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Cultivar, nitrogen, and water effects on productivity, and nitrogen-use efficiency and balance for rice–wheat sequences of Bangladesh

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Abstract

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are often grown in sequences under a range of nitrogen (N), water (W), and planting date in South Asia. Field experiments were conducted from 1994–1995 to 1996–1997 to define the effects of two W and three N regimes on growth and productivity, N uptake and N-use efficiencies, and N balance for rice–wheat systems of northern Bangladesh. Mean grain yields of rice and wheat were greatest (4.9 and 3.1 t ha^{-1}, respectively) during the first and smallest (2.2 and 2.4 t ha^{-1}, respectively) during the third year. The cultivars of rice and wheat responded to irrigation and to N, with greater response to irrigation in rice, but to N in wheat. Delayed wheat seeding reduced wheat yields in all years. Agronomic N-use efficiency (kg grain yield per kg N applied), physiological efficiency (kg grain yield per kg N absorbed), and fertilizer N-recovery efficiency (kg N absorbed per kg N applied, expressed as %) for rice across treatments ranged from 2.8 to 10.8, 5.2 to 27.5, and 33 to 61, respectively, and all were greater for N application at 90 compared with 135 kg N ha^{-1}. For wheat, those values ranged from 15 to 27, 33 to 51, and 45 to 63, respectively, and were greater at 120 compared with 180 kg N ha^{-1}, and under irrigation than rainfed. All those parameters had greater values under irrigation than rainfed. Total soil N increased slightly after 3 years of cropping, while organic carbon and pH decreased slightly in all treatments. There was a net increase of soil ammonium N (80 kg ha^{-1}) and a zero balance of N after the first year of cropping under irrigation with high N (135 and 180 kg ha^{-1} for rice and wheat, respectively), but without N there was a decrease of soil mineral N (70 kg ha^{-1}) with a balance of +16 kg ha^{-1}. Biological N fixation accounted for N balance in N-omitted as well as N-applied treatments. The results emphasize the need for regular monitoring of weather, crop performance, irrigation water, and soil and plant mineral N for further understanding the growth, productivity, N-use efficiencies, and balance in rice–wheat systems. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Cultivar; Nitrogen; Productivity; Rice–wheat; Water

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Abbreviation: C, cultivar; FL, flowering; MT, maximum tillering; N, nitrogen; NUE, nitrogen-use efficiency; PD, sowing date; PE, physiological efficiency; PI, panicle initiation; PM, physiological maturity; RF, fertilizer-recovery efficiency; W, water

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1. Introduction

Rice–wheat cropping systems are a major cereal production system in South Asia, occupying approximately 14 Mha of cultivated land that extends across the Indo-Gangetic Plain (IGP) into the Himalayan foothills (Timsina and Connor, 2001). Weather patterns in the areas under rice–wheat sequences, especially in the northeast IGP, are erratic and dominated by heavy monsoon rainfall and dry mild winters. Management practices (choice of cultivars, amounts of irrigation water and fertilizers, pest and disease control measures, etc.) vary tremendously in those areas, often with sub-optimal inputs, resulting in variable, and often low, grain yields. Choice of appropriate cultivars in rice–wheat systems is important, as is the amount of irrigation water and nitrogen (N). Early-maturing cultivars of rice allow early harvest followed by timely sowing of succeeding wheat. In rice–wheat systems, timely sowing of wheat and use of early-maturing cultivars are important to complete the life cycle before the high temperatures occur later in the season. In Bangladesh, e.g., yield loss, often attributed to high temperatures, is about 1.3% or 44 kg ha^{-1} for each day delay in seeding after 30 November (Ahmed and Meisner, 1996). Likewise, irrigation generally increases yield of wheat but mostly under the conditions of low residual soil moisture at sowing. With the high residual soil moisture that generally prevails during the wheat season, especially following heavy monsoon, e.g., in northern Bangladesh, wheat yields under rainfed conditions are up to 4 t ha^{-1} (Timsina et al., 1998).

There are contradictory results regarding the long-term responses of rice and wheat in rice–wheat sequences to N fertilizer. For example, N application significantly increased grain and straw yields, and uptake of N by these crops when sown at the optimum time in a sequence at Pantnagar, India (Singh and Modgal, 1978). In contrast, also in India, when sowing of wheat was delayed after the harvest of rice, N fertilizer decreased N uptake by wheat (Kapur et al., 1985). Recent analyses from several long-term rice–wheat experiments in south Asia and China revealed site-to-site differences in response of rice and wheat to N. In all cases, however, N fertilizer increased grain yields of both crops. Over years, there were no declining yield trends in high-N, but yields declined in control treatments (Dawe et al., 2000; Yadav et al., 2000a,b).

Apparent recovery of fertilizer N (RE) by rice varies widely from 0 to 100% and for wheat, from 6 to 89% (Craswell and Vlek, 1979; Craswell and Godwin, 1984), while agronomic efficiency (AE) for rice ranges from 0 to 45 kg grain per kg N applied (Craswell and Godwin, 1984). In farmers' fields of rice–wheat systems in Nepal, mean recovery efficiencies for rice and wheat, with researchers' recommended practices, were 31 and 51%, respectively. The corresponding AEs were 16 and 23 kg grain per kg N applied, and the physiological efficiencies (PE) were 19 and 27 kg grain per kg N uptake (Adhikari et al., 1999). A summary of eight long-term rice–wheat experiments from India also revealed lower agronomic N-use efficiency and lower N-recovery for rice than wheat (Duxbury et al., 2000). Lower N-use efficiencies in rice are attributed to larger losses of N from the soil-floodwater system than from the aerobic wheat system. As a result of N losses during rice cropping, the residual effects to wheat are minimal.

Year-to-year variability in growth and nutrient uptake by component crops, and the productivity of the rice–wheat systems as a whole may be due to differences in soil nutrient availability, water availability, and weather. Studies at a number of sites over the period 1967–1995 established that mean soil organic carbon (OC) and total N (TN) in the top 100 cm declined by 16.2 and 1.38 t ha^{-1}, or, by 580 and 49 kg ha^{-1} per year, respectively, in Bangladesh (Ali et al., 1997a) as did pH, exchangeable bases, and effective CEC (Ali et al., 1997b). The soil OC and TN budgets showed a fall of 42.8 Gg C and 3.36 Gg N during the 28-year period of the 10 study areas covering 2.99×10^6 ha throughout Bangladesh. The changes in TN were mainly attributed to the intensive cultivation of land without replenishment of nutrient removed by crops, but the declines in OC were due to accelerated decomposition of organic matter, changes in cropping systems, and differences in soil characteristics of the various physiographic units.

Increased productivity of rice–wheat systems depends on choice of appropriate cultivars, timely planting, large inputs of inorganic N fertilizer, and appropriate management of water and N. The present experiments were, therefore, designed to determine the effect of cultivar (C), N, and water (W) on grain and straw yields, total system productivity, dry matter accumulation, N uptake, use and efficiency, and N balances for rice–wheat sequences in Bangladesh.

2. Materials and methods

2.1. Site, treatments, and crop management

Experiments were carried out on a Haplaquept, non-calcareous brown floodplain soil at the experimental farm of the Wheat Research Centre, Nashipur, Bangladesh (25°5′N, 88°4′E, 30 m elevation) from 1994 to 1997. Soil texture was sandy clay loam, with bulk density of 1.6 g cm^{-3} at all depths. Initial soil chemical parameters reflected lower values (TN: 0.63, 0.41, 0.33, 0.30 g kg^{-1}; olsen available P: 7.5, 1.6, 1.4, 2.5 ppm; exchangeable K: 0.15, 0.12, 0.13, 0.13 cmol kg^{-1}; OC: 6.2, 4.4, 4.0, 3.6 g kg^{-1}; pH: 5.6, 6.0, 5.9, and 5.8, respectively, for 0–0.15, 0.15–0.30, 0.30–0.45, and 0.45–0.60 m depths) than most soils of the region. Two rice cultivars (cvs. BR14 and BR11, with seed-to-seed duration of 130 and 150 days, respectively) were grown under three N (0, 90, and 135 kg ha^{-1}) and two W (rainfed and irrigated) regimes. After rice harvest each year, plots were split to allow two sowing dates (early, mid-November; and late, early-to-mid-December) for two spring wheat cultivars (cvs. Kanchan and Sowgat, with 105–108 days maturity) under two W (rainfed and irrigated) and three N (0, 120, and 180 kg ha^{-1}) rates. Treatments for rice were on a split–split plot, whereas those for wheat were on a split–split–split plot design. The experimental plan and site, initial soil physical and chemical analyses, crop establishment and management, seasonal soil water measurements, and weather conditions for the first year have been described in detail elsewhere (Timsina et al., 1998). Treatments and crop management practices for second and third years were similar to those in the first year.

2.2. Crop measurements and plant N analyses

During the first year (1994–1995) of experimentation, detailed measurements were made of crop growth and dry matter partitioning, and plant N concentrations. During the second and third years (1995–1996 and 1996–1997), however, data collection was limited to final straw and grain yields, and yield components. Aboveground dry matter was sampled from two 1.0 m lengths at maximum tillering (MT), panicle initiation (PI), 95% flowering (FL), and physiological maturity (PM) of rice, and at spike emergence (PI), booting (BT), FL, and PM of wheat. The sample plants were separated into leaves (blade), stems (leaf sheath plus culm), panicles (up to FL), and additionally into grain (during PM), and dried for dry matter content at 60°C for 48 h. Sub-samples from each treatment were ground and analyzed for TN in grain and straw at harvest. TN concentrations in plant tissue were determined using the Kjeldahl method (Yoshida et al., 1972) and N uptake was calculated from dry weight and concentrations.

2.3. Soil carbon and mineral N analyses

KCl-extractable soil mineral N (NO_3^- and NH_4^+) and TN for 0–0.15, 0.15–0.30, 0.30–0.45, and 0.45–0.60 m depths were determined before the start, and after the first year of experimentation, according to procedures described in Bremner and Keeney (1966). Soil OC was determined by the modified Walkley-Black method (Page et al., 1982) and TN by Kjeldahl digestion, distillation, and titration (Bremner and Keeney, 1966) before the start, and after the completion of the experiment. NO_3^- in KCl extracts was determined by Cd reduction and absorption measurements at a wavelength of 540 nm. NH_4^+–N was determined by steam distillation with MgO. Both NO_3^- and NH_4^+–N were expressed on a dry-soil basis in kilogram per hectare.

2.4. N-use efficiencies

Physiological efficiency (PE, kg grain yield per kg N absorbed), fertilizer N-recovery efficiency (RE, kg N absorbed per kg N applied), and agronomic N-use efficiency (AE, kg grain yield per kg N applied) were compared for various treatments. PE reflects the efficiency in using the N actually absorbed and approximates the effects of plant factors, RE focuses on N absorption from applied N and explains the effects of soil factors, and AE reflects the efficiency of applied N (Novoa and Loomis, 1981). System-level efficiency was calculated as follows:

$$\text{System-level efficiency} = \frac{\text{N removed by crops} + \text{available N in soil after 1-year of cropping}}{\text{N additions through various sources}} \times 100$$

2.5. Net N balance

The N balance was calculated by accounting for changes in available mineral N before and after the first year of experimentation: the N inputs from fertilizer, irrigation and rainfall, and weeds and crop residues; and net N removal in grain and straw, as follows:

$$\begin{aligned}\text{Net N balance} &= (\text{N removed by crops} + \text{change in mineral}\\ &\quad \text{N after 1-year of cropping})\\ &\quad - (\text{N additions through various sources})\end{aligned}$$

Nitrogen inputs in rainfall and irrigation water were computed from rainfall and irrigation water measured at the site, and were similar to typical N concentrations of 6.5 and 9.2 g $\text{ha}^{-1}\,\text{mm}^{-1}$, respectively, in rainfall and irrigation water in Bangladesh (Abedin et al., 1991). Other major pathways of N input or output not measured include N inputs from biological nitrogen fixation (BNF), gaseous N losses from ammonia volatilization and denitrification, and leaching losses. Hence, the N balance estimates only net N gains or losses. Seepage and leaching losses were probably small, however, because plots were separated with plastic sheets.

2.6. Statistical analyses

Statistical analyses using SAS software (SAS, 1989) on grain and straw yields, and harvest indices (HI) were performed using standard procedures of split–split plot design for rice and split–split–split plot design for wheat. In the analyses of variance (ANOVA) for rice, the degrees of freedom (d.f.) were partitioned as: replication $(\text{R}) = 3$, water regime $(\text{W}) = 1$, nitrogen $(\text{N}) = 2$, cultivar $(\text{C}) = 1$, $\text{W} \times \text{N} = 2$, $\text{W} \times \text{C} = 1$, $\text{N} \times \text{C} = 2$, $\text{W} \times \text{N} \times \text{C} = 2$, and $\text{W} \times \text{R}$ or error $(\text{a}) = 3$, $\text{W} \times \text{N} \times \text{R}$ or error $(\text{b}) = 12$, and $\text{W} \times \text{N} \times \text{C} \times \text{R}$ or error $(\text{c}) = 18$. For wheat, the ANOVA also included sowing date (PD) in the sub-sub-sub-plots and thus was also partitioned to $\text{PD} = 1$, $\text{W} \times \text{PD} = 1$, $\text{N} \times \text{PD} = 2$, $\text{W} \times \text{N} \times \text{PD} = 2$, $\text{C} \times \text{PD} = 1$, $\text{W} \times \text{PD} \times \text{C} = 1$, $\text{N} \times \text{PD} \times \text{C} = 2$, $\text{W} \times \text{N} \times \text{PD} \times \text{C} = 2$, $\text{W} \times \text{N} \times \text{PD} \times \text{R}$ or error $(\text{c}) = 18$, and $\text{W} \times \text{N} \times \text{PD} \times \text{C} \times \text{R}$ or error $(\text{d}) = 36$. For remaining data sets, standard errors for means (S.E.) for various treatments were computed. In long-term trials, where the treatments for any 1-year or season cannot be re-randomized, and is influenced by previous-season factors, repeated measures of variances (SAS, 1988) can be used to overcome the dependence in estimates of variance. The data presented in these experiments, which were conducted for 3 years, were subjected to repeated measures of analysis.

3. Results

3.1. Crop environment

Temperature, rainfall, and radiation data are presented for each of the three experimental years (1994–1997) in Fig. 1. That summary, in the form of daily averages of maximum and minimum temperatures for consecutive 2-week periods and rainfall totals for the same intervals, reveals the relative year-to-year consistency of maximum temperature, solar radiation, and the duration of the rainless period. In contrast, minimum temperature varied significantly from year-to-year during the winter season. In 1994–1995, a relatively cold period commenced in November and persisted, compared with 1995–1996, until March. While the timing of the rainy season is relatively predictable, there is considerable variation in the amount, intensity, and distribution. Rainfall totals for the three cropping years were 840, 600, and 1490 mm, respectively. Insolation is relatively stable and constant from year-to-year, but low (ca. 15 MJ m^{-2} per day) in summer, and 10–15 MJ m^{-2} per day in winter. Clear-day

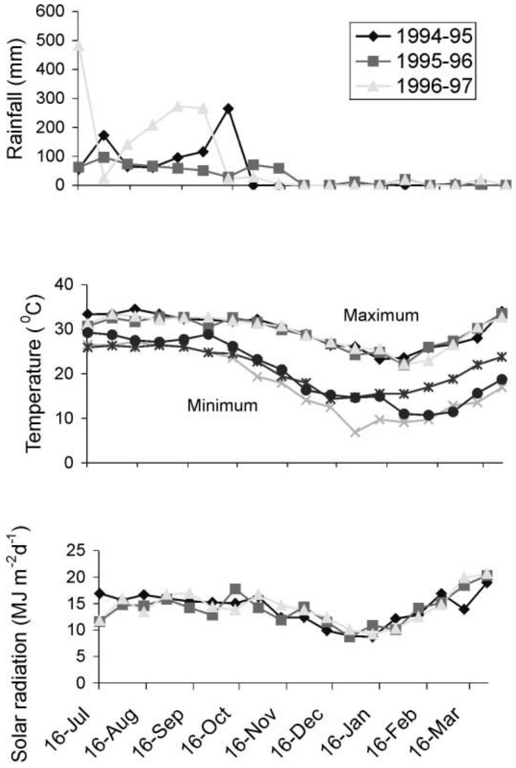

Fig. 1. Rainfall, temperature (maximum and minimum), and solar radiation for rice–wheat cropping during 1994–1995, 1995–1996, and 1996–1997 seasons.

sunshine hours at this latitude would be 10–11 h in winter, and about 13–14 h in the rainy, season. The low radiation during the cloudy and wet (monsoon) season is not surprising, but the low radiation during the prolonged dry season reveal the importance of haze to insolation, and hence to crop productivity.

There was incidence of rice bug (*Leptocorisa oratorius* (*Fabricious*)), especially in the 135 kg N ha^{-1} treatment, in the second and third years. Substantial rain, together with strong winds in those years caused lodging in rice, especially in that treatment. Scorings for rice bug damage and lodging together at 135 kg N treatment revealed about 20% unfilled spikelets in the second, and 40% in the third year. Yield data were adjusted accordingly for those years. We suspect that heavy rainfall (1490 mm) in the third, and substantial water application from rainfall and irrigation (>1100 mm) in the second year might have resulted loss of water and N, especially from the N-added plots. Those losses could not, however, be estimated.

3.2. Grain and straw yields

3.2.1. Rice

The reproductive and vegetative yields of rice as influenced by water, nitrogen, and cultivar are presented in Table 1. ANOVA for grain yield revealed that during the first year, only the main effects of W and C were significant, while during the second year, most main and interaction effects were significant. In the third year, however, only the W × N interaction was significant. Yields of individual treatments ranged widely from 1.7 to 7.4 t ha^{-1} over the 3-year period during which mean yield fell consistently from 4.9 to 3.0 t ha^{-1} and then to 2.4 t ha^{-1}, respectively. Within this period, the effect of cultivar was significant because the late-maturing BR11 (mean 3.7 t ha^{-1}) always out-yielded the early-maturing BR14 (mean 3.2 t ha^{-1}). While there was an overall response to irrigation (4.1 t ha^{-1} vs. 2.8 t ha^{-1}), it was large in the first year (6.3 t ha^{-1} vs. 3.5 t ha^{-1}), small in the second (3.4 t ha^{-1} vs. 2.5 t ha^{-1}), and nonexistent in the third (mean 2.4 t ha^{-1}). Overall, crops responded to N fertilizer up to 90 kg ha^{-1} (overall 3.6 t ha^{-1} vs. 3.1 t ha^{-1}), but with no further response to the additional N (to 135 kg ha^{-1}) for which mean yield was 3.6 t ha^{-1}. Overall, while irrigation and 90 kg N ha^{-1} resulted in higher yield, the response declined and was finally reversed during the period of experimentation. In the first year, it was large (6.8–3.8 t ha^{-1}), smaller in the second year (3.6–2.4 t ha^{-1}), and negative in the third year (2.3–2.6 t ha^{-1}).

Vegetative yields (straw mass at harvest) are also presented in Table 1. Across the years, the main effects of N and C were significant but not the interactions. The response of vegetative growth to irrigation, cultivar, and N fertilizer is most readily interpreted by reference to HI. That characteristic reveals little impact of treatment on the partition of biomass between vegetative and reproductive growth. There was no significant effect of cultivar on HI, and irrigation increased HI significantly in the first year only. The most consistent effect was that of N fertilizer, which reduced HI significantly each year. With the exception of the irrigated treatment in the first year (mean HI = 0.43), HI was generally low, with a minimum of 0.25 for the rainfed treatment in the second year.

Repeated measures of ANOVA for grain yield showed significant ($p \leq 0.05$) main effects of W, N,

Table 1
Grain and straw yields (kg ha^{-1}) and HI of rice as influenced by W, N, and C during 1994–1996 (WRC, Nashipur, Bangladesh)[a]

Water regime	Nitrogen[b]	Cultivar	1994			1995			1996			Mean (3 years)		
			Grain yield	Straw yield	HI	Grain yield	Straw yield	HI	Grain yield	Straw yield	HI	Grain yield	Straw yield	HI
Rainfed														
	0	BR14	2725	4227	0.39	1667	4382	0.28	1735	4085	0.30	2042	4231	0.33
		BR11	3260	5231	0.38	2255	5748	0.28	1708	3285	0.34	2408	4755	0.34
	90	BR14	3529	7505	0.32	1814	7268	0.20	2817	6983	0.29	2720	7252	0.27
		BR11	4142	7778	0.35	3047	9495	0.24	2400	7550	0.24	3196	8274	0.28
	135	BR14	3480	7794	0.31	2588	8964	0.22	3087	8349	0.27	3052	8369	0.27
		BR11	3922	7776	0.34	4005	9638	0.29	2663	6187	0.30	3530	7867	0.31
		Mean	3510	6735	0.34	2563	7582	0.25	2402	6073	0.29	2825	6797	0.29
Irrigated														
	0	BR14	5327	6589	0.45	3333	6542	0.34	2715	5054	0.35	3792	6062	0.38
		BR11	6405	8360	0.43	3775	7501	0.33	2475	4589	0.35	4218	6817	0.38
	90	BR14	6238	8156	0.43	2745	9779	0.22	2245	8013	0.22	3743	8649	0.30
		BR11	7377	9712	0.43	4412	10268	0.25	2342	5815	0.29	4710	8599	0.35
	135	BR14	5736	8603	0.40	2707	8476	0.24	2493	7872	0.24	3645	8317	0.30
		BR11	6789	10305	0.40	3823	10392	0.27	2356	6076	0.28	4323	8924	0.33
		Mean	6312	8621	0.42	3466	8826	0.28	2438	6237	0.29	4072	7895	0.34
S.E.														
	W means		63	NS[c]		NS	NS	NS	NS	NS	NS			
	N means		NS	169		53	218	0.004	NS	150	0.005			
	C means		35	67		25	111	NS	NS	69	NS			
	W × N means		NS	NS		106	NS	NS	118	NS	NS			
	N × C means		NS	NS		76	NS	NS	NS	NS	NS			
	W × N × C means		NS	NS		NS	NS	NS	NS	NS	NS			

[a] *Significant at 5% level.

[b] Nitrogen rate is in kg ha^{-1}.

[c] Not significant.

C, and Y, and interaction effects for W × N, Y × W, and Y × C. For straw yield, there were significant ($p \leq 0.05$) main effects of W, N, C, and Y and for the interaction effect of Y × C only, while for HI, the significant effects were observed for W, N, Y, Y × W, and Y × N (detailed analyses not shown).

3.2.2. Wheat

The reproductive and vegetative yields of wheat as influenced by water, nitrogen, cultivar, and time of sowing are presented in Table 2. ANOVA for grain yield revealed significant ($p \leq 0.01$) main effects of N across years and sowing date (PD) for the first 2 years, while most other means were not significant. As with rice, individual treatments resulted in a wide range of yields although smaller, i.e. from 0.9 to 5.0 t ha^{-1} over the 3 years. As with rice, mean yield was highest in the first (3.1 t ha^{-1}) and lowest in the third (2.4 t ha^{-1}) year. The two cultivars responded similarly to irrigation and N fertilizer, although the early-sown crops yielded consistently more than the late-sown ones (overall mean 2.8 t ha^{-1} vs. 2.6 t ha^{-1}). There was a consistent response to fertilizer at 120 kg N ha^{-1} (1.2 t ha^{-1} vs. 3.3 t ha^{-1}) that continued to the higher application level of 180 kg N ha^{-1} (overall mean 3.7 t ha^{-1}). Surprisingly, irrigation had a relatively minor effect, with 2.8 t ha^{-1} grain yield for irrigated, compared to 2.6 t ha^{-1} for rainfed crops. Overall, irrigation and 180 kg N applied to early-sown crops resulted in the highest average yield over 3 years (4.0 t ha^{-1}) compared with the lowest yield in the late-sown crops without fertilizer or irrigation (1.2 t ha^{-1}).

The vegetative yields at harvest are also presented in Table 2. There was no consistent effect of cultivar or N

Table 2
Grain and straw yields (kg ha^{-1}) and HI of wheat as influenced by W, N, C, and PD during 1994–1995 to 1996–1997 (WRC, Nashipur, Bangladesh)[a]

Water regime	Sowing	Cultivar	Nitrogen[b]	1994–1995			1995–1996[c]			1996–1997[c]			Mean of 3 years		
				Grain yield	Straw yield	HI	Grain yield	Straw yield	HI	Grain yield	Straw yield	HI	Grain yield	Straw yield	HI
Rainfed															
	Early	Sowgat	0	1193	1792	0.4	1258	3013	0.3	963	1537	0.39	1138	2114	0.36
			120	3696	4703	0.44	3255	6276	0.35	2663	6587	0.29	3205	5855	0.36
			180	4274	5332	0.45	3750	6927	0.35	3036	7214	0.30	3687	6491	0.37
		Kanchan	0	1201	1803	0.4	1354	2865	0.32	1038	1463	0.43	1198	2043	0.38
			120	3662	4831	0.43	3438	6719	0.34	2587	6246	0.29	3229	5932	0.35
			180	4101	4765	0.46	3750	7188	0.35	3187	7564	0.30	3679	6505	0.37
		Mean		3021	3871	0.43	2801	5498	0.34	2246	5102	0.33	2689	4823	0.37
	Late	Sowgat	0	941	1552	0.38	1258	3326	0.28	1576	1341	0.39	1258	2073	0.35
			120	3553	4479	0.4	3166	6938	0.32	2775	6975	0.29	3165	6131	0.34
			180	4002	5568	0.42	3183	6922	0.31	2557	6194	0.29	3247	6228	0.34
		Kanchan	0	991	1519	0.39	1275	3308	0.28	1346	1655	0.47	1204	2161	0.38
			120	3397	4519	0.43	2991	6384	0.32	2682	5818	0.32	3023	5574	0.36
			180	3680	5053	0.42	3351	6962	0.33	2702	7632	0.27	3244	6549	0.34
		Mean		2761	3782	0.41	2537	5640	0.31	2273	4936	0.34	2524	4786	0.35
Irrigated															
	Early	Sowgat	0	1235	1919	0.39	1250	2396	0.36	1460	2415	0.40	1315	2243	0.38
			120	4443	6901	0.39	3086	7070	0.32	2842	8544	0.29	3457	7505	0.33
			180	4979	7696	0.39	3854	7292	0.35	3456	8825	0.24	4096	7937	0.33
		Kanchan	0	1359	2215	0.38	1302	2552	0.34	1377	2415	0.37	1346	2394	0.36
			120	4320	6536	0.39	2969	6979	0.3	3178	9327	0.29	3489	7614	0.33
			180	5038	7479	0.4	3896	7094	0.36	3839	9073	0.27	4258	7882	0.34
		Mean		3562	5458	0.39	2726	5564	0.34	2692	6766	0.31	2993	5929	0.35
	Late	Sowgat	0	1156	1662	0.41	891	2365	0.28	1062	2021	0.36	1036	2016	0.35
			120	4185	6659	0.38	3110	7098	0.3	2867	9300	0.24	3387	7686	0.31
			180	4367	7037	0.38	2942	7735	0.28	2994	8173	0.27	3434	7648	0.31
		Kanchan	0	1192	1680	0.41	929	3238	0.24	936	1731	0.36	1019	2216	0.34
			120	3791	6645	0.36	3001	7155	0.3	2652	8349	0.24	3148	7383	0.30
			180	4204	6838	0.38	3223	8054	0.29	3112	8597	0.27	3513	7829	0.31
		Mean		3149	5087	0.39	2349	5941	0.28	2270	6362	0.29	2590	5796	0.32
S.E.															
	W means			NS	28.8	0.0007	NS	NS	NS	22.2	42.9	NS			
	N means			21.8	27.8	0.0005	34.2	60.2	NS	30.9	74.7	0.01			
	PD means			11.9	NS	0.0003	13.9	NS	0.002	NS	NS	NS			
	C means			NS	NS	0.0004	NS	NS	NS	NS	NS	NS			
	W × N means			NS	55.6	0.0009	NS	NS	NS	NS	NS	NS			
	W × PD means			NS	NS	0.0007	NS	NS	NS	NS	NS	NS			
	N × PD means			NS	NS	0.001	NS	NS	NS	NS	NS	NS			
	W × N × PD means			NS	NS	0.002	NS	NS	NS	113.2	NS	0.03			
	N × PD × C means			NS	NS	0.003	NS	NS	NS	NS	NS	NS			

[a] *Significant at 5% level.

[b] Nitrogen rate is in kg ha^{-1}.

[c] During 1995–1996 and 1996–1997, Sowgat was replaced by Protiva cultivar.

on HI, but it was consistently lower under irrigation. Likewise, late sowing consistently resulted in lower HI in all years.

Repeated measures of ANOVA for grain yield across years showed significant ($p \leq 0.01$) effects for W, N, PD, Y, Y × W, Y × N, and Y × W × N × P. For straw yield, only the main effects of W, N, and Y, and interaction effects of W × N, Y × W, and Y × N were significant ($p \leq 0.01$), whereas, for HI, main effects of W, N, and Y and interaction effects of Y × N and Y × PD were significant (detailed analyses not shown).

Table 3
Annual and mean total system productivity (kg ha^{-1}) for rice–wheat systems,[a] with wheat grown after early (BR14) and late (BR11) rice under three nitrogen and two water regimes

	Nitrogen[b]	Cultivar	Year 1	Year 2	Year 3	Mean
Rainfed						
	0–0	BR14	3922	2973	2735	3210
		BR11	4226	3521	3169	3639
	90–120	BR14	7208	5160	5442	5937
		BR11	7617	6125	5128	6290
	135–180	BR14	7668	6338	6198	6735
		BR11	7763	7272	5292	6776
		Mean	6401	5232	4661	5431
Irrigated						
	0–0	BR14	6624	4609	4134	5122
		BR11	7579	4684	3474	5246
	90–120	BR14	10620	5773	5255	7216
		BR11	11365	7467	5101	7978
	135–180	BR14	10745	6582	6141	7823
		BR11	11075	6905	5409	7796
		Mean	9668	6004	4919	6863

[a] Total system productivity refers to combined yields of rice and wheat, respectively.

[b] Nitrogen rate is in kg ha^{-1} (the first value is for rice and the second is for wheat).

3.3. Total system productivity

Total annual and mean system productivity for rice–wheat systems as influenced by cultivar, moisture, and N are presented in Table 3. System productivity for individual treatments and years ranged from 2.7 to 11.4 t ha^{-1}, while for the mean of 3 years across treatments it ranged from 3.2 to 8.0 t ha^{-1}. Annual system productivity across treatments was greatest (3.9–11.4 t ha^{-1}) during the first, and smallest (2.7–6.2 t ha^{-1}) during the third year. Across years, system productivity was greatest for the irrigated treatments with N applications (ranging from 5.1 to 11.4 t ha^{-1}) and smallest for the rainfed treatments without N applications (ranging from 2.7 to 4.2 t ha^{-1}).

3.4. Biomass accumulation

3.4.1. Rice

Total biomass accumulation during the growth cycle strongly varied between the two rice cultivars and was significantly affected by W and N regimes (Fig. 2). Biomass accumulation up to PI was similar for both cultivars in all N regimes, but was slightly greater under irrigation. From PI, however, the pattern of biomass accumulation altered under two W and N regimes. By FL stage, total biomass of BR11, the late-maturing cultivar, was significantly greater than of BR14, the early-maturing cultivar, under all N and W regimes. Total biomass tended to increase continuously up to PM and remained greater for BR11 than for BR14. The greater biomass accumulation at PM by BR11 was due to longer duration up to FL.

Within each N regime, biomass accumulation by both cultivars was significantly faster under irrigation than rainfed. In each W and N regime, BR11 partitioned a greater proportion of biomass to leaves than did BR14 during early-vegetative growth (at MT stage). Under rainfed conditions, at PI, BR11 had greater partitioning of biomass to stems than to leaves, while under irrigation, BR14 partitioned more biomass to leaves than to stems. At flowering, stem was the dominant assimilate sink for both cultivars, but BR14 partitioned more biomass to panicles than did BR11. At maturity, however, both cultivars had partitioned similar proportions of biomass to panicles (data not shown). The results reveal that HI was similar for both cultivars.

3.4.2. Wheat

Total dry matter accumulation by each cultivar at each sowing date was significantly affected by N rate (Figs. 3 and 4). At all rates, total biomass progressively increased up to PM. At PI, more than 70% of biomass was partitioned to leaves, while at BT and FL, stem contained the greatest proportion of biomass. At PM, panicle dry weight accounted for at least 55% of biomass. The pattern of biomass accumulation in wheat contrasted with rice in which leaves and stems accounted for the major proportion of dry matter at all growth stages (data not shown). Crop growth was poor without any added N; only 35% as much dry matter accumulated as with N applied at 180 kg ha^{-1}. The dry matter was less in cv. Sowgat than in cv. Kanchan.

Total dry matter was lower under rainfed conditions than under irrigation at all N rates and for both sowing times. The relative dry weight of both cultivars without-added N under rainfed conditions was, however, greater than that under 180 kg N ha^{-1}, because biomass production was limited by drought stress. Contrary to the results of Pearman et al. (1978) and

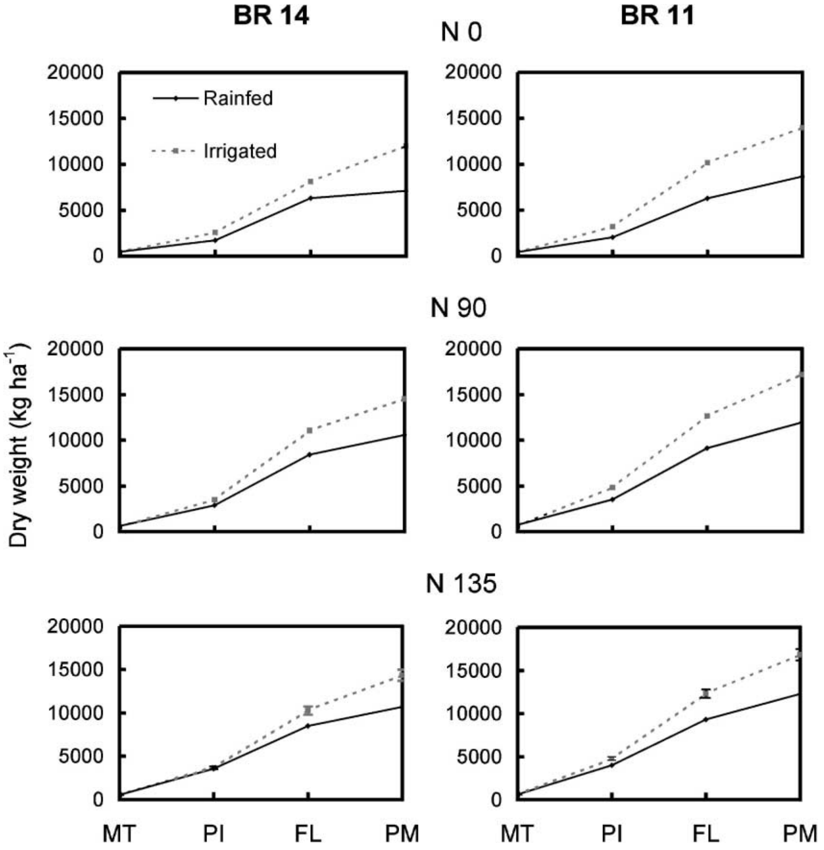

Fig. 2. Total dry biomass of two rice cultivars for three nitrogen and two water regimes during 1994 season. Standard error bars compare differences among nitrogen means for each cultivar and water interaction. MT, PI, FL, and PM represent maximum tillering, panicle initiation, flowering, and physiological maturity stages, respectively.

Makunga et al. (1978), the effect of N on dry matter distribution varied with water regime and sowing date, with delayed sowing slightly reducing total biomass (Figs. 3 and 4).

3.5. Total N uptake and N-use efficiencies

3.5.1. Rice

Effective soil N supplying capacity, estimated by crop N uptake in the control treatment under irrigation, was about 94 kg ha^{-1} for BR14 and 95 kg ha^{-1} for BR11, but was almost half (46 and 54 kg ha^{-1}, respectively) under rainfed conditions. The initial values of KCl-extractable soil NH_4^+–N were 18 and 14.5 mg kg^{-1} and NO_3^-–N was 50.7 and 27.6 mg kg^{-1} for 0–0.3 and 0.3–0.6 m depths, respectively. Incorporated weeds and rice stubble in year 1 contained 23.3 kg N ha^{-1}, about 80% of which was derived from weeds with N concentration of 0.97% (Timsina et al., 1998). For both cultivars, grain yields increased with N uptake to a maximum before declining (data not shown). Our results are similar to other experiments in the irrigated rice–wheat systems in South Asia, where there were also increases in TN uptake by rice with increased N application (Subramanian and Rajagopalan, 1980; Adhikari et al., 1999).

Both cultivars, under either water regime, had similar AE values ranging from 8.9 to 10.8 kg grain kg^{-1} N applied at 90 kg N ha^{-1}. AE of BR11 under irrigation decreased from 10.8 to 2.8 and that of BR14 from 10.1 to 3.0 when N rate was increased from 90 to 135 kg N ha^{-1}. PE of BR14 at 90 kg N was 17.0 and 24.9 and that of BR11 was 27.5 and 17.7 kg grain yield per kg N absorbed under rainfed and irrigation,

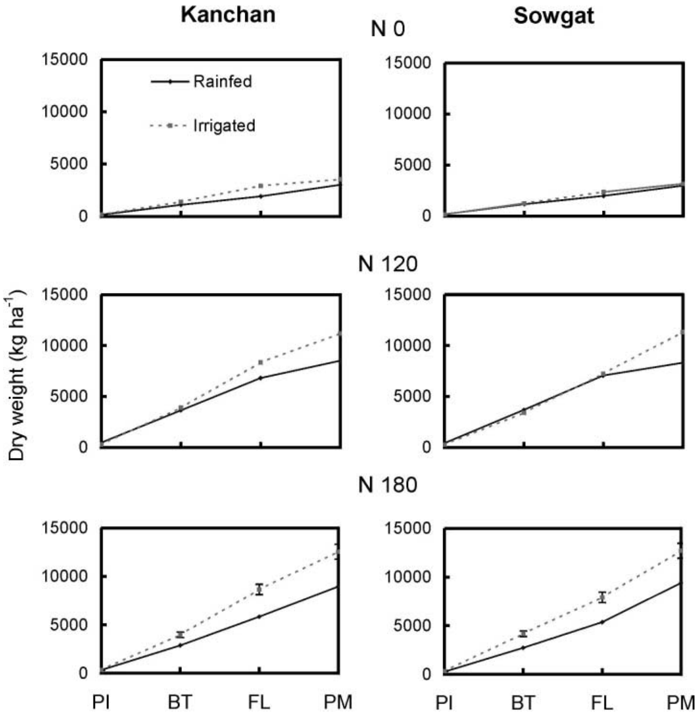

Fig. 3. Total dry biomass of two wheat cultivars for three nitrogen and two water regimes under early-sowing condition during 1994–1995 season. Standard error bars compare differences among nitrogen means for each cultivar and water interaction. PI, BT, FL, and PM represent panicle initiation, booting, flowering, and physiological maturity, stages, respectively.

respectively. These values reduced to 11.9 and 7.0 in BR14, and 14.6 and 5.2 in BR11, at 135 kg ha^{-1}. RE for both cultivars decreased, but not significantly, with increase of N from 90 to 135 kg ha^{-1} under both water regime. Under rainfed conditions, RE was greater for BR14 (53% vs. 41%) but under irrigation, it was greater for BR11 (61% vs. 36%) (Table 4). The former was associated with much lower N uptake under rainfed conditions than under irrigation in the control treatment. As noted earlier, we suspect N losses in high-N treatments, resulting in lower grain yields and ultimately lower RE and AE under 135 kg N ha^{-1}, in comparison with 90 kg N ha^{-1}.

3.5.2. Wheat

TN uptake by the two cultivars of wheat at PM varied with sowing date, water, and N (Table 5). TN uptake across treatments ranged from 17 to 119 kg ha^{-1}. Under rainfed conditions, TN uptake ranged from 17 to 108 kg ha^{-1} but under irrigation from 19 to 119 kg ha^{-1}. Early-sown crops had greater uptake (22–119 kg ha^{-1}) than late-sown ones (17–107 kg ha^{-1}). Uptake without N application ranged from 17 to 26 kg ha^{-1}, but with 180 kg N, from 102 to 119 kg ha^{-1}. The early-sown sowgat cultivar, with 180 kg N ha^{-1} under irrigation, had the highest N uptake (119 kg ha^{-1}), slightly higher than for the same cultivar under rainfed conditions (108 kg ha^{-1}). Under late-sown conditions, the corresponding values were 105 and 103 kg ha^{-1} (Table 5).

All N-use efficiency parameters were significantly affected by C, N, and W. PE under irrigation ranged from 36 to 51 kg grain per kg N absorbed, while under rainfed conditions it was 33–45. PE for early sowing was significantly higher (33–44 kg grain per kg N absorbed) than for late sowing (33–44 grain per kg N absorbed). RE under irrigation was 47–63%, while under rainfed conditions it was 45–51%. RE for late sowing was higher (45–63%) than for early sowing (45–52%). RE for Sowgat was greater (46–63%) than for Kanchan (45–57%). AE was significantly higher under irrigation (19–27 kg grain

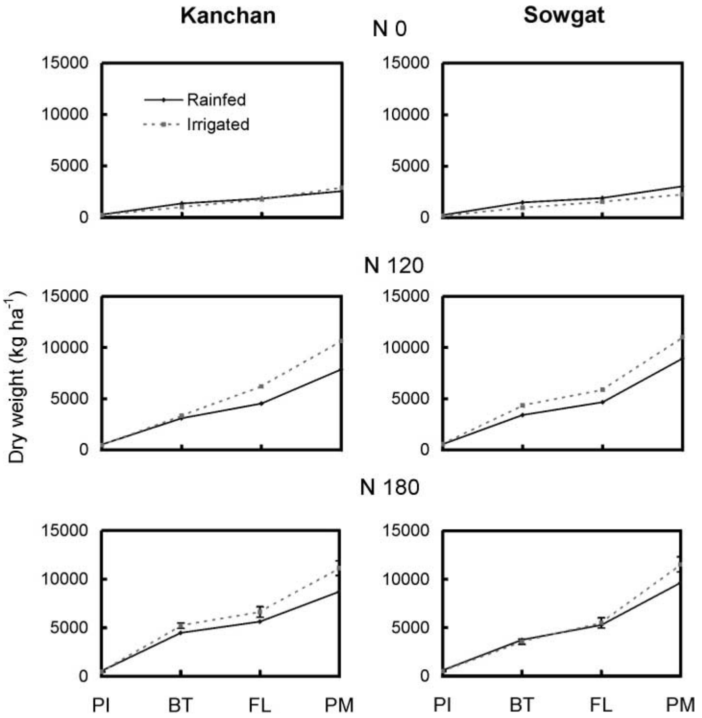

Fig. 4. Total dry biomass of two wheat cultivars for three nitrogen and two water regimes under late-sowing condition during 1994–1995 season. Standard error bars compare differences among nitrogen means for each cultivar and water interaction. PI, BT, FL, and PM represent panicle initiation, booting, flowering, and physiological maturity, stages, respectively.

Table 4
N-use efficiency parameters and N uptake for 2 rice cultivars as influenced by nitrogen and water (1994 season)

		N uptake (kg ha^{-1})	N efficiency parameters[a]		
			PE (kg kg^{-1})	RE (%)	AE (kg kg^{-1})
Rainfed					
N0	BR14	46	–	–	–
	BR11	54	–	–	–
N90	BR14	94	17.0	52.7	8.9
	BR11	86	27.5	35.7	9.8
N135	BR14	110	11.9	47.2	5.6
	BR11	99	14.6	33.0	4.9
Irrigated					
N0	BR14	94	–	–	–
	BR11	95	–	–	–
N90	BR14	130	24.9	40.7	10.1
	BR11	150	17.7	61.0	10.8
N135	BR14	152	7.0	43.0	3.0
	BR11	168	5.2	54.0	2.8
S.E. (mean)		15.5	3.3	0.12	2.4

[a] PE, RE, and AE denote physiological efficiency, recovery efficiency, and agronomic efficiency, respectively.

Table 5
N-use efficiency parameters and N uptake for two wheat cultivars as affected by nitrogen, water, and sowing dates (1994–1995 season)

				N uptake (kg ha^{-1})	N efficiency parameters[a]		
					PE (kg kg^{-1})	RE (%)	AE (kg kg^{-1})
Rainfed							
	14 November	Sowgat	N0	22		–	
			N120	78	44.6	47.00	20.9
			N180	108	36.0	48.00	17.1
		Kanchan	N0	22			
			N120	83	40.2	51.00	20.5
			N180	102	36.2	45.00	16.1
	7 December	Sowgat	N0	22			
			N120	82	39.5	51.00	20.0
			N180	103	34.8	46.00	15.8
		Kanchan	N0	17			
			N120	72	44.4	45.00	20.1
			N180	100	32.7	46.00	14.9
Irrigated							
	14 November	Sowgat	N0	25			
			N120	88	51.1	52.00	26.7
			N180	119	39.9	52.00	20.8
		Kanchan	N0	26			
			N120	84	50.7	49.00	24.7
			N180	109	44.4	46.00	20.4
	7 December	Sowgat	N0	19			
			N120	95	42.7	63.00	27.0
			N180	105	39.5	48.00	19.0
		Kanchan	N0	24			
			N120	85	42.3	51.00	21.7
			N180	107	35.9	47.00	16.7
S.E.				12.4	14.9	3.5	4.5

[a] PE, RE, and AE denote physiological efficiency, recovery efficiency, and agronomic efficiency, respectively.

per kg N applied) than under rainfed conditions (15–21 kg grain per kg N applied), but did not differ between the two sowing dates. All efficiencies were lower when N was increased from 120 to 180 kg ha^{-1}. For example, PE ranged from 40 to 51 kg grain per kg N absorbed at 120 kg N and from 35 to 40 at 180 kg N. RE ranged from 45 to 63% at 120 kg N and from 45 to 52% at 180 kg N. AE decreased from 20 to 27 kg grain at 120 kg N to 15–21 kg at 180 kg N.

3.5.3. *System-level efficiencies*

System-level N efficiencies for various treatments as shown in Table 6 ranged from 70 to 82% for rainfed, and from 98 to 112% for irrigated treatments. The efficiencies under irrigation were highest for the control treatments but the reverse was the case under rainfed conditions. Similar to these results, Tripathi et al. (1997) reported 24–93% system-level efficiencies in the Philippines, and Singh et al. (1999) reported 53–100% efficiencies in India, both for rainfed-rice-based cropping systems.

3.6. *Mineral N balance*

TN, OC, and pH as affected by N and W after 3 years of rice–wheat cropping are shown in Table 7. Total soil N for most treatments increased significantly at all depths whereas OC and pH decreased at most depths. The control treatments generally had greater decline in pH than the N treatments.

Of the total input of 459 kg N ha^{-1} in the highest N treatment under irrigation, 277 and 260 kg ha^{-1} was removed by irrigated rice (BR11 and BR14,

Table 6
Apparent N balance (kg ha^{-1}) from 0 to 0.3 m depth after the first year (early-sown wheat) of rice–wheat cropping

	Cultivar	Fertilizer		Available soil N before rice		N additions from weeds and residues	N additions from irrigation and rain	N removed		Available N after wheat, NH_4^+-N	Net N balance[a]	System-level efficiency (%)[b]
		Rice	Wheat	NH_4^+-N	NO_3^--N			Rice	Wheat			
Rainfed (kg N ha^{-1})												
0	BR11	0	0	68.7	42.1	23.3	5.5	54	21.9	30	−33.7	75.9
	BR14	0	0	68.7	42.1	23.3	5.5	46.1	21.9	30	−41.6	70.2
135	BR11	135	180	68.7	42.1	23.3	5.5	99.2	102.1	160	−93.3	79.5
	BR14	135	180	68.7	42.1	23.3	5.5	109.8	102.1	160	−82.7	81.8
Irrigated (kg N ha^{-1})												
0	BR11	0	0	68.7	42.1	23.3	10.0	95.1	25.8	40	16.8	111.7
	BR14	0	0	68.7	42.1	23.3	10.0	93.6	25.8	40	15.3	110.6
135	BR11	135	180	68.7	42.1	23.3	10.0	168.3	108.8	190	8	101.7
	BR14	135	180	68.7	42.1	23.3	10.0	151.7	108.8	190	−8.6	98.1
S.E.				–	–	–		7.8	5.6	12.4		

[a] Net N balance = (N removed by crops + mineral N after wheat) − (N additions through various sources + mineral N before rice).

[b] System-level efficiency = (N removed by crops + mineral N after wheat)/(N additions through various sources + mineral N before rice) × 100.

Table 7
TN and OC (g kg^{-1}), and pH at 0.15 m depth intervals as affected by nitrogen and water after 3 years of cropping[a]

	TN (g kg^{-1})				Organic C (g kg^{-1})				pH			
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60
Rainfed												
N0	0.65	0.37	0.35	0.25	4.8	2.9	2.6	2.0	4.8	5.4	5.6	5.6
N1	0.73	0.42	0.35	0.30	6.2	3.0	2.8	2.2	4.9	5.4	5.6	5.6
N2	0.74	0.43	0.50	0.40	6.3	3.5	3.7	3.2	5.1	5.5	5.7	5.7
Irrigated												
N0	0.70	0.54	0.50	0.45	5.3	3.8	4.4	3.7	4.9	5.0	5.1	5.1
N1	0.72	0.55	0.50	0.45	5.4	3.9	4.1	4.0	5.2	5.6	5.5	5.5
N2	0.90	0.58	0.45	0.40	5.8	4.2	3.9	3.1	4.7	5.4	5.3	5.4
S.E.	0.1	0.12	0.1	0.12	0.14	0.16	0.12	0.13	NS	NS	NS	NS

[a] Initial soil analysis taken before rice during July 1994 showed the following values: TN: 0.63, 0.41, 0.33, 0.30 g kg^{-1}; OC: 6.2, 4.4, 4.0, 3.6 g kg^{-1}; pH (H_2O; 1:1): 5.6, 6.0, 5.9, 5.8, for 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60 m, respectively.

respectively) and wheat (Kanchan) crops in the system. Thus, in the 315 kg N ha^{-1} treatment, there was a net increase in mineral N of 80 kg ha^{-1}, with net N balance of 8 and -9 kg ha^{-1} for the rotation of wheat sown after late and early rice, respectively. In contrast, without fertilizer N, TN input was 144 kg ha^{-1}, with total combined crop uptake of 121 and 119 kg ha^{-1}, respectively. This results in a net decrease in available soil N of 70 kg ha^{-1}, with balances of 17 and 15 kg ha^{-1}, respectively, after 1-year of rice–wheat cropping (Table 6). The irrigated treatments maintained greater available N than rainfed ones. Nitrogen accumulation occurred in irrigated treatments, despite greater N removal in harvested grain and straw than in rainfed treatments. Since N balances have already accounted for N inputs from irrigation and atmospheric deposition, the net balances of 15–17 kg N ha^{-1} under irrigation without N were presumably derived from BNF. A small net positive N balance (8 kg ha^{-1}) in the high-N treatment with BR11 rice also indicates N input from BNF. In the rainfed treatments, net N losses exceeded N inputs by 34–93 kg ha^{-1}. In all treatments, however, BNF contribution would be underestimated by the amount of N losses from volatilization or denitrification.

4. Discussion and conclusions

The release of photoperiodically insensitive cultivars of rice and wheat made timely sowing and harvesting of both crops possible in rice–wheat systems. Though shortening the growth cycle without the inclusion of other physiological benefits almost inevitably reduces site potential of individual crops, the issue in rice–wheat systems is the aggregate yield of the system. Now, short-duration cultivars of both crops are available; e.g., in Bangladesh, rice cultivars BR14, BR32, BR33, and BR39 are now being introduced into the rice–wheat systems to the benefit of greater aggregate yields. Further, the requirement for selection or breeding of cultivars with appropriate patterns of phenological development is evident for rice–wheat areas in subtropical Asia where high temperatures (>30/25°C, day/night) frequently occur during the flowering and grain-filling stages of late-seeded wheat. High temperature shortens the grain-filling period (Midmore et al., 1984; Rawson, 1988) induces water stress leading to slow growth rates and even some level of sterility (Saini and Aspinall, 1982), and thus becomes a major constraint to wheat production, especially when sowing is delayed beyond the optimum date (Saunders and Hettel, 1994). In Bangladesh, e.g., there is reduction by 44 kg ha^{-1} for each day delay in sowing after 1 December (Ahmed and Meisner, 1996). In such heat-stressed environments, where rice–wheat systems are practised, either short- or medium-season cultivars of rice are required so that wheat can be sown early to complete its growth cycle before the high temperatures of the ensuing spring, or wheat cultivars with heat tolerance during grain-filling are required.

Another important issue in rice-wheat systems is the need for the timely sowing and establishment of wheat after rice, of which two aspects cause concern (Timsina and Connor, 2001). One is the need for rapid germination to avoid entrapment under surface seals that often result from the structural decline of puddled soils. The second is tolerance to water-logging during establishment where previously saturated paddies are exposed to rainfall and irrigation. Crop establishment techniques, such as zero-, reduced-, or minimum-tillage, and surface seeding, and the use of raised beds and small machines are now available to facilitate timely sowing and establish wheat quickly and reliably after rice. Timely sowing and rapid establishment allow the crop to grow and mature before high temperature occur during the grain-filling stage. The development of wheat cultivars able to withstand water-logging during the seedling stage, however, still remains a challenge for breeders, because that ability should also be combined with resistance to drought and heat during grain filling (Timsina and Connor, 2001).

Across the 3 years of experimentation in northern Bangladesh, grain yields of rice in rice–wheat systems varied widely. Rice yields under irrigation and without N ranged from 2.5 to 6.4 t ha^{-1}, while under rainfed conditions and without N they ranged from 1.7 to 3.3 t ha^{-1} (Table 1). The yields without N were generally greater than in the N-applied treatments during the second and third years, which was attributed to rapid mineralization and recovery and utilization of soil organic matter (SOM) by rice plants in the warm moist conditions during the monsoon season. Bouldin (1986) also reported that lowland rice soil can supply adequate N for grain yields of 2.5–3.5 t ha^{-1} without the addition of fertilizer N at least for the initial few years. Recent data from IRRI indicate that N supplied by lowland rice soils ranges from 30 to 105 kg ha^{-1}, sufficient to produce 3.0–7.0 t ha^{-1} grain yield (Singh et al., 1995). In a 1-year study in farmers' fields in Bangladesh and Nepal, Adhikari et al. (1999) reported 3.3 and 2.9 t ha^{-1} of rice yield in rice–wheat systems without N application. However, although lowland rice soils can supply substantial N, especially under irrigation, soil N will be exhausted in the long run due to its continued uptake by the crop. This requires the supply of inorganic N fertilizer to meet crop demand and maintain N balance in the soil.

Heavy rainfall in the third (1490 mm), and substantial rainfall plus irrigation in the second (>1100 mm) year added approximately 10.0 and 9.0 kg ha^{-1} of N to rice (6.5 and 9.2 g N ha^{-1} mm^{-1}, respectively, in rainfall and irrigation water). These concentrations of N were similar to those earlier reported by Abedin et al. (1991) for Bangladesh. Considering a percolation rate of 6 mm per day for that soil for a 120-day period, the estimates of leaching losses are around 4.7 kg ha^{-1}. Further, there would be similar magnitudes of losses through lateral seepage. Thus, additions of N through rain and irrigation would probably balance losses through leaching and seepage. It is also possible that there were significant N losses through volatilization (up to 50 kg ha^{-1}) as has been reported by the same authors. Further, there might have been losses through denitrification. The environmental conditions during the second and third years were perhaps not as suitable as in the first year as evident from the lower grain yields of rice in all treatments. As mentioned previously, yields in the second and third years were also affected by insect attacks and lodging due to heavy rain, and hence the yields during those years were much lower than in the first year.

Low mean minimum temperatures and high solar radiation throughout the wheat growth cycle during the first year were more favorable for yield than the relatively higher temperatures and lower solar radiation in the second and third years. There was a favorable water balance during the wheat sowing and establishment period due to plentiful rainfall during and after harvest of rice in the first and second years, resulting in high yields even under rainfed conditions. High temperatures coupled with high solar radiation during the grain-filling period, especially for the late sowing, caused heat stress to wheat resulting into lower yields, especially in the second and third years.

Annual system productivities were small during the second and third years because, as discussed earlier, rice yields were reduced by lodging and insect damages. The overall results, however, suggest that system productivity of rice–wheat systems could be increased with greater amounts of N and irrigation.

The lower RE, AE, and PE for rice at 135 kg N ha^{-1} compared with those at 90 kg ha^{-1} revealed no yield benefit from additional application of N above

90 kg ha^{-1}. AE and PE values are much smaller, whereas the RE values are similar to those reported for wetland rice in tropical and temperate environments (Cassman et al., 1993; Craswell and Godwin, 1984). For Bangladesh, an earlier study conducted by FAO/IAEA (IAEA, 1978) reported an apparent recovery of 6–53%, PE of 16–85 kg grain yield per kg N uptake, and an AE of 4–16 kg grain per kg N applied. In field experiments, depending on how N is applied, flooded rice generally recovers 20–40% of applied N, whereas under non-flooded situations, upland crops normally recover about 40–60% of N (Vlek and Byrnes, 1986).

Under both rainfed and irrigated conditions, all the N-use efficiencies were higher for wheat than for rice. AE was much lower for rice than for wheat under both rainfed (4.9–9.8 vs. 14.9–20.9 kg grain per kg N applied) and irrigated (2.8–10.8 vs. 16.7–27.0 kg grain per kg N applied) conditions. The mean REs for wheat were substantially higher than for rice (45–51% vs. 33–53%). Likewise, PE was also much greater in wheat than rice under rainfed (32.7–44.6 vs. 11.9–27.5 kg grain kg^{-1} N absorbed) as well as under irrigated (35.9–51.1 kg grain kg^{-1} N absorbed vs. 5.2–24.9 kg grain kg^{-1} N absorbed) conditions. Our results are similar to those of Adhikari et al. (1999), who reported mean RE of 31 and 51%, PE of 31 and 53 kg grain per kg N uptake, and AE of 8.5 and 23.5 kg grain per kg N applied for rice and wheat, respectively, in rice–wheat systems in Nepal, and of Bronson et al. (1997), who reported greater PE for wheat than rice in northwest India. The results, however, differ from those of Yadav et al. (2000a), who reported smaller mean AE for wheat (12.0–21.5 kg grain per kg N applied) than for rice (12.6–25.1 kg grain per kg N applied) from long-term rice–wheat experiments conducted at six locations in India, and of Duxbury et al. (2000), who reported almost similar mean AE (16–17 kg grain per kg N applied), but different RE (21 and 26% for rice and wheat, respectively) from eight long-term experiments, also from India. In all of those studies, as in our study, loss processes were not measured. We suspect that nitrification–denitrification and leaching losses of fertilizer N were greater in rice than in wheat, resulting in smaller N-use efficiencies in rice.

Cassman et al. (1993), on the other hand, found nearly identical PE for irrigated wheat in California and for dry-season irrigated rice in the Philippines. In our study, there was greater PE for wheat than rice, which was probably due to the greater solar radiation and the cooler temperature during the wheat season. Seasonal conditions were, therefore, more conducive to favorable grain development for wheat than for rice, resulting in greater PE in wheat. High temperatures can exacerbate volatile losses of N during grain filling in both rice (Stutte and da Silva, 1981) and wheat (Papakosta and Gagianas, 1990), and would result into greater PE in the cool wheat, compared to warm rice, season. Further, high N concentration in wheat plants at maturity would have contributed to yield formation, leading to higher PE in wheat.

The supply of N is influenced by soil conditions. Nitrate leaching, denitrification, ammonia volatilization, immobilization, and mineralization of SOM are influenced by water supply. Fernandez and Laird (1959) showed that wheat yielded 24 kg grain per kg applied N under optimum soil water but only 11 kg grain kg^{-1} N when water was limiting. This, however, could also be due to the inability of N being 'diluted' due to lack of photosynthates. Decreased water supply affects growth rate, availability of soil-N, and recovery of fertilizer-N (Spratt and Gasser, 1970a,b). The present findings also reveal that AE of wheat is lower under rainfed conditions than under irrigation. During the wheat season, there is less N loss by various processes, resulting in greater N-use efficiency, compared to flooded rice where N-use efficiency is low due to substantial loss. Further, overall system-level efficiencies were lower under rainfed conditions due to more losses during wetting and drying cycles compared to under irrigation, suggesting that irrigated rice–wheat systems are more efficient than the rainfed systems in terms of utilization of N.

In a few earlier studies (Bansal et al., 1980; Sharma et al., 1980), N fertilizer increased available N content of the soil. Other studies (e.g. Cassman et al., 1995) indicate that rice–rice cropping is generally associated with the release of N from SOM and its conservation or even increase over time, but with lower availability. Rice–wheat cropping, on the other hand, may promote breakdown of SOM compared to rice–rice systems, and thus may reduce SOM over time (Hegde and Dwivedi, 1992).

Net BNF inputs to the irrigated rice–wheat system without applied N were estimated to be about

15–17 kg N ha^{-1}, and a smaller balance of up to 8 kg ha^{-1} for high-N treatments implies a smaller net BNF input than in the control treatment. Assuming that 30–40% of the applied N was lost to volatilization, which is typical for irrigated lowland rice (Fillery et al., 1986), net BNF inputs in the high-N (135 and 180 kg ha^{-1} for rice and wheat, respectively) treatment of the irrigated rice–wheat system would be more than that for the control. Our results are similar to those of Cassman et al. (1998), who reported 40 kg BNF ha^{-1} per crop in control plots. Likewise, Witt et al. (2000) estimated net BNF inputs of 50 kg ha^{-1} per crop in control and 10 kg ha^{-1} per crop in high-N plots of rice–rice systems (190 and 120 kg N ha^{-1} for dry- and wet-season rice), and of ~22 kg N ha^{-1} per crop in control plots of maize–rice systems in the Philippines. Although BNF is generally negatively affected by the presence of inorganic N (Greenland, 1997), our results do not suggest inhibition of BNF by applied N fertilizer when most of the N is broadcast into floodwater in several split applications (Witt et al., 2000).

The N balance was largely influenced by N losses and N inputs that were not measured directly. Denitrification losses would occur in both irrigated and rainfed systems during soil drying and wetting cycles between rainfall events in fallow periods and upon soil flooding before puddling for the rice crop (George et al., 1993). The primary N-loss pathways probably differed in rainfed and irrigated systems, because most gaseous N losses in flooded rice result from volatilization (Freney et al., 1985), while denitrification would account for most N losses in flooded-drained systems that occurred in the rainfed rice–wheat system.

There has often been concern about yield declines and of slower rates of yield gains than achieved previously, and thus of the viability and sustainability of rice–wheat systems in south Asia. This is mostly because rice and wheat extract a lot of nutrients, especially at high levels of productivity. For example, for rice–wheat systems with grain yields of 5 t ha^{-1} and HI of 0.5 for each crop, N concentrations in grain of 1.26 and 1.98%, and in straw of 0.70 and 0.48%, respectively for rice and wheat, the system would extract 162 kg N ha^{-1} in grain, or 221 kg N ha^{-1}, if straw were also removed. If a legume (e.g. mungbean, 1 t ha^{-1}; HI, 0.4; N concentrations of 4.5 and 1.5%, respectively, in grain and straw) were also included further intensifying those systems, as has been commonly practised in Bangladesh, the extraction would increase to 207 and 289 kg ha^{-1} in grain and grain plus straw, respectively. If extraction is continued year-after-year without replenishment, then there will be nutrient mining from the soil. Management should aim to apply fertilizer adequate for crop demand and to do so ways that minimize loss, maximize the efficiency of use, and maintain N balance. The amount required depends on many factors, including the indigenous or native sources (e.g. irrigation and rainwater, BNF, soil microbial pool, etc.) of N. However, though indigenous sources can supply some N, they are generally small compared to its extraction. Thus, yields in rice–wheat systems can be sustained at high productivity levels if they are supplied with adequate amounts of inorganic fertilizers, coupled with organic and indigenous sources of N.

Finally, it must be stressed that application of N fertilizer and optimum irrigation water according to the demand of component crops as well as their improved management are essential for increasing the productivity of the rice–wheat systems and for meeting the food demand of the growing population of South Asia, where these systems contribute largely to food security of farmers. Our results emphasize further need for detailed measurements of water and nutrient losses, losses to pests and diseases, and of losses due to lodging and catastrophic events (e.g. floods, typhoon, etc.) in irrigation and N studies. There are, however, increasing challenges because the erratic, and often high, monsoonal rainfall damages crops as well as contributing to both nutrient inputs into and losses from the systems. Nevertheless, for proper understanding of the N demand of the component crops, and to devise N fertilizer recommendations and water-management strategies for rice–wheat systems, continuing analyses of N- and water-use efficiencies and their thorough balance sheets are essential.

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