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Seasonal Patterns of the Energy Balance Components in a Mango (*Mangifera indica* L.) Orchard grown in Northeast Brazil

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Abstract: Measurements of energy balance components were obtained in a field experiment to analyze the energy balance components on a mango orchard during two fruiting cycle. The Bowen Ratio-energy Balance (BREB) method was applied in order to estimate the energy fluxes while the reference evapotranspiration (ET_o) was obtained according to FAO 56. It was establish a relationship between latent heat flux (LE) and the net Radiation (R_n) for three availability energy levels. The results showed that during both field campaigns LE was found to be the major component of the energy balance, comprising more than 80% of the available energy, while G was always a small component, comprising less than 6% of total R_n. The daily mean values of ET_o and ET_c were similar in both measurement periods even though these were higher slightly in the 1998 fruiting cycle than values observed in 1999. For the 1998 and 1999 fruiting cycles the cumulative estimates of crop evapotranspiration (ET_c) were 719.3 and 675.8 mm, respectively, while the ET_o for these two experimental periods were 819.8 and 784.8 mm, respectively. The determination coefficients (r^2) values for the linear relationships between of net radiation and latent heat flux varied according to the available energy level, ranging from 0.82 for the moderate level in the 1998 fruiting cycle to 0.99 for the high available energy in 1999.

Key words: Net radiation, energy fluxes, phenological stages

INTRODUCTION

The mango fruit has become a great commercial interest in several countries due to its good acceptance in the international market. Currently, the mango fruit has been considered as an important economical alternative to Northeast Brazil. The semi-arid climate of this region presents very favorable aspects for the growth of many crops, mainly due to its energetic availability although offers some restrictions of water availability. The economic importance of tropical fruit has motivated the research development in many countries in the world, mainly those related to crop water use and evapotranspiration: vitis vinifera grape[1] strawberry plants[2] sweet lime[3] peach orchard[4] lemon orchard[5] and mango orchard[6].

The Bowen-ratio energy balance method has been widely applied[7,8,9], due to its relative simplicity and precision of water vapor vertical fluxes estimates. However, according to Steduto and Hsiao[10], this technique must be used with caution once it does not reproduce the turbulent nature of the evapotranspiration process. The least squares linear regression method has been used by some authors for establishing relationships between energy fluxes[11,12]. Since previous studies have shown high correlations between latent heat flux and net radiation data. This procedure has been very useful in agricultural meteorological studies. Thus, the estimates of the latent heat flux based on net radiation measurements can be important information to the purpose of irrigation scheduling of crops.

The objective of this research was to analyze the energy balance components throughout the fruiting cycle of a mango orchard grown in the climatic conditions of Northeast Brazil. It also attempted to establish relationships between net radiation and latent heat flux for different energy availability levels.

MATERIALS AND METHODS

Crop management and site description: A field experiments was conducted at the Bebedouro Experimental Station of the Brazilian Organization for Agriculture and Animal Research (*Embrapa Semi-Árido*) located in the middle reaches of San Francisco River Valley in Petrolina, PE, Brazil (latitude: 09°09'S longitude: 40°22'W altitude: 365.5 m above sea level). The Fig. 1 shows the location of site where the filed observations were made. Measurements were taken during the 1998 and 1999 fruiting cycles (from June to November) of a 7-years old mango (*Mangifera indica* L.) orchard, variety "Tommy Atkins". The orchard trees had

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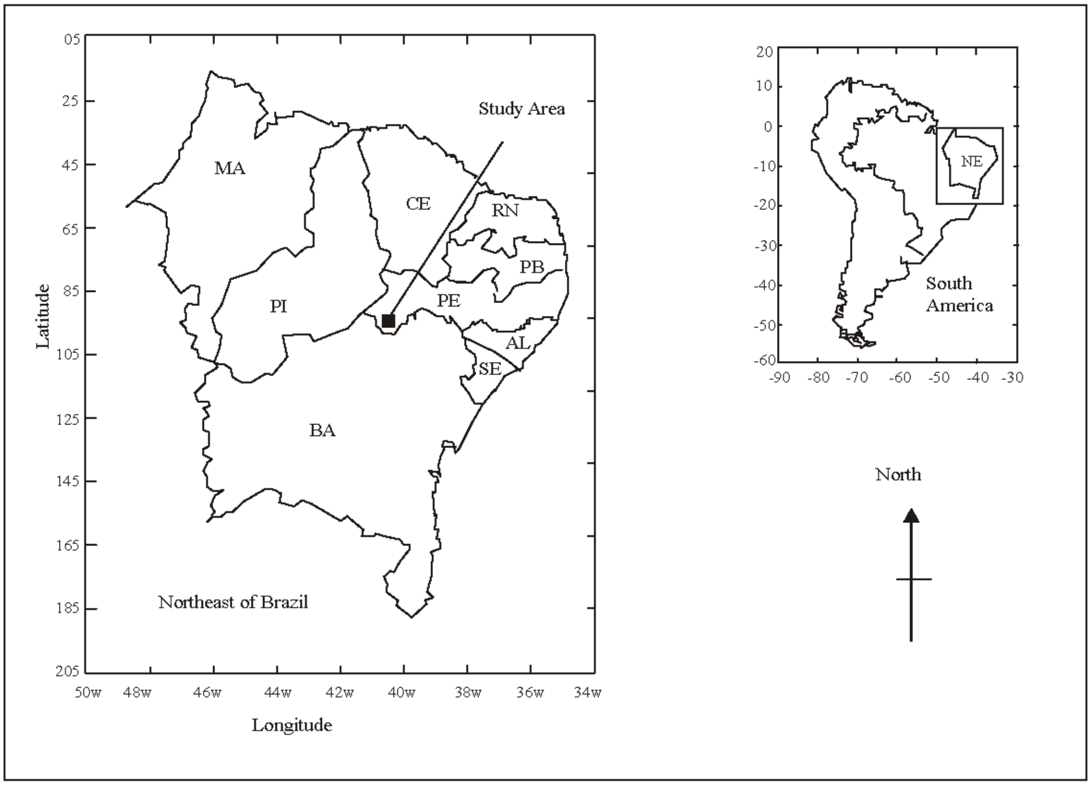

Fig. 1: Location of the study site [Embrapa Experimental Station of Bebedouro, Petrolina, PE, Brazil] and Northeast Brazil states: Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE) and Bahia (BA)

an average height of 5.2 m and were planted in February 1992, spaced of 8.0 m between rows by 5.0 m between trees. In both years, the fruiting cycle started with a flowering induction (application of a 4 % solution of potassium and calcium nitrate) and was divided into the following phenological stages, as a function of the Days After Flowering (DAF): flowering (from $0 \leq DAF \leq 20$) fruit fall ($21 \leq DAF \leq 70$) fruit growth ($71 \leq DAF \leq 120$) fruit maturation ($121 \leq DAF \leq 150$). In terms of day of year (DOY), the measurements covered the period from DOY = 161 to DOY = 319 with the phenological stages starting in the following dates: flowering: DOY = 161 (June, 10) fruit fall: (DOY = 182 (July, 1st) fruit formation: DOY = 222 (August, 10) fruit maturation: DOY = 272 (September, 29). In both measurement periods, the mango orchard was daily irrigated, using a well designed drip irrigation system with a water volume calculated according to procedures given by Azevedo *et al.*[6]

Measurements: A micrometeorological tower was mounted between two selected mango trees to collect energy flux data during two measurement periods. The sensors of net radiation, global solar radiation and wind speed were installed about 1 m above the canopy. Also, sensors of dry and wet bulbs temperature were installed at two levels (20 and 160 cm) above the orchard canopy. Three soil heat flux plates were buried at 2 cm beneath the soil surface under trees canopy (between two plants, close to the trunk of a plant and between two rows). All these sensors were connected to a 21X data logger (Campbell Scientific Inc, Logan, UT) which was programmed for collecting data once every 5 s and storage averages for every 10 min. Daily mean values of wind speed at 2 m height, maximum and minimum air temperature, relative humidity and sunshine were used to obtain the reference evapotranspiration (ET_o). The measurements of these variables were taken at the Bebedouro Meteorological Station, 300 m far from the experimental plot.

Bowen ratio-energy balance: The latent heat flux (LE) was obtained from the energy balance equation, neglecting the effects of advection, the energy stored in the canopy and photosyn thetic energy flux. Thus, assuming equality

Table 1: Average climate variables (± standard deviation) throughout the phenological stages of the mango orchard (flowering, fruit fall, fruit growth, fruit maturation) and total fruiting cycle in 1998 and 1999

Variables	Year	Flowering	Fruit Fall	Fruit Growth	Fruit maturation	Total cycle
Maximum temperature (°C)	1999	31.7±1.3	30.1±1.5	31.9±1.8	32.8 ± 2.5	31.7±2.1
	1998	31.2±1.6	31.4±1.4	32.9±1.4	35.3±1.1	33.0±2.1
Minimum temperature (°C)	1999	21.5±1.4	19.1±1.5	18.0±2.3	19.4 ± 2.5	19.2±2.4
	1998	21.6±1.1	21.5±1.3	22.3±1.3	24.4±1.3	22.6±1.7
Mean temperature (°C)	1999	25.5±0.8	23.9±1.2	24.6±1.4	25.8 ± 1.6	24.9±1.5
	1998	25.1±1.0	25.3±0.9	26.4±1.0	28.4±0.9	26.6±1.6
Relative humidity (%)	1999	59.2±8.9	65.2±10.7	66.9±6.8	68.9 ± 1.6	66.1±9.2
	1998	76.9±6.1	73.9±4.9	72.2±1.4	69.3±1.1	72.3±6.0
Global radiation ($MJm^{-2}d^{-1}$)	1999	15.4±3.6	14.3±3.8	19.3±3.9	18.9 ± 1.6	17.4±4.6
	1998	15.1±3.3	15.9±3.0	19.8±3.6	22.1±4.2	18.9±4.5
Pan evaporation (mm)	1999	6.2±1.5	6.7±1.6	7.9±2.2	8.1 ± 2.3	7.5±2.1
	1998	6.5±1.8	6.9±1.6	8.7±1.4	10.1±1.6	8.4±2.1
Wind speed (ms^{-1})	1999	2.4±0.6	2.2±1.4	3.2±0.6	1.7 ± 1.5	2.4±1.3
	1998	2.9±0.7	2.9±0.6	3.0±0.5	2.6±0.7	2.9±0.6
sunshine (h)	1999	8.0±3.1	7.3±2.9	8.6±2.6	7.0 ± 3.8	7.7±3.2
	1998	7.1±3.0	7.5±2.3	9.0±1.9	9.5±1.8	8.5±2.3
Total rainfall (mm)	1999	0	3.2	31.6	18.1	52.9
	1998	4.6	0.7	7.2	34	46.5

Table 2: Equations for the estimation of the latent heat flux for low, moderate and high levels of available energy and energy consumed ratios as latent heat flux (LE/R_n), sensible heat flux (H/R_n) and soil heat flux (G/R_n)

Available energy	Equation	r^2	ϵ_{yx} ($W m^{-2}$)	LE/R_n (%)	G/R_n (%)	H/R_n (%)
Year 1998						
Low	$LE = - 9.28 - 0.87 R_n$	0.87	19.2	91.3	0.8	7.9
Moderate	$LE = -16.35 - 0.71 R_n$	0.82	49.1	76.1	2.8	21.1
High						
High	$LE = -13.58 - 0.69 R_n$	0.88	44.5	74.6	5.9	19.5
Year 1999						
Low	$LE = -18.18 - 0.84 R_n$	0.94	20.7	94,1	2,9	3.0
Moderate	$LE = - 2.22 - 0.92 R_n$	0.98	18.0	93.0	3.9	3.1
High	$LE = -18.77 - 0.77 R_n$	0.99	9.0	81.6	5.6	12.8

r^2 = determination coefficient, ϵ_{yx} = standard error of estimation

between the turbulent diffusion coefficients of sensible heat flux (K_h) and latent heat flux (K_w) and considering that the relation between the gradients of air temperature and vapor pressure $(/Z) / (e_a/Z)$ is approximately equal to $\Delta T/\Delta e_a$, as well as the Bowen ratio (β = H/LE ≅ γ ÄT/Äe$_a$), LE ($W m^{-2}$) was obtained as[7]:

$$LE = -\left(\frac{R_n - G}{1 + \gamma \Delta T / \Delta e_a}\right) \quad (1)$$

where R_n ($W m^{-2}$) is the net radiation, G ($W m^{-2}$) the soil heat flux, γ ($kPa\ °C^{-1}$) the psychometric constant, $\Delta T = T_2 - T_1$ (°C) and $\Delta e_a = e_2 - e_1$ (kPa) are air temperature and water vapor pressure measurements at two levels above the canopy, respectively. Then, the sensible heat flux (H, in $W m^{-2}$) was computed as residuals of the energy balance equation, as follows:

$$H = -\left(R_n + LE + G\right) \quad (2)$$

Reference evapotranspiration: The daily reference evapotranspiration (ET_o) was obtained by FAO Penman-Monteith approach. Thus, considering a hypothetical crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and albedo of 23%, ET_o ($mm\ d^{-1}$) was obtained as:[13]

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left(\frac{900\,U_2}{T + 273}\right)(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

where R_n is the daily net radiation ($MJ\ m^{-2}d^{-1}$), G the soil heat flux ($MJ\ m^{-2}d^{-1}$), Δ the slope of the vapor pressure curve ($kPa°C^{-1}$), γ the psychometric constant ($kPa°C^{-1}$), T the air temperature (°C), U_2 (ms^{-1}) the wind speed measured at 2 m height and e_s-e_a (hPa) the vapor pressure deficit. The soil heat flux was assumed to be zero in a 24-hours period.

All the energy balance components were obtained for the daytime periods (i.e., $R_n > 0$). Moreover, the fluxes were considered positive when downwards and negative when upwards of the surface.

RESULTS AND DISCUSSION

Climatic conditions: The 1998-1999 fruiting cycles had groundwater table about of 250 cm below soil surface while the major roots concentration occurred in the soil layer between 140 and 200 cm. For each phenological

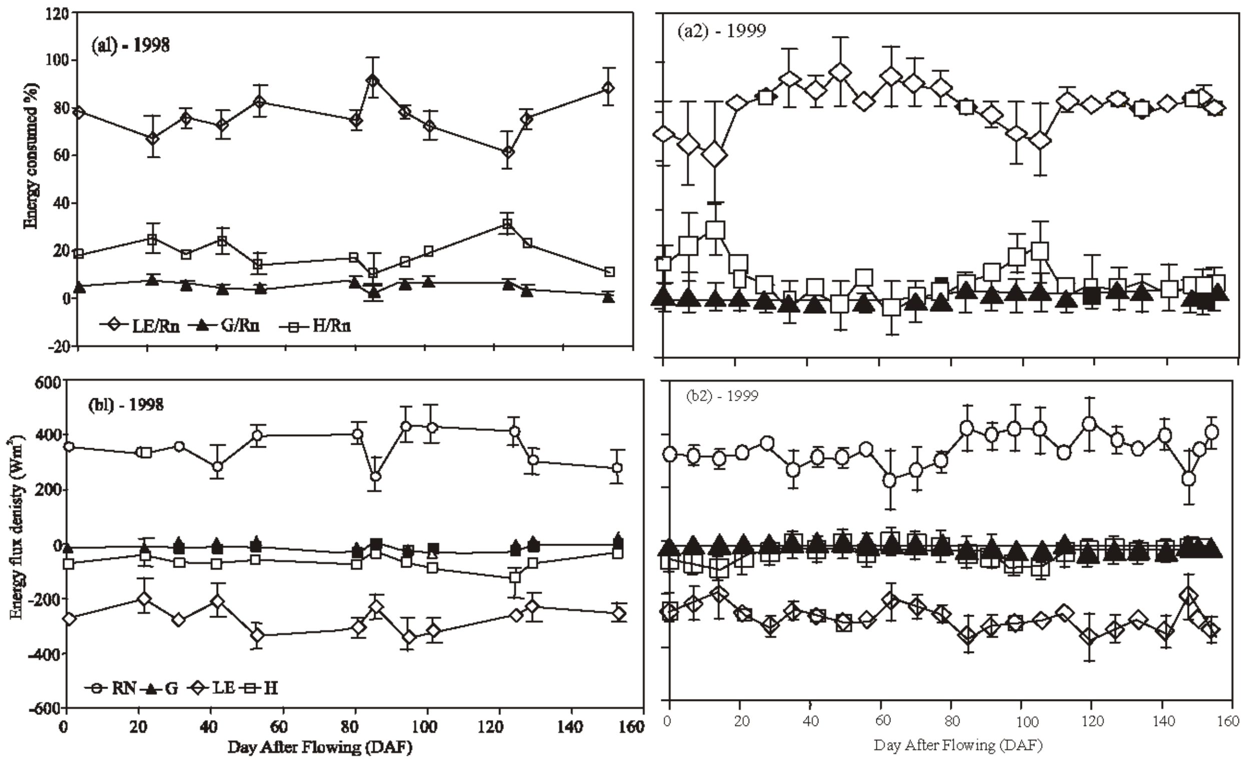

Fig. 2: Time course of the energy consumed (a1 and a2) and the energy balance components (b1 and b2). Vertical bars indicate the mean ± standard deviation, 1998 (n @ 13) and 1999 (n @ 7)

stage of the mango orchard fruiting cycle, the mean and standard deviation of the climatic variables in 1998 (1) and 1999 (2) are shown in Table 1. The total cycle means of the all analyzed climatic variables were less in 1999 than 1998. This behavior also occurred in all stages of development of the fruiting cycle except in the flowering stage where the mean values of maximum and mean air temperatures, global solar radiation and sunshine were higher in 1999 than in 1998. Also, the accumulated rainfall in 1999 was higher than in 1998. The daily mean air temperature observed in 1998 and 1999 were 26.6 ± 1.6 °C and 24.9 ± 1.5 °C, respectively, while the long-term normal is 26.2 ± 0.9 °C[6].

Relationship between net radiation and sensible heat flux: The cloudiness affects the order of magnitude of several atmospheric variables, such as solar radiation, air temperature, relative humidity and sensible and latent heat fluxes. Since well calibrated, both net radiometers and heat flux plates provide good measurements of net radiation and soil heat flux, respectively. However, the measurements of the vertical gradients of air temperature and relative humidity may show inconsistent values due to instrumental maintenance and calibration. So that, it was established three ranges of evaporative demand as a function of the net radiation: a) low ($R_n \leq 250$ W m^{-2}), moderate (250 W $m^{-2} < R_n <$ 350 W m^{-2}) and high ($R_n \geq$ 350 W m^{-2}), corresponding to high, average and low cloudiness, respectively. Table 2 presents the regression equations for three levels of evaporative demand. The high values of the determination coefficient (r^2) indicated good relationships between LE and R_n. This result may be used in the current management practices in mango orchard such as provide the crop evapotranspiration missing data from the regression equations. Hölscher *et al.*.[14] obtained missing data of LE as a function of the average evaporative ratio (LE/R_n) for the four months period before occurrence of instrumental technical problems. The relationship between LE and R_n, throughout the mango orchard fruiting cycle, was lower in 1998 than in 1999, due to the strong variability of cloud cover in 1998. This can be observed from the relatively low values of r^2 and the large values of the estimation standard errors. Silberstein *et al.*. [11] also attributed the larger values of the standard errors to the cloudiness changing. Zhang and Lemear[15] observed that the latent heat flux strongly respond to the magnitude of the incident solar radiation. Also, considering that LE follows the daytime course of the solar radiation, Sugita and Brutsaert[16] obtained the latent heat flux in terms of its similarity with others components of the energy balance.

Energy consumed ratios: The percentage of net radiation consumed as latent heat flux was higher for periods with low evaporative demand (Table 2), which reached 91.3 and 94.1% in 1998 and 1999, respectively. Inversely, for periods with high evaporative demand, LE comprised 74.6% and 81.6% of R_n in 1998 and 1999, respectively. In both years, the percentage of R_n used as soil heat flux was less than 6% for all available energy level. On the other hand, the H/R_n ratio varied from minimum value of 3% in 1999 (low level) to maximum value of 21.1% in 1998 (moderate level). Lafleur[17] observed that G was always a small component of the energy balance in subartic forest, comprising 9% of total R_n.

Time course of energy balance components: Figure 2 shows the time course of the energy consumed (a1 and a2) and the energy balance components (b1 and b2) throughout the 1998 and 1999 mango orchard fruiting cycles. In both years, the energy consumed was higher during the fruit fall and fruit growth phenological stages and lower during the flowering and fruit maturation stages. In the 1998 measurement period, the average percentages of net radiation consumed were: LE/R_n = 77.7% H/R_n = 18.0% and G/R_n = 4.4%, while in the 1999 fruiting cycle these percentages were: LE/R_n = 81.7% H/R_n = 10.1% and G/R_n = 5.7% (Figs. 2a1 and a2). On the other hand, the mango orchard daytime average values of the energy balance components in the 1998 fruiting cycle were: R_n = 354.5 W m^{-2} LE = 292.5 W m^{-2} H = 65.16 W m^{-2} and G = 16.4 W m^{-2}, while in the 1999 fruiting cycle these values were: R_n = 340.8 W m^{-2} LE = 280.8 W m^{-2} H = 40.5 W m^{-2} and G = 21.1 W m^{-2} (Figs. 2b1 and b2). In general, H and G changed relatively little throughout both fruiting cycles as compared to the variation of R_n and LE, which presented high values of the standard deviation for the same period of the fruiting cycle. Although the energy fluxes were greater in 1998 than in 1999, H and G showed little values throughout both fruiting cycles. It is suggests that in an irrigated area, the soil water availability for the plants and thus their transpiration result in lower sensible heat transfer to the air and to the soil. The 1998 fruiting cycle had evaporative demand as well as ET_0 and ET_c greater than in 1999.

Cumulative evapotranspiration: The cumulative ET_0 and ET_c during 1998-1999 mango orchard fruiting cycles are presented in Fig. 3. All cumulative estimates observed in 1998 were greater than those observed in 1999. The 1998 fruiting cycle had higher energy availability (Table 1 and Fig. 2), which was responsible for the greater values of ET_0 and ET_c observed in that year. Cumulative estimates of ET_c during the 1998-1999 fruiting cycles were 719.3 and 675.8 mm, respectively, while those of ET_0 were 819.8 and 784.8 mm, respectively. In general, cumulative ET_c and ET_0 were greater in 1998 than in 1999 due to the high evaporative demand recorded in 1998. Inman-Bamber and McGlinhey[18] observed that simulated cumulative ET_c was similar to measured cumulative ET_c until the summer of 1968/1969 when the simulated values increased more rapidly than the measured values. On the other hand, analyzing the seasonal pattern of cumulative energy balance fluxes, Lafleur[17] observed that early in the study, the cumulative value of H was larger than that of LE.

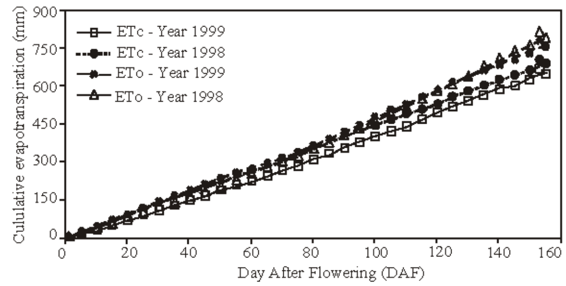

Fig. 3: Cumulative reference (ET_0) and crop (ET_c) evapotranspiration in the 1998-1999 fruiting cycle

The results obtained indicated that the latent heat flux (LE) can be obtained, with reasonable precision, as a function of the net radiation (R_n). The relationship between LE and R_n is better for high than for moderate and low energy availability, mainly for conditions of little cloudiness variability. The amount of net radiation used for the crop evapotranspiration process was greater for the fall and growth stages and lesser for the flowering and fruits maturation stages. The results also indicate that the daily mean values of ET_0 and ET_c were similar in both fruiting cycle in spite of higher slightly in 1998 than 1999. This was due to the greater atmospheric demand during the 1998 fruiting cycle.

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