

Nighttime Evapotranspiration from Alfalfa and Cotton in a Semiarid Climate

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ABSTRACT

Nighttime evapotranspiration (ET_N) has typically been neglected in estimating water loss from land surfaces. Our objective was to quantify the contribution of ET_N to daily (24-h) ET (ET_{24}) of irrigated and dryland cotton (*Gossypium hirsutum* L.) and irrigated alfalfa (*Medicago sativa* L.) grown in a semiarid climate. The results were then examined using a Penman–Monteith ET model which separates control of ET into its radiation (equilibrium) and atmospheric demand (imposed) components. Nighttime ET was measured at Bushland, TX using weighing lysimeters containing monolithic soil cores of Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) for alfalfa in 1998 and cotton in 2001. Measured ratios of ET_N to ET_{24} ranged from an average of 3% for a dryland cotton crop to 7.2% for irrigated alfalfa over a season. In the largest events, ET_N was as much as 12% of ET_{24} with single nighttime losses approaching 2 mm. Model calculations showed that virtually all ET_N was the result of imposed atmospheric conditions, primarily vapor pressure deficit. However, ET_N was also related to sensible heat transfer to the canopy. Nighttime ET can be an important part of total ET of irrigated crops in a semiarid environment.

THE contribution of ET_N to ET_{24} is largely ignored in methods that estimate water loss from land surfaces, especially those that use only solar radiation as the energy source to vaporize water. But, the limited research that has been performed has shown that ET_N accounted for 7% of ET_{24} from tall grass prairie vegetation (Sugita and Brutsaert, 1991), 4.1% of the mean ET_{24} from a willow (*Salix viminalis* L.) stand (Iritz and Lindroth, 1994), and from 1.7% to about 14% of ET_{24} for an irrigated alfalfa (*Medicago sativa* L.) field in a semiarid mountain valley as wind speed increased (Malek, 1992). The ET_N proportion of ET_{24} measured by weighing lysimeters for alfalfa was 8% in North Carolina as reported by England (1963), while Rosenberg (1969) found that it varied from 7 to 21% in spring and 0 to 15% in summer for the central Great Plains.

Nighttime ET has been shown to include water losses from plants. Reported nighttime transpiration losses were 19% of daily totals for kiwifruit [*Actinidia deliciosa* (A.Chev.) C.F. Liang et A.R. Ferguson] vines and 6% for apple trees (*Malus sylvestris* Mill. 'Red Delicious') (Green et al., 1989), and 8% of daily losses in unstressed wheat (*Triticum aestivum* L.) grown in a dry environment (Rawson and Clarke, 1988). Partially open stomata during

the night were found in cotton (Sharpe, 1973), and in kenaf (*Hibiscus cannabinus* L.) (Muchow et al., 1980).

Other ET_N sources identified were soil water (Iritz and Lindroth, 1994), dew (Malek, 1992), and canopy-intercepted rainfall (Pearce et al., 1980). Using 24-h totals from a weighing lysimeter, Jackson et al. (1983) concluded that the ET of wheat predicted from one time of day meteorological measurements needed to be multiplied by 1.1 to account for ET_N , but that the accuracy of the multiplier depended on prevailing environmental conditions.

Penman (1948) presented a general formula for the rate of open water evaporation and later applied to bare soil and grass that was a function of meteorological elements such as temperature, vapor pressure, wind, and radiation. Monteith (1965, 1981) later added resistances (e.g., aerodynamic and surface) to fluxes of momentum, heat, and water vapor through the system.

It can reasonably be assumed that different processes determine nighttime and daytime ET in what later became known as the Penman–Monteith ET model. McNaughton and Jarvis (1983) presented a form of the Penman–Monteith ET model which helps examine these processes. It consisted of an equilibrium ET (ET_{eq}) component, in which ET was a function of available energy at the surface, and an imposed ET (ET_{imp}) component, in which ET was a function of bulk atmospheric conditions. The contributions of the two components were then weighted by a plant–atmosphere decoupling factor Ω . The equation was written as

$$\lambda E = \Omega[\Delta(R_n + G)/(\Delta + \gamma)] + (1 - \Omega)[(\rho c_p VPD)/(\gamma r_s)] \quad [1]$$

where λE is latent heat flux, R_n is net radiation, and G is soil heat flux, all in $W m^{-2}$ with fluxes toward the surface positive in sign; Δ is the slope of the saturation vapor pressure–temperature curve ($kPa \text{ } ^\circ C^{-1}$); λ is the latent heat of vaporization ($J kg^{-1}$); ρ is air density ($kg m^{-3}$); c_p is the specific heat of air at constant pressure ($J kg^{-1} K^{-1}$); VPD is the vapor pressure deficit (kPa); γ is the psychrometric constant ($kPa \text{ } ^\circ C^{-1}$); r_s is surface (crop and soil) resistance ($s m^{-1}$); and Ω is defined as

$$\Omega = \{1 + [\gamma/(\Delta + \gamma)](r_s/r_a)\}^{-1} \quad [2]$$

where r_a is aerodynamic resistance ($s m^{-1}$).

In this form, Ω sets the relative importance of the equilibrium, $\Delta(R_n + G)/(\Delta + \gamma)$, and imposed, $(\rho c_p VPD)/(\gamma r_s)$, terms. When Ω is near 1, the ET rate is

Abbreviations: DOY, day of year; ET, evapotranspiration; ET_{eq} , equilibrium ET; ET_{imp} , imposed ET; ET_N , nighttime ET; ET_{24} , daily (24-h) ET; G , soil heat flux; H , sensible heat flux; IRT, infrared thermometer; LAI, leaf area index; λE , latent heat flux; $(R_n + G)$, net radiation + soil heat flux; Ω , decoupling factor; r_a , aerodynamic resistance; r_s , surface resistance; VPD, vapor pressure deficit.

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in equilibrium with $(R_n + G)$ and is “decoupled” from bulk atmospheric conditions by large aerodynamic and small surface resistances. When Ω approaches zero, the ET rate becomes “coupled” to bulk atmospheric conditions such as VPD because turbulent atmospheric mixing due to wind and crop canopy characteristics has reduced r_a while r_s has increased. During the day, high $(R_n + G)$ and low surface resistance tend to control the ET rate. At night, when $(R_n + G)$ is low and surface resistance is high ET rate is controlled by the ET_{imp} term, which can be important in a windy, semiarid environment. For example, when VPD is high (2 kPa), such as can occur in a semiarid climate, the ET_{imp} term of Eq. [1] predicts that ET_{imp} can contribute more than 0.15 mm h^{-1} to ET_N when $\Omega = 0.13$, T_a is 25°C , r_a is 25 s m^{-1} , and r_s is 300 s m^{-1} .

Rawson and Clarke (1988) found that the pattern and amount of nighttime transpiration losses of wheat was changed by current VPD, as did Green et al. (1989) for kiwifruit and Iritz and Lindroth (1994) for willow. Katul and Parlange (1992) found that when wind speed was large ($>10 \text{ m s}^{-1}$), nighttime evaporation from bare soil could be one-third of the total daily evaporation, with the predominant transport mechanism for heat and water vapor being mechanical mixing resulting in lowered r_a . Rosenberg (1969) credited sensible heat advection for nocturnal ET of irrigated alfalfa.

The objectives of this study were to (i) quantify the contribution of ET_N to ET_{24} of irrigated alfalfa and irrigated and dryland cotton using ET measurements made by large weighing lysimeters and (ii) examine the processes involved using the McNaughton and Jarvis (1983) decoupling model.

MATERIALS AND METHODS

The study was conducted in 1998 and 2001 at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX [$35^\circ 11' \text{ N}$, $102^\circ 06' \text{ W}$; 1170 m elev. above mean sea level]. The soil is classified as Pullman clay loam (USDA-NRCS, 2003), which is described as slowly permeable because of a dense Bt2 horizon about 0.3 to 0.5 m below the surface. The weighing lysimeter facility used in this research contained four large weighing lysimeters (Marek et al., 1988), each located in the center of a 4.7-ha field (210 m E-W by 225 m N-S). The four fields were arranged in a block pattern, with the east subblock containing two contiguous fields (designated NE and SE), and the west subblock containing two contiguous fields (designated NW and SW). The east and west subblocks were separated by a 9-m wide road. Irrigations were applied to the east subblock with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, NE). The sprinkler system was aligned N-S, and irrigated E-W or W-E. Both subblocks were used in the cotton project, with irrigation applied only to the east subblock. The east subblock only was used in the alfalfa project.

Alfalfa (‘Paymaster 5454’) was sown in the autumn of 1995 at a seeding rate of 28 kg ha^{-1} on 0.2-m rows with a double pass to increase plant density. Cutting dates in 1998 were Day of Year (DOY) 138 (18 May), 174 (23 June), 202 (21 July), 237 (25 August), and 281 (8 October). Alfalfa received 1110 mm in irrigation and/or rainfall, with irrigations being 20 to 25 mm usually applied two to three times weekly until about 1 wk before cutting.

Cotton (‘Paymaster 2145’) was planted on DOY 136 to 137, 2001, and harvested on DOY 303 for the irrigated fields and DOY 295 for the dryland fields. Row spacing was 0.76 m for the NE, SE, and NW lysimeter fields and 0.25 m for the SW field, and rows were oriented E-W with a prevailing S-SW wind direction. The SW field row spacing was part of another study concerning row geometry. Plant density was 17 plants m^{-2} on the east field, 14 plants m^{-2} for the NW field, and 10 plants m^{-2} on the SW field. The irrigation and/or precipitation received by the deficit-irrigated NE lysimeter was about 300 mm, and the full-irrigated SE lysimeter received about 430 mm. The NW and SW lysimeters received 110 mm. Irrigations on the east lysimeters were applied two to three times weekly from DOY 183 through DOY 232. Details can be found in Howell et al. (2004).

Plant samples were collected periodically from the fields associated with each lysimeter, with four replicate samples of 1 m^2 per field for alfalfa and 1.5 m^2 for cotton. Leaf area was determined using a leaf area meter (model 3100, LI-COR, Inc., Lincoln, NE), and leaf area index (LAI, in $\text{m}^2 \text{ m}^{-2}$) calculated after sample drying. Leaf area index of alfalfa on the lysimeters was measured at each cutting. Crop height of each sample was also measured. Daily estimates of LAI and crop height for each crop were made by linear extrapolation between samples.

Lysimeter Measurements

The lysimeters contained monolithic Pullman cores with a 9-m^2 surface area and a 2.3-m depth. Changes in lysimeter mass were determined using a data logger (model CR7-X, Campbell Scientific, Inc., Logan, UT) to measure and record the lysimeter load cell (model SM-50, Interface, Scottsdale, AZ) with the signal sampled at 0.17-Hz (6 s) frequency. The lysimeters were calibrated before the experiment similarly to the methods used by Howell et al. (1995), but not as detailed. The lysimeter mass measurement accuracy was 0.01 mm, as indicated by the root mean squared error of calibration. The load cell signal was averaged for 5 min and composited to 30-min means. The lysimeter mass data were reported on the midpoint of the 30 min, that is, data were averaged from 0 to 30 min and reported at the midpoint of the averaging period. The ET_{24} was calculated as the difference between lysimeter mass recorded at 1145 h CST of 1 d and 1145 h CST of the next day to determine mass losses (from evaporation and transpiration) to which lysimeter mass gains (from irrigation or precipitation) were added. Normally, the period for calculation of ET_{24} was from 2345 h CST to 2345 h CST of the next day but, to include the nighttime period, the time frame was shifted 12 h. Calculation of ET_N was similar to that for ET_{24} , representing the difference in lysimeter mass at the beginning and ending of the period when measured solar radiation was zero (e.g., 2015 h CST of DOY 186 and 0515 h CST of DOY 187). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here).

Micrometeorological Measurements

Identically instrumented meteorological masts were located at each weighing lysimeter and held, among other instrumentation, a cup anemometer (model 014A, Met One, Grants Pass, OR, in 1998; and model 12102, R.M. Young, Traverse City, MI, in 2001), net radiometer [model Q*5.5 in 1998 and model Q*7.1 in 2001, Radiation and Energy Balance Systems (REBS),

Seattle, WA], temperature–humidity probe (model HT225R, Rotronics Huntington, NY, in 1998; and model HMP45, Vaisala, Helsinki, Finland, in 2001), and a thermocouple infrared thermometer (IRT) (model 2G-T-80F/27C, Exergen, Watertown, MA). The IRT, which was used to measure canopy temperature, had a 1:2 field of view, and was mounted at an average 45° angle to view to the SW. The angle varied to minimize viewing the soil. Wind, humidity, and temperature sensors were 2 m and the net radiometer and IRT were at 0.5 to 1 m above the crop surface.

Soil heat flux was measured using heat flux plates (model HFT-1, Radiation and Energy Balance Systems, Seattle, WA) installed at 50 mm below the soil surface. Soil heat flux at the soil surface was estimated using corrections for heat storage above the heat flux plate that required soil temperature and soil moisture (Evet, 2002). Soil temperature was measured with four pairs of copper-constantan thermocouples (model 304SS, Omega Engineering, Stamford, CT). Each pair had one thermocouple installed at a 10-mm depth and the other at 40 mm, which were wired in parallel to integrate soil temperature. Soil moisture content in the soil layer above the heat flux plate was estimated using the ENWATBAL model (Evet and Lascano, 1993). Weather data needed for ENWATBAL, including solar radiation, were measured at a weather station 200 to 400 m from the lysimeter fields.

Lysimeter load cell and micrometeorological instrumentation data were collected by the same data logger for output as 30-min means. Vapor pressure deficit was calculated using Murray's (1967) computation of dew point temperature, using measured air temperature and relative humidity.

Resistance and Sensible Heat Flux Calculations

Aerodynamic resistance was calculated as the aerodynamic resistance to momentum transport from Thom (1975) using crop height (CH , in m) and measurement reference height (Z , in m) given as $r_a = \ln[(Z - d)/Z_{om}]^2/k^2U$, where d is zero plane displacement ($0.63 CH$), Z_{om} is roughness length [$0.35(CH - d)$], k is von Karman's constant (0.41), and U is wind speed ($m s^{-1}$) at reference height Z . This approach was evaluated by Tolk et al. (1995). Sensible heat flux (H , in $W m^{-2}$) was calculated as the residual of the energy balance equation (Rosenberg et al., 1983) or $H = -\lambda E - R_n - G$.

Surface resistance was calculated by rearranging the Penman–Monteith ET model, and converting measured ET_N to λE using the latent heat of vaporization λ ($2.45 MJ kg^{-1}$), or

$$r_s = [r_a \Delta (R_n + G) + \rho c_p VPD] / (\lambda E \gamma) - r_a (\Delta + \gamma) / \gamma \quad [3]$$

with Δ , ρ , c_p , γ and other related parameters calculated according to procedures described in ASCE (2005).

Data Selection

The criteria for selection of ET_N measurements to be used in the analysis included that ET_N was not negative, and the cumulative 30-min mass gains during the nighttime period must be less than 0.05 mm and could not exceed cumulative mass loss. This helped prevent load cell noise (minimum accuracy 0.01 mm) from being a factor in the analysis and eliminated periods of rainfall and periods of mass gain whose origin could not be determined (such as dew formation that could not be identified because it was not measured by separate instrumentation). Negative ET_N was typically greater than -0.05 mm. Additionally, no micrometeorological measurements could be missing.

RESULTS

Nighttime Climatic Conditions

Mean VPD for the selected days for both the alfalfa crop in 1998 (Fig. 1A) and the cotton crops in 2001 (Fig. 2A) was about $1.0 (\pm 0.5)$ kPa, but tended to be larger in the first half of the season with values approaching 2.5 kPa, and frequently staying well below 1 kPa in the last half. Average nighttime wind speed was $3.3 (\pm 1.4)$ $m s^{-1}$ in 1998 (Fig. 1B) and $2.5 (\pm 1.0)$ $m s^{-1}$ in 2001 (Fig. 2B), with periods in 1998 when wind speeds were 6 to 8 $m s^{-1}$. Except for a few nights, the canopy was a sink for sensible heat flux (positive flux toward the canopy) throughout the season for both crops (Fig. 1C, 2C). Mean nighttime air temperatures were similar for both seasons (Fig. 1D, 2D), averaging about 20°C, but usually remaining between 20 and 25°C for July (DOY 182) through August (DOY 243).

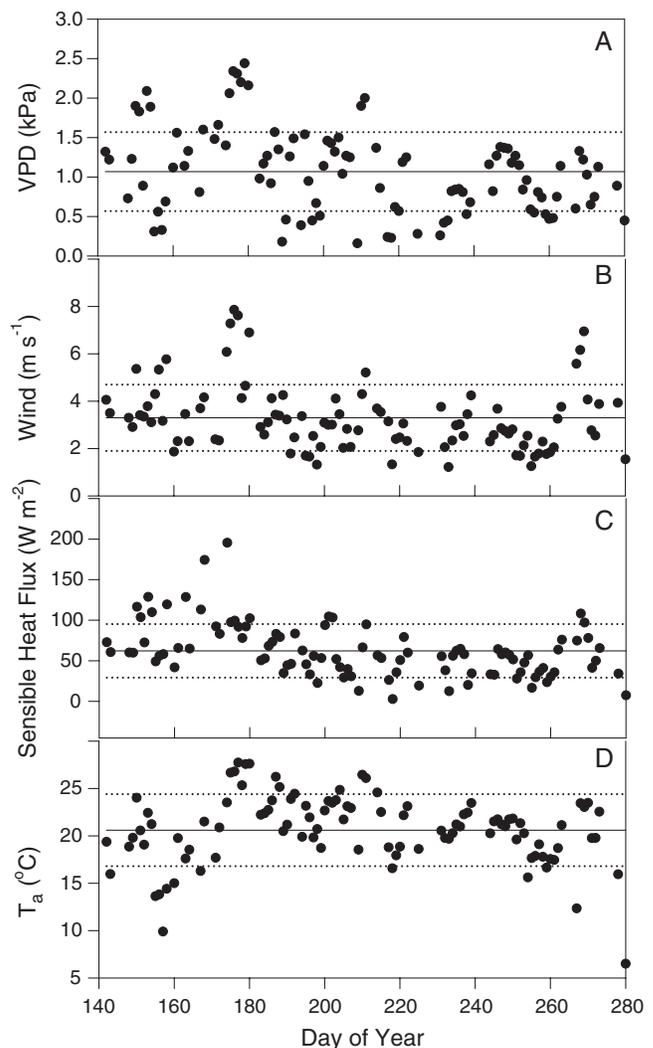


Fig. 1. The mean nightly micrometeorological parameters of (A) vapor pressure deficit (VPD), (B) wind speed, (C) sensible heat flux, and (D) 2-m air temperature (T_a) for 1998 during the alfalfa growing season as measured at the SE lysimeter. The solid line represents the seasonal mean, and the dotted lines ± 1 standard deviation.

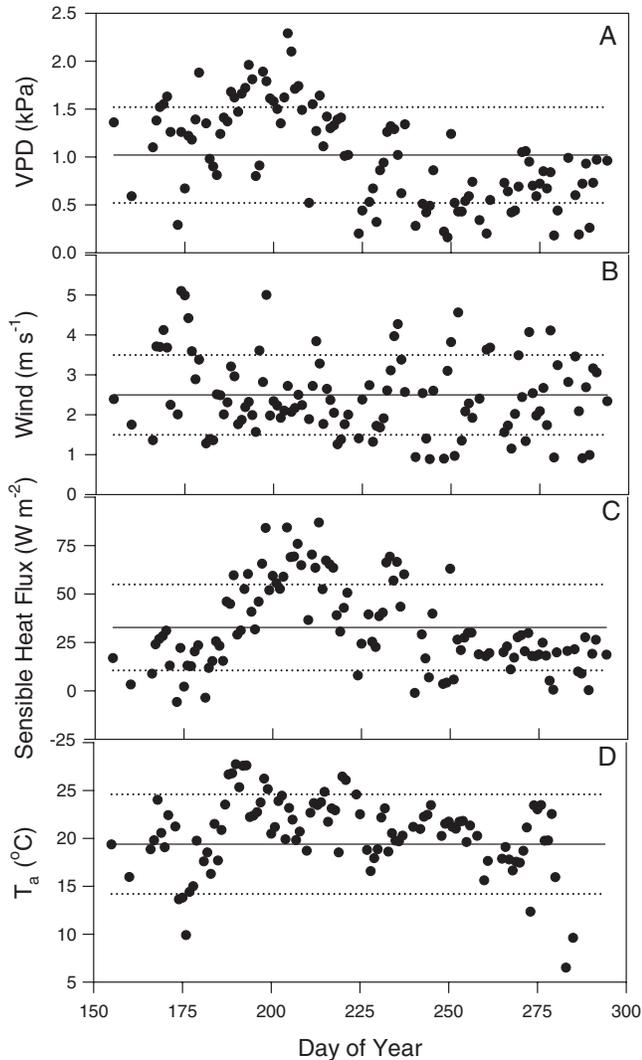


Fig. 2. The mean nightly micrometeorological parameters of (A) vapor pressure deficit (VPD), (B) wind speed, (C) sensible heat flux, and (D) 2-m air temperature (T_a) for 2001 during the cotton growing season as measured at the SE lysimeter. The solid line represents the seasonal mean, and the dotted lines ± 1 standard deviation.

Measured Nighttime Evapotranspiration

Alfalfa

The portion of the 1998 alfalfa cropping season evaluated was 142 d long, beginning on DOY 139 after the first cutting and ending on DOY 281 after the final cutting on DOY 280. For the NE lysimeter, 33 d were eliminated, of which three were due to missing data, 29 were due to gains of 0.05 mm or greater that included 12 with gains >1 mm, and one with negative ET_N . For the SE lysimeter, 39 d were eliminated, of which 14 were due to missing data, 24 were due to gains of 0.05 mm or greater of which 12 were gains >1 mm, and one with negative ET_N .

Summed ET_N measured by the NE lysimeter was 56.5 mm, which was 6.5% of the 864.5 mm of ET_{24} totaled for 109 d, resulting in an average rate of 0.52 (± 0.31) mm per night. Summed ET_N measured by the SE lysimeter was 60 mm, which was 7.2% of the

829.6 mm of ET_{24} totaled for 103 d, for an average rate of 0.58 (± 0.32) mm per night.

Losses of 1 mm or more occurred on 10 nights from the NE lysimeter and 12 nights from the SE lysimeter (Fig. 3). The largest single ET_N loss for alfalfa occurred during the night ending on DOY 174 when 1.94 mm had evaporated from the SE lysimeter, which was 12% of the ET_{24} of 15.73 mm. All of the 1 mm or more events but two on the NE lysimeter and three on the SE lysimeter were between cutting 1 (DOY 138) and cutting 2 (DOY 174) beginning on about DOY 150, during nights when wind speed averaged 4.1 (± 1.4) $m s^{-1}$, VPD averaged 1.4 (± 0.4) kPa, and mean H transfer to the canopy was 129 (± 29) $W m^{-2}$, all larger than the seasonal averages (Fig. 1).

Cotton

Cotton was planted on DOY 136, but early season missing data limited the analysis period to selected days from DOY 149 through harvest on DOY 295. For the NE lysimeter, 63 d were eliminated, of which 3 were due to missing data, 55 to gains >0.05 mm of which 10 were >1 mm, and 5 with negative ET_N . For the SE lysimeter, 36 d were eliminated, of which 3 were due to missing data, 28 to gains >0.05 mm with 11 of these >1 mm, and 5 with negative ET_N . Only about 50 d were selected for each of the dryland cotton lysimeters, with gains >0.05 mm eliminating 85 nights from the NW lysimeter and 67 nights from the SW lysimeter with only about 10 of these with gains being >1 mm for each lysimeter.

Accumulated ET_N contributed 26 mm, or 6%, to the ET_{24} of 425 mm for the 83 d selected for the deficit-irrigated (NE) lysimeter, with an average rate of 0.31 (± 0.24) mm per night. Cumulative ET_N over 110 d from the fully irrigated (SE) lysimeter was 45.4 mm, or 7% of 620 mm of ET_{24} , making an average rate of 0.41 (± 0.34) mm per night. Losses exceeding 1 mm occurred six times from the SE lysimeter (Fig. 4). The largest single ET_N event for cotton was 1.24 mm by dawn of DOY 198 from the SE lysimeter, which was 11% of the ET_{24} of

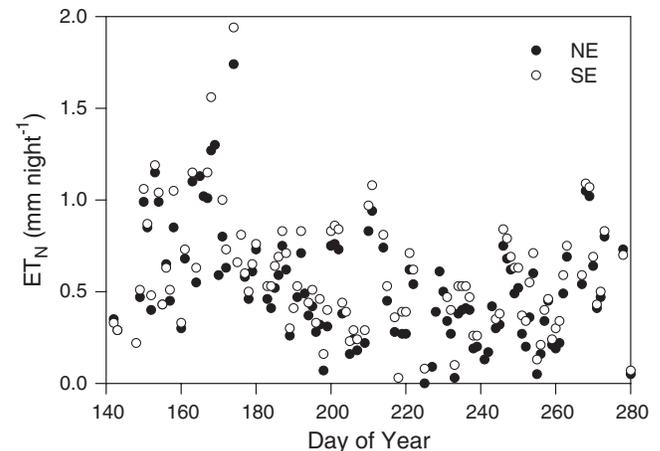


Fig. 3. Measured nighttime evapotranspiration (ET_N) of alfalfa measured at the NE and SE lysimeters which received the same irrigation amounts.

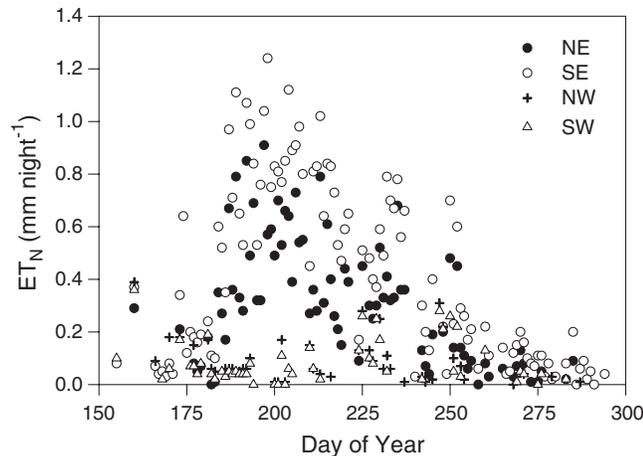


Fig. 4. The measured nighttime evapotranspiration (ET_N) of the NE (deficit-irrigated), SE (fully irrigated), NW (dryland), and SW (dryland) cotton crops.

11.53 mm. This was during a period from DOY 187 to 217 when the average ET_N of $0.84 (\pm 0.2)$ mm was more than double the seasonal value, and the average T_a of $24 (\pm 1.5)$ °C and VPD of $1.5 (\pm 0.4)$ kPa were consistently larger than seasonal means (Fig. 2). Maximum LAI did not occur until about DOY 230, and was about 4 on the SE, 1.7 on the NE, and 0.5 on the west lysimeters. Dryland LAI was limited due to drought.

The ET_N of the dryland cotton crops (NW, SW) was minimal, with an accumulated ET_N for each lysimeter of about 4.4 mm, or 3% of about 160 mm of ET_{24} . Seasonal average rate was $0.09 (\pm 0.08)$ mm per night from each lysimeter. The largest single ET_N of about 0.4 mm on DOY 160 followed a 20 mm rainfall on DOY 159. Other ET_N events exceeding 0.25 mm were also associated with rainfall.

McNaughton–Jarvis Model Simulations

The McNaughton–Jarvis model indicated that only about 0.2 mm of a total of 132.8 mm of alfalfa ET_N simulated for both lysimeters and 1.4 mm of 80.5 mm of irrigated cotton ET_N simulated for both lysimeters was due to ET_{eq} . The contribution by ET_{eq} to simulated ET_N of dryland cotton was 0.5 mm of a cumulative 12.9 mm. For irrigated cotton, ET_{eq} contributed from 2 to 10% to simulated ET_N during the period of largest measured ET_N rates from DOY 187 to 197 before maximum leaf area. The nighttime ET_{eq} resulted from ET_{eq} daytime losses continuing for a period after sunset due to large soil heat fluxes ($90\text{--}100 \text{ W m}^{-2}$) toward the soil surface. Most nights with the largest ET_N rates for cotton before DOY 200 included contributions from ET_{eq} . The very small amount of simulated ET_{eq} of alfalfa was not associated with nights with the largest ET_N .

The ET_{imp} term represents the effects of bulk atmospheric conditions, including the independently measured VPD. Increases in ET_N were related to increases in VPD for the irrigated crops (Fig. 5). For alfalfa over the entire season, changes in VPD explained 31% of variation in ET_N (Fig. 5A). During the period when

irrigation was applied from DOY 183 through DOY 232, changes in VPD explained 30% of the variation in ET_N for deficit-irrigated cotton on the NE lysimeter (Fig. 5B), which increased to 59% when the cotton was fully irrigated on the SE (Fig. 5C). For the same period as the irrigated cotton, the trend in ET_N of the dryland cotton was to decline with increasing VPD (Fig. 5D). For the analysis shown in Fig. 5D, all nights where rainfall had occurred within 3 d were eliminated to remove potential effects of surface soil water content on VPD, yet the trend remained. One possibility for the trend is some change in factors that reduce nighttime plant water loss that are related to VPD (Snyder et al., 2003).

The decoupling factor Ω generally remained below 0.5 for both crops (Fig. 6 and 7), with Ω peaking between cuttings during irrigation and leaf area development for alfalfa (Fig. 6) and at the beginning of irrigation for fully irrigated cotton before maximum LAI (Fig. 7). Changes in the size of Ω are related to the ratio r_s/r_a . Given the limited range in r_a , which averaged $29.6 (\pm 12.2) \text{ s m}^{-1}$

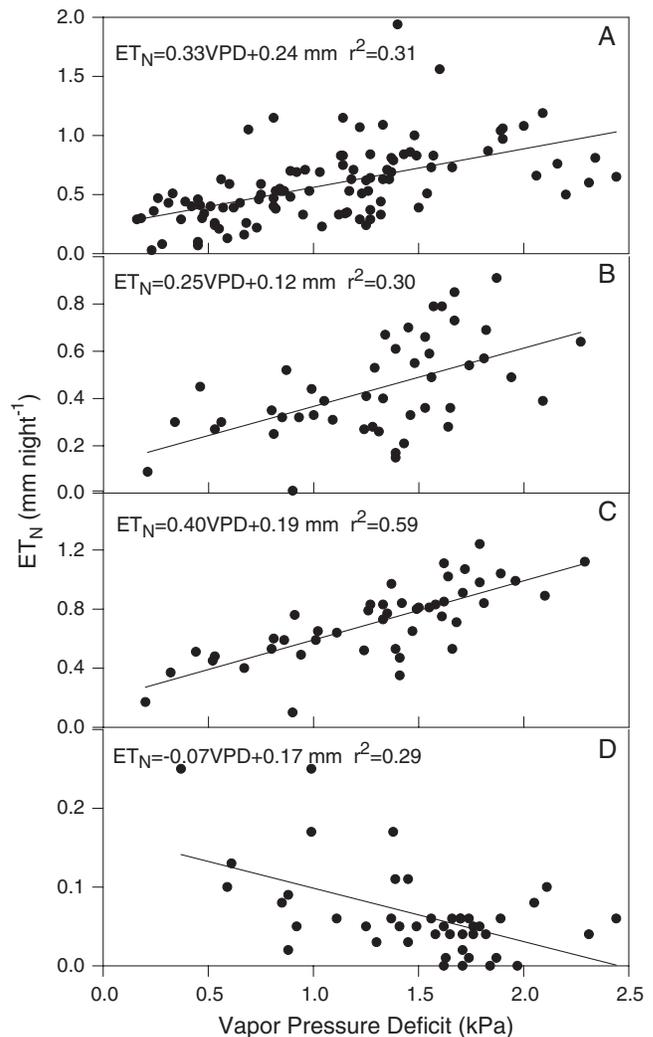


Fig. 5. The relationship of vapor pressure deficit (VPD) and nighttime evapotranspiration (ET_N) for (A) alfalfa, (B) deficit-irrigated cotton on the NE lysimeter, (C) fully irrigated cotton on the SE lysimeter, and (D) dryland cotton on the west lysimeters.

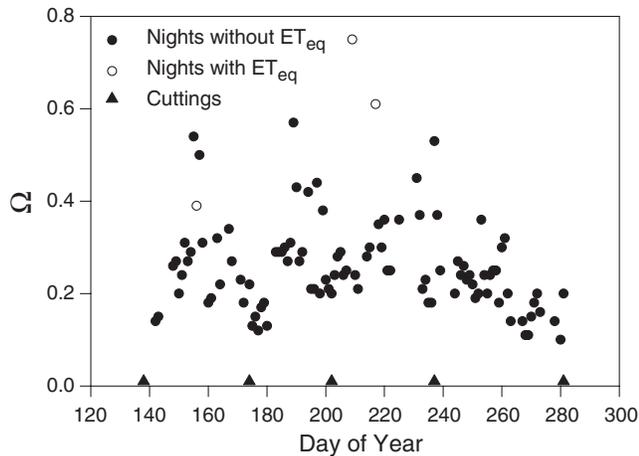


Fig. 6. The decoupling factor Ω calculated for the alfalfa on the SE lysimeter, indicating Ω values for nights with and without equilibrium evapotranspiration (ET_{eq}) calculated using the McNaughton–Jarvis model.

for alfalfa and $26.9 (\pm 18.6) \text{ s m}^{-1}$ for fully irrigated cotton, the increases in Ω reflected the decreases in r_s resulting from increased ET_N due primarily to irrigation and possibly to leaf area development. For irrigated alfalfa, r_s ranged seasonally from 55 to 1420 s m^{-1} , and for fully irrigated cotton from about 170 to 3250 s m^{-1} . The largest values are over four times the size of the maximum stomatal resistance (inverse of stomatal conductance) of 330 s m^{-1} for alfalfa as reported by Wright et al. (1986), and three times the size of 1100 s m^{-1} for cotton leaf resistance as reported by Quisenberry et al. (1985). In this case, the r_s includes both crop and soil resistances.

Increased Ω also suggests contributions to ET_N by ET_{eq} . As mentioned earlier, virtually none of the ET_N of alfalfa was supplied by ET_{eq} , and the open circles on Fig. 6 show the three nights on the SE lysimeter that included small contributions by ET_{eq} . Contributions by ET_{eq} were associated with larger Ω (Fig. 7, open circles)

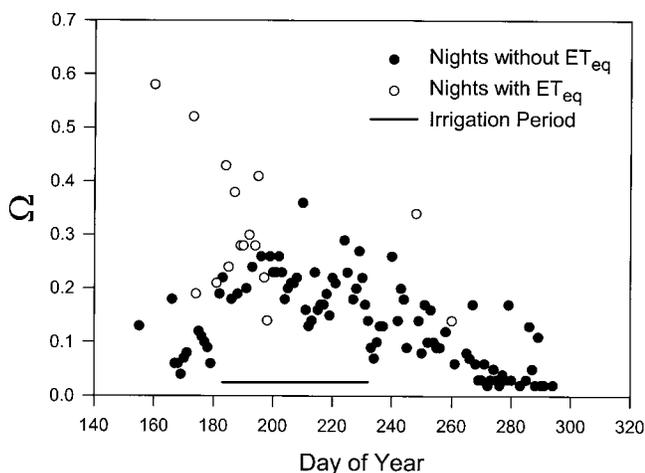


Fig. 7. The decoupling factor Ω calculated for the fully irrigated cotton on the SE lysimeter, indicating Ω values for nights with and without equilibrium evapotranspiration (ET_{eq}) calculated using the McNaughton–Jarvis model.

during the irrigation of the fully irrigated cotton, but Ω declined to near zero as r_s increased by season's end.

DISCUSSION

An additional energy source other than that supplied by $(R_n + G)$ was necessary for ET_N to have occurred. In water-deficient areas such as the western USA, advected sensible heat may be a major source of energy used in ET (Abdel-Aziz et al., 1964; Rosenberg, 1969; Hanks et al., 1971; Brakke et al., 1978; Todd et al., 2000). Advection is the transport of an atmospheric property (e.g., vapor and heat), solely by the mass motion of the atmosphere expressed in terms of wind and the atmospheric property and its gradient (Rosenberg et al., 1983). Irrigated areas represent “oases” into which wind transports drier, hotter air from surrounding water-deficient landscapes (Tanner, 1957).

During all but two nights for alfalfa and all nights for irrigated and dryland cotton, crop canopy temperature was cooler than air temperature by an average of $3.4 (\pm 1.6) ^\circ\text{C}$ for alfalfa, $1.8 (\pm 0.7) ^\circ\text{C}$ for deficit-irrigated cotton, $2.3 (\pm 0.7) ^\circ\text{C}$ for fully irrigated cotton, and $2.1 (\pm 0.6) ^\circ\text{C}$ for dryland cotton. Residually calculated H showed flux transfer to the canopy at an average of $59.8 (\pm 31.8) \text{ W m}^{-2}$ for alfalfa, $23.2 (\pm 13.2) \text{ W m}^{-2}$ for deficit-irrigated cotton, $33.8 (\pm 22.8) \text{ W m}^{-2}$ for fully irrigated cotton, and $18.0 (\pm 9.6) \text{ W m}^{-2}$ for dryland cotton.

An examination of the energy balance and climate of the largest ET_N event for each crop helped determine some of the processes involved. During the ET_N event of 1.94 mm for alfalfa, the energy balance and climate was fairly constant throughout the night. The crop had received an irrigation 4 d previously, and LAI was approaching 2.7. The sum of $(R_n + G)$ was always negative at an average rate of $-49.0 (\pm 6.0) \text{ W m}^{-2}$. Latent heat flux declined slowly from -163 W m^{-2} after sunset to -95 W m^{-2} by sunrise, maintained by a positive H flux of 215 to 151 W m^{-2} . Vapor pressure deficit also declined slowly from 1.5 to 1.0 kPa with a mean of $1.4 (\pm 0.2) \text{ kPa}$, with a fairly stable wind speed averaging $6.1 (\pm 0.7) \text{ m s}^{-1}$. The ET_N increased with VPD ($ET_N = 0.07\text{VPD} + 0.01 \text{ mm}$, $r^2 = 0.66$), but was only loosely related to wind ($ET_N = 0.01\text{wind} + 0.05 \text{ mm}$, $r^2 = 0.23$). The persistent climatic conditions resulted in the extremely large ET_N loss.

For fully irrigated cotton, flux exchanges were fairly high until about midnight for the ET_N event of 1.24 mm. Estimated LAI was 1.5 and the crop had received an irrigation 2 d previously. Before midnight, $(R_n + G)$ was initially positive averaging $24.4 (\pm 20.2) \text{ W m}^{-2}$; λE averaged $-133.3 (\pm 19.6) \text{ W m}^{-2}$, requiring H to supply $108.9 (\pm 13.1) \text{ W m}^{-2}$ of the energy used in λE . After midnight, $(R_n + G)$ dropped to near zero, averaging $4.9 (\pm 5.9) \text{ W m}^{-2}$; λE also dropped to an average of $-74.6 (\pm 14.7) \text{ W m}^{-2}$, with H providing $69.7 (\pm 16.2) \text{ W m}^{-2}$ to maintain λE . The ET_N also increased with VPD ($ET_N = 0.03\text{VPD} + 0.02 \text{ mm}$, $r^2 = 0.61$), but was not related to wind speed possibly because of its variability (average of $5.0 \pm 1.1 \text{ m s}^{-1}$). The moderation of climatic conditions by midnight had limited ET_N losses.

CONCLUSIONS

Contributions by ET_N to ET_{24} ranged from an average of 3% for a dryland cotton crop to 7.2% for irrigated alfalfa over a season. In the largest events, ET_N of alfalfa was as much as 12% of ET_{24} with single nighttime losses approaching 2 mm which was the result of persistently large VPD, wind speed, and sensible heat gain. Losses of 1 mm or more occurred on 12 out of 109 nights for alfalfa on one lysimeter, and 6 of 110 nights for fully irrigated cotton. Simulations by the McNaughton–Jarvis model indicated that virtually all ET_N was due to imposed ET, which is a function of VPD. Changes in VPD explained 31% of the variation in ET_N over the season for alfalfa and, for the period of irrigation applications, 30% of the variation in ET_N for deficit-irrigated cotton and 59% for fully irrigated cotton. In the largest ET_N events for alfalfa, the association increased to 66%. With limited ($R_n + G$), energy to maintain ET_N was provided by H flux to the canopy in an environment where nighttime air temperatures averaged at least 2°C higher than crop canopy temperatures in the irrigated crops. The persistence of large VPD, wind speed, and sensible heat flux gains throughout the night led to the largest ET_N losses. The irrigated crop environment provided a ready vapor source for nighttime water loss, especially in the semiarid environment of the southern High Plains.

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