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REVIEW

# Energy balance and crop water stress in winter maize under phenology-based irrigation scheduling

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**Abstract** In eastern India, cultivation of winter maize is getting popular after rainy season rice and farmers practice irrigation scheduling of this crop based on critical phenological stages. In this study, crop water stress index of winter maize at different critical stages wase determined to investigate if phenology-based irrigation scheduling could be optimized further. The components of the energy budget of the crop stand were computed. The stressed and non-stressed base lines were also developed (between canopy temperature and vapor pressure deficit) and with the help of base line equation, [$(T_c - T_a) = -1.102$ VPD $- 3.772$], crop water stress index (CWSI) was determined from the canopy-air temperature data collected frequently throughout the growing season. The values of CWSI (varied between 0.42 and 0.67) were noted just before the irrigations were applied at critical phenological stages. The soil moisture depletion was also measured throughout the crop growing period and plotted with CWSI at different stages. Study revealed that at one stage (silking), CWSI was much lower (0.42–0.48) than that of recommended CWSI (0.60) for irrigation scheduling. Therefore, more research is required to further optimize the phenology-based irrigation scheduling of winter maize in the region. This method is being used now by local producers. The intercepted photosynthetically active radiation and normalized difference vegetation index over the canopy of the crop were also measured and were found to correlate better with leaf area index.

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## Introduction

The energy budget of the active surface such as vegetation can be described by the energy balance equation in a steady state form by

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

The net radiation ($R_n$) going into or from the surface, the sensible or turbulent heat flux ($H$), latent heat flux ($\lambda E$) going into or from the atmosphere, and the heat flux going into or out of ground ($G$). The net radiation flux occurs as a result of the radiation balance at the surface, whereas the latent heat or water vapor flux is a result of evaporation and transpiration, or water condensation at the surface. Sensible heat loss 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 (Brown and Halweil 1998; Shen et al. 2004; Figuerola and Berlinger 2006). The Bowen ratio energy balance (BREB) is a micrometeorological method to quantify crop water use and is used by many authors in crop water use models (Perez et al. 1999; Mo and Liu 2001; Shen et al. 2002, 2004).

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 latent heat decreases. With the decrease of latent heat flux, leaf temperature increases and the crop may face water stress (Reginato and Howe 1985; Zhang and Lemeur 1995; Rana and Katerji 2000; Zhang et al. 2002). The crop water stress is thus 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). Earlier, many scientists (Idso et al. 1981; Jackson et al. 1981; Hatfield 1990; Orta et al. 2002; Moran et al. 1994; Nielsen and Gardner 1989; Grelle et al. 1999; Calvet 2000; Irmak et al. 2000; Kar and Kumar 2007) worked on CWSI for irrigation scheduling for many crops in different parts of the world, and they recommended the CWSI of 0.6 for scheduling an irrigation event.

The CWSI for monitoring water status and irrigation scheduling of different crops was studied by many earlier workers. There is still a need for a better understanding of the process controlling evapotranspiration and energy partitioning of the important emerging crops like winter maize in eastern India where farmers' traditional practice is to irrigate the crop based on phenological stages. Earlier studies on phenologically based irrigation scheduling of maize in the region (Kar et al. 2006) revealed that four irrigations were required to provide optimum yield, and now based on this recommendation, local producers schedule irrigation for growing the crop. In this study, the water stress before irrigation in terms of CWSI values at different phenological stages was monitored. The extent of crop water stress at different phenological stages before irrigation is assessed to investigate if this irrigation scheduling could be optimized further.

## Materials and methods

### Study area

To study the energy balance and crop water stress at critical growth stages, maize crop was grown at Dhenkanal district, Orissa, India (Lat. 20°50′–20°55′; Long. 85°45′–85°50′; 139 m above msl.) during two winter seasons (2004–2005 to 2005–2006). The study area belongs to sub-humid subtropical agro-ecological zone where average annual rainfall is 1,440 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; hence, cropping system is mainly confined to rainy season, dominated by rice. But now winter maize is getting popular in the region as an important cash crop. The crop is being grown with the help of carry-over residual soil moisture and supplemental irrigations at critical growth stages from harvested rainwater of rainy season, hence optimum use of water is required for growing the crop.

### 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 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 and 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 and 27.5 mm occurred in the first (2003–2004) and second (2004–2005) seasons, respectively. Weather during crop growth periods was found almost comparable with that of the normal.

### Soils of experimental site

Taxonomically, the soils of the experimental area belong to category of Fine, Loamy, Mixed Hyperthermic Typic Haplaustalf. The upper layer (0–0.15 m) of the soil profile

**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 |

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 1.58 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 1.65 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 (0.65%) at the upper layer (0–0.15 m), while at the deeper layer (0.9–1.2 m), it was only 0.157%. The Olsen P and available K ($NH_4OAc$–K) were 13 and 121 kg $ha^{-1}$, respectively, at upper soil layer (0–0.15 m). The available water ranged between 0.131 and 0.16 $m^3$ $m^{-3}$ at different soil depths.

## Crop management

A maize hybrid of 120 days duration was sown on 5 November 2004 and 8 November 2005 after harvesting medium duration rice (cv. Lalat of 120 days) in the region. The crop was grown with local recommended package of practices. The fertilizer dose of 80:50:50 was applied in the soil. The N was applied in three split doses, one-third during sowing, one-third at knee-high stage and one-third at tasseling stage; on the other hand, whole amount of $P_2O_5$ and $K_2O$ was applied during sowing. The herbicide 'Atrazine' at 1.5 kg $ha^{-1}$ a.i. was applied pre-emergence to control weeds in the plots. The crop was cultivated with four irrigations, applied at four critical phenological stages viz., early vegetative + tassel initiation + silking + grain filling. Each irrigation consisting of a metered amount of 60 mm depth of water applied through gated pipe. To measure the weather parameters mainly temperature, wind velocity and relative humidity over the crop, the weather measurement sensors were kept above the canopy at three heights at 0.5 m interval (Kar and Kumar 2007).

## Measurement of leaf area index (LAI) and soil water depletion

For measuring leaf area index (LAI) of the crop, three plant samples were randomly uprooted from the plot at 7–10 day interval. The green leaf portions were separated, and the area of the separated leaves was measured. Mean values per plant was used in calculating the LAI, which was derived using the following relationships (Kar and Verma 2005):

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

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

## 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 was 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 ($\beta$) energy balance method was used to compute latent heat flux as per the equations given below:

$$R_n = \text{LE} + H + G \tag{3}$$

$$\Rightarrow R_n - G = \text{LE}\left(1 + {}^{H}\!/_{\text{LE}}\right) = \text{LE}(1 + \beta) \tag{4}$$

$$\text{LE} = {}^{(R_n - G)}\!/_{(1+\beta)} \tag{5}$$

On the other hand,

$$\text{Bowen ratio } (\beta) = \frac{\text{Sensible heat loss } (H)}{\text{Evaporative heat loss (LE)}} \tag{6}$$

$$= \frac{C_p P_a (T_2 - T_1)}{L\varepsilon \ (e_2 - e_1)} \tag{7}$$

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 (2,449 J $g^{-1}$); $\varepsilon$, ratio of the molecular weight of water to that of air (0.622) So,

$$\beta = \frac{(1 \times 101.3)}{(2{,}449 \times 0.622)} \frac{(T_2 - T_1)/z_2 - z_1}{(e_2 - e_1)/z_2 - z_1} = 0.067 \frac{(\delta T/\delta z)}{(\delta e/\delta z)} \tag{8}$$

$R_n - G$, available energy. $T_1$ is the temperature at height, $z_1$, $T_2$ is the temperature at height, $z_2$. $e_1$ is the vapor pressure at height, $z_1$, $e_2$ is the vapor 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, $G = 0.4 \times R_n(\text{Exp}(-K \times \text{LAI}))$, where '$K$' is the extinction coefficient, LAI, leaf area index, extinction coefficient of maize was taken as 0.38.

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 output of all meteorological sensors was recorded with a data logger and retrieved afterward with the help of a PC.

## 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 related to the air vapor pressure deficit (VPD) (Jackson et al. 1981; Kustas et al. 1989) as per the equation below.

$$T_c - T_a = \frac{r_a(R_n - G)}{\rho C_p} \times \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma\left(1 + {}^{r_c}/_{r_a}\right)} \times \frac{\text{VPD}}{\Delta + \gamma\left(1 + {}^{r_c}/_{r_a}\right)} \tag{9}$$

where $r_a$ and $r_c$ are the aerodynamic and canopy resistances ($sm^{-1}$), derived as per the procedure of Allen et al. (1998). $R_n$, net radiation ($Wm^{-2}$); $C_p$, volumetric heat capacity of air ($Jm^{-3}c^{-1}$); $\gamma$ is the psychrometric constant ($P_a$ °$C^{-1}$); $\Delta$, slope of the temperature-saturated vapor pressure relation ($P_a$ °$C^{-1}$). 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).

$$\text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)l_0}{(T_c - T_a)u_a - (T_c - T_a)l_0} \tag{10}$$

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 the cropped period was determined by making canopy minus air temperature and vapor pressure deficit measurements 2 days after a crop has received full irrigation. The measurements were made from 11.00 to 14.00 h both in humid and in dry days, resulted wide range of vapor pressure measurements. With the wide range of relationship between crop canopy minus air temperature and vapor 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 transpiration of plant approached zero. For the winter maize crop, upper base temperature was measured as −1°C under existing climatic and soil conditions of the present study area.

Intercepted photosynthetically active radiation (IPAR)

The variation of radiation interception and spectral indices (Normalized Difference Vegetation Index, IR/R) over maize canopy was observed throughput the growing period, and interrelationships were obtained between radiation interception and spectral indices. Light transmission meter (EMS-7) instrument was used to measure the intercepted photosynthetically active radiation (IPAR) by the whole canopy of the crop when grown with irrigations.

*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.

$$\text{IPAR}\ (\%) = \frac{\text{PAR received at any height}\ (\mu\ \text{Es}^{-1}\ \text{m}^{-2})}{\text{PAR received at any height}\ (\mu\ \text{Es}^{-1}\ \text{m}^{-2})} \times 100 \tag{11}$$

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

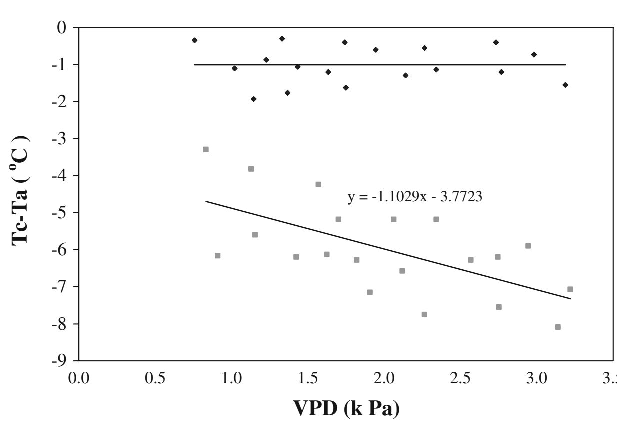


**Fig. 1** Relationship between ($T_c - T_a$) and VPD of maize for computing CWSI

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.

An Spectro-radiometer (UNISPEC) of PSP, USA was used to measure the spectral reflectance of the crop. Measurements were made at 7–10 days interval, and reflectance of the vegetative growth period (when leaf area index was maximum) has been presented. Three measurements were performed at each observation, and calibrations were made using a surface of maximum reflectance. Based on spectral reflectance data, spectral indices like normalized difference vegetation index (NDVI) and Infrared/Red ratio were derived and related to the leaf area index and above-ground biomass of the crop.

$$\mathrm{NDVI} = \frac{\mathrm{IR} - \mathrm{R}}{\mathrm{IR} + \mathrm{R}}, \quad \mathrm{IR} = \mathrm{Infrared}, \mathrm{R} = \mathrm{Red}. \qquad (12)$$

Meteorological data

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

## Results and discussion

### Seasonal variation of surface energy fluxes during crop growth period

The seasonal variation of surface energy fluxes over maize stand 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 is 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 303.8–491.3 w/m$^2$ in the month of January to 437.3–562.3 w/m$^2$ in March during two crop seasons.

The latent heat flux 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 on leaf area index (LAI) and soil moisture content, which shows peak when LAI was maximum. The midday average latent heat flux (on clear days) varied from 110.7 to 408.9 w/m$^2$ at different growth stages. The LE variation over maize stand during growing season mainly occurred due to variation of solar radiation, temperature, vapor pressure deficit and soil

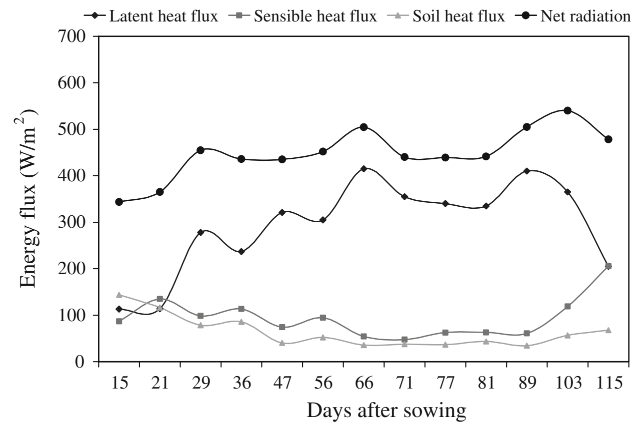


**Fig. 2** Seasonal variation of energy fluxes of maize during 2005–2006

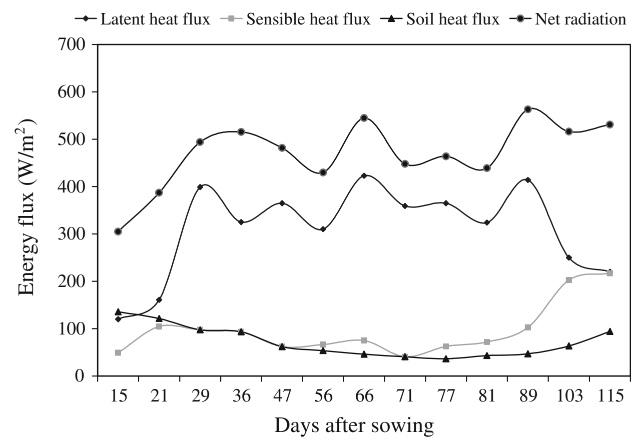


**Fig. 3** Seasonal variation of energy fluxes of maize during 2004–2005

moisture during the crop seasons. The LE by the crop increased immediately after application of irrigation water because after irrigation, water did not limit the transpiration. When soil was wet, latent heat consumed most of the energy from net radiation.

The seasonal course of soil heat flux ($G$) of the crop revealed that variation of '$G$' during growth seasons clearly reflected the change of crop growth. The '$G$' showed peak value during early vegetative and maturity period when crop coverage was minimum and soil was dry. Afterward, the course of '$G$' was affected by development of crop canopy or leaf area index. Midday averaged '$G$' value of maize stand ranged from 34.08 to 144.8 w/m$^2$ with an average value of 59.6 w/m$^2$. The $G$ reduced drastically with the application of irrigation water. The ratio of $G/R_n$ from maximum LAI to senescence stage was found 7–13.5% over the crop. Soil heat flux showed declining trend during peak growth stage, which coincided with maximum leaf area index (LAI) or maximum intercepted photosynthetically active radiation (IPAR). As the soil dried, water became less available for evapotranspiration and the energy must went into heating the soil (soil heat flux) or heating the air (sensible heat flux).

The seasonal variation of Bowen ratio ($\beta$) is depicted in Fig. 4. Study revealed that Bowen ratio was higher (0.41–1.18) during early vegetative 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 29 DAS up to 89 DAS, and there was a sharp fall of Bowen ratio (0.11–0.17) during peak growth stage when leaf area index was maximum (63–67 DAS). The higher LAI led to greater transpiration and therefore latent heat flux density was higher during that period. From 23 to 86 DAS, four irrigations were provided to crop, which led to greater to greater evapotranspiration loss from branching to seed development stages, as a result Bowen ratio ($\beta$) was declined during those periods. The sharp decline of Bowen ratio was also observed after application of irrigation water. After irrigation, when more soil moisture was available to crops, latent heat flux consumed more energy, as a result Bowen ratio was declined.

## Diurnal variation of energy balance

Out of many observations, three observation 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 (01/12/05, 24/01/06 and 25/02/06) 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 11.30–12.00 noon with the values being 542.4, 602.1 and 599.2 w/m$^2$ in three respective dates (Fig. 5a–c). Hourly LE variation on 01/12/05 revealed that it ranged from 93.7 w/m$^2$ at 7.00 am to 40.8 w/m$^2$ at

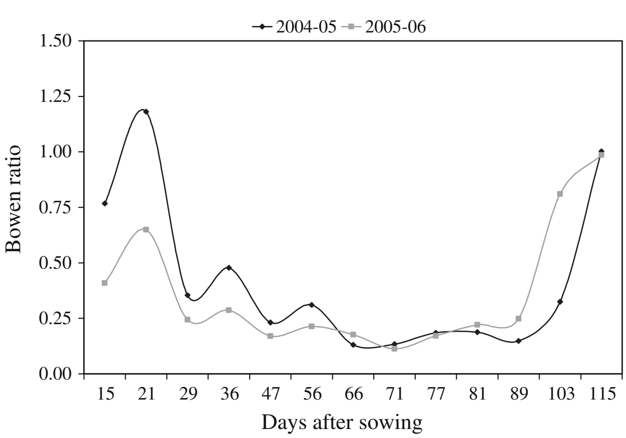


**Fig. 4** Seasonal variation of Bowen ratio of maize

5.00 pm with the highest value of 343.6 w/m$^2$ at 12.00 noon. In other 2 days (24.01.06 and 25.02.06), the highest LE was 451.4 and 374.8 2 w/m$^2$, respectively, during 12.00–13.00 h. Diurnal variation of Bowen ratio (H/LE) for three above-mentioned dates was also computed and is also presented in Fig. 6a–c for representing early peak growth and senescence stages, respectively. Study revealed that the Bowen ratio ($\beta$) has a steep rise in the early morning and reached the peak at around 9.00–10.00 h, which might be due to more sensible or turbulent heat during morning hours. After 10.00 h, $H$ decreased but LE component increased. The peak value of $\beta$ ratio was 0.42, 0.30 and 0.40 at initial, mid and late growth stages, respectively. Study also revealed that $\beta$ ratio was less at the peak growth stage of the crop (24.01.06), which was due to the existence of highest leaf area index (LAI) and more evaporation rate during that stage. After 10.00 h, $\beta$ declined gradually until afternoon for all the growth stages.

## Soil moisture depletion and crop water stress index (CWSI)

In the region, farmer's traditional practice is to apply irrigation at critical phonological stages. Based on our earlier studies (Kar et al. 2006), it is revealed four irrigations at four critical stages viz., (1) early vegetative, (2) tassel initiation, (3) silking and (4) seed filling provided maximum yield when compared with two (tassel initiation + grain filling) or three irrigations (early vegetative + tassel initiation + grain filling). In this research paper, we attempted to study the soil moisture depletion pattern during entire crop growth season, and simultaneously, crop water stress index (CWSI) was computed. CWSI at critical growth stages was compared with that of recommended value (0.6) of irrigation scheduling to assess that under what stress farmers irrigate when they apply irrigation at different critical stages. Study revealed that before irrigation, soil moisture content was 0.145–0.157, 0.125–0.151, 0.165–0.180 and 0.105–0.108 m$^3$ m$^{-3}$ at early vegetative, tassel initiation, silking and seed filling stages, respectively, in 2 years of study. With the change of soil moisture particularly before and after irrigation, the CWSI was derived as per the procedure described in the methodology. Based on the calculation of non-water stress baseline equation, $(T_c - T_a) = -1.1029$ VPD $- 3.772$, and stressed baseline ($-1$°C), the CWSI values were 0.59–0.61, 0.61–0.63, 0.42–0.48 and 0.65–0.67 just before application of irrigation water to early vegetative, tassel initiation, silking and seed filling stages, respectively (Figs. 7, 8). Immediately after irrigation, the CWSI dropped to 0.09–0.12 at different growth stages. Our study revealed that CWSI was much lower (0.42–0.48) than the recommended value (0.60) of irrigation scheduling just before applying irrigation at

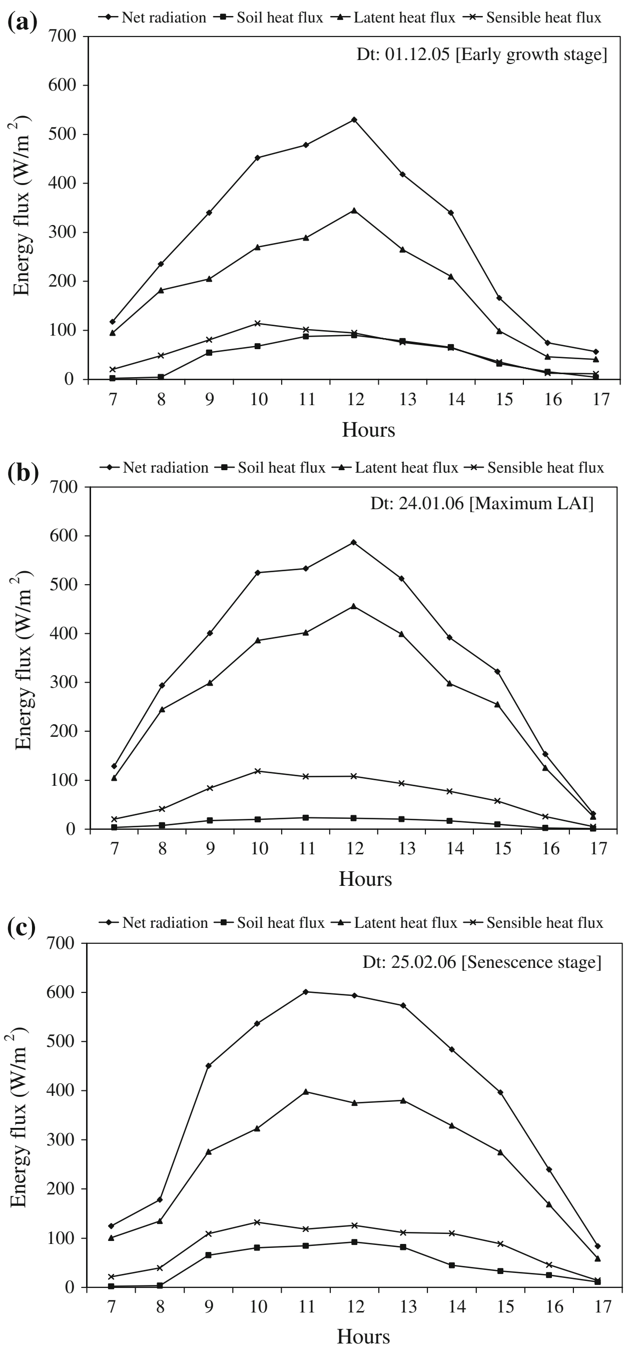


**Fig. 5** Diurnal variation of energy balance of maize at different growth stages

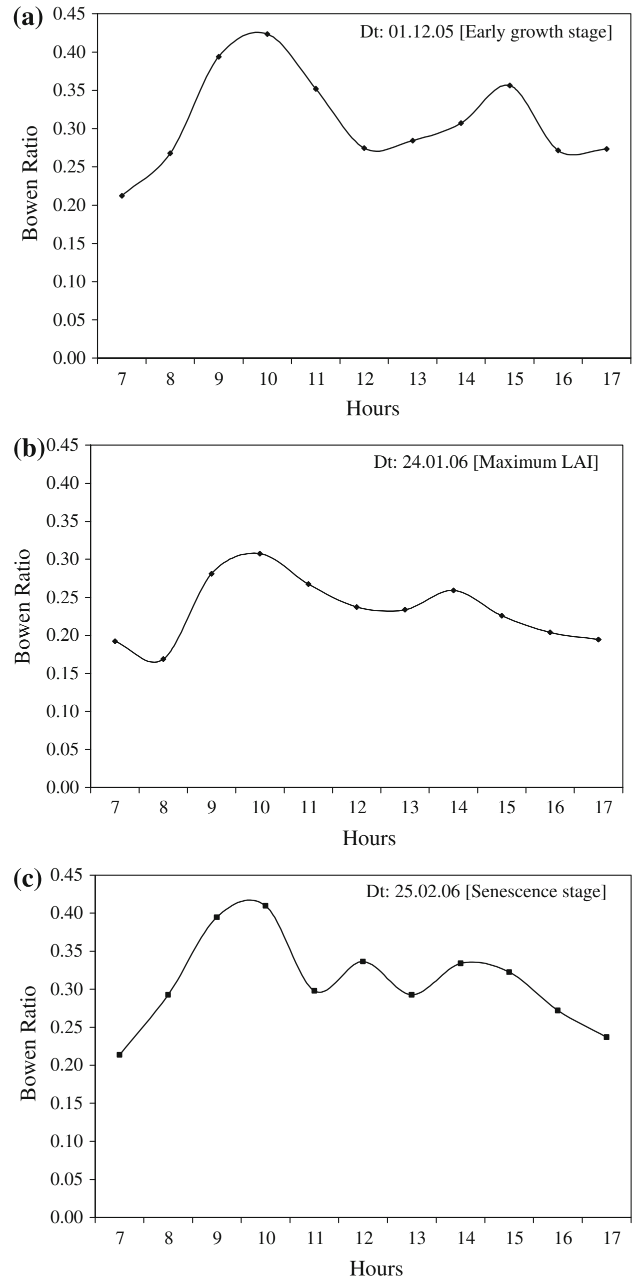


**Fig. 6** Diurnal variation of Bowen ratio over maize crop at different stages

silking stage. In other stages, CWSI values varied between 0.59 and 0.67 just before the application of irrigation to crop. From the CWSI value, it can be said that the crop was not under-stressed at silking stage, so irrigation scheduling could be optimized further when irrigation water is limited for irrigating maize during winter season. In winter season, cropping in eastern India depends on carry-over residual soil moisture and supplemental irrigations from harvested water of rainy season.

## Intercepted photosynthetically active radiation (IPAR) during crop growth period

The intercepted photosynthetically active radiation (IPAR) over maize stand at 7–10 days interval was measured and is depicted in Fig. 9. Maximum interception of 84 and 89% was observed at 69–72 DAS in the seasons 2004–2005 and 2005–2006, respectively. The relationship between IPAR (%) and days after sowing (DAS) was established and a polynomial equation of second order (best fit) was derived

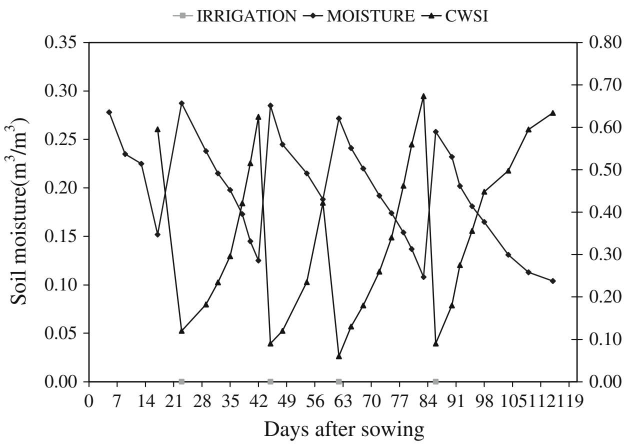


**Fig. 7** Variation of CWSI and soil moisture of maize during 2004–2005

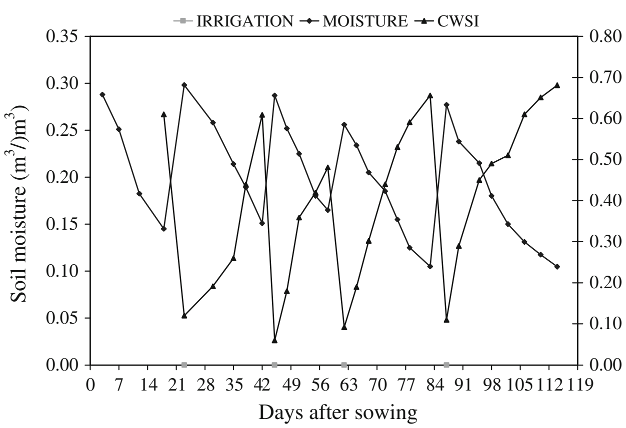


**Fig. 8** Variation of CWSI and soil moisture of maize during 2005–2006

to compute IPAR at different days after sowing (DAS). The highest LAI of 6.4 and 6.2 was computed in first and second seasons, respectively (Fig. 10). The relationship between IPAR and LAI was also established, and equations were developed to predict leaf area index (LAI) of groundnut with IPAR data (Fig. 11). Study revealed that LAI was positively related to intercepted photosynthetically active radiation (IPAR) and with the equation, LAI = 0.086 IPAR (%) − 1.809; the LAI can be determined non-destructively using IPAR values. During the peak growth period, the soil heat flux (*G*) was minimum, and Bowen ratio ($\beta$ 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 vise versa. With the help of predicted LAI or IPAR, soil heat flux, G can be derived.

With four irrigations, the spectral reflectance pattern of maize canopy was studied, and the spectral signature of the

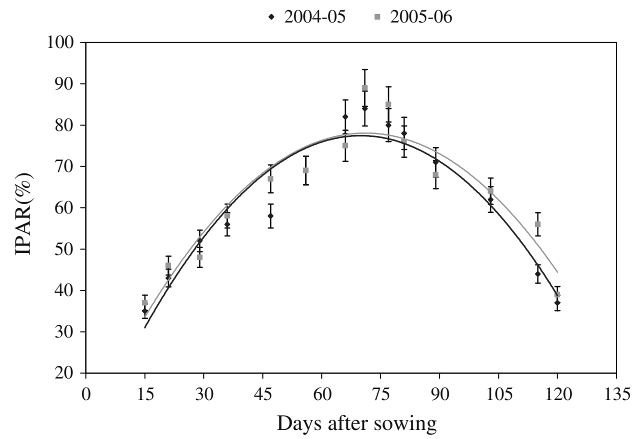


**Fig. 9** Variation of IPAR with days after sowing (DAS) in maize

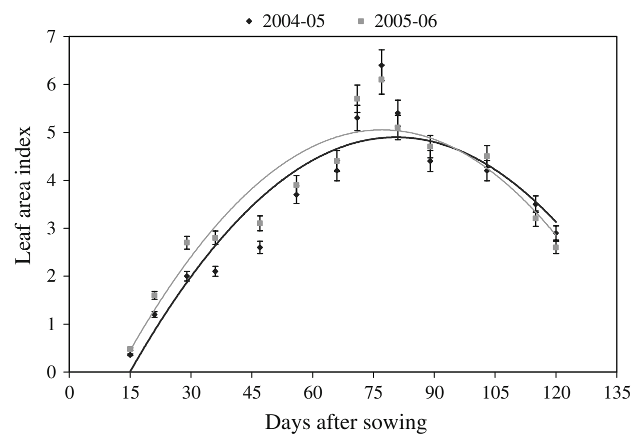


**Fig. 10** Variation of LAI with DAS in maize

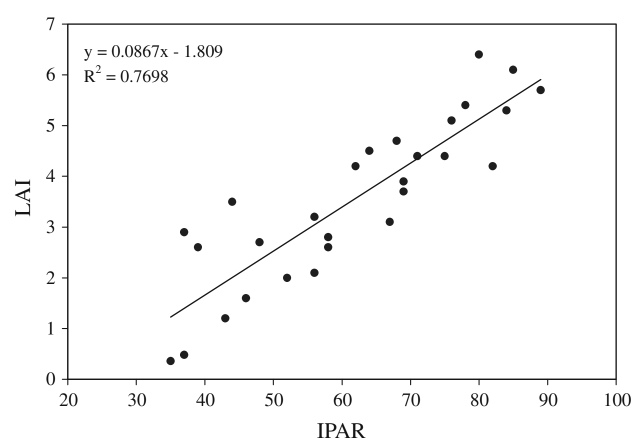


**Fig. 11** Relationship between IPAR and LAI in maize

crop during vegetative period is given in Fig. 12. The spectral signature during vegetative period showed the typical spectral reflectance pattern of green vegetation. At 540-nm wavelength (green band), first reflectance peak was observed, followed by absorption in red band of

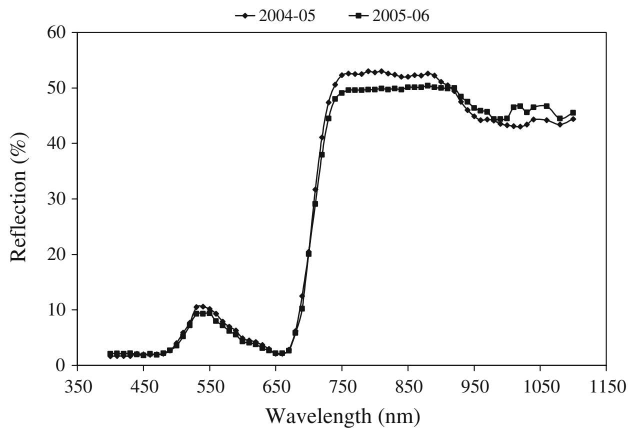


**Fig. 12** Spectral reflectance of maize canopy during vegetative stage (45 DAS)

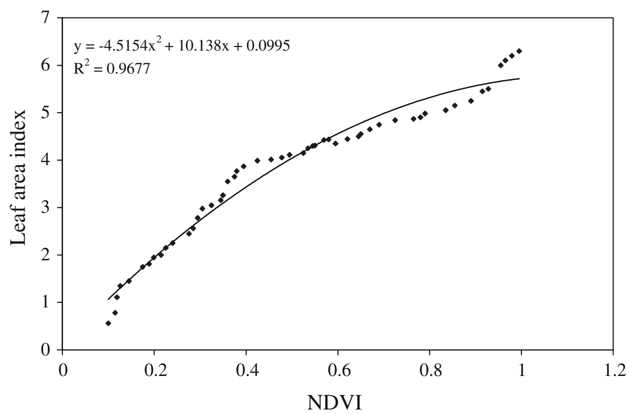


**Fig. 13** Relationship between LAI and NDVI

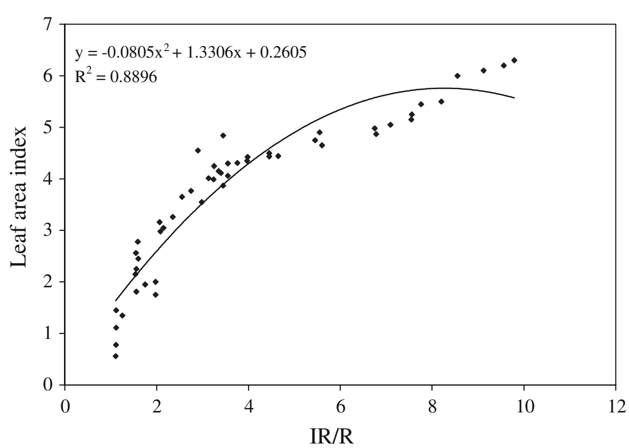


**Fig. 14** Relationship between LAI and IR/R

electromagnetic spectrum. From 690 nm, again the reflectance started to increase and increment trend continued up to 890 nm. From the reflectance pattern at different days after sowing, two vegetation indices viz., normalized difference vegetation index (NDVI) and IR/R were derived and found these were correlated with LAI (Figs. 13, 14). NDVI had better correlation ($R^2 = 0.967$) with LAI than that of IR/R ($R^2 = 0.889$), hence, NDVI can be used to predict LAI at different growth stages.

## Conclusion

Study revealed that at one stage (silking), CWSI were much lower (0.42–0.48) than that of recommended CWSI (0.60) for irrigation scheduling. Therefore, more research is required to optimize the phenology-based irrigation scheduling of winter maize further in the region, which is the method used now by local producers. The intercepted photosynthetically active radiation (IPAR) and normalized difference vegetation index (NDVI) over the canopy of the crop were also measured and was found to have better correlation with leaf area index. This relationship can be useful for development of algorithm of crop simulation model for predicting LAI. The midday average latent heat flux varied from 110.76 to 408.9 w/m$^2$ at different growth stages of two seasons. Their variability can be explained as a result of seasonal changes in the meteorological conditions, the soil water content and the development of the maize stand.

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