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## Energy balance and latent heat flux partitioning in coffee hedgerows at different stages of canopy development

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### Abstract

The energy balance of drip-irrigated coffee (*Coffea arabica* L. cv. Yellow Catuai) hedgerows was evaluated at different stages of canopy development using the Bowen ratio–energy balance technique. Simultaneous measurements of mass flow of water through the coffee stems using the heat balance method allowed total latent heat flux ( $\lambda E$ ) to be partitioned between crop canopy ( $\lambda Ec$ ) and soil and interrow vegetation ( $\lambda Es$ ) components. The average Bowen ratio decreased from 0.92 at leaf area index ( $L$ ) of 1.4 to 0.36 at  $L = 6.7$ . Differences in the Bowen ratio between 2 consecutive years appeared to be related to stomatal response to leaf-to-air vapor pressure difference ( $V$ ) and variations in net radiation ( $R_n$ ). Latent heat loss was the most important component of the energy balance at all stages of canopy development, while sensible heat flux ( $H$ ) remained relatively constant. Soil heat flux ( $G$ ) invariably declined as  $L$  increased.  $\lambda Ec$  was the major form of latent heat loss at all stages of canopy development except at  $L = 1.4$ , where  $\lambda Es$  accounted for 60% of  $\lambda E$ . However, the magnitude of  $\lambda Es$  declined with canopy development, with  $\lambda Ec$  accounting for nearly 100% of total  $\lambda E$  at  $L = 6.7$ . Withholding irrigation dramatically influenced the partitioning of energy, strongly reducing  $\lambda Es$  and increasing  $H$ . After irrigation was discontinued  $\lambda Ec$  dropped rapidly, and the contribution of  $\lambda Es$  to  $\lambda E$  became more important. After irrigation was resumed, a rapid recovery of all energy balance components to their previous values was observed. At low  $L$ , energy balance and latent heat partitioning of coffee hedgerows grown under wide spacing resembled the behavior of sparse row crops, but the development of a tall, dense canopy caused available energy to be partitioned in a way typically found in closed canopies such as those of forests.

### 1. Introduction

Although sparse canopies are an important component of natural and agricultural

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systems, and occur seasonally in agricultural areas (Wilson and Henderson-Sellers, 1985), most studies addressing the energy balance of plant canopies have been conducted on annual crops with fully developed canopies (e.g. Brown and Covey, 1966; Biscoe et al., 1975; McGinn and King, 1990) and on forests (e.g. Sa et al., 1988; Lafleur, 1992). The heterogeneity of the microclimate associated with row crops (Luxmoore et al., 1973; Hatfield, 1989; Ham and Heilman, 1991), and the lack of techniques to partition total latent heat ( $\lambda E$ ) between its crop canopy ( $\lambda Ec$ ) and soil (and interrow vegetation) components ( $\lambda Es$ ), have hampered a better understanding of the energy balance of sparse canopies.

Previous studies have relied mostly on the use of modeling techniques (Shuttleworth and Wallace, 1985; Lafleur and Rouse, 1990; Massman, 1992) and microlysimeters (Shawcroft and Gardner, 1983; Lascano et al., 1987) to provide separate estimates of  $\lambda Ec$  and  $\lambda Es$ . These studies have consistently reported that  $\lambda Es$  may become the predominant component of  $\lambda E$  during periods of partial cover (Lascano et al., 1987; Ham et al., 1990). However, accurate and direct estimates of the dynamics of  $\lambda Ec$  and  $\lambda Es$  at different stages of canopy development are still lacking for a variety of plant canopy types, particularly perennial crops.

The development of the stem heat balance (*SHB*) technique (Vieweg and Ziegler, 1960) and its subsequent improvements (Čermák et al., 1973; Sakuratani, 1981; Baker and Van Bavel, 1987) have allowed a better characterization of the energy balance of sparse crops through direct measurement of the dynamics of  $\lambda Ec$ . Sakuratani (1987) used the *SHB* technique to study the dynamics of evapotranspiration and transpiration of a soybean crop and found that evapotranspiration remained nearly constant throughout canopy development, and that transpiration equalled evapotranspiration at high  $L$  values, with a consequent decrease in soil evaporation. Ham et al. (1991) used the *SHB* technique to make detailed measurements of the canopy and soil energy balances of a developing cotton crop, and found that  $\lambda Es$  accounted for more than 50% of  $\lambda E$  even at  $L > 2$ , and that within-canopy radiation and convective energy transfer strongly influenced the energy balance.

In this report, we present the results of work carried out on a perennial crop growing in a hedgerow configuration under tropical conditions. We used the Bowen ratio–energy balance and the *SHB* techniques to characterize the energy balance of entire coffee fields, and to partition  $\lambda E$  between its soil and canopy components over a wide range of canopy development. We also describe the effects of a 25 day long soil drying–reirrigation cycle on the partitioning of energy loss from a dense coffee canopy.

## 2. Materials and methods

### 2.1. Experimental site

Experiments were conducted in commercial coffee fields at McBryde Sugar Co., Eleele, Island of Kauai (latitude  $21^{\circ}54'$ , longitude  $154^{\circ}33'$ , elevation 98 m), from July to August and again from September to November in 1991 and from July to

Table 1  
Daytime environmental conditions during the measurements periods at McBryde Sugar Co., Island of Kauai

$L^a$	Date	Net radiation ( $\text{W m}^{-2}$ )		Air temperature ( $^{\circ}\text{C}$ )			Vapor pressure (kPa)	Wind speed <sup>b</sup> ( $\text{m s}^{-1}$ )
		max	mean	min	max	mean	daytime mean	
Mean								
1991								
1.4	Aug. 17–22	740	438	23	29	27	1.18	2.3
	Nov. 01–08	616	337	21	28	27	1.18	1.4
5.3	July 24–27	748	409	23	28	26	0.87	1.8
	Oct. 08–12	640	351	22	29	27	0.92	1.2
5.4	July 24–27	748	409	22	26	28	1.02	1.8
	Oct. 08–12	640	351	22	28	26	0.87	1.2
6.7	July 10–14	769	392	22	25	24	0.59	1.8
	Sept. 01–05	736	385	22	29	26	0.91	1.6
1992								
3.4	July 29–05	742	465	24	29	28	1.25	2.3
4.2	June 22–28	771	461	23	29	27	1.29	1.8
8.0	Aug. 25–31	742	399	23	29	27	1.14	2.1

<sup>a</sup> Leaf area index.

<sup>b</sup> Mean daily values.

September in 1992. A summary of the environmental conditions prevailing during the measurement periods is presented in Table 1.

Large fields with the plants grown in a hedgerow configuration oriented predominantly from east to west were selected. The spacing was 3.60 m between rows and 0.71 m between coffee trees (Fig. 1). Crop ages ranged from 1.2 to 5.3 years in the fields selected. Measurements were made in coffee canopies with  $L = 1.4, 5.3, 5.4$  and  $6.7$  in 1991 and  $L = 3.4, 4.2$  and  $7.5$  in 1992. Individual plants consisted of four to five vertical stems, one of which usually became dominant and occupied the upper plant canopy. Average leaf area per plant increased from  $3.67 \text{ m}^2$  at  $L = 1.4$  to  $15.57 \text{ m}^2$  at  $L = 6.7$ . Hedgerow dimensions increased approximately from  $1.25 \times 1 \text{ m}$  at  $L = 1.4$  to  $3 \times 2.5 \text{ m}$  at  $L = 7.5$  (Fig. 1). At low  $L$  (1.4) the plants did not form dense, complete hedgerows and did not shade the bases of the stems completely. At high  $L$ , dense hedgerows had developed and the canopy shaded the ground during most of the day.

Short seedlings of the predominant weeds, no taller than 0.50 m, grew in the interrows in a sparse and irregular pattern. Dominant weeds in the interrows were the Spanish needle (*Bidens pilosa*), purple nutsedge (*Cyperus rotundus*) and several grasses.

Irrigation was applied to the fields through drip irrigation tubes laid along the base of the stems under the plant hedgerows. Approximately 15–20 mm of water were applied to each field during the 36–48 h immediately before each set of energy balance measurements. The soil under the hedgerows was kept at field capacity and soil

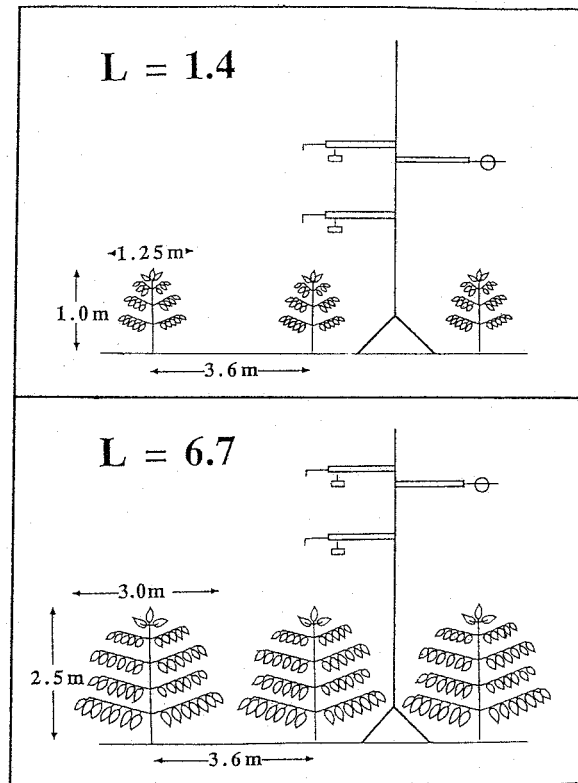


Fig. 1. Diagrammatic representation of the experimental set-up in coffee hedgerows at two different stages of canopy development.

suction was monitored daily through a set of ten 20 cm long tensiometers installed in each field under the hedgerows. This ensured that water availability was adequate during the 4–10 day period during which energy balance measurements were made. In one field ( $L = 6.7$ ), changes in energy balance were monitored during a 25 day drying–reirrigation cycle.

## 2.2. Energy balance measurements

The energy balance of the fields was characterized using the Bowen ratio–energy balance approach (Bowen, 1926; Tanner, 1960). Detailed error analyses (Fuchs and Tanner, 1970; Sinclair et al., 1975; Angus and Watts 1984), and minimum sensor elevation (Garrat 1978; Graser et al., 1985) and fetch requirements (Rosenberg et al., 1983; Heilman et al., 1989) of the technique have been discussed elsewhere.

Most of the required measurements were made from a 7 m movable micrometeorological tower (Fig. 1) which was positioned in each field to provide an upwind fetch more than 100 times the crop height. The tower remained in each field from 7 to 10

days. In the Bowen ratio method, canopy energy balance is expressed as

$$R_n + G + H + \lambda E = 0 \quad (1)$$

where  $R_n$  is net radiation,  $G$  is soil heat flux,  $H$  is sensible heat flux and  $\lambda E$  is latent heat flux. Net radiation was measured with a Fritschen net radiometer (model Q6, Micromet Systems, Seattle, WA, USA) mounted 6.50 m above the ground and positioned on top of the crop canopy–interrow limit. To ensure that the instruments were positioned high enough above the canopy, a second net radiometer was added during the second year so that one was positioned directly above the plant hedgerow and one above the center of the interrow. Agreement between the two was within 10%. Soil heat flux at the surface was measured using the combination method (Kimball and Jackson, 1979). In this method, heat flux plates (heat flux plate method) and soil thermocouples (calorimetric method) are used simultaneously to calculate soil heat flux. One soil heat flux plate (HFT-2, Radiation Energy Balance Systems, Seattle, WA, USA) and two soil thermocouples were placed at a depth of 1 and 2 cm below the soil surface and positioned at the edge of the hedgerow, and a second soil heat flux plate and thermocouples were positioned in the middle of the interrow.

The Bowen ratio ( $\beta$ ), the ratio of sensible to latent heat loss from the canopy was calculated as

$$\beta = H/\lambda E = \gamma \Delta T / \Delta e \quad (2)$$

where  $\gamma$  is the psychrometric constant and  $\Delta T$  and  $\Delta e$  are gradients of temperature and vapor pressure measured over a fixed distance in the canopy boundary layer. Combining Eqs. (1) and (2) gives

$$\lambda E = (R_n - G)/(1 + \beta) \quad (3)$$

The gradient in air temperature was measured with a pair of Chromel-constantan thermocouples connected in parallel at each height. Air samples taken at the same heights were passed through a dew point hygrometer (Dew-10, General Eastern Corporation, Watertown, MA, USA) using a pump and solenoid valve system (model O23, Campbell Scientific, Logan, UT, USA) which automatically switched the heights monitored every 4 min with a 2 min switch in response to a signal from a datalogger (CR21X, Campbell Sci.). Measurements were averaged and stored every 20 min in a solid state storage module (SM192, Campbell Sci.). In a recent comparison, values of  $\lambda E$  obtained with a Bowen ratio system similar in design to that used in the present study were within 10% of those obtained with three other systems of different designs (Dugas et al., 1991). In the same study it was concluded that  $\lambda E$  was consistently underestimated with the eddy correlation technique.

### 2.3. Transpiration measurements and latent heat flux partitioning

The *SHB* technique was used to measure the transpiration of the coffee plants. A detailed description of the theory of operation of the *SHB* technique has been provided elsewhere (Sakuratani, 1981; Baker and Van Bavel, 1987; Ham and

Heilman, 1990). Its satisfactory performance in coffee was verified in greenhouse and field experiments (Gutiérrez et al., 1993). Commercially available stem sap flow gauges (models SGB13 to SGB25, Dyanamax Inc., Houston, TX, USA) consisting of a heating element, a thermopile and individual thermocouples, were used for all measurements and installed at the base of dominant branches containing 1.5–5.5 m<sup>2</sup> of leaf area distal to the gauge in each field.

The gauges were operated under the control of a datalogger (CR21X, Campbell Sci.) equipped with a 32 channel multiplexer (AM416, Campbell Sci.) that permitted up to eight sap flow gauges to be operated simultaneously. Data were recorded at 15 s intervals and 20 min averages were stored in a solid state storage module (SM192, Campbell Sci.). The sheath conductance for each gauge, a proportionality constant relating thermopile output to the radial heat loss at zero flow, was determined from the average values of sheath conductance calculated in the datalogger program between 24:00 and 05:00 h when transpiration was assumed to be zero. The average mass flow rate of water through the coffee stems was multiplied by the heat of vaporization of water to produce an estimate of  $\lambda E_c$ . The resulting estimate of  $\lambda E_c$  was scaled to a unit ground area basis using the corresponding value of  $L$ .  $\lambda E_s$  was determined as a residual by subtracting  $\lambda E_c$  from total  $\lambda E$  estimated with the Bowen ratio technique. The validity of this approach has been tested before in cotton canopies (Ham et al., 1990).

#### 2.4. Additional measurements

Stomatal conductance ( $g_s$ ) was measured with a portable photosynthesis system (model 6200, Li-Cor, Lincoln, NE, USA) on sun and shade leaves from the upper and middle canopy.

Leaf temperature was measured with a set of 18 Cu-constantan thermocouples attached to the adaxial surface of the leaves and distributed throughout the canopy.

Leaf area index ( $L$ ) was determined by completely defoliating eight to ten representative plants in each field and measuring their total leaf area in an area meter (Li-Cor 3100, Lincoln, NE, USA). Average leaf area per plant was then multiplied by the plant density defined at planting to obtain  $L$  for each field.

### 3. Results and discussion

Energy balance was determined during 4–8 mostly clear days in each field. Seasonal environmental trends were characterized by decreasing net radiation and slightly increasing air temperature from July to November in 1991 (Table 1). Net radiation, air temperature and leaf-to-air vapor pressure deficit were greater in 1992 than in 1991.

#### 3.1. Energy balance relationships

Bowen ratio measurements of the daytime energy balance in coffee fields with

Table 2  
Daytime energy balance (08:00–20:00 h) in coffee fields at different stages of canopy development

<i>L</i>	Date	$R_n$	$-\lambda E$	$-H$	$-G$
			$\text{MJ m}^{-2}$		
1.4	Aug. 20, 1991	16.68	6.53	6.05	3.57
3.4	July 22, 1992	15.72	6.87	5.15	3.88
4.2	July 11, 1992	17.71	8.22	6.42	2.78
5.3	July 24, 1991	16.28	9.98	4.01	2.56
5.4	Aug. 11, 1991	15.04	9.73	3.46	2.10
6.7	Sep. 03, 1991	16.67	8.92	4.92	3.07
7.5	Aug. 28, 1992	16.65	9.20	5.12	1.09

different *L* during representative days with similar radiation regimes are summarized in Table 2. Partitioning of the cumulative daily energy received by the fields was similar to that previously reported for crop canopies with high *L* (close to 4) (Brown and Covey, 1966; Anderson and Verma, 1986) and forests (Sa et al., 1988). Our results show that  $\lambda E$  was invariably the major component of the energy balance at all *L* values (Table 2). Evidence for the occurrence of advection, as judged by  $\lambda E$  values exceeding  $R_n$  (Hanks et al., 1971; Brakke et al., 1978) or by positive *H* values (Rosenberg et al., 1983), was observed for only 3 days at the end of the measurement periods in fields with *L* = 5.3 and 5.4 during the first period of measurements in 1991.

The energy balance components were normalized by  $R_n$  to account for daily and year to year variation in the radiation regime (Table 3). The ratio  $\lambda E/R_n$  increased from 0.40 at *L* = 1.4 to a maximum of 0.64 at *L* = 5.4. *H* was the second most important component of the energy balance, consuming an important fraction of  $R_n$  that ranged from 0.22 to 0.34. The ratio  $G/R_n$  consistently decreased from 0.25 to less than 0.1 as *L* increased, reflecting the almost complete canopy cover reached at high *L*. Mean Bowen ratio values decreased from 0.92 at low *L* to near 0.40 at high *L*, reflecting an increasing partitioning of energy to  $\lambda E$  as *L* increased. Bowen ratios obtained in this study were similar to those reported by McGinn and King (1990) for dense alfalfa and maize canopies in southern Ontario, and by Sa et al. (1988) for

Table 3  
Bowen ratio ( $\beta$ ) and average ratio of the energy balance components to net radiation in coffee fields at different stages of canopy development

<i>L</i>	Year	$\lambda E/R_n$	$H/R_n$	$G/R_n$	$\beta^a$
1.4	1991	0.40	0.34	0.24	$0.92 \pm 0.52$
3.4	1992	0.43	0.32	0.25	$0.81 \pm 0.30$
4.2	1992	0.42	0.34	0.14	$0.82 \pm 0.66$
5.3	1991	0.58	0.30	0.13	$0.54 \pm 0.28$
5.4	1991	0.64	0.27	0.14	$0.37 \pm 0.25$
6.7	1991	0.61	0.22	0.18	$0.36 \pm 0.14$
7.5	1992	0.54	0.30	0.05	$0.60 \pm 0.58$

<sup>a</sup> Mean daily values  $\pm$  SD.

tropical forests in the Amazon basin, but substantially larger than the values reported for flood-irrigated cotton fields in Texas by Ham et al. (1991).

Higher Bowen ratios were recorded in 1992 than in 1991 (Table 3), but the principal factors responsible for this pattern were not entirely clear. Variations in the Bowen ratio because of fluctuations in net radiation, canopy resistance and leaf to air vapor pressure difference have been observed before (e.g. Murphy et al., 1981). Average stomatal conductance ( $g_s$ ) was  $0.10 \text{ mol m}^{-2} \text{ s}^{-1}$ ,  $0.12 \text{ mol m}^{-2} \text{ s}^{-1}$  and  $0.07 \text{ mol m}^{-2} \text{ s}^{-1}$  in fields with  $L = 6.7$ ,  $5.4$  and  $1.4$ , respectively, in 1991, while in 1992  $g_s$  was reduced to  $0.08 \text{ mol m}^{-2} \text{ s}^{-1}$ ,  $0.11 \text{ mol m}^{-2} \text{ s}^{-1}$  and  $0.03 \text{ mol m}^{-2} \text{ s}^{-1}$  in fields with  $L = 7.5$ ,  $4.2$  and  $3.4$ , respectively. Mean  $V$  measured simultaneously with  $g_s$  was  $1.35 \text{ kPa}$  in 1991 and  $1.68 \text{ kPa}$  in 1992. Strong stomatal responses to humidity in coffee have been reported before (Kumar, 1979; Fanjul et al., 1985). This suggests that the higher Bowen ratios observed during 1992 may have been partly attributable to greater stomatal restriction of transpiration in 1992, despite maintenance of similar irrigation regimes during the 2 years. As a consequence, the ratio  $\lambda E/R_n$  tended to be lower and the ratio  $H/R_n$  to be higher in all fields measured in 1992 when compared against their counterparts measured under the same irrigation regime in 1991. Nevertheless, the general trend of decreasing Bowen ratios with increasing  $L$  (Table 3) indicated the growing importance of  $\lambda E$  as a sink for  $R_n$  as the canopy developed.

Examination of the diurnal courses of the energy balance components at three stages of canopy development indicated that at  $L = 1.4$  the diurnal courses of  $\lambda E$  and  $H$  were similar (Fig. 2). However,  $\lambda E$  was slightly larger than  $H$ , especially during the morning hours, reaching values close to  $-300 \text{ W m}^{-2}$  at midday.  $H$  steadily increased during the morning hours and equalled  $\lambda E$  in magnitude by 11:00 h. Both  $\lambda E$  and  $H$  then remained similar for the rest of the day.  $G$  was lower than  $\lambda E$  and  $H$  throughout most of the day, but reached a maximum of  $-250 \text{ W m}^{-2}$  between 13:00 and 14:00 h, nearly matching  $\lambda E$  and  $H$ , and then started to decrease until it became positive at approximately 16:00 h, indicating that energy flux was directed away from the soil surface towards the crop canopy. In contrast to the diurnal pattern observed at  $L = 1.4$ ,  $G$  was substantially lower at  $L = 4.2$ , reaching a maximum of  $-100 \text{ W m}^{-2}$  during the late morning hours (Fig. 1). The magnitudes of  $\lambda E$  and  $H$  were similar, rapidly increasing in the early morning hours, reaching a maximum of  $-400 \text{ W m}^{-2}$  around midday, and remaining high into the afternoon. At  $L = 7.5$ ,  $G$  was even lower attaining a maximum value of only  $-75 \text{ W m}^{-2}$  (Fig 1). Unlike the pattern observed at lowest  $L$  values,  $\lambda E$  was the dominant form of energy dissipation until the early afternoon hours, reaching a maximum of  $-500 \text{ W m}^{-2}$  shortly after midday and then decreasing throughout the afternoon. Sensible heat flux, which remained lower than  $\lambda E$  during most of the day, reached a maximum of  $-350 \text{ W m}^{-2}$  during early afternoon, and equalled  $\lambda E$  throughout most of the afternoon.

### 3.1. Partitioning of latent heat loss

Independent estimates of total  $\lambda E$  and its coffee canopy component ( $\lambda E_c$ ) were obtained at different stages of canopy development (Table 4). Measurements of  $\lambda E$



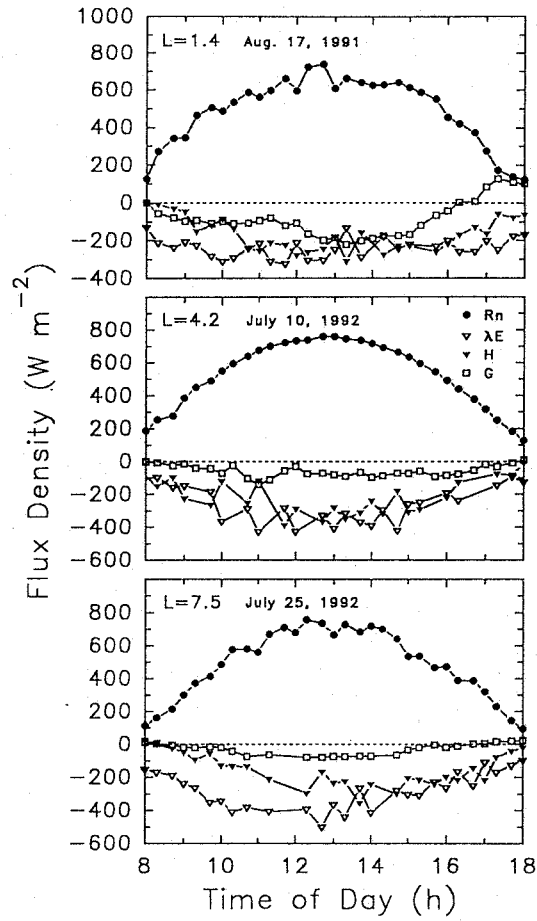


Fig. 2. Diurnal courses of net radiation ( $R_n$ ), latent heat ( $\lambda E$ ), sensible heat ( $H$ ) and soil heat flux ( $G$ ) in coffee fields at three different stages of canopy development.

Table 4

Partitioning of total latent heat flux ( $\lambda E/R_n$ ) between its crop canopy ( $\lambda E_c/R_n$ ) and soil and interrow vegetation ( $\lambda E_s/R_n$ ) components in coffee fields at different stages of canopy development

$L$	Year	$\lambda E/R_n$	$\lambda E_c/R_n$	$\lambda E_s/R_n$	$\lambda E_c/\lambda E$
1.4	1991	0.40	0.12	0.28	0.34
3.4	1992	0.43	0.16	0.26	0.38
4.2	1992	0.42	0.38	0.08	0.85
5.3	1991	0.58	0.44	0.12	0.78
5.4	1991	0.64	0.46	0.18	0.72
6.7	1991	0.54	0.53	0.03	0.95

were obtained using the Bowen ratio technique, and measurements of mass flow of water through the coffee stems using the *SHB* technique allowed latent heat loss from only the coffee canopy ( $\lambda Ec$ ) to be estimated independently. Latent heat flux from the soil and interrow vegetation ( $\lambda Es$ ) was calculated as a residual by subtracting  $\lambda Ec$  from  $\lambda E$ . The contribution of  $\lambda Ec$  to total  $\lambda E$  increased from 34 to 95% as the canopy developed, with a consequent decrease in  $\lambda Es$ . These observations are consistent with previous results obtained through modeling (Shuttleworth and Wallace, 1985) and experimental approaches (Sakuratani, 1987) in which evaporation beneath the canopy decreased curvilinearly with  $L$ . The fraction of  $R_n$  consumed as latent heat loss by the coffee canopy ( $\lambda Ec$ ) increased sharply from 0.12 to 0.53 over the same range of  $L$ . This was associated with a parallel reduction in the ratio  $\lambda Es/R_n$  from 0.28 at low  $L$  to less than 0.03 at  $L = 6.7$ .

Diurnal patterns of  $R_n$  and  $\lambda E$  and its coffee canopy ( $\lambda Ec$ ) and soil and interrow vegetation ( $\lambda Es$ ) components (Fig. 3), indicated that the relative magnitude of  $\lambda Ec$  consistently increased with  $L$ , with a corresponding decrease in  $\lambda Es$  as the fraction of ground covered by the coffee canopy increased. At  $L = 1.4$ ,  $\lambda Es$  accounted for more than 60% of  $\lambda E$ , frequently twice the magnitude of  $\lambda Ec$ , which remained low and relatively constant during the daylight hours (Fig. 3). Similar results have been reported before for flood-irrigated cotton (Lascano et al., 1987; Ham et al., 1991), in which  $\lambda Es$  accounted for 30–50% of  $\lambda E$  at all stages of canopy development (maximum  $L$  less than 3). Even under drip-irrigation management the contribution of  $\lambda Es$  to  $\lambda E$  was large. Wide spacing and very sparse canopies combined with frequent rainfall and dew deposition during the night presumably supplied the otherwise dry interrow spaces with enough moisture at low  $L$ . However,  $\lambda Es$  decreased substantially after  $L$  increased above 3.4. At  $L = 5.3$ ,  $\lambda Ec$  approached total  $\lambda E$  in magnitude and was higher than  $\lambda Es$  throughout the day, although the contribution of  $\lambda Es$  to total  $\lambda E$  was still substantial. In contrast, at  $L = 6.7$   $\lambda Ec$  often equalled total  $\lambda E$ , sharply reducing the contribution of  $\lambda Es$ , which became important only in the early morning hours, possibly through evaporation of dew deposited at night, and during the midday hours when direct radiation reached the narrow spaces of the interrows.

### 3.2. Field energy balance during water stress

Withholding of irrigation water strongly influenced the partitioning of available energy among the energy balance components (Fig. 4). In a well-irrigated field with  $L = 6.7$ ,  $\lambda E$  comprised 60% of  $R_n$  while  $H$  consumed 20% of the available energy. Total latent heat flux started to decrease almost immediately after irrigation was discontinued, with a simultaneous shift in partitioning of available energy increasingly to  $H$ . Fourteen days after the last irrigation,  $\lambda E$  and  $H$  had equalled each other in magnitude, consuming 80% of the energy. This situation remained relatively unchanged for 6 days after which  $\lambda E$  declined further to 30% of  $R_n$  and  $H$  increased to 50% of  $R_n$ . This coincided with evident wilting of the leaves and substantial reductions in stomatal conductance from  $0.10 \text{ mol m}^{-2} \text{ s}^{-1}$  at the beginning of the drying cycle to  $0.02 \text{ mol m}^{-2} \text{ s}^{-1}$  23 days after the drying cycle had been imposed. The

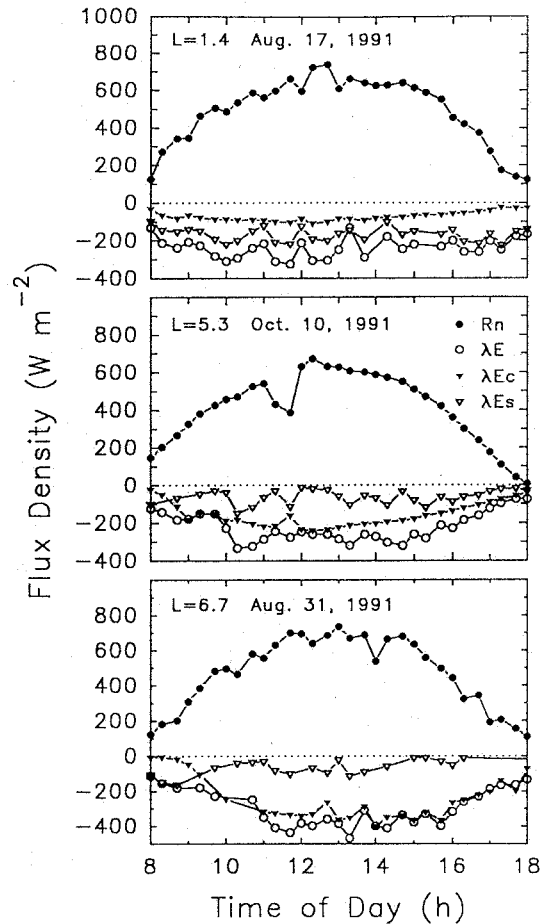


Fig. 3. Diurnal courses of net radiation ( $R_n$ ) total latent heat flux ( $\lambda E$ ) and its canopy ( $\lambda E_c$ ) and soil and interrow vegetation ( $\lambda E_s$ ) components in coffee fields at three different stages of canopy development.

average Bowen ratio increased from 0.3 under well-irrigated conditions to 1.4 just prior to reirrigation (Fig. 4).

Similar trends in partitioning of energy during water stress have been reported previously in soybean canopies in Nebraska (Baldocchi et al., 1983) and in sorghum grown under wide and narrow spacing (Kanemasu and Arkin, 1974).

Partitioning of  $\lambda E$  was also greatly affected by soil drying (Fig. 4). Under well-irrigated conditions, nearly all of  $\lambda E$  was attributable to  $\lambda E_c$ . Latent heat loss from the coffee canopy started to decrease approximately 4 days after irrigation was discontinued, but still accounted for nearly 100% of  $\lambda E$ . However, 9 days after the last irrigation, evaporation from the soil and the interrow vegetation started to contribute significantly to total  $\lambda E$ , reaching a maximum 17 days into the drying cycle, when it comprised 15% of  $R_n$  for approximately 6 days. Leaves were wilted and presumably played a role in causing this response by increasing the ground area

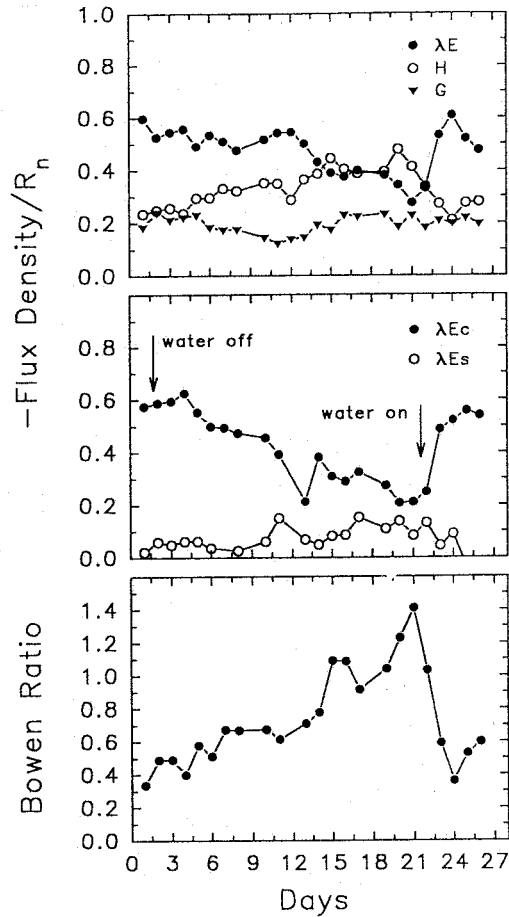


Fig. 4. The effects of a 25 day soil drying–irrigation cycle on the energy balance, partitioning of latent heat loss, and Bowen ratio in a coffee field with  $L = 6.7$  during August–September 1991.

exposed to direct radiation. Irrigation was resumed 25 days after the beginning of the drying cycle, and a quick recovery was observed for all the components of the energy balance, which returned to the original levels within 2 days.

#### 4. Conclusions

Perennial row crops such as coffee develop a tall, extensive canopy that shades the ground with dense foliage at high  $L$ , drastically reducing the area of soil exposed to direct radiation, and the amount of time during which the soil receives direct solar radiation. Under wide spacing and at low  $L$ , coffee hedgerows behaved similarly to annual row crops whose canopies seldom develop beyond  $L = 3$ , in that the contribution of  $\lambda E_s$  to total  $\lambda E$  was very large. At high  $L$ , important differences in energy

partitioning between coffee hedgerows and their annual counterparts became evident. These included the role of  $\lambda E$  as the most important component of the energy balance, and the relatively small contribution of  $\lambda E_s$  to total  $\lambda E$  in coffee fields. This contrasts sharply with annual row crops in which  $\lambda E_s$  accounts for 30–60% of total  $\lambda E$ . Mature coffee hedgerows thus behave more like closed forest canopies than widely spaced annual row crops.

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