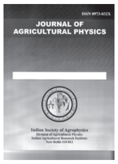
Vol. 22, No. 2, pp. 275-283 (2022)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in



Research Article

Variation of Light Interception and Radiation Use Efficiency in Maize (*Zea maize* L) at Different Crop Growth Stages

VIMAL KUMAR, JOYDEEP MUKHARJEE*, VINAY KUMAR SEHGAL AND D.K. DAS

Division of Agricultural Physics, Indian Agricultural Research Institute (IARI), New Delhi-110012

ABSTRACT

The amount of biomass produced per unit of intercepted light is called radiation use efficiency (RUE) and largely determines the growth and biomass of crops. The variation of light interception and radiation use efficiency (RUE) under optimal growth conditions is required for optimum dry matter accumulation and grain yield of maize (*Zea mays* L.). A field study on maize conducted during two growing seasons (2019-20 and 2020-21) in experimental field of Indian Agricultural Research Institute (IARI) New Delhi to measure variation of intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE) by the use of line quantum sensors in crop field. The leaf area index (LAI) was recorded by the canopy analyser, which was higher in 2019 (3.59) as compared to 2020 (3.39). The mean total intercepted photosynthetically active radiation (TIPAR) was 664.5 MJ m^{-2} in (2019) and 616.2 MJ m^{-2} in (2020). The crop biomass and grain yield were collected from 1 m^2 sampling of experimental field. The average biomass production of maize was 1868 gm^{-2} (2019) and 1827 gm^{-2} (2020) and grain yield was 521 gm^{-2} (2019) and 518 gm^{-2} (2020). The maize crop RUE was calculated by the total intercepted photosynthetically active radiation (TIPAR) for grain and biomass separately, which was 2.32 gMJ^{-1} for biomass and 0.94 gMJ^{-1} for grain in 2019 and 2.41 gMJ^{-1} for biomass and 0.96 gMJ^{-1} for grain in 2020. The radiation use efficiency (RUE) was higher in 2019 than 2020 because IPAR was 7.3% higher in 2019 than 2020, which caused reduction of biomass and grain yield by 2.19% and approximately 1% respectively. Differences in biomass accumulation among years were attributed in part to difference in observed radiation interception, which varied primarily due to differences in LAI of crop.

Key words: Radiation use efficiency, Maize, Biomass, Leaf area index

Introduction

The quantification of light interception by crop canopies provides important information about canopy physiological processes, impacts microclimate and water dynamics, can be used in conjunction with crop biomass data to derive RUE estimates, and is used widely in crop growth, climate, and ecosystem productivity. Muchow *et al*. (1994) used four tube solarimeters in each plot to obtain reliable estimates of radiation interception in a well-managed non-uniform sugarcane (*Saccharum officinarum* L). Due to the cost of radiation sensors and dataloggers to continuously record data, other more cost-effective approaches that rely on spot measurements have increased. The spot measurements typically collected around solar noon on sunny days underestimate intercepted radiation Monteith (1994) and Sinclair and Muchow (1999). Flénet *et al*. (1996) reported that the orientation of row in east-west could improve time-of-day estimates.

---

*Corresponding author,
Email: joydeep.icar@gmail.com

The sensor deployment bias also effects light interception and resulting derivatives because a single deployment method does not exist as reported by Johnson *et al*. (2010). Johnson *et al*. (2010) also suggested that using spot measurements within two hours of solar noon with increasing canopy leaf area index (LAI), the effect of deployment method on the fraction of intercepted radiation decreases, indicating that a universal deployment method is not as critical in canopies with high LAI. The majority of radiation interception studies have been conducted in replicated research plots where it is understood that the replicates minimize the effect of canopy variability.

A number of factors contribute to the variation in reported estimates of RUE (Sinclair and Muchow, 1999). The estimation of RUE depends on whether radiation is measured as total solar radiation or as PAR. While some researchers suggested that conversion of RUE based on solar radiation to that based on PAR is achieved simply by multiplying with the fraction of total solar radiation that is PAR (Sinclair and Muchow, 1999). It has been pointed out that the appropriated multiplication factor depends on canopy LAI (Bonhomme, 2000). The radiation intercepted by a crop is different from that absorbed by it and therefore, introduces variation in RUE calculations. In agreement with Sinclair and Muchow (1999), Bonhomme (2000) suggested that assuming 85% intercepted PAR (IPAR) is absorbed by the leaf canopy is accurate when canopy LAI is larger, but the value is small when canopy was small.

Hikosaka (2005) and Hangs *et al*. (2011) suggested that the intercepted PAR depends mainly on the crop LAI, canopy architecture (affecting how much LAI is effectively exposed to light), and the physiological capacity to intercept radiation. Thus, crop growth and productivity under field conditions are primarily dependent on the potential of the canopy to intercept incoming PAR and to convert it into biomass.

In numerous studies, a linear relationship between IPAR, RUE, LAI, leaf area duration (LAD), and biomass production has been found in bioenergy feedstocks and non-woody (AFCs) such as poplar, willow, barley, wheat, maize, and oilseed rape (Biscoe *et al*., 1977; Liu *et al.,* 2012). The actual RUE and LAI are affected by several factors such as environmental conditions (temperature, water and nutrient availability (Bartelink, 2000), phenology and leaf area duration LAD (Kemanian, 2004).

The quantification of light interception at the field-scale presents additional challenges to account for canopy variability across landscape position and soil type with underlying physical and chemical differences that impact crop growth. Lindquist *et al*. (2005) deployed a single line quantum sensor in an on-farm study in a maize field to estimate transmitted PAR. Arkebauer *et al*. (2009) deployed six-line quantum sensors in two sets of three about 4-5 m apart in fields ranging in size from 47 to 65.4 ha to estimate transmitted PAR. We hypothesized that increasing the number of observations would provide greater accuracy in estimating light interception, that incremental increases in accuracy would decline above a threshold. The specific objectives of this work were to (1) quantify the response of LAI of crop canopy in light intercepted PAR and (2) quantify the variability in RUE of crop in different cropping season and different growth stages.

Materials and Methods

This study was conducted for maize crop in experimental field of Indian Agricultural Research Institute (IARI) New Delhi, (lat. 28.08°N, long. 77.12°E, 228.61 m above mean sea level) during the 2019 and 2020 growing season. Dominant soil was sandy loam. The normal total annual amount of rainfall 858 mm (2019), 948.9 mm (2020) and mean annual air temperature at the research site was 24.5°C (Fig. 1). The area is relatively semi-arid due to medium to low annual precipitation, but most of the precipitation is received in monsoon period (June to September). Due to that the experimental period received enough rainfall. Maize was sown in 60 cm row to row and 20 cm plant to plant spacing in north–south direction with plant population of approximately 83,333 plants ha^{-1}.

A total biomass samples were collected in maize with one final harvest sample of maize crop. All biomass samples were collected from four locations of 1.0 m^2 areas (1.32 m long by 0.76 m wide) each sampling by harvesting as much shoot biomass above the soil surface. Designated biomass sampling areas

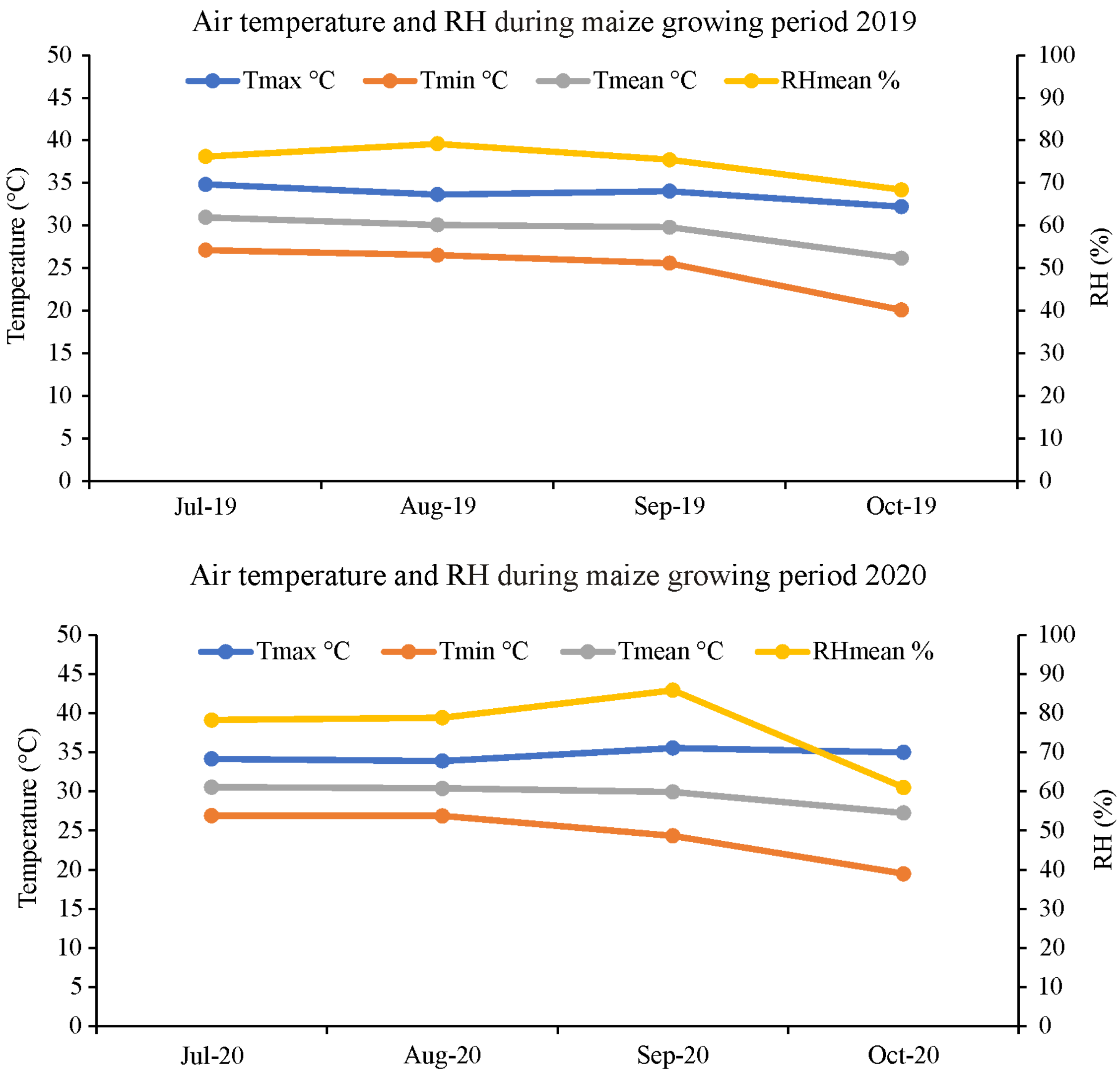


Fig. 1. Air temperature and mean relative humidity during maize growing period (2019 and 2020)

were delineated after crop emergence that accounted for the field topography and did not compromise field scale flux measurements. Within these designated areas, random samples were collected without biased by previous sampling. All biomass samples were dried in air temperature until constant weight. Physiological maturity occurred 115 DAS (days after sowing) of maize crop.

Incident and transmitted PAR were measured using line quantum sensors (LI-191, LI-COR, Inc., Lincoln, NE, USA[1]). A line quantum sensor was mounted at tip of crop in field to measure PAR and reflection by the crop canopy at top, then same time and same place taken the reading at bottom of crop canopy both incoming radiations up to ground and reflection by ground. The incident line quantum sensor was oriented from northwest to southeast, similarly to the line quantum sensor deployed under the canopies. All line quantum sensors were positioned exactly across a single row such that the sensing area of the sensor was measuring transmitted radiation across a 1 m distance between two rows. All line quantum sensors were levelled and cleaned regularly and were recently calibrated. The time of observation of line quantum sensor reading was at 10 days interval from 1030 to 1300 IST.

Output from the radiation sensors was integrated to obtain daily total incident and transmitted PAR, and these values were used to calculate intercepted PAR. Photon flux density (µmol m^{-2} sec^{-1}) from the radiation sensors was converted to energy flux (MJ m^{-2}) using the equation of {MJ m^{-2} day^{-1} = 0.00078261* PAR (µmol m^{-2} sec^{-1})* Bright sun shine hours (BSS)}, (Campbell and Norman, 1998).

Leaf area index was measured periodically non-destructively adjacent to each location where a line quantum sensor was deployed using LAI-2000 Plant Canopy Analyzer (LI-COR, Inc.). Air temperature (Thermometer) and rainfall (Ordinary rain gauge) were collected from a weather observatory located at IARI, New Delhi, which is just near the experimental field.

Results and Discussion

Crop productivity

The maize crop was cultivated in two years growing season (July to September) 2019 and 2020 in subtropical and semi-arid climate. The average rainfall occurred during 2019 and 2020 season was 569 mm and 460 mm, respectively and mean air temperatures of growing period were 29.25°C in 2019 and 29.5°C in 2020 and average RH 74.8%, 76% in 2019 and 2020, respectively (Fig.1).

No period of visual plant stress observed due to weather, nutrient deficiency, or pests. Final harvest samples collected from four 1 m^2 areas of maize fields average biological yield was 1868 g m^{-2} in 2019 and 1830 g m^{-2} in 2020 (Table 1). The average grain yield was 521 g m^{-2} in 2019 and 518 g m^{-2} in 2020, with a harvest index of 0.42 in 2019 and 2020, respectively (Table 1).

Leaf area index in maize was high in 2019 to support the high yields. Maize LAI at 80 DAS recorded highest (4.43, 4.98 in 2019 and 2020, respectively) with a minimum value at 30 DAS as 1.48, 1.67 in 2019 and 2020, respectively. The LAI increased up to 80 DAS and then reduced due to starting of senescence. At mid-grain fill stage LAI peaked at 4.43 to 4.98 which were maximum during the crop growing season (Fig. 2).

Relation of leaf area index (LAI) and fractional Intercepted Photosynthetic Active Radiation (fIPAR)

The fractional Intercepted Photosynthetic Active Radiation (fIPAR) increased with increase of leaf area index (LAI). Fractional Intercepted Photosynthetic Active Radiation (fIPAR) was maximum at 80 DAS in both cropping season, that was 0.83 and 0.89 in 2019 and 2020, respectively; and that time crop received maximum LAI. The FIPAR was minimum at 30 days after sowing, due to minimum LAI. The fIPAR is directly proportional with LAI of healthy crops (Fig. 3). The fIPAR increased with age of the crop and reached maximum at 80 DAS (tasselling stage) and later on decreased. This happened because senescence stage reduced the chlorophyll concentration of the leaf and also chlorophyll activity of the leaf. The photon acceptation of crop increases

Table 1. Grain yield, biomass yield, radiation use efficiency (RUE) based on grain and biomass yield and total intercepted photosynthetic active radiation (TIPAR) of maize crops 2019 and 2020

Particulars	Mean values
Grain Yield (g/m^2) of maize crop 2019	521
Biomass yield (g/m^2) of maize crop 2019	1868
Grain Yield (g/m^2) of maize crop 2020	518
Biomass yield (g/m^2) of maize crop 2020	1830
TIPAR (MJ/m^2) of Maize 2019	665
TIPAR (MJ/m^2) of Maize 2020	705
Radiation Use Efficiency (gMJ^{-1}) based on grain yield in maize crop 2019	0.79
Radiation Use Efficiency (gMJ^{-1}) based on biomass yield in maize crop 2019	2.81
Radiation Use Efficiency (gMJ^{-1}) based on grain yield in maize crop 2020	0.74
Radiation Use Efficiency (gMJ^{-1}) based on biomass yield in maize crop 2020	2.60

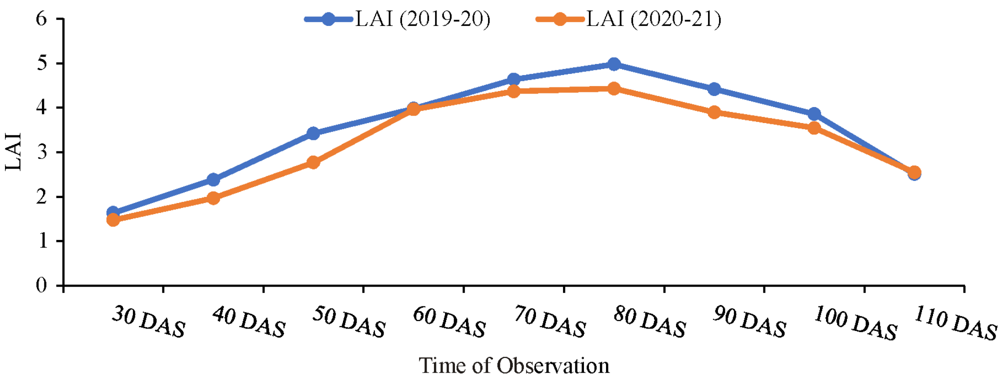


Fig. 2. Leaf Area Index (LAI) maize crop grown in 2019 and 2020

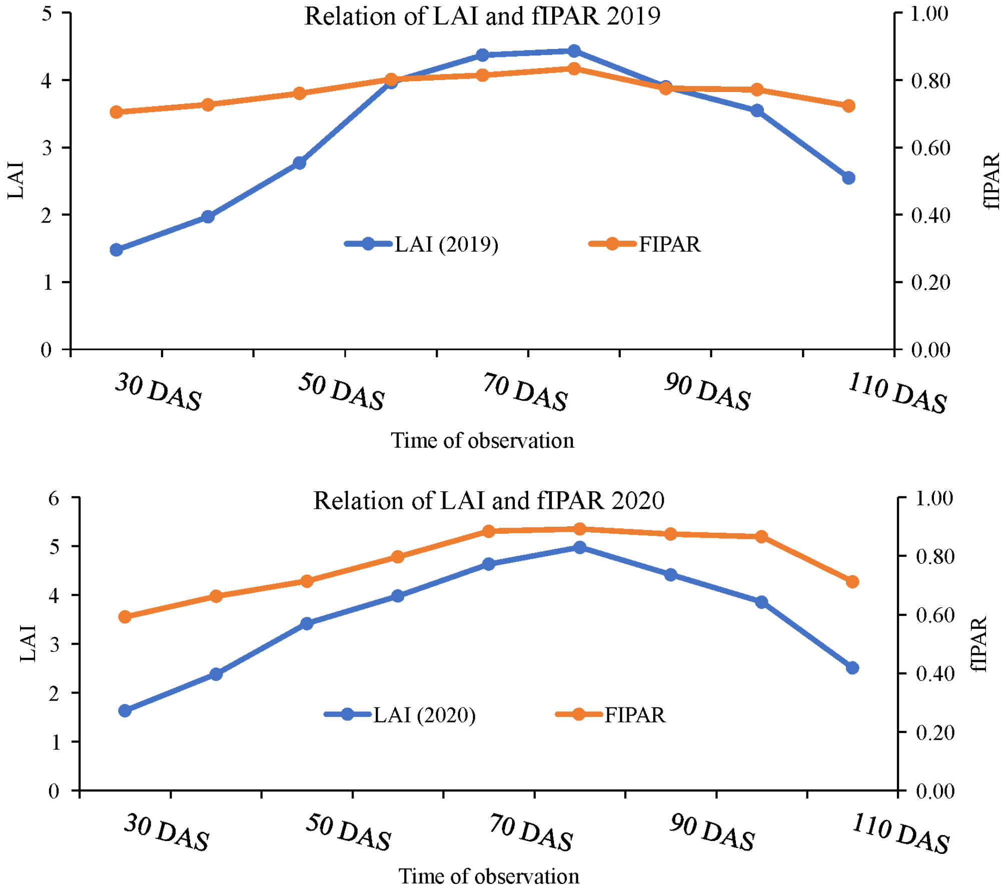


Fig. 3. Relation of leaf area index (LAI) and fractional Intercepted Photosynthetic Active Radiation (FIPAR) in different growing season (2019 and 2020).

with the age of crop and attained maximum level and later on reduced (Fig. 3).

Radiation use efficiency (RUE)

The radiation use efficiency (RUE) is the main determinant for biomass and grain production in crop plants. The average biomass radiation use efficiency was 2.81 gMJ^{-1} and 2.60 gMJ^{-1} in 2019 and 2020, respectively, with respect to total intercepted Photosynthetic Active Radiation (TIPAR) (Table 1). Sinclair and Muchow (1999) reported consistent maximum RUE in maize of 3.2–3.4 g MJ^{-1} and seasonal RUE of 2.6–3.4 g MJ^{-1} from a number of studies. The mean value from this experiment results fall within the range of literature values, however, the maximum values of RUE from minimum value exceeds this range by 9.7% (2019), 12.15% (2020), this study indicated that RUE variation of this experiment was between 10-12% only. The high RUE reported by Lindquist *et al.* (2005) under optimal growing conditions (3.84 ± 0.08 g MJ^{-1} absorbed PAR) was calculated using aboveground biomass at maturity between 2257 and 2916 g m^{-2} and maximum LAI values that ranged between 2.73 to 2.99 (2019) and 2.46 to 2.80 (2020) with maximum aboveground biomass in this study was 1868 g m^{-2} (2019) and 1830 g m^{-2} (Table 1) with a maximum LAI of 4.43 (2019) and 4.98 (2020) (Fig. 2).

This study concluded that the biomass production is directly proportional to LAI and RUE of crop, The RUE is also indicated by fIPAR, means when fIPAR is more in healthy crop canopy then interception of radiation will be more. The more interception of radiation causes more fIPAR, which increased RUE of crop. The fIPAR increased with age of the crop attended maximum at 80 DAS (tasselling stage) (Fig. 3). This study resulted that maximum RUE was at 80 DAS and latter decreased with duration. The radiation use efficiency (RUE) for crop grain production ranged between 0.73 to 0.84 (2019) and 0.69 gMJ^{-1} to 0.81 gMJ^{-1} (2020), with respect to TIPAR (Fig. 4 and 5).

The intercepted photosynthetically active radiation (IPAR) increased with age of crop and

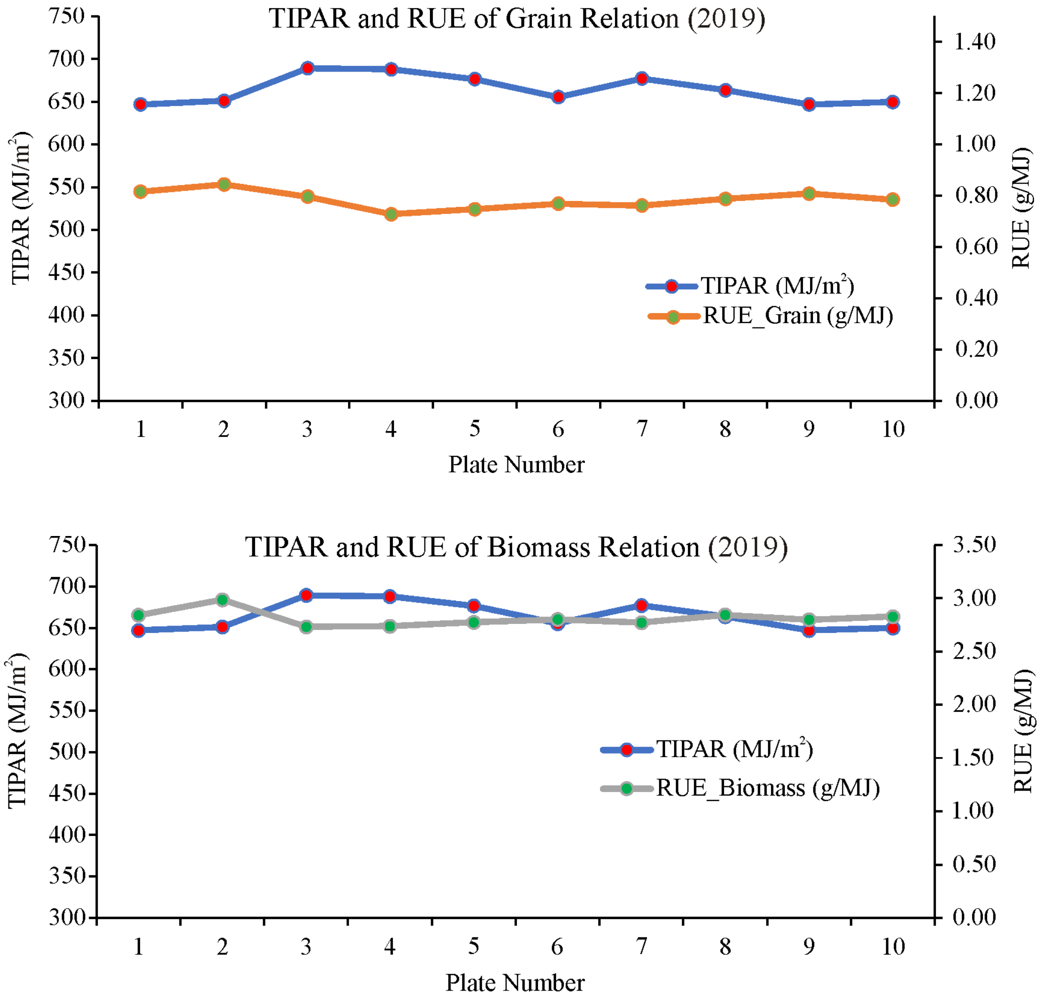


Fig. 4. Radiation Use Efficiency (RUE) in biomass and grain production of maize crop; 2019

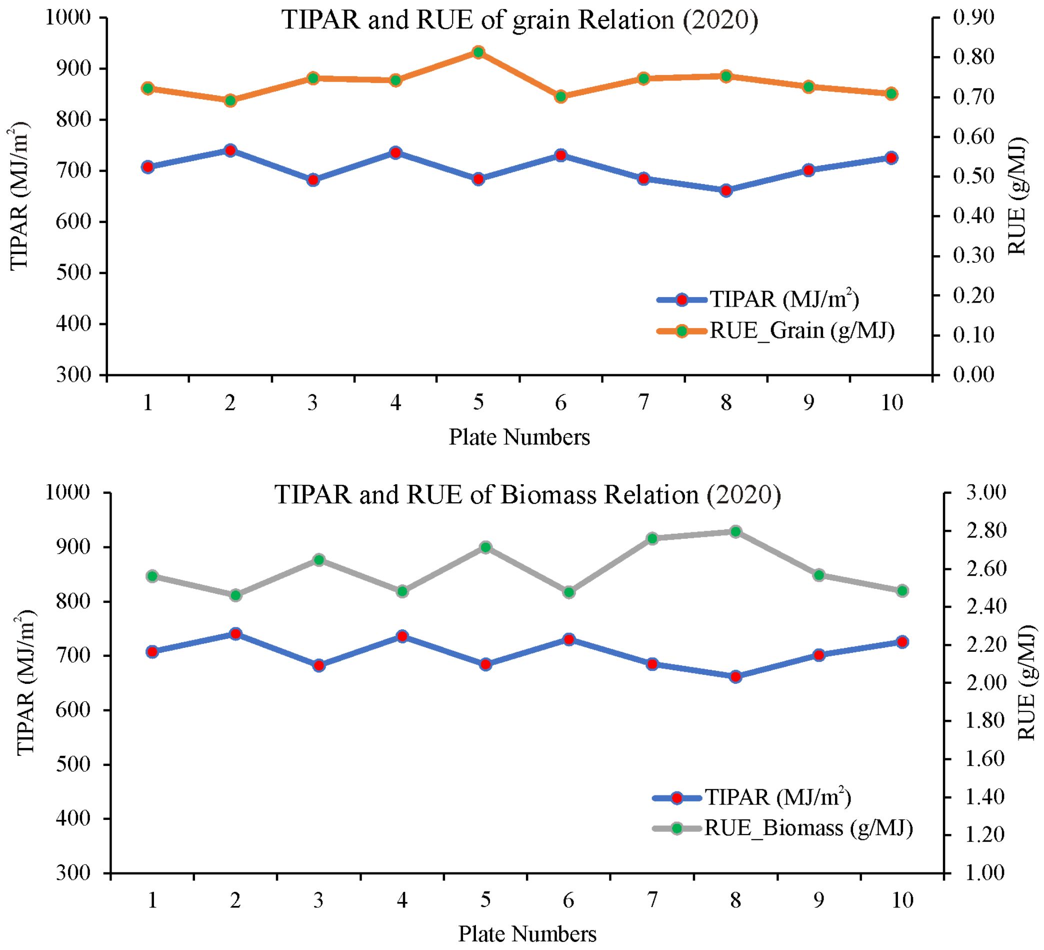


Fig. 5. Radiation Use Efficiency (RUE) in biomass and grain production of maize crop in 2020

Table 2. Intercepted Photosynthetic Active Radiation (IPAR), Absorbed Photosynthetic Active Radiation (APAR) and Fractional Intercepted Photosynthetic Active Radiation (fIPAR) of maize crop at different growth stages

Time of observation	Maize 2019			Maize 2020		
	IPAR (µmol/m²/sec)	APAR (µmol/m²/sec)	fIPAR	IPAR (µmol/m²/sec)	APAR (µmol/m²/sec)	fIPAR
20 DAS	1248	1217	0.70	1082	1063	0.59
30 DAS	1320	1298	0.73	1237	1196	0.66
40 DAS	1409	1376	0.76	1298	1272	0.71
50 DAS	1456	1407	0.80	1519	1461	0.80
60 DAS	1610	1572	0.81	1594	1576	0.85
70 DAS	1652	1602	0.82	1616	1578	0.88
80 DAS	1762	1718	0.83	1660	1606	0.89
90 DAS	1629	1575	0.77	1594	1576	0.87
100 DAS	1552	1501	0.72	1547	1576	0.71
110 DAS	1538	1487	0.70	1594	1472	0.68

received maximum 1762 µmol m^{-2} sec^{-1} (2019) and 1660 µmol m^{-2} sec^{-1} (2020) at 80 DAS (tasselling stage) and later on reduced with time of crop duration, which reduced up to 1538 µmol m^{-2} sec^{-1} (2019), 1594 µmol m^{-2} sec^{-1} (2020) (Table 2). The minimum IPAR was at initial stage of crop {at 20 DAS 1248 µmol m^{-2} sec^{-1} (2019) and 1082 µmol m^{-2} sec^{-1} (2020)} due to low canopy cover at initial stage (Table 2). The absorbed photosynthetically active radiation (APAR) increased with the duration of crop and received maximum 1718 µmol m^{-2} sec^{-1} (2019) and 1606 µmol m^{-2} sec^{-1} (2020) at 80 DAS (tasselling stage) and after that it reduced with time of crop duration, which reduced up to 1487 µmol m^{-2} sec^{-1} (2019), 1472 µmol m^{-2} sec^{-1} (2020). The minimum IPAR was at initial stage of crop {at 20 DAS 1217 µmol m^{-2} sec^{-1} (2019) and 1063 µmol m^{-2} sec^{-1} (2020)} due to low canopy cover at initial stage (Table 2). The fractional intercepted photosynthetically active radiation (fIPAR) increased with the duration of crop and attended maximum 0.83 (2019) and 0.89 (2020) at 80 DAS (tasselling stage) and after that it reduced with time of crop duration, which reduced up to 0.70 (2019), 0.68 (2020) (Table 2).

The observed difference in biomass accumulation during development may result from variation in crop canopy, differential absorption of PAR due to variation in plant population and LAI, or to differences in the efficiency of converting APAR into dry matter (Tollenaar and Aguilera, 1992; Heidari *et al.,* 2012). The fraction of IPAR was shown to differ substantially throughout the growth stage. Therefore, the smaller biomass at initial stage, result from reduction in PAR absorption, which was primarily due to the lower LAI in that stage. The greater biomass accumulation during early reproductive stage as the result of a combination of radiation interception, the efficiency in radiation interception, and RUE. Tripathi *et al.* (2016) observed LAI accumulation was greatest in pre-reproductive stage and smaller in initial stage and maturity. (Fig. 2). Differences in constant LAI also would result in differences in radiation accumulation and potential biomass accumulation. Therefore, it appears that the LAI was insufficient in initial and maturity stage to reach maximum radiation interception, resulting in smaller RUE and biomass accumulation at that stage was smaller than that observed in later stage and it was large enough to reach maximum PAR interception (Fig. 3).

Conclusions

The radiation interception and RUE is directly increased with increase of LAI of maize crop. It was lowest at initial stage and increased up to reproductive stage and later decreased due to senescence in leaf and reduction in LAI. Quantifying the variability of transmitted PAR in plant canopies also provides greater insight into the reliability of RUE estimates and variance effects on its deviation on different growth stage. Overall, it can be concluded conclude that this two-year crop study is useful particularly for crop biomass estimation under different environmental conditions and different growth stages.

Reference

Arkebauer, T.J., Walter-Shea, E.A., Mesarch, M.A., Suyker, A.E. and Verma, S.B. 2009. Scaling up of CO_2 fluxes from leaf to canopy in maize-based agroecosystems. *Agric. For. Meteor.* **149**: 2110–2119.

Biscoe, P.V. and Gallagher, J.N. 1975. Weather, dry matter production and yield. In Environmental Effects on Crop Physiology; Proceedings of the Symposium Held at Long Ashton Research Station, University of Bristol, Bristol, UK, 13–16 April 1975; Academic Press: New York, NY, USA, 1977.

Bonhomme, R. 2000. Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. *Field Crop Res.* **68**: 247–252.

Campbell, G.S. and Norman, J.M. 1998. An Introduction to Environmental Biophysics, *2nd ed. Springer-Verlag, New York*.

Flénet, F., Kiniry, J.R., Board, J.E., Westgate, M.E. and Reicosky, D.C. 1996. Row spacing effects on light extinction coefficients of maize, sorghum, soybean, and sunflower. *Agron. J.* **88**: 185–190.

Hangs, R.D., Van Rees, K.C.J., Schoenau, J.J. and Guo, X. 2011. A simple technique for estimating above-ground biomass in short-rotation willow plantations. *Biomass Bioenergy* **35**: 2156–2162.

Heidari, H., Johansooz, M.R., Hosseini, S.M.B. and Chaichi, M.R. 2012. Alternate furrow irrigation effect on radiation use efficiency and forage quality of foxtail millet (Setaria italica). *Ann. Biol. Res*. **3**: 2565–2574.

Hikosaka, K. 2005. Leaf canopy as a dynamic system: Ecophysiology and optimality in leaf turnover. *Ann. Bot*. **95**: 521–533.

Johnson, M-V.V., Kiniry, J.R. and Burson, B.L. 2010. Ceptometer deployment method affects measurement of fraction of intercepted photosynthetically active radiation. *Agron. J.* **102**: 1132–1137.

Kemanian, A.R., Stöckle, C.O. and Huggins, D.R. 2000. Variability of barley radiation-use efficiency. *Crop Sci.* **44**: 1662–1672.

Larson, P.R. and Isebrands, J.G. 1972. The relation between leaf production and wood weight in first-year root sprouts of two Populus clones. *Can. J. For. Res*. **2**: 98–104.

Lindquist, J.L., Arkebauer, T.J., Walters, D.T., Cassman, K.G. and Dobermann, A. 2005. Maize radiation use efficiency under optimal growth conditions. *Agron. J*. **97**: 72–78.

Liu, W., Yan, J., Li, J. and Sang, T. 2012. Yield potential of Miscanthus energy crops in the Loess Plateau of China. *GCB Bioenergy* **4**: 545–554.

Monteith, J.L. 1994. Discussion: validity of the correlation between intercepted radiation and biomass. *Agric. For. Meteorol.* **68**: 213– 220.

Muchow, R.C., Spillman, M.F., Wood, A.W. and Thomas, M.R. 1994. Radiation interception and biomass accumulation in a sugarcane crop grown under irrigated tropical conditions. *Aust. J. Agric. Res*. **45**: 37– 49.

Sinclair, T.R.and Muchow, R.C. 1999. Radiation use efficiency. *Adv. Agron*. **65**: 215–265.

Tollenaar, M. and Aguilera, A. 1992. Radiation use efficiency of an old and a new maize hybrid. *Agron. J.* **84**: 536–541.

Tripathi, A.M., Fischer, M., Orság, M., Marek, M.V., •alud, Z. and Trnka, M. 2016. Evaluation of indirect measurement method of seasonal patterns of leaf area index in a high-density short rotation coppice culture of poplar. *Acta Univ. Agric. Silvic. Mendel. Brun*. **64**(1): 549–556.

Received: 24 May 2022; Accepted: 31 July 2022