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Do reduced water and nitrogen input in rice production necessarily reduce yield?

Chuanhai Shu[1], *Feijie Li*[1], *Qiaoyi Tang*[2], *Yuemei Zhu*[1], *Jinyue Zhang*[1], *Yongjian Sun*[1], *Na Li*[1], *Jun Ma*[1], *and Zhiyuan Yang*[1]*

[1]Crop Ecophysiology and Cultivation Key Laboratory of Sichuan Province, Rice Research Institute, Sichuan Agricultural University, Chengdu 611130, China
[2]College of Agronomy, Sichuan Agricultural University, Chengdu 611130, China

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A b s t r a c t. This study explored the effects of water and nitrogen management on yields, as well as water and nitrogen use efficiency, in the production of rice (*Oryza sativa* L.). The study aimed to provide theoretical and technical support for high yield practices and efficient resource utilization. Three replicate split-plot experiments were conducted in the field using flooding irrigation and controlled irrigation as the primary treatments. The secondary treatments included no nitrogen application, the farmers' usual nitrogen management, optimized nitrogen treatment, and uniform nitrogen application. Uniform nitrogen achieved the highest yield (11.91-14.12 10^3 kg ha^{-1}) with controlled irrigation, in which case 20% less nitrogen is applied than in the case of optimized nitrogen treatment and farmers' usual nitrogen management. Controlled irrigation + uniform nitrogen required 24.18-35.82% less irrigation than flooding irrigation. Controlled irrigation + uniform nitrogen yielded the lowest reduction (18.52-20.00%) in the dry weight of deep roots (20-30 cm) within 30 days after heading. Comparatively, this reduction was 27.54-30.26 and 38.71-42.11% under controlled irrigation + optimized nitrogen treatment and controlled irrigation + farmers' usual nitrogen management, respectively. At the heading stage, light interception was highest under uniform nitrogen. Nitrogen recovery efficiency under uniform nitrogen was 8.53-17.88 and 46.77-60.79% higher than that under optimized nitrogen treatment and farmers' usual nitrogen management, respectively. Furthermore, nitrogen use efficiency under uniform nitrogen was 19.84-29.70 and 76.16-94.44% higher than that under optimized nitrogen treatment and farmers' usual nitrogen management, respectively, low-intensity/high-frequency nitrogen application combined with water-saving irrigation can greatly reduce water and nitrogen input while maintaining a stable yield to achieve food security and efficient resource utilization in rice production.

K e y w o r d s: rice (*Oryza sativa* L.), water management, nitrogen fertilizer management, water and nitrogen use efficiency, yield

*Corresponding author e-mail: 14236@sicau.edu.cn

INTRODUCTION

Rice is an essential staple food crop for more than half of the world's population (Xiong *et al.*, 2013). China is the leading rice producer worldwide, and rice plays an important role in China's grain production. Moreover, over 65% of China's population consumes rice as their staple food (Zhang *et al.*, 2005).

Nitrogen (N) is an essential nutrient in crop growth and plays a decisive role in ensuring a high and stable crop yield (Erisman *et al.*, 2008). Currently, the average N application rate for rice in China is 180 kg ha^{-1} (Peng *et al.*, 2010; Zhang *et al.*, 2013; Fu *et al.*, 2021). However, the N application rate reaches 350 kg ha^{-1} in the high-yield Taihu Lake area (Jiao *et al.*, 2018). The past two decades have witnessed increased N fertilizer use, promoting essential rice yield growth in China. Unfortunately, the excessive N input has also caused water eutrophication, soil acidification, reduced rice production efficiency, and other adverse effects (Xia *et al.*, 2016; Townsend *et al.*, 2003). Minimizing N application while avoiding yield reduction is thus a research hot spot in China. Taking into account the disadvantages of predominantly applying base fertilizer and low-efficiency tiller fertilizer in traditional rice production (Ling *et al.*, 2014), most agricultural scientists and technological workers promote the split application of N fertilizer based on leaf age (Ling *et al.*, 1983), site-specific N management based on soil testing (Roland *et al.*, 2019; Ling *et al.*, 2005), real-time N management based on the

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relationship between leaf colour and N content (Mohanty *et al.*, 2021), and computer-assisted model optimization to guide fertilization policy (Baral *et al.*, 2021; Sharma S., 2019; Pan *et al.*, 2017; Peng *et al.*, 2002; Angus *et al.*, 1996). These systems have greatly contributed to reduced N use and increased rice yield.

Existing studies have shown that improvements in N application methods have more potential than the optimization of the N application rate to further increase rice yield and nitrogen use efficiency (NUE) (Yang *et al.*, 2020; Chen *et al.*, 2015). Increasing the number of N applications in paddy fields from 3 to 4 and 6 to 7 times can notably enhance NUE and achieve the goal of reducing N without affecting the yield. Nevertheless, increasing the frequency of N application can also add to operational costs and induce high water supply requirements, this has limited the promotion of low-intensity/high-frequency N application (Yang *et al.*, 2020; Ohnishi *et al.*, 1999).

Rice requires more water than any other cereal grain, it accounts for approximately 60-70% of agricultural water use (Pan *et al.*, 2017) and 50% of domestic water consumption. With increasing demands for industrial water and water for both urban and rural residents, the proportion of water allocated to rice production decreases each year. Therefore, researchers have also conducted many water-saving irrigation studies (Tabbal *et al.*, 2002; Belder *et al.*, 2004), including the application of alternate wetting and drying irrigation (AWD) and controlled irrigation (CI) technologies. AWD is a water management technique that employs periodic drying and rehydration to reduce water consumption during the rice-growing season (Wang *et al.*, 2016). Most studies propose that AWD can be used to enhance rice yield (Christy *et al.*, 2018; Pan *et al.*, 2017; Carrijo *et al.*, 2018); however, a reduced yield has also been reported. These inconsistent findings may be related to soil water potential, quality, and pH (Carrijo *et al.*, 2017). Compared with AWD, CI involves the application of more rigid water management techniques (Peng, 2009; Yu *et al.*, 2002). After the rice seedlings have been transplanted, the field surface retains a thin 5-25 mm layer of water to allow the rice seedlings to recover from transplantation stress. However, there is no water layer on the field surface during the stages of growth after recovery. The effectiveness of irrigation is determined by taking the soil moisture of the root layer as the control index. The lower limit of soil moisture at different rice growth stages is 60-80% of the saturated moisture content of the soil, while the upper limit is at the point of soil saturation. This technique, which can be used to promote the migration of N from surface water to soil and increase the water and nutrient uptake of rice plants (Peng *et al.*, 2009), is popular in areas prone to water shortages such as Ningxia, Jiangsu, and Heilongjiang (Peng *et al.*, 2011).

Due to its huge water requirements, rice has a more significant water-fertilizer coupling effect than that of other crops, which necessitates human regulation. Hence, research concerning water-fertilizer coupling in paddy fields has attracted much academic attention (Liu, 2019; Lin *et al.*, 2016). With the large-scale construction of high-standard farmlands and the rapidly increasing availability of low-cost water and fertilizer integration facilities, low-intensity/high-frequency N application in paddy fields has overcome its previous limitations. The three "uniform" technique is an integrated water and fertilizer technology developed to meet the water and N requirements of rice in paddy fields, with "uniform nitrogen application (UN)" and "uniform water with fertilizer application" at its core (Yang *et al.*, 2020). This technology allows for greatly reduced N and water use in rice production, but few studies have focused on the mechanism of action underlying these savings. In order to fill this gap, UN was studied (low-intensity/high-frequency N application) which employed integrated water and fertilizer technology to explore the impact of water and N management on rice yield and the utilization of water and N. This study aimed to provide theoretical and technical support for high-yield practices and the efficient utilization of resources in rice production.

MATERIALS AND METHODS

The experimental sites were located at the experimental farm of the Rice Research Institute of Sichuan Agricultural University (Wenjiang District, Chengdu City, Sichuan Province; 30°43'N, 103°47'E) and also at the experimental farm of the Southwest University of Science and Technology (Fucheng District, Mianyang City, Sichuan Province; 31°32'N, 104°41'E). The Wenjiang site was located in the Chengdu Plain, a subtropical humid monsoon climate zone, with abundant precipitation, less sunshine, and relatively minor diurnal temperature differences. The Fucheng site was located west of the Sichuan Basin, in the north subtropical humid monsoon mountain climate zone, with uneven precipitation distribution, sufficient sunshine, and large temperature differences occurring between day and night. In addition, drought frequently occurs during the rice season of this region. In 2016, field experiments were conducted at both sites (experiments 1 and 2). A third field experiment (experiment 3) was performed at the Wenjiang site in 2017. The nutrient content of the soil at the two experimental sites is listed in Table 1. The Wenjiang site had fine sandy loam soil, whereas the Fucheng site had clay loam soil.

Indica hybrid rice F-you 498 was used as the testing material. This variety is a three-line super hybrid Indica rice planted in a large area in Sichuan in the middle and lower reaches of the Yangtze River.

Table 1. Average values for selected soil characteristics of composite topsoil samples (0-20 cm) from the experimental fields in 2016 and 2017

Year	Soil type	Organic matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)
2016	Clay loam	23.23	1.96	104.10	23.90	106.99
2016	Fine sandy loam	25.00	2.30	125.90	29.13	116.53
2017	Fine sandy loam	22.37	2.16	111.90	24.44	107.51

All three experimental designs were identical: a randomized block experiment involving two factors. The primary block was water management, which was divided into flooding irrigation (FI) and controlled irrigation (CI). In FI, after the rice was transplanted, a 1-3 cm water layer was always maintained above the surface of the paddy fields and dried naturally a week before harvesting. In CI, transplantation was conducted in shallow water (~1 cm), a 2 cm water layer was maintained in the fields for 5-7 days after transplanting to ensure that the seedlings turned green and survived. Subsequently, the surface water was drained and soil moisture of 70-80% was maintained before the booting stage. The fields were dried during the ineffective tillering stage, a 1-3 cm water layer was maintained above the soil surface during the booting stage, and alternate wetting and drying irrigation was implemented from heading to maturity (*i.e.*, irrigated with 1-3 cm layer of water and dried naturally to achieve a soil water potential of -25 kPa). The secondary block was N management, which was divided into CK, farmers' usual nitrogen management (FU), optimized nitrogen treatment (ONT), and uniform nitrogen application (UN). In FU, 150 kg ha^{-1} of N fertilizer was applied according to the ratio of base fertilizer:tillering fertilizer = 7:3, one day before and seven days after transplanting. In ONT, 150 kg ha^{-1} of N fertilizer was applied according to the ratio of base fertilizer:tillering fertilizer:panicle fertilizer = 3:3:4, one day before and seven days after transplanting, and at the reciprocal fourth and second leaf stages (the panicle fertilizer was divided into two equal portions). In UN, 15, 15, 30, 15, 15, 15, and 15 kg (total 120 kg ha^{-1}) of N fertilizer were applied at 7, 14, 35, 49, 56, 70, and 77 days after transplanting. There were 24 blocks in total, and each treatment was repeated three times. The plot area was 12 m^2 (3 × 4 m), and the seedlings were transplanted at a hill spacing of 33.3 × 16.7 cm. There were 216 seedlings (12 rows and 18 seedlings per row) in each plot, and the planting density was 18 plants m^{-2}. The extent of the irrigation was measured using a water meter, and all other field management practices were identical.

Light interception (LI): During the heading stage and 10, 20, and 30 days after the heading stage, the effective solar radiation at the top (30 cm above the flag leaf tip) and base (10 cm from the ground) of the plant were measured using an Li-191 light quantum meter (LI-COR Biosciences, Lincoln, NE, USA) between 10 a.m. and 2 p.m. Within a block group, the side row was excluded, and six positions were selected for each treatment. The average values were taken to calculate LI using the following formula:

$$LI = \frac{\text{top solar effective solar radiation - base effective solar radiation}}{\text{top solar effective solar radiation}} 100\%.$$

Net photosynthetic rate (P_n): At the full heading stage and 10, 20, and 30 days after the full heading stage, the P_n was measured using an LI-6400 portable photosynthetic instrument (LI-COR Biosciences, Lincoln, NE, USA) between 9:30 a.m. and 11:30 a.m. on sunny days. The middle of five representative flag leaves on the main stem was measured for each treatment, and each measurement was repeated three times.

According to the average tiller number, three representative rice plants were labelled in every block at the heading and maturity stages. Using the undisturbed soil column method (Billings *et al.*, 1985; Lin *et al.*, 1997), an iron plate root extractor (3 mm thick, 30 cm long, and 30 cm wide with one sharp end) was used to dig out a soil column. The rice plant was the centre of a 16.68 10^3 cm^3 column, whose length was 33.3 cm and whose width was 16.7 cm. The depth of the column was 30 cm. The excavated root soil layer was divided into three parts: 0-10, 10-20, and 20-30 cm and respectively placed in 40 mesh nylon bags. After washing away the soil impurities with a high-pressure atomization root washer (HR 25, Karcher Corp., Germany) and drying the roots to constant weight at 80°C, the dry weight of the roots in each soil layer was measured.

The morphological indexes of the roots at the heading and maturity stages were measured. The remaining aboveground parts were dried, weighed, crushed, and screened to determine the biomass. The total N content was measured using the Kjeltec™ 8400 Kjeldahl Analyzer (FOSS Analytical, Hillerød, Germany) according to the manufacturer's instructions.

The extent of irrigation was directly measured using a water meter during irrigation.

At the maturity stage, 5 representative plants with an average number of effective panicles were sampled from each block to study the panicle grain structure. The remaining parts were harvested, threshed, and weighed manually. The total yield was calculated according to the number of harvested plants, and the result was converted based on the standard water content of 13.5%.

An analysis of variance (ANOVA) was performed using SPSS (version 27.0, IBM Corp., Armonk, NY, USA). The statistical significance was considered at $p<0.05$, and when the ANOVA results were significant, we compared pairs of values using the least significant difference (LSD) test. Origin Pro v. 2021 (OriginLab, Northampton, MA, USA) was used generate graphs.

RESULTS

Water and N management had a significant impact on the rice yield (Fig. 1). The rice yield of experiments 1 and 2 under CI was significantly higher (1.94-2.20%) than that under FI. However, the average rice yield did not differ significantly under CI and FI in experiment 3 (1.09%). Moreover, the rice yield did not differ significantly (1.30-1.82%) between the CI + UN and CI + ONT treatments, in which there was a 20% reduction in N input from ONT (150 kg ha^{-1}) to UN (120 kg ha^{-1}). The rice yield under the UN and ONT treatments was significantly higher than that under FU (150 kg ha^{-1}). The rice yield under the CI + UN treatment was significantly higher (14.76-21.47%) than that under CI + FU, indicating UN's significant N savings and high-yield promotion under CI conditions. Comparatively, no evident difference in rice yield was observed under the FI + UN and FI + ONT treatment in experiments 2 and 3. Nevertheless, the rice yield under FI + UN was significantly lower than that under the FI + ONT treatment in experiment 1. These findings reveal the different interaction effects between the UN and the two water management modes. However, even under FI, the rice yield with the UN treatment was higher than that under FU. Without N application, the rice yield under FI was significantly higher (11.64-12.36%) than that under CI. However, the average rice yield under CI was 1.83-4.98% higher than that under FI after the application of N fertilizer. These results indicate that a superior soil N environment is beneficial under CI in order to increase yields.

Biomass accumulation of rice plants under CI at the heading stage was significantly lower (4.62-6.85%) than under FI, as shown in Table 2. Biomass accumulation before flowering (BABF) at the fruiting stage was also significantly lower (8.37-19.04%) under CI than under FI. However, the photosynthetic production capacity after flowering was significant, and biomass accumulation at the fruiting stage achieved a notable advantage. Biomass accumulation and BABF at the heading stage were significantly lower (5.46-12.60 and 34.47-54.07%, respectively) under CI + UN than under CI + ONT. Nevertheless, biomass accumulation after flowering was significantly higher under the CI + UN treatment than under CI + ONT and CI + FU (11.41-14.02 and 37.73-42.30%, respectively), which reduced the difference in biomass accumulation between UN and ONT at the maturity stage to 1.38%.

The LI of rice plants in each treatment group decreased rapidly and then decreased more gradually within 30 days after the heading stage, as shown in Fig. 2. Under the CI treatment LI was higher than that under FI. In terms of different N treatments, the order of LI was UN > ONT > FU > CK. Under CI treatment, the average LI at the heading stage was 92.05% (UN), 90.76% (ONT), and 84.95% (FU). At 30 days after the heading stage, the average LI decreased by 25.99-27.87% (UN), 33.34-41.59% (ONT), and 43.98-46.93% (FU). At the full heading stage under both FI and CI conditions, the P_n of the flag leaf values under the UN and ONT treatments were similar and higher than those under FU. With the advancement of the growth process, the P_n of the flag leaf values gradually decreased with all four N treatments, but the gap widened among the four treatments. At 30 days after the heading stage, the order of the P_n of the flag leaf values was: UN > ONT > FU > CK. Although water management did not significantly affect the P_n of the flag leaf, a greater P_n of the flag leaf values were observed under CI than under FI in all three experiments.

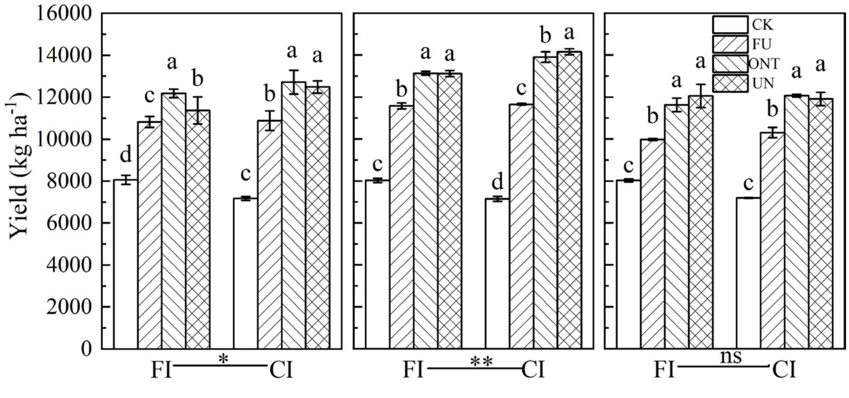

Fig. 1. Effects of different water and nitrogen management modes on rice yield. Exp. 1 – Wenjiang site in 2016, Exp. 2 – Mianyang site in 2016, Exp. 3 – Wenjiang site in 2017; FI – flooding irrigation, CI – control irrigation, CK – no nitrogen application, FU – farmers' usual management, ONT – optimized nitrogen treatment, UN – uniform nitrogen application. Different letters indicate the difference under different water management or fertilization at 5% level. NS – denotes non-significance at $p > 0.05$, significant at: $*p < 0.05$, $** p < 0.01$.

Table 2. Effects of different rice management modes on rice material production and transportation

Year	WM	NM	DWH	BABF	BAAF	DWM	HI
			(kg ha^{-1})				(%)
Exp. 1	FI	CK	10435 d	2934 b	4037 d	14473 d	48.17 a
		FU	14029 c	3334 a	6022 c	20051 c	46.66 ab
		ONT	15883 a	3586 a	6952 b	22836 a	46.15 b
		UN	14372 b	1845 c	7989 a	22361 b	43.97 c
		Mean	13680 a	2924 a	6250 b	19930 a	46.24 b
	CI	CK	8929 d	2727 b	3476.d	12406 d	50.01 a
		FU	13956 b	3913 a	5497 c	19453 c	48.37 ab
		ONT	14989 a	2804 b	8192 b	23181 a	47.43 b
		UN	13100 c	1271 c	9528 a	22628 b	47.72 b
		Mean	12743 b	2679 a	6673 a	19417 b	48.38 a
	F-value	W	693.67 **	9.84 NS	97.12 *	65.11 *	45.35 *
		N	2343 **	129.7 **	2366 **	3389 **	12.44 **
		W*N	37.94 **	14.68 **	156.18 **	55.08 **	2.00 NS
Exp. 2	FI	CK	10464c	2693 b	4247 d	14712 d	47.19 a
		FU	15057 b	3999a	6014 c	21071 c	47.53 a
		ONT	16472 a	3891a	7467 b	23939 b	47.44 a
		UN	15021 b	2357 c	8990 a	24012 a	47.26a
		Mean	14254 a	3235 a	6680 b	209334 a	47.35 b
	CI	CK	8961 d	2217 c	3965 d	12926c	47.84 a
		FU	14498 c	3604a	6476 c	20974 b	48.06a
		ONT	15896 a	2811 b	9214 b	25110a	47.90 a
		UN	15028. b	1842d	10401 a	25429 a	48.16 a
		Mean	13596 b	2619 b	7514 a	21110 a	47.99 a
	F-value	W	57.87 *	1588 **	811.1 **	2.56 NS	19.07 *
		N	1196 **	153.42 **	1736 **	2260 **	0.27 NS
		W*N	14.14 **	6.10 **	61.58 **	46.85 **	0.19 NS
Exp. 3	FI	CK	9735 d	3150 ab	3792 d	13526 d	51.32 a
		FU	12076 c	2973 b	5657 c	17733 c	48.67 b
		ONT	15143 a	3621 a	6436 b	21579 a	46.59 b
		UN	13903 b	2653 b	7193 a	21096 b	46.70 b
		Mean	12715 a	3100 a	5770 b	184834 a	48.31 a
	CI	CK	8725d	2938 b	3279 d	12004 c	51.82 a
		FU	12098 c	3554 a	5357 c	17455 b	51.05 a
		ONT	14138 a	2860 b	7574 b	21713 a	48.06 b
		UN	13170 b	1648 c	8651 a	21821 a	47.23 b
		Mean	12033 b	2751 a	6216 a	182489 b	49.54 a
	F-value	W	387.9 **	5.56 NS	148.1 **	46.32 *	3.44 NS
		N	843.2 **	18.92 **	1781 **	1516 **	18.33 **
		W*N	9.09 **	8.48 **	120.36 **	19.69 **	0.78 NS

WM – water management, NM – nitrogen management, WH – dry weight at heading stage, BABF – biomass accumulation before flowering, BAAF – biomass accumulation after flowering, DWM – dry weight at maturity stage, HI – harvest index, Exp. 1 – Wenjiang site in 2016, Exp. 2 – Mianyang site in 2016, Exp. 3 – Wenjiang site in 2017, FI – flooding irrigation, CI – control irrigation. Different letters in the same column indicate the difference under different cultivars or fertilization at 5% level, NS – denotes non-significance at $p > 0.05$, significant at: *$p < 0.05$, **$p < 0.01$. Biomass accumulation before flowering – dry weight of stems and leaves at heading stage – dry weight of stems and leaves at maturity stage.

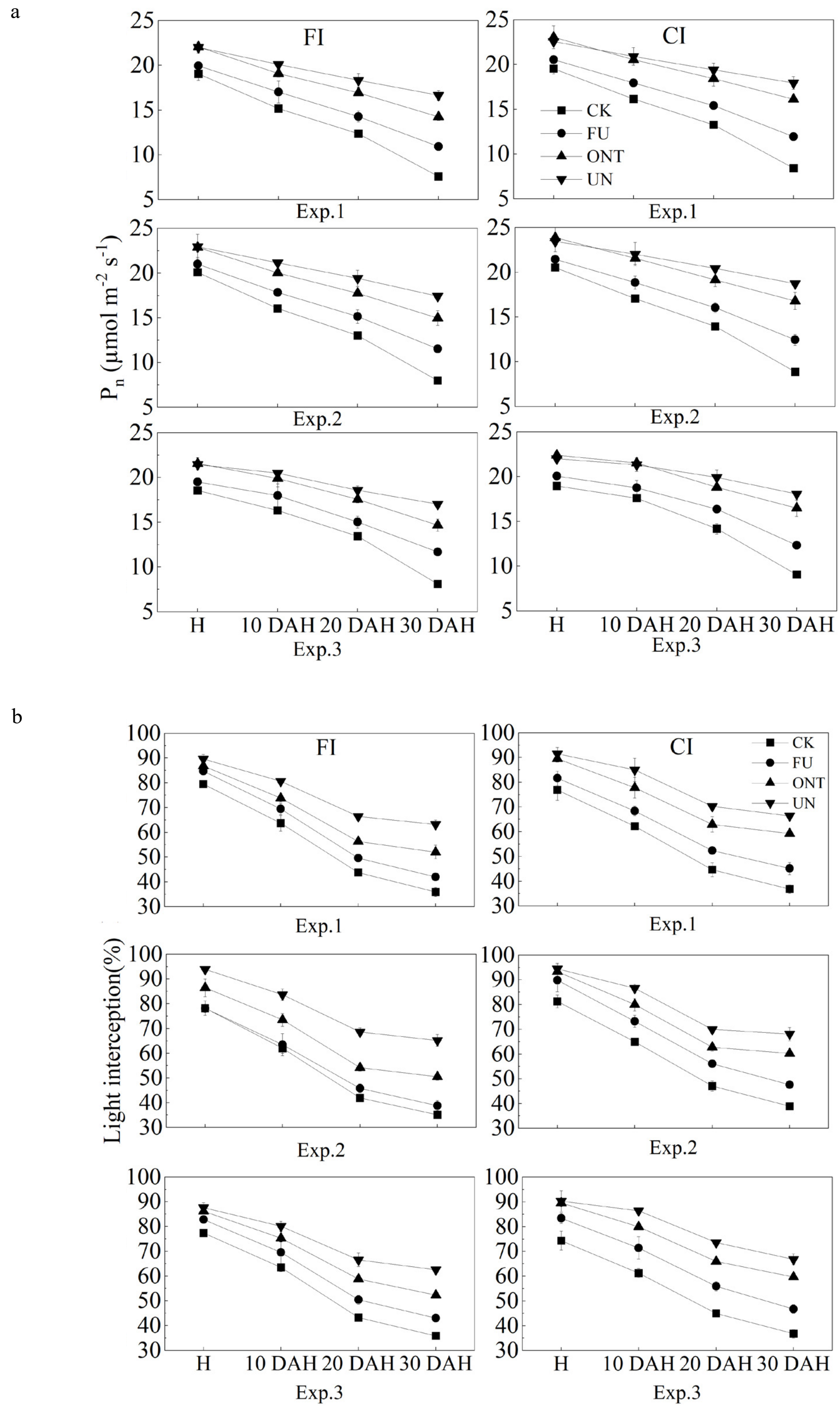

Fig. 2. (a) Effects of different water and nitrogen management on the net photosynthetic rate of the rice flag leaf. (b) Effects of different water and nitrogen management on rice light interception. Exp. 1 – Wenjiang site in 2016, Exp. 2 – Mianyang site in 2016, Exp. 3 – Wenjiang site in 2017, P_n – Net Photosynthetic Rate, 10 DAH – 10 days after heading, 20 DAH – 20 days after heading, 30 DAH – 30 days after heading, FI – flooding irrigation, CI – control irrigation, CK – no nitrogen application, FU – farmers' usual management, ONT – optimized nitrogen treatment, UN – uniform nitrogen application.

The dry weight of the rice plant roots under the CI treatment was significantly higher than that under FI, and the three experiments presented consistent results (Table 3). Within 30 days after the heading stage, the smallest decrease (18.16-21.36%) for the total dry weight (experiment 1) was recorded under the CI + UN treatment. In comparative terms, the total dry weight reduction resulting from the CI + ONT and CI + FU treatments was 26.42-29.64 and 38.14-45.49%, respectively. An analysis of the deep root system (20-30 cm) indicated that the dry weight under FI + UN at the heading stage was greater than that under CI + UN. However, the dry weight of the deep root system under CI + UN decreased the least (18.52-20.00%) in the advancing growth stage. In comparative terms, the dry weight reduction under CI + ONT and CI + FU was 27.54-30.26 and 38.71-42.11%, respectively. CI + UN application may promote the growth of deeper roots and effectively slow down the aging process of deep roots.

Figure 3 illustrates that irrigation volumes were similar for the four N treatments under the same water management conditions. The irrigation volumes under CI in experiments 1, 2, and 3 were significantly lower (25.49-26.55, 34.57-35.82, and 34.57-35.82%, respectively) than those under FI, thereby indicating a remarkable water-saving effect. The irrigation water use efficiency (IWUE) under the CI + UN and CI + ONT treatments was similar (experiments 1 and 3). However, in experiment 2, IWUE was significantly higher with CI + UN than with CI + ONT and CI + FU (15.52-20.27%). The trend in water use efficiency was consistent with that of IWUE, both of which demonstrated considerably improved performance under the UN treatment.

Water and N management affected the total N uptake of the rice plants, nitrogen recovery efficiency (NRE), and nitrogen agronomy efficiency (NAE), except in experiment 2 (Table 4). The total N uptake did not differ significantly under CI and FI, but NRE was significantly higher under CI than FI (with the exception of experiment 2). NAE under CI was significantly higher than under FI in all three experiments, revealing an improved yield with N application. The total N uptake under the CI + UN treatment (177.25-186.36 kg ha^{-1}) was significantly lower than that under the CI + ONT treatment (182.7-196.8 kg ha^{-1}) and 6.07-8.98% higher than that under the FU treatment. NRE and NAE displayed consistent trends during the three years of the experimental period. With UN treatment NRE was significantly higher than under ONT and FU (8.53-17.88 and 46.77-60.79%, respectively). In addition, NAE was significantly higher with UN treatment than under ONT and FU (19.84-29.70 and 79.16-94.44%, respectively). CI enabled the rice plants to grow deeper roots and absorb more nutrients. With 20% less N applied during UN than during ONT, the total N uptake was only 2.38-5.31% less with UN than with ONT. UN treatment promoted higher NRE and NAE, thus reflecting the advantage of a uniform supply of N throughout the rice growth stages. The CI + UN treatment demonstrated a decisive advantage for N absorption and utilization with higher NRE and NAE.

IWUE, NAE, LI, and P_n of the flag leaf were considered to be dependent variables, whereas the root dry weights in the 0-10, 10-20, and 20-30 cm soil layers were as assumed to be independent variables in the partial least squares regression analysis (Table 5). The determination coefficients (R^2) of the equations established between the root dry weight in different soil layers and IWUE, NAE, LI, and P_n of the flag leaf were >0.9, indicating that the root system was closely related to the utilization of light, water, and N in rice plants. With deepening soil layers, the influence of the root system on light, water, and N utilization increased rapidly. Specifically, the deep root system (20-30 cm) had a much higher impact on IWUE, NAE, and P_n of the flag leaf than roots in the 10-20 and 0-10 cm soil layers. Compared with the three indicators above, the root system in the different soil layers had a minor effect on LI, and the deep root system had a weakened impact on LI.

DISCUSSION

The water and N input for rice production in China has increased to achieve high rice yields and China's national goal of food self-sufficiency. However, current water and NUE are low in Chinese rice production. CI can effectively enhance root growth and significantly improve rice yield and water use efficiency (Chu *et al.*, 2016). Considering the low N uptake efficiency of rice plants caused by the highly humid climate in the Sichuan Basin and increasingly convenient fertilization brought about by the popularization of integrated water and fertilizer equipment, our research group proposed studying UN in paddy fields. According to the N requirements and absorption capacity of rice plants, N was applied with increased frequency but in a decreased overall amount, thus enhancing the uptake and efficient use of N by rice plants.

The uptake, transportation, and utilization of nutrients in the soil are closely linked to the soil water content (Cai *et al.*, 2003; Frank *et al.*, 1972). Previous research concerning wheat demonstrated that increasing N levels could reduce the adverse impact of insufficient water if drought or water stress occurs. Adding N significantly increases rice yield with slight soil drought; however, this benefit rapidly decreases if a severe soil drought occurs (Yang *et al.*, 1996). Many studies investigating water-N coupling have reported that a positive water-fertilizer coupling effect relies on the complementary relationship between water and fertilizer quantities to a certain extent. Specifically, a lack of fertilizer could be compensated for by increasing the water content and vice versa (Yang *et al.*, 1996). Some results of the current study are consistent with previous findings. The yield of the control group (without N application) under FI was higher than that under CI (a significant

Table 3. Effects of different water and nitrogen management on the dry weight of rice roots in different soil layers

Year	WM	NM	Heading stage			30 days after heading		
			0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Exp. 1	FI	CK	5.62 c	1.69 c	0.52 d	2.26 d	0.68 d	0.21 d
		FU	6.99 b	1.68 c	0.65 c	3.80 c	0.92 c	0.36 c
		ONT	8.20 a	1.77 b	0.71 b	5.34 b	1.14 b	0.46 b
		UN	8.25 a	2.11 a	0.90 a	6.22 a	1.62 a	0.68 a
		Mean	7.26 A	1.81 B	0.69A	4.41 B	1.09 B	0.43 B
	CI	CK	6.14 d	1.67 d	0.59 d	2.65 d	0.72 d	0.26 d
		FU	7.28 c	1.84 c	0.69 c	4.35 c	1.05 c	0.40 c
		ONT	8.13 b	2.04 b	0.76 b	5.72 b	1.44 b	0.53 b
		UN	8.59 a	2.31 a	0.85 a	6.72 a	1.84 a	0.68 a
		Mean	7.53 A	1.97 A	0.72 A	4.86 A	1.26 A	0.47 A
	F-value	W	18.39 *	1260 **	23.43 *	251.6 **	1242 **	599.3 **
		N	1004.2 **	357.9 **	1217 **	2210 **	1950 **	7787 **
		W*N	11.44 **	24.12 **	56.17 **	1.26 NS	29.11 **	41.48 **
Exp. 2	FI	CK	5.88 d	1.76 d	0.55 d	2.36 d	0.71 d	0.22 d
		FU	7.67 c	1.84 c	0.69 c	4.20 c	1.01 c	0.38 c
		ONT	8.27 b	1.95 b	0.78b	5.32 b	1.27 b	0.51 b
		UN	8.89 a	2.29 a	0.92 a	6.71 a	1.74 a	0.69 a
		Mean	7.68 A	1.96 A	0.74 B	4.65 B	1.18 B	0.45 B
	CI	CK	6.26 d	1.74 d	0.64 d	2.73 d	0.75 d	0.28 d
		FU	7.61 c	1.96 c	0.76 c	4.44 c	1.15 c	0.44 c
		ONT	8.28 b	2.21 b	0.83 b	5.90 b	1.54 b	0.58 b
		UN	8.88 a	2.44 a	0.87 a	7.13 a	1.97 a	0.70 a
		Mean	7.56 A	2.09 A	0.78 A	5.05 A	1.35 A	0.50 A
	F-value	W	26.73 *	55.49 *	33.48 **	12453 **	856.0 **	207.1 **
		N	550.3 **	521.9 **	13051 **	2298 **	3787 **	1522 **
		W*N	3.94 *	24.54 **	75.08 **	3.03 NS	39.84 **	8.69 **
Exp. 3	FI	CK	5.34 d	1.50 c	0.47 d	2.34 d	0.67 d	0.21 d
		FU	6.72 c	1.60 b	0.58 c	4.04 c	0.94 c	0.35 c
		ONT	7.27 b	1.63 b	0.67 b	4.96 b	1.13 b	0.47 b
		UN	7.61 a	2.01 a	0.76 a	5.94 a	1.59 a	0.60 a
		Mean	6.73 A	1.69 A	0.62 B	4.32 B	1.08 B	0.41 A
	CI	CK	5.53 c	1.50 d	0.53 d	2.66 d	0.71 d	0.19 d
		FU	6.59 b	1.60 c	0.62 c	4.09 c	0.98 c	0.38 c
		ONT	7.51 a	1.87 b	0.69 b	5.54 b	1.37 b	0.50 b
		UN	7.56 a	1.98 a	0.81 a	6.19 a	1.62 a	0.66 a
		Mean	6.80 A	1.74 A	0.66 A	4.62 A	1.17 A	0.43 A
	F-value	W	0.78 NS	16.57 NS	383.2 **	131.4 **	177.0 **	3.8 NS
		N	970.4 **	445.3 **	1095 **	14876 **	1936 **	113.8 **
		W*N	11.43 **	36.36 **	5.53 *	72.74 **	34.34 **	1.04 NS

WM – water management, NM – nitrogen management, Exp. 1 – Wenjiang site in 2016, Exp. 2 – Mianyang site in 2016, Exp. 3 – Wenjiang site in 2017, FI – flooding irrigation, CI – control irrigation, within a column followed by different letters are significantly different at $p < 0.05$ between WM or NM. NS – not significant at the $p = 0.05$ level, significant at the: * $p = 0.05$ level, ** $p = 0.01$ level.

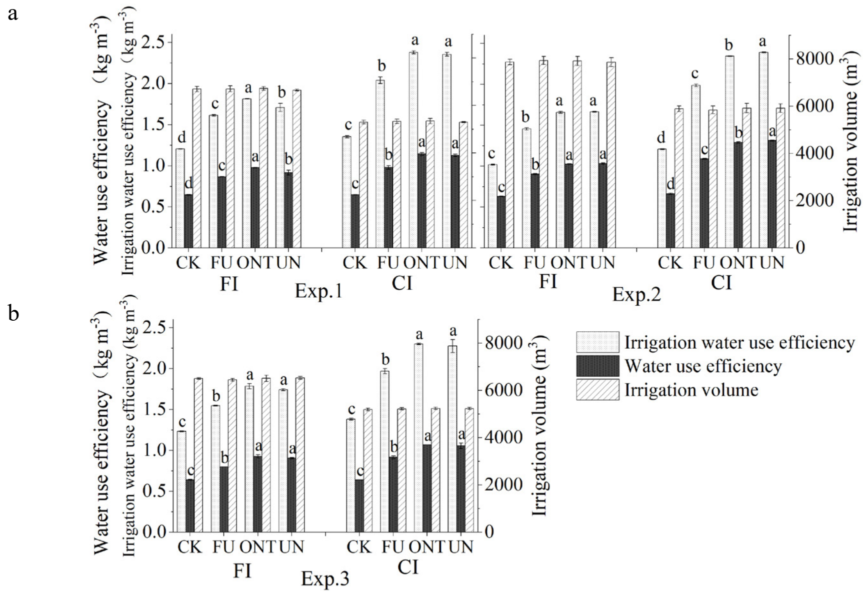

Fig. 3. Effects of different water and nitrogen management on irrigation amount and water use of rice. Exp. 1 – Wenjiang site in 2016; Exp. 2 – Mianyang site in 2016; Exp. 3 – Wenjiang site in 2017; FI – flooding irrigation; CI – control irrigation, CK – no nitrogen application, FU – farmers' usual management, ONT – optimized nitrogen treatment, UN – uniform nitrogen application. Different letters indicate that the differences between irrigation water use efficiency or water use efficiency are significant at a 5% level, irrigation volumes is no significant difference for the four N treatments under the same water management conditions; a – irrigation water use efficiency: rice yield / irrigation water amount; b – water use efficiency: rice yield / [precipitation during the growing period + irrigation water amount].

yield increase was observed in experiments 1 and 2), indicating that the plants used water to compensate for the lack of fertilizer. However, the UN + CI treatment induced a satisfying yield as well as water and NUE, which contradicted previous findings. The UN and CI treatments significantly reduced water and N inputs compared to conventional management (FU), but they achieved higher yields. The possible underlying reason for this could be the difference in the N application methods. Compared with FU and ONT, UN employs integrated water and fertilizer equipment to effectively apply the original high-frequency N application to the paddy fields, which was previously labour intensive and time-consuming. Furthermore, UN treatment may accurately conform to the N demands of rice plants and compensate for the lack of N quantity by reducing N losses. In support of this hypothesis, NRE and NAE were higher with the UN treatment than with ONT and FU. The rice roots were mainly distributed in the surface layer (0-20 cm) of the soil, and the upper roots (0-10 cm) accounted for 80% of the total roots (Cai *et al.*, 2003; Meng *et al.*, 2018). CI promoted the growth of the rice roots in the lower soil layer, and UN delivered more N to the lower soil layer *via* water-fertilizer integration, achieving the coupling of roots and N in a wider space. The efficient interaction between UN and CI may be explained by the mode of action rather than a quantity interaction.

Approximately 90% of the rice grain filling materials originate from photosynthetic compounds after the heading stage. Hence, a high photosynthetic production capacity after flowering is essential for high rice yield (Venkateswarlu *et al.*, 1987; Gelderen *et al.*, 2017). Half of the photosynthetic products fixed by net photosynthesis during the vegetative phase are transferred underground to maintain root growth and construction (Nguyen *et al.*, 2003; Rees *et al.*, 2005). In addition, the growth of the roots will generate feedback from plant photosynthesis and the synergy of carbon and N in the body (Norby *et al.*, 2004). A higher LI after flowering under CI may be related to both the large quantity and vigour of the rice plant roots at the fruiting stage. A Partial Least Squares (PLS) regression analysis indicated that the deep root system (20-30 cm) contributed more to NAE, IWUE, LI, and also to the P_n of the flag leaf than to the roots at other soil depths. Under both FI and CI conditions, UN treatment induced greater advantages in photosynthetic production capacity after flowering, which approached or even exceeded biomass accumulation under ONT treatment. In the three-year experiment, the dry weight of the deep roots under CI + UN produced no obvious advantage at the heading stage compared with FI + UN. However, at 30 days after the heading stage, the deep roots under CI + UN had the highest dry weight and the smallest reduction in the dry weight of roots. CI + UN allowed the roots of the rice plants to grow deep in the soil and delayed senescence, promoting a significant photosynthetic capacity and increased biomass accumulation after flowering and inducing a higher yield.

Table 4. Effects of water and nitrogen management on nitrogen accumulation and utilization in rice

WM	NM	Exp. 1			Exp. 2			Exp. 3		
		TNA (kg ha^{-1})	NRE (%)	NAE (kg kg^{-1})	TNA (kg ha^{-1})	NRE (%)	NAE (kg kg^{-1})	TNA (kg ha^{-1})	NRE (%)	NAE (kg kg^{-1})
FI	CK	118.83 d	–	–	119.38 d	–	–	113.73 d	–	–
	FU	164.23 c	30.27 b	18.38 b	171.77 c	34.92 c	23.68 c	160.64 c	31.28 b	13.01 b
	ONT	183.82 a	43.33 a	27.49 a	193.73 a	49.57 b	34.05 b	180.13 a	44.27 a	24.01 a
	UN	173.06 b	45.19 a	27.58 a	184.85 b	54.56 a	42.46 a	170.16 b	47.03 a	27.98 a
	Mean	159.98 a	29.70 b	18.36 b	167.43 a	34.76 a	25.05 b	156.17 a	30.64 b	16.25 b
CI	CK	108.86 d	–	–	117.36 d	–	–	106.20 d	–	–
	FU	167.11 c	38.83 c	24.71 c	171.00 c	35.76 c	30.03 c	166.30 c	40.07 c	20.76 c
	ONT	184.70 a	50.56 b	36.94 b	196.82 a	52.98 b	45.02 b	182.70 a	51.00 b	32.50 b
	UN	177.25 b	56.99 a	44.27 a	186.36 b	57.50 a	58.39 a	178.35 b	60.12 a	39.32 a
	Mean	159.48 a	36.60 a	26.48 a	167.88a	36.56a	33.36 a	158.39 a	37.80 a	23.15 a
F-value	W	0.23NS	22.96 *	218.63**	0.26NS	2.09NS	282230**	2.03NS	69.74*	146.19**
	N	871.3**	938.7**	444.4**	1579**	1427**	477.3**	1386**	1340**	2220**
	W*N	9.14**	10.83**	20.53**	1.76NS	1.49NS	84.81**	15.70**	17.33**	5.86*

WM – water management, NM – nitrogen management. TNA – total nitrogen accumulation, NRE – Nitrogen recovery and utilization, NAE – nitrogen agronomy efficiency. Exp. 1 – Wenjiang site in 2016, Exp. 2 – Mianyang site in 2016, Exp. 3 – Wenjiang site in 2017, FI – flooding irrigation, CI – control irrigation, CK – no nitrogen application, FU – farmers' usual management, ONT – optimized nitrogen treatment, UN – uniform nitrogen application. Values within a column followed by different letters are significantly different at $p < 0.05$ between WM or NM. NS – not significant at the p = 0.05 level, significant at the *p = 0.05 level, ** p = 0.01 level. [a]Total N accumulation – N accumulation per unit area of rice plant at maturity stage. [b]N recovery and utilization – N accumulation at maturity stage in N application block – N accumulation at maturity stage in no N application block / N application amount. [c]N agronomy efficiency – yield in N application block – yield in no N application block / N application amount.

Table 5. Contribution of root dry weight to water-nitrogen and light utilization efficiency in different soil layers (K = 2)

Soil layer (cm)	IWUE		NAE		LI		P_n	
	SRC	R^2	SRC	R^2	SRC	R^2	SRC	R^2
0-10	-0.14		-0.10		0.09		-0.09	
10-20	0.13	0.91	0.15	0.95	0.24	0.92	0.16	0.95
20-30	0.94		0.92		0.65		0.91	

IWUE – irrigation water use efficiency, NAE – nitrogen agronomy efficiency, LI – light interception, P_n – net light and rate of flag leaf, SRC – standard regression coefficient, R^2 – coefficient of determination.

CONCLUSIONS

1. Controlled irrigation + uniform nitrogen treatment achieved a higher yield with 20% less nitrogen and significantly less irrigation than flooding irrigation, demonstrating that reducing water and nitrogen input will not necessarily reduce production.

2. Uniform nitrogen treatment applied nitrogen fertilizer to rice plants more evenly by increasing the frequency of application and decreasing the overall amount added, thus satisfying the nitrogen demands of rice plants in different growth stages.

3. Uniform nitrogen + controlled irrigation promoted the growth of more and deeper roots and enhanced the efficiency of water and nitrogen use.

4. Uniform nitrogen + controlled irrigation increased the photosynthetic and production capacity of the rice plants after flowering.

5. This model provides strong technical support for achieving high rice yields using environmentally friendly agricultural practices.

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