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Integrated Effect of Plant Density, N Rates and Irrigation Regimes on the Biomass Production, N Content, PAR Use Efficiencies and Water Productivity of Rice Under Irrigated Semiarid Environment

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Abstract

Two field experiments were conducted for two years (2000 and 2001) at Agronomic Research Area, University of Agriculture Faisalabad (UAF), Pakistan. There were 15 treatment combinations for experiment-I having three plant densities, viz., one seedling hill^{-1} (PD_1), two seedlings hill^{-1} (PD_2) and three seedlings hill^{-1} (PD_3) and five nitrogen rates, viz., 0, (N_0); 50, (N_{50}); 100, (N_{100}); 150, (N_{150}); and 200 (N_{200}) kg N ha^{-1}. Experiment-II also included 15 treatments having three plant densities, viz., one seedling hill^{-1} (PD_1), two seedlings hill^{-1} (PD_2) and three seedlings hill^{-1} (PD_3) and five irrigation regimes, viz., 62.5 cm (I_1), 77.5 cm (I_2), 92.5 cm (I_3), 107.5 cm (I_4), and 122.5 cm (I_5). A randomized complete block design (RCBD) was employed with three repetitions. The results for experiment-I revealed that the highest biomass (1438 g m^{-2}), grain yield (497 g m^{-2}), crop growth rate (15.36 g m^{-2} d^{-1}), net assimilation rate (4.24 g m^{-2} d^{-1}) were observed in the treatment having combination of two seedlings hill^{-1} and 200 kg N ha^{-1} (PD_2N_{200}). The agronomic and economic nitrogen and PAR use efficiencies were also higher in this treatment. In case of experiment-II, the highest biomass and grain yield were obtained in case of treatment having combination of two seedlings hill^{-1} and 107.5 cm irrigation regime ($PD_2I_{107.5}$). The irrigation application based water productivity ranged from 0.36 kg mm^{-3} to 0.61 kg mm^{-1}, irrigation plus precipitation based water productivity ranged from 0.32 kg mm^{-3} to 0.55 kg mm^{-3} and evapotranspiration based water productivity ranged from 0.65 kg mm^{-3} to 0.84 kg mm^{-3} among 15 treatments combination of plant density and irrigation regimes. This study concludes that for increasing the benefits for the resource-poor growers, the integration of crop management practices is an optimum strategy to substantially increase the resources use efficiency under irrigated semiarid environment.

Keywords: irrigated rice, nutrient management, planting density, photosynthesis, yield potential

Introduction

Pakistan grows sufficient high quality rice to meet both domestic demand and for export. The majority of the rice is grown in rice-wheat cropping system. Rice is an important food and cash crop in Pakistan and ranks second after cotton (*Gossypium hersutum* L.). In 2008, rice contributed 5.9% in value added agriculture (VAA) and 1.35% in gross domestic product (GDP) and it was sown on 2.963 M ha with total production of 6.952 M tons and average yield of 2,346 kg ha^{-1} (GOP, 2009). In Pakistan, rice is mainly produced in three main areas in three provinces; conventional (rice bowl) and non-conventional zone in Punjab; some parts in Sindh; and Swat valley in North Western Frontier Post with respect to areas under cultivation and production wise, respectively. In 2008, rice export figure for Pakistan is 2809 thousands tons including both basmati and non-basmati cultivars (GOP, 2009) and Fig. 1 shows the area, production, productivity and export of rice from 1974 to 2008.

In semiarid environmental conditions water and nutrients are two important input resources for harvesting good crop yield. In many regions of the world fresh water sources from both surface and ground water are shrinking up, causing a serious treat to the agricultural sector (Mahajan *et al*., 2009; Seckler *et al*., 1998; Tuong and Bhuiyan, 1994). In Asian countries per capita availability of water has declined by 40-60% between 1955 and 1990 (Gleik, 1993; Hira *et al*., 2004; Ladha *et al*., 2003). However, situation is more adverse presently. Rice production in Asia is increasingly constrained by water (Arora, 2006). In Pakistan, rice production is under threat due to shrinking availability of fresh canal surface water due declining of storage capacity of dams. Precipitation is insufficient and concentrated in highly erratic temporally like other regional countries having moon soon season in summer (July-August) (GOP, 2009). Therefore, due to this ground water recharge is also under annul deficit and going deep and deep year by year and gradually pumping becoming unsustainable and costly due to rapid high prices of electricity and fuel. Rice crop in

Pakistan is an important target for reduction in water use compared to other crops (Ahmad *et al*., 2009). Nitrogen is an important element being the structural and functional proteins, chlorophyll, nucleic acid and plays a pivotal role in crop development (Tisdale *et al*., 1990). The reason of nitrogen deficiency in Pakistani soils is the high cropping intensity and failure of sowing of leguminous crops in the existing cropping patterns (Ahmad *et al*., 2009) in addition to other losses, i.e., runoff, de-nitrification and volatilization. The major causes of low yield in Pakistan are deficiency of nutrients particularly nitrogen and less plant density because in Pakistan rice is manually transplanted by the highly un-skilled labor. There is an urgent need to study the integration of various crop management factors such as plant density, nitrogen rates and irrigation regimes to harvest the optimum rice yield under the existing resources situations.

Under interactive effects of various management practices, crop above-ground biomass can be analyzed as a function of the amount of radiation-absorbed by the foliage. In field crops, there is often a linear relationship between cumulative-intercepted photo-synthetically active radiation (PAR) and accumulated-biomass (Ceotto and Castelli, 2002; Gallagher and Biscoe, 1978; Kiniry *et al*., 1989; Loomis and Williams, 1963; Monteith, 1972; 1977; Russell *et al*., 1989; Sinclair and Muchow, 1999). Crop radiation use efficiency (RUE) is defined as the amount of biomass accumulated per unit solar radiation intercepted (Gallagher and Biscoe, 1978; Monteith, 1972; 1977). The fraction of intercepted-radiation may be estimated from zenith-angle, leaf area index (LAI) and leaf angle distribution (Ross, 1975). RUE is a simple measure of carbon assimilation integrated over the whole crop canopy. Crop photosynthetic rates, and hence RUE, is influenced by leaf nitrogen (g N m^{-2} leaf area), when water is not limiting factor (Sinclair and Horie, 1989). The efficiency of the conversion of the intercepted-radiation into dry matter in cereals differs between pre and post-anthesis periods (Gregory *et al*., 1992; Kiniry *et al*., 1989). Therefore, determining RUE is an important approach for understanding crop growth and yield (Sinclair and Muchow, 1999).

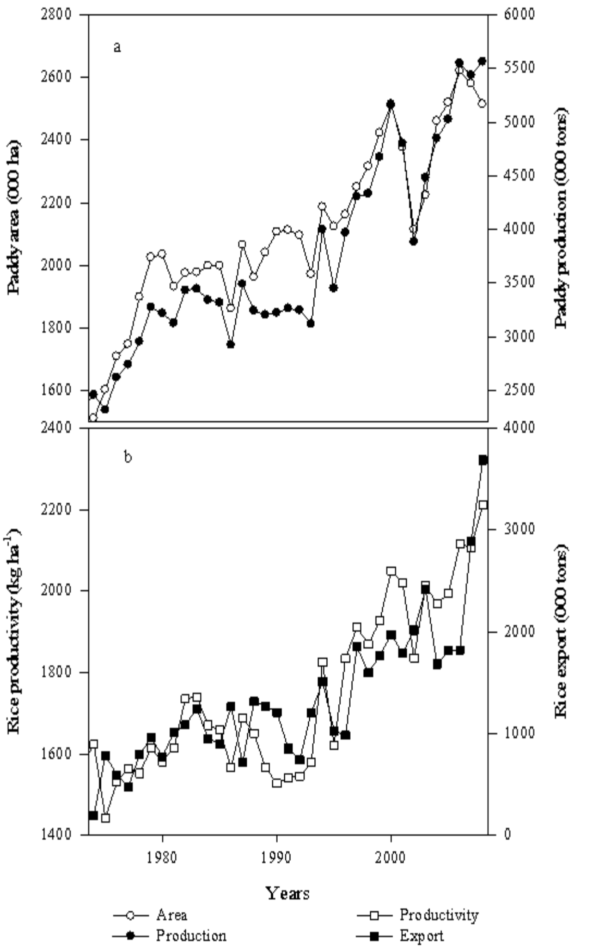

Fig. 1. Rice area, production (a), and productivity and export (b) in Pakistan from 1974-2008

Individual effects of crop management factors above-ground biomass has been applied to rice crop on a number of occasions. However, there are few studies that cover the integration dynamics of different management factors. The aims of this study were (1) to study integrated effects of plant density and nitrogen rates on biomass, grain yield, and nitrogen and PAR use efficiencies and (2) to study the integrated effects of plant density and irrigation regimes on biomass, grain yield, water productivity (grain yield/irrigation applied; grain yield/irrigation + precipitation; grain yield/cumulative ET) and PAR use efficiency under irrigated semiarid environment.

Materials and methods

Location description

The field experiments were conducted in the experimental area of the Department of Agronomy, at University of Agriculture Faisalabad (UAF), Punjab, Pakistan (36.25° N, 73.09° E, and 184.4 m altitude from sea level). The experimental site is located in the rice-based cropping zone in the semiarid area of Pakistan. The soil is a Lyallpur clay loam (aridisol-fine-silty, mixed, hyperthermic Ustalfic, Haplarged in USDA classification and Haplic Yermosols in FAO classification) and physical and chemical characteristics are presented in Tab. 1. The daily agro-meteorological information regarding maximum air temperature, minimum air temperature and precipitation and solar radiation were recorded by an automatic weather station located 500 m from the experimental field.

Field data collection

The experimental data that were collected from field experiments which were conducted during 2000 and 2001 in Faisalabad, Pakistan.

Experiment 1

Interactive effects of plant density and nitrogen rates were evaluated in experiment-I. There were three plant

Tab. 1. Soil physical and chemical properties at 0-15 cm depth at the experimental site

Year	Site	Soil classification	Soil type	pH	OM (%)	Total N (%)	Available P (ppm)	Available K (ppm)
2000	FSD	Aridsol-fine-silty	Clay loam	7.8	0.73	0.046	6.15	193
2001	FSD	Aridsol-fine-silty	Clay loam	7.9	0.76	0.048	6.19	195

FSD, Faisalabad; OM, organic matter

Tab. 2. Treatment combinations of plant density and nitrogen levels (Exp-I) and plant density and irrigation regimes (Exp-II) for field experimentation for rice cultivar 'Basmati-385' at Faisalabad, Pakistan during 2000 and 2001

Experiment-I				Experiment-II	
Sr. No.	Treatment combinations	N levels (kg ha^{-1})	PD (seedlings hill^{-1})	Irrigation regimes (cm)	Treatment combinations
1	PD_1N_0	0	One	62.5	$PD_1I_{62.5}$
2	PD_1N_{50}	50	One	77.5	$PD_1I_{77.5}$
3	PD_1N_{100}	100	One	92.5	$PD_1I_{92.5}$
4	PD_1N_{150}	150	One	107.5	$PD_1I_{107.5}$
5	PD_1N_{200}	200	One	122.5	$PD_1I_{122.5}$
6	PD_2N_0	0	Two	62.5	$PD_2I_{62.5}$
7	PD_2N_{50}	50	Two	77.5	$PD_2I_{77.5}$
8	PD_2N_{100}	100	Two	92.5	$PD_2I_{92.5}$
9	PD_2N_{150}	150	Two	107.5	$PD_2I_{107.5}$
10	PD_2N_{200}	200	Two	122.5	$PD_2I_{122.5}$
11	PD_3N_0	0	Three	62.5	$PD_3I_{62.5}$
12	PD_3N_{50}	50	Three	77.5	$PD_3I_{77.5}$
13	PD_3N_{100}	100	Three	92.5	$PD_3I_{92.5}$
14	PD_3N_{150}	150	Three	107.5	$PD_3I_{107.5}$
15	PD_3N_{200}	200	Three	122.5	$PD_3I_{122.5}$

densities, i.e., one seedling hill^{-1}, two seedlings hill^{-1} and three seedlings hill^{-1}, five nitrogen rates, i.e., 0, 50, 100, 150, and 200 kg N ha^{-1}. The detailed descriptions of the 15 treatments having combinations of plant density and nitrogen rates are presented in Tab. 2. Additional details on plant sampling and observations can be found in Ahmad *et al.* (2008; 2009).

Experiment 2

Interactive effects of plant density and irrigation regimes were studied in experiment-II. There were three plant densities, i.e., one seedling hill^{-1}, two seedlings hill^{-1} and three seedlings hill^{-1} and five irrigation regimes, i.e., 62.5, 77.5, 92.5, 107.5, and 122.5 cm. The detailed descriptions of the 15 treatments having combinations of plant density and irrigation regimes are presented in Tab. 2.

Experimental procedures

Thirty-day-old rice cultivar ('Basmati-385') seedlings were transplanted manually in a half puddled field in standing water at 22.5 cm by 22.5 cm hill to hill and row to row distance in both experiments during both years. The nitrogen was applied in two equal splits through urea in both experiments and years. In exp-I, the nitrogen was applied as per treatment levels. In exp-II, the first dose (75 kg ha^{-1}) was applied during puddling before the final cultivation on 04 July in 2000 and 03 July in 2001. The second dose (75 kg ha^{-1}) was applied 22 days after transplanting (DAT) on 26 July in 2000 and 25 July in 2001. In addition, phosphorus and potassium (P_2O_5 and K_2O; 65 kg each) in the form of single super phosphate (SSP), and potassium sulphate were also applied during puddling prior to final cultivation in both experiments during both years. Zinc at a rate of 25 kg ha^{-1} was applied at puddling before final cultivation to avoid zinc deficiencies under standing water conditions in both experiments during both years. In Exp-I, total 16 irrigations were applied, while in Exp-II, irrigation water was applied as per treatments. The experimental plots in Exp-II were irrigated according to the respective treatments and as per schedules. Water in required amount was applied using a cutthroat flume (90 cm × 20 cm). Time for application of required amount of water wad calculated using the Equation 1, [T = Ad/Q], where *T* is the time required for irrigation for each treatment; *A* is the area to be irrigated; *d* is the depth of irrigation application; and *Q* is discharge or flow rate. The local agronomic practices for weed, disease, and pest control were uniform and crop was harvested in October. Additional details on crop management can be found in Ahmad *et al.* (2008; 2009).

Calculations and derivations

The following measurements and calculations were made following the prescribed standard procedures.

Intercepted photosynthetically active radiation (IPAR; MJ m^{-2} d^{-1})

The daily total incident solar radiation (ISR) was estimated using Equation 2 suggested by the Ångström, (1924), [$SR = SR_0$ (a + b n/N)], where SR_0 is the extra-terrestrial radiation, *N* is the maximum possible sunshine duration, *n* is the measured sunshine duration, while *a*, and *b* are constants. The data for *n* was obtained from the observatory of the Department of Crop Physiology (CP), UAF, which is in the nearby block about 500 m from the experimental field.

Fraction of intercepted radiation (Fi)

The *Fi* was estimated from leaf area index by using the Equation 3 (the exponential attenuation equation) suggested by Monteith and Elston (1983), [Fi = {1-exp (-k × LAI)}], where *Fi* is the fraction of intercepted radiation, *k* is extinction coefficient for total solar radiation. The PAR was calculated by multiplying 0.5 to the total incident radiation. The PAR intercepted (Sa) was estimated by multiplying *Fi* values to their respective *Si* values by using Equation 4 as suggested by Szeicz (1974), [Sa = (Fi × Si)], where *Fi* is the fraction of intercepted radiation and *Si* is the total incident radiation. The cumulative intercepted phototosynthetically active radiation (CIPAR) was also estimated.

Radiation use efficiency (RUE; g MJ^{-1})

The RUE for above-ground biomass (RUE_{AB}) and grain yield (RUE_{GY}) is the amount of above-ground biomass or grain yield produced per unit cumulative intercepted PAR, and was estimated by using Equation 5 suggested by Monteith (1977), [RUE_{AB} = AB/CIPAR], or [RUE_{GY} = GY/CIPAR], where, *AB* and *GY* and *CIPAR* are the above-ground biomass, grain yield and cumulative intercepted photosynthetically active radiation, respectively.

Agronomic nitrogen use efficiency (ANUE; kg kg^{-1})

The ANUE was estimated by following the Equation 6 suggested by Saleem (1994). [ANUE = (GY_F-GY_C)/Rate of N applied], where GY_F is the grain yield with *F* rate of nitrogen fertilizer application and GY_C is the grain yield without nitrogen application.

Economic nitrogen use efficiency (ENUE; rupees kg^{-1})

For benefits of the grower for decision making ENUE was also calculated by using the Equation 7 suggested by Saleem (1994) and Yadav (2003), [ENUE = (cost of GY_F-cost of GY_C) / cost of N fertilizer applied], where, cost of GY_F is the monetary return with particular rate of nitrogen fertilizer and GY_C is the monetary return without fertilizer application.

Leaf area duration (LAD; days)

The LAD is cumulative stay green time for assimilatory surface area (leaf area) and is calculated by Equation 8 suggested by the Watson (1947), [LAD = (LAI_1 + LAI_2)/2 × (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 of rice crop.

Crop growth rate (CGR; g m^{-2} d^{-1})

The CGR was calculated by Equation 9 proposed by Hunt (1978), [CGR = (W_2-W_1) / (T_2-T_1), where W_1 and W_2 are above-ground biomass at times T_1 and T_2, respectively.

Net assimilation rate (NAR; g m^{-2} d^{-1})

The mean NAR was estimated by following Equation 10 suggested by Hunt (1978), [NAR = AB / LAD], where AB and LAD are final above-ground biomass and cumulative leaf area duration, respectively.

Estimation of water use

The cumulative evapotranspiration (CET) was determined by multiplying potential Evapotranspiration (PET) with appropriate value of crop coefficient, which usually corresponds closely with the green crop cover as suggested by Dooreboss and Pruitt (1977). Daily Penman's PET was calculated by using standard program of "CROPWAT" developed by the FAO (1992).

Water productivity (WP; kg m^{-3})

The WP was calculated as above-ground biomass or grain yield produced per unit of water applied and was calculated by using the Equation 11, [I-WP = Grain yield / irrigation applied]. The irrigation + precipitation (I+P-WP) was calculated by using the Equation 12, [I+P-WP = Grain yield / irrigation applied + precipitation] and evapotranpiration (ET) based water productivity was also estimated by using the Equation 13, [ET-WP = Grain yield/ cumulative ET].

Transpiration efficiency (TE; g l^{-1})

The TE for above-ground biomass was estimated by using Equation 11 suggested by Tanner and Sinclair (1983), [TE = AB/T], where *AB* is the above-ground biomass and *T* is the transpiration in mm.

Statistical analysis

The data were statistically analyzed using MSTSTC software (Freed and Scott, 1986). Analysis of variance techniques were employed to test the overall significance of the data, while differences between treatment means were compared using the least significant difference (LSD) test at $P \leq 0.5$ (Steel *et al.*, 1997).

Results

Growing environment

The climate of the area is semiarid with an average annual maximum and minimum temperatures of 31.2°C and 17.2°C, respectively, and annual precipitation ranges from 400 to 800 mm. However, during the rice cropping season for local basmati (*indica*) varieties in Pakistan (June-October), the average seasonal maximum and minimum temperatures are 37.1°C and 24.3°C, respectively. In general, in both 2000 and 2001 average maximum air temperature and average minimum temperature which were 16% and 29.2% higher than their respective annual temperatures. Overall, 75% of the total annual precipitation occurs during the rice season (GOP, 2009). The monthly average solar radiation during the rice season ranges from 20 to 24.5 MJ m^{-2} d^{-1} versus an annual average range of 14-16 MJ m^{-2} d^{-1}, which is 30% and 35% higher than their respective annual values. The detailed weather data for rice seasons 2000 and 2001 are presented in Fig. 2.

Experiment-I

Rice biomass, grain yield, crop growth rate, net assimilation rate, agronomic and economic nitrogen and PAR use efficiencies as influenced by 15 treatment combinations of plant density and nitrogen rates during 2000 and

Tab. 3. Final biomass, grain yield, crop growth rate, net assimilation rate, water productivity and PAR use efficiency of rice cultivar 'Basmati-385' as affected by plant density and nitrogen rates during 2000 and 2001 at Faisalabad, Pakistan

Exp-I Treatments	Biomass (g m^{-2})	GY (g m^{-2})	CGR (g m^{-2} d^{-1})	NAR (g m^{-2} d^{-1})	$ANUE_{AB}$ (kg kg^{-1})	$ANUE_{GY}$ (kg kg^{-1})	$ENUE_{GY}$ (Rs. kg^{-1})	RUE_{AB} (g MJ^{-1})	RUE_{GY} (g MJ^{-1})
				2000					
PD_1N_0	964	276	10.63	3.62	-	-	-	0.98	0.28
PD_1N_{50}	1046	309	11.34	3.71	10.27	3.03	3.65	1.03	0.31
PD_1N_{100}	1150	344	12.48	3.78	11.40	3.41	3.92	1.10	0.33
PD_1N_{150}	1233	409	13.32	3.83	12.27	4.07	4.29	1.15	0.38
PD_1N_{200}	1260	423	13.59	3.75	12.56	4.22	4.47	1.15	0.39
PD_2N_0	995	311	10.94	3.74	-	-	-	1.01	0.32
PD_2N_{50}	1090	340	11.89	3.87	10.71	3.34	3.74	1.08	0.34
PD_2N_{100}	1200	401	12.99	3.95	11.90	3.98	4.11	1.15	0.38
PD_2N_{150}	1297	438	13.95	4.03	12.91	4.36	4.47	1.21	0.41
PD_2N_{200}	1350	472	14.49	4.02	13.46	4.70	4.65	1.24	0.43
PD_3N_0	985	313	10.84	3.70	-	-	-	1.00	0.32
PD_3N_{50}	1074	336	11.72	3.81	10.54	3.30	3.78	1.06	0.33
PD_3N_{100}	1173	375	12.71	3.86	11.63	3.72	4.12	1.12	0.36
PD_3N_{150}	1274	423	13.72	3.96	12.67	4.21	4.39	1.19	0.39
PD_3N_{200}	1312	446	14.10	3.90	13.07	4.44	4.52	1.20	0.41
				2001					
PD_1N_0	1026	287	11.25	3.83	-	-	-	1.23	0.34
PD_1N_{50}	1113	326	12.12	3.91	10.93	3.20	3.84	1.29	0.38
PD_1N_{100}	1224	362	13.22	3.99	12.14	3.59	4.11	1.36	0.40
PD_1N_{150}	1313	431	14.11	4.03	13.06	4.29	4.51	1.42	0.47
PD_1N_{200}	1342	446	14.40	3.95	13.37	4.45	4.69	1.43	0.47
PD_2N_0	1060	327	11.58	3.96	-	-	-	1.27	0.39
PD_2N_{50}	1161	353	12.59	4.07	11.40	3.46	3.86	1.34	0.41
PD_2N_{100}	1278	423	13.76	4.16	12.67	4.20	4.31	1.42	0.47
PD_2N_{150}	1381	461	14.79	4.24	13.74	4.59	4.69	1.50	0.50
PD_2N_{200}	1438	497	15.36	4.23	14.33	4.95	4.88	1.53	0.53
PD_3N_0	1057	329	11.55	3.94	-	-	-	1.27	0.39
PD_3N_{50}	1143	354	12.41	4.01	11.22	3.47	3.94	1.32	0.41
PD_3N_{100}	1249	360	13.47	4.07	12.38	3.57	4.24	1.39	0.40
PD_3N_{150}	1356	446	14.54	4.16	13.49	4.44	4.6	1.47	0.48
PD_3N_{200}	1396	470	14.95	4.11	13.91	4.68	4.74	1.49	0.50

GY, Grain yield; CGR, Crop growth rate; NAR, Net assimilation rate; ANUE, Agronomic nitrogen use efficiency; ENUE, Economic nitrogen use efficiency; RUE, Radiation use efficiency

2001 are presented in Tab. 3. Averaged over the treatment combinations, the rice biomass ranged from 964 g m^{-2} to 1350 g m^{-2} during 2000 and 1026 g m^{-2} to 1438 g m^{-2} during 2001 (Tab. 3). The seasonal above-ground biomass accumulation for 15 treatment combinations of plant density and nitrogen rates is presented in Figs. 3 and 4 (a, c, and e) during 2000 and 2001. The Figs. 3 and 4 shows that the accumulation pattern of above-ground biomass was similar during both years and it was slow up to active tillering stage and then there was a linear increase followed by a slow increase phase. The comparatively superior performance of above-ground production at high rates of nitrogen responded positively and this was associated with higher leaf area duration integral of leaf area index over time. This enabled the crop plants in these treatments to intercept more of the available radiation and thus higher crop growth rate. Biscoe and Gallagher (1978) reported that higher crop growth rate is usually upon rapid expansion of leaf area index to intercept available radiation in the growing season. The grain yield ranged from 276 g m^{-2} to 472 g m^{-2} in 2000 and 287 g m^{-2} to 497 g m^{-2} in 2001 (Tab. 3). The treatment combination having two seedlings hill^{-1} and 200 kg N ha^{-1} produced the highest biomass and grain yield during both years. The crop growth rate ranged from 10.63 g m^{-2} d^{-1} to 14.49 g m^{-2} d^{-1} in 2000 and 11.25 g m^{-2} d^{-1} to 15.36 g m^{-2} d^{-1} in 2001, while, the net assimilation rate ranged from 3.62 g m^{-2} d^{-1} to 4.03 g m^{-2} d^{-2} in 2000 and 3.83 g m^{-2} d^{-1} to 4.24 g m^{-2} d^{-1} in 2001 (Tab. 3). Agronomic nitrogen use efficiency for biomass ranged from 10.27 kg kg^{-1} to 13.46 kg kg^{-1} in 2000 and 10.93 kg kg^{-1} to 14.33 kg kg-1 in 2001, while, the agronomic nitrogen use efficiency for grain yield ranged from 3.03 kg kg^{-1} to 4.70 kg

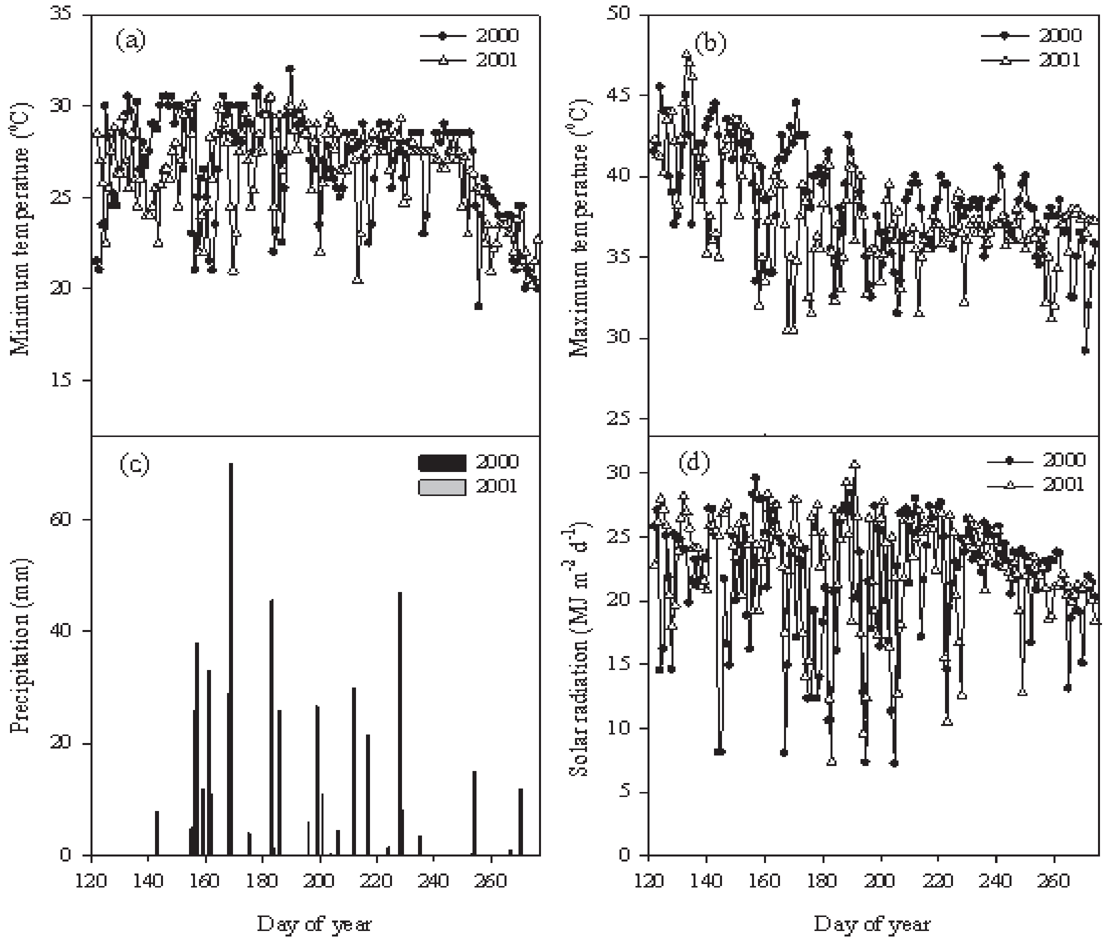

Fig. 2. Rice season daily weather conditions for Faisalabad, Pakistan: minimum temperature (a), daily maximum (b), daily precipitation (c) and daily solar radiation (d) for years 2000 and 2001

kg^{-1} in 2000 and 3.20 kg kg^{-1} to 4.95 kg kg^{-1} in 2001. The economic nitrogen use efficiency ranged from 3.65 rupees kg^{-1} to 4.65 rupees kg^{-1} in 2000 and 3.84 rupees kg^{-1} to 4.88 rupees kg^{-1} in 2001 (Tab. 3). The highest agronomic and economic nitrogen use efficiencies were obtained in the treatment having combination of two seedlings $hill^{-1}$ and 200 kg N ha^{-1} (PD_2N_{200}). Total incident PAR was 1958 MJ m^{-2} in 2000 and 1974 MJ m^{-2} in 2001, out oh which about 52.8% and 45.2% were intercepted. The radiation use efficiency for biomass ranged from 0.98 g MJ^{-1} to 1.24 g MJ^{-1} during 2000 and 1.23 g MJ^{-1} to 1.53 g MJ^{-1} in 2001. The radiation use efficiency for grain yield ranged from 0.28 g MJ^{-1} to 0.43 g MJ^{-1} in 2000 and 0.34 g MJ^{-1} to 0.53 g MJ^{-1} in 2001 (Tab. 3). The highest values of the radiation use efficiencies were found in case of treatment having combination of two seedlings $hill^{-1}$ and 200 kg N ha^{-1} (PD_2N_{200}).

Experiment-II

Rice biomass, grain yield, crop growth rate, net assimilation rate, irrigation, irrigation plus precipitation and evapotraspiration based water productivity and PAR use efficiencies as influenced by 15 treatment combinations of plant density and irrigation regimes during 2000 and 2001 are presented in Tab. 4. Averaged over the treatment combinations, the rice biomass ranged from 1174 g m^{-2} to 1448 g m^{-2} during 2000 and 1114 g m^{-2} to 1428 g m^{-2} during 2001 (Tab. 4). The seasonal above-ground biomass accumulation for 15 treatment combinations of plant density and irrigation regimes is presented in Figs. 3 and 4 (b, d, and f) during 2000 and 2001. The Figs. 3 and 4 shows that the accumulation pattern of above-ground biomass was slow during initial four or five weeks and then there was a linear increase. The treatment combinations having higher levels of irrigation application significantly and linearly increased above-ground biomass accumulation in both years. The grain yield ranged from 306 g m^{-2} to 471 g m^{-2} in 2000 and 355 g m^{-2} to 497 g m^{-2} in 2001 (Tab. 4). The treatment combination having two seedlings $hill^{-1}$ and 107.5 cm irrigation regime produced the highest biomass and grain yield during both years. The crop growth rate ranged from 9.72 g m^{-2} d^{-1} to 12.36 g m^{-2} d^{-1} in 2000 and 9.29 g m^{-2} d^{-1} to 12.27 g m^{-2} d^{-1} in 2001, while, the net assimilation rate ranged from 4.41 g m^{-2} d^{-1} to 4.69 g m^{-2} d^{-2} in 2000 and 4.07 g m^{-2} d^{-1} to 4.63 g m^{-2} d^{-1} in 2001 (Tab. 4). Irrigation application water productivity ranged from

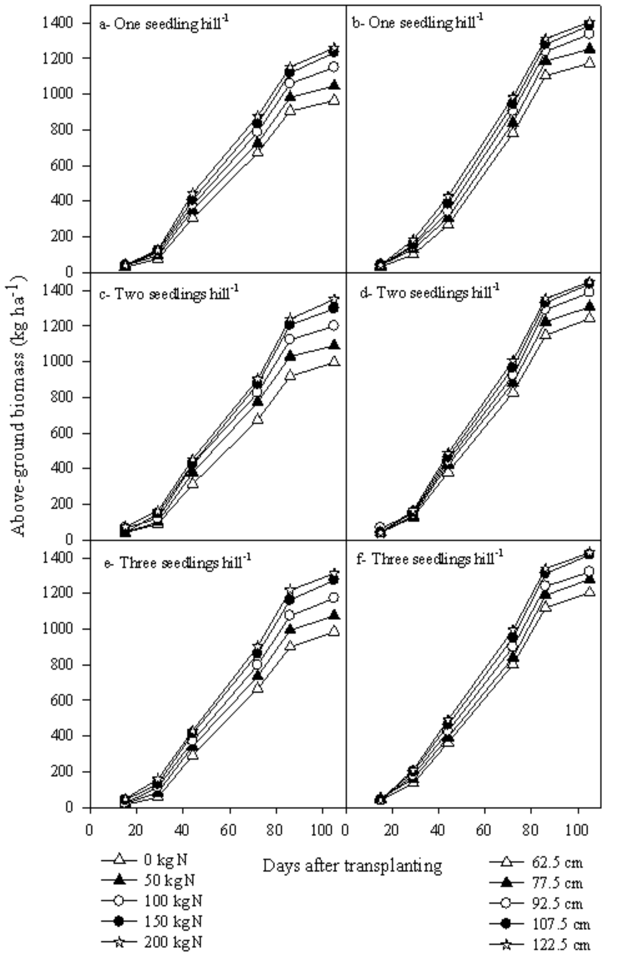

Fig. 3. Seasonal above-ground biomass accumulation as effected by plant density and nitrogen rates (a, c, and e) and plant density and irrigation regimes (b, d, and f) of rice cultivar 'Basmati-385' at Faisalabad, Pakistan during 2000

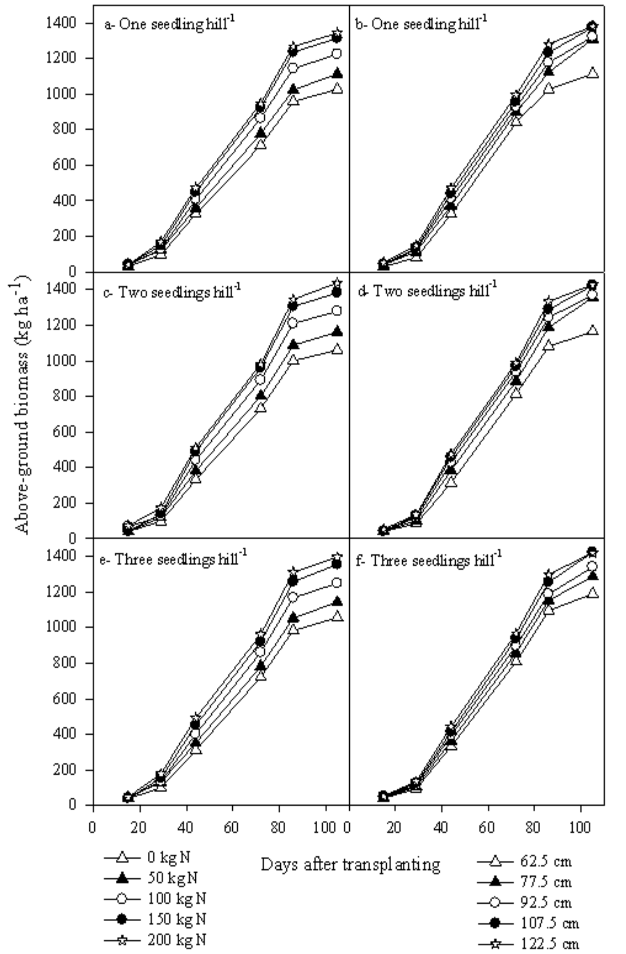

Fig. 4. Seasonal above-ground biomass accumulation as effected by plant density and nitrogen rates (a, c, and e) and plant density and irrigation regimes (b, d, and f) of rice cultivar 'Basmati-385' at Faisalabad, Pakistan during 2001

0.36 kg mm^{-3} to 0.59 kg mm^{-3} in 2000 and 0.34 kg mm^{-3} to 0.61 kg mm^{-3} in 2001. Total precipitation during both rice seasons was 115.7 mm in 2000 and 165 mm in 2001. Irrigation plus precipitation based water productivity ranged from 0.34 kg mm^{-3} to 0.52 kg mm^{-3} in 2000 and 0.34 kg mm^{-3} to 0.55 kg mm^{-3} in 2001. Evapotranspiration based water productivity ranged from 0.65 kg mm^{-3} to 0.78 kg mm^{-3} in 2000 and 0.73 kg mm^{-3} to 0.84 kg mm^{-3} in 2001 (Tab. 4). The water productivity values were higher at lower water regimes, while lower at higher water regimes. The radiation use efficiency for biomass ranged from 1.18 g MJ^{-1} to 1.36 g MJ^{-1} during 2000 and 1.31 g MJ^{-1} to 1.56 g MJ^{-1} in 2001, while, the radiation use efficiency for grain yield ranged from 0.31 g MJ^{-1} to 0.44 g MJ^{-1} in 2000 and 0.42 g MJ^{-1} to 0.54 g MJ^{-1} in 2001 (Tab. 4). The highest values of the radiation use efficiencies were found in case of treatment having combination of two seedlings $hill^{-1}$ and 107.5 cm irrigation regime ($PD_2I_{107.5}$).

Discussion

Among the improved cultural practices, number of seedling $hill^{-1}$ can play important roles in boosting yield of rice (Hasanuzzaman *et al.,* 2009a, b; Hossain *et al*., 2003). Number of seedlings $hill^{-1}$ is important factor for successful rice production because it influences the tiller formation, solar radiation interception, total sunshine reception, nutrient uptake, rate of photosynthesis and other physiological phenomena and ultimately affects the growth and development of rice plant. In densely populated rice field the inter specific competition between the plants is high in which sometimes results in gradual shading and lodging and thus favour increased production of straw instead of grain (Faruk *et al*., 2009). Irrigation levels also an important factor for plant productivity which plays vital role in biomass accumulation, dry matter partitioning and grain development (Hasanuzzaman and Karim 2007; Hasanuz-

Tab. 4. Final biomass, grain yield, crop growth rate, net assimilation rate, water productivity and PAR use efficiency of rice cultivar 'Basmati-385' as affected by plant density and irrigation regimes during 2000 and 2001 at Faisalabad, Pakistan

Exp-II Treatments	Biomass ($g\ m^{-2}$)	GY ($g\ m^{-2}$)	CGR ($g\ m^{-2}\ d^{-1}$)	NAR ($g\ m^{-2}\ d^{-1}$)	I-WP ($kg\ m^{-3}$)	I+P-WP ($kg\ m^{-3}$)	ET-WP ($kg\ m^{-3}$)	RUE_{AB} ($g\ MJ^{-1}$)	RUE_{GY} ($g\ MJ^{-1}$)
				2000					
$PD_1I_{62.5}$	1174	306	9.72	4.41	0.49	0.44	0.65	1.18	0.31
$PD_1I_{77.5}$	1254	368	10.43	4.42	0.48	0.43	0.70	1.23	0.36
$PD_1I_{92.5}$	1336	408	11.25	4.52	0.44	0.41	0.72	1.29	0.39
$PD_1I_{107.5}$	1386	430	11.74	4.46	0.40	0.37	0.70	1.31	0.41
$PD_1I_{122.5}$	1406	437	12.04	4.41	0.36	0.34	0.69	1.31	0.41
$PD_2I_{62.5}$	1242	366	11.31	4.67	0.59	0.52	0.78	1.25	0.37
$PD_2I_{77.5}$	1307	391	11.05	4.60	0.51	0.46	0.74	1.28	0.38
$PD_2I_{92.5}$	1388	430	11.76	4.69	0.47	0.43	0.76	1.34	0.41
$PD_2I_{107.5}$	1436	464	12.24	4.62	0.43	0.40	0.76	1.36	0.44
$PD_2I_{122.5}$	1448	471	12.36	4.54	0.38	0.36	0.74	1.35	0.44
$PD_3I_{62.5}$	1204	350	10.03	4.53	0.56	0.50	0.74	1.22	0.35
$PD_3I_{77.5}$	1279	379	10.67	4.50	0.49	0.45	0.72	1.25	0.37
$PD_3I_{92.5}$	1320	407	11.09	4.46	0.44	0.41	0.72	1.27	0.39
$PD_3I_{107.5}$	1416	451	12.15	4.55	0.42	0.39	0.74	1.34	0.43
$PD_3I_{122.5}$	1428	460	12.27	4.48	0.38	0.35	0.73	1.33	0.43
				2001					
$PD_1I_{62.5}$	1114	355	9.29	4.07	0.57	0.48	0.78	1.31	0.42
$PD_1I_{77.5}$	1309	388	11.08	4.47	0.50	0.43	0.75	1.49	0.44
$PD_1I_{92.5}$	1322	430	11.20	4.33	0.46	0.41	0.77	1.48	0.48
$PD_1I_{107.5}$	1376	454	11.65	4.29	0.42	0.38	0.75	1.51	0.50
$PD_1I_{122.5}$	1381	463	11.79	4.20	0.38	0.34	0.73	1.49	0.50
$PD_2I_{62.5}$	1165	384	9.64	4.26	0.61	0.52	0.84	1.37	0.45
$PD_2I_{77.5}$	1356	411	11.44	4.63	0.53	0.46	0.79	1.54	0.47
$PD_2I_{92.5}$	1368	454	11.67	4.49	0.49	0.43	0.81	1.53	0.51
$PD_2I_{107.5}$	1424	490	12.23	4.44	0.46	0.41	0.81	1.56	0.54
$PD_2I_{122.5}$	1428	497	12.27	4.34	0.41	0.37	0.79	1.55	0.54
$PD_3I_{62.5}$	1190	369	9.83	4.34	0.59	0.50	0.81	1.40	0.43
$PD_3I_{77.5}$	1287	400	11.39	4.58	0.52	0.45	0.77	1.53	0.46
$PD_3I_{92.5}$	1340	430	10.85	4.22	0.46	0.41	0.77	1.44	0.48
$PD_3I_{107.5}$	1423	475	12.22	4.44	0.44	0.40	0.78	1.56	0.52
$PD_3I_{122.5}$	1421	486	12.19	4.32	0.40	0.36	0.77	1.54	0.53

GY, Grain yield; CGR, Crop growth rate; NAR, Net assimilation rate; I-WP, Irrigation based water productivity; I+P-WP, Irrigation + precipitation based water productivity; ET-WP, ET based water productivity; RUE, Radiation use efficiency

zaman 2008; Hasanuzzaman *et al.,* 2008). In rice N fertilization was also found to be very effective in rice biomass production and yield of rice (Hasanuzzaman *et al.*, 2009; 2010). However, the biomass and grain yield values are less than other scientists (Arora *et al.*, 2006; Katsura *et al.*, 2008; Rashid *et al.*, 2009; Zhang *et al.*, 2009) working with rice in other regional countries, i.e., India, Bangladesh and China. The main reason might be the integration of genetic, crop management, and soil and environmental factors. Nitrogen (N) is one of the most yield-limiting nutrients in lowland rice production around the world. Use of N efficient genotypes is an important complementary strategy in improving rice yield and reducing cost of production (Fageria and Barbosa Filho, 2001).

In this study, both the radiation use efficiency, biomass yield are greatly affected by N management which ultimately affected the final yield. The present results are in line with the findings of Katsura *et al.* (2008) and Zhang *et al.* (2009). However, they studied different management factors under different soil and environmental conditions in China. Kiniry *et al.* (1989) reported radiation use efficiency of 2.2 $g\ MJ^{-1}$ of intercepted PAR for a non-stressed rice crop. Water productivity express the capacity of plant to produce economic yield using per unit of applied water. As the plant density, N management and irrigation levels greatly affected the growth and yield of rice crop, it obviously improved the water productivity values.

Water productivity refers to the ratio between output (e.g. yield) and water use. However, the issue of most concern to this paper is not how to define water productivity, but rather how to measure it. In this study water productivity of rice is influenced by planting density and N levels.

The water productivity values are line with the findings of scientists (Arora *et al*., 2006; Jalota *et al*., 2009; Mahajan *et al*., 2009; Rashid *et al*., 2009; Singh *et al*., 2001) working with rice in other countries, i.e., Bangladesh and India. The values for irrigation and precipitation based water productivity are in good agreement with the observed values of Rashid *et al*. (2009) under soil and climatic conditions of Bangladesh, Mahajan *et al*. (2009) in India and Kato *et al.* (2009) in Japan. However, they used other rice cultivars than in the present study.

Conclusions

The results indicate that studies having integration of management factors provide a wide window for decision making for higher resource use efficiencies for the benefits of the producers. The treatments having combinations of two seedlings hill^{-1} and 200 kg N ha^{-1} (PD_2N_{200}) or 107.5 cm irrigation regime ($PD_2I_{107.5}$) are the most appropriate options for increasing the nitrogen, irrigation and radiation use efficiencies under irrigated semiarid environmental conditions. However, there is a need to validate technology through producer's participatory approach in diverse agro ecological conditions.

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