Soil and Canopy Energy Balances of a Row Crop at Partial Cover

J. M. Ham,* J. L. Heilman, and R. J. Lascano

ABSTRACT

When crops are grown in a row configuration, heat and mass transfer within the soil-canopy system influence the energy and water balance of the crop. Field experiments were conducted near Lubbock, TX, to examine the energy balance of the soil and canopy separately, in cotton (*Gossypium hirsutum* L.) under a variety of aerial and soil moisture conditions. Bowen ratio techniques were used to obtain the field energy balance, including total latent heat flux (LE). Latent heat flux from the crop canopy (LE_c) was determined from sap flow measurements of transpiration. Latent heat flux from the soil (LE_s) was computed as the difference between LE and LE_c. These measurements were coupled with radiation measurements at the soil surface to partition the energy balance into soil and canopy components every 12 min throughout the day. Results indicate that detailed measurements of energy exchange within the soil-canopy-atmosphere system can be obtained without making simplifying assumptions about energy transfer. Daily energy balances were strongly influenced by sensible heat transport, and the radiation balance alone did not account for the magnitude or diurnal pattern of LE_s and LE_c. When the soil surface was dry, the canopy simultaneously absorbed sensible heat originating from the soil and above-canopy air, accounting for more than 21 and 12% of LE_c, respectively. After an irrigation, LE_s accounted for more than 50% of LE even when the leaf area index was greater than two, and 12 to 21% of daily LE_s occurred at night. The soil surface absorbed sensible heat from the canopy after irrigation, which increased LE_s while decreasing LE_c. Analysis indicates that within-canopy radiative and convective energy transfer must be considered to accurately characterize LE_s and LE_c in row crops during periods of partial cover.

LATENT HEAT FLUXES (LE) from the crop canopy (LE_c) and the soil surface (LE_s) are complex processes governed by energy exchange between the soil, canopy, and the aerial environment. When crops are grown in a row configuration, the crop canopy does not completely cover the soil throughout a large portion of the growing season, and the exposed soil represents an important source and/or sink of energy. Thus, investigating evaporation and energy exchange in the row crop system requires that the energy balance of the soil and canopy be examined separately (Tanner and Jury, 1976; Shuttleworth and Wallace, 1985; Lascano et al., 1987). Unfortunately, detailed energy balance measurements of the soil and canopy have been unattainable due to limitations in measurement techniques.

While the knowledge of energy transfer in partial canopies is incomplete, past research suggests that bidirectional radiative and convective energy exchange can occur between the soil and canopy surface, and that these processes affect the dynamics of LE_c and LE_s. Energy exchange in full canopies has been examined by making within-canopy flux profile measurements of heat and water vapor and using a Bowen ratio approach to calculate the energy balance of vertical layers within the canopy (Begg et al., 1964; Brown and Covey, 1966). Results from Begg et al. (1964) indicate that sensible heat from the soil and lower leaves could increase LE_c near the top of the canopy. Brown and Covey (1966) showed that regions of high temperature could develop within a corn (*Zea mays* L.) canopy resulting in sensible heat transport to the soil surface and the upper canopy, simultaneously. Hanks et al. (1971) also used within-canopy flux profile measurements to investigate advection in wide row sorghum [*Sorghum bicolor* (L.) Moench]. They found soil temperatures often exceeded canopy temperatures by 20 °C, and that 21% of LE_c was the result of the sensible heat flux absorbed from the soil surface. Kanemasu and Arkin (1974) and Chin Choy and Kanemasu (1974) examined the energy balance of wide and narrow row sorghum. They partitioned the energy balance of the soil and canopy by assuming that LE_s was a given fraction of LE, which was measured with a lysimeter. Measurements indicated that the canopy absorbed sensible heat from the soil surface during dry conditions, increasing LE_c in the wide row case. Walker (1984) measured evaporation from a wet soil under a row crop and found that LE_s often exceeded the available radiative energy, suggesting sensible heat transport from the crop to the soil was influencing LE_s. Radiation balance studies of row crops indicate that radiative exchange between the soil and canopy can also influence LE_c and LE_s (Tanner et al., 1960; Fuchs, 1972).

Previous research on energy dynamics of soil-canopy system has documented a variety of transfer processes. However, inadequate measurement techniques have limited research to a specific set of conditions or the examination of a singular process. Horizontal gradients and high turbulence within row crops makes the use of traditional within-canopy flux profile measurements questionable during partial cover (Luxmoore et al., 1973; Legg and Monteith, 1975), and has forced researchers to make assumptions about soil or canopy conditions. Additionally, soil and canopy energy balance measurements are needed on a time scale comparable to the transfer processes themselves (Walker, 1984), but are currently unavailable. In a summary of evapotranspiration research, Stanhill (1973) suggested that the three dimensional nature of the row crop system was so complex that partitioning the energy balance into soil and canopy components was impossible using traditional measurement techniques without making simplifying assumptions.

Sakuratani (1987) made an important advancement by documenting the separate diurnal patterns of LE_c and LE_s without making simplifying assumptions or

---

J.M. Ham, Dep. of Agronomy, Throckmorton Hall, Kansas State Univ., Manhattan, KS 66506; J.L. Heilman, Dep. of Soil and Crop Sci., Texas A&M Univ., College Station, TX 77843; and R.J. Lascano, Texas Agric. Exp. Stn., Lubbock, TX 79401. Technical article TA25416 from the Texas Agric. Exp. Stn., College Station, TX 77843. Received 19 Feb. 1990. *Corresponding author.

Published in Agron. J. 83:744–753 (1991).

Abbreviations: LE, latent heat flux; Rn, net radiation; *H*, sensible heat flux density; *G*, soil heat flux density; CD, calendar day; and LAI, leaf area index.

using within-canopy flux profile measurements. He partitioned LE from a well-watered soybean [*Glycine max* (L.) Merr.] field by measuring $\mathrm{LE_c}$ with the heat balance sap flow technique (Sakuratani, 1981) and LE with the Bowen Ratio method (Tanner, 1960). Latent heat flux from the soil was then determined as the difference between LE and $\mathrm{LE_c}$. Diurnal measurements of $\mathrm{LE_c}$ and $\mathrm{LE_s}$ were highly correlated with net radiation above the canopy. Sakuratani (1987) showed that $\mathrm{LE_c}$ was more sensitive to air temperature than was $\mathrm{LE_s}$, and that $\mathrm{LE_s}$ could account for almost half of LE under certain conditions even when a well-developed canopy was present. However, Sakuratani did not partition the soil and canopy energy balance, or examine how soil conditions affect the crop microclimate.

The objective of our study was to evaluate, in detail, the energy balance of the soil and canopy separately during partial cover. Earlier studies were conducted to validate and perfect Sakuratani's (1987) approach for partitioning LE (Ham et al., 1990). Here, we show how $\mathrm{LE_c}$ and $\mathrm{LE_s}$ can be coupled with additional measurements to obtain the soil and canopy energy balances without making limiting assumptions. Specifically, energy balances were determined without using flux profile measurements within the canopy, nor was one flux assumed negligible or a constant proportion of another flux. Detailed measurements under a range of aerial conditions and surface soil water conditions were recorded to examine how radiative and convective energy transfer between the soil, canopy, and atmosphere affect $\mathrm{LE_s}$ and $\mathrm{LE_c}$. A better understanding of these transfer processes could lead to improved row crop management, and assist in the development and validation of predictive models that simulate the energy balance of the soil and canopy separately.

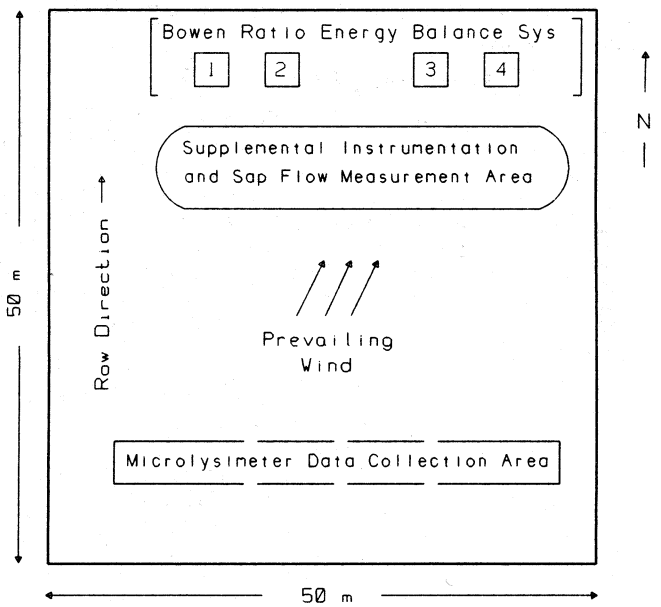

Fig. 1. Diagram showing the position of the Bowen ratio measurement systems and supplemental instrumentation within the field plot, and the location of the sap flow and microlysimeter data collection areas.

MATERIALS AND METHODS

Experimental Site

Studies were conducted during the 1989 growing season on a 50 by 50-m plot at the Texas Agric. Exp. Stn. near Lubbock, TX (33.6° N, 101.8° W, 1000 m above msl). Cotton (var. Paymaster 404) was planted on 16 May 1989 at a density of 18 plants m^{-2}. The crop was established on a flat soil surface within a 1 m row spacing and north-south row orientation. No furrows or raised beds were present in the field. The soil at the site was classified in the Olton series (fine, mixed, thermic Aridic Paleustoll) with a sandy clay loam surface texture. The cotton was flood irrigated throughout the growing season, and was bordered by other irrigated cotton fields.

Field Energy Balance Measurements

The surface energy balance of the field (soil and canopy) can be represented as,

$$\mathrm{Rn} + \mathrm{LE} + H + G = 0 \qquad [1]$$

where Rn is net radiation, LE is latent heat flux density, H is sensible heat flux density, and G is soil heat flux density, all with units of W m^{-2}. In Eq. [1], fluxes toward the surface are considered positive, while fluxes away from the surface are negative. The field energy balance was determined with the Bowen ratio method (Tanner, 1960) utilizing four measurement systems designed by Gay and Greenberg (1985). Bowen ratio masts were positioned 8 m from the north edge of the plot to maximize fetch when prevailing southerly winds were present (Fig. 1). Each Bowen ratio system consisted of two exchanging wet and dry bulb psychrometers, a net radiometer, and three soil heat flux plates. The exchange distance for each pair of psychrometers was 1 m. The lowest psychrometer on Systems 1 and 3 was positioned 0.2 m above the crop canopy, while the lowest psychrometer on Systems 2 and 4 was 0.45 m above the crop. Wet and dry bulb sensors were repeatedly sampled over 3-min periods, followed by a 3-min interval in which the psychrometers exchanged position and equilibrated with the environment. This procedure eliminated the effect of instrument bias and allowed the determination of the Bowen ratio every 12 min. All psychrometric calculations were adjusted for barometric pressure based on elevation. Minimum fetch:height ratios within the plot were 21:1, an adequate value for Bowen ratio measurements (Heilman et al., 1989). However, the field was bordered to the south by other irrigated cotton fields which provided an effective fetch:height ratio in excess of 300:1 when winds were from the prevailing, southerly direction. Only days with consistent southerly winds were used for analysis. Net radiometers (Model Q3, Radiation and Energy Balance Systems, Inc., Seattle, WA) were mounted 2 m above the soil surface with sensors on Systems 1 and 3 positioned directly over the plant rows, and sensors on Systems 2 and 4 positioned over the soil, between plant rows. Soil heat flux was determined using the combination approach (Kimball and Jackson, 1979). Flux plates (Model HFT-1, Radiation and Energy Balance Systems Inc.) were positioned 0.05 m below the soil surface, and the change in heat storage above the plates was determined from measurements of soil temperature in the 0- to 0.05-m layer, and an estimate of the heat capacity (DeVries, 1963). The three heat flux plates and corresponding temperature probes associated with each system were spaced 0.25 m apart in an east-west line below the canopy to measure the spatial average of soil heat flux. The energy balance at each Bowen ratio mast was determined independently from measurements of the Bowen ratio, Rn, and G at the mast location. Energy balance terms from each mast were then averaged to compute the field energy balance.

Partitioning Latent Heat Flux

Latent heat flux density from the crop canopy ($\mathrm{LE_c}$) was determined from sap flow measurements of transpiration. The heat balance technique (Sakuratani, 1981) was used to continuously monitor sap flow in eight to 10 plants upwind of the Bowen ratio sensors (Fig. 1). Sap flow measurements were made for the duration of the study with gauges being exchanged every 3 to 4 d because of plant growth. Plants used for sap flow measurement were typically positioned in an irregular pattern within the measurement area. Prior to Calendar Day (CD) 215, all sap flow measurements were obtained with commercial gauges (Model SGA10, Dynamax Inc., Houston, TX). After CD 215, sap flow measurements were made with gauges built in our laboratory. The switch from commercial to laboratory gauges was primarily due to an increase in plant size. Laboratory gauges were constructed according to the design described by Baker and Van Bavel (1987) using the wiring configuration of Steinberg and Van Bavel (1990). Approximately 0.15 W of power was applied to the stem using a thin resistance heater 12 mm wide in accordance to the recommendations of Ham and Heilman (1990). Axial temperature gradients were measured with two pairs of thermocouples positioned on the stem surface, above and below the heater. Radial heat flow was measured with a 10-junction thermopile. The entire gauge was encapsulated in foam insulation 13 mm thick and 60 mm in length. Commercial and laboratory gauges were sampled every 15 s using a datalogger-multiplexer unit (Model 21X/AM32, Campbell Scientific Inc., Logan, UT), and 12-min averages computed for storage. The heat balance method is unintrusive, and has been shown to measure transpiration in small herbaceous plants, including cotton, to within 5 to 10% (Sakuratani, 1981; Baker and Van Bavel, 1987; Ham and Heilman, 1990).

Sap flow measurements from individual plants were converted to latent heat flux per unit land area by normalizing the data on a leaf area basis (Ham et al., 1990). Mean $\mathrm{LE_c}$, in W m^{-2}, was determined from sap flow measurements in n plants as

$$\mathrm{LE_c} = L\cdot\Sigma(f_i/X_i)/n\cdot\mathrm{LAI} \qquad \{i=1,2,\ldots,n\} \qquad [2]$$

where f_i is measured stem flow, kg s^{-1}, X_i is the leaf area, m^2, of plant i, LAI is the leaf area index of the plot, m^2 m^{-2}, and L is the latent heat of vaporization of water, J kg^{-1}. The latent heat flux density from the soil surface, $\mathrm{LE_s}$, in W m^{-2}, was then calculated as

$$\mathrm{LE_s} = \mathrm{LE} - \mathrm{LE_c} \qquad [3]$$

where LE represents total latent heat flux, W m^{-2}, from the field surface as measured with the Bowen ratio systems. Ham et al. (1990) tested the above procedure for partitioning LE in cotton by comparing results from Eq. [3] to direct microlysimeter measurements of $\mathrm{LE_s}$, and found that calculated and measured values of $\mathrm{LE_s}$ agreed to within 11%.

Day and night measurements of $\mathrm{LE_s}$ were also obtained with soil microlysimeters following the procedures of Lascano and Van Bavel (1986). Microlysimeters, 0.13 m long and 0.074 m in diameter, were installed midway between the rows, approximately 5 to 15 m from the south edge of the plot (Fig. 1). Walker (1984), Lascano et al. (1987), and validation measurements at our own site indicated that a midrow microlysimeter measurement provided a spatial average of daily soil water evaporation. Twenty to 30 microlysimeters were installed before dawn each day, and then removed, weighed, and reinstalled at sunset. The following morning the microlysimeters were weighed a second time to determine night $\mathrm{LE_s}$, and then a new set of instruments were installed to start the next measurement sequence.

Soil and Canopy Energy Balance Determination

The energy balance that accounts for all sources and sinks of energy at the soil surface can be expressed as

$$\mathrm{Rn_s} + \mathrm{LE_s} + H_s + G = 0 \qquad [4]$$

where $\mathrm{Rn_s}$ is net radiation at the soil, $\mathrm{LE_s}$ is soil latent heat flux density, H_s is sensible heat exchange between the soil and air, and G is soil heat flux density, all with units of W m^{-2}. Soil heat flux was measured in conjunction with the Bowen ratio systems while $\mathrm{LE_s}$ was computed with Eq. [3]. Net radiation at the soil surface was calculated from measurements of the shortwave and thermal components of radiation balance. This required measurements of soil, canopy, and air temperatures, and their corresponding emissivities. Measurements of soil irradiance and albedo were also needed to compute absorbed shortwave irradiance.

Soil and canopy temperatures were measured with an optically chopped infrared transducer (IRT) with a 4° field of view (Model 4000A, Everest Interscience, Fullerton, CA). Three IRT units at a height of 2 m above the soil and a view angle of 30° from horizontal were pointed at the soil surface between plant rows. A single IRT at a height of 1 m above the canopy and a view angle 30° from horizontal was aimed at the top of the crop canopy. Soil and canopy temperatures were corrected for emissivity and reflected longwave irradiance (Fuchs and Tanner, 1966). Soil emissivity was measured under wet and dry conditions using a procedure similar to that described by Fuchs and Tanner (1966), and ranged between 0.93 and 0.91. Canopy emissivity was assumed to be 0.97. Shortwave irradiance at the soil surface was measured with two Eppley pyranometers (Model 8-48, Eppley Laboratory, Newport, RI) which traversed below the canopy at separate locations. Pyranometers traveled continuously at a speed of 0.015 m s^{-1} atop a 2-m-long rail normal to the plant rows. Simulation studies indicated this system would provide an integrated measure of soil irradiance beneath a row crop canopy (Ham, 1990). Air temperature and water vapor density were determined with a wet and dry bulb psychrometer positioned 2 m above the soil surface. Total longwave sky irradiance was calculated from air temperature and sky emissivity, determined from vapor density using the equation of Brutsaert (1975). Temperature and radiation sensors were sampled every 10 s with a datalogger (Model CR7X, Campbell Sci. Inc.), and 12-min averages computed for storage. All supplemental instrumentation was positioned upwind of the Bowen ratio masts near the center of the plot (Fig. 1).

Net radiation at the soil surface, $\mathrm{Rn_s}$, in W m^{-2}, was computed as

$$\mathrm{Rn_s} = (1-\alpha_s)\mathrm{Rs_s} + \epsilon_s(V_{\mathrm{sky}}\epsilon_{\mathrm{sky}}\sigma T_a^4 + (1-V_{\mathrm{sky}})\epsilon_c\sigma T_c^4) - \epsilon_s\sigma T_s^4 \qquad [5]$$

where $\mathrm{Rs_s}$ is shortwave soil irradiance, W m^{-2}, α_s is soil albedo, σ is the Stephan-Boltzmann constant, and ϵ_s, ϵ_c, and ϵ_{sky} are the emissivity for the soil, canopy, and sky, respectively. Temperature, kelvin, of the air, soil, and canopy are represented by T_a, T_s, and T_c, respectively. Equation [5] assumes that canopy and soil surface temperature can be described with single parameters, and neglects the effect of spatial temperature variations on $\mathrm{Rn_s}$. The variable V_{sky} is the hemispherical view factor of the sky from the soil surface and represents the fraction of long-wave sky irradiance incident on the soil. Alternatively, $(1-V_{\mathrm{sky}})$ is the view factor of the canopy from the soil surface. A rectangular, opaque, hedgerow model was developed to calculate V_{sky} based on the size of the canopy. An analytical solution yielded the equation,

$$V_{\mathrm{sky}} = \{[(L_r - L_c)^2 + Z_c^2]^{1/2} - Z_c\}/L_r \qquad [6]$$

Table 1. Measured daily (24-h) values of total global irradiance, Rs; maximum and minimum air, T_{air}, and dewpoint, T_{dew}, temperatures; and average wind speed, u. Also included is volumetric soil water content, θ, from 0 to 4 cm, and rain plus irrigation, $R+I$.

Calendar day	Rs	T_{air} max	T_{air} min	T_{dew} max	T_{dew} min	u	θ	$R+I$
	MJ m^{-2}	°C	°C	°C	°C	m s^{-1}	m^3 m^{-3}	mm
212	26.8	33.6	18.8	14.4	13.8	2.9	0.23	
213	26.0	29.9	19.3	19.4	15.5	2.1		
214	16.2	31.1	19.7	19.3	17.5	2.4	0.20	10
215	26.9	31.1	19.3	21.4	16.4	4.4	0.23	
216	27.0	32.0	20.7	19.9	14.5	3.4		
217	25.0	33.4	21.3	18.9	15.8	2.2	0.19	15
218	24.4	31.1	17.8	21.8	15.8	2.3		43
219	7.7	22.0	16.1	17.3	15.9	3.5		7
220	25.9	24.7	13.7	15.9	12.0	1.1	0.32	
221	26.3	26.1	12.8	15.0	10.4	2.4	0.29	
222	24.1	28.5	16.3	17.1	10.1	3.3	0.29	
223	25.5	26.5	17.7	17.8	13.8	2.8		
224	16.1	26.5	18.4	18.4	14.5	2.3	0.21	
225	13.6	25.6	17.1	19.1	14.6	1.9		11
226	24.7	25.8	17.3	19.6	16.2	1.8		
227	25.1	29.0	16.1	18.5	15.5	1.2	0.27	

where L_r is the row width, meters, L_c is the canopy width, meters, and Z_c is canopy height, meters (Ham, 1990). Comparisons of Eq. [6] to the LAI-based view factor equation of Lascano et al. (1987) showed both methods produced similar results over the growing season. The complete energy balance of the soil surface was obtained by rearranging Eq. [4] to solve for sensible heat flux from the soil, H_s, as

$$H_s = -(\mathrm{Rn}_s + \mathrm{LE}_s + G) . \tag{7}$$

The surface energy balance of the crop canopy can be expressed as

$$\mathrm{Rn}_c + \mathrm{LE}_c + H_c = 0 \tag{8}$$

where Rn_c is the net radiation of the canopy, LE_c is canopy latent heat flux, and H_c is sensible heat exchange between the canopy and the air, all in W m^{-2}. Applying the principle of continuity and the definition of net radiation, it can be shown that the Rn_c is the difference between net radiation above and below the canopy,

$$\mathrm{Rn}_c = \mathrm{Rn} - \mathrm{Rn}_s \tag{9}$$

where Rn was measured and Rn_s was calculated from Eq. [5]. Several researchers have used a similar approach to explore soil-canopy radiation relationships (Fuchs, 1972; Kanemasu and Arkin, 1974). The sensible heat flux density from the canopy, H_c, can then be computed as a residual by rearranging Eq. [8],

$$H_c = -(\mathrm{Rn}_c + \mathrm{LE}_c) . \tag{10}$$

The key to separating the soil and canopy energy balances hinged on measurements of LE_c and Rn_s, which allowed the determination of LE_s and Rn_c, respectively (Eq. [3] and [9]). This permitted residual calculations of H_s and H_c (Eq. [7] and [10]), and circumvented the use of flux profile theory within the canopy.

Data acquisition equipment was synchronized to provide averages of all field, soil, and canopy energy balance components at 12-min intervals throughout the day. Daytime energy balance values were determined by integrating the 12-min averages from sunrise to sunset.

Additional Measurements

Leaf area index was measured every 5 to 7 d throughout the growing season by sampling 10 random plants and multiplying the measured leaf area for each plant by the plant density at the harvest location. Estimates of LAI for periods between measurement days were obtained by fitting a curve to the measured values (Fig. 2). Other measurements such as canopy height and width were made on a weekly basis. Soil water content at the surface was determined volumetrically every 1 to 2 d from samples of the 0- to 4-cm layer. Subsoil water content was measured on a weekly basis using the neutron method. Within-canopy air temperature was measured with aspirated thermocouples positioned midway between the plant rows, 0.2 and 0.6 m above the soil surface. Additional environmental measurements included wind speed at 1.5 m, wind direction, global irradiance, and rainfall.

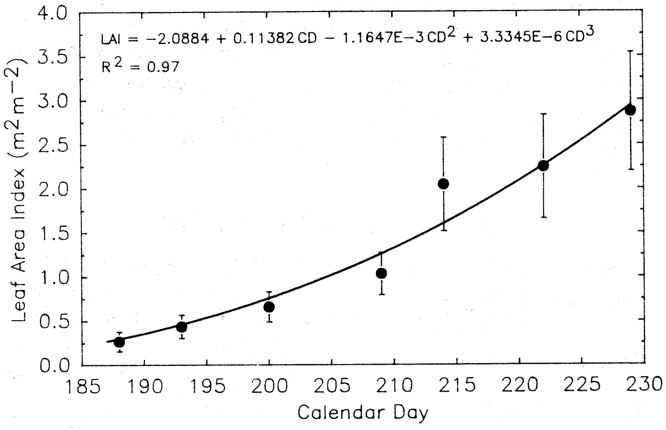

Fig. 2. Leaf area index (LAI) of the cotton canopy vs. calendar day (CD) for the 1989 growing season. The vertical error bars for the measured values represent ± one standard deviation.

RESULTS AND DISCUSSION

Measurements were made between 31 July (CD 212) and 15 Aug. (CD 227) 1989. The LAI of the crop increased from 1.5 and 2.7 during the test period (Fig. 2), while canopy height and width averaged 0.48 m and 0.50 m, respectively. Several small rains occurred during the period and the plot was flood irrigated on CD 218 (Table 1). Complete energy balances of the field, soil, and canopy were obtained for 11 d during the study. Environmental and soil surface conditions for these days are outlined in Table 1. Skies were mostly clear on the measurement days, with the exception of CD 224. Air temperatures were seasonally normal prior to CD 218, but a cold front reduced air temperatures after the irrigation. Surface volumetric water

Errata: The units for the energy balances in Tables 3 and 4 are MJ m^{-2}

Table 2. Daytime (sunrise to sunset) energy balance of the cotton field between calendar days (CD) 212 and 227. Included are net radiation (Rn), latent heat flux (LE), sensible heat flux (*H*), and soil heat flux (*G*). Also included are the ratios of latent and soil heat flux to net radiation. Irrigation occurred on CD 218.

CD	Rn	LE	*H*	*G*	−LE/Rn	−*G*/Rn
	MJ m^{-2}†					
212	20.4	−20.3	3.1	−3.2	0.99	0.16
213	19.4	−17.9	1.9	−3.4	0.92	0.18
215	20.7	−19.9	2.0	−2.8	0.96	0.14
217	18.4	−15.9	1.3	−3.8	0.86	0.21
220	19.4	−15.0	−2.0	−2.4	0.77	0.12
221	20.0	−18.9	0.4	−1.5	0.95	0.08
222	18.6	−19.3	2.4	−1.7	1.04	0.09
223	19.7	−18.4	0.3	−1.6	0.93	0.08
224	11.2	−10.7	0.5	−1.0	0.96	0.09
226	17.8	−15.0	−1.3	−1.5	0.84	0.08
227	18.4	−15.4	−0.6	−2.4	0.84	0.13

† Daytime totals were calculated from detailed measurements integrated over a 12.6-h period.

Table 3. Daytime (sunrise to sunset) energy balance of the soil surface between Calendar Days (CD) 212 and 227. Also included are the ratios of latent and soil heat flux to net radiation.

CD	Rn_s†	LE_s	H_s	*G*	$-\mathrm{LE}_s/\mathrm{Rn}_s$	$-G/\mathrm{Rn}_s$
	Mg m^{-2}‡					
212	11.3	−5.5	−2.6	−3.2	0.49	0.28
213	9.1	−2.0	−3.7	−3.4	0.22	0.37
215	10.1	−3.8	−3.5	−2.8	0.38	0.28
217	7.5	−1.5	−2.2	−3.8	0.20	0.51
220	8.5	−7.6	1.5	−2.4	0.89	0.28
221	10.0	−10.2	1.7	−1.5	1.02	0.15
222	8.0	−9.5	3.2	−1.7	1.19	0.21
223	9.2	−10.2	0.6	−1.6	0.89	0.17
224	8.7	−2.8	0.1	−1.0	0.75	0.27
226	6.4	−5.4	0.5	−1.5	0.84	0.23
227	6.2	−5.6	1.8	−2.4	0.92	0.38

† Rn_s = net radiation at the soil surface; LE_s = latent heat flux from the soil; H_s = sensible heat flux from the soil; G = soil heat flux.
‡ Daytime totals were calculated from detailed measurements integrated over a 12.6-h period.

content was 0.19 and 0.32 cm^3 cm^{-3} before and after the irrigation, respectively. Neutron probe measurements of subsoil water content indicated that soil moisture was not limiting during the experiment. In general, the soil surface was visibly dry prior to CD 218, and was visibly wet for the remainder of the study.

Energy Balance Relationships

Bowen ratio measurements of the daytime energy balance for the field are given in Table 2. Bowen ratios typically ranged between −0.2 and 0.2 during the day, and good agreement among the Bowen ratio systems was observed. There was little variation in Rn despite large changes in soil surface conditions. Latent heat flux accounted for a large portion of the available energy as would be expected under nonstressed conditions. Slightly stable conditions above the canopy resulted in a positive sensible heat flux on all but 3 d. Soil heat flux accounted for 8 to 21% of Rn, and was slightly larger early in the study when the canopy was small. The LE/Rn ratios ranged from 0.77 to 1.04, and were not correlated with soil surface wetness. Ritchie (1971) measured LE/Rn ratios from cotton of similar size and found LE to be within 10% of Rn when soil surface was wet and soil water was not limiting. Our results show more variation in LE/Rn, suggesting sensible heat transport was having a greater influence on how the energy balance was partitioned.

The daytime soil surface energy balance was strongly influenced by surface soil water conditions (Table 3). Before irrigation on CD 218, Rn_s was partitioned almost equally among LE_s, H_s, and G. The $\mathrm{LE}_s/\mathrm{Rn}_s$ ratios were small, ranging from 20 to 49%. Sensible heat flux was always negative during this period, indicating energy flux away from the soil surface. Soil heat flux accounted for 23 to 51% of the available energy when the soil surface was dry. After the irrigation, $\mathrm{LE}_s/\mathrm{Rn}_s$ ratios increased, and LE_s often exceeded Rn_s. Positive H_s values indicate the soil was absorbing convective heat from the within-canopy airstream, which provided energy for LE_s. The G/Rn_s ratios decreased after the irrigation, but still represented a significant form of energy transfer.

The canopy energy balance shows the Rn_c was relatively stable throughout the study, but increased slightly as the canopy enlarged (Table 4). The crop canopy absorbed sensible heat prior to CD 218, which increased LE_c and resulted in $\mathrm{LE}_c/\mathrm{Rn}_c$ ratios greater than unity. After CD 218, reduced air and soil temperatures resulted in sensible heat flux away from the canopy, and $\mathrm{LE}_c/\mathrm{Rn}_c$ ratios were reduced. Comparison of CD 217 and 220 shows how convective transport can influence the energy balance of near identical canopies. The net radiation was the same for both days, however LE_c on CD 220 was about half the magnitude of that on CD 217. This difference was caused solely by a reversal in the direction of sensible heat flux.

Comparison of the daytime field, soil, and canopy energy balances show that Rn_s was more variable than Rn_c (Tables 2, 3, and 4). This was probably due to daily variation in soil temperature and albedo caused by changes in soil surface water content. The LE/Rn ratios for the field, soil, and canopy were strongly influenced by the magnitude and direction of sensible heat flux. The variability in LE/Rn ratios for the field, soil, and canopy indicates that partitioning LE using radiation relationships has limited feasibility. Results suggest that H_s, H_c, and G must be considered when examining the energy and water balance of sparse crops.

Diurnal Energy Balance Patterns

While integrated daily energy balance values are informative, the main objective was to examine detailed diurnal energy balance patterns under a variety of conditions. Here, we present the analysis of 2 d, CD 215 and 221, which were representative of conditions before and after the irrigation. On CD 215, soil surface conditions were dry, air temperatures were high and wind speeds averaged 4.4 ms^{-1}. Conversely, on CD 221, the soil surface was wet, air temperatures were lower, and wind speeds averaged 2.4 ms^{-1} (Table 1). Skies were clear during both days, and solar noon occurred near 1300 h.

Diurnal patterns of latent heat flux from the field, soil, and canopy on CD 215 are presented in Fig. 3. Latent heat flux from the canopy, LE_c, was the dom-

Table 4. Daytime (sunrise to sunset) energy balance of the crop canopy between Calendar Days (CD) 212 and 227. Also included is the ratio of latent heat flux to net radiation.

CD	Rn_c†	LE_c	H_c	$-LE_c/Rn_c$
	Mg m^{-2}‡			
212	9.1	−14.8	5.7	1.63
213	10.3	−15.9	5.6	1.55
215	10.6	−16.1	5.5	1.52
217	10.9	−14.4	3.5	1.32
220	10.9	−7.4	−3.5	0.68
221	10.0	−8.7	−1.3	0.87
222	10.6	−9.8	−0.8	0.92
223	10.5	−10.2	−0.3	0.97
224	7.5	−7.9	0.4	1.05
226	11.4	−9.6	−1.8	0.84
227	12.2	−9.8	−2.4	0.80

† Rn_c = net radiation of the canopy; LE_c = latent heat flux from the canopy; H_c = sensible heat flux from the canopy.

‡ Daytime totals were calculated from detailed measurements integrated over a 12.6-h period.

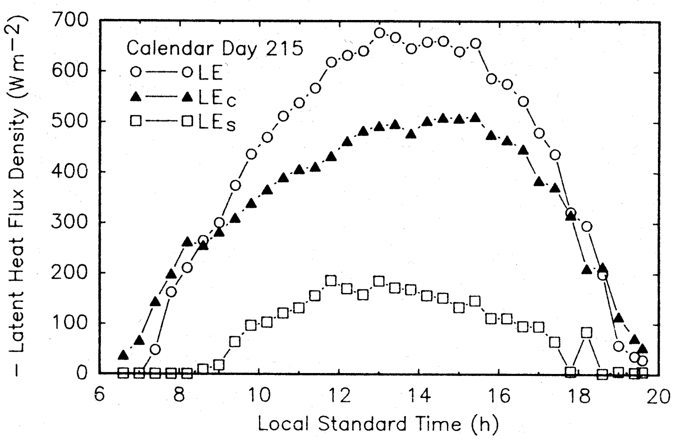

Fig. 3. Latent heat flux density from the field (LE), canopy (LE_c), and soil surface (LE_s) for Calendar Day 215. The soil surface was visibly dry and skies were clear. The leaf area index of the canopy was 1.7 m^2 m^{-2}.

inant form of water loss since LE_s was restricted by the dry soil surface layer. Latent heat flux from the canopy accounted for almost all of LE until 0900 h when LE_s began to increase. This response was probably caused by an increase in soil irradiance as the shift between a fully shaded to partially shaded soil occurred (Nakano et al., 1983). Figure 3 indicates that a larger portion of daily LE_s and LE_c occurred after solar noon.

Figure 4 shows detailed energy balances of the field, soil, and canopy for CD 215. The field energy balance indicates that near neutral conditions were present in the morning with some sensible heat advection occurring in the afternoon (Fig. 4a). Net radiation above the field followed the diurnal course of solar radiation, and soil heat flux reached −179 W m^{-2} at 1236 h, just before solar noon. The energy balance of the soil shows that Rn_s increased rapidly near 0800 h as soil irradiance increased (Fig. 4b) . Sensible heat from the soil was negative and variable throughout the day, suggesting flux away from the surface was influenced by changes in wind speed near the soil. Soil heat flux and LE_s were almost identical until 1400 h when G began to decrease in magnitude. The energy balance of the canopy on CD 215 shows that Rn_c increased rapidly and then reached a plateau near 350 W m^{-2} between 1100 and 1500 h (Fig. 4c). Positive H_c values indicate the canopy was absorbing sensible heat throughout the day, with maximum values near 250 W m^{-2} occurring at 1700 h (Fig. 4c). Advective energy caused LE_c to exceed Rn_c, and skewed the LE_c curve toward the afternoon. Inspection of Fig. 4a and 4b shows that both H and H_s were toward the canopy. A more detailed discussion of this observation is provided later.

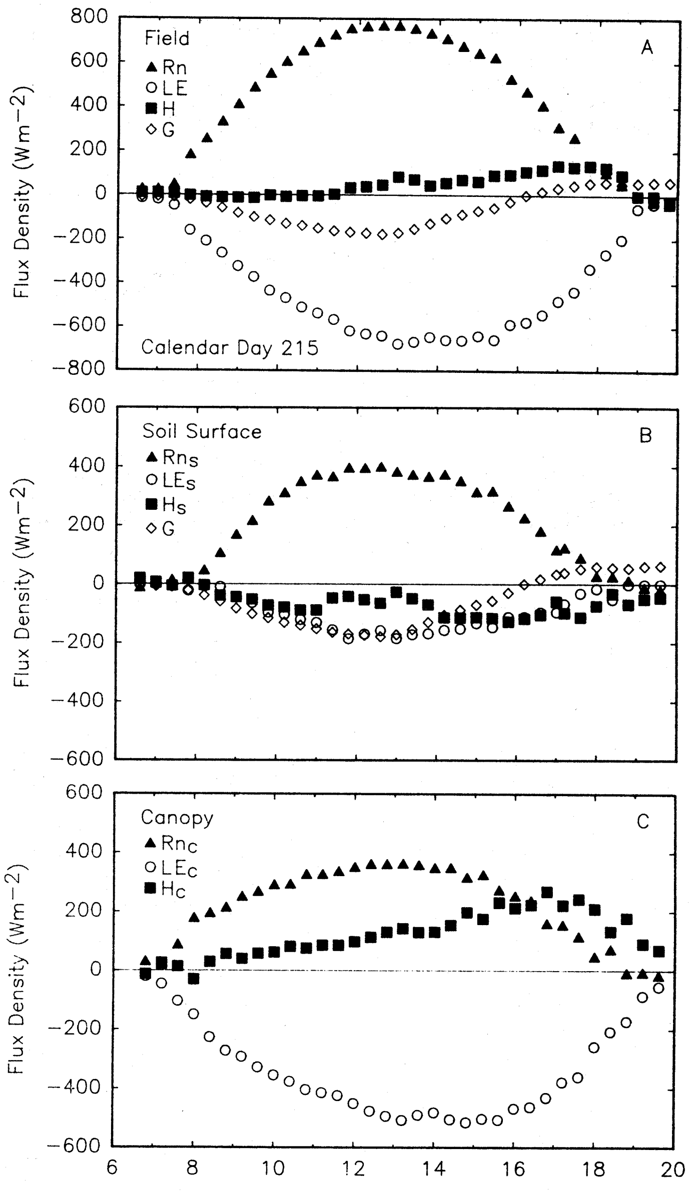

Fig. 4. Separate surface energy balances of the field (A), soil (B), and crop canopy (C) on Calendar Day 215. Latent heat fluxes are repeated from Fig. 3 to provide reference to other fluxes.

The diurnal course of LE from the field, soil, and canopy on CD 221 (Fig. 5) was different from that on CD 215 (Fig. 3). A wet soil surface enhanced LE_s, while lower temperatures reduced LE_c. Latent heat flux from the canopy was again the primary form of LE early and late in the day when the soil was shaded by the

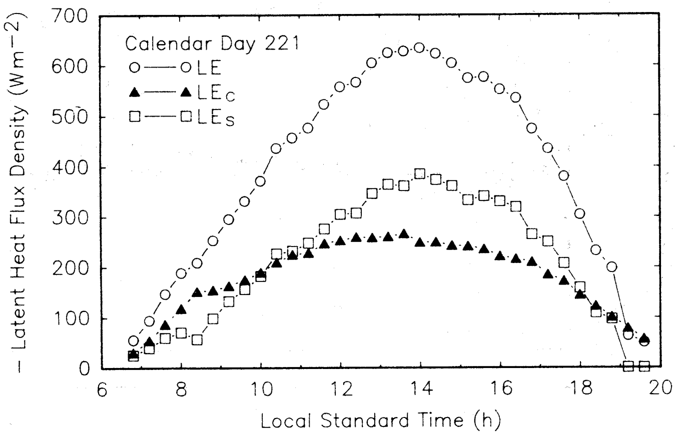

Fig. 5. Latent heat flux density from the field (LE), canopy (LE_c), and soil surface (LE_s) for Calendar Day 221, 2 d following an irrigation. The soil surface was visibly wet and skies were clear. The leaf area index of the canopy was 2.2 m^2 m^{-2}.

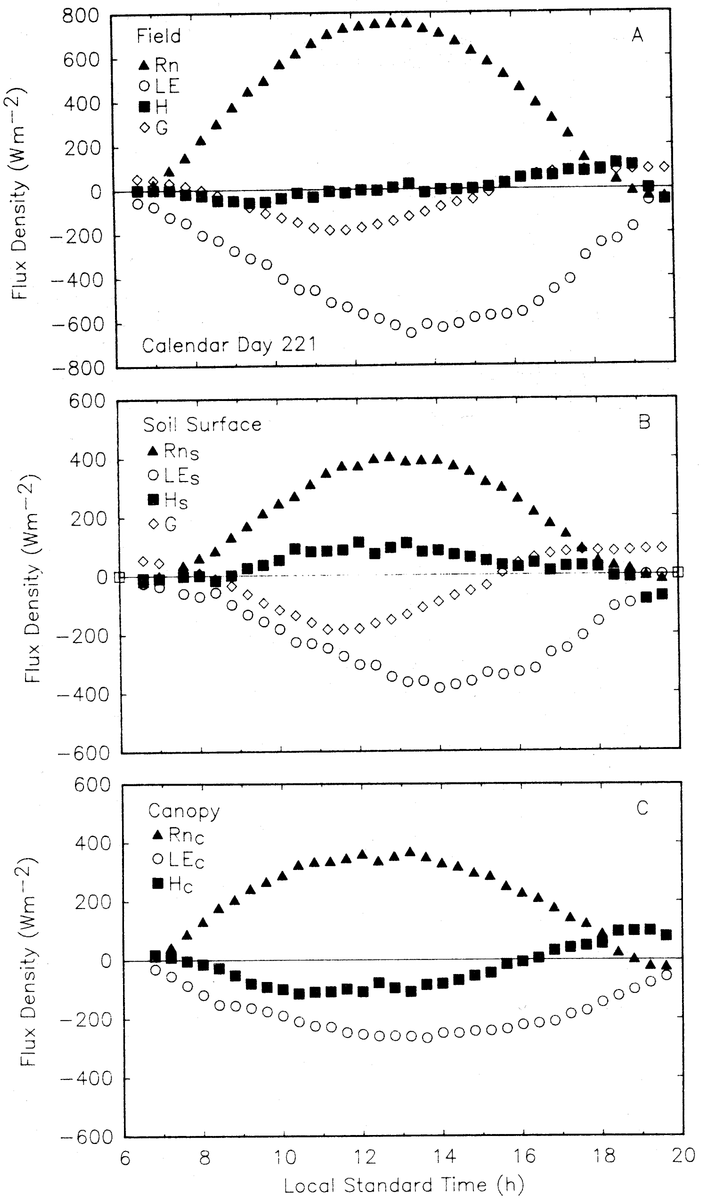

Fig. 6. Separate surface energy balances of the field (A), soil surface (B), and crop canopy (C) on Calendar Day 221. Latent heat fluxes are repeated from Fig. 5 to provide reference to other fluxes.

canopy. However, LE_s increased rapidly near 0900 h and reached its maximum magnitude of −385 W m^{-2} near midday, and accounted for over 60% of total LE during this period (Fig. 5). This indicates that soil evaporation can be the dominant and most dynamic form of LE even when the LAI is greater than two.

Energy balances of the field, soil, and canopy on CD 221 are presented in Fig. 6. Near neutral conditions existed above the canopy, and little convective heat exchange occurred in the fully adjusted layer. The diurnal pattern and magnitude of LE and Rn (Fig. 6a) were quite similar to that on CD 215. The soil energy balance shows the soil was absorbing sensible heat from the within-canopy airstream (Fig. 6b). Since H was small above the canopy, most of H_s originated from the canopy. The convective heat from the canopy and high Rn_s caused LE_s to be the principle form of LE near midday. Note that Rn_s was almost identical for CD 215 and 221, thus the larger LE_s on CD 221 was caused by the input of advective energy coupled with a decrease in G. On a daily basis, LE_s and G accounted for 87 and 13% of the available energy, respectively (Table 3). However, between 1100 and 1200 h, G was over 40% of $Rn_s + H_s$. This shows that while soil heat flux was a minor component of the daily energy balance, it played a crucial role in how energy was partitioned on a diurnal basis. The net radiation of the canopy on CD 221 (Fig. 6c) was similar to that on CD 215 (Fig. 4c). Negative H_c values indicate sensible heat flux was away from the canopy (Fig. 6c), enhanced by cool aerial and soil surface conditions. The loss of convective energy reduced the amount of available energy for LE_c, and the diurnal pattern of LE_c was highly correlated with, but less than, the diurnal pattern of Rn_c.

Field energy balances for CD 215 and CD 221 were almost identical, while soil and canopy energy balances were quite different (Fig. 4 and 6). This demonstrates that field energy balance measurements alone provide virtually no information on how energy balances of the soil and canopy are partitioned.

Soil-Canopy Interactions

Figures 4 and 6 show that the magnitude and direction of sensible heat transfer both within and above the canopy had a major influence on the diurnal pattern of LE_s and LE_c. The sensible heat flux for the field, soil, and canopy for CD 215 is given in Fig. 7a. Sensible heat flux at sunrise was negligible due to near isothermal conditions within the soil-plant-atmosphere continuum. As air and soil temperatures increased throughout the day, the magnitude of H_c and H also increased. Negative H_s and positive H indicate sensible heat was converging on the canopy from two directions. Thus, the canopy was absorbing sensible heat from the fully adjusted layer and the soil surface simultaneously. Temperature profile measurements confirmed that above and below canopy gradients were towards the canopy (Fig. 8). The largest gradients occurred near 1400 h when the canopy temperature was 7 and 4 °C less than soil and above-canopy air temperatures, respectively. The shape of the profiles suggests that advective energy was absorbed just below the top of the canopy. Hanks et al. (1971) reported similar profiles in sorghum during late afternoon periods. Between 1600 and 1700 h, advective energy from the fully adjusted layer and the soil accounted for 37 and 31% of LE$_c$, respectively. Over the day, H_s and H accounted for 21 and 12% of daily LE$_c$, respectively.

The pattern of sensible heat flux on CD 221 shows an almost direct exchange of sensible heat between the canopy and soil (Fig. 7b). Soil surface temperatures were low after the irrigation, creating an energy sink at the soil. Sensible heat flux from the canopy was greatest near midday when H_c contributed 30% of the available energy at the soil surface. Thus, H_c increased soil evaporation, and caused LE$_s$ to exceed LE$_c$ near midday (Fig. 5). Results indicate that 15% of the incident energy at the soil surface was due to sensible heat advection, and 75% of this energy came from the canopy.

While sensible heat flux tends to influence the magnitude of LE$_s$ and LE$_c$, the diurnal pattern is principally related to the radiation balance of each system. Soil and canopy shortwave irradiance on CD 221 is given in Fig. 9. Canopy irradiance is only a relative measure of the radiation incident on the foliage, since it was computed as the difference between the global and soil irradiance, and does not account for reflected radiation. Canopy irradiance exceeded soil irradiance during the early morning and late afternoon period. However, at approximately 0900 h, soil irradiance increased rapidly and exceeded canopy irradiance by 150 W m^{-2} near midday. Canopy irradiance increased rapidly then reached a plateau for a 6-h period. This response may be due to the apparent rotation of the sun around the north-south hedgerow canopy, which caused absorption to remain almost constant during the period. The pattern of soil and canopy irradiance seems to explain the difference between the behavior of Rn$_s$ and Rn$_c$ observed in Fig. 4 and 6. Additionally, the shortwave irradiance curves for CD 221 (Fig. 9) resemble the latent heat flux curves (Fig. 5). This suggests that when the soil is wet and near neutral conditions exist above the canopy, the pattern of LE$_c$ and LE$_s$ are primarily controlled by solar irradiance.

Longwave radiation emitted from the soil also contributed to the radiation balance of the canopy. Figure 10 shows estimates of the longwave radiation emitted from the soil that was incident on the canopy for 3 d during the study. The incident longwave irradiance was computed on a unit leaf area basis as

$$\text{Rl}_s \text{ incident} = ([1-V_{\text{sky}}]\ \epsilon_s\sigma T_s^4)/\text{LAI}. \qquad [1]$$

Calendar Day 217 had the driest soil conditions during the study, and the diurnal pattern of radiant energy on the canopy showed a dramatic increase near 1000 h with incident longwave radiation reaching 220 W m^{-2} at 1300 h (Fig. 10). On a unit land area basis, longwave radiation from the soil contributed over 450

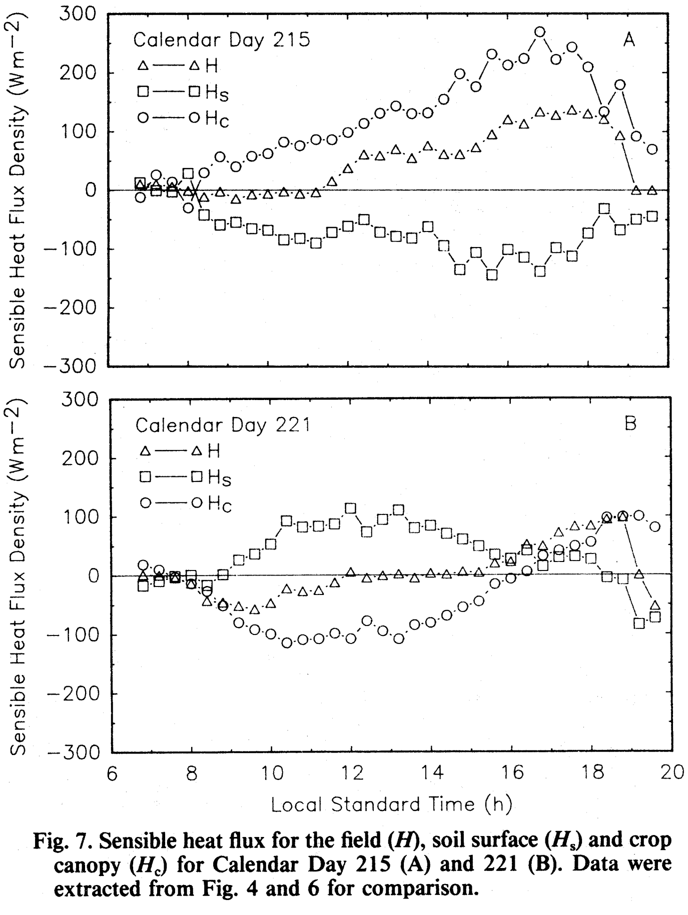

Fig. 7. Sensible heat flux for the field (H), soil surface (H_s) and crop canopy (H_c) for Calendar Day 215 (A) and 221 (B). Data were extracted from Fig. 4 and 6 for comparison.

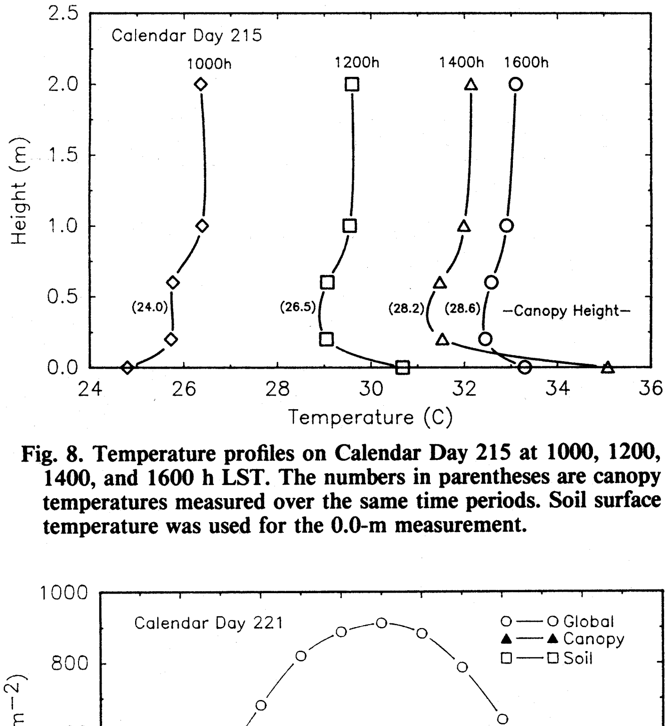

Fig. 8. Temperature profiles on Calendar Day 215 at 1000, 1200, 1400, and 1600 h LST. The numbers in parentheses are canopy temperatures measured over the same time periods. Soil surface temperature was used for the 0.0-m measurement.

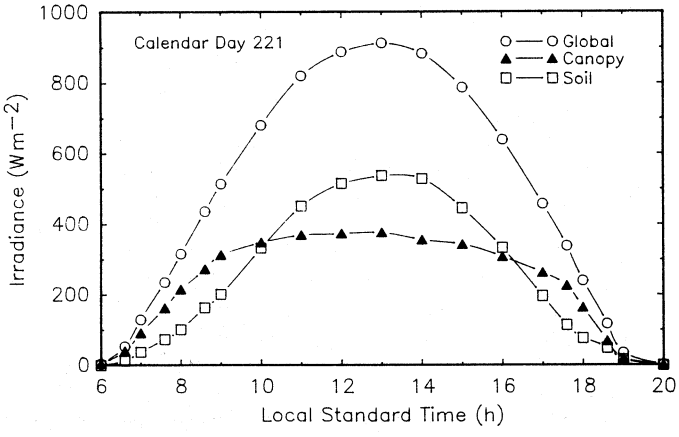

Fig. 9. Diurnal course of global and soil shortwave irradiance for Calendar Day 221 as measured above and below the crop, respectively. Canopy shortwave irradiance was computed as the difference between global and soil irradiance, and represents a relative measure of the irradiance intercepted by the canopy.

Table 5. Day and night soil evaporation as measured with soil microlysimeters following the irrigation. Also included is the night soil surface energy balance for the period corresponding to the night evaporation measurement.

Calendar day	Soil evaporation				Night soil energy balance			
	Day	Night	Total	Night/total	$\mathrm{Rn_s}$†	$\mathrm{LE_s}$	H_s	G
	mm			%	MJ $\mathrm{m^{-2}}$			
220	3.2	0.8	4.0	20	−0.96	−1.94	−0.25	3.15
221	5.2	1.4	6.6	21	−0.56	−3.45	1.71	2.30
222	3.4	0.5	3.9	12	−0.48	−1.18	0.09	1.57
223	2.7	0.4	3.1	13	−0.52	−1.03	0.18	1.37
227	2.2	0.3	2.5	12	−0.62	−0.76	−0.46	1.84

† $\mathrm{Rn_s}$ = net radiation at the soil surface; $\mathrm{LE_s}$ = latent heat flux from the soil; H_s = sensible heat flux from the soil; G = soil heat flux.

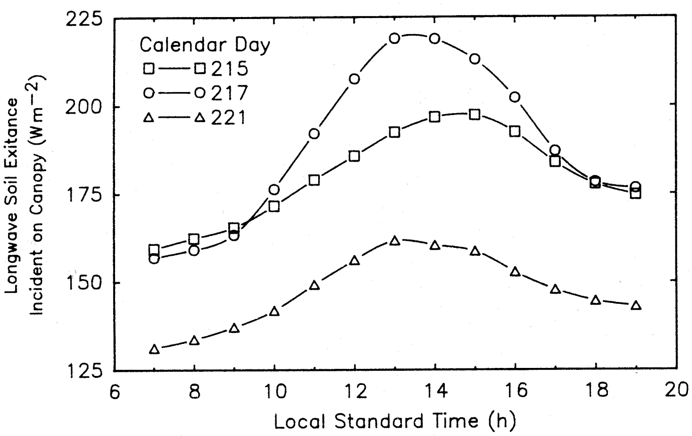

Fig. 10. Longwave soil exitance incident on the canopy for Calendar Days 215, 217, and 221. Incident radiation is expressed as flux per unit leaf area.

W $\mathrm{m^{-2}}$ to the radiation balance of the canopy near midday. Longwave soil exitance was lower on CD 215, but still represented a significant energy source for the canopy. After the irrigation, on CD 221, a much cooler soil surface reduced the thermal radiation load on the canopy. Figure 10 suggests that thermal radiation from the soil can also influence the pattern and magnitude of $\mathrm{LE_c}$ when the soil surface is dry. These conclusions may need to consider that midrow soil surface temperature measurements and the opaque view factor model may have caused an overestimate of $\mathrm{Rl_s}$ near midday.

Night Soil Evaporation

Soil microlysimeter measurements provided a unique opportunity to examine the soil energy and water balance during the night. Soil heat flux was measured, while $\mathrm{Rn_s}$ was computed from Eq. [5]. Microlysimeter measurements of $\mathrm{LE_s}$ allowed the determination of the complete nighttime energy balance by computing H_s as a residual (Eq. [7]). Table 5 shows day and night soil evaporation for 5 d following the irrigation. Nighttime soil evaporation accounted for 20% of daily evaporation for the first 2 d after the irrigation, then decreased to approximately 12% of the total. Night soil evaporation was especially large on CD 221. The night soil energy balance reveals that H_s enhanced evaporation. Since canopy temperatures were lower than air temperatures, H_s probably originated from the above-canopy air, and was not transferred from the canopy foliage.

CONCLUSIONS

Results indicate that the energy balance of the soil and canopy can be measured separately without making simplifying assumptions about energy transfer within the system. We have shown that the radiation balance of the soil and canopy does not adequately describe $\mathrm{LE_c}$ and $\mathrm{LE_s}$ during periods of partial cover. Sensible heat can be transferred between the soil and canopy and has a major influence on magnitude of $\mathrm{LE_c}$ and $\mathrm{LE_s}$. Additionally, during dry soil conditions, $\mathrm{LE_c}$ can be enhanced by the absorption of sensible heat from the soil and equilibrium boundary layer, simultaneously. Soil moisture conditions influenced convective and radiative transfer within the system, and had a major impact on how the energy was partitioned. A wet soil surface appears to reduce $\mathrm{LE_c}$ by acting as a sink for advective energy, while also reducing the radiation load on the canopy. Soil evaporation proved to be the primary form of latent heat flux when the soil was wet, even when the LAI was between two and three. Soil evaporation was markedly reduced by dry surface conditions. However, within row advection increased $\mathrm{LE_c}$ during these periods, and the difference in total LE from the wet and dry soil case was not significant. These results suggest that management practices aimed at reducing soil evaporation may increase transpiration and not reduce total evapotranspiration.

The complexity of energy transport observed in this study reinforces the concept that the energy balance of the soil and canopy must be considered separately during periods of partial cover. Attempts to understand or predict the behavior of the row crop system must include sensible heat exchange and soil heat flux. The use of simple radiation relationships to partition LE is inadequate. Future studies are needed to examine how canopy size, crop type, and plant water stress affect the soil and crop energy balances. Data of this type will be useful in developing and validating mechanistic models of energy exchange in sparse crops.

REFERENCES

Baker, J.M., and C.H.M. van Bavel. 1987. Measurement of mass flow of water in the stems of herbaceous plants. Plant Cell Environ. 10:777–782.

Begg, J.E., J.F. Bierhuizen, E.R. Lemon, D.K. Misra, R.O. Slatyer, and W.R. Stern. 1964. Diurnal energy and water exchanges in bulrush millet in an area of high solar radiation. Agric. Meteorol. 1:294–312.

Brown, K.W., and C. Covey. 1966. The energy-budget evaluation of the micrometeorological transfer processes within a cornfield. Agric. Meteorol. 3:73–96.

Brutsaert, W. 1975. On a derivable formula for long-wave radiation from clear skies. Water Resour. Res. 11:742–744.

Chin Choy, E.W., and E.T. Kanemasu. 1974. Energy balance comparisons of wide and narrow row spacings in sorghum. Agron. J. 66:98–100.

DeVries, D.A. 1963. Thermal properties of soils. p. 210–235. *In* W.R. van Wiik (ed.) Physics of the plant environment. John Wiley & Sons, New York, NY.

Fuchs, M. 1972 The control of the radiation climate of plant communities. p. 173–191. *In* D. Hillel (ed.) Optimizing the soil physical environment toward greater crop yields. Academic Press, New York, NY.

Fuchs, M., and C.B. Tanner. 1966. Infrared thermometry of vegetation. Agron. J. 58:597–601.

Gay, L.W., and R.J. Greenberg. 1983. The AZET battery-powered Bowen ratio system. Proc. 17th Conf. Agric. For. Meteorol. 7:329–334.

Ham, J.M. 1990. Soil water evaporation and transpiration from a row crop at partial cover. Ph.D. diss. Texas A&M Univ., College Station, TX (Diss. Abstr. 90–27217).

Ham, J.M., and J.L. Heilman. 1990. Dynamics of a heat balance stem flow gauge during high flow. Agron. J. 82:147–152.

Ham, J.M., J.L. Heilman, and R.J. Lascano. 1990. Determination of soil water evaporation and transpiration from energy balance and stem flow measurements. Agric. For. Meteorol. 52:287–301.

Hanks, R.J., L.H. Allen, and H.R. Gardener. 1971. Advection and evapotranspiration of wide-row sorghum in the central Great Plains. Agron. J. 63:520–527.

Heilman, J.L., C.L. Brittin, and C.M.U. Neale. 1989. Fetch requirements of Bowen ratio measurements of latent and sensible heat fluxes. Agric. For. Meteorol. 44:261–273.

Kanemasu, E.T., and G.F. Arkin. 1974. Radiant energy and light environment of crops. Agric. Meteorol. 14:211–225.

Kimball, B.A., and R.D. Jackson. 1979. Soil heat flux. p. 211–229. *In* B.J. Barfield and J.F. Gerber (ed.) Modification of the aerial environment of plants. Monograph No. 2, American Society of Agricultural Engineers, ASAE, St. Joseph, MI.

Lascano, R.J., and C.H.M. van Bavel. 1986. Simulation and measurement of evaporation from a bare soil. Soil Sci. Soc. Am. J. 50:1127–1132.

Lascano, R.J., C.H.M. van Bavel, J.L. Hatfield, and D.R. Upchurch. 1987. Energy and water balance of a sparse crop: Simulated and measured soil and crop evaporation. Soil Sci. Soc. Am. J. 51:1113–1121.

Legg, B., and J. Monteith. 1975. Heat and mass transfer within plant canopies. p. 168–186. *In* D.A. deVries and N.H. Afgan (ed.) Heat and mass transfer in the biosphere, Part 1: Transfer processes in the plant environment. John Wiley & Sons, New York, NY.

Luxmoore, R.J., R.J. Millington, and D.B. Peters. 1973. Row crop microclimate. p. 377–388. *In* R.O. Slatyer (ed.) Plant response to climatic factors. Unesco, Paris.

Nakano, Y., T. Cho, and D. Hillel. 1983. Effect of transient partial-area shading on evaporation from a bare soil. Soil Sci. 135:282–295.

Ritchie, J.T. 1971. Dryland evaporation flux in a subhumid climate: I. Micrometeorological influences. Agron. J. 63:51–55.

Sakuratani, T. 1981. A heat balance method for measuring water flux in the stem of intact plants. J. Agric. Meteorol. 37:9–17.

Sakuratani, T. 1987. Studies on evapotranspiration from crops. (2) Separate estimation of transpiration and evaporation from a soybean field without water storage. J. Agric. Meteorol. 42:309–317.

Shuttleworth, J.W., and J.S. Wallace. 1985. Evaporation from sparse crops—an energy combination theory. Q. J.R. Meteorol. Soc. 111:839–855.

Stanhill, G. 1973 Evaporation, transpiration and evapotranspiration: A case study for Ockham's razor. p. 207–220. *In* A. Hadas, D. Swartzendruber, P.E. Rijtema, M. Fuchs, and B. Yaron (ed.) Physical aspects of soil water and salts in ecosystems. Springer-Verlag, New York, NY.

Steinberg, S., and C.H.M. van Bavel. 1990. Improved sap flow gauge for woody plants. Agron. J. 82:851–854.

Tanner, C.B. 1960. Energy balance approach to evapotranspiration from crops. Soil Sci. Soc. Am. Proc. 24:1–9.

Tanner, C.B., A.E. Peterson, and J.R. Love. 1960. Radiant energy exchange in a corn field. Agron. J. 52:373–379.

Tanner, C.B., and W.A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. J. 68:239–243.

Walker, G.K. 1984. Evaporation from wet soil surfaces beneath plant canopies. Agric. For. Meteorol. 33:259–264.