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Farm Level Water Footprints, Water Productivity and Nitrogen Use Efficiency in Irrigated Rice under Different Water and Nitrogen Management

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Attempt was made to study the impact of intermittent irrigations and different nitrogen (N) doses on growth, yield, N use efficiency and water footprints of rice. A rice cultivar, 'Lalat' was grown with 3 water regimes in main plots (W_1 = continuous flooding of 5 cm, W_2 = irrigation after 2 days of water disappearance, W_3 = irrigation after 5 days of water disappearance) and 5 N levels in subplots (N_1=0 kg N ha^{-1}, N_2=60 kg N ha^{-1}, N_3=90 kg N ha^{-1}, N_4=120 kg N ha^{-1}, N_5=150 kg N ha^{-1}). Among water management, lowest mean water footprint (WFP) was observed with W_2 but it was at par with W_1. Yield, biomass and leaf area also did not significantly differ ($P > 0.05$) between W_1 and W_2, but these were significantly lower in W_3. These results suggest W_2 can reduce water input without affecting rice yields. On the other hand, water productivity in terms of irrigation was higher in W_3 though grain yield was less under this treatment. Among N treatments, the lowest average WFP of 1277 m^3 t^{-1} was achieved under 150 kg N ha^{-1} which was at par with 120 kg N ha^{-1} but highest WFP of 2532 m^3 t^{-1} was observed when no N was applied. The reduction of WFP with higher dose of N was attributed to mainly increased grain yield of rice. No significant water×nitrogen interactions on biomass, grain yield, WFP, N uptake and N use efficiency were observed.

Key words: Water footprints, water productivity, rice, nitrogen, water balance

Changing global climatic patterns coupled with declining per capita availability of surface and ground water resources have made submerged rice cultivation a great challenge in India. With increasing water demand for high value crops and other sectors, rice cultivation in India will face stiff competition for scarce water resource in future. Adoption of suitable agro-techniques for rice cultivation is the need of the hour to produce more rice with less water so as to check the decline of surface and ground water resources in most of the rice growing Asian countries (Sandhu *et al*. 1980). Recognizing the importance of the above facts, many Asian countries developed water saving irrigation (WSI) technologies to achieve more water productivity and to record less WFP (Sandhu *et al*. 1980; Cabangon *et al*. 2004). Among various WSI management practices, the most commonly practiced is intermittent submergence (IS) or alternate wetting and drying (AWD) of method of irrigation in rice. In AWD, soil is dried out to some degree in between irrigation events. A fundamental part of understanding and improving water productivity is quantitative estimates of the major components of field water balance like evapo-transpiration, seepage, percolation *etc*. and to compute crop water productivity and water footprints as an indicator for efficient use of water under a particular irrigation management system. Water footprints indicate direct (the green and blue water footprint) and indirect (grey water footprint) appropriation of freshwater resources and lower water footprint from a crop management system reflects its efficiency to produce more biological yield with less amount of water (Postel *et al*. 1996; Hoekstra and Chapagain 2008). Under such condition intermittent submerged irrigation may be useful to reduce WFP and to improve water productivity. Water productivity of rice of 0.14-0.56 kg m^{-3} was obtained by Usman *et al*. (2014) in land between the Ravi and Chenab. Mulching improves water productivity, yield and quality of fine rice under water saving rice production

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system (Jabran *et al*. 2014). A number of studies have been conducted to quantify the water footprint of a large variety of different crop products and crops (Gerbens-Leenes and Hoekstra 2009; Chapagain and Orr 2009). These studies provided a broad-brush to the global picture since the primary focus of these studies was to establish a first estimate of global virtual water flows and/or national water footprints. More recently, though a few studies have separated global water consumption for crop production into green and blue water with a better spatial resolution (Liu and Yang 2010; Hanasaki *et al*. 2010) but still information on water footprints based on inflow and outflow of water at farm level under different management practices are lacking.

Along with the proper water management, appropriate amount of plant nutrient also strongly affect plant growth, crop water productivity, and nutrient use efficiency. Among the mineral nutrients, nitrogen (N) is the key element in achieving consistently high yield in cereals (Ponnamperuma and Deturck 1993; Shafi *et al*. 2011; Weih 2014). Depending upon the soil condition and socio-economic status, farmers of eastern India apply anywhere between nil to 150 kg N ha^{-1}, thus optimum N rate under different water management is still a promising management recommendations in order to increase profit for low income rice farmers of the region (Kar *et al*. 2004; Kar *et al.* 2013). Keeping the importance of above points in view, this study was conducted to study the impacts of continuous and intermittent irrigations under different rates of N on rice growth, yield and water footprints in typical irrigated lowland during post-rainy season of eastern India.

Materials and Methods

Study Site

Two years on-farm experiments were conducted during post-rainy season (December to March of 2007-08 and 2008-09) in a representative place of east coast of India (Alisha, Sattyabadi block, Puri, Odisha). In the region, mean maximum temperature ranges from 37 °C in May to 26 °C in December-January. The region receives 1500 mm average annual rainfall but 80% of it occurs during rainy season (June-October). High rainfall during rainy season, saucer shaped land form and poor drainage condition make the region waterlogged in this season. After receding the flood water, the land remains dry from January to May because rainfall during winter/summer season is meager and as a result successful crop cultivation is not possible without irrigation. But farmers grow rice during dry season to obtain food security though irrigation water is limited during this season.

Crop and Water Management

The on-farm experiment was laid out in a split plot design with three replications during 2007-08 and 2008-09. The 3-week old seedling of 'Lalat', a predominant medium duration (120 days) rice cultivar in the region was transplanted in hills spaced by 0.20 m × 0.15 m. The treatments consisted of three water management practices *viz.*, W_1 = continuously submerged (CS) of 5 cm depth, W_2 = intermittent submergence (IS) of 5 cm and irrigation after 2 days of disappearance of water from soil surface and W_3 = intermittent submergence of 5 cm and irrigation after 5 days of water disappearance from the soil surface in main plots and five N fertilizer application rates, *viz.*, N_1 = 0 kg N ha^{-1}, N_2 = 60 kg N ha^{-1}, N_3 = 90 kg N ha^{-1}, N_4 = 120 kg N ha^{-1} and N_5 = 150 kg N ha^{-1} in sub-plots. For the first 15 days after transplanting (DAT), shallow water layer of 30-40 mm was kept for all the water management treatments which facilitated to overcome transplanting shock and turning the crop green quickly. Thereafter, CS and IS plots were managed separately. In CS plots the water depth of 30-50 mm was kept until the terminal drainage at about 15 days before the harvest. In IS, plots were allowed to be intermittently submerged and re-flooded to a depth of 50 mm after 2 days and 5 days of disappearance of water from the surface in W_2 and W_3, respectively except one week during flowering when a water layer of 50 mm was established for these treatments also. Thereafter, AWD cycles were continued till the necessary drainage before harvest. Each main plot was irrigated separately based on the treatment imposed.

Crop Growth, Leaf Area, Nitrogen Uptake and Nitrogen Efficiency Parameters

Samples for above ground biomass, leaf area and N uptake were collected from the 10-hill area at active tillering, panicle initiation, flowering, grain filling and physiological maturity stages. At full harvestable maturity, plants from an area of 5 m^2 area were taken for yield measurement. Sub-samples of straw and grain were analyzed for N uptake. The parameters related to N use efficiency like N harvest index, physiological N use efficiency, Agronomic N use efficiency, apparent recovery of N applied were derived. Soil evaporation, crop evapo-transpiration, seepage and percolation during crop growth period were mentioned daily using drum technique of Dastane (1966). The water depth above the ground under 3 water regimes were measured in this study and are presented in Fig. 1 (a, b, c).

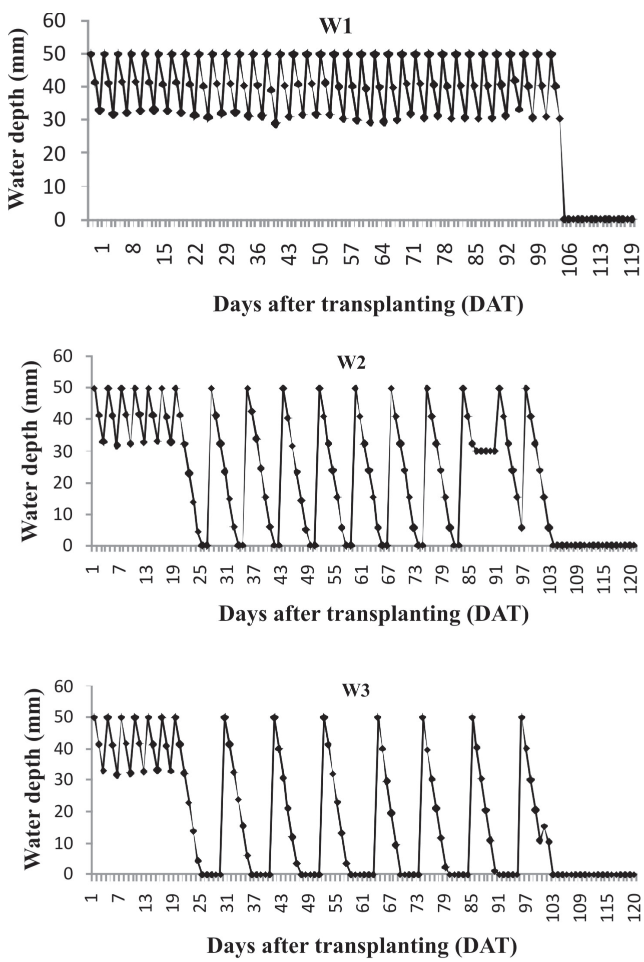

Fig. 1. Water depth above ground under (a) W_1 treatment, (b) W_2 treatment and (c) W_3 treatment

Water Footprints and Water Productivity

Water footprint (WFP) is expressed as the volume of water consumed or evaporated and/or polluted to grow a crop per unit mass of its economic yield, usually the unit is expressed as m^3 t^{-1} or litre kg^{-1} (Hoekstra and Chapagain 2008). The WFP has three components: the green water footprint, WFP_{green} (evaporation of water supplied from the rain in crop production), blue water footprint, WFP_{blue} (evaporation of the irrigation water supplied from surface and renewable groundwater sources) and the grey water footprint, WFP_{grey} (volume of fresh water polluted in the production process which represents the amount of freshwater required to mix pollutants and maintain water quality according to agreed water quality standards). Water footprints of the crop, WFP_{total} (m^3 t^{-1}) were thus calculated by dividing the total volume of blue, green or grey evapo-transpired or water used (m^3 ha^{-1}) by the quantity of the grain yield of the crop (t ha^{-1}).

$$WFP_{total} = (WFP_{green}) + (WFP_{blue}) + (WFP_{grey}) = \frac{CWU_{green} + CWU_{blue} + CWU_{grey}\ (m^3\ ha^{-1})}{Economic\ yield\ of\ the\ crop\ (t\ ha^{-1})}$$

The water productivity (WP) is the amount of crop yield produce (kg) per unit volume of water used (m^3) which can be derived in terms of water used for irrigation (WP_{IRRI}), gross inflow or total crop water demand (WP_{TCW}) and evapo-transpiration (WP_{ETc}). The WP_{IRRI} is the rice yield production divided by the irrigation inflow. The WP_{TCWD} is the rice yield divided by the rain, irrigation plus other inflow. The WP_{ETc} is the rice yield divided by the rice evapo-transpiration. Water productivity indicators under different water and N management treatments were computed.

Statistical Analysis

Data recorded were subjected to analysis of variance (GLM procedure) using SAS software version 9.2 (SAS Institute 2010). Duncan's Multiple Range Test was employed to test significant differences between means of treatment combinations.

Results and Discussion

Soil Profile Information of the Study Site

The soil within the experimental area was found to be relatively homogeneous and soil texture is clayey in nature. The clay content in the soil varied from 41.6% (0-0.15 m) to 63.5% (0.30-0.45 m). The bulk density was 1.45 Mg m^{-3} at 0-0.15 layer and it increased with soil depth, at 0.90-1.20 m layer it was 1.61 Mg m^{-3}. The pH was slight to moderately acidic and no salt problem was detected in the soil. The organic carbon content was relatively higher (6.11 g kg^{-1}) at upper layer (0-0.15 m) while at deeper layer it was 3.12 g kg^{-1}. The water content at field capacity was 0.452 m^3 m^{-3} at 0-0.15 m layer and the highest water content was 0.555 m^3 m^{-3} at 0.30-0.45 m soil depth.

Total Aboveground Dry Matter and Leaf Area Index

Total aboveground dry matter (TAGDM) of the crop as influenced by water management and N are analyzed and are presented in fig. 2. Water

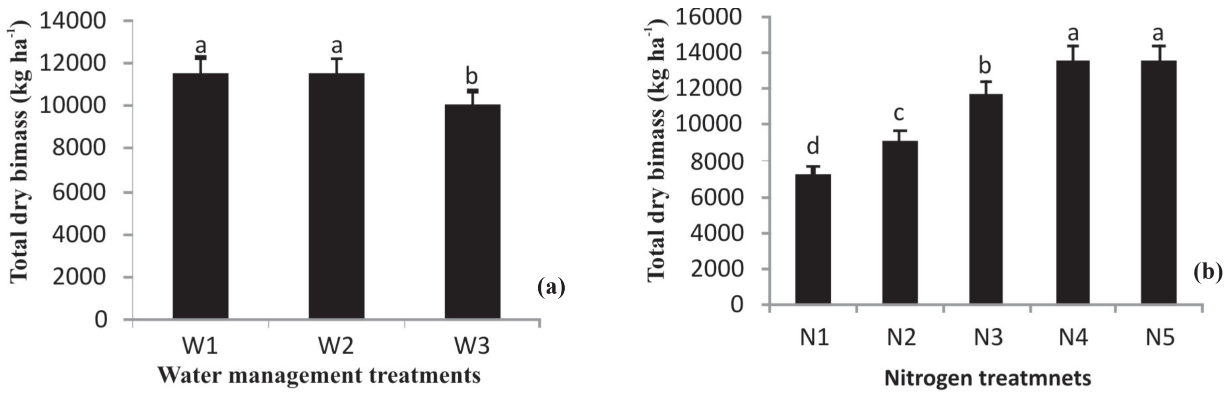

Fig. 2. Aboveground biomass as influenced by (a) water and (b) nitrogen treatments. Means in different histograms followed by same letter are not significantly different as per Duncan's multiple range test

management effect on total aboveground dry biomass (TAGDB) accumulation was non-significant between W_1 and W_2 but TAGDM under W_3 was significantly reduced. On the other hand, TAGDB production responded positively to N application. Averaged over sowing dates, maximum TAGDB at maturity to value of 14757 kg ha^{-1} was achieved in N_5 followed by in N_4 (14561 kg ha^{-1}), N_3 (11694 kg ha^{-1}) and N_2 (9092 kg ha^{-1}) treatments which were statistically significant. The treatments N_4 and N_5 produced maximum plant height, LAI and ultimately produced more biomass. Lowest LAI and AGDB were recorded when no N was applied (N_1).

No significant difference was observed between W_1 and W_2 in the case of leaf area development but in W_3 LAI was reduced significantly (Fig. 3a). Averaged over years and water management practices, maximum LAI reached to a value of 5.57 in the N_5 treatment followed by N_4 (5.34), N_3 (5.30), N_2 (3.91) and N_1 (2.59) treatments (Fig. 3b). Greater leaf expansion in rice was ascribed in N_4 and N_5 treatments due to higher growth rate and rapid leaf area development. W × N interaction was observed in the total dry matter and LAI in both the study years.

Grain Yield

No significant yield difference was also achieved between W_1 and W_2 water management treatments but under W_3 treatment yield was reduced significantly (Fig. 4a). Nitrogen dose significantly influenced grain yield. Highest grain yield (5331 kg ha^{-1}) was obtained under N_5 treatment which was statistically at par with N_4 (5297 kg ha^{-1}). Results also showed that with increased N levels from 0 to 120 kg ha^{-1}, grain yield was increased significantly (Fig. 4b). Plots with 0 kg N ha^{-1} (N_1) produced significantly less grain yield (2667 kg ha^{-1}) as compared to plots fertilized with 60 kg N ha^{-1} and above. Under N_2 (60 kg ha^{-1}) and N_3 (90 kg ha^{-1}), grain yield of 3723 and 4696 kg ha^{-1} were obtained, respectively. There was no observed W × N interaction in grain yield production in both the years.

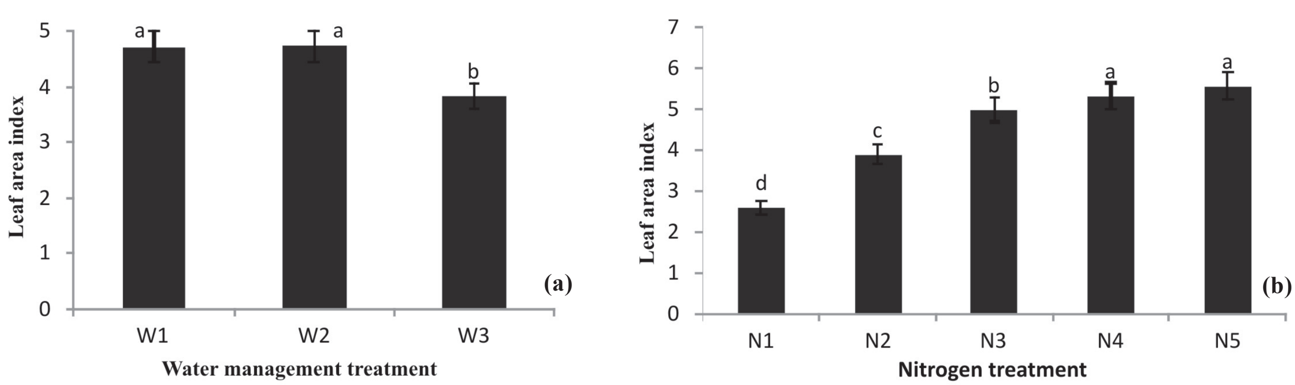

Fig. 3. Leaf area index as influenced by (a) water management treatments and (b) nitrogen treatments. Means in different histograms followed by same letter are not significantly different as per Duncan's multiple range test

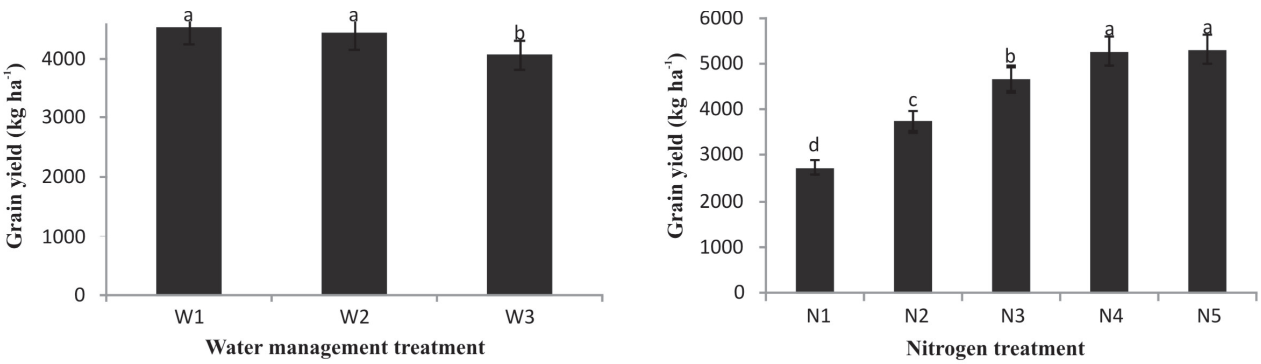

Fig. 4. Grain yield as influenced by (a) water management treatments and (b) nitrogen treatments. Means in different histograms followed by same letter are not significantly different as per Duncan's multiple range test

Crop Evapo-transpiration, Seepage and Percolation and Total Water Demand

The outflows of water from a rice field are evaporation, transpiration, seepage, percolation and over bund flow. Since there was no excess or overflow water from the field, over bund flow was nil. Other outflow parameters were measured in the field. The crop evapo-transpiration (ETc) recorded a value of 3.2 to 5.8 mm day^{-1} under different treatments which largely depended on climatic conditions, crop growth stage and crop vigour. During entire crop growth period the ETc was measured as 623, 604 and 581 mm under W_1, W_2 and W_3, respectively. The seepage and percolation depths of water during the entire growth period under W_1 were measured as 413 mm which was significantly different from W_2 (337 mm) and W_3 (253 mm). Total amount of seepage and percolation were higher in W_1 than that of W_2 and W_3 which can be attributed to the greater number of days with standing water in W_1 followed by W_2 and W_3. But the mean seepage and percolation rate (varied from 3.8 to 3.95 mm day^{-1}) among the three water treatments did not vary significantly due to similar soil hydro-physical properties in all the treatment plots (Table 2).

The 192 mm of water was estimated to require for land preparation and soaking which included 105 mm to meet soil evaporation and 87 mm of water to fulfill seepage percolation. A water layer of 50 mm was established for about 15 days after transplanting for all the treatments which facilitated to overcome transplanting shock and to turn the crop green quickly. Thus, the total water demand for land preparation, maintaining the water layer after transplanting and to meet the crop evaporative demand and percolation during the crop growth period was determined as 1228, 1133 and 1026 mm for W_1, W_2 and W_3, respectively. Out of that 929, 862 and 722 mm were fulfilled from blue water (irrigation) under 3 respective treatments.

Field Level Water Footprints of Rice under Different N Doses

Total crop water demand for the rice cultivation is the water required for crop evapo-transpiration, seepage and percolation during crop growth period and water needed for evaporation and percolation during land preparation. Since water footprint refers to a real loss to the catchment, only crop evapo-transpiration and evaporation during land preparation were considered for WFP calculation. Thus, the WFP (m^3 t^{-1}) of rice production is the sum of the volume of water evaporated or evapo-transpired per unit quantity of rice yield production. Since, percolation is actually not a loss to the catchment, therefore, this loss during crop growth period and land preparation was not included for farm level water footprint computation. But the grey WF of the crop due to N pollution was computed and was added with green and blue WF to determine total WF. The table 2 shows the water footprint and the volume of total percolation water per unit amount of yield under different water regimes and different N doses. The highest total water footprint (WF_{Total}) was observed under W_3 with the value being 1762 m^3 t^{-1} whereas, WFs_{Total} of 1666 and 1663 m^3 t^{-1} were computed under W_1 and W_2 treatments, respectively. Among N treatments, highest WFP_{Total} was observed when no N was applied with the values being 2465, 2478, 2654 m^3 t^{-1} in W_1, W_2 and W_3 treatments, respectively. On the other hand, the lowest WFP_{Total} of 1302, 1279 and 1328 m^3 t^{-1} were achieved under 150 kg N ha^{-1} in three respective water regimes. Study revealed that total WFP achieved under 150 kg N ha^{-1} was statistically at par with the

Table 1. Grain yield and water footprints of rice under different water and nitrogen management practices

Treatments	GY (kg ha^{-1})	ETC (mm)	PER_C (mm)	E_LP (mm)	PER_LP (mm)	TOT_LP (mm)	PRF (%)	TWD (mm)	IRRI (mm)	GWFP (m^3 t^{-1})	BWFP (m^3 t^{-1})	GrWFP (m^3 t^{-1})	TWFP (m^3 t^{-1})	PERC_V (m^3 t^{-1})	TWU_V (m^3 t^{-1})
W_1															
N_1	d2880	623	413	87	105	192	67.1	1228	929	0	2465	0.0	a2465	1799	a4264
N_2	c3920	623	413	87	105	192	67.1	1228	929	0	1811	1.5	b1813	1321	b3134
N_3	b4955	623	413	87	105	192	67.1	1228	929	0	1433	1.8	c1435	1045	c2480
N_4	a5404	623	413	87	105	192	67.1	1228	929	0	1314	2.2	d1316	959	d2275
N_5	a5465	623	413	87	105	192	67.1	1228	929	0	1299	2.7	d1302	948	d2250
Mean	4524.8	623	413	87	105	192	67.1	1228	929	0	1569		1666	1145	2811
W_2															
N_1	d2789	604	337	87	105	192	70.1	1133	862	0	2478	0.0	a2478	1585	a4062
N_2	c3825	604	337	87	105	192	70.1	1133	862	0	1807	1.3	b1808	1156	b2963
N_3	b4755	604	337	87	105	192	70.1	1133	862	0	1453	1.9	c1455	930	c2385
N_4	a5345	604	337	87	105	192	70.1	1133	862	0	1293	2.2	d1295	827	d2122
N_5	a5415	604	337	87	105	192	70.1	1133	862	0	1276	2.8	d1279	816	d2095
Mean	4425.8	604	337	87	105	192	70.1	1133	862	0	1561		1663	999	2662
W_3															
N_1	d2517	581	253	87	105	192	80.5	1026	722	0	2654	0.0	a2654	1422	a4076
N_2	c3465	581	253	87	105	192	80.5	1026	722	0	1928	1.4	b1929	1033	b2962
N_3	b4267	581	253	87	105	192	80.5	1026	722	0	1566	2.1	c1568	839	c2407
N_4	a5032	581	253	87	105	192	80.5	1026	722	0	1328	2.4	d1330	711	d2041
N_5	a5042	581	253	87	105	192	80.5	1026	722	0	1325	3.0	d1328	710	d2038
Mean	4064.6	581	253	87	105	192	80.5	1026	722	0	1643		1762	881	2642

GY = Grain yield, ETC = Crop evapotranspiration, E_LP = Evaporation during land preparation, PER_LP = Percolation during land preparation, TOT_LP = Total water required during land preparation, ER= Effective rainfall, IWD = Total irrigation water demand, IRRI = Irrigation applied, BWFP= Blue water footprint, GWFP = Green water footprint, GrWFP = Grey water footprint, TWFP = Total water footprint, PERC_V = Volume of percolation water , TWU_V = Volume of total water use

Significance

Factor	Grain yield	TWFP	TWU_V
Water regimes(W)	Significant at 5% level	Significant at 5% level	Significant at 5% level
Nitrogen (N)	Significant at 5% level	Significant at 5% level	Significant at 5% level
W×N	not significant	not significant	not significant

Means within a column followed by the same letter are not significantly different as per Duncan's multiple range test values obtained at 120 kg N ha^{-1}. The WFP of the crop was higher when no or lower doses of N were applied which might be attributed to low grain yield obtained in N stress plots. The WFP reduced significantly with increased dose of N from 0 to 120 kg ha^{-1} due to significant yield enhancement under all water regimes. On the other hand, total WFP was significantly lower under W_1 and W_2 than that of W_3. Since no rainfall was received during the crop growth period, green WFP was nil and entire WFP was blue WFP.

The highest volume of total percolation water per unit quantity of yield (m^3 t^{-1}) was also observed when no N was applied with the values being 1799, 1585 and 1422 m^3 t^{-1} under W_1, W_2 and W_3 treatments, respectively. On the other hand, the lowest volume of total percolation water per unit of yield (m^3 t^{-1}) of 948, 816 and 710 m^3 t^{-1} were achieved under 150 kg N ha^{-1} in three respective water regimes. The reduction of volume of percolation water with higher doses of N was attributed to mainly increased grain yield of the crop, whereas, decreased percolation volume under W_2 and W_3 was mainly due to reduction of duration of standing water. The volume of total water use per unit quantity of yield was higher in W_1 (2811 m^3 t^{-1}) than that of W_2 (2662 m^3 t^{-1}) and W_3 (2642 m^3 t^{-1}) due to continuous submergence under the former treatment, as a result more percolation was experienced under W_1. These infer that the water footprint and volume of percolation water to a large extent was influenced by agricultural management rather than by the agro-climate under which the crop was grown. This provides an opportunity to improve yield and water productivity through different improved agro-management practices. It is also inferred that optimum application of N has the potential to enhance the yield and in turn to reduce WFP of rice production under all water management treatments.

Water Productivity, Water Use and Irrigation Use Efficiency of Rice

The water productivity per unit quantity of irrigation water (WP_{IRRI}), gross or total crop water demand (WP_{TCW}) and evapo-transpiration (ETc) under different water and N management were computed and are presented in table 2. Highest WP_{IRRI} was obtained under W_3 (0.56 kg m^{-3}) followed by W_2 (0.51 kg m^{-3}) and W_1 (0.48 kg m^{-3}) water regimes. Under W_3 though yield was 12 per cent less than that of W_1 but water productivity per unit of irrigation water was 19 per cent higher under W_3 because of production of more yield with less water. The yield difference between W_1 and W_2 was not statistically significant however, when we assess water productivity per unit of irrigation water, it showed that under W_2 the water productivity was significantly higher than that of W_1. The WP_{IRRI} was enhanced when higher doses of N was applied with the values being 0.33, 0.45, 0.56, 0.63 and 0.64 kg m^{-3} under N_1, N_2, N_3, N_4 and N_5, respectively. On the other hand, water productivity in terms of total crop water need (WP_{TCW}) was 0.37, 0.39 and 0.40 kg m^{-3} under W_1, W_2 and W_3 water management treatments, respectively. Though rice plant needed almost same amount of water for transpiration for all the treatments but water savings come from less evaporation and percolation due to alternate and drying under W_2 and W_3 treatments. As a result WP_{TCW} was at par among three water management treatments though yield was significantly lower under W_3. The WP_{TCW} was gradually increased with increasing doses of N but estimated water productivity was at par between N_4 and N_5. Similar trend was also observed when water productivity in terms of only evapo-transpiration was estimated (Table 2).

The process fraction of gross inflow {(ET/(rain plus irrigation)} indicates the amount of gross inflow that is depleted by rice ET. At the field scale, this

Table 2. Water productivity indicators under different water and nitrogen management practices

Treatments	WP_IRR (kg m^{-3})	WP_TCW (kg m^{-3})	WP_ETC (kg m^{-3})
Water management treatments (W)			
W_1	0.48^C	0.37^B	0.73^A
W_2	0.51^B	0.39^A	0.73^A
W_3	0.56^A	0.40^A	0.70^B
Mean	0.51	0.38	0.72
Significance	**	*	NS
Nitrogen treatments (N)			
N1	0.33^D	0.24^D	0.45^D
N2	0.45^C	0.33^C	0.61^C
N3	0.56^B	0.41^B	0.77^B
N4	0.63^A	0.47^A	0.87^A
N5	0.64^A	0.47^A	0.88^A
Mean	0.64	0.37	0.73
Significance	**	**	**
Interaction			
W×N =	NS	NS	NS

** Significant at 5% level, * Significant at 1% level, NS- Non significant

Means within a column followed by the same letter are not significantly different as per Duncan's multiple range test process fraction ranged from 67 to 81% indicating that much effort has been made to make full use of irrigation water and rainfall. It was also found that at the field scale, process flow was significantly higher under AWD irrigation, represents fairly precise rice irrigation practices under AWD irrigation than under the traditional irrigation method.

The water and irrigation use efficiency of rice were also computed under different water regimes and N doses and are presented in fig. 5. Study revealed that lowest water use efficiency (3.68 kg ha^{-1} mm^{-1}) and irrigation use efficiency (4.87 kg ha^{-1} mm^{-1}) were obtained under continuous submergence (W_1), whereas under IS treatment (W_3), highest water use efficiency (3.96 kg ha^{-1} mm^{-1}) was obtained (Fig. 5). Both the water and irrigation use efficiency were increased with increased doses of N but like yield both the parameters were at par between N_4 and N_5.

Total Nitrogen Uptake and Nitrogen Use Efficiency

Nitrogen uptake ranged from 49.9 to 124.3 kg N ha^{-1} under different water management and N treatments (Table 4). The N uptake tends to increase with the higher doses of N fertilizer. Among the N treatments, the average N uptake was highest in N_5 (115.8 kg ha^{-1}) and the lowest was observed in N_0 (52.3 kg ha^{-1}). The low N uptake in N_0 and N_1 treatments was due to combined effects of low yield of rice and the lower N concentration in the grain and the straw. Among water management treatments, higher uptake was observed in W_1 and W_2 than in W_3 in agreement with the higher total above ground biomass. In most cases, N uptake in the continuously flooded treatment was higher than that of alternate wetting and drying treatment. Average over the N treatments, N uptake in the continuously flooded treatment (W_1) was higher (95.9 kg ha^{-1}) than in the W_2 (93.1 kg ha^{-1}) and W_3 (82.1 kg ha^{-1}) treatments; however the difference in average N uptake between W_1 and W_2 was not significant at 5% level. Like crop growth and yield, there was no observed W × N interaction on N uptake in crops during both the study years.

Agronomic N use efficiency (ANUE) ranged from 13.6 to 19.8% under different water and N treatments. Average over the N treatments, higher ANUE was recorded under alternate wetting drying treatments (W_2 and W_3) than that of the continuous submergence (W_1). Study also revealed that average ANUE was higher at 90 kg N ha^{-1} (18.1%) but not at higher doses of N (14.7% at 150 kg N ha^{-1}). The NHI in water management treatments did not vary greatly, ranging from 59.0 to 61.2%. The level of significance was also not consistent for NHI among different N treatments.

The physiological N use efficiency (PNUE) values ranged from 37.8 to 45.8 kg grain/kg N uptake with decreasing values as the N doses increased (Table 3). The PNUE values tend to decrease with increasing N doses due to higher N uptake and higher N concentrations in both the grain and straw. But PNUE values in W_1, W_2 and W_3 were comparable and statistically non-significant. Values of AR ranged from 34.1 to 56.2% among different N and water management treatments. The higher AR was recorded under 120 kg N ha^{-1} (N_4) due to higher ANUE. This was because of the more difference of grain yield between the zero N (N_1) and N_4 treatments (about 2.5 t ha^{-1}). There was no observed W × N interaction in N use efficiency parameters as in the case of agronomic parameters.

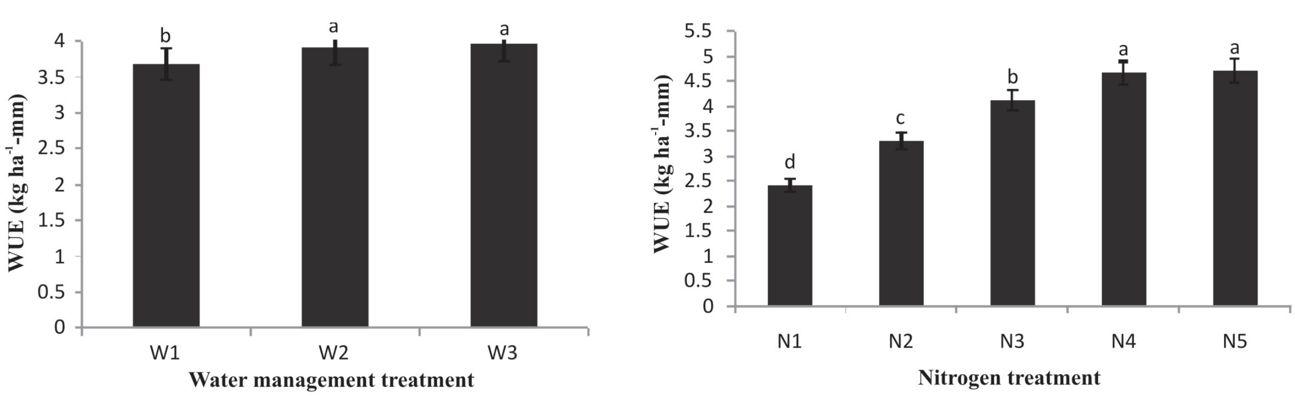

Fig. 5. Water use efficiency (WUE) as influenced by (a) water management treatment and (b) nitrogen treatment. Means in different histograms followed by same letter are not significantly different as per Duncan's multiple range test

Table 3. Nitrogen uptake and N efficiency parameters under different water and nitrogen management practices

Treatments	Total N uptake (kg ha^{-1})	Nitrogen harvest index (%)	PNUE	ANUE (%)	AR (%)
W_1					
N_1	54.0^D	59.9	45.8	-	-
N_2	76.2^C	65.3	44.2	14.9	37.0
N_3	103.6^B	61.6	41.1	19.8	55.1
N_4	121.5^A	59.5	38.2	18.0	56.2
N_5	124.3^A	59.8	37.8	14.8	46.8
Mean	95.9	61.2	40.5	13.5	39.0
W_2					
N_1	53.2^D	58.6	45.0	-	-
N_2	74.1^C	59.4	44.4	14.8	34.7
N_3	100.7^B	59.5	40.6	18.7	52.6
N_4	117.2^A	58.3	39.2	18.3	53.3
N_5	120.2^A	59.0	38.7	15.0	44.6
Mean	93.1	59.0	40.8	16.7	37.0
W_3					
N_1	49.9^D	55.9	43.3	-	-
N_2	70.4^C	59.0	42.3	13.5	34.1
N_3	85.6^B	61.6	42.8	16.7	39.6
N_4	101.5^A	60.4	42.6	18.0	43.0
N_5	103.1^A	62.2	42.0	14.4	35.4
Mean	82.1	59.8	42.6	15.7	38.0
Significance					
Water regimes (W)	**	NS	**	**	**
Nitrogen (N)	**	NS	**	**	**
W×N	NS	NS	NS	NS	NS

Significant at 5% level, NS = Non significant
PNUE=Physiological nitrogen use efficiency, ANUE= Agronomic nitrogen use efficiency, AR = Apparent recovery of applied nitrogen; Means within a column followed by the same letter are not significantly different as per Duncan's multiple range test

Conclusions

The volume of total water use per unit quantity of yield was higher in W_1 (2811 m^3 t^{-1}) than that of W_2 (2662 m^3 t^{-1}) and W_3 (2642 m^3 t^{-1}) due to continuous submergence under the former treatment, as a result more percolation was experienced under W_1. These infer that the water footprint and volume of percolation water to a large extent was influenced by agricultural management rather than by the agro-climate under which the crop was grown. This provides an opportunity to improve yield and water productivity through different improved agro-management practices. It is also inferred that optimum application of N has the potential to enhance the yield and in turn to reduce WFP of rice production under all water management treatments.

Better irrigation management and efficient application methods will reduce the blue water foot-prints of the country under irrigated agriculture. Higher percolation need in the first phase of the land preparation can be reduced by water saving seeding/ planting methods of rice like direct dry seeding, system of rice intensification (SRI) which will in turn reduce blue water demand during land preparation. The grey component of the water footprint and N efficiency parameters can be reduced with a reduction in the leaching of fertilizers from the field, *e.g.*, by increasing water use efficiency, using slow-release fertilizers and nitrification inhibitors, puddling the rice fields, planting catch and cover crops and using crop residues in-situ. Higher water productivity and water use efficiency were obtained enhance.

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