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# Evapotranspiration Partitioning Techniques for Improved Water Use Efficiency

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## 1. Introduction

Improvement of agricultural water use efficiency is a key issue to alleviate the pressure of the ever-expanding world population on water resources (Zeggaf and Filali, 2010). In areas such as the Southern Mediterranean, where the agricultural sector consumes more than 80 % of renewable water resources in most countries, as little as 10 % increase in water use efficiency by the agricultural sector would provide 40 % more water for domestic and industrial use (Lacirignola et al., 2003). In other words, the challenge for the 21<sup>st</sup> century will be undoubtedly to produce more food with less water to cope with the increasing water demand by the water sector usages (agriculture, industry, domestic).

An efficient irrigation scheduling at crop field level minimizes water losses by soil evaporation and maximizes water uptake by crop transpiration. To be achieved, monitoring separately crop transpiration and soil evaporation, and quantifying their inter-relations is paramount. However, most of the scientific and technical literature concerned with crop water requirements and irrigation scheduling foster soil water consumption at field level as a whole “evapotranspiration” (ET), which is the water amount used at field level for plant transpiration and soil evaporation.

## 2. Separate measurements of transpiration and soil evaporation

Evaporation is the process by which liquid water is converted to water vapor (vaporization) and then removed from the evaporating surface (vapor removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Where the evaporating surface is soil, the degree of shading of the canopy and the amount of water available at the evaporating surface are other factors that affect soil evaporation process.

Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. Transpiration, like direct evaporation, depends on the energy supply, vapor pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do water logging and soil water salinity. The transpiration rate is also influenced by crop characteristics, environmental aspects and cultivation practices.

In the following, a number of measuring methods of transpiration and soil evaporation are listed.

## 2.1 Transpiration

Transpiration has been measured on surfaces varying in area from part of a leaf, entire fields to forests, and the methods used have varied equally widely. Originally, most measurements were made on individual plants, but in agriculture and forestry interest has turned toward study of the water balance of large stands of plants (Kramer, 1983). In the following, some methods for measuring transpiration are listed.

## 2.2 Gravimetric method

From the time of Hales (1727) to the present, investigators had grown plants in containers and measured transpiration by weighing the containers at appropriate intervals. It was necessary to grow the plants in waterproof containers and to cover the soil to prevent loss by soil evaporation (Kramer, 1983). Soil moisture had to be replenished frequently so that water supply did not become limiting, a common defect of many early experiments (Raber, 1937). This technique was routinely used for measuring trees transpiration (Fritschen and Gay, 1979). The containers in which plants were growing should be protected from direct sun to prevent overheating, and the ideal arrangement was to have them set with the tops flush with the surrounding soil in the habitat where they would normally grow.

## 2.3 Cut-shoot method

Measurements of transpiration were made on detached leaves weighted at intervals of a minute or two on a sensitive balance. Such measurements could proceed for only a few minutes after cutting the leaf because transpiration tends to decline with decreasing leaf water content (Kramer, 1983). Sometimes, there was a transient increase in transpiration shortly after detaching a leaf or branch, the Ivanov effect, probably resulting from release of tension in the xylem. This method was used for measuring transpiration of trees (Roberts, 1977). However, the tree-cutting procedure could affect the entry of water to the conducting tissues. Also, large differences could be caused by detaching the plant organ, and by measuring transpiration in an environment different from that of its location on the plant. Hence, extrapolation of results could not be attempted. In spite of its inherent errors, the cut-shoot method was used to measure differences in transpiration among species (Hygen, 1953; Kaul and Kramer, 1965).

## 2.4 Measurement of water vapor loss

Measurement of transpiration could be made by monitoring the change in humidity of an air stream passed through a container enclosing the plant material. The containers were usually made of plastic and vary from tiny cuvettes holding one leaf or part of a leaf (Slavik, 1974) to those holding a branch (Kaufmann, 1981). This method eliminated errors caused by detaching leaves or branches, but imposed a somewhat artificial environment on the leaf or plant enclosed in the container. Grieve and Went (1965) described the use of cuvettes containing a humidity sensor to enclose a single leaf for short-term measurements. This method has been developed into equipment that can make a measurement of transpiration and stomatal resistance in less than one minute. Several porometers are described by Jarvis and Mansfield (1981) and Kaufmann (1981).

## 2.5 Canopy-chamber method

Canopy-chamber method remains an appropriate approach for plot-sized experimental agriculture (Steduto et al., 2002). Two major canopy-chamber systems can be identified for field applications:

Steady-state open-systems include the open-top chambers, most widely used for long-term studies of field-grown plants mainly exposed to elevated CO<sub>2</sub> or atmospheric polluting gases (Leadley and Drake, 1993). These chambers have the advantage of continuously monitoring the plant response throughout the season, but with the drawback of altering the microclimate of the crop. Moreover, they require flow measurements and, most of the times, climate control (Steduto et al., 2002).

The canopy-chambers operating as transient-state closed-systems, instead, do not need any flow measurement or climate conditioning and are mainly used for ambient-level CO<sub>2</sub> and water vapor gas-exchange measurements. These chambers are placed over the crop for a very short time (about a couple of minutes) and then removed for a subsequent measurement, allowing enough replicates and minimal disturbance of the plant environment. Nevertheless, during the time of measurement, the natural gradients of temperature, CO<sub>2</sub> and water vapor are reduced due to forced ventilation (Held et al., 1990), and the orientation pattern of leaves at the chamber borders can be modified during the placement (Reicosky et al., 1990).

## 2.6 Sap flow method

A method that has shown promise is the steady-state heat balance method developed by Sakuratani (1981, 1984). Use of this method does not alter any of the environmental or physiological factors affecting the transpiration process and Sakuratani (1981) reported an accuracy of  $\pm 10\%$ . This result was supported by Baker and Van Bavel (1987). The method works in the following way. A steady, known amount of heat is applied to a small segment of the stem from a thin flexible heater that encircles the stem and is itself encircled by foam insulation. In the steady state, this heat input to the segment must be balanced by four heat fluxes out of the segment: conduction up the stem, conduction down the stem, conduction outward through the foam sheath and convection in the moving transpiration stream. Subtraction of the conductive fluxes from the known heat input yields the heat transported by the moving sap flow (Baker and Nieber, 1989). The method is direct, requires no calibration or knowledge of the cross-sectional area of the xylem vessels. However, some authors reported that high sap flow rates may cause some systematic errors in estimating the heat balance components (Baker and Nieber, 1989). Also, Ishida et al. (1991) suggested that the gauge accuracy may be influenced by stem vascular anatomy, with potentially greater accuracy in dicotyledons than in monocotyledons.

## 2.7 Soil evaporation

Most soil evaporation ( $E_s$ ) takes place in two stages: the constant and the falling rate stages (Philip, 1957):

In the constant rate stage (stage 1), the soil is sufficiently wet for the water to be transported to the surface at a rate at least equal to the evaporation potential. In this stage, evaporation is determined by atmospheric demand and soil conditions, rather than the conductive properties of the soil profile. The transition to the second stage of drying occurs when cumulative soil evaporation reaches a soil-specific threshold (Ritchie, 1972).

In the falling rate stage (stage 2), the surface soil water content has decreased below a threshold value, so that  $E_s$  depends on the flux of water through the upper layer of soil to the evaporating site near the surface (Ritchie, 1972). The cumulative soil evaporation was found to be proportional to the square root of time (Philip, 1957). The proportionality between second stage soil evaporation and the square root of time has been supported by

several laboratory and field studies (Hillel, 1980). In the following, some methods for measuring soil evaporation are listed.

### 2.8 Micro-lysimeter

The theory and inherent assumptions of micro-lysimetry have been examined by Boast and Robertson (1982) and Walker (1983). To ensure accurate measurement of soil evaporation, the soil core within a micro-lysimeter must have a moisture content profile similar to that of the surrounding soil. Once the core has been cut from the plot, the two profiles begin to diverge as extraction of water by roots and vertical fluxes are prevented by the walls and the base of the micro-lysimeter. Daily soil evaporation from the micro-lysimeters can be calculated from weight loss and rainfall. Micro-lysimeters have been used to measure soil evaporation from both bare soil and soil beneath sparse canopy. Some authors reported that the micro-lysimeters can measure soil evaporation accurately during dry periods, but are unreliable on days when rainfall is present (Allen, 1990). Unless soluble by changes in design, this problem seriously limits the usefulness of micro-lysimeters for evaluating the contribution of soil evaporation to the seasonal water use by crops in rainfed dryland agriculture (Allen, 1990).

### 2.9 Energy balance method

Ben-Asher et al. (1983), building on work by Fox (1968), developed an energy balance method (EBM) for measuring soil evaporation. This method used average daily wind speed and the difference between midday maximum soil surface temperatures of a reference dry soil and a drying soil to estimate daily soil evaporation from the drying soil. Soil surface temperature can be measured by infrared thermometry, and then soil evaporation can be calculated by the energy balance method described by Ben-Asher et al. (1983). The Ben-Asher method calculates evaporation using the difference between dry and drying soil surface temperatures.

## 3. Combined measurements of transpiration and soil evaporation

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes (Allen et al., 1998). Apart from the water availability in the topsoil, soil evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil. This fraction decreases over the growing period as the crop develops and the canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process.

Latent heat fluxes from the canopy and the soil are complex processes governed by energy exchange between the soil, canopy, and the aerial environment. Investigating evaporation and energy exchanges in the crop field requires energy balance of the soil and the canopy to be examined separately (Ham et al., 1991).

Several methods are used to measure or determine evapotranspiration ( $ET$ ) components simultaneously. Ham et al. (1991) showed that energy balances of canopy and soil in a cotton field could be determined by combining sap flow with BREB measurements of transpiration ( $T$ ) and evapotranspiration respectively. Also,  $ET$  in a drip-irrigated vineyard was determined from separate measurements of  $T$  by sap flow gauges and soil evaporation

( $E_s$ ) by micro-lysimeters at various positions (Yunusa et al., 2004). However, when different methods are used to determine  $ET$  components, the consistency among these methods deserves attention (Jara et al., 1998). Ham et al. (1990) reported a comparison of  $E_s$  calculated by difference between  $ET$  measured by BREB method and  $T$  measured by heat balance stem flow measurements, with that measured by micro-lysimeters. A rapid decline in the precision of calculated  $E_s$  at low soil evaporation levels was reported, which indicated that the utility of the approach might be limited when  $E_s$  is less than 20 % of  $ET$ . This restriction might hinder quantification of surface energy balance relationships and transport processes during certain soil and canopy conditions (Ham et al., 1990). The expensiveness of the measurement equipments involved in similar experiments and the different scales at which these measurements are performed limit the large scale adoption of these techniques by research scientists. Cheaper and precise methods for studying energy balance exchange in the crop field are needed.

The BREB method is considered to be fairly robust for measuring  $ET$  (Steduto and Hsiao, 1998b), and has compared favorably with other methods, e.g., soil water balance (Malek and Bingham, 1993), aerodynamic method (Malek, 1993), eddy covariance method (Dugas et al., 1991), and weighing lysimeter (Prueger et al., 1997; Tanner, et al., 1960). The validity of this method has been established over various vegetation stands (Ham et al., 1991; Heilman et al., 1994), and natural vegetation (Kalthoff et al., 2006). Ashktorab et al. (1989) used a micro-Bowen ratio system for energy balance determination close to bare soil, and reported  $E_s$  readings within 10 % of the weighing lysimeter measurements. Accordingly, it was suggested that the BREB method should be considered an excellent candidate for the determination of the soil component of  $ET$  from row crops (Ashktorab et al., 1989).

#### 4. Double Layer Bowen Ratio Energy Balance system (DOLBOREB): A case study

##### 4.1 Energy budget at crop field level

###### a. Energy balance of maize field

The energy balance of maize field can be expressed as:

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

where

$R_n$ : net radiation above canopy,  $\lambda E$ : 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.  $\lambda E$  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 ( $\beta$ ) is calculated by:

$$\beta = \gamma (\delta T / \delta \zeta) / (\delta \varepsilon / \delta \zeta) = \gamma \Delta T / \Delta \varepsilon \quad (2)$$

Where

$\Delta T$  and  $\Delta e$ : temperature and vapor pressure differences between two measurement levels ( $z$ ), respectively,  $\gamma = c_p p / \varepsilon \lambda$ : psychrometric constant,  $c_p$ : specific heat of air at constant pressure ( $1.01 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ),  $p$ : atmospheric pressure (kPa),  $\varepsilon$ : ratio between molecular weights of water vapor and air (0.622), and  $\lambda$ : latent heat of vaporization ( $\text{kJ kg}^{-1}$ ).

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

$$\beta = H / \lambda E \quad (3)$$

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

$$\lambda E = (R_n - G) / (1 + \beta) \quad (4)$$

$$H = (R_n - G) \beta / (1 + \beta) \quad (5)$$

The energy balance of the maize field is measured by a BREB unit. Air temperature and vapor pressure gradients are determined from two dry and wet bulb ventilated psychrometers. The distance between the two psychrometers is 1 m, and the lowest psychrometer is positioned at 0.2 m above the canopy. Net radiation at 1 m above the canopy, is measured by a net radiometer. Soil heat flux is calculated as an average value of two or more heat flux plates measurements at 2 cm below soil surface. Wind speed is measured, 1 m above the canopy, by a wind speed sensor. All data are measured every minute by a datalogger and multiplexer and averaged over 10 minutes's time interval.

#### b. Energy balance over soil surface

The energy balance over soil surface can be expressed as:

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

where

$R_{ns}$ :  $R_n$  to soil surface,  $\lambda E_s$ : soil latent heat flux, and  $H_s$ : sensible heat flux from soil, all units of  $\text{W m}^{-2}$ .

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

$$\beta_s = H_s / \lambda E_s \quad (7)$$

where

$\lambda E_s$  and  $H_s$ : determined from Eq. 6 and 7 as by Eq. 4 and 5, respectively.

The energy balance over soil surface is 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 are determined from two dry and wet bulb ventilated psychrometers. The distance between the two psychrometers is 0.1 m, and the lowest psychrometer is positioned 0.05 m above soil surface.

#### c. Energy balance of canopy

The energy balance of canopy can be expressed as:

$$R_{nc} = \lambda E_c + H_c \quad (8)$$

where

$R_{nc}$ :  $R_n$  intercepted by canopy, and  $\lambda E_c$  and  $H_c$ : fluxes of latent and sensible heat from canopy, respectively.

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

$$R_{nc} = R_n - R_{ns} \quad (9)$$

where

$R_n$  and  $R_{ns}$  are measured by net radiometers.

Canopy latent heat flux is calculated by Eq. 10, while  $H_c$  is calculated as a residual from Eq. 8.

$$\lambda E_c = \lambda E - \lambda E_s \quad (10)$$

#### 4.2 DOLBOREB set-up

A DOLBOREB system consists of four dry and wet bulb ventilated psychrometers mounted on moveable arms, two net radiometers, and two or more soil heat flux plates (figure 1). The first two dry and wet bulb ventilated psychrometers are used to determine air temperature and vapor pressure gradients above the crop. The distance between the two psychrometers is 1 m, and the lowest psychrometer should be positioned at 0.2 m above the canopy. The other two dry and wet bulb ventilated psychrometers are used to determine air temperature and vapor pressure gradients above the soil surface. Following a similar set-up made by Ashktorab et al. (1989) over bare soil, air temperature and vapor pressure gradients within the rows are determined from two dry and wet bulb ventilated psychrometers. The distance between the two psychrometers is 0.1 m, and the lowest psychrometer is positioned 0.05 m above soil surface.

Net radiation at 1 m above the canopy and over soil surface is measured by net radiometers. Soil heat flux is calculated as an average value of two or more heat flux plates measurements at 2 cm below soil surface. Wind speed is measured, 1 m above the canopy, by an anemometer. All data are measured every minute by dataloggers and multiplexers and averaged over 10 minutes' time interval.

#### 4.3 DOLBOREB system outputs

Use of the DOLBOREB system enables measurements of all energy components at crop field level. It also permits to explore energy exchange at crop field level (Zeggaf et al., 2008). In the following, diurnal trend of energy balances of maize field, soil and canopy by the DOLBOREB system for a sample day will be presented and discussed (Fig. 2). This day was selected because of clear sky and variable wind speed. Maximum air temperature and  $R_n$  were 32°C and 645 W m<sup>-2</sup>, respectively. Wind speed at 1 m above the canopy ranged from 1.1 m s<sup>-1</sup> at early morning to 3.9 m s<sup>-1</sup> around noon.

During most part of the day,  $\lambda E$  was less than net radiation at maize field level, except at early morning and late afternoon (Fig. 2A).  $\lambda E$  exceeding  $R_n$  suggested that there might be some brief periods when advection of sensible heat supported evapotranspiration. Similar observations were reported for vineyard (Yunusa et al., 2004), and for cotton (Ham et al., 1991). During daytime, most of  $R_n$  was used to drive  $\lambda E$  (Fig. 2A). Only 8.5 % of available energy ( $R_n - G$ ) was used to generate  $H$ . Similar results have been reported for cotton

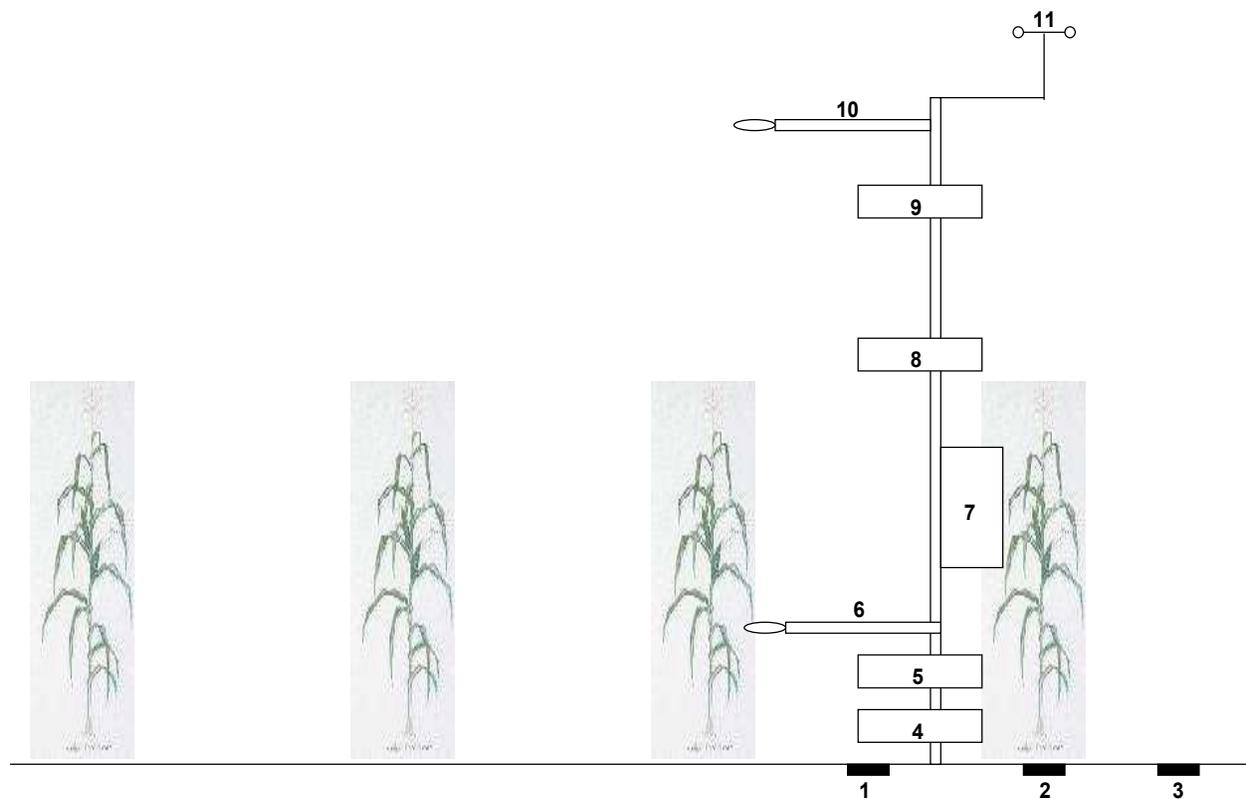


Fig. 1. DOLBOREB system set-up. 1,2,3 : Soil heat flux plates. 4 : Lower ventilated psychrometer over soil surface. 5: Upper ventilated psychrometer over soil surface.6: Net radiometer over soil surface. 7: Datalogger. 8: Lower ventilated psychrometer over crop canopy. 9: Upper ventilated psychrometer over crop canopy. 10: Net radiometer over crop canopy. 11: Anemometer.

(Ritchie, 1971; Ham et al., 1991) and for maize (Steduto and Hsiao, 1998a). During daytime,  $\beta$  ranged from -0.3 to 0.1. Accordingly, Steduto and Hsiao (1998a) reported positive  $\beta$  values less than 0.25 under incomplete maize canopy ( $L = 0.58$ ). Soil heat flux was less than 10 % of  $R_n$ , this value is commonly found in the literature (Yunusa et al., 2004).

During daytime,  $\lambda E_s$  was less than  $R_{ns}$ , and  $H_s$  remained positive (Fig. 2B), indicating convective transport of heat away from soil surface.  $R_{ns}$  was used almost equally to drive  $\lambda E_s$  (52 %) and to generate  $H_s$  (48 %), with  $\beta_s$  ranging from 0.20 to 0.96 as shown in Fig. 2. Other authors reported  $\lambda E_s$  accounting for 29 to 47 % of  $R_{ns}$  for vineyard (Heilman et al., 1994).

At canopy level,  $\lambda E_c$  exceeded  $R_{nc}$  during most of the daytime period. Negative  $H_c$  values were obtained as shown in Fig. 2C indicating the canopy was absorbing convective heat from soil surface, which provided supplement energy for  $\lambda E_c$ . Redistribution of available energy by sensible heat transfer occurs when there is (i) abundant supply of soil water (ii) absence of significant physiological restraint of water vapor flux through stomata, and (iii) high evaporative demand (Oke, 1987). In similar conditions, this redistribution of energy has been reported to supply up to one third of the energy needed for transpiration (Hicks, 1973; Heilman et al., 1996; Sene, 1996).

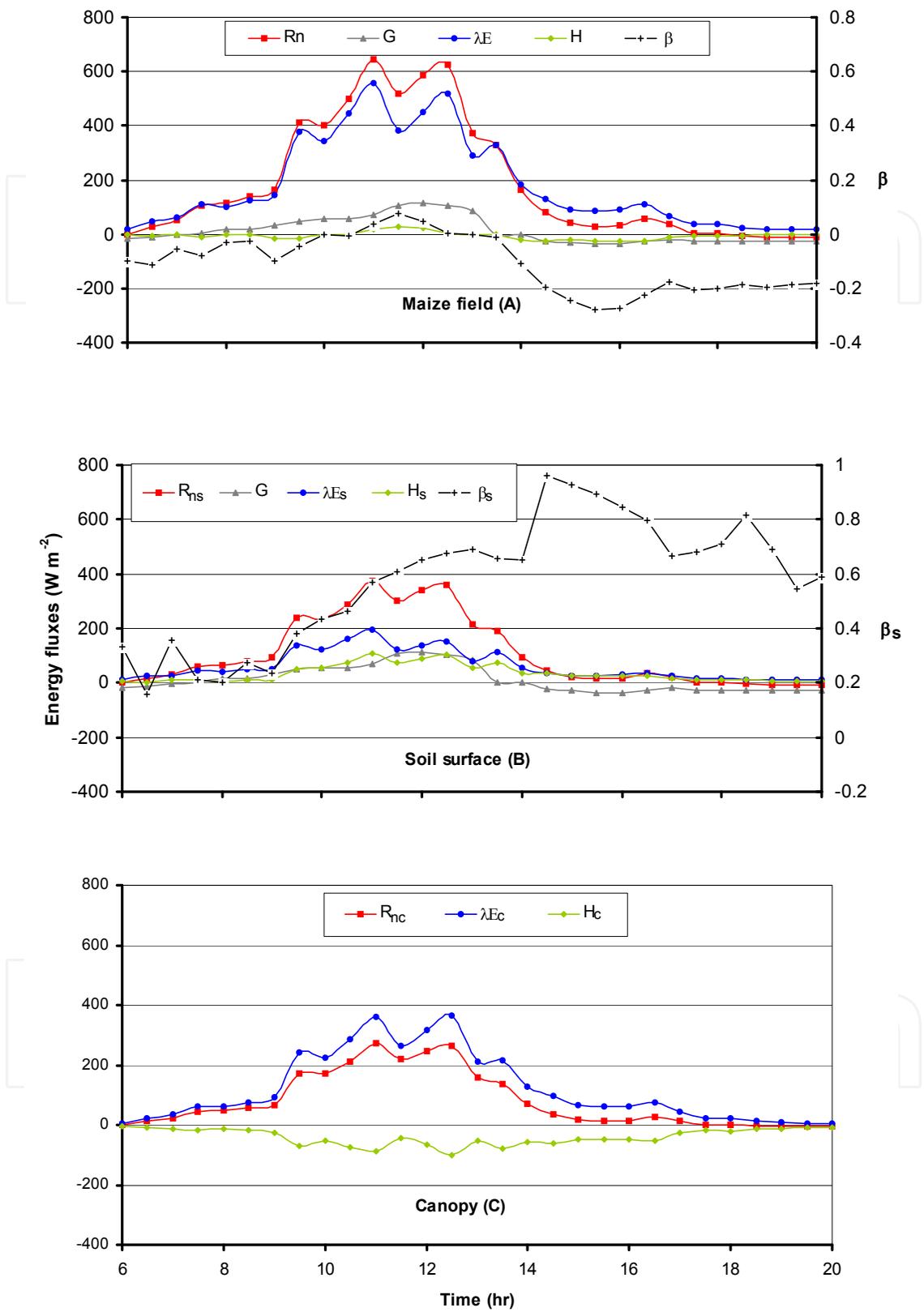


Fig. 2. Diurnal trend of energy balances of maize field, soil surface and canopy by the DOLOBOREB system for a sample day.

For 12 days, results of energy balance measurements from the DOLBOREB system compared positively to other direct methods measurements (Zeggaf et al., 2008). Latent heat flux over maize field from The DOLBOREB system showed a coefficient of determination of 0.72 with that measured with weighing lysimeter. Also, a coefficient of determination of 0.77 was obtained between DOLBOREB system and sap flow measurements of latent heat flux from maize transpiration. This shows that the DOLBOREB system can be used with reasonable accuracy in place of other expensive and separate measurements of evapotranspiration components to measure all energy balance components at crop field level.

## 5. Use of the DOLBOREB system for water use efficiency at crop field level

A comparison between energy balance patterns at maize field level between 2 periods: a wet period where maize field was irrigated daily and a dry period where irrigation was halted, was studied (Zeggaf et al., 2007).

### 5.1 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 DOLBOREB system are shown in Fig. 3. 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, 1998b). As reported by Steduto and Hsiao (1998b), latent heat flux from maize field ( $\lambda E$ ) was closely coupled to  $R_n$ , giving rise to a nearly perfect coincidence between  $R_n$  and  $\lambda E$  in their rise and fall shown in Fig. 3, when changing clouds effected rapid fluctuation of radiation. This result is expected as the net radiation is the main source of energy for evapotranspiration.

For the wet period,  $\lambda E$  was at its full rate as shown in Fig. 3-wet. Sensible heat flux was very small and could be accounted as negligible. During this period,  $\lambda E$  was always smaller or equal to net radiation indicating no major advective conditions prevailed. 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. 3-dry. Sensible heat was almost positive during daytime and ranged from 5 and 8 % of  $R_n$ . The Bowen ratio ( $\beta$ ) 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,  $\lambda E$  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.

Linear regression lines between available energy ( $R_n - G$ ) and  $\lambda E$  from maize field for the wet and dry periods produced high values of  $r^2$  as shown in the following Eqs. 11 and 12. Similar results were obtained by Ham et al. (1991) who reported that within row advection increased  $\lambda E_c$ , and that the difference in total  $\lambda E$  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:

$$\lambda E = 0.97 (R_n - G), \text{ with } r^2 = 0.99 \quad (11)$$

For the dry period:

$$\lambda E = 0.95 (R_n - G), \text{ with } r^2 = 0.97 \quad (12)$$

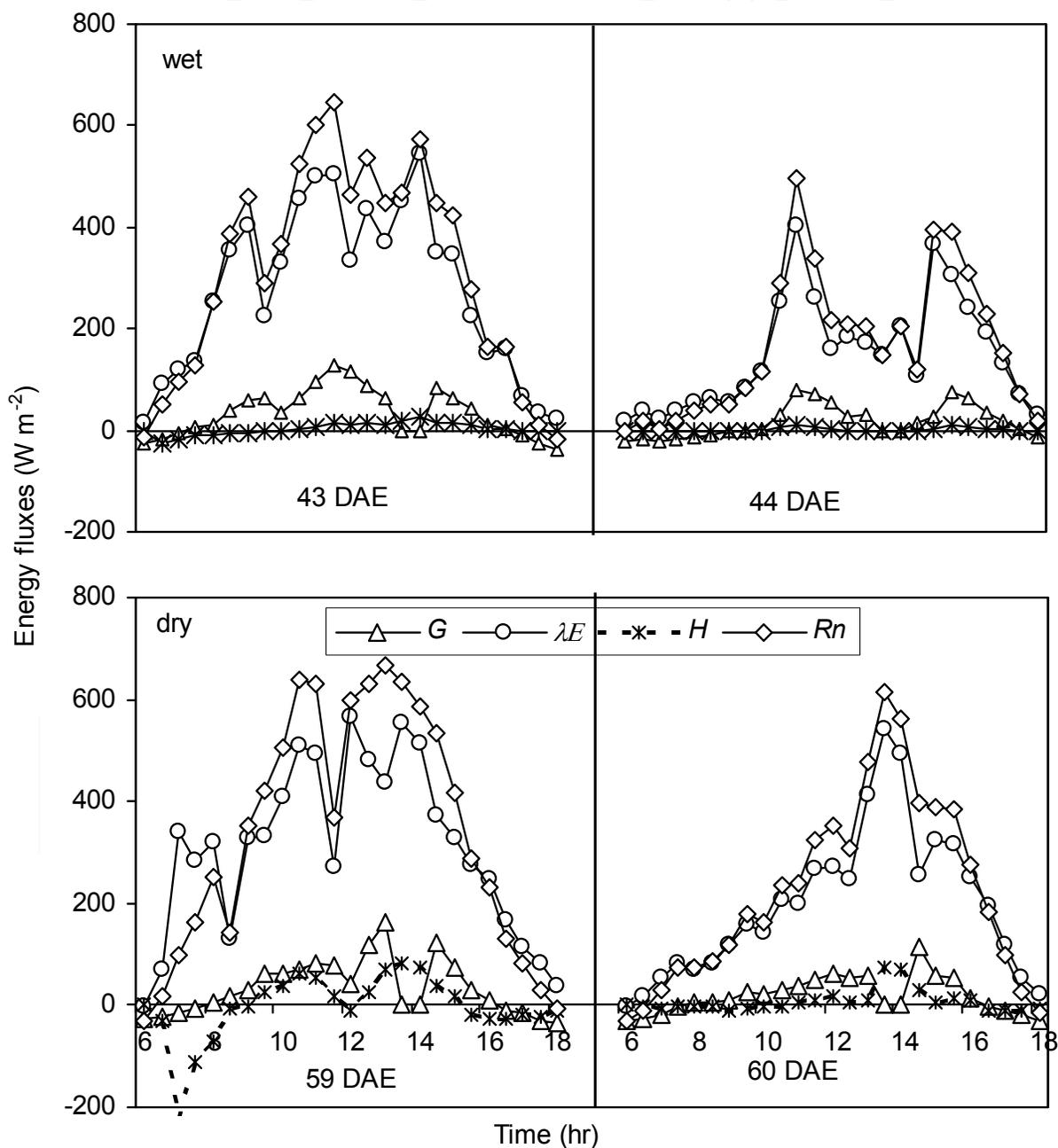


Fig. 3. Diurnal patterns of energy fluxes from maize field for the wet and dry periods

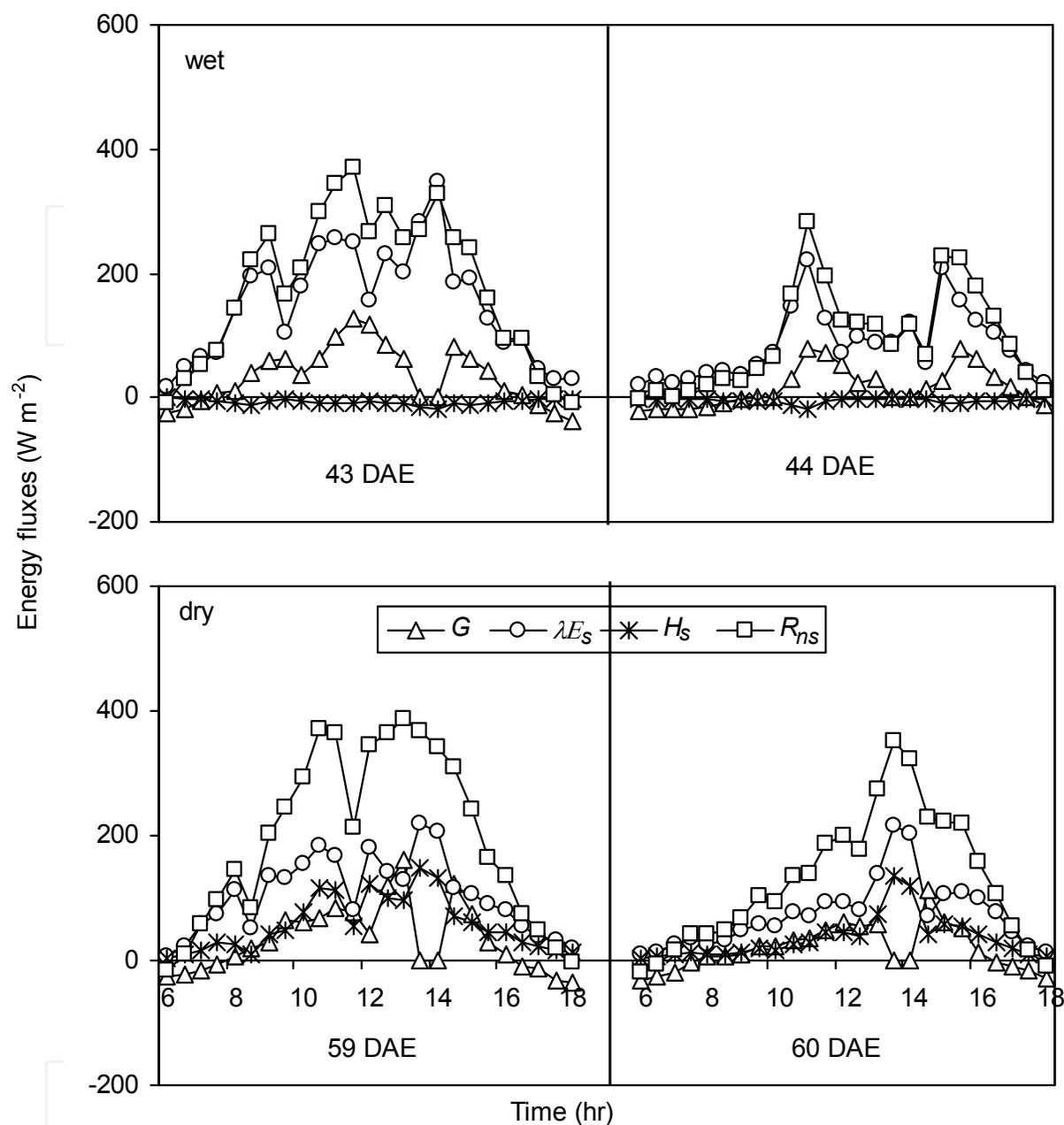


Fig. 4. Diurnal patterns of energy fluxes from soil surface for the wet and dry periods

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

Diurnal patterns of energy fluxes from soil for the wet and dry periods by the DOLBOREB system 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  $\lambda E_c$  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.

Linear regression between available energy ( $R_{ns} - G$ ) and latent heat flux from soil for the wet and dry periods showed a reduction of  $\lambda E_s$  for the dry period of about 35 % of available energy to soil surface. 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:

$$\lambda E_s = 1.07 (R_{ns} - G), \text{ with } r^2 = 0.99 \quad (13)$$

For the dry period:

$$\lambda E_s = 0.65 (R_n - G), \text{ with } r^2 = 0.94 \quad (14)$$

### 5.3 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 DOLBOREB system are shown in Fig. 5. 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  $\lambda E_c$ , 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°C lower than air temperature. Also, Ham et al. (1991) reported for cotton that a wet soil appears to reduce  $\lambda E_c$  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 can influence  $\lambda E_c$  and  $\lambda E_s$  (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).

The linear regression lines between  $\lambda E_c$  and  $R_{nc}$  were obtained with high values of  $r^2$  as shown in the following Eqs. 15 and 16.

For the wet period:

$$\lambda E_c = 0.87 R_{nc}, \text{ with } r^2 = 0.99 \quad (15)$$

For the dry period:

$$\lambda E_c = 1.26 R_{nc}, \text{ with } r^2 = 0.93 \quad (16)$$

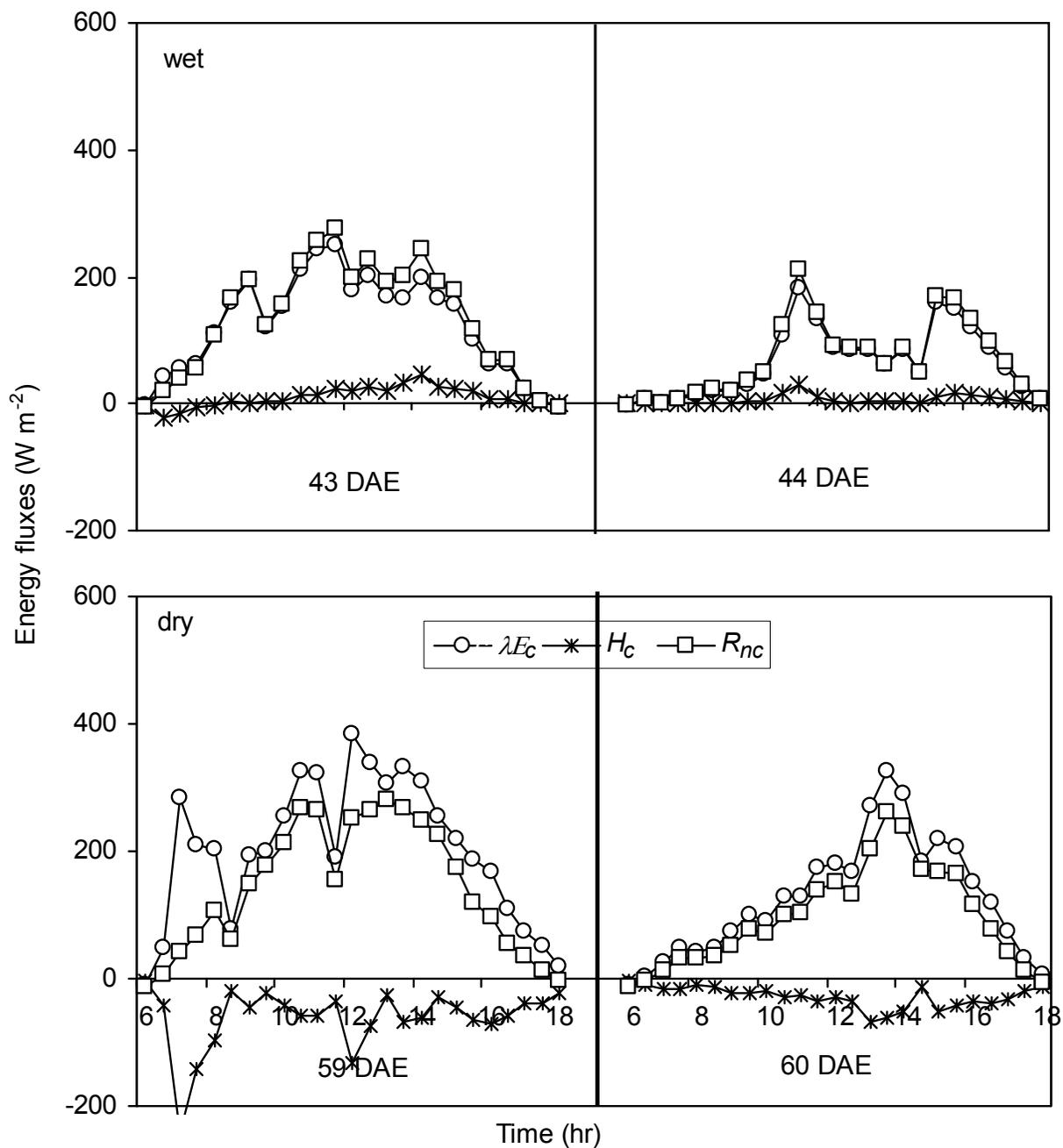


Fig. 5. Diurnal patterns of energy fluxes from canopy for the wet and dry periods

#### 5.4 Summary of energy balance differences between wet and dry periods

Figure 6 shows a summary of the typical patterns of energy balances over maize field, soil surface and maize canopy by the DOLBOREB system during wet and dry periods. No major differences were observed, at maize field level, for energy balance patterns between wet and dry period. Evapotranspiration at maize field level remained high during both periods, and ratio of sensible heat, and soil heat fluxes to daily net radiation too. In fact, maize field energy balance measurements alone provide virtually no information on how energy balances of soil surface and canopy are partitioned. This shows clearly the limitations of considering crop field evapotranspiration as a whole, especially when addressing such

important issues as would be water use efficiency improvement. A number of factors have contributed to this situation. The high cost of the equipment involved in such experiments and the inherent errors associated with the use of different measurement devices and measurement scales tremendously hinted the large-scale adoption of such techniques either by research scientists and/or by irrigation practitioners (Zeggaf et al., 2008). The DOLBOREB system indicated that soil had a major impact on the energy balance over maize canopy level. Also, the experiment shows that a frequent irrigation regime, as during the wet period, is not necessarily a synonym of maximum plant transpiration. In accordance with these results, Ham et al., (1991) concluded that a wet soil appears to reduce  $\lambda E_c$  by acting as a sink for advective energy, while reducing the radiation load on the canopy.

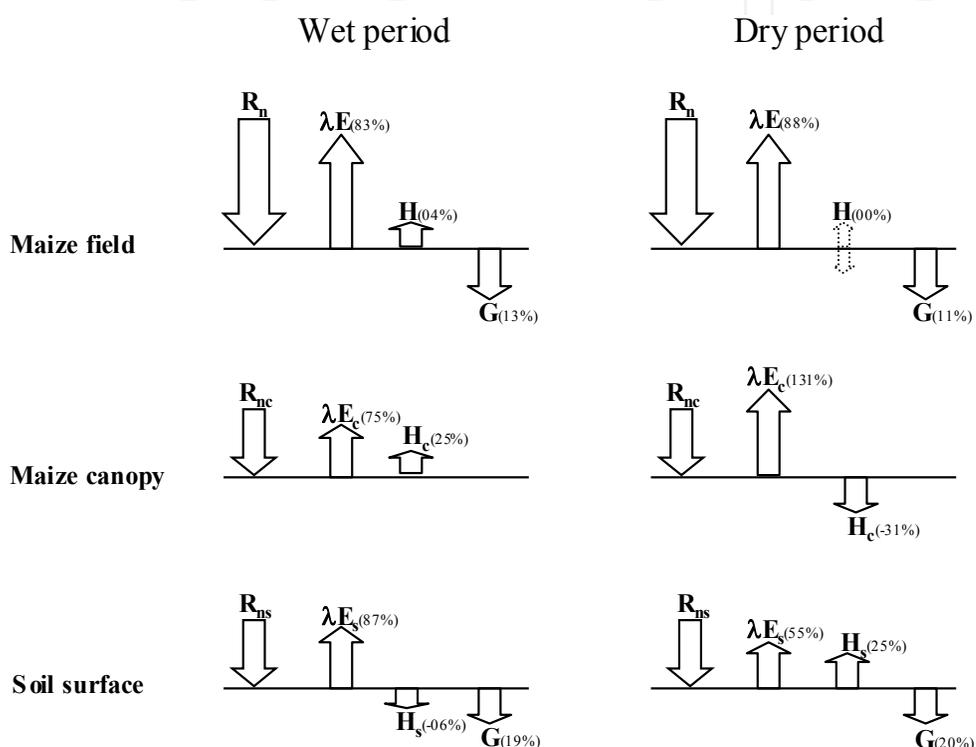


Fig. 6. Typical patterns of energy balances over maize field, soil surface and maize canopy by the DOLBOREB system during wet and dry periods.

The DOLBOREB system proved effective in depicting energy exchange phenomena between maize canopy and soil surface. These energy exchanges, mainly soil surface advection, boosted maize canopy transpiration during the dry period. Sensible heat flux generated from soil surface was absorbed by maize canopy, which increased dramatically latent heat flux from maize canopy. Similar results were obtained by Ham et al. (1991) who reported that within row advection increased  $\lambda E_c$ . This finding corroborates the concept of “more crop per drop” which summarizes the objective of water use efficiency studies. In fact, proper irrigation management practices aimed at improving water use efficiency at crop field level might increase canopy transpiration, reduce soil evaporation, but not reduce total evapotranspiration. We suppose that this objective could be achieved through adoption of appropriate irrigation scheduling aiming to take advantage of soil surface advection or supplemental irrigation in arid and semiarid areas. Finally, the use of the DOLOBOREB system for irrigation scheduling could improve water use efficiency at crop field level and save up to 56 % of irrigation water without compromising crop production.

## 6. Conclusions

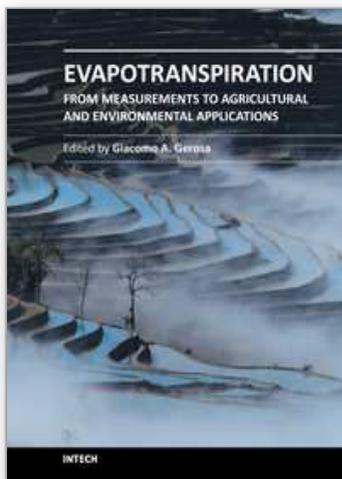
Future studies for other crops and under different climatic conditions are needed to improve our knowledge of water relations at crop field level. Examining the effect of factors such as canopy size, crop type, and plant water stress...etc. on soil surface and canopy energy balances is of considerable importance. Energy flux data generated by the DOLBOREB system would be useful for building evapotranspiration, and crop growth models.

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## **Evapotranspiration - From Measurements to Agricultural and Environmental Applications**

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This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and students who intend to address these issues.

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