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**Research Paper**

# Yield, water, radiation and nitrogen use efficiencies of wheat (*Triticum aestivum*) as influenced by nitrogen levels in a semi-arid environment

S. PRADHAN[1], V.K. SEHGAL[2], R.N. SAHOO[3], K.K. BANDYOPADHYAY[4] AND RAVENDER SINGH[5]

*Indian Agricultural Research Institute, New Delhi 110 012*

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## ABSTRACT

A field experiment was conducted during the winter (*rabi*) season of 2009–10 and 2010–11 on a sandy-loam soil in New Delhi, to study the effect of nitrogen levels on the water, radiation and nitrogen-use efficiencies of wheat [*Triticum aestivum* (L.) emend. Fiori. & Paol.] cultivars. The treatments comprising 2 wheat cultivars ('PBW 502' and 'DBW 17') and 3 nitrogen levels ($N_0$: 0kg N/ha, $N_{60}$: 60 kg N/ha and $N_{120}$: 120 kg N/ha) were laid out in factorial randomized block design (RBD). Both cultivars were statistically at par for grain yield, above-ground biomass yield, water-use efficiency (WUE) and radiation-use efficiency (RUE). Treatments $N_{120}$ registered 71% and 25% higher grain yield than $N_0$ and $N_{60}$ treatments respectively. Water-use efficiency (WUE) of $N_{120}$ (9.92 kg/ha/mm) was significantly highest, followed by $N_{60}$ (8.40 kg/ha/mm) and $N_0$ (6.56 kg/ha/mm) treatments. Similarly, radiation-use efficiency (RUE) of $N_{120}$ (2.49 gm/MJ) was significantly higher than $N_{60}$ (1.90 gm/MJ) and $N_0$ (1.85 gm/MJ) treatments. The partial factor productivity of nitrogen (PFPN) of the cultivar 'PBW 502' (48.96 kg grain/kg nitrogen applied) was significantly higher than that of 'DBW 17' (42.23 kg grain/kg nitrogen applied). Nitrogen @ 60 kg/ha ($N_{60}$) showed significantly higher PFPN (56.08 kg grain/kg nitrogen applied) than $N_{120}$ (35.10 kg grain/kg nitrogen applied) treatment. Therefore, cultivar 'PBW 502' or cultivar 'DBW 17' can be grown with 120 kg N/ha for obtaining higher grain yield, above ground biomass, WUE and RUE in the semi-arid tropical environment of Delhi region.

***Key words :*** Crop production, Nitrogen, Nitrogen-use efficiency, Radiation-use efficiency, Wheat, Water-use efficiency

Wheat is the second most important cereal crop in India after rice, covering an area of 29 million ha with a production of 87 million tonnes (http://eands.dacnet.nic.in/). Water and fertilizer (nutrients) are the two most important inputs, which have maximum contribution to wheat crop productivity (Lenka *et al*., 2009) more specifically in the arid and semi-arid tracts of India, where wheat is mostly grown as a *rabi* (dry) season crop. Among the several nutrients, nitrogen is the most important nutrient responsible to a great extent for the higher yields of intensive agriculture. Application of nitrogen enhances not only biomass production but also yield and yield components (Latiri-Souki *et al*., 1998). Nitrogen affects production through a number of mechanisms, viz. at cellular level, N increases the cell number and cell volume, whereas at the leaf level it increases the photosynthetic rate and efficiency (Lawlor *et al*., 1988). Fertilizer N also increases proteins, the plant's metabolic component, as shown by increased nitrogen percentage in the plant tissues at higher N supply (Greenwood *et al*., 1991). Increased crop growth due to nitrogen fertilization is attributed to increased leaf-area index (LAI) and radiation interception (Caviglia and Sadras, 2001).

Now-a-days, high cost and limited availability of nitrogenous fertilizers is great concern, and it is strongly felt that this element must be used efficiently. Efficiency is the ratio of output : input and in agriculture, efficiency need not be dimensionless and less than one (Monteith, 1984). The water-use efficiency (WUE, the ratio of dry matter produced to water consumed), essential for planning cropping strategies and irrigation schedules in arid and semi-arid regions and the identification of water stress-tolerant plant traits (Caviglia and Sadras, 2001), is known to decrease due to nitrogen deficiency (Nielson and Halvorson, 1991). Similarly, radiation-use efficiency (RUE, dry matter produced/unit of either incident radiation or intercepted radiation), the major component of crop-growth analysis is also known to decrease with nitrogen deficiency through

[1]**Corresponding author Email:** sanatan28@gmail.com
[1]Scientist; [2,3]Senior scientist; [4]Prncipal Scientist; [5]Head, Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi 110 012

decreased light interception (Monteith, 1984). However, the nitrogen-use efficiency (grain yield per unit of fertilizer applied), used as conceptual tool in agronomy and ecology (Hirose and Bazzaz, 1998), decreases at higher level of nitrogen application (Bandyopadhyay *et al*., 2009; Pradhan *et al*., 2013) due to losses of N at higher N levels. There is a need to improve the water, nitrogen and radiation-use efficiency in agriculture to make it economically viable and environmentally sustainable. However, there is very limited study, which addresses all these three efficiencies. Therefore, present study was undertaken to study the effect of nitrogen levels on water, radiation and nitrogen-use efficiencies of wheat cultivars.

## MATERIALS AND METHODS

The field experiments was conducted during *rabi* (winter) 2009–11 at the Research Farm of the Indian Agricultural Research Institute, New Delhi, India (77°89'N, 28°37'E, 228.7 m above-sea level) with wheat as a test crop. The climate is semi-arid with warm summer and mild winter. Summers are long (April–August) with the monsoon setting in between July and September. The soil was sandy loam (Typic Haplustept) with medium to angular blocky structure, non-calcareous and slightly alkaline. The soil was low in organic carbon and available nitrogen and medium in available P and K content. The bulk density varied from 1.51 $Mg/m^3$ to 1.62 $Mg/m^3$ in the 0–1.20 m layer. The soil moisture content was 26–29% at 0.33 MPa (field capacity) and 8–11% at 1.5 MPa (permanent wilting point) in different layers of 0 to 1.20 m soil depth.

The field experiment was laid out in a factorial randomized block design (RBD) with 6 treatments and 3 replications during 2009–10 and 2010–11. The factors included two wheat cultivars ($V_1$, 'PBW 502' and $V_2$, 'DBW 17') and three nitrogen levels ($N_0$, 0 kg N/ha, $N_{60}$, 60 kg N/ha and $N_{120}$, 120 kg N/ha). The plot size was 5m × 5m. Wheat crop was sown in the third week of November and harvested in the second week of April in both the years of study. Wheat was sown at the seed rate of 100 kg/ha using tractor-drawn seed-drill with a row spacing of 22.5 cm. Nitrogen in the form of urea was applied in three splits– 50% during sowing, 25% during crown-root-initiation stage and 25% during flowering stage. All the treatments received the recommended dose of phosphorus (60 kg $P_2O_5$/ha as single superphosphate) and potassium (60 kg $K_2O$/ha as muriate of potash). The plots were kept weed free by hand-weeding (2 times). Crops were also kept free from insect and pest attack by taking appropriate control measures. In all the treatments, irrigations were applied at critical crop-growth stages (crown-root initiation, tillering, booting, flowering and grain formation) in measured amount using Parshall flume. Soil-moisture content in the profile (0–120 cm) was determined gravimetrically at regular intervals during the crop-growth period to study the distribution and redistribution of the soil water in the profile.

Seasonal evapo-transpiration (ET) was computed using the field water balance equation as given below:

$$ET = (P + I + C) - (R + D + S) \quad .. (1)$$

Where, ET is the seasonal evapo-transpiration (mm), P is the precipitation (mm), I is the irrigation (mm), C is the capillary rise (mm), R is the runoff (mm), D is the deep percolation (mm) and S is change in profile soil moisture (mm).

The groundwater table depth was very low (8–10 m) therefore, C was assumed negligible. There was no runoff (R) from the field plots, as they were bunded to a sufficient height (40 cm height)

and also no case of bund overflow was observed during the period of study. D was considered negligible beyond 120 cm because of negligible changes in the soil-moisture storage.

Thus Eq. (1) boils down to,

$$ET = (P + I) - (\Delta S) \quad .. (2)$$

Precipitation data (P) were collected from the meteorological observatory of the IARI, which is located about 50 m distance from the experimental plot. Irrigation amount (I) was measured by Parshall Flume. Changes in soil-moisture content (S) were calculated by the difference in the soil-moisture content measured gravimetrically at sowing and harvest.

Evapo-transpiration production function (ETPF), the relation between wheat grain yield or above-ground biomass yield and seasonal evapo-transpiration was derived as:

$$Y = a + (b \times ET) \quad .. (3)$$

where a is intercept and b is the slope of the ETPF.

Water-use efficiency based on above-ground biomass (WUEagb) was estimated as:

$$WUEagb = \frac{agb}{ET} \quad .. (4)$$

where agb is above-ground biomass (kg/ha) and ET is seasonal evapo-transpiration (mm).

Water-use efficiency based on grain yield (WUEgy) was estimated:

$$WUEgy = \frac{gy}{ET} \quad .. (5)$$

where gy is grain yield (kg/ha).

WUE will increase with ET if a < 0 and decrease with increasing ET if a > 0 (Liu *et al*., 2002).

The net plot (5m × 5m) was harvested manually by cutting the plants close to ground after leaving the border rows. The plant samples were dried and weighed for above-ground biomass yield and expressed in kg/ha. Threshing of wheat was done by mechanical thresher and the grain yield was expressed in kg/ha.

Both incoming and outgoing photosynthetically active radiation (PAR) values were measured periodically at the top and bottom of the mustard canopy on clear days between 11.00 and 12.00 hr IST throughout the crop season using line quantum sensor LI-191SA (LICOR Inc., Lincoln, NE, USA). The intercepted photosynthetically active radiation (IPAR) for a particular day was computed as the difference between PAR at the top and bottom of canopy. The fraction intercepted photosynthetically active radiation (fIPAR) for a particular day was computed as the ratio between IPAR and total incident PAR for that particular day (Jha *et al*., 2012). Values for fIPAR for each day after sowing were interpolated between actual measurements by linear interpolation throughout the crop season. Daily incoming solar radiation was calculated as per Allen *et al.* (1998). The daily incoming solar radiation was multiplied by a factor 0.48 (Jha *et al.,* 2012) to compute incident PAR. Then the daily incident PAR values were multiplied by corresponding daily fIPAR values to compute daily intercepted PAR (IPAR). The daily IPAR was integrated for the whole crop season to get total seasonal IPAR. The radiation-use efficiency (RUE) was calculated by dividing total above-ground biomass ($g/m^2$) with the total IPAR (TIPAR, $MJ/m^2$) for the whole crop duration (Saha *et al*., 2012).

The partial factor productivity of applied nitrogen (PFPN, kg grain/kg N applied) was determined using Eq. 6:

$$PFPN = \frac{Y_N}{F_N} \quad .. (6)$$

where $Y_N$ is grain yield of N-fertilized plot (kg/ha) and $F_N$ is amount of fertilizer N (kg/ha applied).

Normalized difference vegetation index (NDVI) was calculated as follows (Raun *et al.,* 2001):

$$NDVI = \frac{(R_{780} - R_{670})}{(R_{780} + R_{670})} \quad .. (7)$$

where R and the subscript numbers indicate the light reflectance at the specific wavelength (in nm). The reflectance at different wavelengths (350 to 2,500 nm) were measured by hand held ASD FieldSpec Spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO, USA). NDVI is a function of canopy photosynthetic area and is linearly related to leaf-area index (LAI).

The data were statistically analysed using analysis of variance (ANOVA) as applicable to randomized block (RBD) design (Gomez and Gomez, 1984). The significance of the treatment effects was determined using F-test, and the difference between the means was estimated using least significance difference and Duncan's multiple range tests at 5% probability level. Regression analyses were determined using the data analysis tool pack of MS excel.

## RESULTS AND DISCUSSION

### *Weather*

Mean monthly air temperature, pan evaporation, relative humidity, sunshine hours and total rainfall during the period of study (2009–10 and 2010–11) are presented in Table 1. Mean monthly temperatures were similar in both the years except in March and April. The monthly mean temperatures were higher (>3°C) in March and April during 2009–10 resulting in higher atmospheric evaporative demand of 6.5 mm/day in 2009-10 compared to 4.4 mm/day in 2010-11 March and 9.5 mm/day during 2009–10 compared to 6.3 mm/day in 2010–11 in April. The higher temperature encountered during March and April of 2009–10 coincided with the reproductive period of wheat-crop growth. Rainfall during crop-growing season during 2010–11 (65.7 mm) was significantly higher than 2009–10 (29.4 mm). There was a good amount of rainfall in February of the year 2010–11, which coincided with the booting, flowering and milking stage of wheat crop. The average humidity was similar for both the years and the sky was cloud free in most of the time during crop growth period.

### *Soil-moisture dynamics*

Soil-moisture storage of wheat crop was measured to a soil depth of 120 cm at regular intervals by thermo-gravimetric method for both the years of study (Fig. 1), only nitrogen effects are shown as cultivar effect on soil-moisture storage was not significant. The peaks in the soil moisture of the profile (0-120cm) corresponds to either irrigation or rainfall events. For the year 2009–10, the soil moisture storage in all the treatments remained well within the FC and PWP (the classical lower and upper limit suction for plant available water throughout the crop-growth period). However, in 2010–11, towards the harvesting stage, the soil moisture-storage under $N_{60}$ (106 mm) and $N_{120}$ (74 mm) treatments was below the PWP. At early crop-growth period (up to 50 days after sowing for both the years of study) showed lower soil moisture storage under $N_0$ treatment compared to $N_{60}$ and $N_{120}$ treatments. Poor canopy coverage as indicated by lower NDVI values (Fig. 2) under $N_0$ treatment exposed the soil for evapora-

**Table 1.** Weather conditions during the period of study.

| Months | Mean Temperature (°C) | Rainfall (mm) | Panevaporation (mm/day) | Mean relative humidity (%) | Sunshine hours (h) |
|---|---|---|---|---|---|
| | | | 2009–2010 | | |
| November | 19.3 | 14.2 | 2.8 | 70.3 | 5.1 |
| December | 14.6 | 1.0 | 2.0 | 67.1 | 4.3 |
| January | 12.3 | 0.0 | 1.6 | 78.0 | 2.5 |
| February | 17.0 | 13.0 | 2.7 | 66.1 | 6.1 |
| March | 24.4 | 0.0 | 6.5 | 55.0 | 8.5 |
| April | 31.1 | 1.2 | 9.5 | 39.0 | 8.4 |
| | | | 2010–2011 | | |
| November | 21.1 | 10.6 | 3.4 | 70.5 | 3.3 |
| December | 13.6 | 0.7 | 2.2 | 67.3 | 3.0 |
| January | 11.7 | 0.0 | 2.8 | 67.0 | 3.8 |
| February | 16.3 | 49.9 | 2.9 | 69.7 | 5.4 |
| March | 21.1 | 2.3 | 4.4 | 62.0 | 9.6 |
| April | 26.4 | 2.2 | 6.3 | 45.0 | 7.9 |

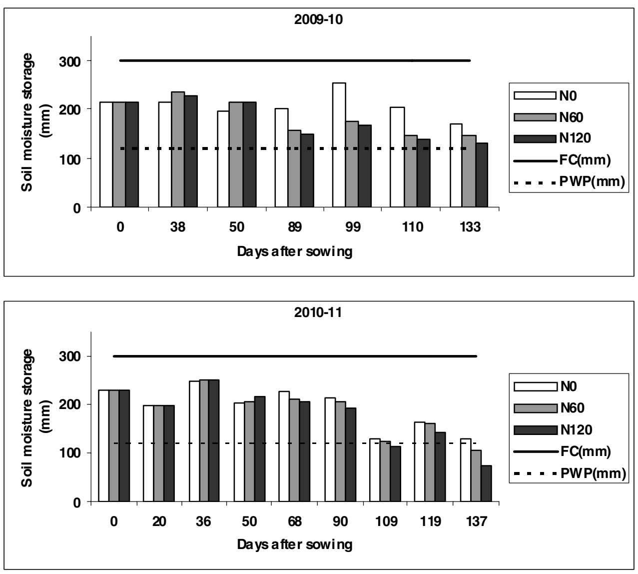


**Fig. 1.** Temporal variation of soil-moisture storage under nitrogen treatments for the year 2009–10 and 2010–11.

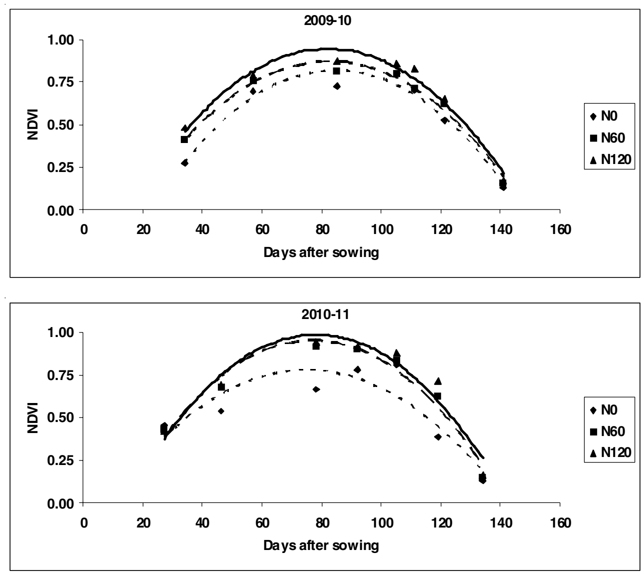


**Fig. 2.** Temporal variation of normalized difference vegetation index (NDVI) under nitrogen treatments for the year 2009–10 and 2010–11.

tion under continuous wetting condition resulting lower soil-moisture storage. However, at peak and later growth stages, lowest soil-moisture storage was observed in $N_{120}$ treatment, followed by $N_{60}$ and $N_0$ treatments, probably because of better crop growth as indicated by higher NDVI (Fig. 2) and correspondingly higher uptake of soil water by the crop. Hati *et al.* (2001) reported similar results for wheat crop in *Vertisol* for manured and fertilized plots than unfertilized plot, Bandyopadhyay *et al.* (2010) in soybean crop in Vertisol with INM treatments compared to the control and Pradhan *et al.* (2013) in maize crop in Inceptisol for nitrogen at the rate of 180 kg/ha compared to no or lower doses of nitrogen. The distribution of moisture content in the profile (data not given) depicts that difference in the moisture content due to different doses of nitrogen fertilizers was more prominent in the upper layer than in the lower layers, which emphasizes higher moisture extraction from upper layers than the lower layers. Highest water extraction from the profile was observed from $N_{120}$ treatments followed by $N_{60}$ and $N_0$ treatment.

### *Seasonal evapo-transpiration (ET)*

The seasonal evapo-transpiration (ET) among all the treatments varied between 352 mm and 402 mm with a mean value of 378 mm for 2009–10 and between 389 mm and 450 mm with a mean value of 418 mm for 2010–11 (Fig. 3). Averaged over the years and nitrogen, the cultivars did not show significant variation with respect to ET (399 and 397 mm for V1 and V2 respectively). Averaged

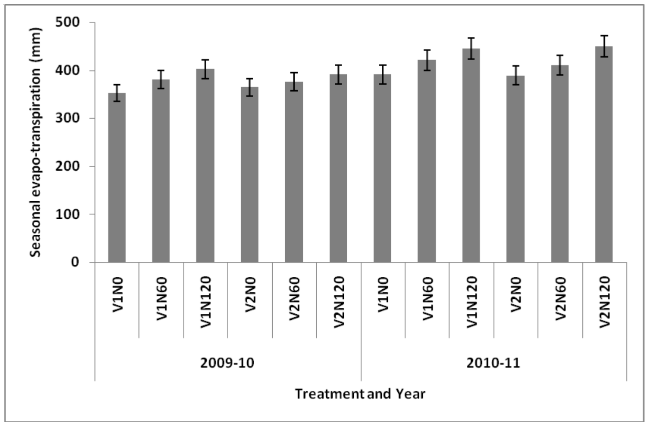


**Fig. 3.** Seasonal evapo-transpiration of wheat during the year 2009–10 and 2010–11 as influenced by variety ($V_1$, PBW 502 and $V_2$, DBW 17) and nitrogen levels ($N_0$, $N_{60}$ and $N_{120}$, 0, 60 and 120 kg N/ha).

over the years and cultivars, the $N_{120}$ treatment registered 13% and 6% higher ET compared than $N_0$ and $N_{60}$ treatments respectively. The evapo-transpiration production function (ETPF), the relation between ET and wheat grain or above-ground biomass yield, for the years 2009–11 is presented in (Fig. 4), showing linear and significant (P=0.01) relationship between ET and wheat grain or aboveground biomass yield. Hati *et al.* (2001) and Bandyopadhyay *et al.* (2010) also reported linear ETPF for wheat crop. The ETPF showed that about 84% variation in grain yield and 80% variation in above-ground biomass yield of wheat could be explained by ET (Fig. 4). The intercept of ETPF is less than 0 for both grain (–9,235) and above-ground biomass (–31,035) yield of wheat indicating scope of increase in WUE (both WUEgy and WUEagb) with increase in ET (Liu *et al*., 2002).

### *Fraction intercepted photosynthetically active radiation (fIPAR)*

The seasonal profile of fIPAR (%) of nitrogen treatments for both the years are shown in Fig 5. In all the treatments, fIPAR increased from sowing to booting stage due to crop development and increase in canopy coverage and later decreased till maturity due to crop ageing and leaf senesance. The temporal variation of fIPAR followed the similar trend as the variation of NDVI. Serrano *et al.* (2000) studied the relationships between reflectance based VI and canopy variables, i.e. above-ground biomass, LAI, canopy chlorophyll A content and fIPAR for wheat growing under different N supplies in an Aquic Xerofluvent soil of Spain and observed that changes in LAI and fIPAR followed similar trend with time. Averaged over the cultivars, the highest fIPAR was observed under $N_{120}$ treatment, followed by $N_{60}$ and $N_0$ treatments (Fig. 5) in both the years. This could be attributed to the greater canopy development under $N_{120}$ treatment compared to $N_{60}$ and $N_0$ treatments as indicated by higher NDVI (Fig. 2). Caviglia and Sadras (2001) also observed reduced light interception due to nitrogen deficiency in wheat. Averaged over the nitrogen treatments, the wheat cultivars were statistically similar with respect to fIPAR for both the years.

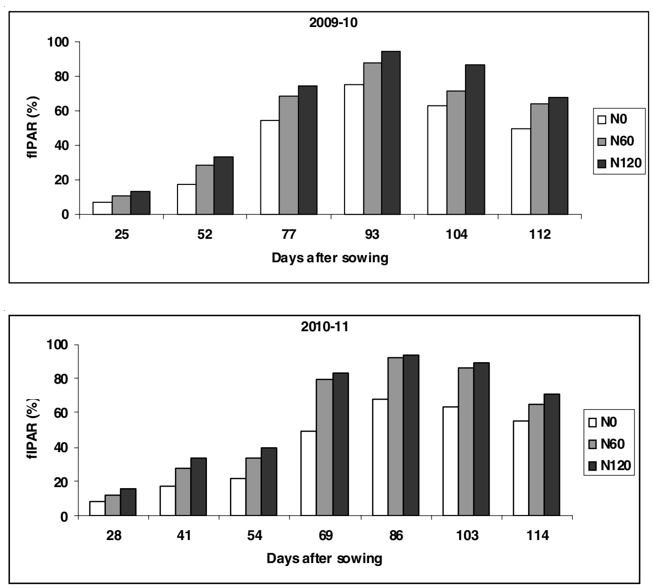


**Fig. 5.** Temporal variation of fraction intercepted photosy nthetically active radiation (fIPAR) (%) in nitrogen treatments for the year 2009-10 and 2010-11

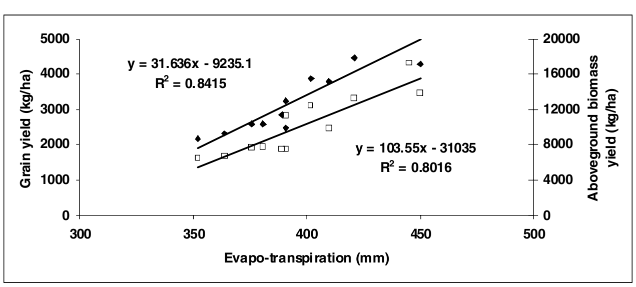


**Fig. 4.** Relation between seasonal evapo-transpiration and wheat grain and above-ground biomass yield (pooled data of 2009–10 and 2010–11)

### *Total seasonal intercepted PAR (TIPAR)*

The total seasonal intercepted PAR (TIPAR) is an important determinant of production of any crop (Monteith, 1984). The TIPAR varied between 360 and 505 MJ/m$^2$ during 2009–10 and 399 and 607 MJ/m$^2$ during 2010–11 (data not shown). Averaged over years and cultivars, $N_{120}$ registered 9% and 44 % higher TIPAR than $N_{60}$ and $N_0$ treatments. It may be attributed to the better crop growth and more number of green crop duration under $N_{120}$ compared with $N_{60}$ and $N_0$ treatments. Latiri-Souki *et al.*

(1998) also observed higher IPAR in nitrogen-applied treatment compared to no nitrogen treatment in wheat. Averaged over years and nitrogen, cultivars 'PBW 502' had only 2% higher TIPAR than 'DBW 17'. Pooled over the years, a significant and positive correlation (0.93**) was observed between TIPAR and above-ground biomass of wheat and 86% variation in the above-ground biomass could be explained by TIPAR (Fig. 6). Similar relationship was reported by Saha *et al.* (2012) for pigeonpea and Singer *et al.* (2011) for soybean and maize. This indicates increased interception of radiation is the main driving force for the increased crop biomass (Monteith, 1984; Latiri-Souki *et al*., 1998).

### *Grain and above-ground biomass yield*

The mean grain yield during 2010–11was 39% higher than that of 2009–10. Similarly, the mean above-ground biomass yield of 2010–11 was 32% higher that of 2009–10 (Table 2). This could be attributed to the exceptional high temperature for March and April (3.7°C in March and 4.7°C in April) of the year 2009–10 compared to 2010–11, which coincided with the flowering and grain-filling period of the wheat. Chakraborty *et al.* (2008) has also observed decrease in wheat yield due to sudden rise in temperature during flowering and grain-filling period of wheat.

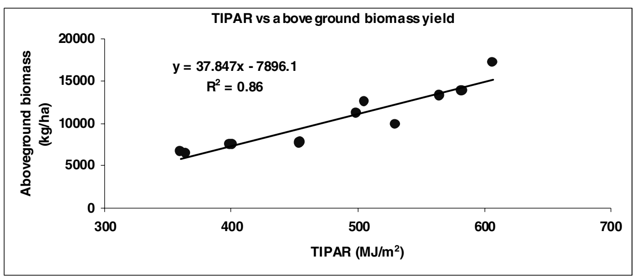


**Fig. 6.** Relation between total intercepted photosy nithetically active radiation (TIPAR) and above-ground biomass of wheat (pooled data of 2009–10 and 2010–11)

The cultivars 'PBW 502' and 'DBW 17' were statistically (P=0.05) at par with respect to grain yield for both the years (Table 2). The nitrogen levels significantly (P=0.05) influenced the grain yield of wheat (Table 2). During 2009–10, $N_{120}$ showed significantly (P=0.05) higher grain yield compared to $N_{60}$ and $N_0$ treatments, whereas $N_0$ and $N_{60}$ were statistically at par. However for 2010–11, $N_{120}$ registered significantly higher grain yield than $N_0$ treatment, but was statically on a par with the $N_{60}$ treatment. Pooled over the years, $N_{120}$ treatment showed 71% and 25% higher grain yield than $N_0$ and $N_{60}$ treatments respectively. There was significant interaction between cultivars and nitrogen levels with respect to grain yield. The cultivar 'PBW 502' or 'DBW 17' in combination with $N_{120}$ treatment nitrogen level gave the highest grain yield (Table 2).

Similar to grain yield, the cultivars 'PBW 502' and 'DBW 17' were statistically at par with respect to above-ground biomass yield for both the years (Table 2). The

**Table 2.** Effect of cultivar and nitrogen grain yield and above-ground biomass (t/ha) of wheat

| Treatment | Grain yield (t/ha) 2009–10 | 2010–11 | Pooled | Above-ground biomass (t/ha) 2009–10 | 2010–11 | Pooled |
|---|---|---|---|---|---|---|
| *Variety* | | | | | | |
| 'PBW 502' | 2.88 | 4.14 | 3.51 | 8.93 | 12.67 | 10.8 |
| 'DBW 17' | 2.71 | 3.65 | 3.18 | 8.57 | 10.42 | 9.49 |
| SEm± | 0.08 | 0.24 | 0.13 | 0.21 | 0.77 | 0.4 |
| CD(P=0.05) | NS | NS | NS | NS | NS | 1.26 |
| *Nitrogen* | | | | | | |
| $N_0$ | 2.26 | 2.66 | 2.46 | 6.63 | 7.50 | 7.07 |
| $N_{60}$ | 2.59 | 4.14 | 3.37 | 7.73 | 11.56 | 9.64 |
| $N_{120}$ | 3.55 | 4.88 | 4.21 | 11.89 | 15.56 | 13.72 |
| SEm± | 0.10 | 0.29 | 0.15 | 0.25 | 0.95 | 0.49 |
| CD(P=0.05) | 0.36 | 1.07 | 0.49 | 0.91 | 3.44 | 1.54 |
| *Variety (V) × nitrogen (N)* | | | | | | |
| $V_1N_0$ | 2.19 | 2.46 | 2.33 | 6.51 | 7.50 | 7.00 |
| $V_1N_{60}$ | 2.6 | 4.49 | 3.54 | 7.75 | 13.25 | 10.50 |
| $V_1N_{120}$ | 3.87 | 5.46 | 4.67 | 12.52 | 17.25 | 14.89 |
| $V_2N_0$ | 2.33 | 2.86 | 2.59 | 6.76 | 7.50 | 7.13 |
| $V_2N_{60}$ | 2.58 | 3.80 | 3.19 | 7.70 | 9.88 | 8.79 |
| $V_2N_{120}$ | 3.23 | 4.29 | 3.76 | 11.25 | 13.88 | 12.56 |
| SEm± | 0.14 | 0.41 | 0.22 | 0.36 | 1.34 | 0.69 |
| CD(P=0.05) | 0.51 | 1.51 | 0.69 | 1.29 | 4.87 | 2.18 |

nitrogen treatments significantly influenced the above-ground biomass yield of wheat. The highest aboveground biomass was observed under $N_{120}$ treatment, followed by $N_{60}$ and $N_0$ treatments for both the years. Pooled over the years, $N_{120}$ treatment registered 94 % and 42 % higher above-ground biomass yield than $N_0$ and $N_{60}$ treatments respectively. There was significant interaction between cultivars and nitrogen levels for above-ground biomass. Similar to grain yield, the cultivar 'PBW 502' or 'DBW 17' in combination with $N_{120}$ treatment gave the maximum above-ground biomass (Table 2). The increased crop production under N application can be attributed to larger LAI, intercepted radiation, and green crop duration (Latiri-Souki *et al*., 1998; Barthwal *et al*., 2013).

### *Water-use efficiency*

The water use efficiency of grain yield (WUEgy) and above-ground biomass (WUEagb) for different treatments are presented in Table 3. For both the years of study cultivars 'PBW 502' and 'DBW 17' were statistically (P=0.05) at par with respect to WUEgy and WUEagb. Pooled over the years, the cultivar 'PBW 502' showed 9% higher WUEgy and 12 % higher in WUEagb than 'DBW 17'. For the year 2009–10, $N_{120}$ treatment showed significantly higher (P=0.05) WUEgy and WUEagb than $N_{60}$ and $N_0$ treatment, whereas $N_{60}$ and $N_0$ treatments were statistically at par. However, for the year 2010–11, $N_{120}$ treatment registered significantly higher WUEgy and WUEagb compared to the N0 treatment but was statistically at par with the $N_{60}$ treatment. Pooled over the years, $N_{120}$ treatment showed 51% and 18% higher WUEgy and 72% and 34% higher WUEagb compared to $N_0$ and $N_{60}$ treatments respectively. There was significant interaction between cultivars and nitrogen levels with respect to WUEgy and WUEagb. Similar to grain and above-ground biomass yield, the cultivar 'PBW 502' or 'DBW 17' in combination with $N_{120}$ nitrogen level produced highest WUEgy and WUEagb. The correlation between grain yield and WUEgy (0.99) and between above-ground biomass yield and WUEagb (0.99) was higher compared to the correlation between ET and WUEgy (0.87) and between ET and WUEagb (0.84). This showed that the variation in WUEgy and WUEagb was mostly due to grain yield and above-ground biomass yield, respectively under different treatments.

### *Radiation use efficiency*

The radiation use efficiency of wheat cultivars under different nitrogen levels presented in Table 4 showed that cultivars 'PBW 502' and 'DBW 17' were statistically at par for RUE for both the years. For the year 2009–10, RUE of $N_{120}$ treatment was significantly higher than $N_{60}$ and $N_0$ treatments, whereas N0 and $N_{60}$ treatments were statistically at par. However, for the year 2010–11, $N_{120}$ treatment showed significantly higher RUE than $N_0$ treatment but $N_{120}$ and $N_{60}$ treatments, and $N_{60}$ and $N_0$ treat-

**Table 3.** Water-use efficiency of wheat as affected by variety and nitrogen

| Treatment | WUEgy (kg/ha/mm) | | | WUEagb (kg/ha/mm) | | |
|---|---|---|---|---|---|---|
| | 2009–10 | 2010–11 | Pooled | 2009–10 | 2010–11 | Pooled |
| *Variety* | | | | | | |
| 'PBW 502' | 7.56 | 9.74 | 8.65 | 23.32 | 29.81 | 26.56 |
| 'DBW 17' | 7.18 | 8.71 | 7.94 | 22.60 | 24.73 | 23.67 |
| SEm± | 0.24 | 0.58 | 0.31 | 0.60 | 1.85 | 0.97 |
| CD(P=0.05) | NS | NS | NS | NS | NS | NS |
| *Nitrogen* | | | | | | |
| $N_0$ | 6.31 | 6.82 | 6.56 | 18.52 | 19.23 | 18.87 |
| $N_{60}$ | 6.84 | 9.95 | 8.40 | 20.41 | 27.78 | 24.09 |
| $N_{120}$ | 8.94 | 10.90 | 9.92 | 29.96 | 34.80 | 32.38 |
| SEm± | 0.29 | 0.71 | 0.38 | 0.74 | 2.27 | 1.19 |
| CD(P=0.05) | 1.05 | 2.58 | 1.21 | 2.69 | 8.25 | 3.76 |
| *Variety (V) × nitrogen (N)* | | | | | | |
| $V_1N_0$ | 6.22 | 6.29 | 6.26 | 18.48 | 19.19 | 18.83 |
| $V_1N_{60}$ | 6.83 | 10.65 | 8.74 | 20.34 | 31.48 | 25.91 |
| $V_1N_{120}$ | 9.63 | 12.27 | 10.95 | 31.15 | 38.77 | 34.96 |
| $V_2N_0$ | 6.40 | 7.34 | 6.87 | 18.56 | 19.28 | 18.92 |
| $V_2N_{60}$ | 6.87 | 9.26 | 8.06 | 20.48 | 24.09 | 22.28 |
| $V_2N_{120}$ | 8.26 | 9.54 | 8.90 | 28.77 | 30.83 | 29.80 |
| SEm± | 0.41 | 1.00 | 0.54 | 1.04 | 3.21 | 1.69 |
| CD(P=0.05) | 1.49 | 3.65 | 1.71 | 3.80 | 11.67 | 5.32 |

**Table 4.** Radiation-use efficiency (g/MJ) and partial factor productivity of nitrogen (kg grain/kg nitrogen) of wheat as affected by cultivar and nitrogen

| | RUE (g/MJ) | | | PFPN (kg grain/kg nitrogen) | | |
|---|---|---|---|---|---|---|
| | 2009–10 | 2010–11 | Pooled | 2009–10 | 2010–11 | Pooled |
| *Variety* | | | | | | |
| 'PBW 502' | 1.99 | 2.36 | 2.18 | 37.79 | 60.13 | 48.96 |
| 'DBW 17' | 1.94 | 2.04 | 1.99 | 34.96 | 49.50 | 42.23 |
| SEm± | 0.06 | 0.16 | 0.08 | 0.50 | 2.95 | 1.50 |
| CD(P=0.05) | NS | NS | NS | 2.26 | 13.27 | 5.17 |
| *Nitrogen* | | | | | | |
| $N_0$ | 1.83 | 1.88 | 1.85 | - | - | - |
| $N_{60}$ | 1.70 | 2.11 | 1.90 | 43.17 | 69.00 | 56.08 |
| $N_{120}$ | 2.37 | 2.62 | 2.49 | 29.58 | 40.63 | 35.10 |
| SEm± | 0.08 | 0.19 | 0.10 | 0.50 | 2.95 | 1.50 |
| CD(P=0.05) | 0.27 | 0.70 | 0.32 | 2.26 | 13.27 | 5.17 |
| *Variety (V) × nitrogen (N)* | | | | | | |
| $V_1N_0$ | 1.79 | 1.88 | 1.84 | - | - | - |
| $V_1N_{60}$ | 1.71 | 2.35 | 2.03 | 43.33 | 74.75a | 59.04 |
| $V_1N_{120}$ | 2.48 | 2.84 | 2.66 | 32.25 | 45.50bc | 38.88 |
| $V_2N_0$ | 1.88 | 1.87 | 1.87 | - | - | - |
| $V_2N_{60}$ | 1.70 | 1.86 | 1.78 | 43.00 | 63.25ab | 53.13 |
| $V_2N_{120}$ | 2.25 | 2.38 | 2.32 | 26.92 | 35.75c | 31.33 |
| SEm± | 0.11 | 0.27 | 0.15 | 0.71 | 4.17 | 2.11 |
| CD(P=0.05) | 0.39 | NS | 0.46 | 3.20 | 18.76 | 7.32 |

ments were statistically similar. Pooled over the years, $N_{120}$ treatment registered 35 and 31% higher RUE than $N_0$ and $N_{60}$ treatments respectively. There was significant interaction between cultivars and nitrogen levels for RUE. Similar to WUE, the cultivar 'PBW 502' or 'DBW 17' in combination with $N_{120}$ level resulted in the highest RUE. The RUE showed better correlation with above-ground biomass yield (0.95) than the TIPAR (0.77) indicating that the variation in RUE was mostly due to variation in above-ground biomass under different treatments. Han *et al.* (2008) also observed good correlation between RUE and crop yield of wheat.

### *Nitrogen-use efficiency*

The nitrogen-use efficiency in terms of partial factor productivity of nitrogen (PFPN) was significantly higher in 'PBW 502' than the cultivar 'DBW 17' for 2009–10 (Table 4). However, in 2010–11, both the cultivars 'PBW 502' and 'DBW 17' were statistically at par for PFPN. Pooled over the years, cultivar 'PBW 502' showed 16% higher PFPN than 'DBW 17'. The PFPN was significantly lower in $N_{120}$ treatment than the $N_{60}$ treatment for both the years. Pooled over the years, $N_{60}$ treatment showed 60% higher PFPN compared to $N_{120}$ treatments. The decrease in PFPN with the increase in nitrogen doses may be attributed to the fact that with the increase in nitrogen levels there was increase in the losses of nitrogen through leaching, volatilization and deep percolation. Bandyopadhyay *et al.* (2009) in cotton and Pradhan *et al.* (2013) in maize also observed decreased PFPN at higher doses of nitrogen.

It was observed that there was significant increase in grain yield, aboveground biomass, WUE and RUE but decrease in PFPN of wheat cultivars with increase in nitrogen levels for both the cultivars under study. However there was no significant difference between the cultivars 'PBW 502' and 'DBW 17' with respect to grain yield, above-ground biomass yield, WUE, RUE. So, cultivar 'PBW 502' or 'DBW 17' can be grown with 120 kg N/ha for obtaining higher grain yield, above-ground biomass, WUE and RUE in the semi-arid tropical environment of Delhi region.

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