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Research paper

Interactive effect of tillage, residue, nitrogen, and irrigation management on yield, radiation productivity and water productivity of winter wheat in semi-arid climate

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ABSTRACT

Water, nutrients, and energy are the three main inputs in agricultural production and recently there has been a drop in the factor productivity of these inputs because of their improper management and deterioration of soil health. To maximize agricultural productivity while lowering strain on natural resources, the best synergistic combinations of tillage, residue, nitrogen, and water management should be identified for improving resource use efficiency of wheat. Hence, an attempt has been made to evaluate the impact of contrasting tillage, crop residue mulch, nitrogen, and irrigation interaction on yield, radiation productivity (RP), and water productivity (WP) of wheat in a split-factorial design. Results showed that wheat yield was higher under no-tillage (4.8%) than that of conventional tillage. Crop residue mulch (CRM) and higher nitrogen application enhanced RP, WP, and yield of wheat; although RP increased with increase in nitrogen application up to 100% recommended dose of nitrogen (RDN). CRM significantly reduced the seasonal evapotranspiration (6.0–7.2%) as compared to residue removal treatment. Deficit irrigation enhanced the WP while it lowered the crop yield significantly. Therefore, wheat can be grown under no-tillage, CRM, 100% RDN with deficit irrigation to obtain higher WP but with full irrigation to obtain higher yield, and RP in the semiarid climate of India.

Key words: Conservation agriculture, radiation productivity, water productivity, wheat, deficit irrigation, crop residue

Wheat (*Triticum aestivum L.*) is the most important cereal crop in the world. It provides staple food to 40% of the world's population with more calories and 20% of daily dietary protein than any other cereal (LACC/IGW, 2018), contributing significantly to socio-economic growth and global food security (FAO, 2017). During 2020–21, wheat production in India reached 108.75 million tonnes with an average national productivity of 3424 kg ha^{-1} (ICAR Report, 2021). Water, nitrogen, and solar radiation are the three key inputs in wheat production and recently there has been a drop in the factor productivity of these inputs because of their improper management and deterioration of soil health. Wheat is primarily grown in India's semiarid and arid regions throughout the winter, which is typically dry. So it needs additional irrigation for maximum production. Due to heavy subsidies and lax regulations, irrigation, and freshwater resources are becoming increasingly scarce each year in India and many other regions of the world (Haddeland *et al.*, 2014). Given this situation, it may be anticipated that there will be less water resources available for irrigated agriculture in the near future and that there will be more rivalry for water in this area. To maximize agricultural productivity while lowering the strain on natural resources, a significant improvement in water productivity is necessary for this situation (Teixeira *et al.*, 2014). It is crucial

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to find strategies to improve wheat's water productivity because domestic and industrial sectors in India's arid and semi-arid regions compete fiercely for water (Kijne *et al*., 2003). Due to the depletion of land resources, loss of biodiversity, and inefficient use of inputs, traditional agricultural techniques involving indiscriminate tillage and uneven fertilizer and pesticide use have come under intense scrutiny. Contrary to traditional agriculture, conservation agriculture (CA), which involves less tillage, residue retention, and crop rotation, has positive effects on the environment as well as crop yield by saving water, energy and restoring soil degradation across diverse ecologies (Das *et al*., 2014; Jat *et al*., 2013). According to Das *et al*., (2018), conservation agriculture techniques could increase the yield and water productivity of the maize-wheat system in the Indo-Gangetic Plain. Apart from tillage and residue management, nitrogen is also a key factor which synergistically interact with water in influencing growth and yield of crops (Pradhan *et al.,* 2018).

Besides moisture, crop biomass production depends on the interception of photosynthetically active radiation (PAR) and the efficiency of conversion into dry matter, that is, radiation productivity (RP) (Yan *et al*., 2022). The amount of solar radiation in India's western and northwest parts, where there is the majority of wheat is grown, is incredibly variable and inconsistent during the winter (Pradhan *et al*., 2014). The leaf area index (LAI) and light extinction coefficient (k) are used to calculate the amount of light that a crop canopy intercepts (Hikosaka *et al*., 2016). Crop morphological characteristics or crop architecture, such as the spatial and temporal distribution of leaf area, affect the amount of light intercepted and the use of intercepted light for photosynthesis (Song *et al*., 2013).

Radiation productivity (RP) is primarily impacted by management elements including the application of water and nitrogen (Stöckle and Kemanian 2009). Water stress in the field can change a plant's leaf morphology, restrict photosynthetic activity, and alter stomatal conductance, which influences the performance of the entire plant, reducing crop production and grain quality, among many other factors (Fancelli and Dourado Neto, 1991). The management of nutrients also has an impact on RP (Plénet *et al.,* 2000) and nitrogen has the greatest impact of all the nutrients on RP (Muurinen and Peltonen-Sainio 2006). Lower specific leaf nitrogen content correlates with lower RP under lower nitrogen application conditions, and RP rises linearly with nitrogen application until the specific leaf nitrogen remains below saturating N content (Sinclair and Muchow 1999). Under different levels of management practices, water productivity can be interlinked with radiation productivity. For effective utilization of the available solar radiation and the limited water resources, it is, therefore, necessary in the north-west region of India to optimize both the WP and RP of the wheat. In light of this, the objective of this study was to examine the distribution of radiation interception and the effectiveness of radiation use and water use under contrasting tillage, residue, nitrogen and irrigation management practices.

MATERIALS AND METHODS

Study area

The field experiments were conducted in MB-4C experimental field of Division of Agricultural Physics, ICAR-IARI, New Delhi, situated at a latitude of 28°35' N and longitude of 77°12' E with an altitude of 228.6 meters above the MSL. The area is characterized by a semi-arid climate, with dry hot summer being intercepted by short but severe winter. The monthly average minimum temperature (ranging from 5.9°C to 19.9°C) occurs in January, while the maximum temperature (ranging from 24.4°C to 38.6°C) occurs in May. About 75% of annual precipitation (mean annual rainfall 651 mm) of the site occurs as a South-west monsoon in the months of July to September. The surface soil (0–15 cm) is sandy loam in texture, with an average bulk density of 1.58 Mg m^{-3}, pH of 7.8; organic C of 4.2 g kg^{-1}; available N, available (Olsen) P and available K content of 251, 7.1, and 281 kg ha^{-1}, respectively.

Experimental details

The field study was carried out with maize-wheat cropping system in a six-year-old continuing CA field experiment during the seasons of 2019-20 and 2020-21 with wheat as a test crop. The experiment was laid out in split-factorial design with three replications. The main plot factors comprise of two levels of tillage [conventional tillage (CT), and no-tillage (NT)] and two levels of crop residue mulching [crop residue mulch (R+) @ 5 Mg ha^{-1} and residue removal (R0)]. The sub-plot factors comprise of three levels of nitrogen application [50 (N50%), 100 (N100%), and 150% (N150%) of RDN] and two levels of irrigation [full irrigation (IF) and deficit irrigation (ID)].

Crop management

Wheat crop (cv. HD2967) was sown on the 21st and 26th of November in 2019 and 2020, respectively with a row spacing of 22.5 cm at a seed rate of 100 kg ha^{-1}. The crop was harvested in the second week of April. A fertilizer dose of 120 kg N + 60 kg P_2O_5 + 60 kg K_2O per hector was followed as a recommended dose (N100% treatment). A fertilizer dose of 60 and 180 kg of N/ha was applied for N50% and N150% treatment, respectively while other fertilizer doses (P_2O_5 and K_2O) are kept constant. The 50% of N along with the entire P_2O_5 and K_2O, were applied as the basal at the sowing time. The remaining N was applied at an equal split (i.e 25% each) at CRI and flowering stages, respectively. Under the full irrigation (IF) treatments, irrigation was applied at five critical growth stages of wheat (CRI, tillering, jointing, flowering, and milking) @ 6 cm per irrigation event. Under the deficit irrigation (ID) treatments, irrigation was applied only at the CRI, jointing, and flowering stages. The tillage was implemented with one ploughing with the help of disc harrow followed by a spring–tine cultivar in CT treatment whereas the crop was directly drilled using a ZT multi-crop planter in NT treatments. In the residue mulch treatment, the previous season maize residue was applied as a mulch @ 5 Mg ha^{-1} at CRI stage of wheat. In the NT plots, weeds were managed only by the application of herbicide like Atrazine @ 0.75 kg a.i. per hector + Pendimethalin @ 750 ml a.i. per hector. While, the field was kept weed free by spraying of herbicide as well as employing manual weeding 3–4 times during crop growth stages under CT plots.

Weather parameters

The weather parameters were collected from the agrometeorological observatory situated adjacent to the field. Different weather parameters like minimum (Tmin) and maximum (Tmax) temperatures, rainfall , morning (RHmax) and evening (RHmin) relative humidity, wind speed, bright sunshine hours (BSS), and pan evaporation were recorded on daily basis.

Grain and biomass yield

The crop was harvested at physiological maturity, in the second week of April. The data of grain and biomass yields were estimated from harvested net plots (after excluding the border rows from both directions). The grain and above ground biomass (AGB) yield were calculated and represented as kg ha^{-1} at 12% moisture content.

Fraction intercepted photosynthetically active radiation (fIPAR) and radiation productivity (RP)

The photosynthetically active radiation (PAR) measurements were taken using Line quantum sensor LI191SA (LICOR Inc., Lincoln, NE, USA) (between 11:30 and 12:00 hours IST) from the top and bottom of the wheat canopy. The fraction intercepted PAR (fIPAR) for a particular day is obtained from the following formula (Monteith, 1981):

$$\text{fIPAR} = (I_o - I_t)/I_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, 'I_o' is incident radiation and 'I_t' is transmitted radiation through the canopy.

Daily insolation was calculated using the Angstrom equation (using coefficients a=0.32, b=0.46), where bright sunshine hours observation was used as an input (Allen *et al*., 1998). Subsequently, incident PAR was calculated by multiplying a factor of 0.48 with the daily insolation values. Over the course of the crop season, linear interpolation was used to convert values for fIPAR for each day following sowing. Later, daily intercepted PAR (IPAR) was estimated by multiplying incident PAR with fIPAR. Similarly, total IPAR (TIPAR) was obtained by the integration of daily IPAR for the entire crop season.

The radiation productivity (RP) was calculated using the following formula

$$\text{RP} = \text{AGB}/\text{TIPAR} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, RP = radiation productivity (g MJ^{-1}), AGB = above ground biomass yield (g m^{-2}), TIPAR = total intercepted photosynthetically active radiation (MJ m^{-2})

Seasonal evapotranspiration (ET) and water productivity (WP)

Soil moisture content in 0–120 cm profile was determined gravimetrically at regular intervals during the crop growth period. Seasonal evapotranspiration (ET) was computed using the field water balance equation as given below:

$$\text{ET} = (P + I + C) - (R + D + \Delta S) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where 'P'is the precipitation, 'I' is the irrigation, 'C' is the capillary rise, 'R' is the runoff, 'D' is the deep percolation, and 'ΔS' is the change in profile soil moisture all expressed in mm. 'C' was considered to be negligible due to very low ground water table (8-10 m). Since the field plots were bunded to a sufficient height (40 cm height), there was no runoff (R) from them, and no instances of bund overflow were noticed throughout the study period. D was deemed insignificant above 120 cm because to the minimal changes in soil moisture storage. Thus, Eq. (3) simplifies to,

$$\text{ET} = (P + I) - (\Delta S) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Data on precipitation (P) was gathered at IARI's meteorological observatory, and irrigation volume (I) was gauged using a Parshall Flume. The difference between the soil moisture content measured gravimetrically at sowing and harvest was used to quantify changes in soil moisture content (S). Water productivity (WP) was calculated using the formula below.

$$\text{WP} = \text{AGB}/\text{ET} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, WP = Water productivity (kg m^{-3}), AGB = above ground biomass yield (kg ha^{-1}), ET = seasonal evapotranspiration (m^3 ha^{-1})

Statistical analysis

All the data were statistically analyzed using analysis of variance (ANOVA) as applicable to split factorial design (Bingham *et al*., 2004). The significance of the treatment effects was determined using F-test, and the difference between the means was estimated by using the Duncan's Multiple Range Test (DMRT) at 5% probability level.

RESULT AND DISCUSSION

Weather parameters

The monthly average of T_{max}, T_{min}, RH_{max}, RH_{min}, SSH, rainfall, and evaporation during the growth period of wheat for the year 2019–20 and 2020–21 are presented in Table 1. It was observed that during the year 2020–21, the crop experienced higher monthly average maximum temperature during the month of December, February, and March by 4.6, 3.5, and 5.2 °C, respectively as compared to the year of 2019–20. It coincides with the tillering, booting, flowering and grain filling stages. The crop growing season of 2019–20 (295.1 mm) received significantly higher rainfall compared to 65.9 mm of the season of 2020–21. The mean relative humidity for both the years was comparable except in March which was lower for the year of 2020–21 than that of 2019–20 by 11%. It could be attributed to the higher March rainfall in 2019–20. The higher average reference evaporation in February, March, and April in 2020–21 compared to the season of 2019–20 may be due to more solar energy being received during the same time period corresponding to the previous period. The heat stress during the reproductive stage of wheat and comparable lower rainfall during 2020–21 resulted in lower wheat yield as compared to 2019–20. Overall, the weather was more congenial for the wheat crop in 2019–2020 than it was for the crop in 2020–2021.

Table 1: Monthly weather data during the crop growing period of the study area

	Max. Temp (°C)		Min. Temp (°C)		Max. RH (%)		Min. RH (%)		Sunshine hours (h)		Rainfall (mm)		Evaporation (mm)	
Month	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
November	26.3	24.9	13.1	10.2	86.9	77.6	47.7	34.6	3.3	6.3	4.8	0.0	2.4	2.7
December	17.8	22.4	6.5	6.2	87.2	89.3	60.4	48.1	2.3	5.4	66.0	0.6	2.6	2.0
January	18.3	18.0	7.2	6.0	89.8	88.5	60.2	60.7	3.8	2.9	47.7	56.3	1.6	1.5
February	22.9	26.4	8.4	8.7	89.0	88.6	48.0	38.8	6.1	6.9	2.0	7.0	2.4	3.2
March	27.0	32.2	13.9	14.6	86.9	78.3	49.0	35.5	6.8	6.5	174.6	2.0	2.8	4.2
April	34.9	36.6	18.3	17.4	69.0	67.5	26.7	27.4	9.0	9.1	8.6	0.0	4.0	6.1

Table 2: Grain and biomass yield as influenced by tillage, residue, N, and irrigation management

Treatments	Grain yield (kg ha^{-1})		Biomass yield (kg ha^{-1})	
	2019–20	2020–21	2019–20	2020–21
Effect of tillage				
Conventional tillage (CT)	4759$^{b\#}$	3963^{b}	14048^{b}	12128^{b}
No-tillage (NT)	4987^{a}	4153^{a}	14593^{a}	12627^{a}
Effect of residue				
No residue (R0)	4683^{b}	3773^{b}	13803^{b}	11685^{b}
Crop residue (R+)	5063^{a}	4343^{a}	14838^{a}	13070^{a}
Effect of nitrogen				
N50%	4269^{c}	3486^{c}	12792^{c}	10970^{c}
N100%	4929^{b}	4216^{b}	14537^{b}	12777^{b}
N150%	5421^{a}	4473^{a}	15633^{a}	13386^{a}
Effect of irrigation				
Deficit irrigation (ID)	4675^{b}	3679^{b}	13802^{b}	11496^{b}
Full irrigation (IF)	5071^{a}	4438^{a}	14839^{a}	13259^{a}
Effect of Tillage × Residue × Nitrogen × Irrigation				
CTR0N50%ID	3776^{m}	3029^{k}	11559^{n}	9846^{j}
CTR0N50%IF	4087^{l}	3448^{ij}	12315^{lmn}	10848^{i}
CTR0N100%ID	4474^{jk}	3490^{hij}	13479^{ijk}	10954^{i}
CTR0N100%IF	4720^{ghij}	4122^{bcde}	14112^{hij}	12772^{df}
CTR0N150%ID	4866^{fgh}	3536^{ghij}	14318^{ghi}	11113^{hi}
CTR0N150%IF	5196de	4213^{bcd}	15061^{efg}	12930de
CTR+N50%ID	4242^{kl}	3576^{fghi}	12573^{lm}	11072^{i}
CTR+N50%IF	4579^{ij}	3775^{efghi}	13644^{ijk}	11739^{gh}
CTR+N100%ID	4819^{fghi}	3922^{cdef}	14082^{hij}	12016^{g}
CTR+N100%IF	5251^{d}	5140^{a}	15532^{cde}	14664^{ab}
CTR+N150%ID	5250^{d}	4016^{cde}	15337^{def}	12370^{efg}
CTR+N150%IF	5843^{a}	5291^{a}	16565^{ab}	15211^{a}
NTR0N50%ID	4075^{l}	3188^{jk}	12051^{mn}	10102^{j}
NTR0N50%IF	4287^{kl}	3480^{hij}	12887^{klm}	10962^{i}
NTR0N100%ID	4618^{hij}	3527^{ghij}	13452^{jk}	10992^{i}
NTR0N100%IF	5305^{cd}	4260^{bc}	15290^{def}	13111^{cd}
NTR0N150%ID	5079^{def}	3876^{defg}	14914^{efgh}	12112^{fg}
NTR0N150%IF	5710^{ab}	5105^{a}	16201^{abc}	14472^{b}
NTR+N50%ID	4439^{jk}	3536^{ghij}	13143^{kl}	11098^{hi}
NTR+N50%IF	4669^{ghij}	3852^{defgh}	14163^{hij}	12090^{fg}
NTR+N100%ID	4912^{efg}	3993^{cde}	14636^{fgh}	12660^{def}
NTR+N100%IF	5333^{cd}	5273^{a}	15709^{bcde}	15049^{ab}
NTR+N150%ID	5554^{bc}	4452^{b}	16081^{abcd}	13618^{c}
NTR+N150%IF	5868^{a}	5291^{a}	16584^{a}	15259^{a}

#Values in a column followed by same letters are not significantly different at $p<0.05$ as per DMRT

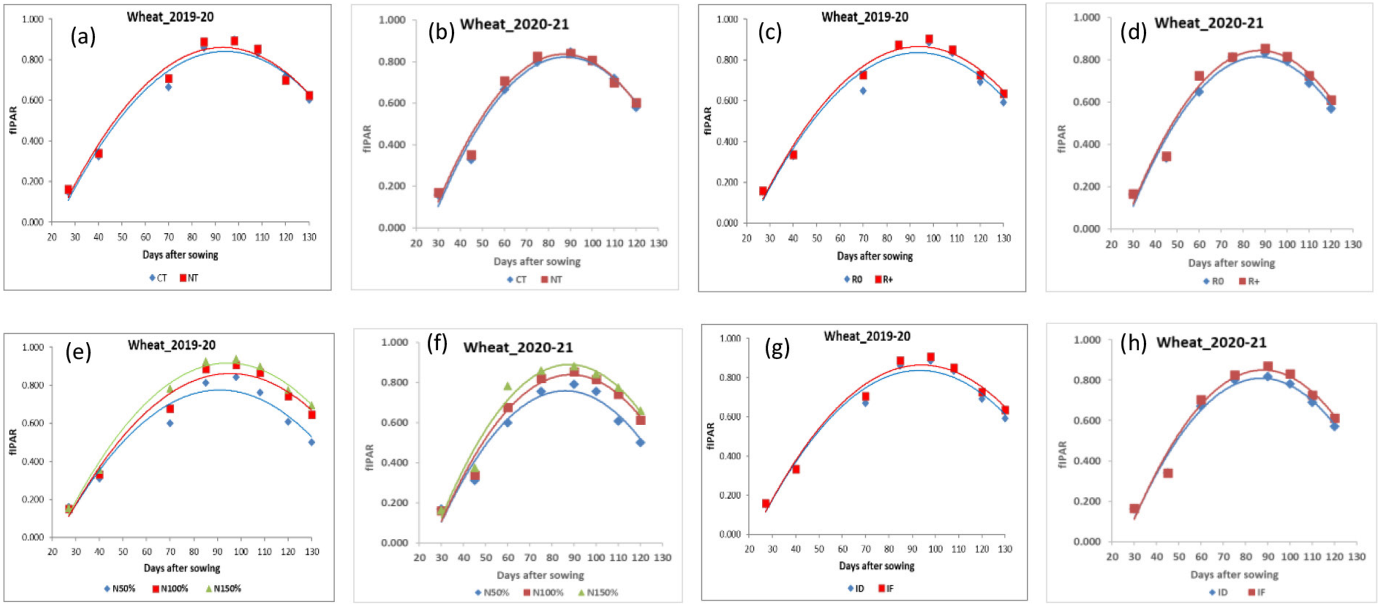

Fig. 1: Effect of tillage, residue, N, and irrigation management on fraction intercepted photosynthetically active radiation (fIPAR) of wheat during 2019–20 and 2020–21

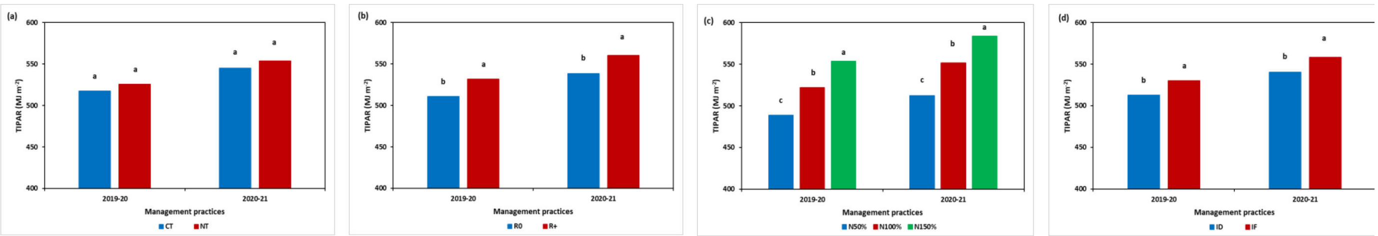

Fig. 2: Effect of tillage, residue, N, and irrigation management on total intercepted photosynthetically active radiation (TIPAR) of wheat during 2019–20 and 2020–21

Grain and biomass yield of wheat

The average grain and above ground biomass (AGB) yield in 2019–20 was higher than that of year 2020–21 (Table 2), which may be attributed to the higher and well distributed rainfall and lower maximum temperature during the growing season of 2019–20. The grain and AGB yield under NT were higher than that of CT by 4.8 and 3.9%, respectively in 2019–20 and by 4.8 and 4.1%, respectively in 2020–21. CRM improved the grain yield than that of no mulch treatment by 8.1 and 15.1% in 2019–20 and 2020–21, respectively. Similarly, there was 1.07- and 1.10-fold improvement in the AGB under R+ as compared to R0 in 2019–20 and 2020–21, respectively. The present findings of higher wheat yield under NT and residue retention could be due to the compound effects of additional nutrients (Kaschuk *et al*., 2010), improved soil physical health (Singh *et al*., 2016), better water regimes (Govaerts *et al*., 2009) and improved nutrient use efficiency compared to CT (Jat *et al*., 2013). N150% treatment registered 27.0 and 28.3% higher grain yield compared to N50% treatment during the years 2019–20 and 2020–21, respectively. Similarly, N100% treatment registered 15.5 and 21.0% higher grain yield compared to N50% treatment during the years 2019–20 and 2020–21, respectively. Similarly, the AGB increased with the increase in N applications. These results can be attributed to increased LAI, green spikes area, and crop duration with greenness, which resulted in the increased interception of radiation (Adak *et al*., 2021). In both the years of study, grain yield increased significantly with the increased level of irrigation. The higher yield with increasing levels of irrigation is attributed to better water and nutrient availability, which gave rise to better plant growth and yield. Similar results have been reported in wheat by many workers (Pradhan *et al*., 2014). The interaction effect of tillage, residue, N, and irrigation management was significant on the grain yield and AGB of both the years of study. The highest grain yield was observed in NTR+N150%IF (5868 kg ha^{-1} in 2019–20 and 5291 kg ha^{-1} in 2020–21) and lowest in CTR0N50%ID (3776 kg ha^{-1} in 2019–20 and 3029 kg ha^{-1} in 2020–21) treatment for both the year of study. Similar results were also found for the above ground biomass.

Fraction intercepted photosynthetically active radiation (fIPAR)

The temporal variation of fIPAR for both the years 2019–20 and 2020–21 followed a second order polynomial function (Fig. 1). Serrano *et al.,* (2000) have also observed similar kind of temporal variation in wheat. There was no significant impact of tillage on maximum fIPAR (Fig 1a, 1b). However, the maximum fIPAR under CRM treatments was 2.1 and 2.6 % higher than that of residue removal treatments in 2019–20 and 2020–21, respectively (Fig 1c, 1d). This showed that, the application of CRM could improve the radiation interception may be due to better leaf area

Table 3: Radiation productivity (RP) and water productivity (WP) as influenced by tillage, residue, N, and irrigation management

Treatments	Radiation productivity (g MJ^{-1})		Water productivity (kg m^{-3})	
	2019–20	2020–21	2019–20	2020–21
	Effect of tillage			
Conventional tillagein (CT)	$2.71^{a\#}$	2.22^{a}	4.39^{a}	4.10^{a}
No-tillage (NT)	2.77^{a}	2.27^{a}	4.51^{a}	4.09^{a}
	Effect of residue			
No residue (R0)	2.70^{b}	2.17^{b}	4.17^{b}	3.72^{b}
Crop residue (R+)	2.79^{a}	2.33^{a}	4.74^{a}	4.48^{a}
	Effect of nitrogen			
N50%	2.62^{b}	2.14^{b}	3.96^{c}	3.80^{c}
Nitrogen N100%	2.79^{a}	2.31^{a}	4.60^{b}	4.06^{b}
N150%	2.82^{a}	2.29^{a}	4.80^{a}	4.42^{a}
	Effect of irrigation			
Deficit irrigation (ID)	2.69^{b}	2.13^{b}	4.69^{a}	4.24^{a}
Full irrigation (IF)	2.80^{a}	2.37^{a}	4.22^{b}	3.95^{b}
	Effect of Tillage × Residue × Nitrogen × Irrigation			
CTR0N50%ID	2.48^{k}	2.02^{jk}	3.60^{gh}	3.65^{i}
CTR0N50%IF	2.55^{jk}	2.13^{ghij}	3.47^{h}	3.14^{k}
CTR0N100%ID	2.65^{ghij}	2.03^{jk}	4.61^{c}	3.57^{ij}
CTR0N100%IF	2.72^{cdefgh}	2.33^{cde}	3.86^{fg}	3.62^{i}
CTR0N150%ID	2.64^{ghijk}	1.94^{k}	4.64^{c}	4.19^{f}
CTR0N150%IF	2.70^{efghij}	2.20^{fgh}	3.92^{f}	3.73^{hi}
CTR+N50%ID	2.63^{ghijk}	2.20^{fgh}	4.66^{c}	4.49^{cd}
CTR+N50%IF	2.71^{defghi}	2.23^{efg}	4.05^{ef}	3.68^{hi}
CTR+N100%ID	2.71^{efghij}	2.18^{gh}	5.23^{a}	4.69^{bc}
CTR+N100%IF	2.90^{ab}	2.59^{a}	4.63^{c}	4.74^{b}
CTR+N150%ID	2.85^{abcde}	2.18^{gh}	5.10^{ab}	5.01^{a}
CTR+N150%IF	2.99^{a}	2.60^{a}	4.95^{b}	4.73^{b}
NTR0N50%ID	2.56^{ijk}	2.05^{ijk}	3.93^{f}	3.37^{j}
NTR0N50%IF	2.68^{fghij}	2.17^{ghi}	3.58^{h}	3.88^{gh}
NTR0N100%ID	2.78^{bcdefg}	2.13^{ghij}	4.50^{c}	3.56^{ij}
NTR0N100%IF	2.98^{a}	2.41^{bcd}	4.23^{de}	3.66^{i}
NTR0N150%ID	$2.77^{bcdefgh}$	2.13^{ghij}	5.10^{ab}	4.23^{ef}
NTR0N150%IF	2.88^{abc}	2.44^{bc}	4.57^{c}	3.97^{g}
NTR+N50%ID	2.61^{hijk}	2.10^{hij}	4.43^{cd}	4.60^{bcd}
NTR+N50%IF	2.73^{cdefgh}	2.22^{efg}	3.97^{ef}	3.60^{i}
NTR+N100%ID	2.72^{cdefgh}	2.23^{efg}	5.27^{a}	4.41^{de}
NTR+N100%IF	2.83^{abcdef}	2.57^{a}	4.47^{cd}	4.25^{ef}
NTR+N150%ID	2.87^{abcd}	2.31^{def}	5.17^{ab}	5.10^{a}
NTR+N150%IF	2.87^{abcd}	2.51^{ab}	4.95^{b}	4.40^{de}

#Values in a column followed by same letters are not significantly different at $p<0.05$ as per DMRT

production. This finding is in agreement with Bag *et al.,* (2020). The fIPAR increased significantly with the increase in nitrogen doses in both years (Fig 1e, 1f). This is attributed to better canopy development under the increased N doses. The lower fIPAR in N50% treatments compared to N150% and N100% treatments can be attributed to lower LAI in the former than the later. Bassu *et al.,* (2011) have also observed lower fIPAR in durum wheat due to lower LAI. The maximum fIPAR under IF treatments showed 2.6 and 6.3% increment as compared to ID treatments in 2019–20 and 2020–21, respectively (Fig 1g, 1h). Similar findings were also reported by Pradhan *et al.,* (2018).

Total intercepted photosynthetically active radiation (TIPAR)

The TIPAR was not statistically influenced by the tillage treatments in both the years (Fig. 2a). However, it was significantly affected by the CRM in both the years. TIPAR under CRM treatments was 4.1 and 4.0% higher than that of no mulch treatments in 2019–20 and 2020–21, respectively (Fig. 2b). Averaged over tillage, residue, and irrigation management, TIPAR in N150% treatment was higher than N100% and N50% treatments by 6.1 and 13.3%, respectively in 2019–20 and by 5.8 and 13.9%, respectively in 2020–21, while N100% treatment enhanced TIPAR than that of N50% by 6.8 and 7.7% in the year of 2019–20 and 2020–21, respectively (Fig. 2c).

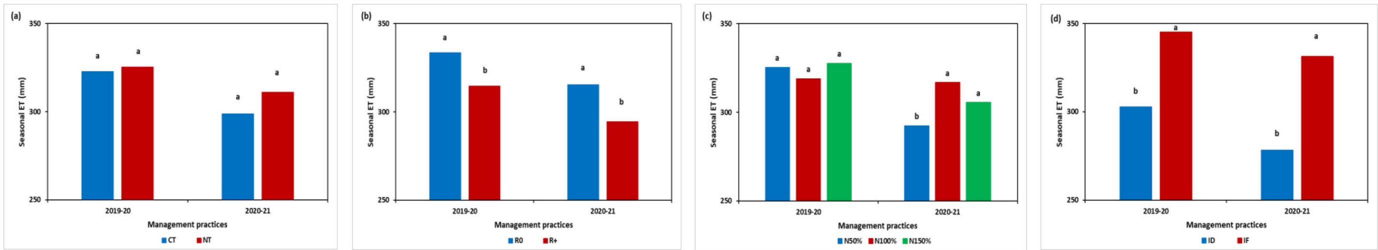

Fig. 3: Effect of tillage, residue, N, and irrigation management on seasonal evapotranspiration (ET) of wheat during 2019–20 and 2020–21

Similarly, averaged over tillage, residue, and N management, IF plots attained 3.39 and 3.37% higher TIPAR compared to ID plots in 2019–20 and 2020–21, respectively (Fig. 2d). The higher TIPAR at higher irrigation and nitrogen levels is attributed to higher LAI (Bandyopadhyay *et al*., 2021).

Radiation productivity (RP) of wheat

The radiation productivity (RP) of wheat varied between 2.48 (CTR0N50%ID) and 2.99 (CTR+N150%IF) g MJ^{-1} in 2019–20 with an average value of 2.74 g MJ^{-1} and 1.94 (CTR0N150%ID) and 2.60 (CTR+N150%IF) g MJ^{-1} with an average value of 2.25 g MJ^{-1} for the year 2020–21 (Table 3). Like TIPAR, RP was not significantly affected by different tillage practices. Though, there was 3.2 and 7.4% improvement in the RP under CRM treatments as compared to no mulch in 2019–20 and 2020–21, respectively (Table 3). Averaged over tillage, residue, and irrigation managements, N150% and N100% treatments showed comparable RP in both the years. However, application of N150% and N100% treatments enhanced the RP than that of N50% plots by 7.8 and 6.4%, respectively in 2019–20 and by 7.0 and 8.0%, respectively in 2020–21 (Table 3). Higher RP at higher N-doses may be attributed to higher leaf area duration (LAD) at higher N-levels (Pradhan *et al.,* 2014). Application of full irrigation also significantly enhanced the RP compared to deficit irrigation by 4.0 and 11.4% in the year of 2019–20 and 2020–21, respectively (Table 3). Pandey *et al.,* (2004) also observed higher RP of wheat under higher moisture regimes compared to moisture stress conditions. This may be due to higher biomass production and higher radiation interception at higher irrigation levels.

Seasonal evapotranspiration (ET) and Water productivity (WP) of wheat

Result showed higher seasonal ET in the year 2019–20 (324 mm) as compared to the year 2020–21 (305 mm) due to higher rainfall received during the year 2019–20. The effect of tillage practices was not significant on the seasonal ET (Fig. 3a). However, plots under CRM reduced the seasonal ET by 6.0 and 7.2% than that of no mulch treatments in 2019–20 and 2020–21, respectively (Fig. 3b). The retention of residue at the soil surface helped in reducing evaporation losses and hence conserved soil moisture. This finding is also in agreement with Parihar *et al.,* (2017). The seasonal ET of wheat increased with the increase in the irrigation levels by 14.0 and 19.1% in 2019–20 and 2020–21, respectively (Fig. 3d). However, we have not found any significant effect of N management on seasonal ET (Fig. 3c).

The effect of tillage, residue, N, and water management and their interaction on the water productivity is presented in the Table 3. NTR+N100%ID and NTR+N150%ID treatments were found to register the highest WP during 2019–20 and 2020–21, respectively whereas CTR0N50%IF registered lowest WP during both the years. The tillage treatments were statistically similar with respect to WP of wheat. However, WP under CRM treatment was 13.7 and 20. 5% higher than that of no mulch treatment in 2019–20 and 2020–21, respectively. The retention of residue at the soil surface in ZT system helped in reducing evaporation losses and hence conserving soil moisture. Conserved soil moisture in the seed-zone not only provided better crop establishment and crop growth but also increased WP. Further, this increased moisture in seed-zone led to crop yield enhancement with lesser water consumption. The significantly higher ($P < 0.05$) WP under CA practices compared to CT was also due to lesser water use (by 6.0–7.2%) in CA plots compared to CT plots. The higher water productivity under CA compared to CT in the same ecology has been reported by other researchers (Jat *et al*., 2013; Das *et al*., 2014). Averaged over tillage, residue and water management, WP in N150% treatment was higher than N100% and N50% treatments by 21.2 and 4.4%, respectively in 2019–20 and by 16.3 and 8.9%, respectively in 2020–21 (Table 3). Whereas N100% treatment enhanced WP than that of N50% treatment by 16.1 and 6.8% in the year of 2019–20 and 2020–21, respectively (Table 3). It might be ascribed to improved crop development, which would result in higher production of root biomass and more biomass returning from leftover surface plant residues. The higher water productivity at higher nitrogen doses was also due to higher grain yield of crops with similar water use at higher nitrogen doses or synergistic interaction between water and nitrogen management (Adak *et al.*, 2019; Pradhan *et al*., 2014). WP of wheat decreased with the increase in the irrigation level by 11.0 and 7.3% in 2019–20 and 2020–21, respectively (Table 3). This may be attributed to loss of water at higher irrigation levels. Also, the yield increase with the increase in the irrigation level was not in the same proportion as the increase in ET at higher level of irrigation, which resulted in decrease of WP at higher irrigation levels. This finding is in agreement with Pradhan *et al.,* (2014). It was observed that RP was significantly and positively correlated with the WP of wheat ($r=0.48^*$). This finding is in agreement with Bandyopadhyay *et al.,* (2021). The regression equation ($RP = 0.2486WP+1.4315$) showed that per unit increase in the WP, the RP increased by 0.25 time

CONCLUSIONS

Thus, from this study it may be concluded that grain yield of wheat increased significantly under NT and crop residue mulching. So, this practice may be recommended in the IGP region for saving of energy and also improving soil health. Crop residue mulching significantly improved the water productivity and radiation productivity. With the increase in N and irrigation level the grain yield and RP increased significantly; although the RP increased up to 100% RDN. WP increased with the increase in the N level while decreased at higher irrigation level. The WP under deficit irrigation was improved at a cost of lower grain yield and RP. Therefore, wheat should be grown under NT, crop residue mulch, 100% RDN and with full irrigation to obtain higher yield and radiation productivity without much loss in WP in semiarid climate of India.

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