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Research Article

Seasonal Energy Flux Pattern over Irrigated Maize and Wheat under Subtropical Semi-arid Condition using BREB Method

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ABSTRACT

Using the Bowen Ratio Energy balance method (BREB), energy flux components were obtained for two distinct crop season *kharif* and *rabi* under maize and wheat respectively, in northern subtropical India under semiarid climate. The seasonal energy balance pattern was studied in terms of absolute values of flux components as well as their ratios of net radiation (Rn). These components included latent heat flux (LE), sensible heat flux (H) and ground heat flux (G). The H/Rn ratio increased from dough to maturity stage for wheat (9% and 19% respectively) and maize (24% and 36% respectively). LE/Rn ratio approached 91% and 82% during the start of the reproductive phage i.e., the flowering and silking stage in wheat and maize respectively. For wheat, it further increased to a staggering value of 97% in the dough stage. This suggests, the severe susceptibility of wheat to terminal heat stress during this period in absence of irrigation. G was a small portion of the total net radiation (0.13 G/Rn) entire crop, but it showed a very strong relationship with LAI. As the LAI attains peak the value of ground heat flux decreases. LE/Rn always showed very high value for both season (60% to 97%), when compared to H/Rn (0.1% to 36%) indicating that a very high proportion of available energy gets transformed to latent heat flux. This effect was more pronounced and consistent in case of *rabi*, which may be explained by consistently high LAI value for wheat canopy as compared to maize.

Key words: Bowen ratio, Latent heat flux, Sensible heat flux, Ground heat flux, Energy balance

Introduction

Energy fluxes over crops are very important because the partitioning of available energy into complex fluxes dictates evapotranspiration, soil temperature, and canopy temperature. According to the second law of thermodynamics, the earth's surface energy must remain conserved. This basic physical law is exploited in devising all weather and climatic models. Net radiation (Rn), sensible heat flux (H), latent heat flux (LE), and ground heat flux (G) are the key components of energy balance at the surface. (Oncley *et al*., 200 and Mallick *et al*., 2012). For an infinitesimally thin layer and in the absence of horizontal advection, net radiation is the sum of latent, sensible and ground heat fluxes (Irmak *et al*., 2014). Tanner (1960) reported that vertical energy balance produced dependable estimates of the evapotranspiration when the measurements were made close to a reasonably homogeneous surface. He also reported that heat exchange at the soil

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surface is a considerable portion of the total energy exchange even in a high population mature corn crop. Oncley *et al.* (2007) performed an energy balance on cotton crop under flooding water regime and he reported that the total available energy for partitioning sensible heat flux was very small as compared to latent heat flux. Evapotranspiration is a very energy-intensive process requiring a large amount of energy for the latent heat of vaporization. This makes the energy balance method the most common method to estimate latent heat flux and ultimately ET (Jensen and Allen, 2016). Bowen (1926) gave a ratio based on the resemblance of the evaporative and diffusion process of water vapour from any water surface to that of conduction or "diffusion" of specific heat energy from the water surface into the same body of air. Evaporation can be estimated by calculating the Bowen ratio from temperature and vapour pressure data and then incorporating it in the Cumming's energy balance equation (Bowen, 1926). This method of partitioning available energy into sensible (H) and latent heat (LE) flux came to be known as the Bowen ratio energy balance method (BREB). Even though it was originally developed for water surface, but it has been increasingly used for the other surface types as well. BREB is the most conservative of the meteorological methods for estimating latent heat flux because in this method net radiation component (Rn), puts rational limits on the magnitudes of H and LE (Perez *et al.*, 2008). Due to these reasons, the partition of energy at the surface is usually obtained using the Bowen ratio-energy balance method (Kustas *et al.,* 1999; Bhattacharya *et al.*, 2009; Mukherjee *et al*., 2012) employing the Bowen ratio as the ratio of sensible and latent heat fluxes. At the surface, energy partitioning is a multifaceted function of interactions between the development of the atmospheric boundary layer and plant physiology. Considering this fact Bowen ratio can be articulated as the function of climatic, aerodynamic and surface resistance (Lockwood, 1979).

Wheat crop scenario in India for 2015-16 was estimated as 30.23 million hectares in terms of area and 93.50 million tonnes as total production, out of which most of the area (93.6%) under wheat crop is irrigated (Agricultural Statistics at a Glance, 2016). It is also one of the most crucial crops in the world and its production increment is essential. This increase is of more importance for developing countries like- South-East Asian countries, to meet the demands of the ever-increasing population and to boost growth in their economy (Reynolds *et al*., 2008). This is a big task that will be further complicated by reduced water availability (Shiklomanov and Rodde, 2011) and global warming-induced rise in atmospheric temperature (Fischer *et al.,* 2002; Sehgal *et al*., 2013). Extreme heat (or sensible heat flux) affects the wheat senescence and hastens maturity (Lobell *et al.,* 2012; Chakraborty *et al.,* 2019). In India, maize (*Zea mays*) crop was (2015-16) grown over an area of 8.69 million hectares out of which 27.2% is irrigated with a total production of 21.18 million tonnes (Agricultural Statistics at a Glance, 2016). So, maize is the third most important food crop in our country after rice and wheat. It has a significant place particularly with wheat as the maize-wheat cropping system is the third most important cropping system in this country after rice-wheat and rice-rice. (Saad *et al.,* 2015). The yield of maize shows the best positive correlation with the evapotranspiration parameter (Payero *et al*., 2006) and any form of water stress can lead to reduced growth, delayed maturity and reduced crop growth (Denmead and Shaw, 1960). In the present study, two distinct crop season data during *kharif* 2017 and *rabi* 2017-18 under irrigated wheat and maize were used to quantify surface energy flux component using BREB method. The main objectives were to determine the flux pattern under the irrigated condition and identify the main factors governing the pattern observed.

Material and Methods

Site description

The experiment was conducted in the research farm located at ICAR-Indian Agricultural Research Institute (ICAR-IARI) at New Delhi over two crop seasons *kharif* and *rabi* with maize and wheat crops. This region belongs to 'Trans-

Gangetic plains’. Minimum temperature ranging from 3.4 °C to 5.5 °C is experienced in the month of January during winter. The field covered an area of 1620 m^2 so that it satisfies the fetch requirement for the flux tower, representing measurements of the crop under study. PMH-1 and HD 2967 varieties of maize and wheat, respectively were selected because they are widely grown in this region by the farmers. The maize crop was sown on 19th July 2017 during first year of experiment and wheat was sown on 24th November 2017. The field consisted of a homogeneous crop under uniform management practices. The climate at the location of the experimental site is subtropical to semi-arid characterized by hot and dry summer and cold winter season. Annual mean rainfall is 710 mm with July- August as the wettest months during the whole year. Major amount of the annual rainfall (about 80%) is received from south-west monsoon during the period of July to September. The soil of the study site has sandy loam texture in the upper 30cm layer. Standard agronomic management practices recommended for the experimental region were followed for both crops. Maize crop was given four irrigations (seedling, knee-high, silking and dough stage) and fertilizer dose of N: P_2O_5: K_2O @ 150:75:75. The wheat crop was given five irrigations (CRI, tillering, jointing, flowering, and grain filling stage) and a recommended fertilizer dose of N: P_2O_5: K_2O @ 120:60:60.

The flux tower with multiple sensors at various levels was installed including temperature and relative humidity sensors at height of 0.5 m, 1 m, 2 m, and 4 m above the ground (Fig. 1). Hydrometeorological variables were recorded at 10-minute interval by the channel data logger (DeltaT Devices Ltd., UK). Air temperature and relative humidity were measured with a high accuracy sensor (with a sensitivity of 0.1-degree Centigrade for temperature and 2% for relative humidity) provided by DeltaT Device Ltd, UK. USWA class A pan evaporimeter was also utilized to measure the pan evaporation. Soil heat flux (G) was measured by flux plates (Hukseflux, Netherlands) installed 5 cm below the soil surface. Leaf Area Index (LAI) were also measured at critical stage using LAI- 2000 Plant Canopy Analyzer (LI-COR, USA). For wheat it includes 50% germination, crown root initiation (CRI), tillering, jointing, flowering, milking, dough, and physiological maturity. For maize, the LAI readings were taken during crop emergence, knee-high, tasseling, silking, dough and grain maturity stage.

Calculation of energy fluxes

Energy fluxes were calculated using the reliable Bowen Ratio Energy Balance Method. This method was chosen over other methods because it ensures the closure of energy balance components. To put the available energy into component energy fluxes so that we don’t have to worry about residual components. Bowen ratio is calculated as the ratio of vertical air temperature to water vapor pressure gradients. The formula used for Bowen ratio, B = c (dT / d e). Where, B = Bowen ratio, c = psychometric constant (0.065701 k Pa $°C^{-1}$), dT = temperature gradient (°C m^{-1}) and d e = vapour pressure gradient (k Pa m^{-1}). The Bowen ratio can also be

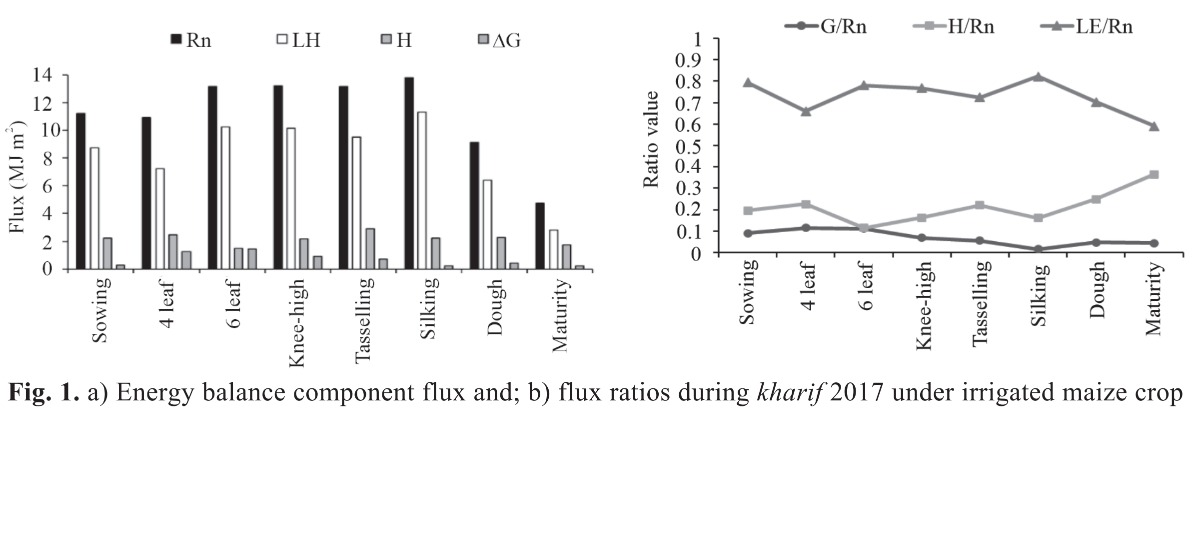

Fig. 1. a) Energy balance component flux and; b) flux ratios during *kharif* 2017 under irrigated maize crop

expressed as the ratio of sensible (H) and latent heat fluxes (LE) i.e. B= H / LE. After the Bowen ratio was calculated using temperature and vapour pressure gradients, it was then applied to partition the net available energy into components fluxes. The equation utilized to calculate component fluxes are H = (Rn - G) / (1 + B-1), LE = (Rn - G) / (1 + B). Where (Rn – G) term denotes the net available energy for partitioning.

Results and Discussion

Phenological stages of crops in different season

The phenological stages of the crop are most important as they represent important milestones of development during a crop life cycle. Every stage of the crop is characterized by its unique set of characteristics. With respect to canopy development, the most important stage for wheat is flowering and for maize it's silking. The wheat attained its flowering stage at approximately 90 DAS. For maize silking arrived 65 DAS and dough stage finally at 85 DAS (Table 1).

LAI of kharif maize and rabi wheat

LAI is an important trait to characterize plant canopy because it is an indicator of canopy cover and the extent of light interception. The seasonal profile of LAI for *rabi* wheat 2017-18 and *kharif 2017* maize are given in Table 2. Both wheat and maize were characterized by an initial increase in LAI till their reproductive phase and then it decreases as the physiological maturity arrived. Wheat and maize showed a time difference in attaining peak LAI. While maize attained its peak LAI at 80 DAS (4.5), wheat crop reached the peak value of 90 DAS (5.4). So, the LAI peak was more pronounced and delayed in the case of wheat as compared to the maize. It was found for maize that LAI peaked during the dough stage and for wheat during the flowering stage, which is about 80 DAS and 90 DAS respectively. Taking into account the entire crop season, wheat peak LAI value during flowering stage was higher that the maize maximum LAI value. This can be explained based on the sowing pattern. Wheat was sown in continuous rows 22.1 cm apart, while maize was sown with a spacing of 60 cm x 25 cm.

Open pan evaporation in different seasons

Pan evaporation (Epan) is a very useful indicator of atmospheric evaporativity. This property influence evapotranspiration and thus latent heat flux. It widely varied during the

Table 1. Timeline of Phenology stages (DAS) of maize crop during *kharif* 2017 and wheat crop during *rabi* 2017-18

Phenological stages (Maize)	DAS	Phenological stages (Wheat)	DAS
Crop sowing	19th July	Crop sowing	24th Nov 2017
Crop emergence (4leaf stage)	10	Germination	7
Knee high stage	35	CRI	23
Tasseling (50%)	50	Tillering	45
Silking (50%)	60	Booting	80
Dough	90	Flowering	90
Physiological Maturity	108	Grain filling	106

Table 2. Variation of LAI in maize crop at different growth stages under irrigated condition during *kharif* season 2017 and during *rabi* season 2017-18

Crop	Days after sowing (DAS)					
	20	40	60	80	90	120
Wheat (LAI)	0.14	1.58	2.59	2.98	5.4	2.8
Maize (LAI)	1.48	2.39	3.91	4.50	2.65	1.43
	20	30	50	60	90	108

growing season. The *kharif* 2017 showed higher initial Epan with a Epan value of 5.9 mm day^{-1} for the month of June which showed a decreasing trend with the advancement of the season reaching to a value of 3.9 mm day^{-1} in October. On the contrary *rabi* 2017-18 showed an increasing trend of the Epan value with the advancement in crop season with almost doubling of Epan values from 2.3 mm day^{-1} in November to 4.2 mm day^{-1} in March.

The monthly average values of Epan showed that the pan evaporation during the *rabi* season was comparatively higher during the month of February (3.5) and March (4.5) which overlapped with the flowering, grain filling and maturity stages of wheat crop (Table 3). This period was also characterized by high LAI of the wheat crop as the canopy is fully developed after flowering in the case of wheat. *Kharif* season showed higher early season pan evaporation that the *rabi*. The whole *kharif* season is characterized by low intra-seasonal variability in pan evaporation as compared to the *rabi.*

Kharif energy flux pattern under maize crop

The time series analysis of energy balance flux components over a period is very crucial to find the seasonal flux pattern. It was observed that Rn, LE, H, and G varied throughout the *kharif* season (Fig. 1). For the study of the seasonal trend, daytime fluxes for clear days were considered which is associated with a significant amount of net radiation. The maximum mean daytime Rn was recorded during the silking stage 3833.12 W m^{-2} (13.79 MJ m^{-2}) for clear days. The LE was also maximum during this period with a value of 3149.3 W m^{-2}(11.34 MJ m^{-2}). LE/Rn ratio reveals that the latent heat flux component accounted for 82.2% of the net radiation. The Rn was higher during the initial stage of the *kharif* season and decreased in later stages. The absolute values of flux are hard to interpret and compare. So, they are transformed into ratio for better pattern analysis and comparison. The LE/Rn ratio was found to be maximum during the silking stage and minimum during maturity. The G/Rn ratio was found minimum during the silking stage. The H/Rn ratio was maximum during the maturity stage indicating that more proportion of net radiation was going to sensible heat flux at the maturity stage. This maybe explained by high pan evaporation during these periods and low soil moisture as irrigation was stopped before maturity. This showed that most of the incoming net radiation is converted to latent heat flux during the silking stage. LE/Rn ratio varied between 60% to 82%, which showed that latent heat flux remained a significant portion of total net radiation during the whole kharif season. G/Rn ratio with a value of 1.6% was found to be minimum during the silking stage. During the early stages of crop growth, G/Rn ratio varied around 11%. It was observed that even though ground heat flux was high during the start of the season, its value plummeted with the advancement of season. The LE/Rn and H/Rn showed maximum variation over the season while G/Rn showed the least variability (Fig. 1). When LE/Rn showed crest, H/Rn peaks, and vice versa. This produced an inverse pattern curve between these ratios. All information mentioned above makes it obvious that flux ratios revealed more insights about the pattern of surface energy balance components in comparison to its absolute values.

Table 3. Monthly mean pan evaporation of *kharif* 2017 and *rabi* 2017-18

Kharif 2017		*Rabi* 2017-18	
Month	Epan (mm day^{-1})	Month	Epan (mm day^{-1})
June	5.9	November	2.3
July	4.5	December	2.3
August	4.7	January	2.4
September	4.4	February	3.5
October	3.9	March	4.2

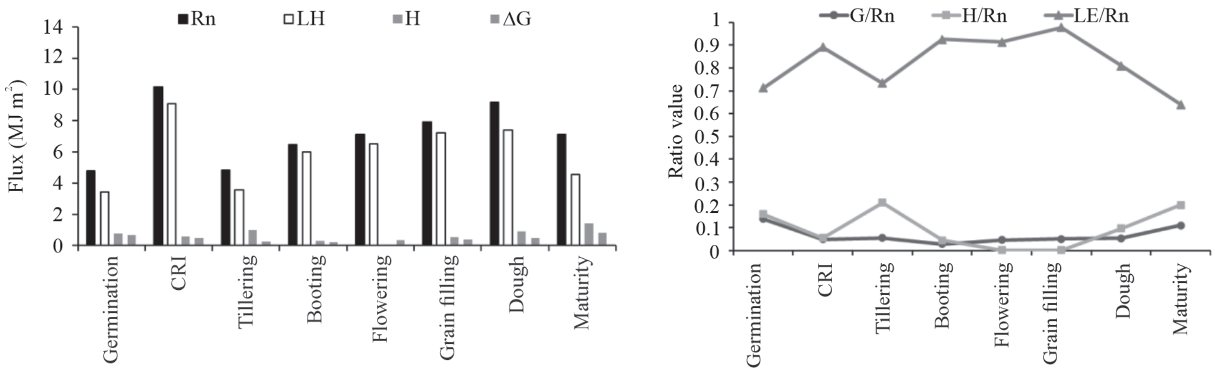

Fig. 2. a) Energy balance component flux and; b) flux ratios during *rabi* 2017-18 under irrigated wheat crop

Rabi energy flux pattern under wheat crop

R*abi* season time series analysis showed its unique surface energy balance component pattern (Fig. 2). The net radiation varied from 4.80 MJ m^{-2} to 9.17 MJ m^{-2} during *rabi*, 2017-18. The partitioning of Rn to LE was more in the grain filling stage (97.74%) but decreased thereafter. The partitioning of Rn to H was highest in the tillering stage (21.04%) followed by physiological maturity (19.00%). This suggests that Rn conversion to sensible heat flux was maximum when the crop canopy is not well developed or has undergone significant senescence. On the contrary most of the net radiation was converted to latent heat flux during flowering and grain filling stage. The partitioning of Rn towards G (G/Rn ratio) was highest (11.12%) at the maturity of wheat crop. Also, irrigation was given during this period as per the irrigation schedule recommended for this region. Contemporary LAI and pan evaporation values were also higher during the flowering stage and grain filling stage. This suggests that a well-developed canopy combined with water availability under high atmospheric evaporativity converts most of the Rn to latent heat flux. This ratio increased for wheat to a staggering value of 97% in the dough stage. This suggests the susceptibility of wheat to terminal heat stress is severe during this period. As in the absence of irrigation water, most of the energy will get partitioned to sensible heat flux adversely affecting the crop yields. Among abiotic stresses, terminal heat caused by high temperatures during wheat kernel development is an important constraint to wheat production (Rane *et al.,* 2000; Sharma *et al.,* 2007).

G/Rn ratio variation with LAI

Ground heat flux is a very significant portion of surface energy flux, particularly in semiarid reason. Mid-day G varied from 13 to 3% for the chosen experimental site and followed a consistent pattern throughout the crop growing season. The Rn showed high variation over the whole season (Fig. 3). As the G/Rn ratio (mid-day at 12.30 pm) was not varying much, a relationship was developed with LAI of each crop in both the crop growing season. In case of maize, initial G/Rn ratio was maximum, and it decreased as LAI increased, reaching its minima when LAI was highest (5.4) at the silking stage in maize. While transitioning from silking to maturity stage with decrease in LAI, the G/Rn ratio increased consistently till maturity.

During *rabi*, 2017-18 in the wheat, similar relationship was found (Fig. 3b). Initially, G/Rn was more with values of 26%, 10%, 13% and 11% at sowing, CRI, tillering and booting stage respectively. It was observed to be reduced drastically to a minimum value of 7%, with the advent of the flowering stage (90 DAS). It showed that with an increase in LAI the G/Rn ratio decreases. This suggests that the crop canopy exerts a very high influence on the ground heat flux. So, with an increase in LAI more and more of the incoming net radiation is converted to available energy (Rn-G) as the soil heat flux component decreases. G/Rn value of maize was

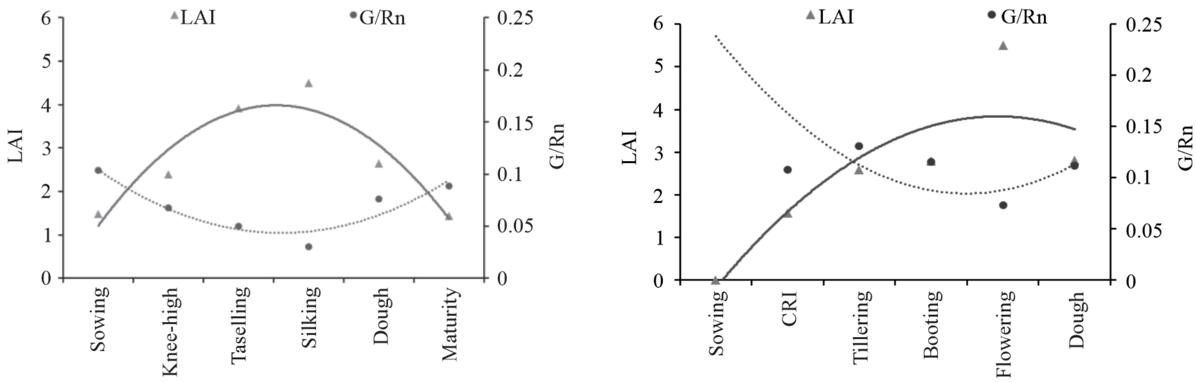

Fig. 3. a) G/Rn ratio (dotted line) variation with changes in LAI (continuous line) in maize during *kharif* 2017 and b) wheat during *rabi* 2017-18

found to be higher than wheat at all stages. The above findings were consistent with the previous work done by Shen *et al.* (2004) who also reported that the mid-day G/Rn ratio has a strong relationship with LAI, showing a significant drop in its value with increase in LAI of the crop. Zhang *et al.* (2004) also reported that G/Rn ratio for the wheat crop (at jointing to senescence is approximately 10 to 13% which is higher than maize crop (5-7%). Mukherjee *et al*. (2015) also reported soil heat flux to be higher in initial and maturity stage (14 to 16% of Rn) as compared to peak growth stages (4 to 7% of Rn) in mustard crop.

Conclusion

This study showed that, the variation of crop phenology and seasonal variation of atmospheric evaporativity was the dominant factor in dictating the pattern of surface energy flux components in the case of maize and wheat. The H/Rn ratio increased from dough to maturity stage for both wheat (9 and 19% respectively) and maize (24 and 36% respectively). Meteorological factors showed maximum influence on flux pattern during crop maturity stage which is characterized by low values of LAI and soil moisture. The crop canopy influence energy balance the most when it is fully developed. In other words, higher the LAI the more will be influence of canopy on energy balance flux components in case of irrigated condition, where water availability is ensured at critical stages of the crop growth. This is consistent with the observed LE/Rn ratio approaching 91% and 82% during the start of the reproductive phage i.e.; the flowering and silking stage in wheat and maize respectively. This ratio increased for wheat to a staggering value of 97% in the dough stage. This confirms the susceptibility of wheat to terminal heat stress during this period in the absence of irrigation. Ground heat flux was a small portion of the total net ration during crop growth, even after that it showed a very strong relationship with LAI. As the LAI attains peak the value of ground heat flux decreases. LE/Rn always showed very high value for both season when compared to H/Rn indicating that a very high proportion of available energy gets transformed to latent heat flux during whole growing season. This effect was more pronounced and consistent in case of wheat during *rabi* season which may be explained by consistently high LAI value for wheat canopy as compared to maize.

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