Pak. J. Bot., 41(3): 1241-1257, 2009.

SEASONAL GROWTH, RADIATION INTERCEPTION, ITS CONVERSION EFFICIENCY AND BIOMASS PRODUCTION OF *ORYZA SATIVA* L. UNDER DIVERSE AGRO-ENVIRONMENTS IN PAKISTAN

A. AHMAD[1], S. IQBAL[1], S. AHMAD[2*], T. KHALIQ[1], W. NASIM[1], Z. HUSNAIN[2], A. HUSSAIN[1], M. ZIA-UL-HAQ[2] AND G. HOOGENBOOM[3]

[1]*Agro-Climatology Lab, University of Agriculture, Faisalabad-38040, Pakistan*
[2*]*Department of Agronomy & Chemistry, Bahauddin Zakariya University, Multan-60800, Pakistan*
[3]*Biological and Agricultural Engineering, University of Georgia, Griffin, USA.*

Abstract

The effects of major agronomic practices on growth and above-ground dry biomass production have been studied individually or in combinations of two, but not studied collectively and deeply. This research was carried out to study the effects of transplanting dates, and split nitrogen application on (I) growth (Leaf area index; LAI, crop growth rate; CGR, leaf area duration; LAD, mean net assimilation rate; NAR), (II) intercepted photosynthetically radiation (IPAR) & radiation use efficiency (RUE) and (III) above-ground total dry matter (ATDM) production of two fine rice cultivars under diverse agro-environmental conditions. Field trials were conducted in 2004 and 2005 in kallar tract (conventional rice zone) of Pakistan. The results revealed that early transplanting (1st week of July) enhanced LAI over late transplanting (3rd week of July) significantly throughout the growth period. Peak LAI values were reached at 75 DAT in all the treatments. Similarly, early transplanting significantly enhanced cumulative IPAR (R^2 = 94.4–97.9%). Seasonal differences in ATDM production were mainly associated with the amount of IPAR and to a lesser degree on its efficiency of conversion. RUE for ATDM varied from 1.18 g MJ^{-1} to 1.94 g MJ^{-1} IPAR at different locations of conventional rice belt of Pakistan.

Introduction

Crop productivity is determined by above-ground total dry matter (ATDM) accumulation (areal total dry biomass) along with its partitioning to various parts of plants (Van der werf, 1996). ATDM and crop growth rates (CGR) are dependent on the ability of the crop canopy to (a) either the interception of photo synthetically active radiation (IPAR) (Bisco & Gallagher, 1977) which is function of leaf area index (LAI) and crop canopy architecture or (b) conversion of IPAR to ATDM, i.e., radiation use efficiency (RUE) (Sinclair & Muchow, 1999).

Agronomic practices directly or indirectly variably affect the IPAR and RUE in terms of ATDM production. The most important are (i) transplanting time in case of transplanted rice (Rao *et al*., 1996; Iqbal *et al*., 2008) effecting mainly the exposure of young seedlings to soil and external environmental conditions from transplanting to harvesting, (ii) cultivars exhibiting genetic potential under various agro-ecological conditions and (iii) nitrogen management (Patel & Thakur, 1997; Ehsanullah *et al*., 2001; Manzoor *et al*., 2005; Ahmad *et al*., 2008; Ahmad *et al*., 2009) in terms of correct time of application keeping in view the losses i.e. leaching, volatilization and runoff etc. after application. Nutrient deficiency may affect both IPAR and RUE (Salvagiotti & Miralles, 2008). RUE is dependent on net CO_2 assimilation (Loomis & Amthor, 1999) and nitrogen is a source of this mechanism by increasing Rubisco content in leaves (Sinclair & Horie, 1989). Therefore, an increase in leaf photosynthesis, CGR and leaf area duration (LAD) is expected with split nitrogen application.

*Corresponding author e-mail: shakeel.agronomy@gmail.com

Review of literature depicted that many workers have investigated the effect of N rates, or cultivars on growth, IPAR, and RUE of various crops (Ahmad *et al*., 2005; Khaliq *et al*., 2008; Ahmad *et al*., 2009). Rice is one of the most important cereal crops and is the staple food of the majority of the people of the world. In Pakistan it ranks 2^{nd} in consumption after wheat (Anon., 2008). But there is lack of information regarding the effect of transplanting dates, cultivars and split N application of fine rice on growth, IPAR and RUE under diverse agro-environmental conditions. This study was designed to determine the influence of transplanting dates, cultivars and split N application on (I) LAI, LAD, CGR, NAR and (II) ATDM, IPAR and RUE in fine rice grown under diverse agro-environmental conditions in the conventional rice zone (Kalar track) of Pakistan.

Materials and Methods

A field study was conducted at Faisalabad (FSD), Kala Shah Kaku (KSK) and Gujranwala (GUJ) in Pakistan during 2004 and 2005 to evaluate the effect of transplanting dates, cultivars and split nitrogen application on growth, radiation interception and its utilization efficiency of fine rice. The data pertaining to site and soil, soil analysis, and crop husbandry has been described in detail by Iqbal *et al*., (2008). Additional information regarding experimental sites is given in Table 1.

Design and treatments: The experiments were laid out in split-split plot design with three replications. Treatments including three factors were two transplanting dates (1^{st} week of July & 3^{rd} week of July) in main plots, two genotypes (cvs. Super Basmati & Basmati, 2000) in sub-plots and three split nitrogen (N) fertilizer application in sub-sub-plots. Nitrogen fertilizer treatments placed in each plot were: Full N at transplanting, ½ N at transplanting + ½ N at 30 days after transplanting (DAT) and 1/3 N at transplanting + 1/3 N after 30 DAT + 1/3 N at 50 DAT. Plot size was 1.8 by 12 m with row to row and plant to plant spacing of 22.5 cm apart.

Observations: One half of each plot area was allocated to destructive used for the growth parameters and the remaining half plot reserved for final harvest data.

Sampling procedure for growth data: A sample of four plants from each plot was harvested at ground level fortnightly intervals leaving appropriate borders. Fresh and dry weights of component fractions of plant (eg., leaf, stem and panicle) were determined. A sub-sample of each fraction was taken to dry in an oven at 70^{o}C to a constant weight. ATDM was obtained by adding weight of all the components. An appropriate sub sample (10g) of green leaf laminae was used to record leaf area using Li-Cor 3100 leaf area meter (LI-COR Inc. Lincoln, NE). These measurements of leaf area and dry weights were used to calculate the growth of rice crop.

Leaf area index: LAI was calculated as the ratio of leaf area to land area (Hunt, 1978). LAI = Leaf area / Land area

Leaf area duration (days): LAD was estimated according to the formula suggested by Hunt (1978). LAD = $(LAI_1+LAI_2)/2 \times (T_2–T_1)$ where LAI_1 and LAI_2 were the leaf area indices at time T_1 and T_2, respectively. Cumulative LAD was calculated at final harvest by adding all the LAD values attained at different stages.

Table 1. Monthly mean weather conditions during crop growth season (July-Nov.).

Months	Temperature (ºC)			Rainfall (mm)			Solar radiation (MJ m^{-2} d^{-1})			Relative humidity (%)		
	FSD	KSK	GUJ	FSD	KSK	GUJ	FSD	KSK	GUJ	FSD	KSK	GUJ
07	32.7	31.3	28.9	87.2	246.9	133.0	22.0	24.3	23.5	65.8	56.7	61.1
08	33.9	32.0	29.5	51.6	196.2	112.5	21.4	20.6	20.8	53.9	66.2	69.8
09	31.7	29.2	28.8	78.0	76.0	64.0	22.6	21.7	22.0	51.8	62.3	59.4
10	27.1	25.7	25.8	10.0	0.8	1.0	19.8	18.0	18.3	44.2	57.0	53.5
11	20.8	20.1	17.6	0.0	0.0	0.0	17.6	14.0	16.0	50.5	52.5	54.9

Source: Depart of Crop Physiology, University of Agriculture, Faisalabad, Pakistan Rice Research Institute, Kala Shah Kaku, Lahore, Pakistan Adaptive Research Farm, Gujranwala

Crop growth rate (g $m^{-2}d^{-1}$): CGR was calculated as proposed by Hunt (1978) for each harvest after 15 days interval. CGR = $(W_2 - W_1) / (T_2 - T_1)$ where W_1 and W_2 was the total dry weights harvested at times T_1 and T_2 respectively. Mean CGR was calculated between first harvest and the last harvest.

Net assimilation rate (g $m^{-2}d^{-1}$): The mean net assimilation rate (NAR) was estimated by using the formula of Hunt (1978). NAR = ATDM / LAD, where, ATDM and LAD are the final total dry matter and leaf area duration, respectively.

Interception of radiation: The fraction of intercepted radiation (Fi), twice a month at Faisalabad, Kala Shah Kaku and Gujranwala was calculated by the method of Gallagher & Biscoe (1978) as Fi = 1- exp (-K x LAI), where, K is an extinction coefficient for total solar radiation equal to 0.63 for rice (Ritchie *et al*., 1998). The amount of IPAR was determined by multiplying values of Fi with daily IPAR during the season. Daily IPAR values were taken as 50% of total solar radiation values (Szeicz, 1974).

Radiation use efficiency (RUE): RUE was calculated as the ratio of ATDM to cumulative IPAR for each plot, and the plot values subjected to anova. Alternatively, RUE was also estimated from the slope of the linear regression of cumulative IPAR on ATDM obtained from the sequential samplings for all crops (Montieth, 1977; Kiniry *et al*., 2001).

$$RUE_{ATDM} = ATDM/\sum Sa$$

Statistical analysis: Data collected on growth and RUE were analyzed statistically and significance of treatments means was tested using least significant difference test at 5% probability level (Steel *et al*., 1997).

Results

Leaf area index (LAI): The date of transplanting had a significant effect on LAI at all the locations, throughout the growth (Fig. 1). Early transplanting (1st week of July) significantly enhanced LAI over late (3rd week of transplanting) planting and maximum values were reached 7.79, 6.70 and 5.33 at Faisalabad, Kala Shah Kaku and Gujranwala, respectively. Equivalent LAI values were 4.11, 5.72 and 4.72, respectively in case of late transplanting (Table 2). At all sites, cultivar differences in maximum LAI development were non-significant (Table 2). Maximum LAI values in cv. Super Basmati were 6.24, 6.19 and 5.01 at Faisalabad, Kala Shah Kaku and Gujranwala, respectively. Equivalent values, in Basmati-2000 were 6.15, 6.23 and 5.03, respectively. LAI was significantly but differentially affected by nitrogen split application at different sites. The peak LAI reached a value greater than 6.0 at 75 DAT in all the N treatments (Table 2). N split application (2 or 3 applications) significantly increased LAI over full N at transplanting, at Kala Shah Kaku but not at Faisalabad or Gujranwala sites; thereafter, LAI declined until final harvest (Fig. 3).

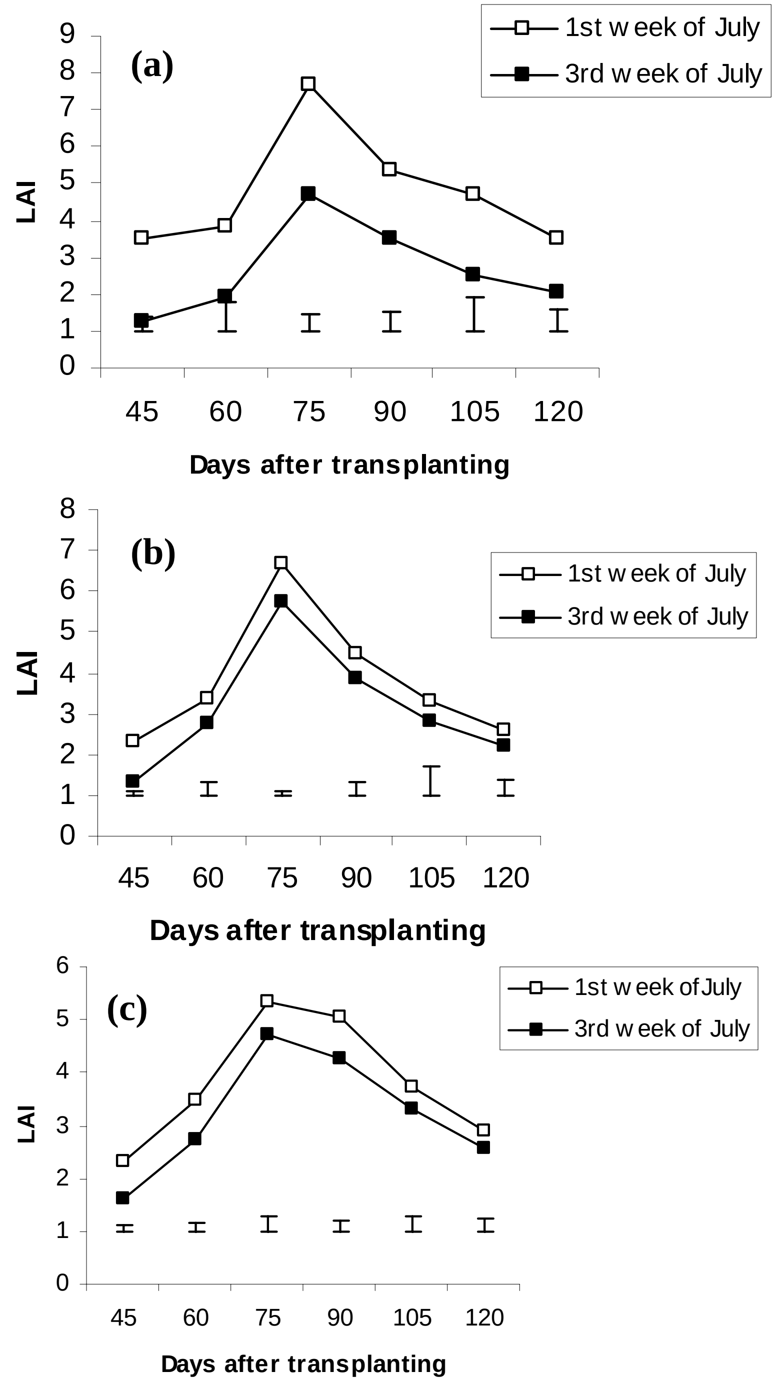

Fig. 1. Effect of transplanting dates on seasonal LAI at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

Table 2. Effect of transplanting dates and nitrogen split application on maximum leaf area index, leaf area duration and crop growth rate of two rice cultivars under diverse agro-environments.

Treatments	Max. LAI			LAD (days)			CGR (g m^{-2} day^{-1})		
	FSD	KSK	GUJ	FSD	KSK	GUJ	FSD	KSK	GUJ
Transplanting dates									
1st week of July	7.79a	6.70a	5.33a	407.32a	304.82a	303.07a	15.20a	12.45a	12.64b
3rd Week of July	4.11b	5.72b	4.72b	231.94b	253.60b	256.17b	13.78b	11.50b	13.86a
LSD 5%	0.43	0.13	0.28	18.13	18.54	14.16	1.79	0.64	0.53
Cultivars									
Super Basmati	6.24ns	6.19ns	5.01ns	321.82	278.98	280.06	14.93a	12.22a	12.15b
Basmati-2000	6.15	6.23	5.03	317.44	279.44	279.19	14.04b	11.74b	14.36a
LSD 5%	0.31	0.23	0.33	10.43	8.99	9.17	0.61	0.45	0.38
Split N application									
Full N at transplanting	6.12	5.74	5.07	318.93	262.49c	279.08	14.84	11.37b	13.52b
1/2 N at transplanting + 1/2 N at 30 DAT	6.26	6.54	4.96	325.81	293.92a	277.16	14.37	12.15a	14.27a
1/3 N at transplanting + 1/3 30 DAT + 1/3 N at 50 DAT	6.21	6.34	5.05	314.16	281.21b	282.63	14.27	12.42a	11.97c
LSD 5%	0.13	0.28	0.27	12.77	11.01	11.23	0.75	0.55	0.37

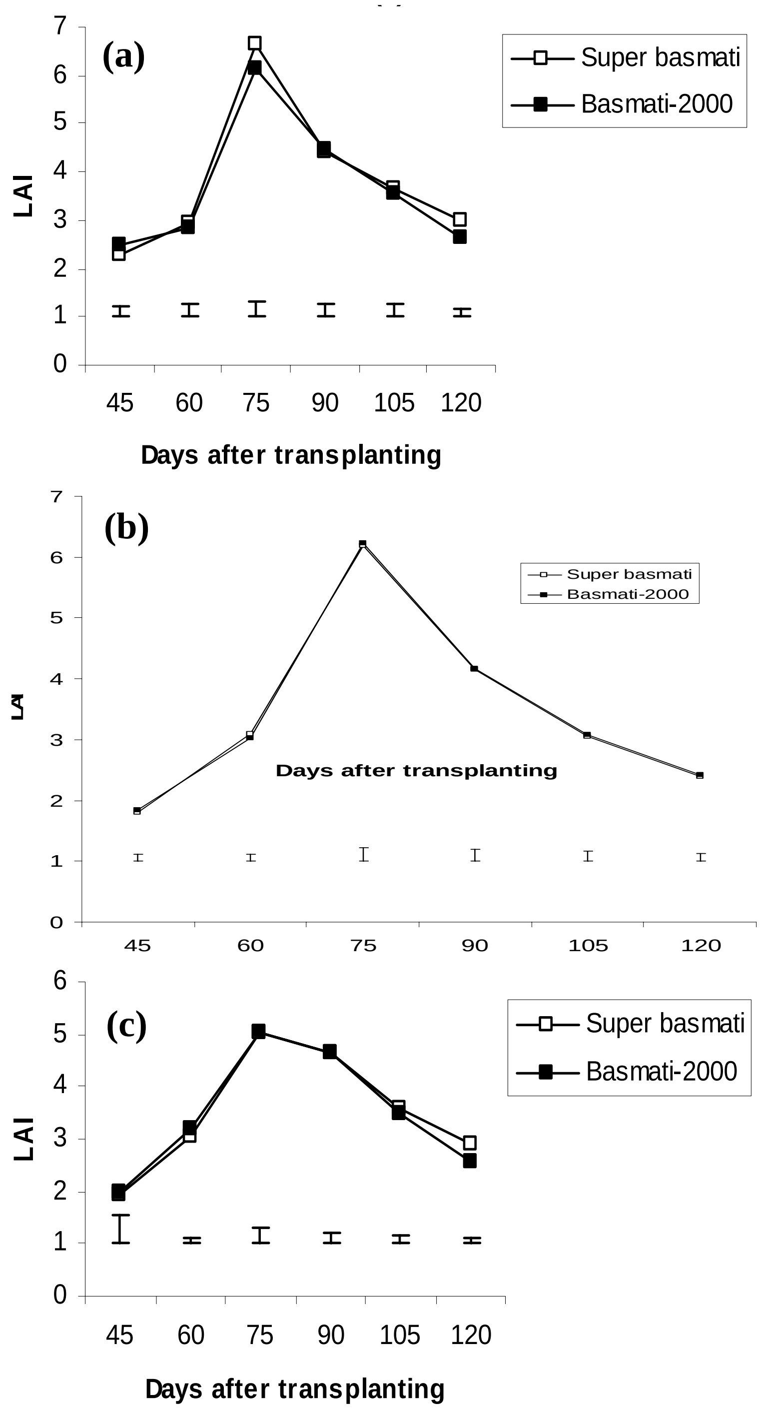

Fig. 2. Effect of cultivars on seasonal LAI at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

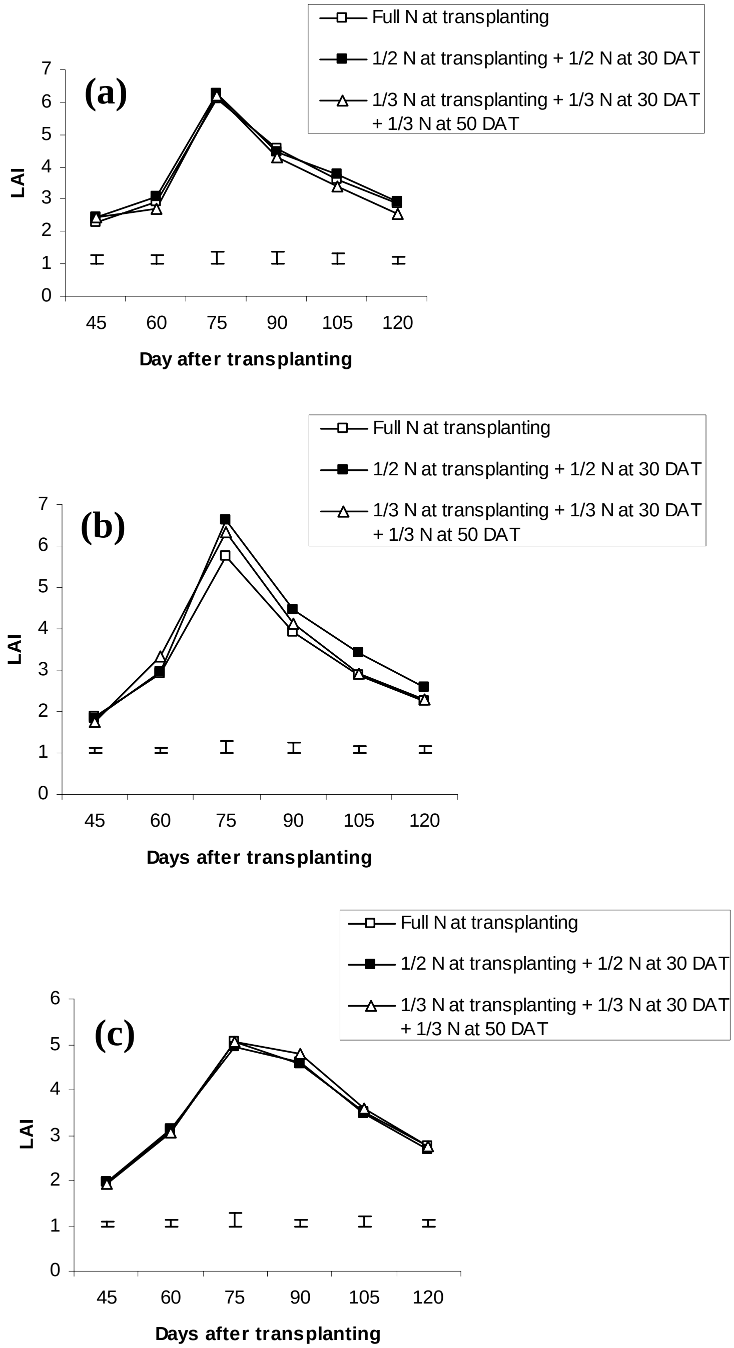

Fig. 3. Effect of split N application on seasonal LAI at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

Above-ground total dry matter accumulation (ATDM): Early transplanting (1st week of July) significantly increased ATDM over late transplanting (3rd week of July) at all sites (Fig. 4). Averaged over all locations, maximum ATDM was 1814 g m^{-2} in early transplanting as compared to 1499 g m^{-2} in late transplanting at final harvest (120 DAT). Cultivar differences in ATDM production were significant. Super Basmati increased ATDM by 32.85% (1998 g m^{-2} vs 1504 g m^{-2}) at Faisalabad and 9.92% (1839 g m^{-2} vs 1673 g m^{-2}) at Gujranwala. In contrast, cv. Basmati-2000 significantly enhaced ATDM by 3.21% (1639 g m^{-2} vs 1588 g m^{-2}) at Kala Shah Kaku. Averaged over all the sites, cv. Super Basmati increased ATDM by 12.64% (1808 g m^{-2} vs 1605 g m^{-2}) over cv. Basmati-2000 at the final harvest (120 DAT). Generally ATDM production responded positively to N application. Three N split application significantly increased ATDM accumulation over two split N or full N applications at final harvest.

Leaf area duration (LAD): Table 2 presents the effect of treatments on cumulative LAD at all the locations. The early transplanting significantly increased LAD by 75.4% (407 days vs 231 days) at Faisalabad, 20.1% (305 days vs 254 days) at Kala Shah Kaku and 16.61% (307 days vs 256 days) at Gujranwala. Cultivar differences in LAD were non-significant at all the locations and it varied from 294 days in cv. Super Basmati to 292 days in cv. Basmati-2000 (Table 2). Split N application did not affect LAD at Faisalabad and Gujranwala sites. However, significant differences were found between N application treatments at Kala Shah Kaku (Table 2), where split N application increased LAD by 9.92% (288 days vs 262 days) over full N application treatment. Differences in LAD between two and three N split treatments were also significant.

Net assimilation rate (NAR): The late transplanting significantly increased NAR over early transplanting at all the sites (Table 3). Cultivar differences in average NAR were non-significant at all the sites and it varied from 4.32 g m^{-2} d^{-1} to 4.75 g m^{-2} d^{-1}. Averaged over all sites, mean NAR was 4.48 g m^{-2} d^{-1} and 4.53 g m^{-2} d^{-1} in Super Basmati and Basmati-2000, respectively (Table 3). Differences between different N splits were non-significant at Faisalabad and Kala Shah Kaku but not at Gujranwala where two N split application significantly enhanced NAR over the three split N application.

Crop growth rate (CGR): Table 2 shows the effect of treatments on mean CGR calculated between first and final harvest. Early transplanting significantly increased mean CGR by 10.30% (15.20 g$m^{-2}$$d^{-1}$ vs 13.78 g m^{-2} d^{-1}) at Faisalabad and 8.26% (12.45 g m^{-2} d^{-1} vs 11.50 g m^{-2} d^{-1}) at Kala Shah Kaku. In contrast, mean CGR was significantly higher by 9.65% (12.64 g m^{-2} d^{-1} vs 13.26 g m^{-2} d^{-1}) in late transplanting than early transplanting at Gujranwala. Cultivar differences in mean CGR were significant at Faisalabad and Kala Shah Kaku, where cv. Super Basmati increased CGR by 6.34% (14.93 g vs 14.04 g m^{-2} d^{-1}) and 4.09% (12.22 g vs 11.74 g m^{-2} d^{-}1) over cv. Basmati-2000 at Faisalabad and Kala Shah Kaku, respectively. In contrast, cv. Basmati-2000 significantly increased mean CGR by 18.19% (12.15 g vs 14.36 g m^{-2} d^{-}1) over Super Basmati. The split N application significantly enhanced mean CGR over full N application at Kala Shah Kaku and Gujranwala sites. Differences between two N splits and three N splits were also significant at Gujranwala (Table 2).

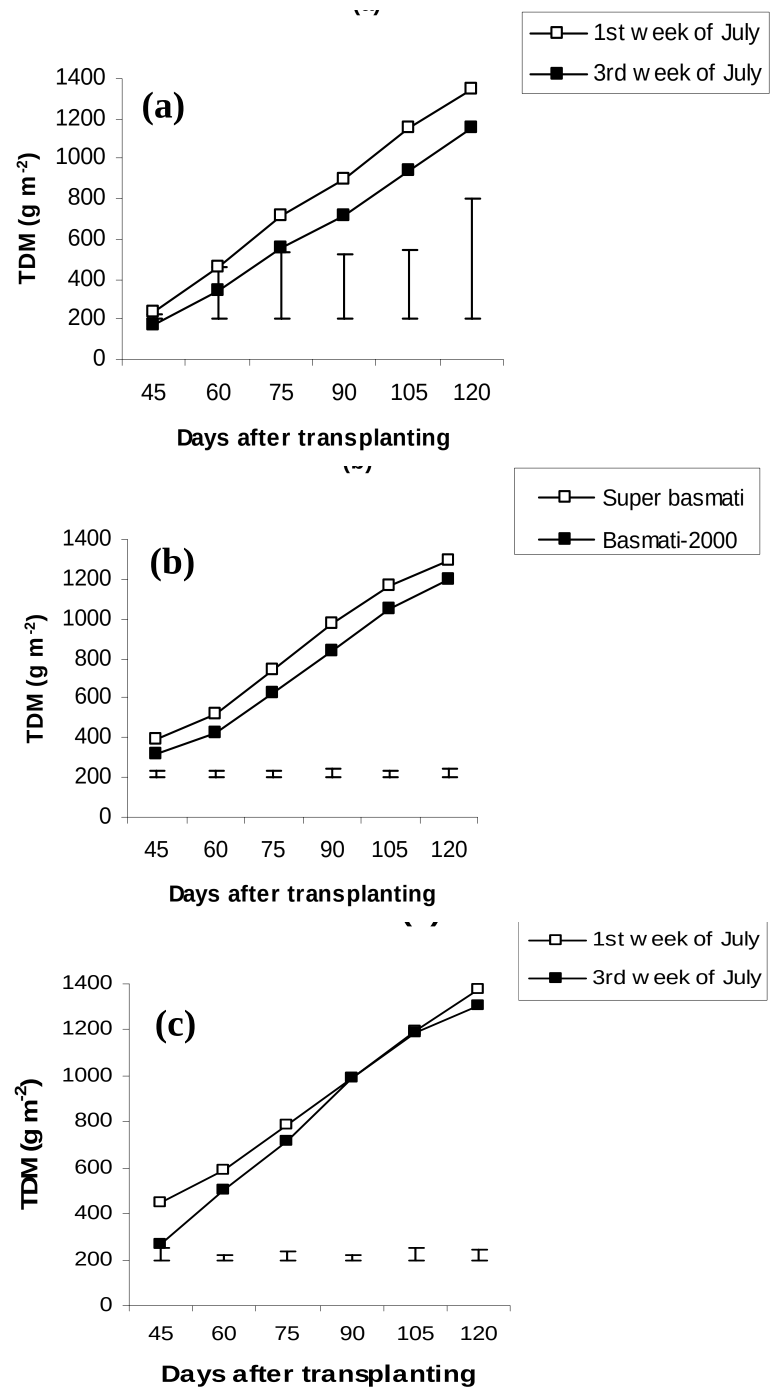

Fig. 4. Effect of transplanting dates on seasonal areal total dry biomass at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

Table 3. Effect of transplanting dates and nitrogen split application on net assimilation rate, intercepted radiation and radiation utilization efficiency of two rice cultivars under diverse agro-environments.

Treatments	NAR (g m^{-2} day^{-1})			Intercepted PAR (MJ m^{-2})			RUE_{TDM} (g MJ^{-1})		
	FSD	KSK	GUJ	FSD	KSK	GUJ	FSD	KSK	GUJ
	Transplanting dates								
1st week of July	3.46b	4.26b	4.45b	1146a	773a	813a	1.18b	1.67b	1.65b
3rd Week of July	5.24a	4.79a	4.85a	727b	618b	692b	1.60a	1.94a	1.86a
LSD 5%	0.63	0.25	0.07	62.46	27.56	11.93	0.12	0.11	0.03
	Cultivars								
Super Basmati	4.32	4.58	4.55	939	694	749	1.41	1.83	1.74b
Basmati-2000	4.38	4.46	4.75	934	696	756	1.37	1.78	1.77a
LSD 5%	0.22	0.18	0.24	18.37	12.97	10.50	0.06	0.06	0.04
	Split N application								
Full N at transplanting	4.46	4.76a	4.51b	934	687b	752	1.42	1.81	1.71b
1/2 N at transplanting + 1/2 N at 30 DAT	4.21	4.33b	4.92a	948	709a	752	1.36	1.79	1.81a
1/3 N at transplanting + 1/3 30 DAT + 1/3 N at 50 DAT	4.39	4.47b	4.52ba	927	690b	754	1.38	1.82	1.74b
LSD 5%	0.27	0.22	0.29	22.51	15.89	12.86	0.07	0.07	0.04

Table 4.Effect of transplanting dates and nitrogen split application on grain yield and final above-ground total dry matter of two rice cultivars under diverse agro-environments.

Treatments	Grain yield ($g\ m^{-2}$)			Above-ground total dry matter ($g\ m^{-2}$)		
	FSD	**KSK**	**GUJ**	**FSD**	**KSK**	**GUJ**
	Transplanting dates					
1st week of July	408a	490a	425a	1346a	1293a	1376a
3rd Week of July	355b	453b	370b	1158b	1196b	1309b
LSD 5%	9.0	19.0	8.0	50.8	42.0	30.0
	Cultivars					
Super Basmati	377b	472ns	401a	1268a	1258a	1309b
Basmati-2000	386a	471	391b	1236b	1230b	1380a
LSD 5%	7.0	8.0	6.0	19.0	24.0	48.0
	Split N application					
Full N at transplanting	391a	468b	387c	1272a	1232b	1347b
1/2 N at transplanting + 1/2 N at 30 DAT	390a	459b	397b	1253ab	1263a	1442a
1/3 N at transplanting + 1/3 30 DAT + 1/3 N at 50 DAT	362b	488a	404a	1231a	1238ab	1238c
LSD 5%	8.0	9.0	6.0	22.0	25.0	35.0

Incident and intercepted radiation (IPAR): Table 3 presents the effect of treatments on the amount of IPAR during the growth cycle at all the sites. The values of IPAR were 51.65%, 44.62% and 39.00% at Faisalabad, Kala Shah Kaku and Gujranwala sites, respectively. Early transplanting significantly increased IPAR over late transplanting at all sites. Average amount of IPAR was 1146 MJ m^{-2}, 773 MJ m^{-2} and 814 MJ m^{-2} at Faisalabad, Kala Shah Kaku and Gujranwala, respectively. Equivalent values in the late transplanting were 727 MJ m^{-2}, 618 MJ m^{-2} and 693 MJ m^{-2}, respectively (Table 3). Cultivar differences in IPAR were non-significant at all the sites. Split N split application did not significantly affect the amount of IPAR at Faisalabad and Gujranwala. But at Kala Shah Kaku, N split application (2-or 3 splits) slightly but significantly increased IPAR over full N application treatment.

Radiation utilization efficiency (RUE): Table 3 presents the effect of treatments on RUE_{ATDM} at all the locations. The late transplanting significantly increased RUE by 35.59% (1.60 MJ^{-1} vs 1.18 g MJ^{-1}) at Faisalabad, 16.16% (1.94 MJ^{-1} vs 1.67 g MJ^{-1}) at Kala Shah Kaku and 12.73% (1.86 g MJ^{-1} vs 1.65 g MJ^{-1}) at Gujranwala. Cultivar differences in RUE were significant at Gujranwala site only where cv. Basmati-2000 increased RUE_{ATDM} over cv. Super Basmati. At all locations, average RUE_{ATDM} was 1.66 g MJ^{-1} and 1.64 g MJ^{-1} in cv. Super Basmati and cv. Basmati-2000, respectively. Non-significant differences were found in RUE_{ATDM} between N application treatments at Faisalabad, Kala Shah Kaku and Gujranwala sites. Differences in RUE_{ATDM} between two and three N split treatments were also non-significant except Gujranwala site, where two N split significantly increased RUE over three N split. Averaged over three sites, mean RUE was 1.65 g MJ^{-1} in different N (Table 3).

Grain yield (GY): Table 4 presents the effect of treatments on GY of rice. Transplanting in the first week of July significantly enhanced rice GY as compared to transplanting in the third week of July at all sites. Cultivar differences in GY were significant at Faisalabad and Gujranwala sites. N split application-increased rice GY over control at Gujranwala and Kala Shah Kaku but not at Faisalabad. Differences in rice GY between two N split and three split were also significant at Faisalabad, Kala Shah Kaku and Gujranwala. Averaged rice GY was higher at Kala Shah Kaku than Gujranwala and Faisalabad. Almost similar response was observed with respect to total dry biomass.

Discussion

LAI values steadily increased and reached maximum at 75 DAT at all the locations; thereafter LAI declined in all the treatments and reached its minimum values at less than 3 by 120 DAT (Figs. 1, 2, 3). The peak LAI reached a value greater than 6.0 at 75 DAT in all the N treatments. The results are in line with the findings of Tanaka *et al.,* (1966); Murty & Murty (1981); Hasegawa & Horie, (1996); Dingkuhn *at al*., (1999); Campbell, (2000) and Grigg *et al*., (2000) who reported maximum LAI values ranging 5.0-7.0 for rice in various agro-ecological conditions. At all the three locations, total ATDM accumulation followed the pattern of sigmoid growth curve and maintained a positive slope throughout the growth in all treatments (Figs. 4, 5, 6). ATDM production increased steadily after crop establishment until maturity and responded positively to all the treatments. In the present experiments, the comparatively superior performance of the early transplanting in ATDM production may be associated with its higher LAIs during

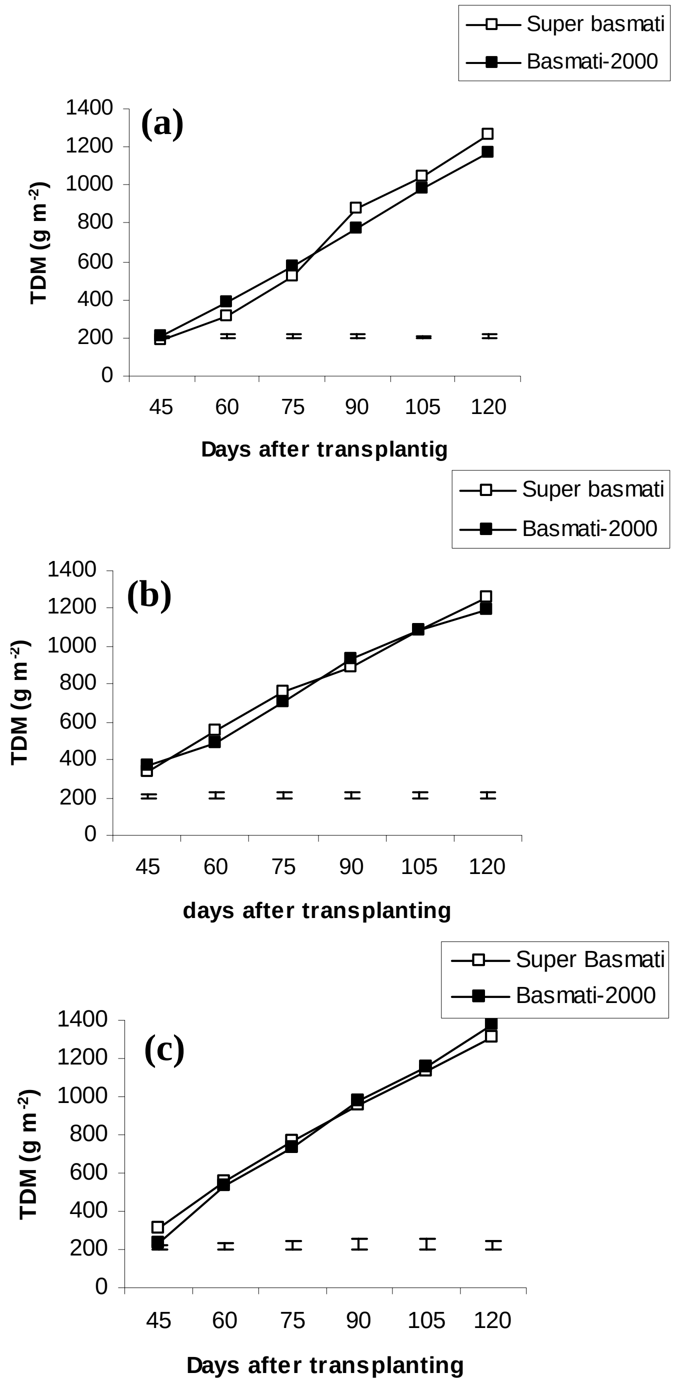

Fig. 5. Effect of cultivars on seasonal areal total dry biomass at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

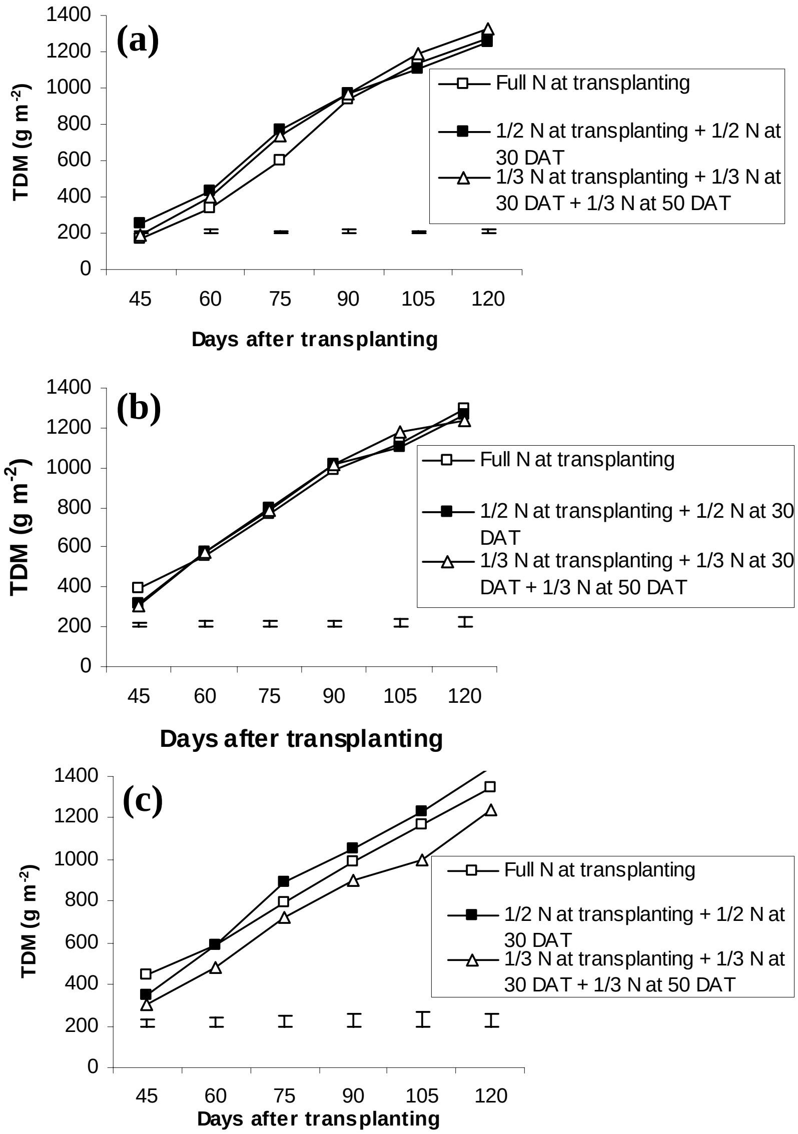

Fig. 6. Effect of split N application on seasonal areal total dry biomass at (a) Faisalabad, (b) Kala Shah Kaku and (c) Gujranwala, bars represent LSD value at 5%.

the growing seasons. This enabled the early transplanted plants to intercept more of the available radiation and thus increasing mean CGR (Table 3). The increase in mean CGR was associated with both the vegetative and reproductive phases when CGR differences were also pronounced between the treatments. High CGR is usually dependent upon rapid expansion of LAI or LAD to intercept available radiation especially early in the season. The relatively poor performance of the late transplanting of rice crops in ATDM production was, therefore, associated with their lower LAIs or LAD (Table 2), and thus less radiation interception during the growing seasons. Similar growth curves of rice crop were reported by others (Schnier *et al*., 1990; Dingkuhn *et al*., 1992). Seasonal ATDM accumulation was positively and linearly related with the seasonal LAD at all the locations, and 89.5% variance was accounted for the pooled data, indicating that 4.25gm^{-2} d^{-1} of ATDM was produced. However, Monteith (1981) found that relationship between ATDM or paddy yield and LAD will however depend on climatic conditions prevailing during a particular season, thus making it difficult to generalize over different sites and seasons. Seasonal ATDM accumulation was linearly related with the cumulative IPAR at all the locations. These values are similar to others who also demonstrated similar linear relationships between seasonal ATDM accumulation and cumulative IPAR (Kiniry *et al*., 2001; Ahmad *et al*., 2008). The late transplanting significantly increased RUE_{ATDM} as compared to early transplanting irrespective of cultivars. However, this response was markedly higher in cv. Basmati-2000 as compared to cv. Super Basmati. A significant interaction between date of transplanting and N split application affecting RUE_{ATDM} showed that two N split application significantly enhanced RUE_{ATDM} over full N or three N split and this response was significantly higher in late transplanting than early transplanting. In particular, radiation directly influences the plant ATDM (Monteith, 1977; Horie & Sakuratani, 1985). Many results showed that crop yield was positively related to RUE (Chen *et al*., 2003; Li *et al*., 2006; Whimeld & Smith, 1989, Ahmad *et al*., 2008; Quanqi *et al*., 2008). The findings presented in this study are in line with the results of above-mentioned scientists. Notwithstanding, treatment effects on RUE were also important. N split application increased RUE in the initial period before panicle initiation as noted by Horie *et al*., (1997). At this stage Fi was maximal and the greater $RUE_{\ ATDM}$ increased ATDM production.

References

Ahmad, S., T.H. Awan, A. Hussain, A. Ahmad and H. Ali. 2005. Effect of plant density and nitrogen rates on growth radiation use efficiency and yield of fine rice. *Proceedings of the International Seminar on Rice Crop*, Oct. 2-3, 2005. Rice Research Institute, Kala Shah Kaku, pp. 212-220.

Ahmad, S., M. Zia-ul-Haq, H. Ali, S.A. Shad, A. Ahmad, M. Maqsood, M.B. Khan, S. Mehmood and A. Hussain. 2008. Water and radiation use efficiencies of transplanted rice (*Oryza sativa* L.) at different plant densities and irrigation regimes under semi-arid environment. *Pak. J. Bot*., 40(1): 199-209.

Ahmad, S., A. Ahmad, M. Zia-ul-Haq, H. Ali, M.A. Anjum, M.A. Khan, T. Khaliq, A. Hussain and G. Hoogenboom. 2009. Resources use efficiency of field grown transplanted rice (*Oryza sativa* L.) under irrigated semiarid environment. *Journal of Food, Agriculture & Environment*, 7(2): 487-492.

Anonymous. 2008. *Economic Survey of Pakistan* 2007-2008, Finance Division, Economic Advisory Wing, Islamabad, Pakistan.

Biscoe, P.V. and J.N. Gallagher. 1978. Physical analysis of cereal yield. I. Production of dry matter. *Agric. Progress*, 34-50.

Campbell, C.S. 2000. *A field-scale study of earhon, water, and energy flow in irrigated rice*. *Ph.D. dissertation*, Texas A & M Univ., College Station.

Chen, Y.H., S.L. Yu and Z.W. Yu. 2003. Relationship between amount of PAR interception and grain output of wheat communities. *Acta Agron. Sin*., 29(5): 730-734.

Dingkuhn, M., H.F. Schnier, S.K. DeDatta, K. Dorffling, C. Javellana and R. Pamplona. 1990. Nitrogen fertilization of direct seeded flooded and R. transplanted rice. II Interaction among canopy properties. *Crops Science*, 30: 1284-1292.

Dingkuhn, M., S.K. De Datta, C. Javellana, R. Pamplona and H.F. Schnier. 1992. Effect of late-season N fertilization on photosynthesis and yield of transplanted and direct-seeded tropical flooded rice. I. Growth dynamics. *Field Crops Research*, 28: 223-234.

Dingkuhn, M., D.E. Johnson, A. Sow and A.Y. Audebert. 1999. Relationships between upland rice canopy characteristics and weed competitiveness. *Field Crops Res*., 61: 79-95.

Ehsanullah, Attaullah, M.S. Cheema and M. Usman. 2001. Rice Basmati-385 response to single and split application of nitrogen at different growth stages. *Pak. J. Agric. Sci*., 38: 1-2, 84-86.

Gallagher, J.N. and P.V. Biscoe. 1978. Radiation absorption, growth and yield of cereals. *J. Agric. Sci. Camb*., 19: 47-60.

Grigg, B.C., C.A. Beyrouty, R.J. Norman, E.E. Gbur, M.G. Hanson and B.R. Wells. 2000. Rice responses to changes in floodwater and N timing in southern USA. *Field Crops Res*., 66: 73-79.

Hasegawa, T. and T. Horie. 1996. Leaf N, plant age and crop DM production in rice. *Field Crops Res*., 23: 107-116.

Horie, T., M. Ohnishi, J.F. Angus, L.G. Lewin, T. Tsukaguchi and T. Matano. 1997. Physiological characteristics of high-yielding rice inferred from cross-location experiments. *Field Crops Res*., 52: 55-67.

Horie, T. and T. Sakuratani. 1985. Studies on crop-weather relationship model of rice. I. Relation between absorbed solar radiation by the crop and dry matter production. *J. Agric. Met*., 40: 31-242.

Hunt, R. 1978. *Plant Growth Analysis*. The Inst. of Bio. Studies in Bio. Edward Arnold (Pub.) Ltd. 96: 8-38.

Iqbal, S., A. Ahmad, A. Hussain, M.A. Ali, T. Khaliq and S.A. Wajid. 2008. Influence of transplanting date and nitrogen management on productivity of paddy cultivars under variable environments. *International Journal of Agriculture & Biology*, 10(3): 288-292.

Khaliq, T., A. Ahmad, A. Hussain and M.A. Ali. 2008. Maize hybrids response to nitrogen rates at multiple locations in semiarid environment. *Pak. J. Bot*., 41(1): 207-224.

Kiniry, J.R., G.Mc-Cauley, Y. Xie and J.G. Arnold. 2001. Rice parameters describing crop performance of four rice Cultivars. *Agron. J*., 93: 6, 1354-1361.

Li, Q.Q., Y.H. Chen, W. Wu, S.Z. Yu, X.B. Zhou, Q.Y. Dong and S.L. Yu. 2006. Effects of straw mulching and irrigation on solar energy utilization efficiency of winter wheat farmland. *Chin. J. Appl. Ecol*., 17(2): 243-246.

Manzoor, Z., T.H. Awan, M. E. Safdar, M. Akhtar, S. Hussain and M.M. Ashraf. 2005. Effect of different nitrogen levels on yield and yield components of Basmati-2000. *Proceedings of the International Seminar on Rice Crop.* Oct. 2-3, 2005. Rice Res. Inst. Kala Shah Kaku. pp. 130-134.

Monteith, J.L. 1977. Climate and efficiency of crop production in Britain. *Philosophical transaction of Royal Society London*, B. 281: 277-294.

Montieth, J.L. 1981. Does light limit crop production? In: *Physiological process limiting plant productivity,* (Ed.): C.B. Johnson. Butterworths, pp. 22-38.

Murty, P.S.S. and M.S. Murty. 1981. Influence of LAI at flowering on the productive efficiency of long duration rice cultures. *Oryza*, 18: 35-38.

Patel, S.R. and D.S. Thakur. 1997. Yield of rice as influenced by split application of nitrogen. *J. Maharaeshtra Agri. Univ*., 22: 2, 215-216.

Quanqi, Li., C. Yuhai, L. Mengya, Z. Xunbo, Y. Songlie and D. Baodi. 2008. Effects of irrigation and planting patterns on radiation use efficiency and yield of winter wheat in North China. *Agricultural Water Management*, 95: 469-476.

Rao, K.S., B.T.S. Moorthy, A.B. Dash and S.B. Lodh. 1996. Effect of time of transplanting on grain yield and quality traits of Basmati-type scented rice (*Oryza sativa*) varieties in Coastal Orissa. *Ind. J. Agri. Sci*., 66(6): 333-337.

Ritchie, J.T., U. Singh, D.C. Godwin, and W.T. Bowen. 1998. Cereal Growth, Development and Yield, In: *Understanding options for Agricultural Production*, (Eds.): G.Y. Tsuji, G. Hoogenboom and P.K. Thornton. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 79-98.

Salvagiotti, F. and D.J. Miralles. 2008. Radiation interception, biomass production and grain yield as affected by the interaction of nitrogen and sulfur fertilization in wheat. *Europ. J. Agronomy*, 28: 282-290.

Schinir, H.F., M. Dingkuhn, S.K. DeDatta, K. Mengal and J.E. Faronilo. 1990. Nitrogen fertilization of direct seeded vs transplanted rice. I. Nitrogen uptake photosynthesis, growth and yield. *Crop Science*, 30: 1276-1284.

Sinclair, T.R. and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. *Crop Science*, 29: 90-98.

Sinclair, T.R. and R.C. Muchow. 1999. Radiation use efficiency, In: *Advances in Agronomy*, 215-265.

Steel, R.G.D., J.H. Torrie, and D.A. Dickey. 1997. *Principles and practices of Statistics, A Biometric Approach*. 3rd ed. McGraw Hill, Int. Book Co. Inc. Singapore.

Szeicz, G. 1974. Solar radiation for plant growth. *J. Appl. Ecol*., 11: 617-636.

Takai, T., M. Shoji, N. Takahiro, O. Akikiro, S. Tatsuhiko and T. Horie. 2005. Rice yield potential is closely related to crop growth rate during late reproductive period. *Field Crops Research*, 96: 328-335.

Van der Werf, A. 1996. Growth analysis and photoassimilate portioning. In: *Photoassimilate Distribution in Plants and Crops*: (Eds.): E. Zamski, A. Schaffer, Source-Sink Relationship. Marcel Dekker Inc., New York, pp. 1-20.

Whitfied, D.M., C.J. Smith, O.A. Gyles and G.C. Wright. 1989. Effects of irrigation, nitrogen and gypsum on yield, nitrogen accumulation and water use of wheat. *Field Crops Res*., 20: 261-277.

Whimeld. D.M. and C.J. Smith. 1989. Effect of irrigation and nitrogen on growth, light interception and efficiency of light conversion in wheat. *Field Crop Research*, 20: 279-295.

(Received for publication 21 January 2009)