44	0.45	0.30	0.37				5.94
7/20	202	1.53 (0.26)	0.13 (0.05)	7.52	0.46	0.20	0.29				8.40
7/21	203	1.12 (0.11)	0.05 (0.04)	7.07	0.42	0.16	0.12	6.28	7.40	0.33	8.04
7/22/2008 – irrigation											
7/23	205	1.84 (0.15)	0.14 (0.03)	8.77	0.51	0.21	0.28	8.30	10.14	1.37	7.59
7/24	206	1.01 (0.07)	0.00 (0.03)	7.67	0.38	0.13	-0.01	8.27	9.28	1.62	8.35
7/28/2008 and 7/30/2008 – irrigation											
7/31	213	1.99 (0.20)	0.12 (0.06)	9.88	0.38	0.20	0.32	7.37	9.36	−0.52	7.07
8/2	215	2.19 (0.19)	0.34 (0.08)	10.59	0.92	0.21	0.37				8.28
					Mean	0.28	0.33				
					SD	0.13	0.19				

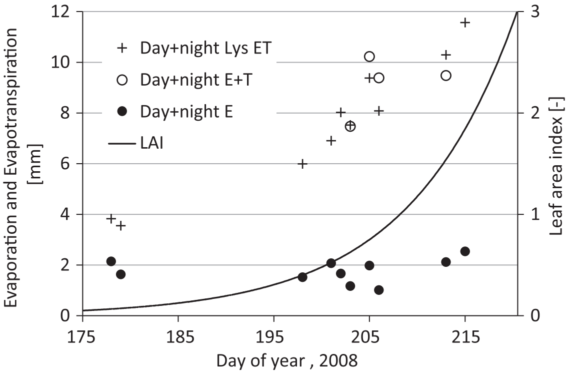

Fig. 4. Totals of daytime and following nighttime evaporation (E) as measured by microlyisimeters, $E + T$ (where transpiration, T, was measured with sap flow gages) and weighing lysimeter (Lys) ET versus days of year (DOY). Data for DOY 178 and 179 were taken before the intensive observation period began. The LAI values were estimated from the exponential relationship shown in Fig. 3.

the IOP (DOY 198-216) as indicated by the rapid increase in LAI, from a mean of 0.43 on DOY 200 to a mean of 1.27 on DOY 210 and a mean of 2.93 on DOY 220 (Fig. 3a). An exponential function described the increase in LAI with $r^2 = 0.99$ ($LAI = 8.0 \times 10^{-09} \exp[0.0898 \times DOY]$). Plant width increased from a mean of 0.12 m on DOY 182 to a mean of 0.29 m on DOY 200 and a mean of 0.44 m on DOY 220 (Fig. 3c). This translates roughly to a cover fraction change of 0.16–0.58 over the entire measurement period considered herein and 0.29–0.58 during the IOP.

3.2. *E + T = ET*

Daytime and nighttime ML measurements of E were collected on 11 days. Daytime E ranged from a high of 2.7 mm on DOY 200 to a low of 1.0 mm on DOY 206; and nighttime E ranged from 0.05 to 0.34 mm (Table 1). The small negative value of nighttime E on DOY 206-207 was due to a rainfall event that was too small to affect the rain gage but that was observed by the weighing lysimeter. Sap flow was measured during daytime on DOY 203-213 (11 days), but on only four days were there concurrent sap flow estimates of T and ML measurements of E (Table 1, Fig. 4) without interference from irrigation or precipitation events. When daytime $E + T$ data were regressed against daytime lysimeter ET ($N = 4$, adjusted $r^2 = 0.16$), neither the intercept nor slope were significantly different from zero. Setting the intercept to zero resulted in a statistically significant relationship ($p = 0.0004$) with slope of 1.08 mm/mm (SE = 1.04 mm, adjusted $r^2 = 0.66$). The standard error of 1 mm for daytime ET ranging from 7.1 to 9.9 mm indicates >=10% overall difference, although the sum $E + T$ was greater than lysimeter ET by 1.4 and 1.6 mm on DOY 205-206 (Table 1, Fig. 4).

When irrigations occurred, T was reduced due to the humidification of the atmosphere within the canopy (Fig. 5). A secondary effect that would have acted to reduce T was that the canopy was cooled by the irrigation, which would have reduced the vapor pressure gradient by depressing the sub-stomatal vapor pressure. Decreases of in-canopy vapor pressure deficit and of corn (*Zea mays* L.) T during, and shortly after, irrigation were reported by Cavero et al. [34], Martinez-Cob et al. [35], and Tolk et al. [36]. Decreases in T compensated for evaporation of canopy-intercepted water, which helped to improve irrigation application efficiency. In the present study, while T increased after the irrigation event, absolute rates tended to not greatly exceed 0.8 mm h^{-1}, even on days when ET absolute rates approached or exceeded 1.2 mm h^{-1}. It appeared that cotton physiology and root water uptake processes were limiting the maximum T rate.

Transpiration exceeded ET on a few occasions and was essentially equal to ET on DOY 205 (Fig. 5). Given the equality $ET = E + T$ and since E was not negligible, values of T equal to, or larger than,

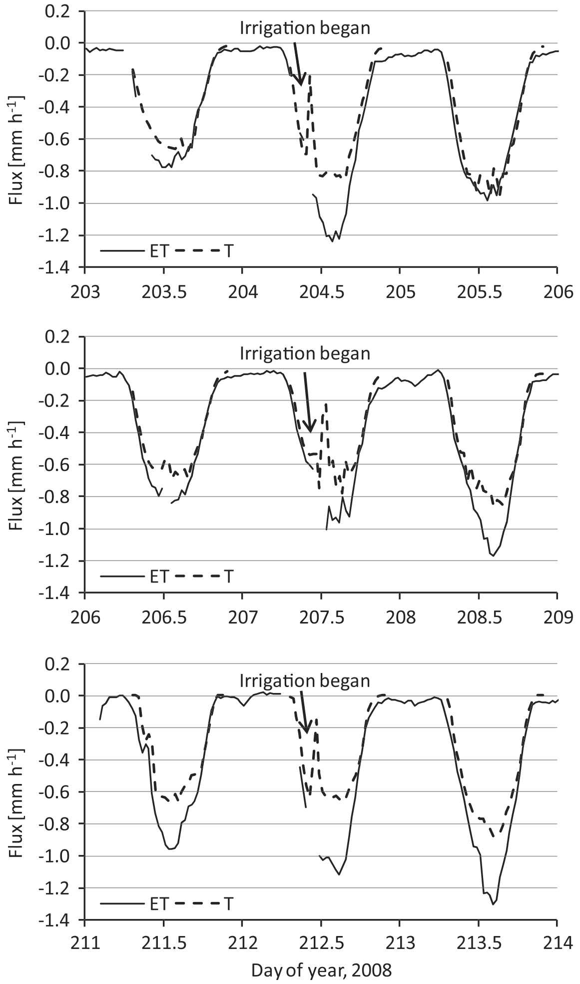

Fig. 5. Suppression of transpiration (*T*) during irrigation events on days of the year 204, 207 and 212, 2008. Also shown are ET and *T* on days before and after those irrigations. Discontinuities in ET data are due to irrigation or precipitation (day of year 203) events.

ET indicate that *T* was likely over estimated. The problems with comparing sap flow data to lysimeter data were that (i) the number of plants with gages (5–10 plants) was much less than the lysimeter population of 135 plants, and (ii) the lysimeter plant population, although within 30 m of the sap flow gage installation and thinned to the same plant density, was somewhat different in phenology, with plant width and height sometimes larger on the lysimeter than in the field (Fig. 3b and c). The determination made by Evett et al. [40] and Alfieri et al. [42] that the NE lysimeter ET values were greater than field scale estimates of ET further supports the indication that *T* was over estimated by the sap flow method, which likely derives from the areal estimation process for converting sap flow data to *T* data. Dugas [49] found that adjusting sap flow of cotton by a stem area ratio factor produced sap flow *T* that was about 9% larger than lysimetrically measured *T*. He noted that determining measurement accuracy was confounded by plant-to-plant variability. Adjustment of *T* on a leaf area basis was not possible in our case because leaf area of the plants on which sap flow gages were installed was not available.

3.3. Ratio of daily total E to ET

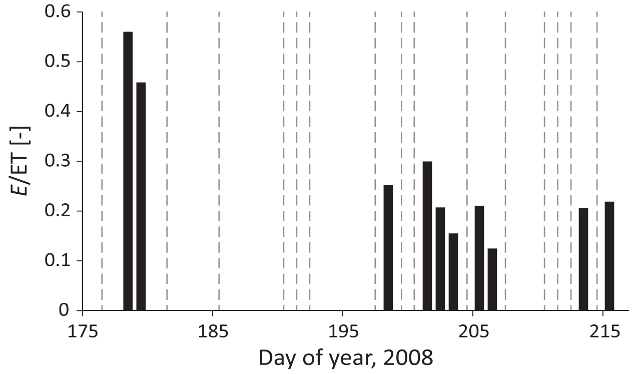

Fig. 6. Daily fractions of soil evaporation (*E*) from evapotranspiration (ET). Gray dashed lines represent rainfall or irrigation events.

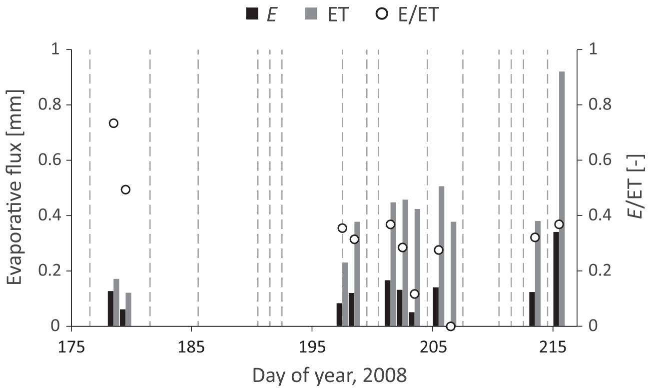

Fig. 7. Nocturnal soil evaporation (*E*), evapotranspiration (ET), and the fraction *E*/ET. Gray dashed lines represent rainfall or irrigation events.

Daytime *E* averaged 28% of lysimeter ET (Table 1). The daily fraction *E*/ET throughout the study period showed two phenomena (Fig. 6). First, a steady decline of *E*/ET on successive days after irrigation or precipitation events occurred for the four events shown in Table 1. Second, a reduction in the *E*/ET ratio as LAI increased was observed. The largest values of daytime *E*/ET occurred on DOY 178, before the IOP (DOY 198-215), when LAI < 0.5. The smallest values of daytime *E*/ET on days immediately after irrigation or precipitation occurred near the end of the IOP when LAI was closer to 3. Early in the growing season, when LAI was <0.2 and canopy cover was less than 10%, *E* was ~50% of daily ET. As LAI approached 2, daily *E* on the day after irrigation or precipitation was closer to 20% of daily ET. Somewhat surprisingly, the daily *E* did not decrease greatly as LAI increased from 0.05 to nearly 3 (Fig. 4), remaining at approximately 2 mm d^{-1} from DOY 178–215.

3.4. Nocturnal E, T and ET

Nighttime (21:00–07:00) ET ranged from 0.12 mm to 0.92 mm (Fig. 7, Table 1). In comparison, Tolk et al. [23] reported mean nighttime ET ranging from 0.52 to 0.58 mm for irrigated alfalfa (*Medicago sativa* L.), with some nighttime losses approaching 2 mm, and mean nighttime ET of 0.31 and 0.41 mm for dryland and fully irrigated cotton, respectively. On average, nighttime lysimeter ET in the present experiment was 6% of daily totals. Similarly to patterns observed for the total daily fluxes, nocturnal *E*/ET was larger earlier in the growing season with an average of 0.61 for DOYs 178–179, and reduced as the canopy developed with an average of 0.30 for DOYs 198–215. In comparison, total daily *E*/ET for DOYs 198–215 was 0.21. This means that nocturnal transpiration was 5% of total daily transpiration. This fraction is within the lower reported range [22–26]. The reduction in the fraction of *E* with increasing time after irrigation events was also noticeable.

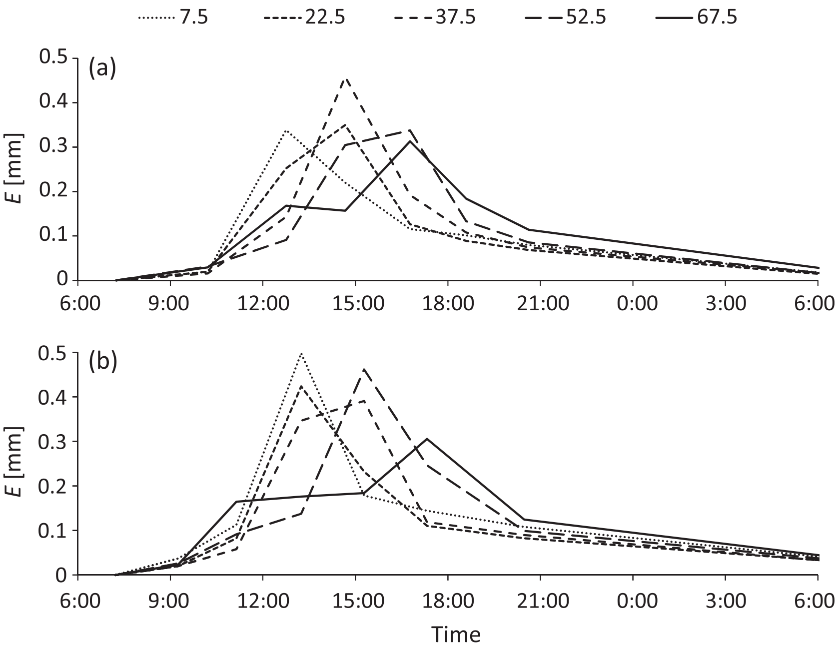

Fig. 8. Soil evaporation at 5 locations across the interrow measured on days of year (a) 213 and (b) 215, 2008. Distances are in cm with distance increasing from the west side of the interrow to the east side.

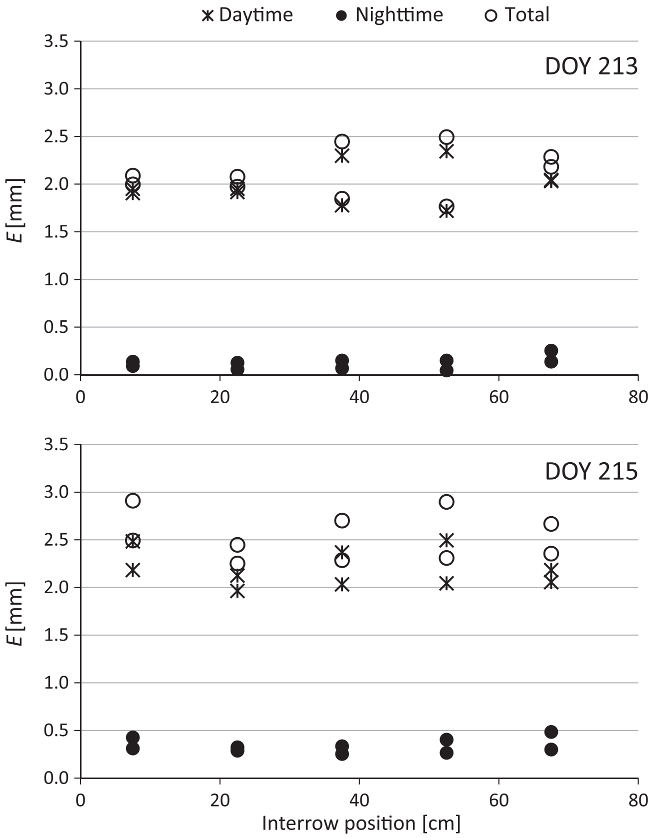

Fig. 9. Total daily evaporation (E) and daytime and nighttime E totals by position from the west side of the interrow for days of the year 213 and 215, 2008.

3.5. Diel dynamics of E

To better understand the dynamics of soil evaporation in a semi-arid row-crop system, the diurnal course of E during two days was analyzed. Measurements were made at approximately two-hour intervals during the daylight hours for the two days, both of them after irrigation on the previous day, which made soil water conditions similar. Over both periods, a distinct effect of measurement location on E was apparent, with a shift in time of peak E from west to east (Fig. 8). This pattern was governed by the solar radiation reaching the soil surface (see Fig. 1 for sun azimuth and zenith angles at the times of measurement). In the morning, the presence of the crop and the sun's position formed shadows on large fractions of the interrow, allowing for radiation to reach the soil only at the narrow western part of the interrow. Therefore, only the western MLs were exposed to direct solar radiation, which drove evaporation. Near noon, sun elevation was higher with a southerly direction (i.e., parallel to the row), and the only shaded areas were those immediately below the canopy, resulting in a peak E at the central ML. In the afternoon and evening, only the eastern part of the interrow was exposed to direct solar radiation, resulting in a peak E from the eastern MLs.

Despite the observed differences between locations in the pattern of diurnal E, total daily E values were not noticeably influenced by position on any of the 11 days during which E was measured (Fig. 9). Moreover, regressions of 24-h E on ET_r and on lysimeter ET for the same 11 days both indicated no significant correlation. This implies that E was not strongly influenced by evaporative demand. The lack of correlation is likely due to the strong interaction of ET with increasing plant height and LAI during the period. To further investigate the relationship between evaporative demand and E, ET_r was binned in 15° directional increments to find the vectors of strongest evaporative demand. During the days for which measurements of E were collected, the winds and evaporative demand were from southerly directions except for DOY 213 and until 7:00 on DOY 214 when evaporative demand was from the east. The ET_r was 7.07 and 8.28 mm d^{-1} on DOY 213 and 215, respectively (Table 1), i.e., 17% larger on DOY 215. The E values on DOY 213 and 215 were 2.1 and 2.5 mm d^{-1}, respectively, with that on DOY 215 being larger by 20%. Since soil, crop and management conditions were similar for both days (both followed an irrigation on the previous day), these differences may be attributed to differences in weather conditions (Fig. 10). Solar

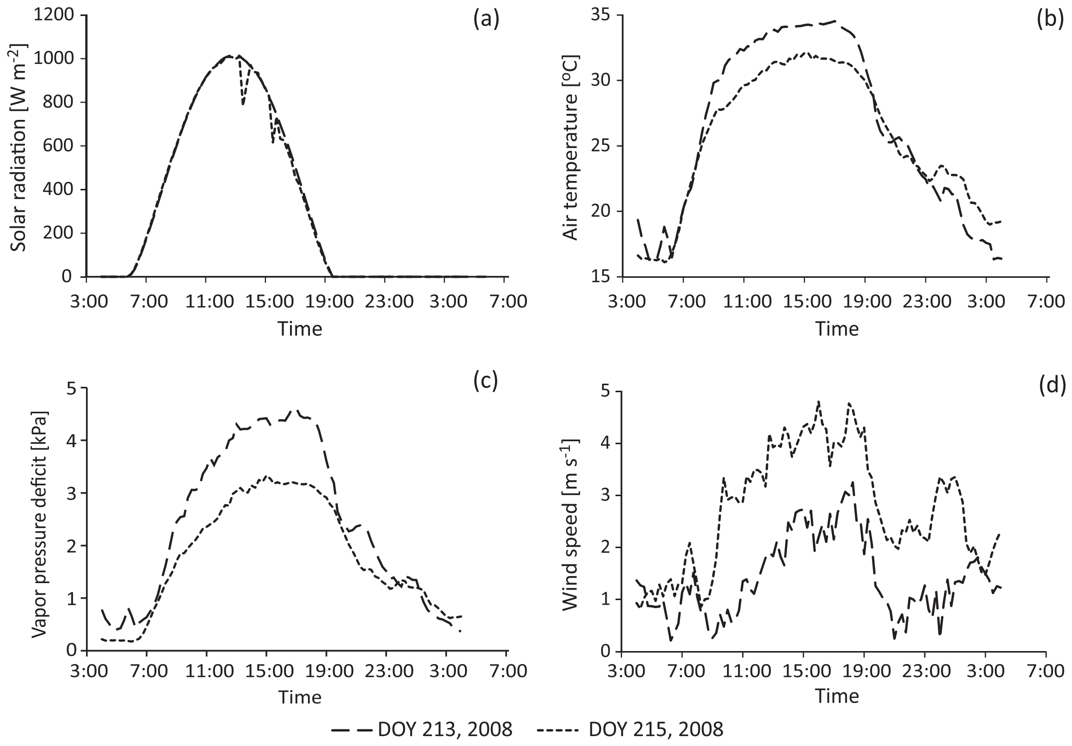

Fig. 10. Meteorological conditions during days of year 213 and 215, 2008, during which diurnal measurements of *E* were conducted: (a) solar radiation; (b) air temperature; (c) vapor pressure deficit; and (d) wind speed (2 m above the ground).

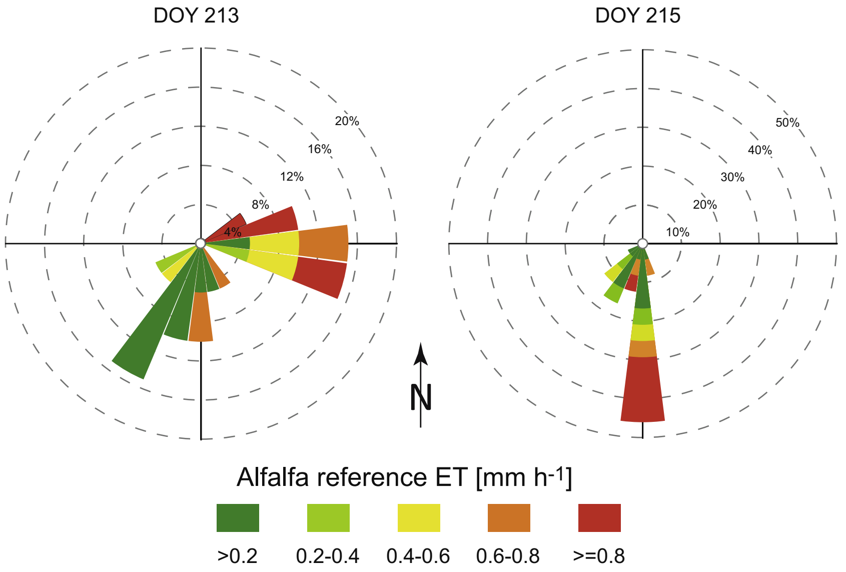

Fig. 11. Wind roses for the 24-h period and the nighttime on days of year (DOY) 213 and 215.

radiation was practically the same on these two days, with a few minor reductions due to clouds on DOY 215 (Fig. 10a). Air temperature was greater during the day and somewhat smaller during the night of DOY 213 (Fig. 10b), and vapor pressure deficit was less throughout on DOY 215 (Fig. 10c). These conditions are expected to result in a greater evaporative demand on DOY 213. Still, evaporative demand was greater on DOY 215. The likely reason for this was the difference in wind speed magnitude being the overriding factor in causing greater evaporative demand on DOY 215 (Fig. 10d, Table 1).

In row crops, not only wind speed is expected to affect evaporation, but also wind direction. The differences in wind directions and speeds for the two days were distinct, causing differences in evaporative demand (Fig. 11). On DOY 213, most of the winds were less than 2 m s^{-1}. In the few instances in which wind speed was greater (never more than 5 m s^{-1}) wind direction was ~east, i.e., perpendicular to the rows. In such a case, the rows served as wind breaks. In contrast, on DOY 215 not only were wind speeds greater, the strong winds came from the south, i.e., parallel to the rows, so that wind speed in the interrow between the plants was likely much greater than on DOY 213.

There were no data for *E* in the east–west (E–W) row direction in this study. Thus we could not distinguish the effect of row orientation on *E* in terms of wind speed and direction. However,

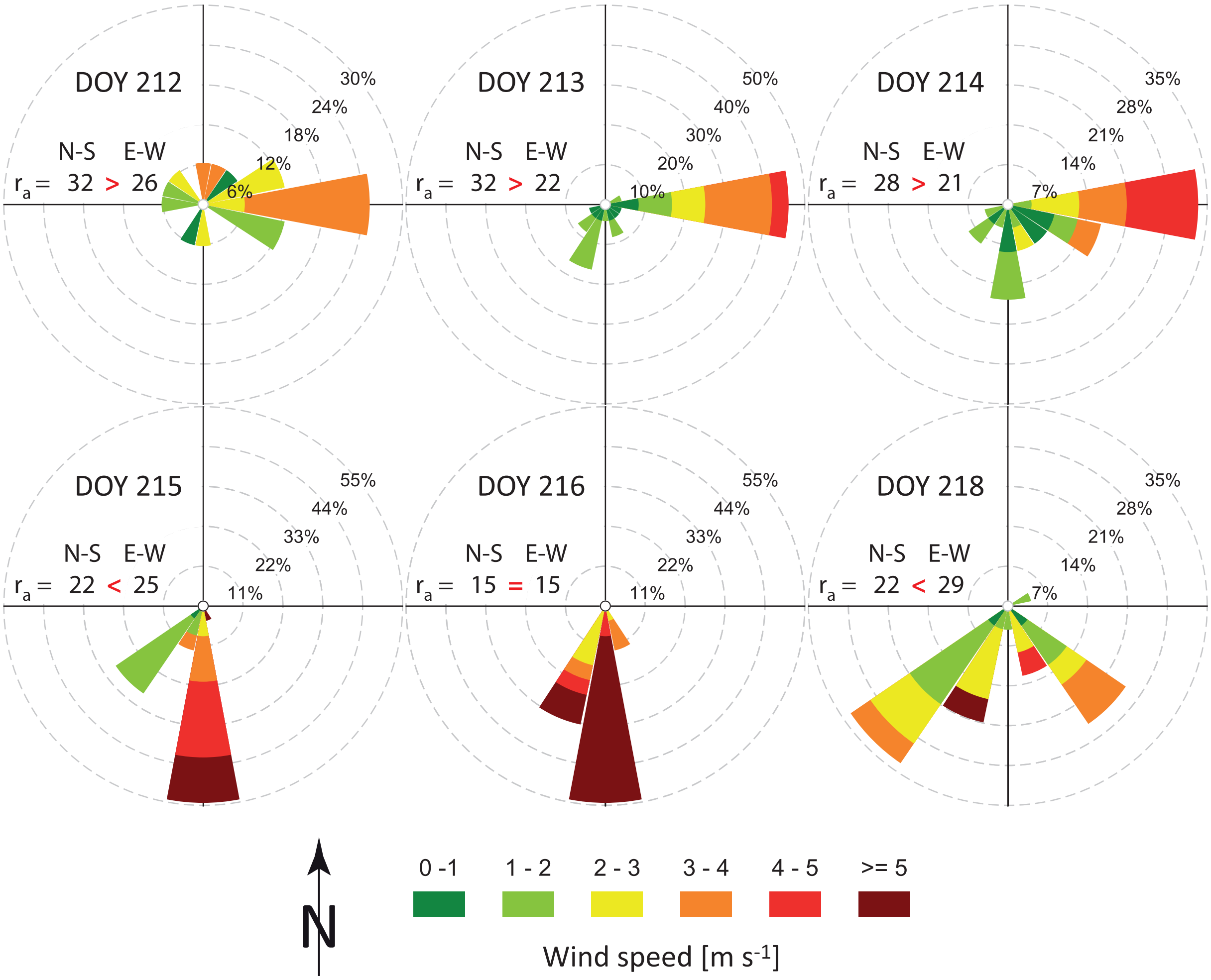

Fig. 12. Wind roses for days of year (DOY) 212-216 and 218 and respective aerodynamic resistances (r_a) at the north–south (N–S) and east–west (E–W) row orientation fields. A greater-than or lesser-than sign indicates a significant one-tail paired Student's test result ($p < 0.05$). An equal sign indicates no significant difference ($p > 0.05$) in either one- or two-tail tests.

comparison of daytime aerodynamic resistances (r_a) in both N–S and E–W row orientations for six days (DOY 212-216 and 218) does suggest that wind speed magnitude and direction, in relation to the row orientation, interacted to have an effect on E (Fig. 12) (Data for DOY 217 gave results very similar to 216 and is not shown). It was hypothesized that rows oriented perpendicular to the wind serve as wind breaks and thus result in larger r_a relative to rows oriented parallel to the wind. On DOY 212–214 the dominant wind was from the east and was relatively low (∼2–3 m/s). DOY 215 and 216 were characterized by stronger winds (more so on DOY 216), and predominantly from the south, while on DOY 218 the winds were again lower but were southerly, although more variable (wind direction varying from southeast to southwest). Based on the hypothesis, it was expected that r_a would be greater in the N–S versus E–W row oriented field on DOY 212–214, and vice versa for DOY 215, 216, and 218. One-tailed paired Student's t-tests verified the hypothesis for all days except for DOY 216, which had wind speeds exceeding 5 m s^{-1} over half the day. On DOY 216, no significant difference in r_a was found between the two fields, which suggests that, for windy days, row orientation has no measurable effect on the rate of E. However, for low to moderate wind speed conditions (i.e., ∼1–4 m/s), rows oriented perpendicularly to the wind can serve as effective wind breaks and may result in decreased turbulent transport of E.

Steiner [50,51] showed that for a 0.76-m row width planting of a sorghum crop in Bushland, row orientation affected light interception with N–S rows intercepting more radiation and having smaller net radiation versus E–W rows. These observations tend to indicate that, in terms of radiation, N–S row orientation may result in smaller E compared to E–W row orientation. Since wind direction is often variable from hour to hour and day to day, the magnitude and direction of the wind can either enhance or dampen the effects of radiation and evaporative demand on E due to row orientation. Minimization of E is one of the ways to improve WUE, thus the relative effect of row orientation on radiation interception and inter-row aerodynamics on the magnitude of E should be further explored.

4. Summary and conclusions

The objectives of this study were to quantify the fractions of E and T compared to ET throughout part of the growing season of irrigated cotton in a strongly advective semi-arid area, and to study the effects of LAI, days after irrigation, wind direction and measurement location within the row on E and the E/ET fraction.

Conclusions are:

- Soil evaporation measured with microlysimeters and canopy transpiration measured with heat balance sap flow gages were combined with moderate success (SE = 1 mm or ∼10% of lysimeter ET) to separate evapotranspiration into its two components in this irrigated cotton field.

- Depending on irrigation frequency, soil evaporation may account for >50% of daytime evapotranspiration and >70% of nighttime ET during early stages of plant growth (LAI = 0.02 to ∼2.0). These percentages are reduced with increase in LAI, mainly due to increase in transpiration (daily soil evaporation remained practically the same throughout).
- Nighttime lysimeter ET was 6% of daily totals. Nocturnal E/ET was larger earlier in the growing season, and reduced as the canopy developed. Nocturnal transpiration was 5% of total daily transpiration.
- Measurement location within the interrow distinctly affected the diurnal course of soil evaporation, with a shift in the time of peak *E* rate from west to east. This pattern is governed by the solar radiation reaching the soil surface.
- Despite the diurnal variation in the spatial pattern of *E*, the total daytime or nighttime *E* was not significantly affected by interrow position of the microlysimeters, indicating that microlysimeters may be used for daily evaporation measurement without regard to interrow position.
- Under low to moderate wind speed conditions (∼1–4 m/s), rows oriented perpendicular to the wind served as effective wind breaks, which was related to greater resistance to the turbulent transport of *E*. Under higher wind speed conditions, row orientation had no measurable effect on the rate of *E*. More detailed studies under N–S and E–W row orientations and a range of canopy cover conditions are required to assess the relative influence of the different meteorological forcings on the magnitude of *E*.

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