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ORIGINAL PAPER

Quantitative estimation of water use efficiency and evapotranspiration under varying nitrogen levels and sowing dates for rainfed and irrigated maize

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Abstract

Water is a key driver of agricultural production, the scarcity of which the production is adversely affected; hence, it is critical for the agriculture system and global food security. Water use efficiency (WUE) can be an effective measure to reduce water demand against crop yield as it depends upon water consumption. Thus, the purpose of this research was aimed to estimate the effect of variation in sowing time (timely and late) and nitrogen (N) level on the evapotranspiration (ET) and WUE for maize crop under irrigated (2013 and 2014) and rainfed (2012 and 2014) conditions. Two evapotranspiration (ET) approaches, i.e., Penman–Monteith (PM) and soil water balance (SWB), were used to estimate the evapotranspiration; thereafter, evapotranspiration was partitioned into soil evaporation (E) and transpiration (T). The results clearly indicated that cumulative evapotranspiration was higher for both rainfed (5.44–10.25%; N_{60}–N_{100}) and irrigated maize (5.87–13.77%; N_{75}–N_{125}) in comparison with N_0 nitrogen level. The delayed sowing dates gave on average a lower value (9.56%) and a higher value (15.68%) of ET for the rainfed and irrigated seasons, respectively, in comparison with timely sowing dates. Additionally, the WUE for maize grain yield was higher for both rainfed (251.12–346.06%; N_{60}–N_{100}) and irrigated maize (113.75–162.62%; N_{75}–N_{125}) in comparison with N_0 nitrogen level. The study further disclosed that a sowing date combination with nitrogen levels could be an effective management strategy to increase the crop yield by minimizing the water losses.

Keywords evapotranspiration · sowing dates · water use efficiency · nitrogen

Abbreviations

N	Nitrogen
N_0	Nitrogen level of 0 kg ha^{-1}
N_{60}	Nitrogen level of 60 kg ha^{-1}
N_{75}	Nitrogen level of 75 kg ha^{-1}
N_{80}	Nitrogen level of 80 kg ha^{-1}
N_{100}	Nitrogen level of 100 kg ha^{-1}
N_{125}	Nitrogen level of 125 kg ha^{-1}
T_{max}	Maximum temperature
T_{min}	Minimum temperature
P1	1st sowing date or timely sowing date
P2	2nd sowing date or late sowing date
LAI	Leaf area index
ET	Evapotranspiration
E	Evaporation
T	Transpiration
VPD	Vapor pressure deficit
r_n	Net radiation
r_s	Solar radiation

1 Introduction

Water and nitrogen (N) are the prime factors which play a convincing role in crop growth, biomass, and yield

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(Gheysari et al. 2009). Optimization of N applications and water use is in great demand for sustainable agricultural management due to lack of an adequate amount of water for irrigation, high costs of irrigation, and environmental pollution due to superfluous use of N (Kiani et al. 2016). Irrigation demand will increase up to 14% with increase in food production to meet the global demand (Payero et al. 2006). Hence, management techniques are needed to optimize the consumption of water and reduce the excess use of water for agriculture production.

Water scarcity has become more acute due to the rise in air temperature, and erratic rainfall distribution, thereby affecting agricultural production adversely (Farrea and Faci 2008; Zhao et al. 2010). Water stress reduces the leaf area, crop height, and shoot growth (Ghesyari et al. 2008; Soler et al. 2007), as well as the crop yield (Payero et al. 2006), thus affecting the crop biomass and harvest index. Ghesyari et al. (2008) stated that crop N demand and N uptake are a function of root and shoot growth. Therefore, there is a need for an optimized N application with the required water demand to enhance the food production. An accurate crop irrigation together with a proper nitrogen management and an optimum sowing date are crucial management factors for an effective maize production (Ghesyari et al. 2008). The water demand in crop production totally depends on the crop evapotranspiration (ET). A precise evapotranspiration estimation from the vegetative area is still critical to curtailing the consumption of water in agricultural production especially in the climate change context.

Management techniques like row spacing (Hernández et al. 2015) and N application (Caviglia and Sadras 2001) have the potential to increase WUE in maize and other crops. However, application of N increases the interception of photosynthetically active radiation (iPAR) (Hernándezet al. 2015), and radiation use efficiency (Sinclair and Muchow 1999). Very few studies reported on the effect of N on the ET component of WUE, and a little bit of information is available on the effect of the N amount in the rainfed season enhancing the ET value (Ogola et al. 2002); on the contrary, some reports suggested that there was an uncertain trend in ET response to the N amount. For the irrigated season, crop yield and WUE response to N amount are closely related with the water and N deficiencies (Hernández et al. 2015). The crop ET response to N supply is crucial because of N effects on its components, i.e., crop transpiration (T) and soil evaporation (E).

The productivity of a crop suitably relies on T which occurs through the stomatal pores of leaves concurrently with photosynthesis (Ding et al. 2013), while soil E is not such a prime factor related to crop productivity, and can be regulated by management practices (Zhao et al. 2010). As T and E are synchronous to each other, no clear separation can be made to distinguish between them (Ding et al. 2013; Er-Raki et al. 2010). Therefore, an accurate partitioning between E and T by models is required to enhance the grain yield, irrigation scheduling, and water use efficiency. Common approaches for partition ET are measurements using sap flow, lysimeter, isotopes, infrared thermometers (Zhongmin et al. 2009), and modeling (Scott et al. 2006). Among these approaches, modeling is more popular and acceptable because of its absolute merits in addressing ecosystem processes (Zhongmin et al. 2009).

The Penman–Monteith (PM) method (Monteith et al., 1965) is a substantially one-layer model that looks upon soil and canopy as a "Big Leaf" (Howell et al. 1998) with factors as surface resistance (r_s) and aerodynamic resistance (r_a) which represent the effect on heat and vapor flux transfer through the plant, soil, and atmosphere (Rana and Katerji 2008; Srivastava et al. 2018b).

The soil water balance (SWB) model is used for computing total water loss from the soil (T and E) (Wilson et al. 2001). The SWB approach requires soil water, deep percolation, precipitation, irrigation, and drainage (Allen et al. 1998, 2005). The prime advantage of this approach is its relevancy while computing the water loss from a crop field (Srivastava et al. 2018a).

Maize (*Zea mays* L.) is the third most cultivated crop after wheat and rice crop which can grow in all types of soil in different climatic conditions but is also susceptible to water stress (Srivastava et al. 2017). Several researches have been administered to estimate the maize water demand (Farréa and Faci, 2008; Djman et al. 2013) while some studies reported increasing nitrogen level to enhance the grain yield and plant biomass, but little information is available on the influence of N on WUE and ET response under different environmental conditions (Cavigila and Sadras 2001; Farréa and Faci 2008). Thus, the objectives of this study are (1) to calibrate the PM model with the SWB method for the recommended N level and sowing date for rained and irrigated maize and (2) to estimate the effect of varying N levels and sowing dates on ET, T, E, and WUE for rainfed (2012 and 2014) and irrigated (2013 and 2014) maize in a sub-tropical region.

2 Materials and methodology

2.1 Study area

Field experiments were investigated at the research farm of Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, India (22.33°N latitude, 87.33°E longitude) from years 2012 to 2014. The soil was of lateritic type with a medium sandy loam texture. Total nitrogen (%) ranged between 0.053 and 0.013 at the 05–60-cm depth. The volumetric soil moisture content ranged in field capacities and wilting points of 0.22–0.24 and 0.094–0.12 m^3/m^3, respectively, with an effective average soil depth of

60 cm and bulk density of 1.64 g/cm^3 (Srivastava et al. 2018a).

2.2 Climatic conditions

The climate of the studied area is categorized as sub-humid and sub-tropical. The area normally receives an annual precipitation of 1500 mm (Halder et al. 2016). The micrometeorological variables were measured at an automated weather station located near the farm. The hourly and daily recorded variables were rainfall (tipping bucket rain gauge), temperature (minimum and maximum), relative humidity (HC2S3 model), wind speed (anemometer, 05103-10 model), and solar irradiation (pyranometer, CS300-L model, Campbell Scientific Inc.). The temporal changes in temperature (minimum and maximum) (°C) and rainfall (mm) of the years 2012–2014 during the crop experiment are presented in Fig. 1. Figure 1 shows the maximum and minimum temperatures and rainfall ranging 25–43 °C and 15–33 °C during the irrigated season and 30–40 °C and 22–25 °C during the rainfed season, respectively, and Fig. 2 represents the daily values of vapor pressure deficit (VPD) (kPa), net radiation (MJ/m^2/day), and solar radiation (MJ/m^2/day) which were recorded higher in the dry season and lower in the wet season for the years 2012–2014. The recorded weather data were validated with double mass analysis and presented in Srivastava et al. (2018b).

2.3 Field experimental particulars

Four field experiments on maize crop were managed with two sowing dates (timely and late) and four N levels under rainfed (years 2012 and 2014) and irrigated (years 2013 and 2014) conditions. The maize seed was sown at a depth of 5 cm with a gap of 50 cm × 20 cm (row × column) with a 5-cm bund height for both sets of field experiment. Out of the four, two field experiments were run under rainfed conditions for maize (cv. Bio 22027) while the other two remained under irrigated conditions for maize (cv. Tx367). The sowing time under rainfed conditions was 10 June (timely) and 25 June (late) during the years 2012 and 2014, respectively. Under irrigated conditions, the sowing time was 5 January (timely) and 25 January (late) in the years 2013 and 2014, respectively. The fertilizer level for rainfed were 0:0:0 (N_0), 60:50:50 (N_{60}), 80:50:50 (N_{80}), 100:50:50 (N_{100}) (N/P/K, kg/ha), and for irrigated 0:0:0 (N_0), 75:50:50 (N_{75}), 100:50:50 (N_{100}), 125:50:50 (N_{125}) (N/P/K, kg/ha), respectively. Furrow irrigation was used to irrigate the crop. Time domain reflectometry (TDR) measured the soil water content on a daily basis. The probe was introduced into access tubes at particular depths of 0–20, 20–40, 40–60, and 60–90 cm which were installed vertically in each plot. The TDR was validated with a gravimetric method two times during the wet to dry conditions for varying depths of 0–20, 20–40, 40–60, and 60–90 cm, respectively (Fig. 3) (Srivastava et al. 2017). Figure 4 represents the irrigation (mm) of the maize crop for different days after sowing.

2.3.1 Crop growth evaluation

Crop growth development was reported after the germination at different stages, i.e., vegetative, developing, maturing, and harvesting stages, of the crop. The crop height, leaf area, top weight including leaf, stem, and cob weight (dry), and grain yield were observed by collecting the sampling observations at various crop growth stages. The leaf area index (LAI) was calculated by dividing the total leaf area measured by the leaf area meter of each plant by the soil surface available for each plant (Srivastava et al. 2018a,b, 2019). A linear interpolation was applied between dates from the emergence to the first measurement to simulate the seasonal dynamics in LAI for varying N levels. The effective leaf area index (LAI_{eff}) applied for estimating ET methods was equal to the actual LAI where the LAI was lower than 2 m^2/m^2 and half the actual LAI for actual LAI values above 4 m^2/m^2 (Yu et al. 2015, 2016).

2.4 Evapotranspiration estimation methods

Actual evapotranspiration was estimated using the soil water balance (SWB) and PM methods for irrigated and rainfed maize. The accuracy of the PM method was validated by the SWB method for rainfed (2012 and 2014) and irrigated (2013 and 2014) maize with recommended nitrogen levels of N_{80} and N_{100}, respectively, after which the PM method was used to portray the effect of varying N levels and sowing dates in rainfed and irrigated conditions.

2.4.1 Soil–water balance

Daily crop evapotranspiration (ET_c) was computed by using the soil–water balance budget equation by TDR (Srivastava et al. 2018a) (Eq. 1):

$$\mathrm{ET_c} = R + I \pm \Delta\mathrm{SM} - D_\mathrm{p} - \mathrm{RO} \quad (1)$$

where ΔSM is the variation of moisture between two successive days measured by TDR, I is the irrigation (mm), ET_c is the crop evapotranspiration, R is the rainfall (mm), D_p is the deep percolation (mm), RO is the surface runoff flux (mm), and CR is the capillary rise flux (mm) which was neglected due to shallow to deep water table depths (3–55 m) leading to no contribution from the groundwater with a capillary rise into the root zone (Ridolfi et al. 2008). Deep percolation was measured twice a day on the basis of soil moisture at various growth stages (Payero et al. 2006 and Bryant et al. 1992).

Runoff was negligible in irrigated conditions while during rainfed conditions, it was determined by the USDA-NRCS

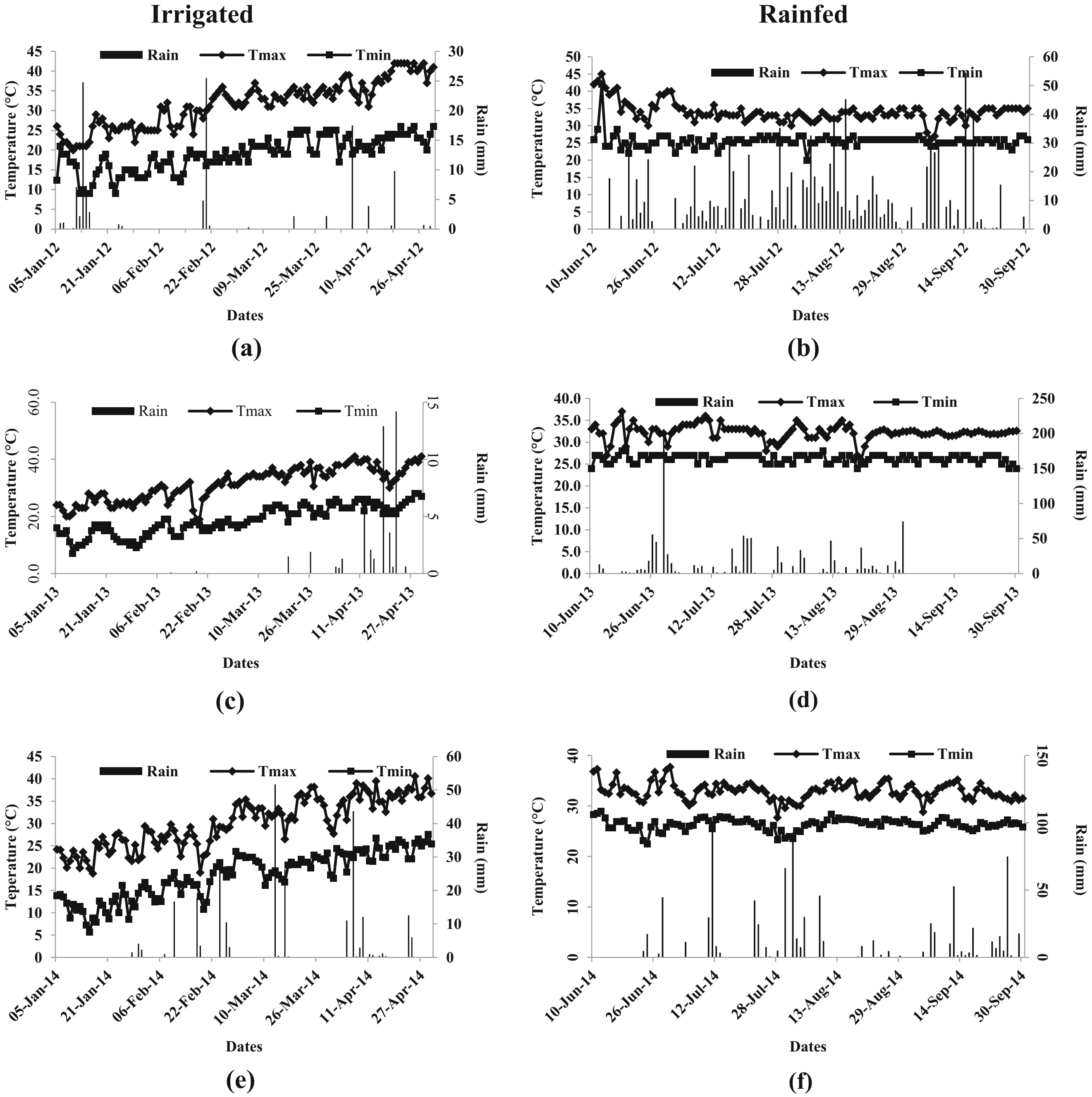


Fig. 1 Daily variation in rain (mm) and $T_{\min}$ and $T_{\max}$ for the years 2012 (**a**, **b**), 2013 (**c**, **d**), and 2014 (**e**, **f**) for the irrigated and rainfed seasons at Kharagpur, respectively

curve number procedure (USDA-NRCS 1964) (Eqs. 2 and 3) (Djaman et al. 2013). The SCS curve number method gives an account of the runoff curve number (CN) to runoff, computing for the infiltration rate of soil and initial abstraction losses (Mishra et al. 2003).

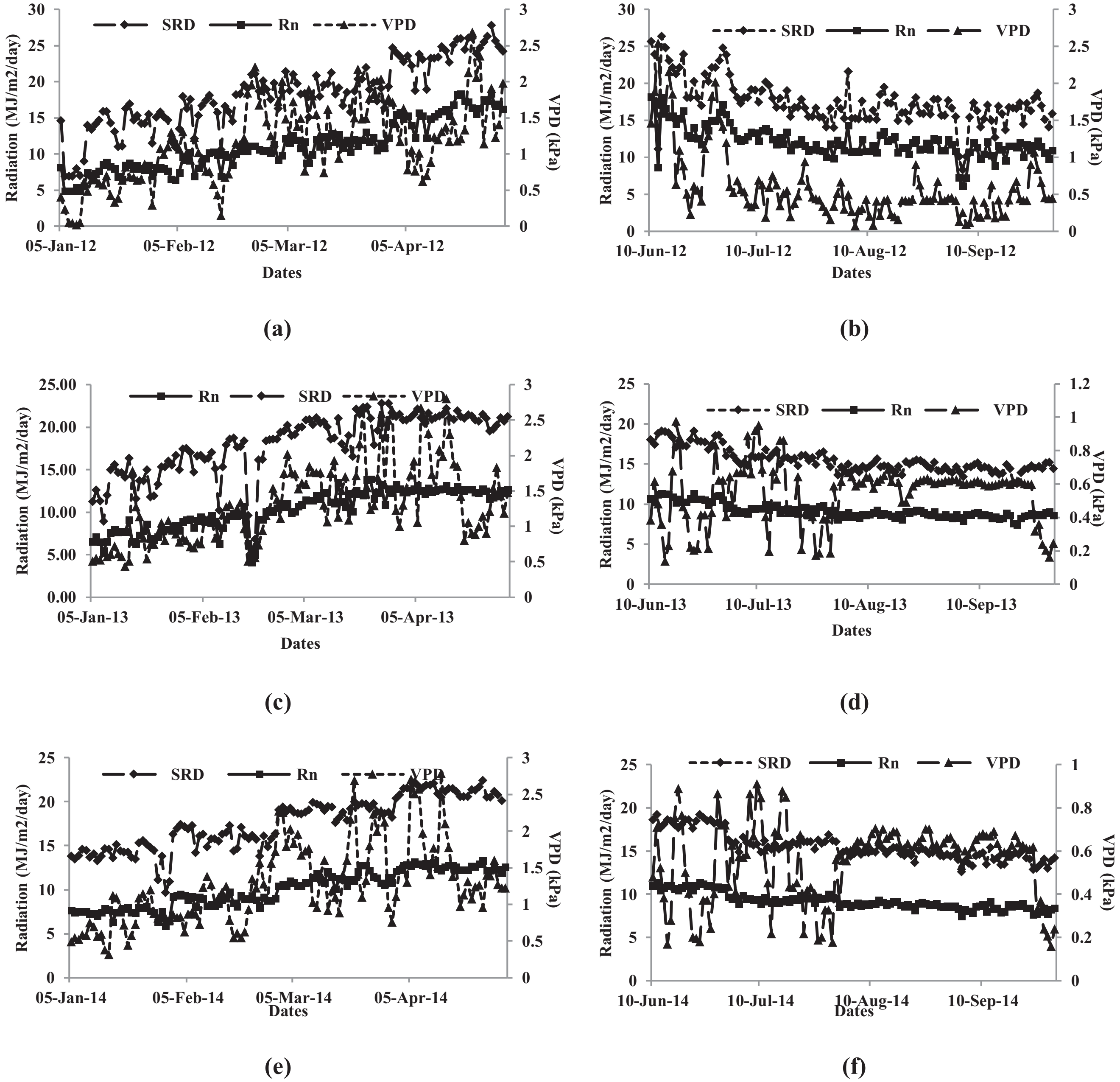
$$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad P > I_a \tag{2}$$

$$R = 0 \qquad P \le I_a \tag{3}$$

where S is the water storage capacity (Eq. 2), and I_a is the initial abstraction which is water loss before runoff begins (Djman et al. 2013) and includes water retained in depressions (Djman et al. 2013) (Eq. 4):

$$I_a = 0.2S \tag{4}$$

$$S = \frac{25400}{\mathrm{CN}} - 254 \tag{5}$$



(a) (b) (c) (d) (e) (f)

Fig. 2 Temporal variation of solar radiation (MJ/m^2/day), net radiation (MJ/m^2/day), and vapor pressure deficit (kPa) for the years 2012 (**a**, **b**), 2013 (**c**, **d**), and 2014 (**e**, **f**) for the irrigated and rainfed seasons, respectively

The curve number varies with the site's soil hydrologic group and land use (Djaman et al. 2013). CN values 48, 68, and 86 for dry, normal, and wet conditions were adopted from the USDA-NRCS (1964) tables based on the soil of the experimental site, and land use (Djaman et al. 2013; Rudnick et al., 2017). The curve number or AMC II was adapted based on the 5-day antecedent precipitation (Ajmal et al. 2015).

2.4.2 The PM model

In this study, the single-source PM model (Eq. 6) (Monteith et al., 1965; Gharsallah et al. 2013) was used as discussed in the following (Srivastava et al. 2018a):

$$\lambda \mathrm{ET} = \frac{\Delta\left(R_n - G\right) + \left(\left(\rho C_p\left(e_c - e_a\right)\right)/r_a\right)}{\Delta + \gamma\left(1 + \left({}^{r_c}/_{r_a}\right)\right)} \qquad (6)$$

where ET is the crop evapotranspiration (W m^{-2}), Δ is the slope of the saturated vapor pressure curve (kPa K^{-1}), λ is the latent heat of vaporization of water (MJ kg^{-1}), R_n is the net radiation (W m^{-2}), ρ is the air density (kg m^{-3}), G is the soil heat flux (W m^{-2}), c_p is the specific heat of moist air (MJ kg^{-1} °C^{-1}), γ is the psychometric constant (kPa °C^{-1}), e_c and e_a are the saturated and actual vapor pressures of the air (kPa), respectively, r_a is the aerodynamic resistance (s m^{-1}), and r_c is

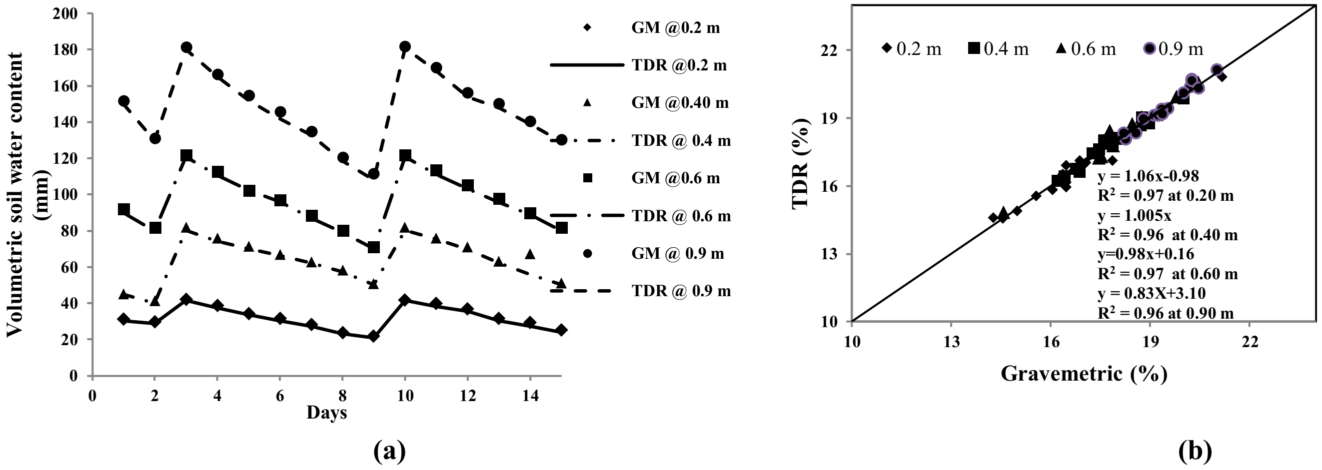


Fig. 3 Validation of TDR against the gravimetric method for two wetting–drying cycles (15 days) for **a** volumetric soil water content (mm) and **b** soil moisture content (%) at depths of 0.20, 0.40, 0.60, and 0.90 m, respectively

the canopy resistance (s m^{-1}). r_a was computed by the model developed by Perrier (1975) and tested by Gharsallah et al. (2013), as shown below (Eq. 7):

$$ra = \frac{\ln((z-d)/(z_0))\ln((z-d)/(h_c-d))}{U(z)k^2} \tag{7}$$

where z_0 is the roughness length governing the momentum transfer (m), z is the reference height of measurement (m), h_c is the mean crop height (m), k is the von Karman's constant, d is the zero plane displacement height (m), and $U(z)$ is the wind speed at height z (m s^{-1}).

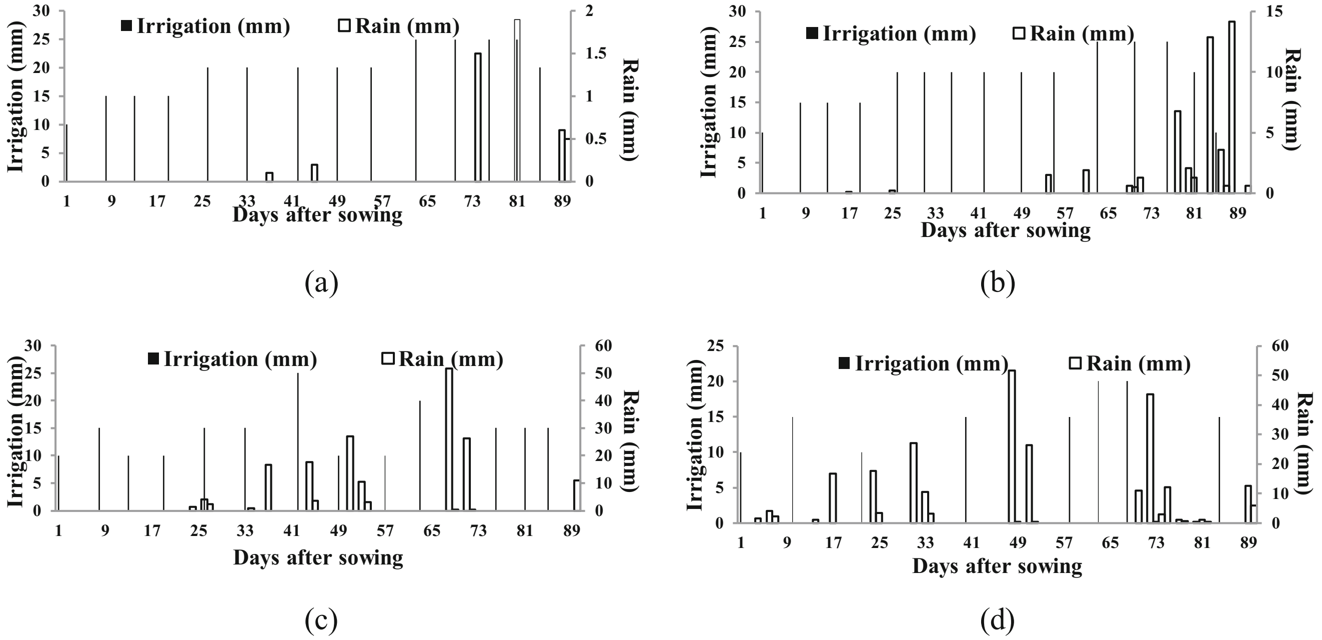
As the PM approach is dependent on canopy resistance, canopy resistance was estimated by the mechanical Todorovic approach which is based on climatological resistance (Todorovic 1999) and is recommended for this region (Srivastava et al. 2018a). The Todorovic approach based on the quadratic equation (Eq. 8) has only one positive solution and is expressed as follows:

$$a^*\left(\frac{r_c}{r_i}\right)^2 + b^*\left(\frac{r_c}{r_i}\right) + c^* = 0 \tag{8}$$

where r_i is the climatological resistance (s m^{-1}) computed by Eq. 9:

$$r_i = \frac{\rho c_p\,(e_s-e_a)}{\gamma(R_n-G)} \tag{9}$$

where a^*, b^*, and c^* are computed in Eqs. 10, 11, and 12, respectively:



(a)

(b)

(c)

(d)

Fig. 4 Applied irrigation (solid bar) and rainfall (blank bar) during the maize crop growth period for the years **a**, **b** 2013 and **c**, **d** 2014

$$a^* = \frac{\Delta + \gamma\left({}^{r_i}/_{r_a}\right)}{\Delta + \gamma}\left(\frac{r_i}{r_s}\right)(e_s - e_a) \tag{10}$$

$$b^* = -\gamma\left(\frac{r_i}{r_a}\right)\frac{\gamma\,(e_s - e_a)}{\Delta + (\Delta + \gamma)} \tag{11}$$

$$c^* = -(\Delta + \gamma)\,\frac{\gamma\,(e_s - e_a)}{\Delta(\Delta + \gamma)} \tag{12}$$

2.4.3 Transpiration

Transpiration (T) (Eq. 13) was estimated by multiplying the reference evapotranspiration (ET_0) (Eq. 14) with the crop basal coefficient K_{cb} (Eq. 15), which is the difference between actual and reference crop surfaces (Yu et al. 2016).

$$T_p = K_{cb} ET_0 \tag{13}$$

ET_0 was estimated using the FAO-56 method (Zhao et al. 2010); Eq. 14 was used to estimate daily ET.

$$ET0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \dfrac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * U_2)} \tag{14}$$

where T_a is the mean daily air temperature (°C).

Also,

$$K_{cb} = K_{cb,max}\left(1 - \exp(-\tau LAI)\right) \tag{15}$$

where τ is the extinction coefficient, set at 0.6 (Yu et al. 2016). $K_{cb,max}$ is the basal crop coefficient at effective full ground cover (Allen et al. 1998, 2005); soil evaporation was estimated using the difference between the ET and T.

2.5 Water use efficiencies

The water use efficiency (WUE, kg ha^{-1} mm^{-1}) was estimated on the basis of plant dry matter (Eichelmann et al. 2016) and grain yield (Payero et al. 2006). The plant dry matter represents an agronomic perspective of water use efficiency (Eichelmann et al. 2016).

2.6 Statistical analysis

Models were evaluated by error analysis, i.e., the root mean square error (RMSE) (Eq. 16), and mean relative error (MRE) (Eq. 17) indices were calculated using equations (Srivastava and Imtiyaz, 2016):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - Y_i)^2} \tag{16}$$

$$MRE = \frac{1}{N}\sum_{i=1}^{n}\frac{X_i - Y_i}{Y_i}\,100 \tag{17}$$

where X_i is the calculated value obtained from different models and Y_i is the estimated value obtained from the soil water balance method.

3 Results

3.1 LAI and evapotranspiration

An interpolated daily LAI is presented in Fig. 5 from the plant emergence to the harvesting stage for varying N levels and

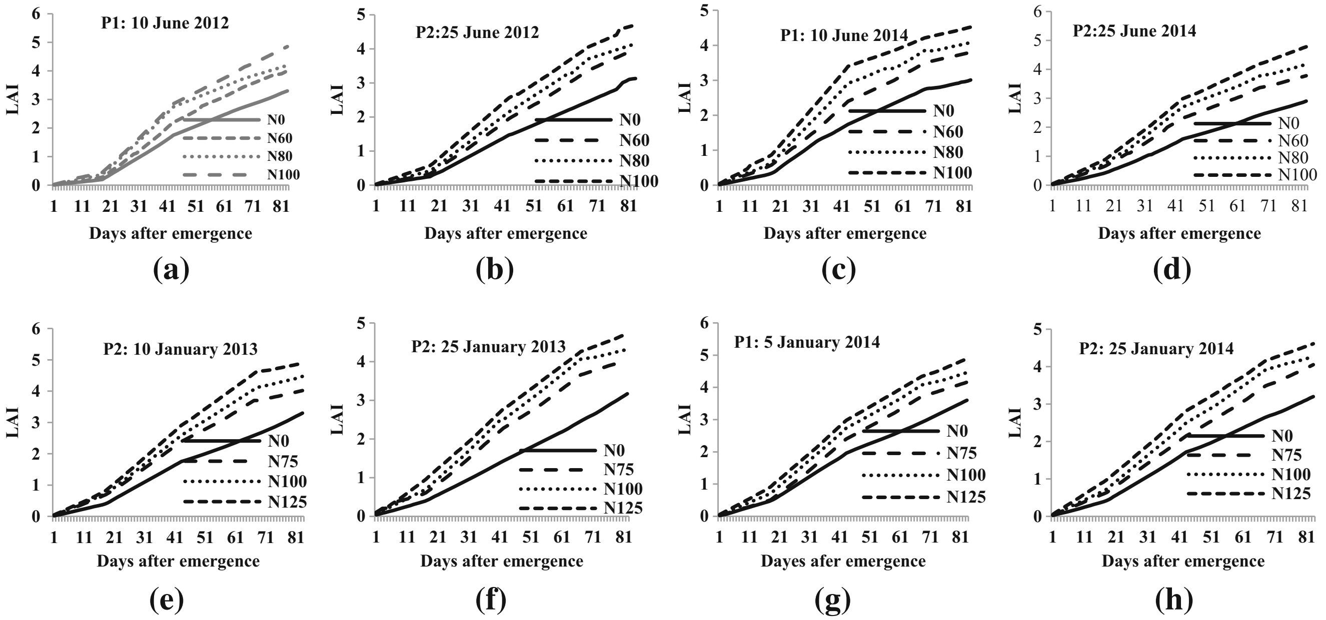


Fig. 5 Temporal variation in LAI for varying N levels and sowing dates for rainfed (**a**–**d**) and irrigated (**e**–**h**) maize

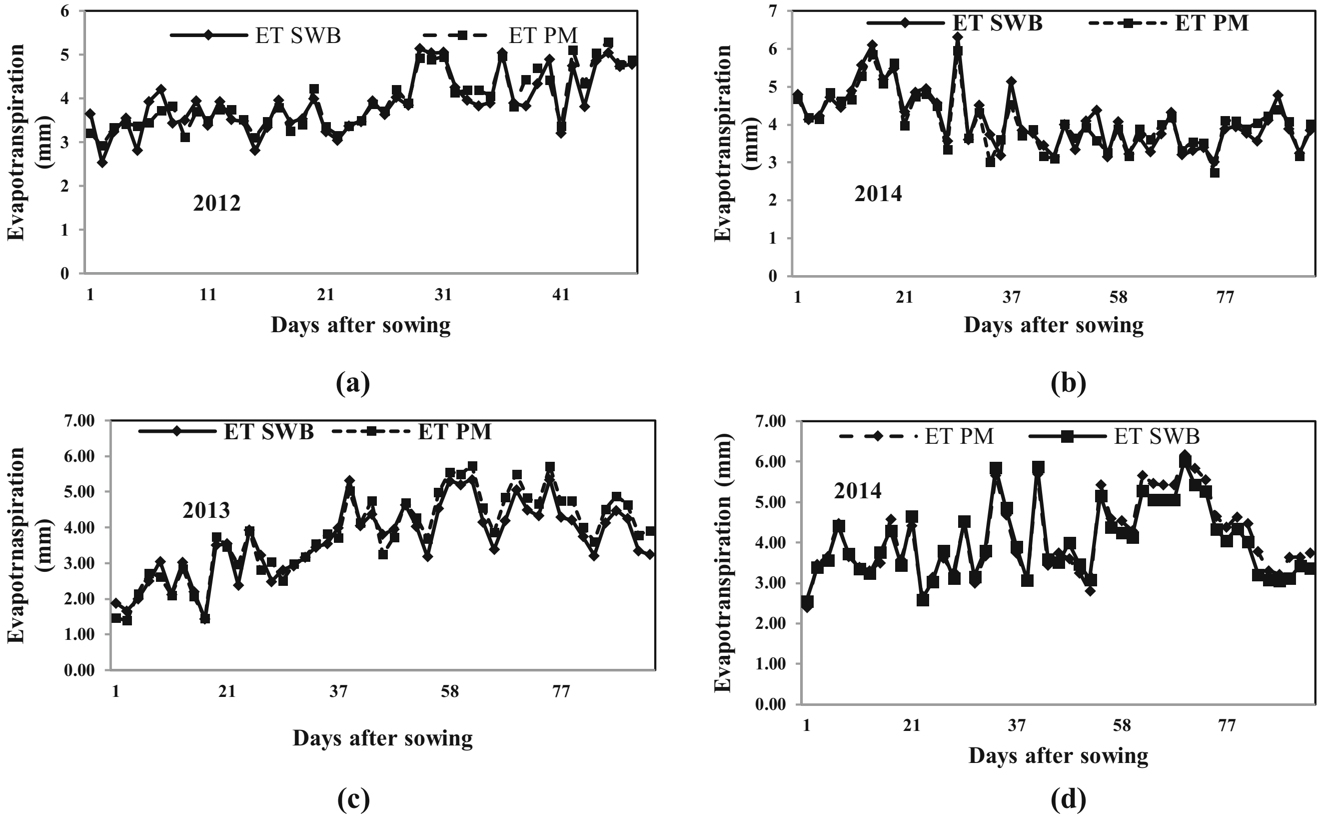


Fig. 6 Temporal evolution of evapotranspiration SWB (rectangular marker) and PM (square marker) **a**, **b** for rainfed conditions and **c**, **d** for irrigated conditions

sowing scenario in maize. Figure 5 indicates a maximum LAI of 4.58 and 4.89 m^3/m^3 with a higher level of N, respectively, in both rainfed and irrigated crops. The timely sowing date effect on average LAI for rainfed conditions was lower (5.49%) and was higher (4.85%) in irrigated conditions with respect to delayed sowing dates.

Sowing dates and nitrogen level had a significant effect on maize yield, yield attributes, and plant dry matter during the study periods of 2012 to 2014 for rainfed and irrigated maize, and data were presented and discussed in Srivastava et al. (2018a).

Measured daily evapotranspiration was compared with estimated evapotranspiration by the PM method (Fig. 6) for rainfed and irrigated seasons. Statistical evaluation suggests that the PM model an averaged R^2 0.82–0.86 during the rainfed and 0.90–0.91 during irrigated season (Fig. 7).

3.2 stimation of T, E, and ET under varying N levels and sowing dates

3.2.1 Evapotranspiration

The cumulative evapotranspiration was higher at 5.13% (N$_{60}$), 7.08% (N$_{80}$), and 10.25% (N$_{100}$) for rainfed maize and 5.87% (N$_{75}$), 10.34% (N$_{100}$), and 13.77% (N$_{125}$) for irrigated maize

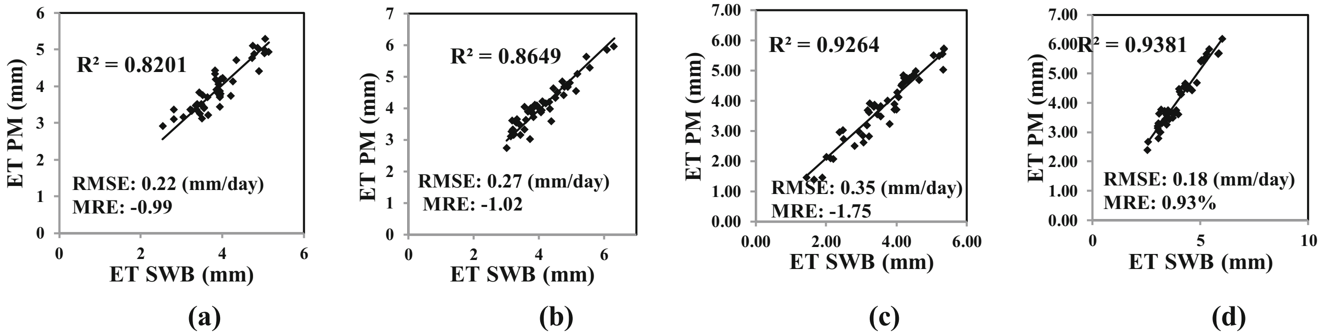


Fig. 7 Statistical evaluation of evapotranspiration by SWB vs PM method during the years 2012 (**a**) and 2014 (**b**) for rainfed and the years 2013 (**c**) and 2014 (**d**) for the irrigated season

Table 1 Crop growth stage wise evaporation (E), transpiration (T), and evapotranspiration (ET) for varying N levels and sowing dates of rainfed maize

	Sowing dates	Crop growth stages	N_0 (kg ha^{-1})			N_{60} (kg ha^{-1})			N_{80} (kg ha^{-1})			N_{100} (kg ha^{-1})		
			T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)
2012	10 June	Vegetative	9.29	60.12	69.41	12.23	59.28	71.51	16.56	58.36	74.92	21.38	56.73	78.11
		Developing	34.56	55.15	89.71	38.04	53.60	91.64	47.40	50.25	97.65	52.23	48.56	100.79
		Maturing	67.08	35.73	102.81	76.24	29.25	105.49	84.67	24.25	108.92	92.23	19.83	112.06
		Harvesting	85.51	25.44	110.95	93.69	23.83	117.52	99.46	19.91	119.37	105.50	14.96	120.46
		Total	196.44	176.44	372.88	220.20	165.96	386.16	248.09	152.77	400.86	271.34	140.08	411.42
	25 June	Vegetative	8.30	56.87	65.17	11.21	52.85	64.06	15.94	50.32	66.26	20.04	48.55	68.59
		Developing	33.22	48.28	81.50	36.46	46.70	83.16	42.62	43.04	85.66	50.39	41.28	91.67
		Maturing	61.52	30.49	92.01	71.85	25.61	97.46	75.78	29.55	105.33	80.13	25.51	105.64
		Harvesting	80.71	22.68	103.39	85.18	20.50	105.68	90.69	18.13	108.82	96.23	15.65	111.88
		Total	183.75	158.32	342.07	204.70	145.66	350.36	225.03	141.04	366.07	246.79	130.99	377.78
2014	10 June	Vegetative	9.79	66.44	76.23	15.65	62.44	78.09	20.64	59.48	80.12	25.88	56.56	82.44
		Developing	38.51	57.71	96.20	46.66	52.58	99.24	52.33	48.56	100.89	57.87	44.53	102.40
		Maturing	63.84	35.43	99.27	71.03	32.29	103.32	75.00	31.60	106.60	82.08	29.97	112.05
		Harvesting	79.55	25.07	104.62	89.14	18.83	107.97	95.85	15.40	111.25	103.73	12.62	116.35
		Total	191.69	184.65	376.32	222.48	166.14	388.62	243.82	155.04	398.86	269.56	143.68	413.24
	25 June	Vegetative	8.66	64.50	73.16	12.02	60.38	72.40	17.26	58.50	75.76	22.87	55.51	78.38
		Developing	32.97	45.58	78.55	43.39	41.30	84.69	47.25	38.78	86.03	53.52	34.84	88.36
		Maturing	60.69	30.44	91.13	69.47	25.43	94.90	76.12	21.42	97.54	87.17	16.55	103.72
		Harvesting	74.70	23.43	98.13	81.66	18.71	100.37	90.34	14.17	104.51	97.95	11.39	109.34
		Total	177.02	163.95	340.97	206.54	145.82	352.36	230.97	132.87	363.84	261.51	118.29	379.8

in comparison with N_0 (Tables 1 and 2). The effect of varying N levels (N_0, N_{60}, N_{80}, N_{100} kg ha^{-1}) on evapotranspiration (mm) for two sowing dates in rainfed and irrigated maize is shown in Figs. 8 and 9, respectively. The delayed sowing date effect on cumulative evapotranspiration was lower at 10.28% (N_0), 9.33% (N_{60}), 8.67% (N_{80}), and 8.07% (N_{100}) for the rainfed maize and higher at 18.78% (N_0), 17.32% (N_{75}), 15.70% (N_{100}), and 14.37% (N_{125}) for the irrigated maize in comparison with timely sowing date.

3.2.2 Transpiration

The average cumulative transpiration was higher at 11.74, 20.90, and 30.25% for N_{60}, N_{80}, and N_{100} for the rainfed maize, and 15.48, 20.27, and 26.05% for N_{75}, N_{100}, and N_{125} for the irrigated maize in comparison with N_0 (Tables 1 and 2). The highest increase in transpiration was found with a higher N level (N_{100} and N_{125}) in comparison with N_0 (Figs. 10 and 11) for both conditions. Furthermore, the effect of sowing dates (Tables 1 and 2) on average cumulative transpiration was higher in delayed sowing at 5.87% (N_0), 8.29% (N_{75},), 9.59% (N_{100}), and 11.9% (N_{125}) for irrigated maize, while it was lower at 10.67% (N_0), 8.49% (N_{60}), 8.07% (N_{80}), and 7.01% (N_{100}) for rainfed maize in comparison with timely sowing date. For better clarity, the figures are represented at an interval of 10 days regardless of daily values.

3.2.3 Evaporation

The average cumulative evaporation (Tables 1 and 2) was lower at 9.40% (N_{60}), 16.05% (N_{80}), and 22.16% (N_{100}) for irrigated maize, and 10.96% (N_{75}), 20.28% (N_{100}), and 30.02% (N_{125}) for rainfed maize in comparison with N_0 (Figs. 12 and 13). The delayed sowing date effect (Tables 1 and 2) on cumulative evaporation was lower at 11.21% (N_0), 12.29% (N_{60}), 14.29% (N_{80}), 17.73% (N_{100}) for the rainfed maize while it was higher at 20.70% (N_0), 24.66% (N_{75}), 28.31% (N_{100}), and 33.72% (N_{125}) for irrigated maize in comparison with timely sowing dates.

3.3 Estimation of WUE

Tables 3 and 4 represent WUE based on plant dry matter and yield for varying N levels and sowing dates. Increase in N increased the WUE calculated from biomass and yield for both rainfed and irrigated conditions (Table 4). The WUE calculated from biomass was higher at 81.53% (N_{60}), 127.62% (N_{80}), 159.23% (N_{100}) for rainfed maize and 56.19% (N_{75}), 84.91% (N_{100}), and 115.79% (N_{125}) for

Table 2 Crop growth stage wise evaporation (E), transpiration (T), and evapotranspiration (ET) for varying N levels and sowing dates of irrigated maize

Year	Sowing dates	Crop growth stages	N_0 (kg ha^{-1})			N_{75} (kg ha^{-1})			N_{100} (kg ha^{-1})			N_{125} (kg ha^{-1})		
			T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)	T (mm)	E (mm)	ET (mm)
2013	5 January	Vegetative	8.46	46.69	55.15	13.62	43.39	57.01	17.31	41.00	58.31	22.69	38.13	60.82
		Developing	37.27	37.92	75.19	46.70	32.62	79.32	51.92	29.79	81.71	55.28	28.34	83.62
		Maturing	69.16	31.84	101.00	80.24	27.41	107.65	85.13	24.22	109.35	86.36	19.35	105.71
		Harvesting	104.90	28.02	132.92	113.27	25.71	138.98	119.00	21.71	140.71	125.72	18.74	144.46
		Total	219.79	144.47	364.26	253.83	129.13	382.96	273.36	116.72	390.08	290.05	104.56	394.61
	25 January	Vegetative	10.53	52.46	62.99	17.24	49.28	66.52	21.48	47.34	68.82	26.92	43.91	70.83
		Developing	42.40	48.54	90.94	57.40	43.99	101.39	64.02	39.73	103.75	68.91	35.63	104.54
		Maturing	73.91	42.15	116.06	81.04	37.70	118.74	90.47	33.63	124.10	96.55	29.49	126.04
		Harvesting	105.87	36.06	141.93	114.26	31.16	145.42	119.74	27.49	147.23	126.42	22.79	149.21
		Total	232.71	179.21	411.92	269.94	162.13	432.07	295.71	148.19	443.9	318.80	131.82	450.62
2014	5 January	Vegetative	7.62	44.28	51.90	12.62	42.37	54.99	16.86	39.64	56.50	21.92	36.31	58.23
		Developing	38.24	34.75	72.99	44.82	30.59	75.41	51.91	27.83	79.74	60.72	23.69	84.41
		Maturing	60.33	28.05	88.38	74.88	23.64	98.52	81.80	19.86	101.66	87.00	14.06	101.06
		Harvesting	106.77	23.85	130.62	114.67	19.19	133.86	120.27	16.48	136.75	127.90	13.17	141.07
		Total	212.96	130.93	343.89	246.99	115.79	362.78	270.84	103.81	374.65	297.54	87.23	384.77
	25 January	Vegetative	10.37	52.25	62.62	15.27	50.18	65.45	18.10	48.84	66.94	21.89	46.81	68.70
		Developing	43.08	41.38	84.46	51.96	37.18	89.14	56.64	33.21	89.85	63.72	29.09	92.81
		Maturing	74.90	35.85	110.75	84.25	30.94	115.19	92.94	27.78	120.72	98.75	23.76	122.51
		Harvesting	110.31	31.98	142.29	121.53	26.13	147.66	126.86	23.24	150.10	135.87	18.49	154.36
		Total	238.66	161.46	400.12	273.01	144.43	417.44	294.54	133.07	427.61	320.23	118.15	438.38

irrigated maize in comparison with N_0, while the WUE calculated from yield was higher at 251.12% (N_{60}), 321.51% (N_{80}), and 346.06% (N_{100}) for rainfed maize and 113.75% (N_{75}), 140.45% (N_{100}), and 162.62% (N_{125}) for irrigated maize. Sowing dates showed that WUE calculated from biomass was lower at 23.50% (N_0), 19.79% (N_{60}), 16.90% (N_{80}), and 7.72% (N_{100}) for rainfed maize and 24.79% (N_0), 20.53% (N_{75}), 15.78% (N_{100}), and 13.10% (N_{125}) for irrigated maize, while that calculated from grain yield was lower at 18.45% (N_0), 9.83% (N_{60}), 7.11% (N_{80}), and 6.79% (N_{100}) for rainfed maize and 20.84% (N_0), 16.46% (N_{75}), 13.35% (N_{100}), and 11.71% (N_{125}) for irrigated maize.

4 Discussion

Water and nitrogen both play a vital role in agriculture production, of which water is the most limiting factor for reduced productivity of crop (Wang et al. 2017) while N is regarded as the most authoritative factor for crop production and grain quality and is widely accepted as one of the most important ingredients for the improvement of WUE (Hernández et al., 2015). An increased N level enhances the plant biomass which influences the ET, evaporation, and transpiration and WUE (Ogola et al. 2002).

4.1 Evaluation of evapotranspiration models

Several studies reported that the accuracy of the PM method is higher over the SWB method due to LAI, solar radiation, and VPD (Yu et al. 2016).While evaluating the performance of the PM method, the ET estimated by the PM method was found to closely follow the ET estimated by the SWB method at the initial and developing stages in both rainfed and irrigated maize, but at the harvesting stage the model showed underestimation in rainfed maize and overestimation in irrigated maize (Figs. 6 and 7). In the PM method, for the estimation of canopy resistance vapor pressure deficit (VPD) is required which varies linearly with canopy resistance (Katerji et al. 2011). Hence, this under/overestimation was due to lower VPD (0.5–0.7 kPa) (Fig. 2) in the August and September months for the rainfed season (Zhang et al. 2008) and higher (1.23–3.0 kPa) in the March and April months for the irrigated season (Lacina et al. 2003; Shi et al. 2008). Several other researchers compared the PM method with SWB method and found that the PM result varies with changes in LAI

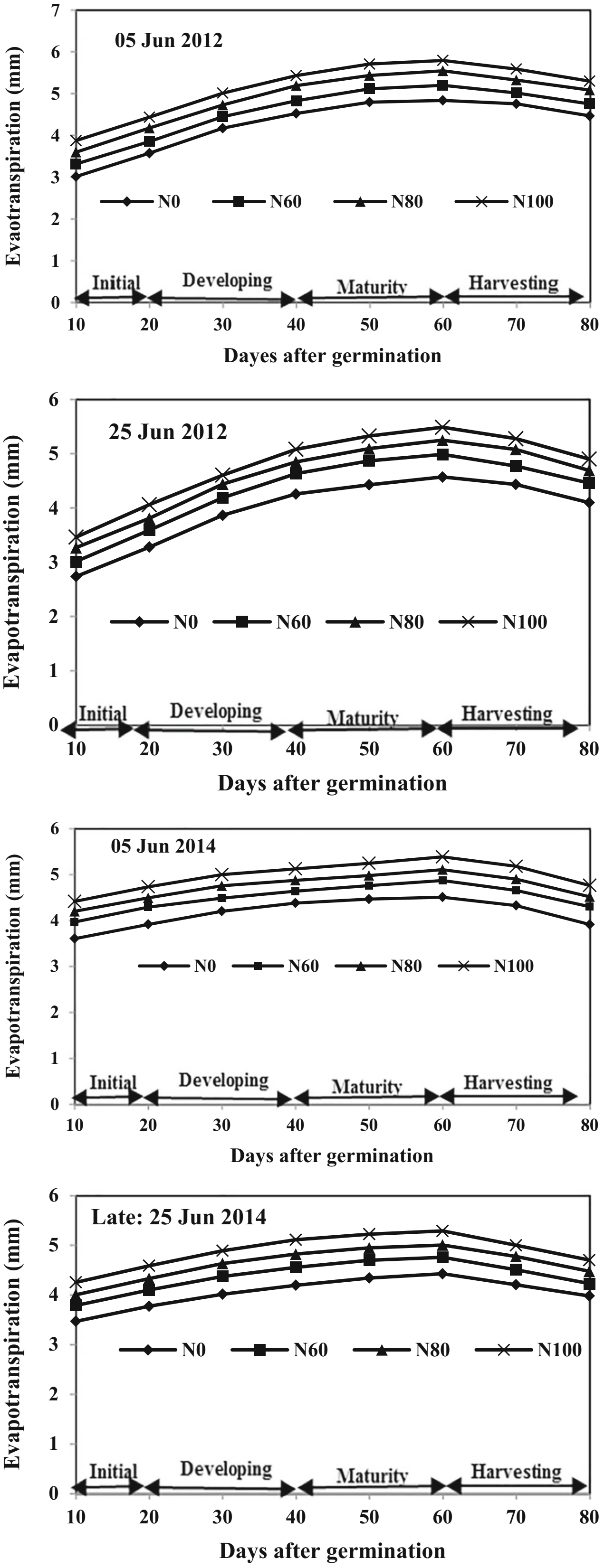


Fig 8. Effect of varying N levels of N_0, N_{60}, N_{80}, and N_{100} kg ha^{-1} on evapotranspiration (mm) under two sowing dates timely (10 June) of the years 2012 and 2014 and delayed (25 June) of the years 2012 and 2014 for rainfed maize

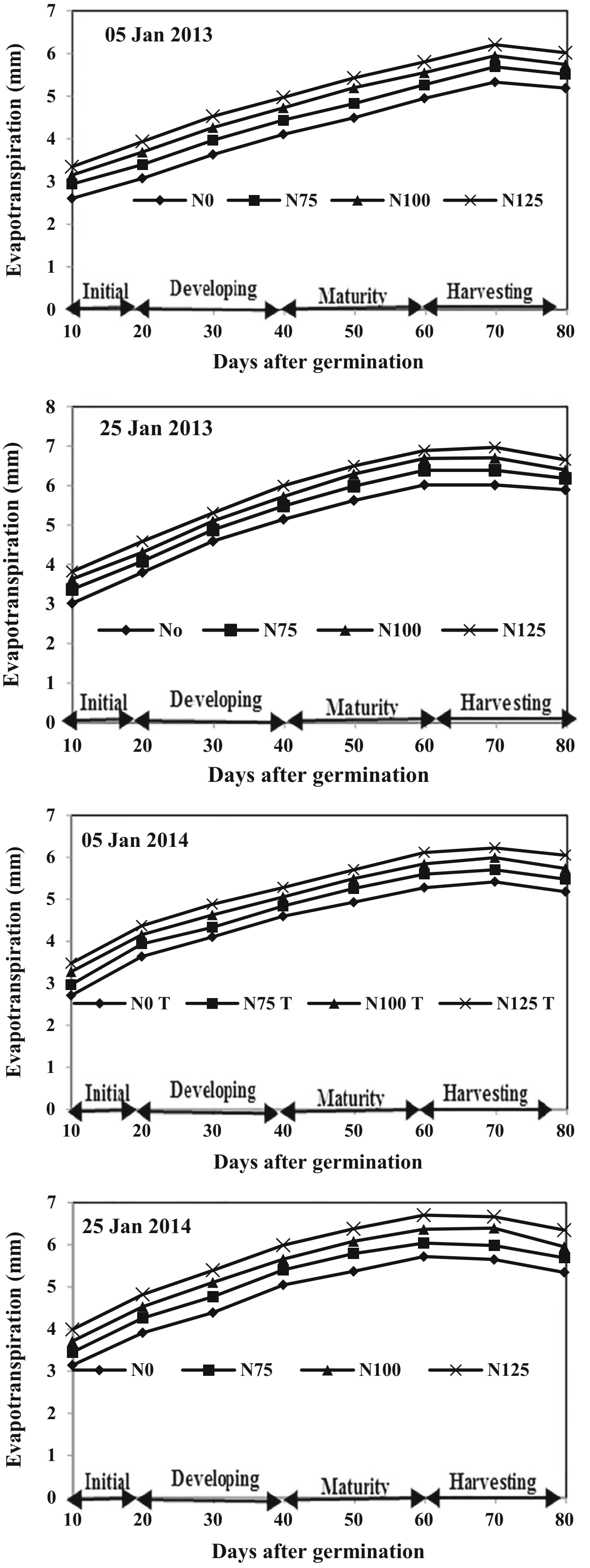


Fig. 9 Effect of varying N levels N_0, N_{75}, N_{100}, and N_{125} kg ha^{-1} and two sowing dates timely (5 January) of the years 2013 and 2014 and delayed (25 January) of the years 2013 and 2014 of irrigated maize irrigated maize

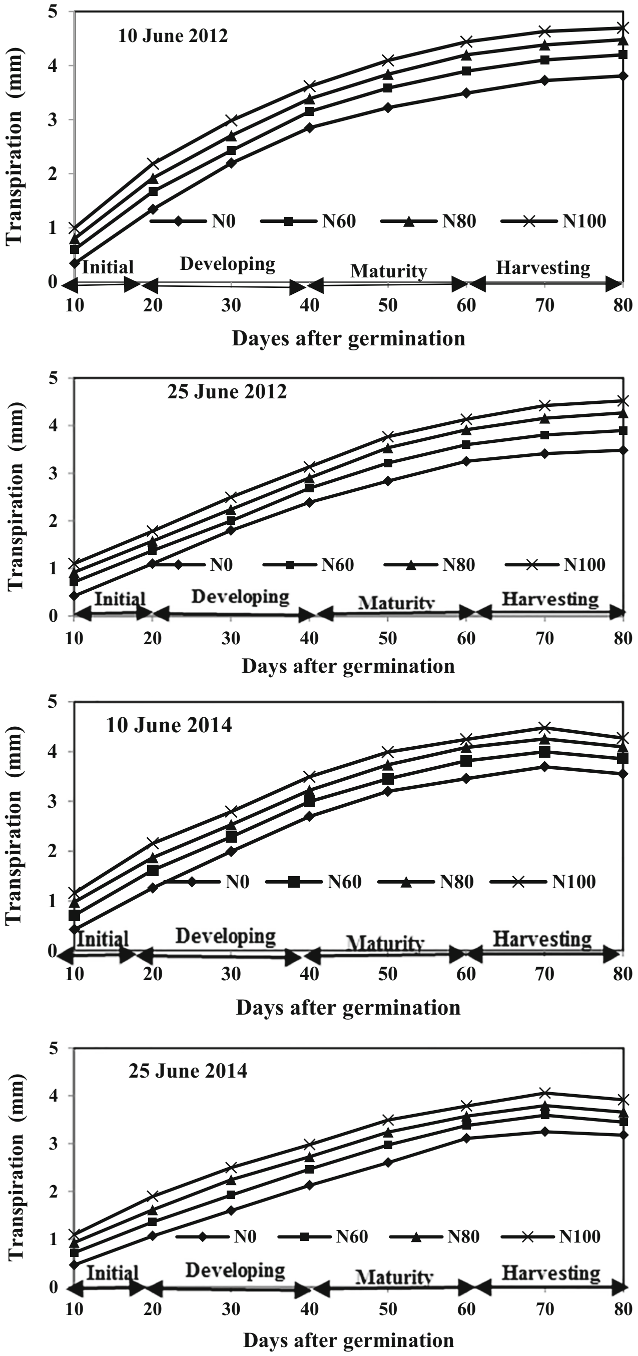


Fig. 10 Temporal variation in transpiration (mm) for varying N levels N_0, N_{60}, N_{80}, and N_{100} kg ha^{-1} with two sowing scenarios timely (10 June) of the years 2012 and 2014 and delayed (25 June) of the years 2012 and 2014 for rainfed maize

(Kato et al. 2004; Gardiol et al. 2003). The statistical evaluation between PM and SWB method also confirmed the model performance to be good (Fig. 7) which was found to be in accordance with a study reported by Gharsallah et al. (2013) (RMSE, MRE; 0.43 mm/day, 9.08%) for maize.

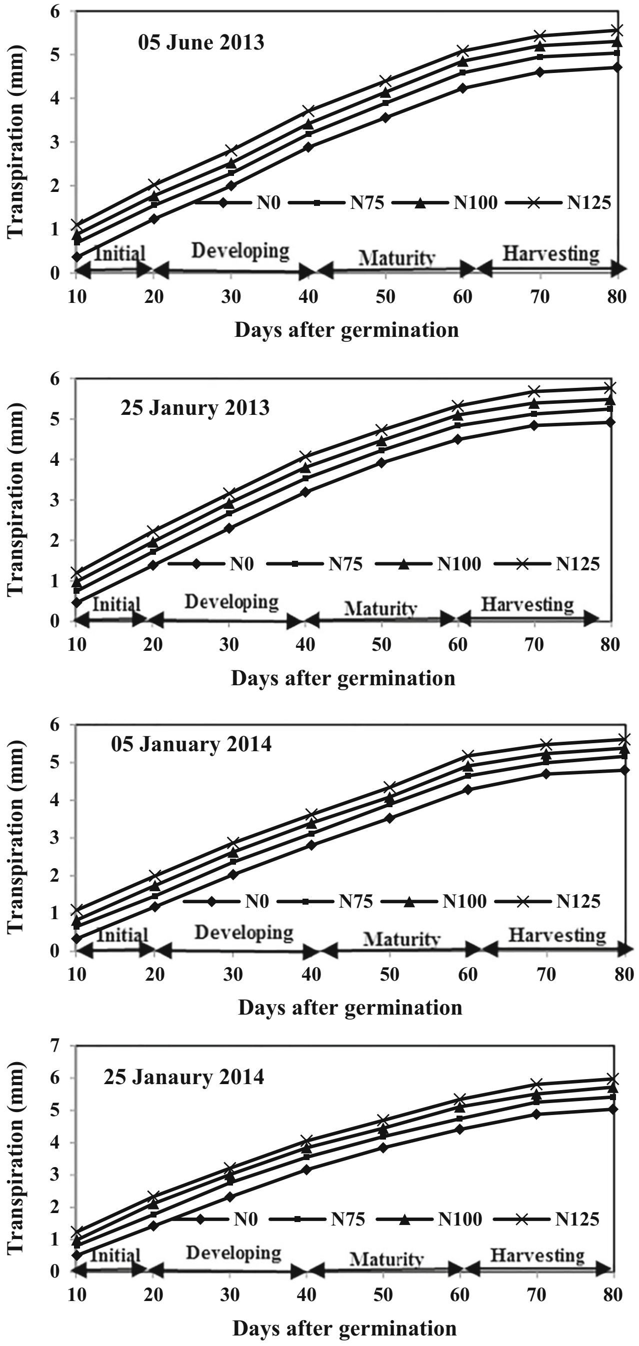


Fig. 11 Effect of sowing scenario on transpiration (mm) at varying N levels N_0, N_{75}, N_{100}, and N_{125} kg ha^{-1} with two sowing scenarios timely (5 January) of the years 2013 and 2014 and delayed (25 January) of the years 2013 and 2014 for irrigated maize

4.2 Portraying of E, T, and ET under varying N levels and sowing scenario

4.2.1 Response to N levels

In the reported study, results clearly indicate that the increase in N level enhances the ET (Figs. 8 and 9) and transpiration

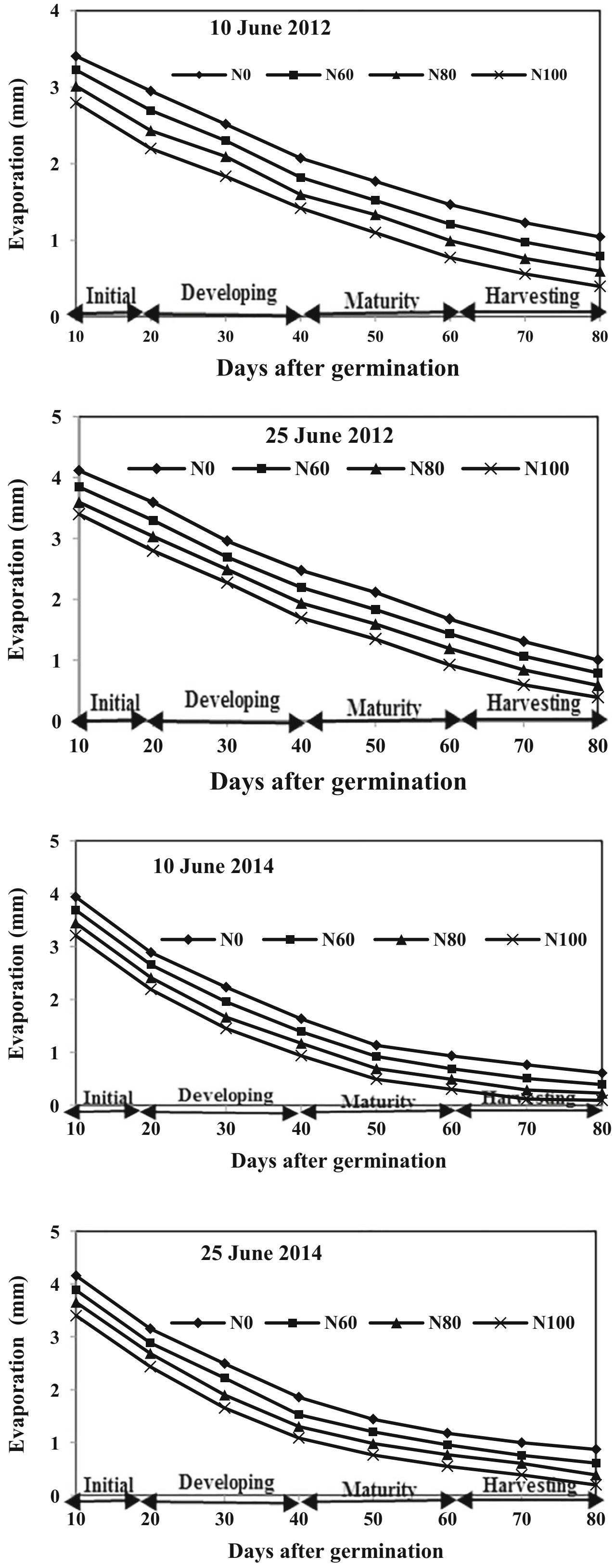


Fig. 12 Temporal variation in evaporation (mm) for varying N levels N_0, N_{60}, N_{80}, and N_{100} kg ha^{-1} with two sowing scenarios timely (10 June) and delayed (25 June) for rainfed maize

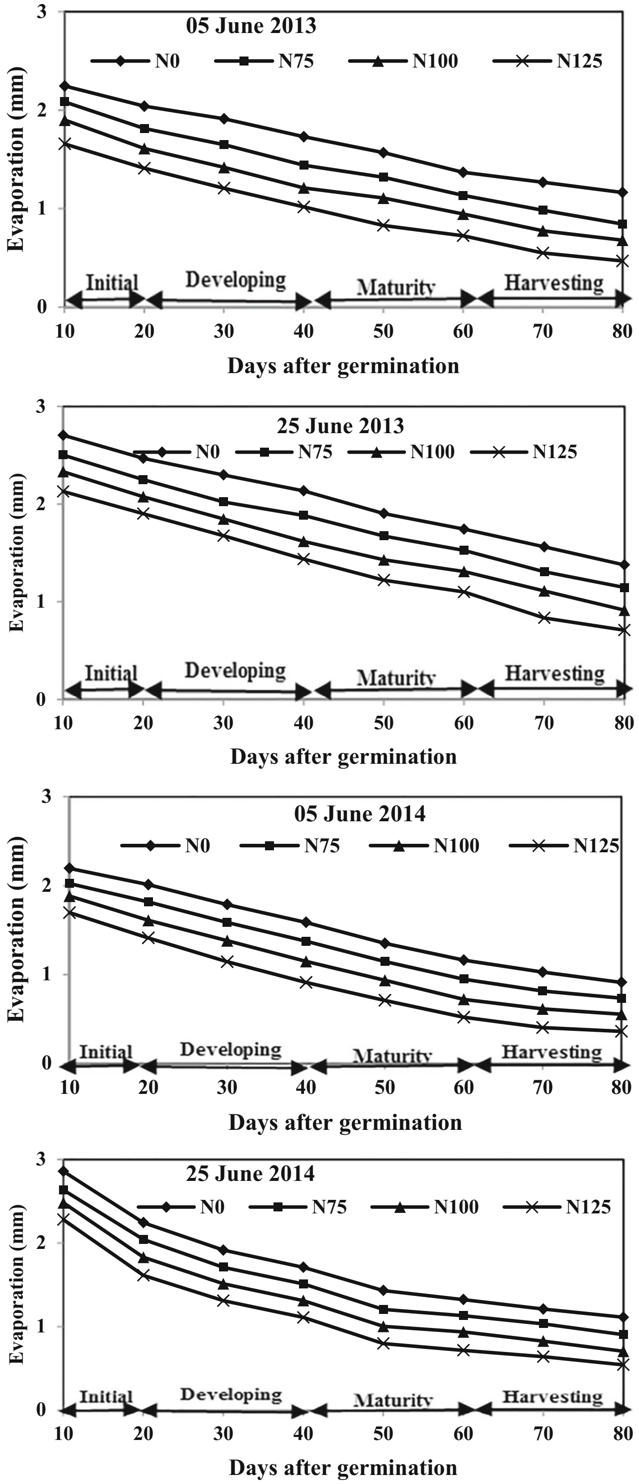


Fig. 13 Effect of sowing scenario on evaporation (mm) at varying N levels N_0, N_{75}, N_{100}, and N_{125} kg ha^{-1} of irrigated maize

(Figs. 10 and 11) while it reduces the evaporation (Figs. 12 and 13) for both rainfed and irrigated maize.

Evapotranspiration Increasing N level enhances the ET with increment in transpiration and reduction in evaporation

Table 3 WUE based on plant dry matter

Rainfed					Irrigated				
N management	2012		2014		N management	2013		2014	
	Normal	Delay	Normal	Delay		Normal	Delay	Normal	Delay
N_0 (kg ha^{-1})	14.89	11.39	15.7	12.11	N_0	29.77	22.39	29.15	22.42
N_{60} (kg ha^{-1})	27.03	21.68	27.18	21.36	N_{75}	46.5	36.95	46.19	37.52
N_{80} (kg ha^{-1})	33.84	28.12	34.15	27.95	N_{100}	55.05	46.36	59.13	50.49
N_{100} (kg ha^{-1})	38.6	35.62	39.99	37.5	N_{125}	64.09	55.69	67.45	58.69

(Tables 1 and 2, Figs. 8 and 9) due to increased leaf photosynthesis, higher leaf area index (Hernández et al. 2015), and higher leaf stomata conductance during the grain filling stage (Cavigila and Sadras 2001; Echarte et al. 2008). However, ET may increase with increase in the N level for both rainfed and irrigated maize, but this increase might not be sufficient in comparison with the increase in transpiration or reduction in evaporation.

Transpiration Increasing N level increased the plant dry matter (Srivastava et al. 2017) and leaf area (Muchow, 1988). Maximum changes in T were observed during the initial stage than the developing stage followed by maturing and harvesting stages in both rainfed and irrigated conditions (Tables 1 and 2, Figs. 10 and 11). Similar results were reported by Cavigila and Sadras (2001) and Yu et al. (2016). The comparative analysis of T between irrigated and rainfed maize showed a higher transpiration rate because of higher stomatal conductance in irrigated than rainfed maize (Zhang et al. 1998; Ogola et al. 2002).

Evaporation Evaporation was highest at the initial stage then was found to decrease during the developing, maturing, and harvesting stages for both rainfed (Fig. 12) and irrigated (Fig. 13) maize (Liu et al. 2002; Hernández et al. 2015). The maximum difference in E was found at the maturing stage when the LAI was at peak in both rainfed and irrigated maize (Tables 1 and 2). A decrease in evaporation was more in rainfed than irrigated conditions due to the increase in intercepted solar radiation, and wet soil (Liu et al. 2002; Teixeira et al. 2014).

4.2.2 Response to sowing dates

Evapotranspiration Delayed sowing dates gave on average a lower ET rate (9.27%) in rainfed and higher ET rate (14.56%) in the irrigated season in comparison with timely sowing dates (Tables 2 and 3). The fluctuations in total ET might be due to the cloud cover and solar radiation (Liu et al. 2002). Moreover, in the rainfed season cloudy condition is greater and radiation declines which thereby reduces the evaporation (Zhang et al. 1998). In contrast, for irrigated conditions, temperature and radiation are higher because of which transpiration is increased and evaporation is decreased due to the increased leaf area (Teixeira et al. 2014).

Transpiration Delay in sowing dates showed lower transpiration (6.45 %) in rainfed maize and higher (14.01%) in irrigated maize in comparison with timely sowing (Tables 1 and 2). The possible reason for the aforesaid is that during the irrigated season, the temperature and net radiation are higher (Figs. 1 and 2) which increases the photosynthesis and stomatal

Table 4 WUE based on maize yield

Rainfed						Irrigated			
N management	2012		2014		N management	2013		2014	
	Normal	Delay	Normal	Delay		Normal	Delay	Normal	Delay
N_0 (kg ha^{-1})	3.63	2.96	3.45	2.86	N_0	6.18	4.98	5.61	4.36
N_{60} (kg ha^{-1})	11.59	10.45	12.25	11.39	N_{75}	13.71	11.39	13.50	11.34
N_{80} (kg ha^{-1})	13.91	12.92	14.19	12.95	N_{100}	14.96	13.15	15.82	13.51
N_{100} (kg ha^{-1})	14.72	13.72	16.13	15.19	N_{125}	16.73	14.98	16.42	14.29

conductance (Echarte et al. 2008) and vice versa for the rainfed season.

Evaporation Delay in sowing dates caused on average a lower E rate (6.71%) in the rainfed season and higher E rate (10.71%) in the irrigated season in comparison with timely sowing date (Tables 1 and 2). Late sowing, high temperature, and solar radiation were some of the probable reasons for the aforesaid phenomenon leading to soil stress and increased leaf area index thereby covering more ground areas (Figs. 1, 2, and 5) which ultimately affected the soil evaporation (Humphreys et al. 2016; Hernández et al. 2015). Another cause for the variance in E was due to the canopy's sparse nature as more water would be lost from the soil surface due to the decreased LAI (Zhongmin et al. 2009).

4.3 Water use efficiency

4.3.1 Response to N levels

The plant dry matter and grain yield response to N level are well documented in the literature (Uhart and Andrade 1995; Wang et al. 2017). The plant dry matter response to N supply is associated with an increased leaf area (Wolfe et al. 1988; Echarte et al. 2008) and radiation use efficiency (Teixeira et al. 2014). Increase in N level enhances the WUE of biomass production as well as grain yield (Tables 3 and 4) in both rainfed and irrigated conditions (Ogola et al., 2002; Caviglia and Sadras, 2001) for maize crop. In contrast, Hernández et al. (2015) reported that N supply does not favor for the increase in WUE in water-limited environments while N supply for well-watered conditions significantly increased the seasonal (17–35%) ET. Similarly, Shangguan et al. (2000) investigated the effect of N on WUE for wheat under well-watered and drought conditions, and found higher WUE (62.2%) in well-watered plants and lower WUE (42.0%) in the drought condition. The WUE for grain yield is higher in rainfed in comparison with irrigated condition due to minimal effect of N on grain yield and dry matter because of the water stress condition caused by higher temperature during irrigated conditions (Teixeira et al. 2014).

4.3.2 Response to sowing dates

Delayed sowing dates reduce the WUE for both rainfed and irrigated conditions in comparison with timely sowing, although the reduction in irrigated conditions was a bit more than in rainfed conditions (Tables 3 and 4). Hence, under water-limited conditions (irrigated), the major key is to regulate the water deficit conditions in order to increase the WUE (Ogretir 1994; Lu et al. 2017). Adjustment of sowing dates affect the soil moisture content, which ultimately affects the grain yield and WUE of maize.

5 Conclusion

In this study, evapotranspiration, transpiration, and evaporation were estimated for rainfed and irrigated maize crops using the validated Penman–Monteith model with the soil water balance model. Higher N levels strengthen the evapotranspiration and transpiration rates while they pull off the evaporation rate. Canopy resistance based on climatic variables and leaf area index played a crucial role in estimating evapotranspiration partitioning into transpiration and evaporation. A close relationship of WUE with biomass production and grain yield augments the seasonal evapotranspiration with elevating N level. Sowing scenario analysis indicated that the delayed sowing dates showed less ET, T, and E in comparison with timely for rainfed maize, but in irrigated conditions, the scenario was reversed. Climatic variables such as temperature, solar radiation, and VPD governed the variance of ET, T, and E. The WUE reduction was higher in irrigated maize than in rainfed maize with delay in sowing dates. The study strongly affirms that enhanced ET, T, and E can be attained for both irrigated and rainfed maize if appropriate management strategies, in terms of combination of nitrogen fertilization level and sowing dates, are taken into consideration so that near potential maize grain yield is obtained.

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