Surface energy fluxes and crop water stress index in groundnut under irrigated ecosystem

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Abstract

Reliable estimation of surface sensible and latent heat flux is the most important process to appraise energy and mass exchanges among atmosphere, hydrosphere and biosphere. In this study the surface energy fluxes were measured over irrigated groundnut during winter (dry) season using Bowen ratio (β) micrometeorological method in a representative groundnut growing areas of eastern India, i.e. Dhenkanal, Orissa. The crop was grown with four irrigations based on phenological stages *viz.*, (i) branching, (ii) pegging, (iii) pod development and (iv) seed filling and assessed what the crop stress was at those times to see if irrigation scheduling cold be optimized further. Study revealed that the net radiation (R_n) varied from 393–437 to 555–612 W m^{-2} during two crop seasons (2004–2005 and 2005–2006). The soil heat flux (G) was higher (37–68 W m^{-2}) during initial and senescence growth stages as compared to peak crop growth stages (1.3–17.9 W m^{-2}). The latent heat flux (LE) showed apparent correspondence with the growth which varied between 250 and 434 W m^{-2} in different growth stages. The diurnal variation of Bowen ratio (β) revealed that there was a peak in the morning (9.00–10.00 a.m.) followed by a sharp fall with the mean values varied between 0.24 and 0.28. The intercepted photosysnthetic photon flux density or photosysntehtically active radiation (IPAR) by the crop was also measured and relationship between IPAR and leaf area index (LAI) was established with days after sowing. This relationship will be useful in developing algorithm of crop simulation model for predicting LAI or IPAR.

The stressed and non-stressed base lines were also developed by establishing relationship between canopy temperature and vapour pressure deficit (VPD). With the help of base line equation, $[(T_c - T_a) = -1.32\text{VPD} + 2.513]$, crop water stress index (CWSI) was derived on canopy-air temperature data collected frequently throughout the growing season. The soil moisture depletion was measured throughout the crop growing period and plotted with CWSI at different stages. The values of CWSI (varied between 0.45 and 0.64) were noted just before the irrigations were applied based on phenological stages. Study revealed that at two stages (branching and pegging), CWSI were much lower (0.46–0.49) than that of recommended CWSI (0.60) for irrigation scheduling. Therefore, more research is required to optimize the phenology based irrigation scheduling further in the region, which method is using now by local producers.

1. Introduction

Groundnut is the dominant oilseed crop in Orissa, eastern India (Latitude 17°22′–22°45′N and Longitude 81°45′–87°50′E), covering an area of 250.46 thousand ha, which is mostly grown without irrigation during rainy season or with carry-over residual soil moisture

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during dry/winter season. But growing of groundnut with irrigation is gaining popularity in the state during winter season (November–December to February–March) when rainfall is limited. It is possible to increase groundnut production in the state after studying energy and water balance, particularly with availability of high yielding varieties for cultivation during winter season.

Solar radiation is the primary energy source that drives most of the processes of importance to soils and plants like evapotranspiration, biomass partitioning, stomatal conductance, carbon exchange and water use efficiency (Figuerola and Berlinger, 2006; Brown and Halweil, 1998; Kar, 2005). The studies of surface energy fluxes, radiation utilization and crop water stress of important crops of any region are of paramount importance to understand the different factors and their influence on plant growth and development (Shen et al., 2004).

Sensible and evaporative heat loss are the most important processes in the regulation of energy and leaf temperature, and the ratio of the two is called the Bowen ratio. The Bowen Ratio Energy Balance (BREB) is a micrometeorological method to quantity crop water use which was used by many authors to evaluate crop water use models (Cargo and Brutsaert, 1996; Grelle et al., 1999; Perez et al., 1999; Mo and Liu, 2001; Nicholas and Cuenca, 1993; Shen et al., 2002, 2004). Generally where water does not limit transpiration and when soil is wet, latent heat flux consumes most of the energy from net radiation. As the soil dries and water becomes less available for evapotransportion, the energy must go into heating the soil (soil heat flux) or heating the air (sensible heat flux).

Jackson et al. (1981) presents the theory behind the energy balance that separates net radiation from the sun into sensible heat which heats the air and latent heat that is used for transpiration. As the crop undergoes water stress due to non-availability of soil moisture the stomata closes and transpiration decreases, as a result leaf temperature increases. The crop water stress is indicated by the crop water stress index (CWSI) which is the measure of the relative transpiration rate occurring from a plant (using a measure of plant temperature).

Number of studies were carried out in different parts of the world based on micrometeorological measurements for energy balance computation (Reginato and Howe, 1985; Zhang and Lemeur, 1995; Rana and Katerji, 2000; Zhang et al., 2002). The CWSI for monitoring water status and irrigation scheduling of different crops was studied by many earlier workers

(Idso et al., 1981; Azam et al., 1986; Sammis et al., 1988; Hatfield, 1990; Moran et al., 1994; Nielsen and Gardner, 1989; Grelle et al., 1999; Calvet, 2000; Irmak et al., 2000; Orta et al., 2002). There is still a need for a better understanding of the process controlling evapotranspiration and energy partitioning of the important crops like groundnut in eastern India where farmers' traditional practice is to irrigate the crop based on phenological stages. Earlier studies on groundnut in the region (Kar et al., 2006) revealed that four irrigations were required to provide optimum yield and based on this recommendation local producers schedule irrigation for growing the crop. But there is a need to assess the stress (in terms of CWSI) at the time of irrigation at different growth stages to investigate if this procedure could be optimized further. Keeping the importance of above aspects in view, in this research work we have attempted to study distribution of surface energy fluxes and crop water stress index (CWSI) with application of irrigation at different growth stages. The values of CWSI were particularly noted just before application of irrigations.

2. Material and methods

2.1. Study area

The study was conducted at Dhenkanal district, Orissa, India (Latitude $20°50'$ to $20°55'$; Longitude $85°45'$ to $85°50'$; 139 m above m.s.l.) during two winter/dry seasons (2004–2005 to 2005–2006). The region belongs to sub-humid subtropical agro-ecological zone where average annual rainfall is 1440 mm and 80% of that received during rainy season (June–September) due to southwest monsoon. The mean monthly maximum temperature ranges from 46.2 °C in May to 29.4 °C in December. On the other hand, mean monthly minimum temperature varies between 24.6 °C in July and 9.0 °C in December. Generally in the region, the winter season is dry, as a result cropping system is mainly confined to rainy season, dominated by rice. But now groundnut is getting popular in the region as an important oilseed crop during dry/winter season with the help of carry-over residual soil moisture and supplemental irrigations from harvested rainwater of rainy season.

2.2. Weather during crop growth period

The normal as well as prevailing weather conditions during two crop growth seasons (2004–2005 and 2005–2006) are given in Table 1. The study revealed that the

Table 1
Normal as well as actual weather data during crop growth period

Parameters	Month				
	November	December	January	February	March
Total rainfall (mm)					
2004–2005	23.8	0.0	0.0	0.0	0.0
2005–2006	20.1	7.4	0.0	10.9	0.0
Normal	25.2	4.5	15.5	17.2	25.4
Mean maximum air temperature (°C)					
2004–2005	33.1	30.5	30.9	36.5	38.7
2005–2006	34.1	31.7	31.2	33.2	37.8
Normal	32.2	29.4	30.9	36.1	38.1
Mean minimum air temperature (°C)					
2004–2005	12.3	10.2	9.7	10.0	12.9
2005–2006	10.9	10.1	10.5	10.3	12.3
Normal	11.5	9.0	9.3	10.3	12.5
Mean relative humidity (%)					
2004–2005	62	61	59	56	63
2005–2006	59	64	63	62	59
Normal	65.5	60.5	61	54	49.5
Mean open pan evaporation (mm day^{-1})					
2002–2003	4.0	4.3	2.8	3.7	5.1
2005–2006	4.3	4.2	2.9	4.3	5.3
Normal	3.9	4.0	3.1	4.2	5.8

mean monthly maximum temperature during crop growth period ranged from 38.7 °C in March (2004–2005) to 30.5 °C in December (2004–2005). On the other hand, mean minimum temperature varied between 12.9 °C in March to 9.7 °C in January in 2004–2005. The pan evaporation varied from 2.8 mm in January (2004–2005) to 5.3 mm in March (2005–2006). As per the expected trend, the actual rainfall was meager during crop growth period (dry/winter season). The rainfall amount of 23.8 mm, 27.5 mm occurred in the first, (2003–2004) and second (2004–2005) seasons, respectively. Study revealed that weather during crop growth periods was almost comparable with that of the normal.

2.3. Soils of experimental site

Taxonomically the soils of the experimental area belongs to category of Fine, Loamy, Mixed Hyperthermic Typic Haplaustalf. The upper layer (0–0.15 m) of the soil profile was sandy loam in texture whereas next two layers (0.15–0.30 and 0.30–0.45 m) were sandy clay loam in nature. The bulk density was 1.55 Mg m^{-3} at 0–0.15 m soil depth and it increased with depth, for the 0.9–1.2 m layer it was 1.62 Mg m^{-3}. The pH was slightly to moderately acidic and no salt problem (low EC) was detected in the soil profile. The fertility status

of the soil was very low. The organic carbon content was the highest (0.60%) at the upper layer (0–0.15 m) while at the deeper layer (0.9–1.2 m) it was only 0.07%. The Olsen P and available K (NH4OAc-K) were 2.9 mg P kg^{-1} and 7.5 mg K kg^{-1} of soils, respectively at upper soil layer (0–0.15 m). The available water ranged between 0.128 and 0.162 m^3 m^{-3} at different soil depths.

2.4. Crop management

Groundnut crop (cv. TMV-2) was sown with the spacing of 30 cm × 20 cm on 15th November, 2004 and 17th November 2005. The size of the experimental plot was 360 m^2 (20 m × 18 m). Four irrigations (60 mm water in each irrigation) were applied through gated pipe from harvested rainwater of rainy season at four critical phenological stages of the crop *viz*., (i) branching, (ii) pegging, (iii) pod development and (iv) seed filling, which coincided with 16–17, 34–35, 53–55, 76–79 days after sowing, respectively in two different seasons. Plots were bordered to prevent runoff. In regard to fertilizer management of this crop, N:P:K was applied in the ratio of 20:40:40, half of the nitrogen and full dose of phosphorus and potash were applied as basal dose at the time of sowing by placement method. The remaining half of the nitrogen was applied at the time of first irrigation. To measure the weather parameters mainly temperature, wind velocity and relative humidity over the crop, the weather measurement sensors were kept at three heights at 0.5 m interval.

2.5. Measurement of leaf area index (LAI) and soil water use

For measuring leaf area index (LAI) of the crop, five plant samples were randomly uprooted from the plot at 7-day interval. The green leaf portions were separated and the area of the separated leaves was measured using a leaf area meter (LICOR 3200). Mean values per plant was used in calculating the LAI, which was derived using the following relationships (Kar and Verma, 2005):

$$\text{LAI} = \frac{\text{measured leaf area per plant (cm}^2)}{100 \times 100 \, (\text{cm}^2)} \times \text{no. of plants/m}^2$$

The actual water use (AWU) was estimated as per the equation,

$$\text{AWU} = \text{ER} + I + \Delta S + V_{\text{f}} - R - D \qquad (1)$$

where ER = effective rainfall (mm), calculated using USDA soil conservation services methods, I = irrigation (mm), ΔS = change in soil moisture storage (mm), R = runoff (mm), estimated using USDA soil conservation service methods, and D = deep drainage (mm). Since crop was irrigated only at critical growth stages and winter rain is meager, deep drainage was considered as nil.

To study the change in soil moisture storage, the soil water content was measured gravimetrically once a week from 0–0.15 m, 0.15–0.30 m, 0.30–0.45 m 0.45–0.60 m, 0.60–0.90 m and 0.90–1.20 m soil layers.

V_f = vertical flux (mm day^{-1}) up to the depth of 1.20 m, computed following Darcy's law

$$V_f = -\frac{K\delta H}{\delta Z} \quad (2)$$

where K is the hydraulic conductivity (mm day^{-1}) and $\delta H/\delta Z$ is the hydraulic gradient. Since the water table depth was deep, the upward flux was found negligible.

2.6. Measurement of surface energy fluxes and Bowen ratio

Seasonal variation of main components of the energy balance equation *viz.*, R_n (W m^{-2}), net radiation flux; G (W m^{-2}), soil heat flux; LE (W m^{-2}), latent heat flux and H (W m^{-2}), sensible heat flux were computed at 1 week interval throughout the growing season. To study the diurnal variation of energy balance, weather parameters were recorded at 1-h interval. Bowen ratio (β) energy balance method was used to compute latent heat flux as per the equations below.

$$R_n = LE + H + G \quad (3)$$

$$\Rightarrow R_n - G = LE\left(1 + \frac{H}{LE}\right) = LE(1 + \beta) \quad (4)$$

$$LE = \frac{R_n - G}{1 + \beta} \quad (5)$$

On the other hand, Bowen ratio

$$\beta = \frac{\text{sensible heat loss } (H)}{\text{evaporative heat loss (LE)}} \quad (6)$$

$$\beta = \frac{c_p P_a}{L\varepsilon} \frac{(T_2 - T_1)}{(e_2 - e_1)} \quad (7)$$

where c_p: specific heat capacity of air (1 J g^{-1} °C^{-1}); P_a: atmospheric pressure (101.3 kPa); L: latent heat of vaporization (2449 J g^{-1}); ε: ratio of the molecular weight of water to that of air (0.622).

So,

$$\beta = \frac{(1 \times 101.3)}{(2449 \times 0.622)} \frac{(T_2 - T_1)/z_2 - z_1}{(e_2 - e_1)/z_2 - z_1} = 0.067 \frac{\delta T/\delta z}{\delta e/\delta z} \quad (8)$$

$R_n - G$ = available energy. T_1 is the temperature at height (z_1); T_2 the temperature at height (z_2); e_1 the vapour pressure at height (z_1); e_2 is the vapour pressure at height (z_2).

R_n was measured using BABUC M net radiometer where the hemispherical polyethylene windshield domes protect the net radiometer sensor devices. G was computed with the equation, $G = 0.4R_n(\exp(-K \times LAI))$, $\times LAI))$, where 'K' is the extinction coefficient, LAI = leaf area index, extinction coefficient of groundnut was taken as 0.35.

The Bowen ratio tower was installed inside the cropped field and weather recording instruments were kept on that tower at a distance of 0.5 m which measures temperature, humidity and wind velocity at 1-h interval. The lowest measuring height was 0.5 m above the canopy. The output of all meteorological sensors were recorded with a data logger and retrieved afterwards with the help of a PC.

2.7. Intercepted photosynthetically active radiation (IPAR)

Photosynthetically active radiation (PAR) is the general radiation term that covers both photon and energy terms. This is the numbers of photons in the 400–700 mm waveband incident per unit time on a unit-distance. Light transmission meter (EMS-7) instrument was used to measure the intercepted photosynthetically active radiation (IPAR) by the whole canopy.

IPAR was computed as per the following relationship.

IPAR by whole canopy = incident radiation on the canopy − reflected radiation by the canopy − transmitted radiation + reflected radiation from the ground.

IPAR (%) =

$$\frac{\text{PAR received at any height } (\mu E\, s^{-1}\, m^{-2})}{\text{PAR incident above the crop canopy } (\mu E\, s^{-1}\, m^{-2})} \times 100 \quad (9)$$

The reflected radiation was obtained by keeping the sensor inverted 0.5 m above the canopy and the sensor was kept on the ground across the rows diagonally to get transmitted radiation at the ground. To get the reflected PAR from the ground, the sensor was held in the inverse

position at 0.05 m above the ground. The measurement was made at regular intervals on clear days between 11.00 and 12.00 h IST when disturbances due to leaf shading and leaf curling were minimum.

2.8. Canopy temperature and crop water stress index (CWSI)

Canopy temperatures were measured with an Infrared Thermometer (Teletemp Model AG 42) with the emissivity adjustment set at 0.95. The Infrared Thermometer was angled at $45°$ from the horizontal while taking observations and aimed at the same predetermined points throughout the trial. The CATD and VPD data were used to compute the crop water stress index (CWSI) as per the procedure given by Idso et al. (1981).

The canopy temperature and canopy-air temperature difference (CATD) were obtained from 11.00 to 14.00 h (Indian Standard Time) at hourly intervals under clear skies. The dry and wet bulb temperatures were measured with an Aspirated Psychrometer at a height of 2.0 m in an open field adjacent to experimental area. The mean VPD was computed using the corresponding instantaneous wet and dry bulb temperatures and the standard psychrometer equation. CWSI is based on the fact that the canopy air temperature difference is linearly to the air vapour pressure deficit (VPD) (Jackson et al., 1981; Kustas et al., 1989) as per the equation below.

$$T_c - T_a = \frac{r_a R_n}{\rho C_p} \times \frac{r(1 + (r_c/r_a))}{\Delta + r(1 + (r_c/r_a))} \times \frac{\text{VPD}}{\Delta + r(1 + (r_c/r_a))} \quad (10)$$

where r_a and r_c are the aerodynamic and canopy resistances (s m^{-1}), derived as per the procedure of Allen et al.

(1998). R_n = net radiation (W m^{-2}), C_p = volumetric heat capacity of air (J m^{-3} c^{-1}), r is the psychrometric constant (Pa $°C^{-1}$) Δ = slope of the temperature-saturated vapour pressure relation (Pa $°C^{-1}$). The relationship between $(T_c - T_a)$ and VPD was established under non-stressed and stressed conditions and upper and lower base lines were drawn (Fig. 1). These base lines were used to calculate CWSI for monitoring irrigation scheduling and irrigation status (Idso et al., 1981; Jackson et al., 1981).

$$\text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)l_0}{(T_c - T_a)u_a - (T_c - T_a)l_0} \quad (11)$$

where CWSI = computed crop water stress index; A CWSI of 0 indicates no water stress, and a value of 1 represents maximum water stress; $(T_c - T_a)$ is the difference between crop canopy (T_c) and air temperature (T_a); $(T_c - T_a)u_a$ is the upper limit of canopy minus air temperature (non-transpiring crop), i.e. upper base line; $(T_c - T_a)l_0$ is the lower limit of canopy minus air temperature (well-watered crop), i.e. lower base line.

The lower base line for the crop during cold season (cropped period) was determined by making canopy minus temperature and vapour pressured deficit measurements 2 days after a crop was received full irrigation. The measurements were made from 11.00 to 14.00 h both in humid and dry days, resulted wide range of vapour pressure measurements. With the wide range of relationship between crop canopy minus air temperature and vapour pressure deficit linear regression was developed for the lower base line.

Upper base line ($-1°C$) was developed based on 18 observations by employing the common procedure (Idso et al., 1981; Jackson et al., 1981). The upper base line was determined by cutting off the plant and then wired the plant back in place and waited for 1 day till the
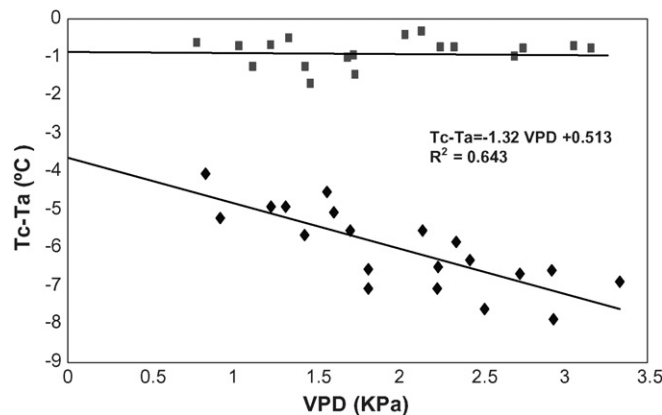

Fig. 1. Relationship between $(T_c - T_a)$ and VPD of groundnut for computing CWSI.

transpiration of plant approached zero. For the ground-nut crop, upper base temperature was measured as $-1\,^{\circ}$C under existing climatic and soil conditions of the present study area.

2.9. Meteorological data

Daily meteorological data, *viz.*, rainfall, evaporation, relative humidity, maximum and minimum temperatures, etc. were recorded from nearby meteorological observatory of Central Rubber Board Regional Station, Dhenkanal, Orissa, India.

3. Results and discussion

3.1. Seasonal variation of surface energy fluxes during crop growth period

The seasonal variation of surface energy fluxes over irrigated groundnut during two crop growth seasons (2004–2005 and 2005–2006) were measured at 7–10 days interval and midday average value of 10.00–15.00 h are depicted in Figs. 2 and 3, respectively. Study revealed that net radiation (R_n), amount of energy available for physical or biological processes over the crop varied from 393–437 W m^{-2} in the month of January to 555–612 W m^{-2} in March during two crop seasons.

The latent heat flux, LE is the energy transfer due to evaporation or condensation which is the most important component of energy balance for irrigation management. Study revealed that LE is largely dependent of leaf area index (LAI) which shows peak when LAI was maximum. The midday average latent heat flux (on clear days) varies from 250 to 434 W m^{-2} at different growth stages. The LE variation during growing season in irrigated groundnut mainly occurred due to variation of solar radiation, temperature, vapour pressure deficit and soil moisture during the crop seasons.

The seasonal course of soil heat flux (G) of irrigated groundnut revealed that variation of 'G' during growth seasons clearly reflects the change of crop growth. The 'G' shows peak value during germination and early crop growth period when crop coverage was minimum. Afterwards, the course of 'G' is affected by development of crop canopy or leaf area index. Midday averaged 'G' value ranged from 11.7 to 79.3 W m^{-2} with an average value of 53.8 W m^{-2} in irrigated groundnut. The ratio of G/R_n from maximum LAI to senescence stage was found 8–11% over the crop. Soil heat flux shows declining trend during peak growth stage which coincided with maximum leaf area index (LAI) or maximum intercepted photosynthetically active radiation (IPAR).

The seasonal variation of Bowen ratio (β) is depicted in Fig. 4. Study revealed that Bowen ratio was higher (0.32–0.58) during early (before branching) and senescence (after seed filling) stages of crop growth which was due to higher sensible heat flux and lower latent heat flux during those periods. The Bowen ratio started to decline from 20 DAS upto 72 DAS and there was a sharp fall of Bowen ratio (0.20–0.30) during peak growth stage when leaf area index was maximum (63
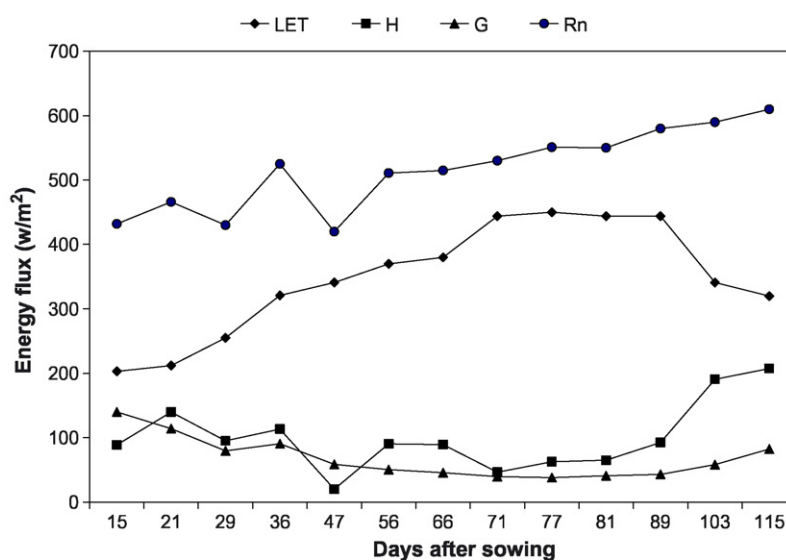

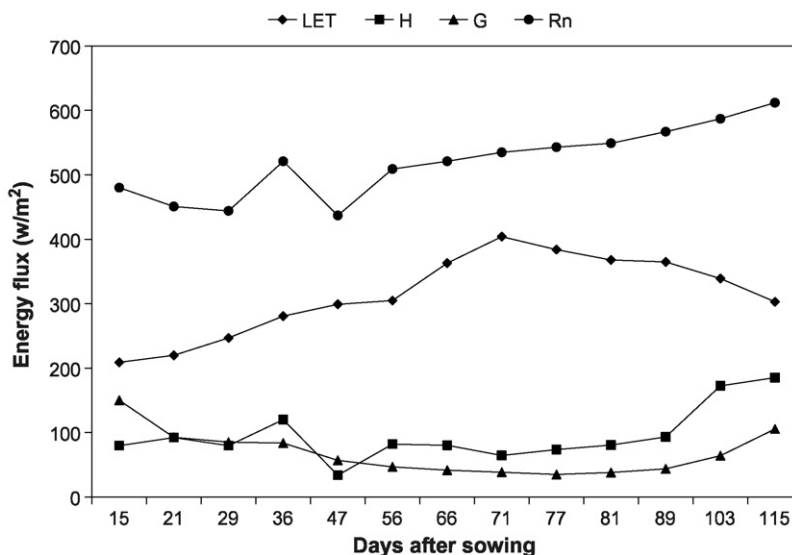Fig. 2. Seasonal variation of energy fluxes of groundnut during 2005–2006.

Fig. 3. Seasonal variation of energy fluxes of groundnut during 2004–2005.

DAS). The higher LAI led to grater transpiration and therefore latent heat flux density was higher during that period. From 16 to 75 DAS four irrigations were provided to crop, which led to greater evapotranspiration loss from branching to seed development stages, as a result Bowen ratio (β) was declined during those periods.

3.2. Diurnal variation of energy balance

Out of many observations, three observations dates coincided with early growth stage, maximum LAI and senescence stages were taken in each crop season for studying diurnal variation of energy balance. Since diurnal variation of energy balance of both the years 2004–2005 and 2005–2006 shows more or less same trend, three observation dates (7 December 2005, 21 January 2006 and 19 February 2006) of the season 2005–2006, were taken in this research paper to depict the diurnal variation of energy balance. Study revealed that net radiation (R_n) was the highest at 12.00 noon with the values being 412, 501 and 567 W m^{-2} in three respective dates (Fig. 5). Hourly LE variation on 7 December 2005 revealed that it ranged from 46 W m^{-2}
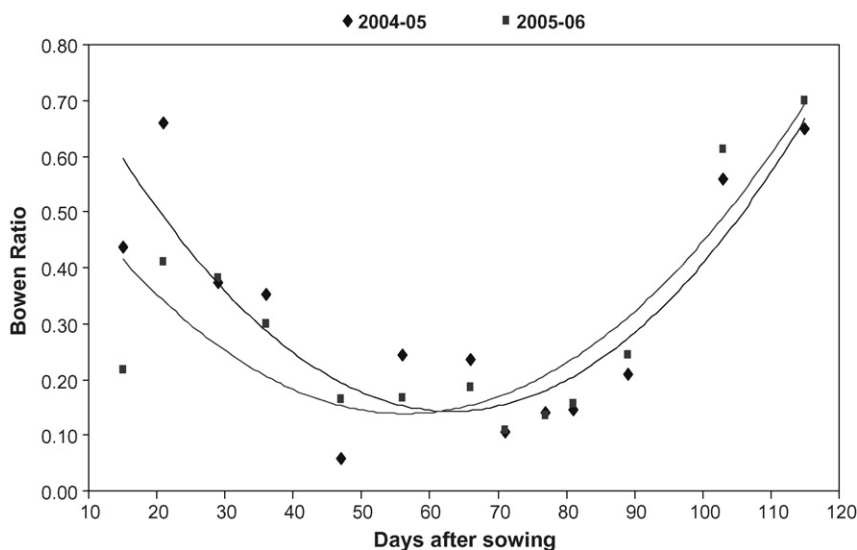

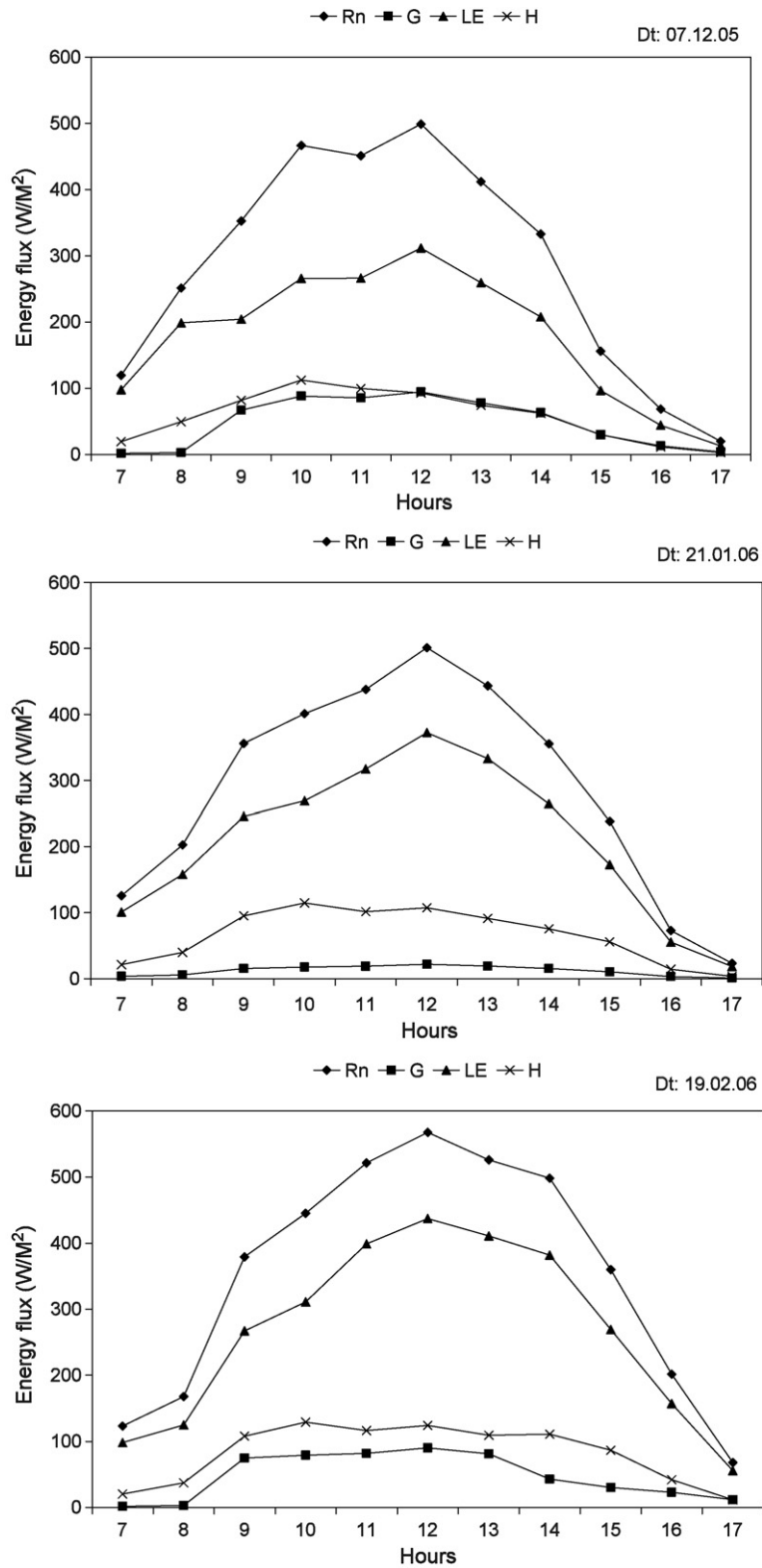Fig. 4. Seasonal variation of Bowen ratio of groundnut.

Fig. 5. Diurnal variation of energy balance of groundnut at different growth stages.
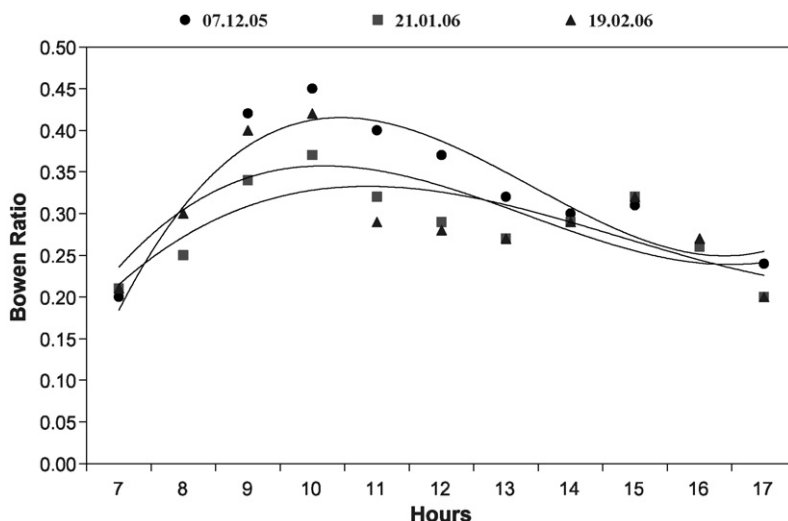
Fig. 6. Diurnal variation of Bowen ratio over groundnut crop at different stages.

at 7.00 a.m. to 13 W m^{-2} at 5.00 p.m. with the highest value of 311 W m^{-2} at 12.00 noon. In other 2 days (21 January 2006 and 19 February 2006), the highest LE was 372 and 437 W m^{-2}, respectively during 12.00 to 13.00 h. Diurnal variation of Bowen ratio (H/LE) for 3 above mentioned dates was also computed and is also presented in Fig. 6 for representing early, peak growth and senescence stages, respectively. Study revealed that the Bowen ratio (β) has a steep rise in the early morning and reached the peak at around 9.00–10.00 h. The peak value of β ratio was 0.45, 0.37 and 0.42 at initial, mid and late growth. Study also revealed that β ratio was less at the peak growth stage of the crop (21 January 2006) which was due to the existence of highest leaf area index

(LAI) and more evaporation rate during that stage. After 10.00 h β declined gradually until sunset for all the growth stages.

3.3. Intercepted photosynthetically active radiation (IPAR) during crop growth period

The variation of intercepted photosynthetically active radiation (IPAR) of groundnut with days after sowing (DAS) was also computed and is presented in Fig. 7. Maximum interception of 89% was observed at 77 DAS when the crop was grown with 4 irrigations. The relationship between IPAR (%) and days after sowing (DAS) was established and a polynomial equation of
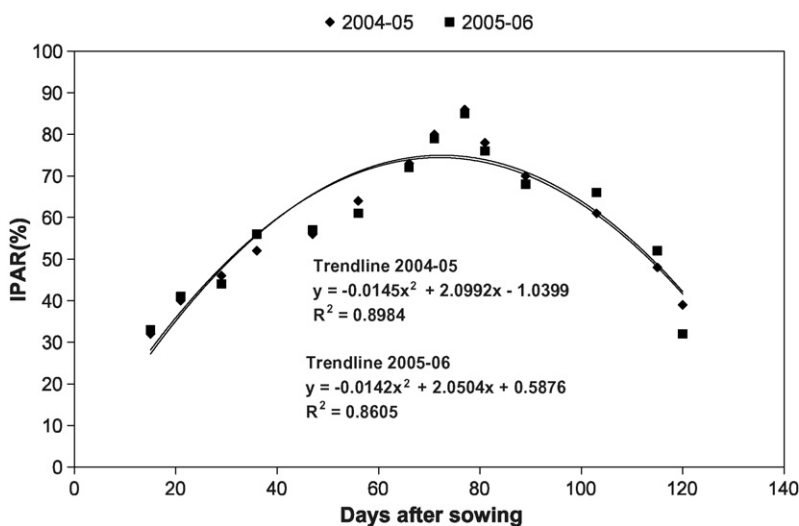

Fig. 7. Variation of IPAR with days after sowing (DAS) in groundnut.
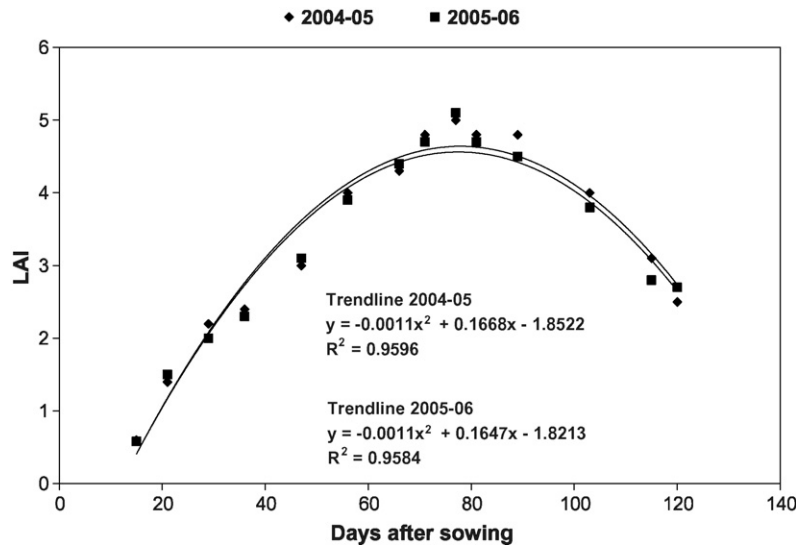
Fig. 8. Variation of LAI with DAS in groundnut.

second order (best fit) was derived to compute IPAR at different days after sowing (DAS) (Fig. 8). The highest LAI of 5.0 and 5.2 were computed in two different seasons (Fig. 8). The relationship between IPAR and LAI was also established and equations were developed to predict leaf area index (LAI) of groundnut with IPAR data. Study revealed that LAI was positively related with intercepted photosynthetically active radiation (IPAR). During the peak period, the soil heat flux was minimum, G and Bowen ratio, β ratio was less due to existence of highest leaf area index. The developed relationship of IPAR with DAS and LAI will be useful for development of algorithm of crop simulation model for predicting LAI

and vice versa (Fig. 9). With the help of predicted LAI or IPAR, soil heat flux, G can be derived.

3.4. Soil moisture depletion and crop water stress index (CWSI)

In the region farmer's traditional practice is to apply irrigation at critical phenological stages. Based on our earlier studies (Kar et al., 2006) it is revealed four irrigations at four critical stages *viz.*, (i) branching, (ii) pegging, (iii) pod development and (iv) seed filling provided maximum yield when compared with two or three irrigations. In this research paper we attempted to
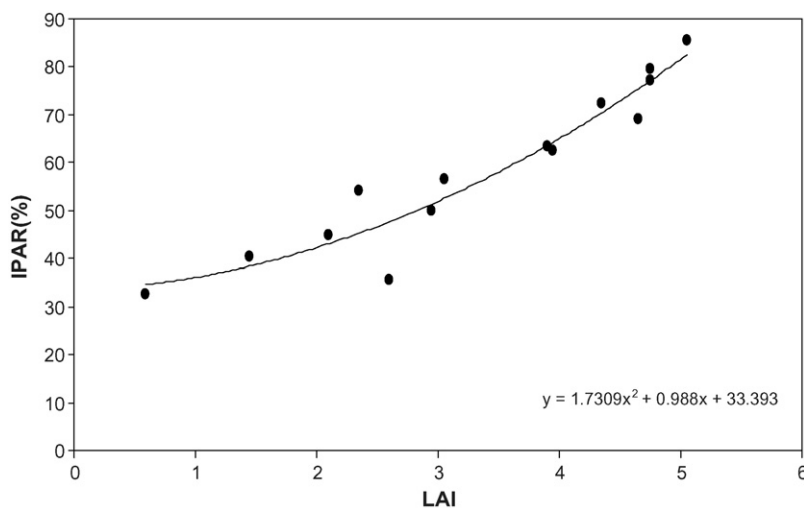

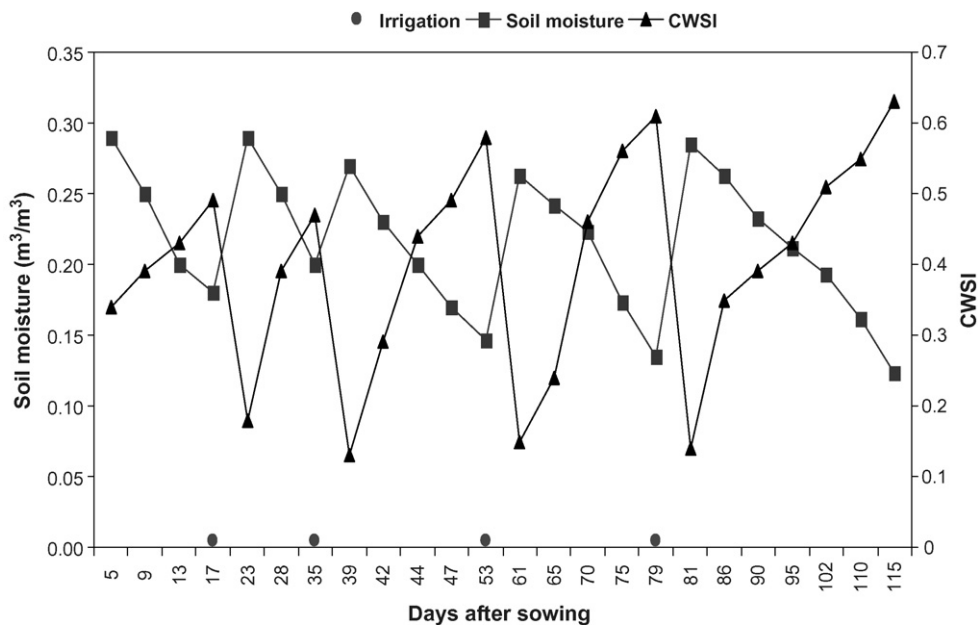Fig. 9. Relationship between IPAR and LAI in groundnut.

Fig. 10. Variation of CWSI and soil moisture of groundnut during 2004–2005.

study the soil moisture depletion pattern during entire crop growth season and simultaneously crop water stress index (CWSI) was computed to assess that under what stress farmers irrigate when they apply irrigation based on critical stages. Study revealed that before irrigation soil moisture content was 0.185–0.193, 0.159–0.201, 0.12–0.14 and 0.113–0.132 $m^3\,m^{-3}$ at branching, pegging, pod development and grain filling stages, respectively. With the change of soil moisture particularly before and after irrigation, the CWSI was derived as per the procedure described in the methodology and are depicted in Figs. 10 and 11 for the seasons 2004–2005 and 2005–2006, respectively. Based on the calculation of non-water stress
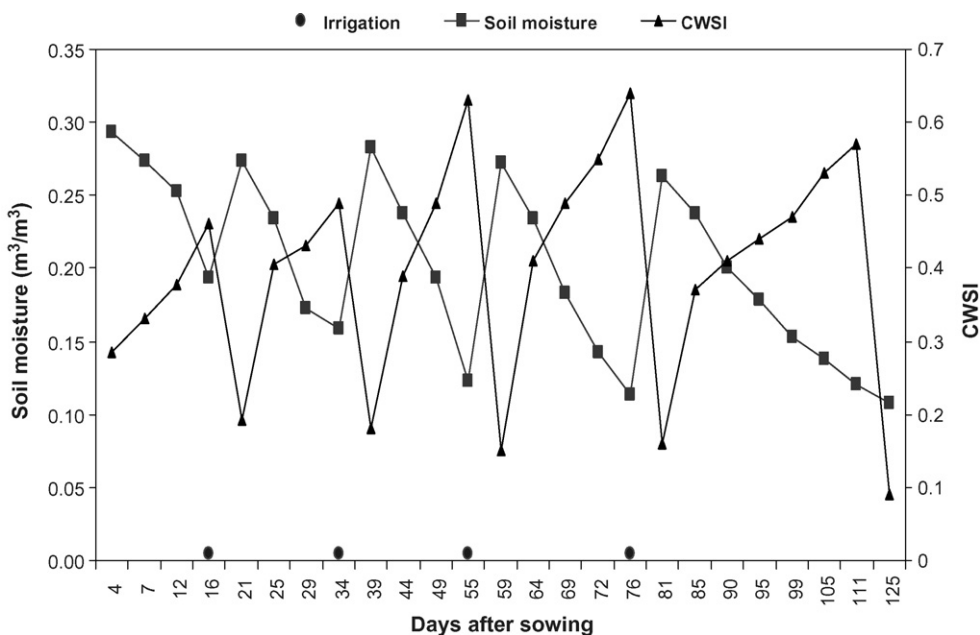

Fig. 11. Variation of CWSI and soil moisture of groundnut during 2005–2006.

baseline equation. $(T_c - T_a) = -1.32$ VPD $+ 2.513$ for groundnut and stressed baseline ($-1\,^\circ$C), the CWSI values were 0.46–0.49, 0.47–0.49, 0.58–0.63 and 0.61–0.64 just before application of irrigation water at branching, pegging, pod development and seed filling stages, respectively (Figs. 10 and 11). Immediately after irrigation, the CWSI dropped to 0.16 to 0.19 at different growth stages. Earlier many scientists (Idso et al., 1981; Jackson et al., 1981; Orta et al., 2002) worked on CWSI for irrigation scheduling for many crops in different parts of the world and they recommended the CWSI of 0.6 for irrigation scheduling. Our study revealed that CWSI was much lower (0.46–0.49) just before applying irrigation at branching and pegging stages. In other two stages, CWSI values varied between 0.61 and 0.63 just before the application of irrigation to crop.

4. Conclusion

Our study revealed that the net radiation (R_n) varied from 393–437 to 555–612 W m^{-2} during two crop seasons. The soil heat flux (G) was higher during initial and senescence growth stages. The latent heat flux (LE) shows apparent correspondence with the development of canopy cover and LAI. The photosysnthetic photon flux density or photosysntehtically active radiation was measured throughout the crop growth period and relationship was established with days after sowing and leaf area index (LAI). These relationship can be useful for development of algorithm of crop simulation model for predicting LAI or IPAR. Derived CWSI was found as lower (0.46–0.49) than that of recommended (0.60) value in both the seasons before application of irrigation at branching and pegging stages. Therefore, more research is required to optimize the phenology based irrigation scheduling further in the region.

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