Partitioning energy fluxes between canopy and soil surface under sparse maize during wet and dry periods

Zeggaf T.A., Anyoji H., Takeuchi S., Yano T.

in

Lamaddalena N. (ed.), Bogliotti C. (ed.), Todorovic M. (ed.), Scardigno A. (ed.).
Water saving in Mediterranean agriculture and future research needs [Vol. 1]

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 56 Vol.I

2007
pages 201-211

PARTITIONING ENERGY FLUXES BETWEEN CANOPY AND SOIL SURFACE UNDER SPARSE MAIZE DURING WET AND DRY PERIODS

T. A. Zeggaf *, H. Anyoji **, S. Takeuchi * and T. Yano *****

* INRA-Settat, BP. 589, Settat, Morocco (e-mail: zeggaf.adel@yahoo.co.uk)

** Arid Land Research Center, Tottori University, 1390 Hamasaka, Tottori 680-0001, Japan

*** Faculty of Engineering, Kyushu Kyouritsu University, 1-8 Jiyugaoka Yahata-nishi-ku, Kitakyushu 807-8585, Japan

SUMMARY- Energy flux measurements were carried out in an open field of sparse maize (4 plants m^{-2}). The Bowen ratio energy balance method was applied both over crop canopy and soil surface levels to measure latent heat fluxes from maize field and soil surface respectively. Canopy latent heat flux was obtained by the difference between that of maize field and soil surface. Measurements were taken during a six-day wet (daily irrigation) and dry (irrigation was halted) periods. Comparisons between energy balances during the two periods were analyzed through the ratio of latent heat fluxes from maize field, canopy and soil surface to respective available energies. Results showed that, during the two periods, maize field latent heat flux was a major part of available energy at maize field level (> 90%). No major differences in energy balance patterns were observed between the two periods at maize field level. However, at soil surface level, sensible heat flux increased and available energy at soil surface was almost equally used to drive latent and sensible heat fluxes during the dry period. During this period, the canopy was absorbing sensible heat flux that was generated at soil surface. Sensible heat flux from soil surface, during the dry period, contributed up to 31 % to latent heat flux from canopy. During the wet period, canopy and soil surface were fully evaporating water and no major energy exchanges between soil surface and canopy were observed. This study showed the importance of irrigation scheduling in reducing soil evaporation and increasing transpiration.

INTRODUCTION

Radiation balance studies of row crops indicate that radioactive exchange between soil and canopy can also influence latent heat flux from the canopy (λEc) and soil (λEs) (Tanner et al., 1960; Fuchs, 1972). Energy exchange in full canopies has been examined by making within-canopy flux profile measurements of heat and water vapor and using the Bowen ratio method to calculate the energy balance of vertical layers within the canopy (Begg et al., 1964). Brown and Covey (1966) showed that regions of high temperature could develop within the maize canopy resulting in sensible heat transport to soil and the upper canopy, simultaneously. Hanks et al. (1971) found soil temperature often exceeded canopy temperatures by 20^{o}C, and that 21 % of λE_c was the result of sensible heat flux absorbed from soil.

Few studies investigated simultaneously canopy and soil energy balances at different water regimes. Steduto and Hsiao (1998) using the Bowen ratio energy balance (BREB) method for measuring evapotranspiration at two different water regimes reported higher Bowen ratios at dry than at wet water regimes. The reason was an increase in radiant energy used for sensible heat flux at dry water regime. Jara et al. (1998) reported that despite reductions in leaf area, dry matter production and grain yield, it was possible to differentiate transpiration rates (sap flow) between dry and wet treatments only at the end of the season.

The objective of this study was to evaluate the ability of the BREB method to measure energy balances of maize field and soil, and to detect differences in water use of maize under two water regimes.

MATERIAL AND METHODS

Energy balances over maize field and soil surface were achieved using the Bowen ratio approach. Comparison of the results of this method with direct measurements and its accuracy were studied by

Zeggaf, 2006. In this experiment, we studied energy fluxes of maize field during two periods. In the first period referred to as wet period, a daily irrigation regime was applied at maize field. In the second period referred as dry period, irrigation was halted during six days and energy fluxes measured.

Experimental site

The experiment was carried out during the 2005 summer season on a 120 m by 40 m plot (Fig. 1) at the experiment station of Arid Land Research Center, Tottori University, Japan (35^o 32' N, 134^o 13' E, 23 m above sea level). Maize (var. Pioneer 31N27) was sown on 20 June 2005 at a density of 4 plants m^{-2}. The crop was established on a flat surface within a 0.5 m row spacing and north-south row orientation. No furrows or raised beds were present in the field and weeds were removed manually prior to the experiment. A sprinkler irrigation system (12 x 15 m) was used to apply irrigation water. Recommended fertility management practices were used to ensure adequate nutrients for crop growth (Eneji, 2003).

The period of measurements started on 42 days after emergence (DAE), when leaf area index (*L*) was 0.67, and terminated on 61 DAE, when *L* was 1.13. During the wet period (from 42 to 47 DAE), a daily irrigation of 8 mm day^{-1} was applied (at night time), which was 10 to 20 % higher than maximum daily evapotranspiration at summer time in Tottori region (Dehghanisanij et al., 2004). During the dry period (from 55 to 61 DAE), irrigation was halted.

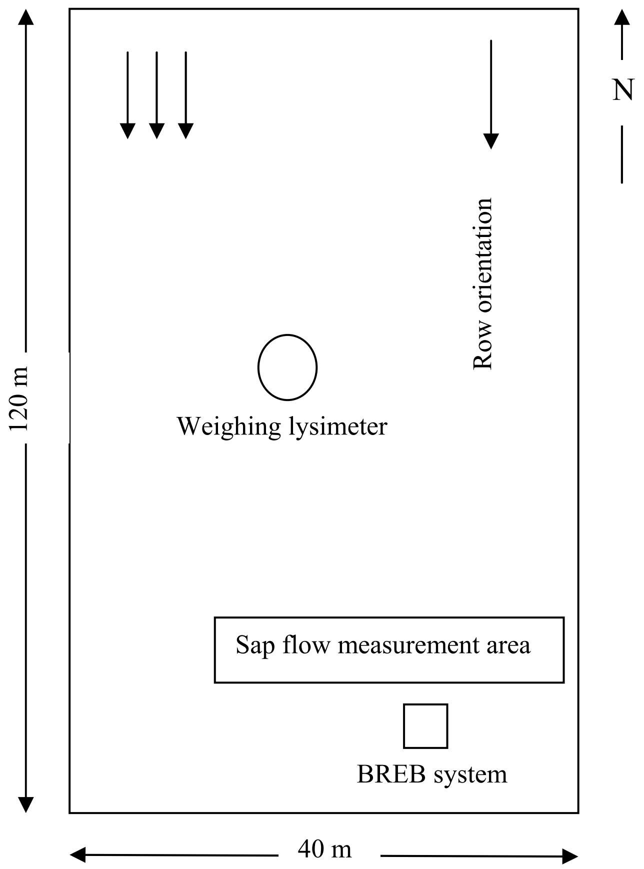

Fig. 1. Position of the BREB method, sap flow and weighing lysimeter measurements

Energy balance of maize field

The energy balance of maize field can be expressed as:

$$R_n = \lambda E + H + G \tag{1}$$

Where:

R_n: net radiation above canopy, λE: latent heat flux, H: sensible heat flux, and G: soil heat flux, all units of W m^{-2}.

In Eq. 1, the convention used for the signs of the energy fluxes is R_n positive downward and G is positive when it is conducted downward from the surface. λE and H are positive upward, with a direction opposite to that of the temperature and vapor pressure gradients.

Over an averaging period, assuming equality of the eddy transfer coefficients for sensible heat and water vapor (Verma et al., 1978), and measuring the temperature and vapor pressure gradients between two levels within the adjusted surface layer, the Bowen ratio (β) is calculated by:

$$\beta = \gamma \frac{\partial T / \partial z}{\partial e / \partial z} = \gamma \frac{\Delta T}{\Delta e} \tag{2}$$

Where:

ΔT and Δe: temperature and vapor pressure differences between the two measurement levels nrespectively,

$\gamma = \frac{c_p\ p}{\varepsilon\ \lambda}$: psychrometric constant

c_p : Specific heat of air at constant pressure (1.01 kJ kg^{-1} ^{o}C^{-1})

p : Atmospheric pressure (kPa), ε : ratio between molecular weights of water vapor and air (0.622)

p and λ: latent heat of vaporization (kJ kg^{-1}).

The partition of energy between λE and H is determined by the BREB method (Tanner et al., 1960; Kustas et al., 1996, Perez et al., 1999) by means of β as:

$$\beta = \frac{H}{\lambda E} \tag{3}$$

The Bowen ratio (Eq. 3) is used with the energy balance (Eq. 1) to yield the following expressions for λE and H:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{4}$$

$$H = \frac{\beta}{1 + \beta} (R_n - G) \tag{5}$$

The energy balance of the maize field was measured by a BREB unit located 10 m from the south edge of the plot to maximize fetch when prevailing northerly winds were present (Fig. 1). Minimum fetch to height ratio within the plot was 40:1. This ratio was well above the minimum of 20:1 reported by Heilman et al. (1989) for Bowen ratio measurements. Air temperature and vapor pressure gradients were determined from two dry and wet bulb ventilated psychrometers. The distance between the two psychrometers was 1 m, and the lowest psychrometer was positioned at 0.2 m above the canopy. Net radiation at 1 m above the canopy, was measured by a Q-7.1 net radiometer (Campbell Scientific, Inc., UT, USA). Soil heat flux was calculated as an average value of two heat flux plates measurements (MF-180M, EKO, Tokyo, Japan) at 2 cm below soil surface. Wind speed was measured, 1 m above the canopy, by a Met One wind speed sensor (Model 014A, Campbell Scientific, Inc., UT, USA). The soil temperature profile was measured by thermocouples (copper-constantan thermocouples) at 0, 3, 5, 7, 10, 20, 30 and 50 cm depths. All data were measured every minute by a 21X datalogger and AM416 multiplexer (Campbell Scientific, Inc., UT, USA) and averaged over 10 minutes's time interval.

Energy balance of soil

The energy balance of soil can be expressed as:

$$R_{ns} = \lambda E_s + H_s + G \quad (6)$$

Where:

R_{ns}: R_n to soil surface
λE_s: soil latent heat flux
H_s: sensible heat flux from soil, all units of W m^{-2}.

Net radiation to soil was determined from the exponential attenuation equation (Eq. 7) of R_n with leaf area index (L) (Uchijima, 1976).

$$R_{ns} = R_n \exp\left(-0.622\, L + 0.055\, L^2\right) \quad (7)$$

Leaf area index was measured weekly by a LAI-2000 Plant Canopy Analyzer (LI-COR, Inc., Nebraska, USA), and linear interpolation was applied between measurements.

Similar to maize field, the Bowen ratio at soil surface level (β_s) was calculated by:

$$\beta_s = \frac{H_s}{\lambda E_s} \quad (8)$$

Where:

λE_s and H_s: determined from Eq. 6 and 8 as by Eq. 4 and 5, respectively.

The energy balance of soil surface was measured at the same location as that of the maize field. Following a similar set-up made by Ashktorab et al. (1989) over bare soil, air temperature and vapor pressure gradients within the rows were determined from two dry and wet bulb ventilated psychrometers. The distance between the two psychrometers was 0.1 m, and the lowest psychrometer was positioned 0.05 m above soil surface.

Energy balance of canopy

The energy balance of canopy can be expressed as:

$$R_{nc} = \lambda E_c + H_c \quad (9)$$

Where:

R_{nc}: R_n intercepted by canopy
λE_c and H_c: fluxes of latent and sensible heat from canopy respectively.

Applying the principle of continuity and the definition of R_n, it can be shown that R_{nc} is the difference between R_n above and below the canopy (Ham et al., 1991).

$$R_{nc} = R_n - R_{ns} \quad (10)$$

Where:

R_n : measured, and R_{ns}: calculated by Eq. 7.

Several researchers used a similar approach (Eq. 7 and 10) to explore soil-canopy relationships (Fuchs, 1972; Kanemasu and Arkin, 1974).

Canopy latent heat flux was calculated by Eq. 11, while H_c was calculated as a residual from Eq. 9.

$$\lambda E_c = \lambda E - \lambda E_s \quad (11)$$

RESULTS AND DISCUSSION

Diurnal pattern of energy fluxes from maize field for the wet and dry periods

Diurnal patterns of energy fluxes from maize field for the wet and dry periods by the BREB method are shown in Fig. 2. Soil heat flux ranged from 7 to 15 % of R_n for both periods, which is close to the common value of 10 % reported by Yunusa et al. (2004). In fact some authors reported very small *G* for dense maize canopy (*L* = 5.3), but this component was larger for incomplete canopy (*L* = 0.58) because of the exposed and dry soil (Steduto and Hsiao, 1998). As reported by Steduto and Hsiao (1998), latent heat flux from maize field (λE) was closely coupled to R_n, giving rise to a nearly perfect coincidence between R_n and λE in their rise and fall shown in Fig. 2, when changing clouds effected rapid fluctuation of radiation. This result was expected as the net radiation is the main source of energy for evapotranspiration.

For the wet period, λE was at its full rate as shown in Fig. 2a, using almost all R_n , indicating that the crop was not suffering from water restriction. Sensible heat flux was very small and could be accounted as negligeable. During this period, λE was always smaller or equal to net radiation indicating no major advective conditions prevailed and that the adopted fetch was adequate to measure energy fluxes for the maize field. Similar results have been reported for other crops as cotton and vineyard (Ham et al., 1991; Yunusa et al., 2004).

For the dry period, *H* slightly increased relatively to the wet period but was still low as shown in Fig. 2b. Sensible heat was almost positive during daytime and ranged from 5 and 8 % of R_n. The Bowen ratio (β) for the dry period was slightly greater than that for the wet period. Similar result was reported by Steduto and Hsiao (1998) for maize for the dry soil water regime. However, even when irrigation was halted, λE still represented a large part of the available energy (around 93 %). This result suggested that water stress was not evident on evapotranspiration for a period of six days after irrigation was halted.

Available energy (R_n - G) and λE from maize field for the wet and dry periods are shown in Fig. 3. The linear regression lines between λE and R_n - G were obtained with high values of r^2 as shown in the following Eqs. 12 and 13. Similar results were obtained by Ham et al. (1991) who reported that within row advection increased λE_c, and that the difference in total λE from the wet and dry soil was not significant. They concluded that management practices aimed at reducing soil evaporation might increase canopy transpiration and not reduce total evapotranspiration. As reported by Steduto and Hsiao (1998) who wrote about the pivotal role of radiation in latent heat flux, our data confirmed the strong dependence of evapotranspiration on the amount of available energy during both periods. However, this dependence was much higher for the wet than for the dry period. Also, greater data scatter was observed during the dry period, especially when energy fluxes were low.

For the wet period:

$$\lambda E = 0.97\left(R_n - G\right), \text{ with } r^2 = 0.99 \quad (12)$$

For the dry period:

$$\lambda E = 0.95\left(R_n - G\right), \text{ with } r^2 = 0.97 \quad (13)$$

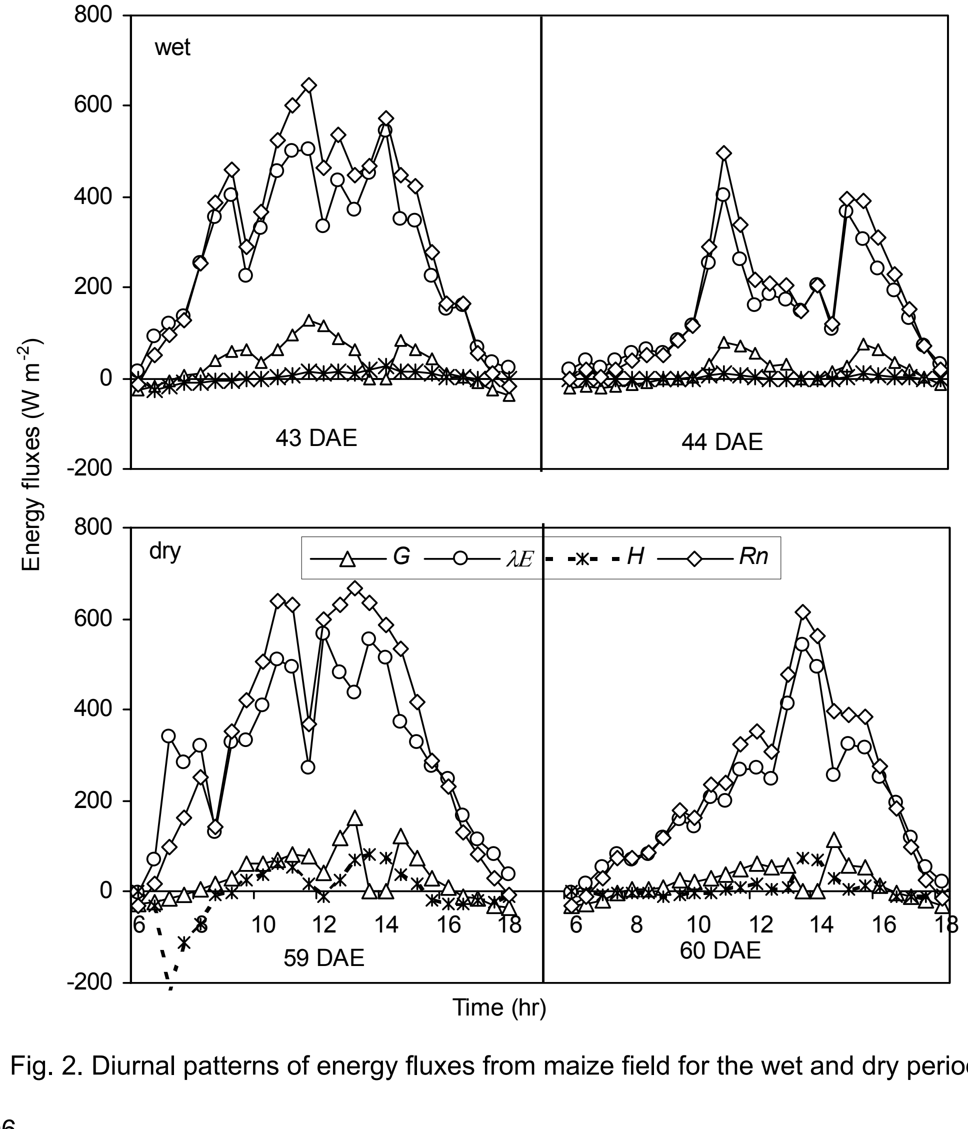

Fig. 2. Diurnal patterns of energy fluxes from maize field for the wet and dry periods

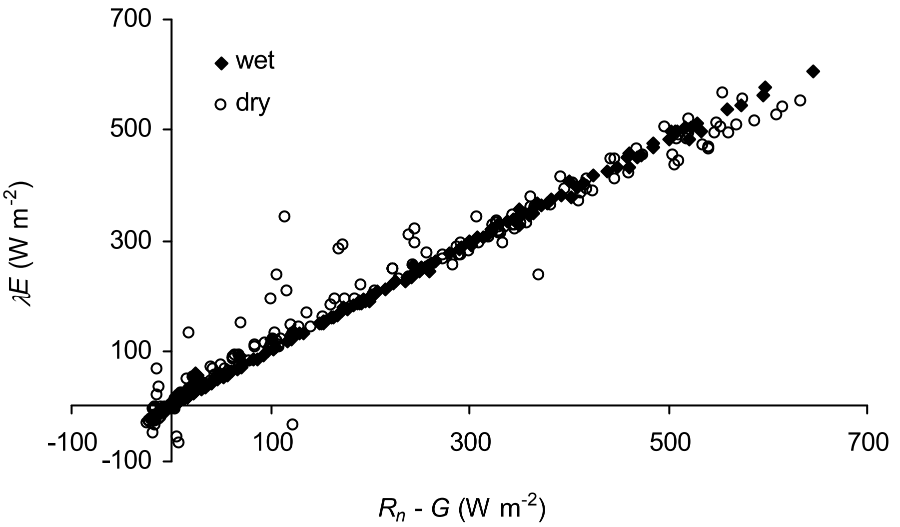

Fig. 3. Available energy (R_n - G) and latent heat flux (λE) from maize field for the wet and dry periods

Diurnal pattern of energy fluxes from soil for the wet and dry periods

Diurnal patterns of energy fluxes from soil for the wet and dry periods by the BREB method are shown in Fig. 4. There were large differences in energy flux patterns between the wet and dry periods. For the wet period, almost all available energy was directed to generate latent heat flux, while soil sensible heat flux (H_s) remained negligible during daytime. At morning, soil sensible heat flux was low and negative indicating that soil surface temperature was low, creating an energy sink at soil surface. The ratio of H_s to net radiation to soil (R_{ns}) was less than 5 % and therefore was negligible. Similar conditions were reported for cotton by Ham et al. (1991) after irrigation. They concluded that a wet soil appears to reduce λE_c by acting as a sink for advective energy, while reducing the radiation load on the canopy. For the dry period, R_{ns} was almost equally divided into outgoing latent and sensible heat fluxes. This suggested that soil was not evaporating at its potential rate. During this period, a shortage of soil water content at the soil upper layer reduced soil evaporation and much energy was directed to warm the soil rather than to evaporate soil water. Similar results were reported by Ham et al. (1991) on cotton, who reported that soil evaporation proved to be the primary form of latent heat flux when soil was wet, even when the L was between two and three, and that soil evaporation was markedly reduced by dry surface conditions.

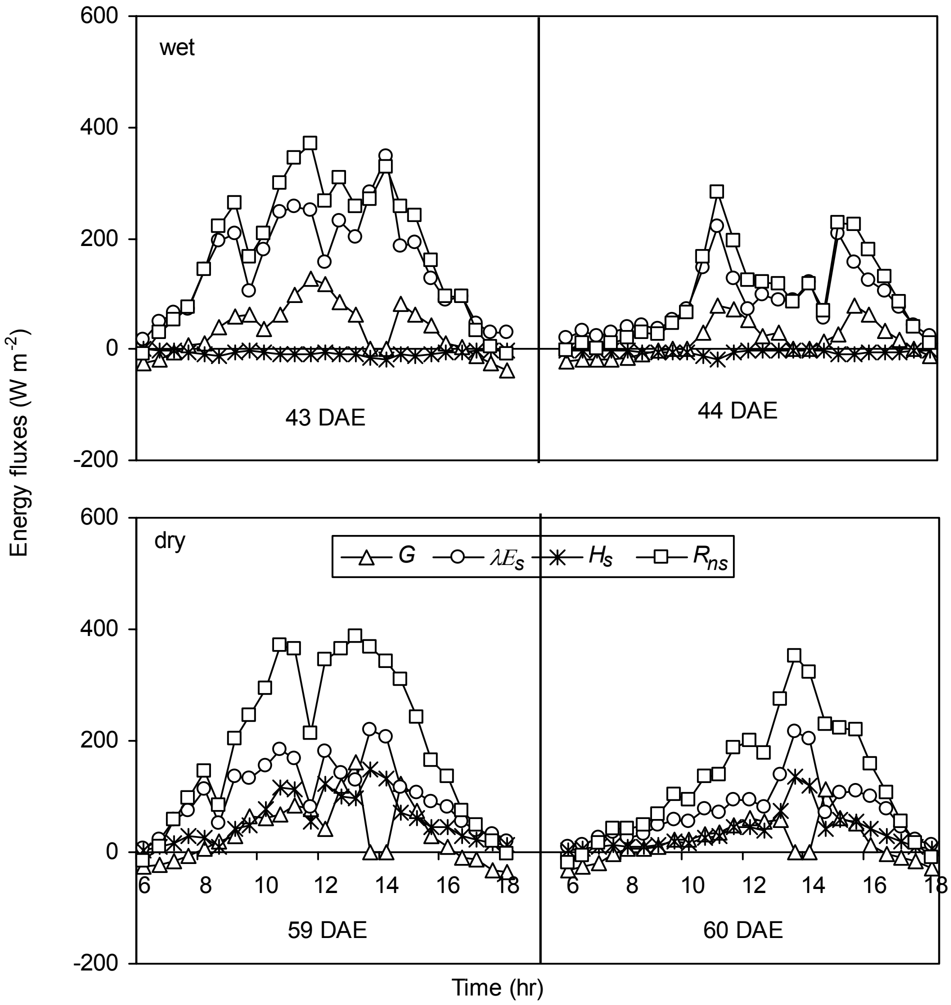

Fig. 4. Diurnal patterns of energy fluxes from soil for the wet and dry periods

Available energy (R_{ns} - G) and latent heat flux from soil for the wet and dry periods are shown in Fig. 5. A reduction of λE_s for the dry period of about 35 % of available energy to soil surface was observed. Also, more scattered data were observed for the dry period, indicating lower dependence of latent heat flux from soil on R_{ns}.

For the wet period:

$$\lambda E_s = 1.07\left(R_{ns} - G\right), \text{ with } r^2 = 0.99 \qquad (14)$$

For the dry period:

$$\lambda E_s = 0.65\left(R_n - G\right), \text{ with } r^2 = 0.94 \qquad (15)$$

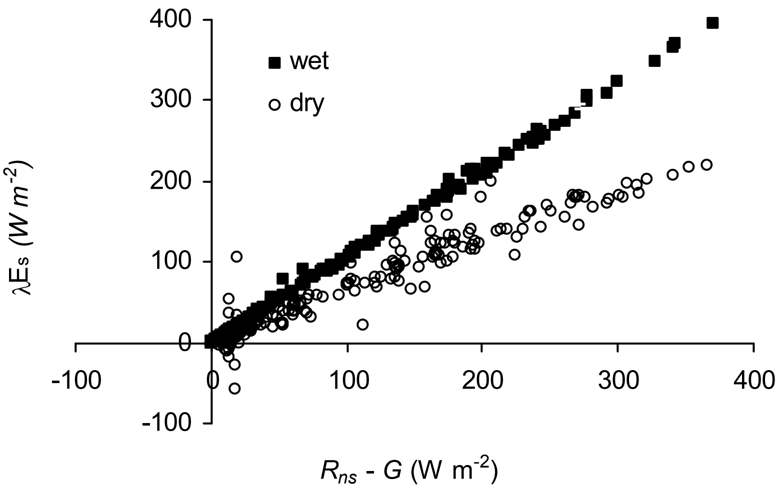

Fig. 5. Available energy (R_{ns} - G) and latent heat flux (λE_s) from soil for the wet and dry periods

Diurnal pattern of energy fluxes from canopy for the wet and dry periods

Diurnal patterns of energy fluxes from canopy for the wet and dry periods by the BREB method are shown in Fig. 6. There were large differences in energy flux patterns from canopy between the wet and dry periods.

For the wet period, canopy latent heat flux (H_c) was low and most of the available energy for canopy was directed to generate λE_c, mainly because of sparse canopy. During this period no major energy exchanges occurred between soil and canopy.

Negative values of H_c, and positive values of H and H_s, indicated that the canopy was absorbing sensible heat that was generated at soil surface during the dry period. The within-row advection occurred during most of the day. However, Heilman et al. (1994) for vineyard reported similar observations occurred mainly in the afternoon where canopy temperature was as much as 5^{o}C lower than air temperature. Also, Ham et al. (1991) reported for cotton that a wet soil appears to reduce λE_c by acting as a sink for advective energy, while also reducing the radiation load on the canopy. Extensive literature concerning radiation balance studies of row crops indicated soil and canopy could influence λE_c and λE_s (Tanner, 1960; Fuchs, 1972). However, inadequate measurements techniques have limited research to a specific set of conditions or the examination of a singular process (Ham et al., 1991).

Available energy (R_{nc}) and latent heat flux from canopy for the wet and dry periods are shown in Fig. 7. λE_c for the dry period was clearly increased relative to the wet period as shown in Fig. 7. The linear regression lines between λE_c and R_{nc} were obtained with high values of r^2 as shown in the following Eqs. 16 and 17.

For the wet period:

$$\lambda E_c = 0.87\ R_{nc}\text{, with } r^2 = 0.99 \quad (16)$$

For the dry period:

$$\lambda E_c = 1.26\ R_{nc}\text{, with } r^2 = 0.93 \quad (17)$$

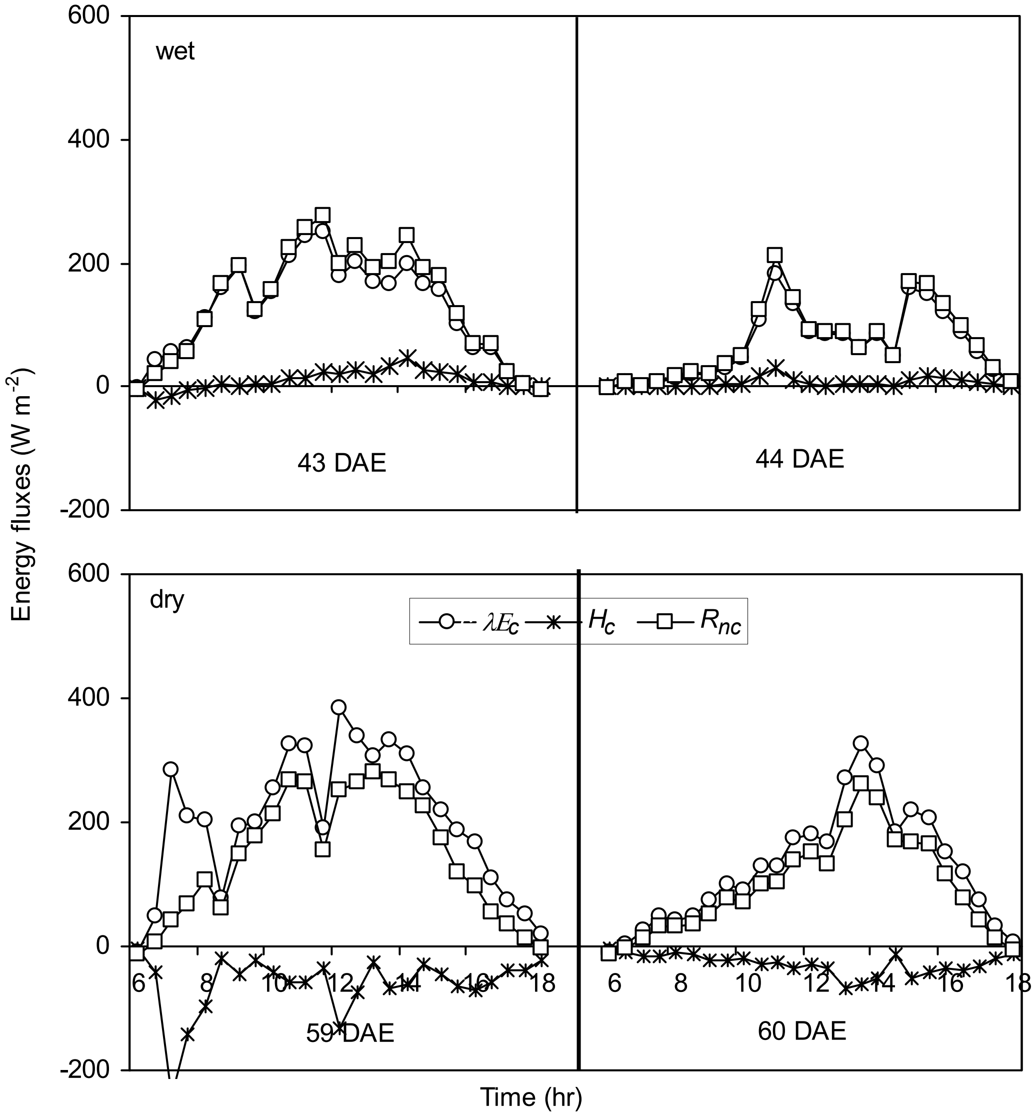

Fig. 6. Diurnal patterns of energy fluxes from canopy for the wet and dry periods

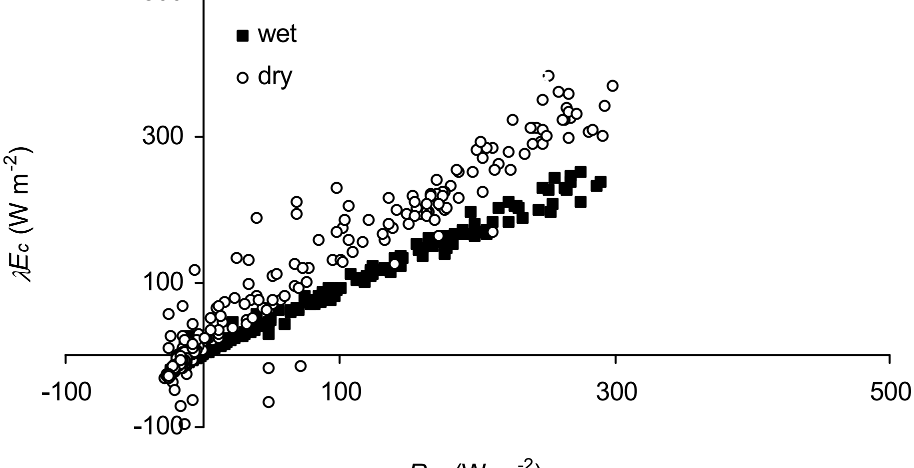

Fig. 7. Available energy (R_{nc}) and latent heat flux from canopy (λE_c) for the wet and dry periods

CONCLUSION

Measurements of energy balances over maize field, soil and canopy by the Bowen ratio Energy Balance method indicated that soil had a major impact on the energy balance between canopy and maize.

Energy balances of maize field for the wet and dry periods were almost identical, while energy balances of soil and canopy were quite different. This demonstrated that maize field energy balance measurements alone provide virtually no information on how energy balances of soil and canopy are partitioned.

Future studies are needed to examine how canopy size, crop type, and plant water stress affect soil and canopy energy balances. Data of this type will be useful to validate evapotranspiration models.

REFERENCES

Ashktorab, H., Pruitt, W.O., Paw U, K.T., George, W.V., 1989. Energy balance determinations close to the soil surface using a micro-Bowen ratio system. Agric.For. Meteorol. 46, 259-274.

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

Dehghanisanij, H., Yamamoto, T., Rasiah, V., 2004. Assessment of evapotranspiration estimation models for use in semi-arid environments. Agri. Water Manage. 64, 91-106.

Eneji, A.E., 2003. Agronomy of Tropical Crops. Tottori Technical Printing Co., Japan, 228p.

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

Ham, J.M., Heilman, J.L., Lascano, R.J., 1991. Soil and canopy energy balances of a row crop at partial cover. Agron. J. 83, 744-753.

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

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

Heilman, J.L., McInnes, K.J., Savage, M.J., Gesch, R.W., Lascano, R.J., 1994. Soil and canopy energy balances in a west Texas vineyard. Agric. For. Meteorol. 71, 99-114.

Jara, J., Stockle, C.O., Kjelgaard, J., 1998. Measurement of evapotranspiration and its components in a corn (*Zea Mays* L.) field. Agric. For. Meteorol. 92, 131-145.

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

Kustas, W.P., Stannard, D.I., Allwine, K.J., 1996. Variability in surface energy flux partitioning during Washita’92: resulting effects on Penman-Monteith and Priestley-Taylor parameters. Agric. For. Meteorol. 82, 171-193.