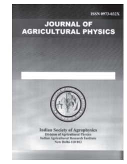
Vol. 19, No. 1, pp. 106-114 (2019)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in



Research Article

Determining Surface Energy Balance, Bowen Ratio and Evapotative Fraction of Irrigated Okra (*Abelmoschus esculentus* (L.) Moench.) Using Eddy Covariance Technique

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ABSTRACT

Surface energy balance over an irrigated okra crop was measured directly using eddy covariance technique under a tropical monsoon climate of India. During two crop seasons, integrate values of energy balance components of 8.00 to 17.00 hours revealed that, the net radiation, R_n varied from 14.6 to 24.69 MJ m^{-2} day^{-1} and surface soil heat flux, G_0 varied from 0.60 to 4.32 MJ m^{-2} day^{-1}. The latent heat flux, *LE* ranged from 6.8 to 17.2 MJ m^{-2} day^{-1} showed an apparent correspondence with the development of phenology e.g. consistent with the trend of LAI. Within a crop season, the Bowen ratio exhibited a 'U'-shaped curve, with the lower values (0.22 to 0.25) at mid and peak growth stages. On the contrary, the evaporative fraction, EF shows the reverse trend with the values being 0.79-0.81 and 0.83-0.84 at mid and peak growth stages, respectively. The correspondence of LE and EF appeared to be more dependent on LAI followed by R_n, but the LE or EF did not correlate to soil moisture status under non-stressed soil moisture condition.

Key words: Latent heat flux, Energy balance, Bowen ratio, Okra

Introduction

The solar energy is the only ultimate source of energy for all bio-physical processes occurring on the earth and its atmosphere. Growth, development and yield of any crop are largely governed by the available energy and it's partitioning into sensible, latent and soil heat fluxes in soil–plant–atmosphere system. The latent heat flux in turns determines crop evapotranspiration and water balance which is the key process that governs plant physiological processes like water and nutrient movement from soil, partitioning of photosynthesis, net primary productivity and crop productivity (Kar and Kumar, 2010; Kar and Kumar 2007; Meena *et al.,* 2017). Okra (*Ablemoschus esculentus* (L.) Monech) is an important vegetables crop grown in both tropic and subtropics. The fruit is a great source of vitamins and minerals for human body. Besides having a good nutritional value, the fruit has good medicinal properties too. Thus, okra has a great scope in world trade also besides having domestic consumption within the countries. The good crop harvest is obtained in dry season but soil water is limited to meet the crop evapo-transpiration, therefore, irrigation is to be applied in this season to grow the crop successfully. Thus, measurement or prediction of evapo-transpiration of the crop is of great interest for water management and irrigation scheduling during dry season.

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Many earlier researchers used eddy covariance technique to evaluate long-term energy balance and evapo-transpiration on various terrestrial surfaces mostly on forest, grasslands and paddy fields in different parts of the world from the tropics to the northern high latitudes (e.g., Steven *et al.*, 2005; Hao *et al.,* 2007; Alberto *et al.,* 2011). But the information on seasonal and diurnal energy balance and relative contribution of energy fluxes on an important vegetable crop like okra under non-stress soil moisture condition are not so far available in literature. The objective of this study was thus set to measure energy balance components, viz., net radiation, soil heat flux, latent heat flux, and the sensible heat flux in the irrigated okra field continuously using eddy covariance technique during two consecutive study years (2013 and 2014).

Materials and Methods

Experimental site and crop management

The on-station experiment was carried out at the research farm (Deras, Khurdha) of ICAR-Indian Institute of Water Management, Bhubaneswar (Lat: 20.2°15.3′ N, Long: 85.4°52.5′ E; Altitude: 30 m above MSL) during two study years (2013 and 2014). A short duration (90 days) variety (cv. 'Avantika Gold') okra was sown with 0.60 m row spacing in the third week of April (Days of the year, DOY 113 to DOY 115) with the recommended package of practices during two study years. The crop was grown under optimum soil moisture conditions and soil moisture depletion of 50% was used to estimate irrigation intervals. The Eddy Covariance system was installed at the middle of 2.6 acres of homogeneous field. Twenty plants were tagged randomly for recording growth (crop height) and phenological observations like dates of occurrence of primary branches, secondary branches, flower bud initiation, flowering, fruiting and maturity or senescence stages.

Measurement of energy flux and other micro-meteorological parameters

The surface energy balance over any crop canopy can be represented by:

$$R_n = H + LE + G_0 + Re \qquad \ldots(1)$$

where, R_n is the net radiation, H and LE are the sensible heat and latent heat fluxes, respectively, G_0 is the soil heat flux at the surface, and Re is the residual energy involved in various processes, such as photosynthesis and respiration. In this study eddy fluxes of sensible heat and latent heat were calculated using measured high frequency wind velocity components and air temperature by a 3-axis sonic anemometer (EC 150 CAST3). High frequency signals of water vapour density were measured by a CO_2/H_2O open path gas analyzer (Campbell Scientific, Inc., USA). Both sensors were installed at 1.5 m height above the ground on an aluminum tripod. Net radiation (Rn) was measured at 1.5 m height using a KIPP and ZONEN net radiometer. A data logger (CR 3000, Campbell Scientific Inc. USA) was used to record the sensor outputs at a sampling rate of 10 Hz and were averaged over 30 min periods. Our Eddy Covariance system also includes: Air Temperature and Relative Humidity probes (HMP 45, Campbell Scientific, Inc. USA) installed on the tripod at 2.0-m above the soil surface to measure the air temperature and vapour pressure, respectively at 30-minutes interval. Fine wire thermocouple with hexagon junction configuration (Campbell Scientific Inc. USA) was used to measure the soil temperature at 4 depths (0.01 m, 0.05 m, 0.15 m, 0.30 m) inside the soil. Our EC system also equipped with HFT3 soil heat flux and TE525M rain gauge (Campbell Scientific Inc. USA). Soil heat flux was measured by embedding two heat flux plates (HFT-3, Campbell Scientific Inc.) at a depth of 0.01 m.

As per the theoretical concept eddy fluxes (Fe) are basically the product of the mean covariance of vertical wind speed fluctuations (w^1) and the scalar fluctuations of parameters of interest e.g., H_2O (q^1) and the density of dry air (e_a).

$$F_e = e_a \overline{w^1 q^1} \qquad \ldots(2)$$

Where w is the vertical wind speed (ms^{-1}), q is the water vapour concentration ($mmol\ mol^{-1}$) and primes denote deviations from a mean as per the equation below

$$w^1 = w - \overline{w} \quad \ldots(3)$$

$$q^1 = q - \overline{q} \quad \ldots(4)$$

The mean vertical fluxes of sensible heat flux (H) and latent heat flux (LE) are represented as per the relationship below:

$$H = \rho C_p \overline{w^1 T^1} \quad \ldots(5)$$

$$LE = L\rho \overline{w^1 q^1} \quad \ldots(6)$$

Where ρ is the density of air, C_p=heat capacity at constant pressure, T^1= fluctuation in temperature, q^1= fluctuation in water vaporization, over bar denotes time averaging.

The partitioning of the available energy balance was evaluated by analyzing the dimensionless evaporative fraction (EF), defined as LE/ (R_n-G_0) and Bowen ratio (H/LE).

Results and discussion

Energy balance closure ratio (EBCR) or Surface heating rate (ε)

The status of energy closure is an important criterion for evaluating the quality of the flux data (Li *et al*., 2004; Leuning *et al*., 2005). As per the methodology, EBCR {(H+LE)/(R_n-G_o)} was applied to estimate whether the surface energy fluxes satisfied the surface energy balance. In our study we found that the sum of the H+LE was less than of (R_n–G_0) by 12-15% due to energy balance "closer error" which might be due to the error in the measurement of turbulent fluxes and not for the measured available energy. As a result, the energy balance closure or surface heating rate was less than 1 (0.84). The value of surface heating rate was improved by eliminating data collected during and after rain events because the sonic anemometer functions during these periods and also by extrapolating the trend of seasonal and diurnal variation of Bowen ratio (Bowen ratio surface energy closure method). After correction the EBCR () increased to 0.96. The regression slope which gives an estimate of energy balance closure between the daily sums (H+LE) against (R_n-G_0) or surface heating rate () is given in fig. 1 (pooled data of two years) after rectification.

Seasonal variation of energy fluxes and their partitioning

The integrated values of day time seasonal variation of net radiation, latent heat flux and sensible flux for 2013 and 2014 seasons are presented in fig. 2a and b, respectively. The day time average net radiation (8:00 AM to 5:00 PM) within two crop seasons ranged from 14.6 to 24.69 MJ m^{-2} day^{-1} through mid-day peak (12:00-12:30 Noon) varied in a range from 30.4 to 45.8 MJ m^{-2} day^{-1}. The ratio of latent heat flux to net radiation, LE/R_n, reached a maximum value (0.79) during peak growth stage with the seasonal average ratio of 0.69. On the other hand, the

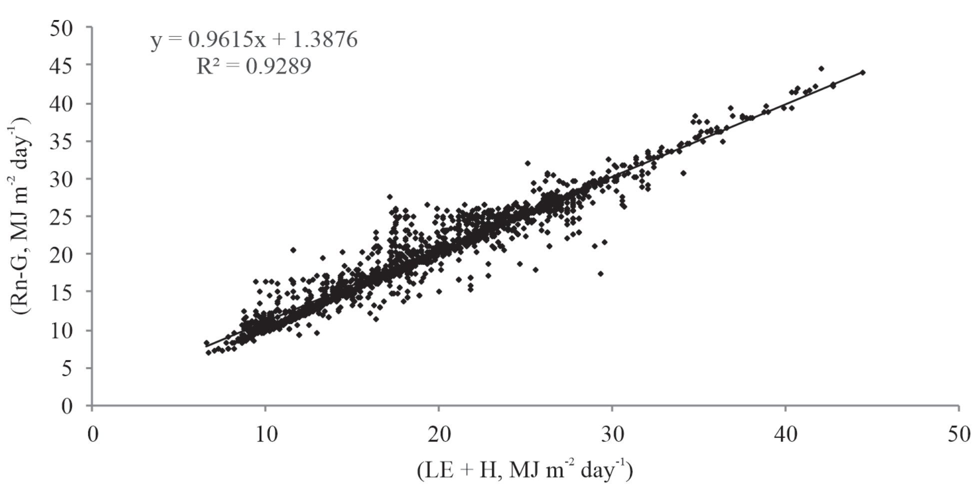

Fig. 1. Energy balance closure balance ratio after correction

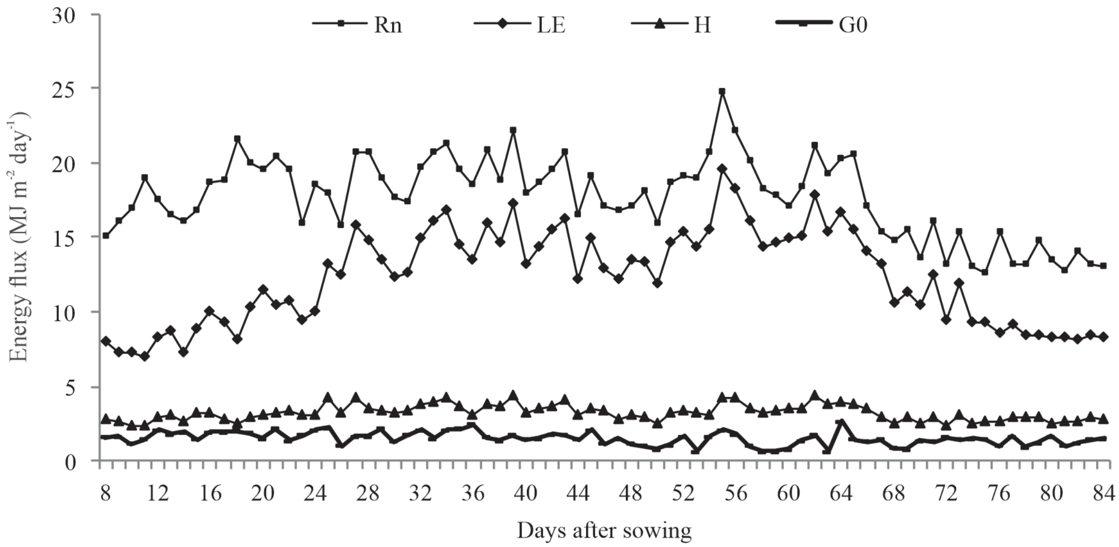

Fig. 2a. Seasonal variation of energy fluxes in 2013

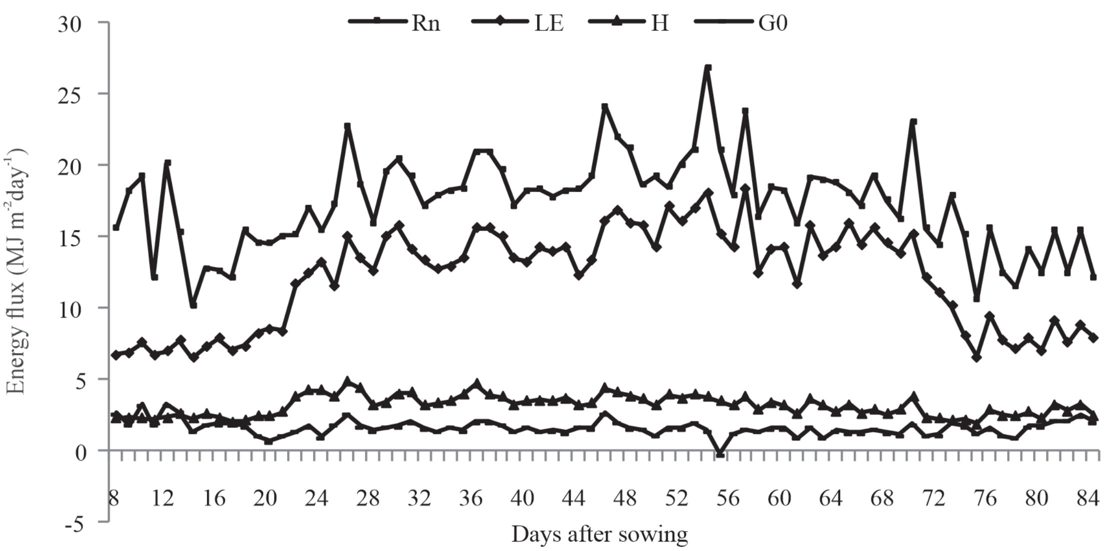

Fig. 2b. Seasonal variation of energy fluxes in 2014

seasonal ratio of sensible heat flux to net radiation (H/R_n) was 0.18 and the course of this heat flux was affected by the development of crop canopy or LAI. The ratio was higher at initial stage and declined during peak growing stage. The day time average G_0 varied from 0.60 to 4.32 MJ m^{-2} day^{-1} with an average ratio of G_0/LE was 0.114. The average ratio of (G_0/R_n) at early vegetative, flowering and senescence stages was 16.67%, 13.9%, 9.4% and 10.2%, respectively.

The Bowen Ratio (β) is widely used for comparing the surface energy partition which is defined as ratio between sensible heat flux (H) and latent heat flux (LE). The seasonal variation of Bowen ratio, β (H/LE) and evaporative fraction, EF (LE/R_n-G_0) for two study years are presented in Fig. 3 and 4, respectively based on the day averaged value of sensible and latent heat fluxes. The annual courses of Bowen ratio for two years basically display the same pattern, i.e. the course follows a 'U-type curve. The higher values were obtained at initial and end growth stages with horizontal bottoms occur during mid and peak growth stages when LAI and ground coverage were maximum. At the initial growth

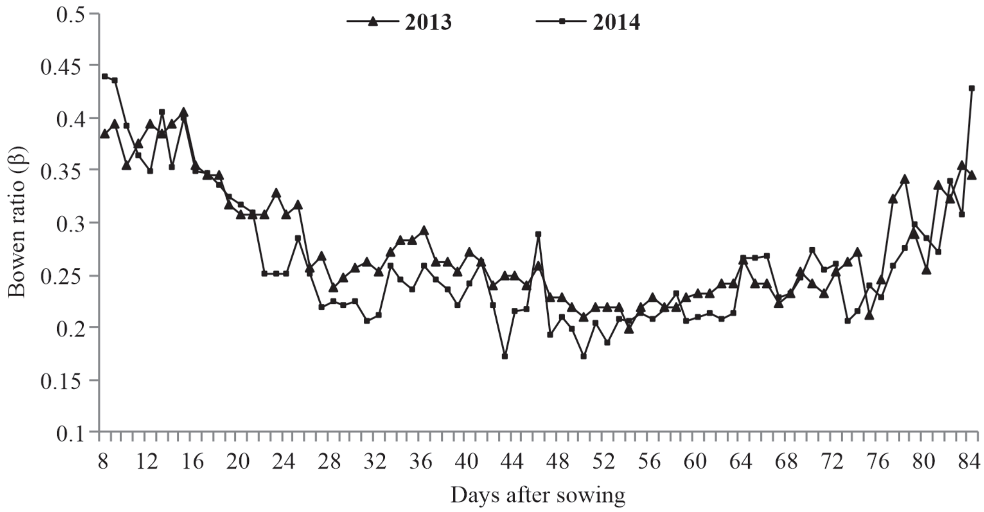

Fig. 3. Seasonal variation of Bowen ratio of okra during two crop seasons

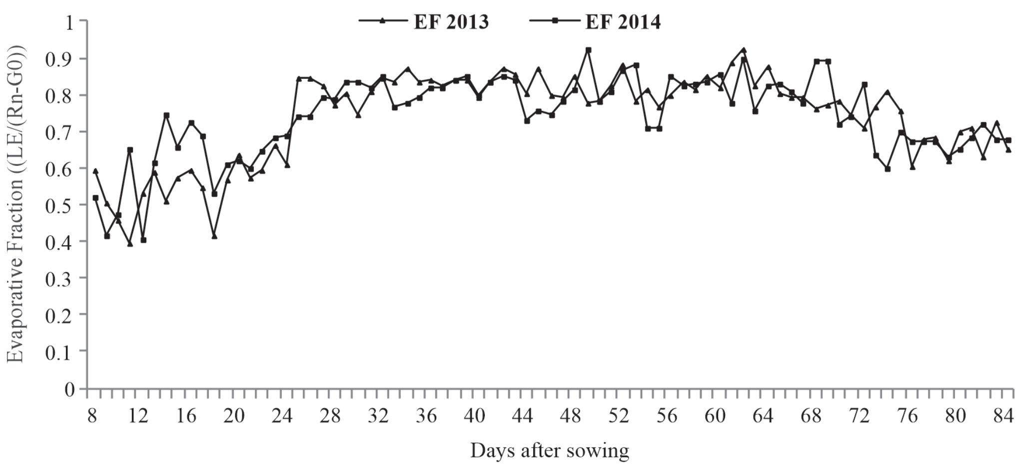

Fig. 4. Seasonal variation of evaporative function of okra during two crop seasons

stage (from germination to 10% ground cover) the Bowen ratio (β) was higher (0.32) but at mid and peak growth stages (from 30 to 68 DAS), the Bowen ratio was almost constant (0.22-0.24) and did not very much, which suggests partitioning surface available energy (R_n–G_0) into sensible and latent heat flux at constant rate at these stage. The higher LAI lead to greater transpiration and therefore, latent heat flux was higher during that period. At senescence stage, again the β ratio was high due to more sensible heat flow. Averaged over two study years, the 'β' values were 0.32. 0.25, 0.22 and 0.29 at initial, mid-growth, peak growth and end growth seasons, respectively. Taking a seasonal average, the Bowen ratio was 0.265 and from 24 to 70 DAS, the β value remained less than 0.3 because of prevalence of non-stressed, green vegetation. The evaporative fraction (EF) shows the reverse trend to that of the Bowen ratio, because EF is an inversely proportional function of 1 + β (Fig.4). Averaged over two study years, the 'EF' values were 0.59, 0.81, 0.84 and 0.71 at initial, mid-growth, peak growth and end growth seasons, respectively

Energy partitioning in relation to LAI, crop height and soil moisture

In order to examine the apparent importance of LAI, biomass, crop height, net radiation and soil moisture in determining latent heat flux and energy partitioning of the irrigated okra field, a

Table 1. Correlation matrix among micro-meteorological and crop growth parameters

	LE	Rn	LAI	CH	ASM	DBM	EF	BR
LE	1.00							
Rn	*0.75	1.00						
LAI	*0.79	0.41	1.00					
CH	*0.60	0.18	*0.78	1.00				
ASM	0.05	0.07	-0.07	-0.14	1.00			
DBM	0.23	-0.11	*0.46	*0.71	-0.42	1.00		
EF	*0.73	*0.42	*0.78	*0.75	0.11	0.39	1.00	
BR	-0.80	*-0.51	-*0.81	-*0.64	0.08	-0.40	-*0.72	1.00

LE = Latent heat flux, Rn = Net radiation, LAI = Leaf area index, CH = Crop height, ASM = Available soil moisture , DBM = Dry above biomass, EF = Evaporative fraction, BR = Bowen ratio

**Significant at 5% probability level*

correlation matrix among these parameters were developed (Table 1). Study revealed that under non-stressed conditions, latent heat flux was commanded mainly by LAI followed by net radiation and crop height. It was found that the during initial, mid, peak and end growth stage and the LAI can be a main controlling factor determining evaporative fraction, Bowen ratio and crop ET and biomass or net assimilation in senescence stages because senescence results in leaf area reduction. Kondoh and Higuchi (2001) found that the ET from grassland responds linearly to the normalized difference vegetation index through the whole growth season, they found that the EF is linearly dependent on LAI before senescence.

Diurnal variation of energy partitioning and Bowen ratio

Diurnal variation of measured surface energy fluxes like net radiation (R_n), sensible heat flux (H), latent heat flux (LE), soil heat flux (G_0) at 4 different growth stages (i) initial growth stage (ii) mid growth stage (iii) peak growth stages and (iv) end growth or senescence were analyzed. (Fig. 5 a, b, c, d). The differences were distinctive in the four stages and the significant difference was the changing amplitude of the heat fluxes. Study revealed that the R_n was the height at 11:30 -12.00 hrs with the values being 37.1, 38.5, 45.1 and 32.6 MJ m^{-2} day^{-1} at initial growth stage, mid growth stage, peak growth stage and end growth or senescence stage, respectively. At end growth

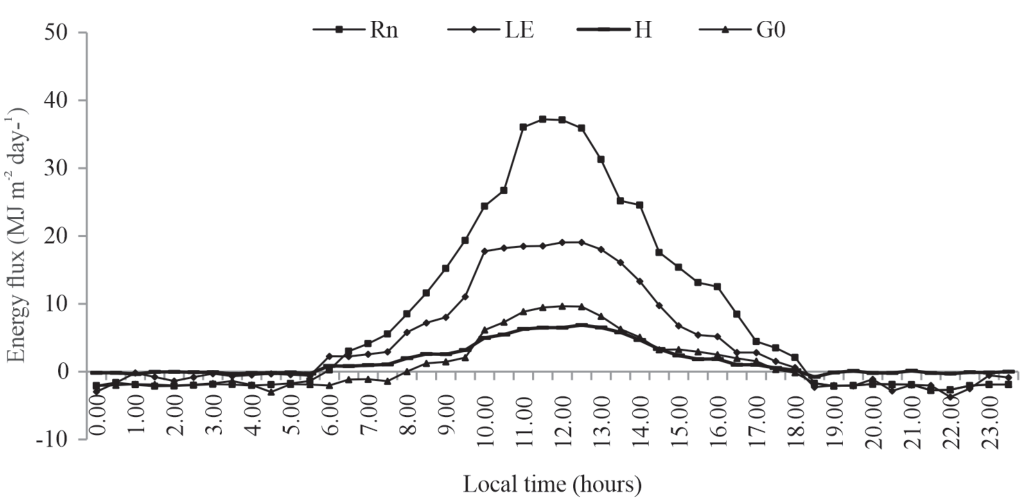

Fig. 5a. Diurnal variation of energy fluxes at initial growth stage

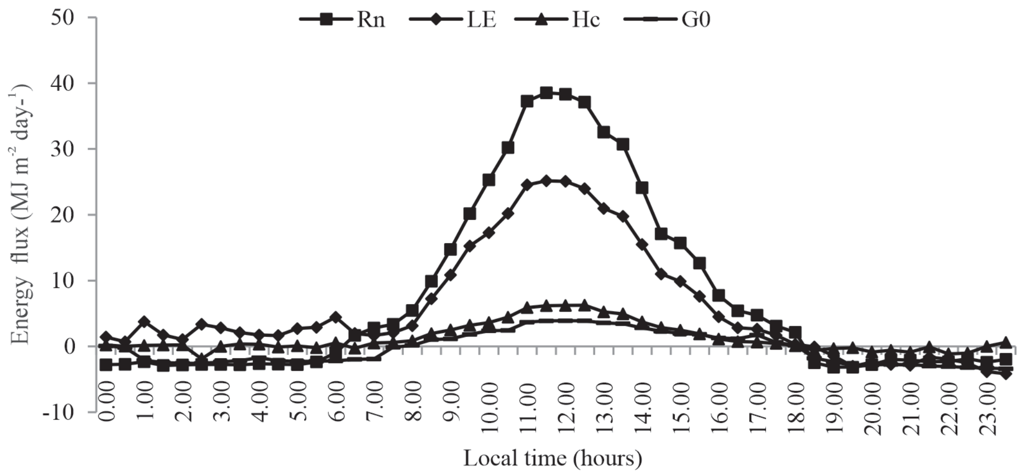

Fig. 5b. Diurnal variation of energy fluxes at initial growth stage

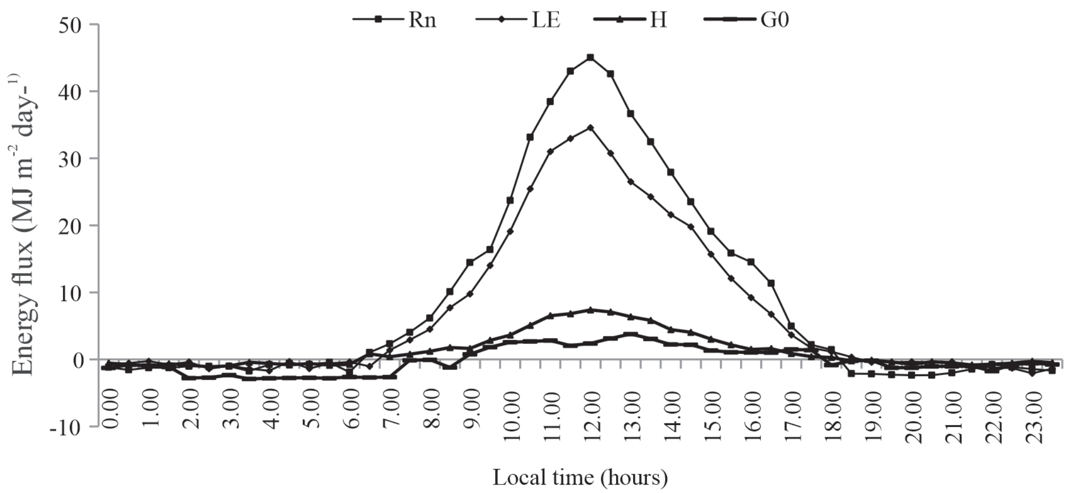

Fig. 5c. Diurnal variation of energy flux at peak growth stage

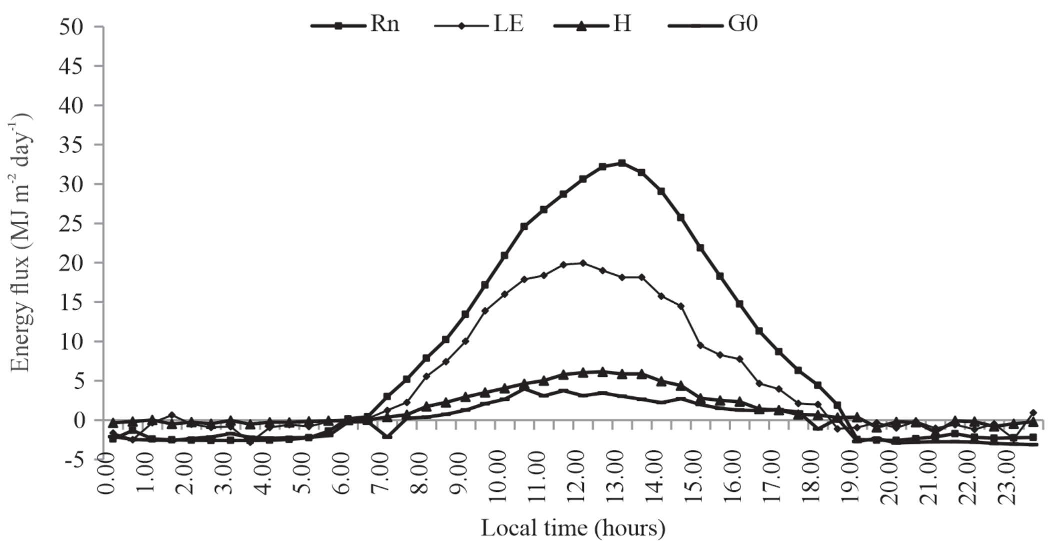

Fig. 5d. Diurnal variation of energy flux at senescence stage

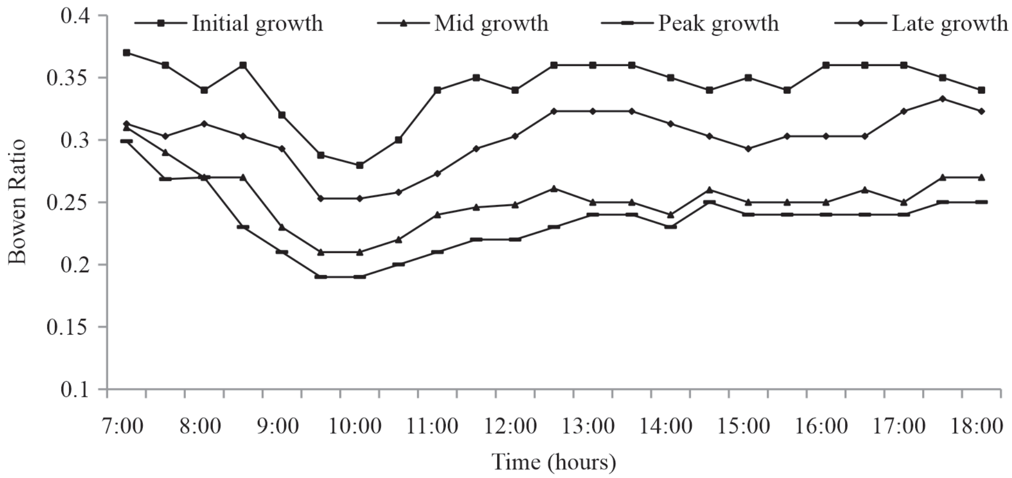

Fig. 6. Diurnal variation of Bowen ratio at different phenophases

or senescence stage Rn lowered down due to onset of southwest monsoon in the region. Hourly day LE variation of peak growth stage revealed that it was the highest at around 12.00 noon at peak growth stage (34.5 MJ m^{-2} day^{-1}). The values of LE/R_n, H/R_n and G_0/R_n were 0.54, 0.18 and 0.16 at initial growth stage whereas these values were 0.76, 0.16 and 0.10, respectively at peak growth sage. From the diurnal variation of Bowen ratio (β) it was revealed that value of 'β' was the lowest at around 9:30-10:00 AM since the latent heat flux was 3-4 times higher than sensible heat flux during that time. From 10.00 AM to 3.30 PM, the Bowen ratio was almost constant and did not very much, which suggests partitioning surface available energy (R_n–G_0) into sensible and latent heat flux at constant rate at these stage. After 3.30 PM the 'β started to increase gradually (Fig. 6). The average Bowen ratio was the lowest (0.23) at peak crop growth stage followed by mid growth stage (0.26) and late or senescence stage (0.30). The β was low during peak growth stage which was due to existence of higher LAI and increased evaporation rate during this stage. The solar radiation penetrates considerably after 0830 hrs for the surface warming so that positive value of G_0 was obtained only from 0830 hrs. The diurnal variation of G_0 was characterized by a cross-over from negative to positive values in the early morning, occurrence of maximum at around noon and return to negative values in the late evening.

The average Bowen ratio was higher (0.03) at this stage than at mid or peak growth stage because of less crop evapo-transpiration (Fig. 6). The day time average β was nearly equal to the mid-day values, thus mean mid-day parameter for energy partitioning or evaporation such as Bowen ratio and evaporative fraction (EF) can be used to estimate evaporative flux to atmosphere during day time hours for temporal up-scaling in this period. The solar radiation penetrates considerably after 0800 h for the surface warming so that positive value of G_0 was obtained only from 0830 hrs. The diurnal variation of G_0 was characterized by a cross-over from negative to positive values in the early morning, occurrence of maximum at around noon and return to negative values in the late evening.

Detailed discussion on estimation of day time evaporation using the instantaneous mid-day Bowen ratio and evaporative fraction (EF) was done by Cargo and Brutsaert (1996). As per this conclusion constant EF assumption is superior to the constant Bowen ratio. In order to study the apparent importance of LAI or soil moisture in energy partitioning of irrigated field, mid-day evaporative fraction versus LAI and soil moisture were studied. Since the soil water was not a constraint, the main controlling factor of the crop ET was LAI and net radiation rather than soil moisture which findings were supported by the report of Steduto and Hsiao (1988).

Conclusions

The latent heat flux, *LE* which ranged from 6.8 to 17.2 MJ m^{-2} day^{-1} shows an apparent correspondence with the development of phenology e.g. consistent with the trend of LAI. Within a crop season, the Bowen ratio exhibits a 'U'-shaped curve, with the lower values (0.22 to 0.25) at mid and peak growth stages, on the contrary, the evaporative fraction, EF shows the reverse trend with the values being 0.79-0.81 and 0.83-0.84 at mid and peak growth stages, respectively. The correspondence of LE and EF appears to be more dependent on LAI followed by R_n, but the LE or EF does not appear correlated to soil water status under non-stressed soil moisture condition. The water footprints of 551.4 and 536.4 m^3t^{-1} were computed in 2013 and 2014, respectively when crop evapotranspiration (ETc) was measured by Eddy covariance technique.

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Received: February 15, 2019; Accepted: April 28, 2019