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ORIGINAL PAPER

Irrigation and fertilization management to optimize rice yield, water productivity and nitrogen recovery efficiency

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Abstract

Increasing water scarcity and environmental contamination with excess chemical nitrogen fertilizer use necessitate the development of water-nitrogen conservation technology in rice production. Therefore, a 2-year field experiment (2017–2018) was conducted with three water regimes, namely (1) continuous flooding irrigation, CF; (2) safe alternate wetting and drying irrigation, $\mathrm{AWD}_{\mathrm{safe}}$; and (3) severe alternate wetting and drying irrigation, $\mathrm{AWD}_{\mathrm{severe}}$, and four nitrogen application ($\mathrm{N}_{\mathrm{app}}$) rates, namely 0 ($\mathrm{N}_0$), 90 ($\mathrm{N}_1$), 180 ($\mathrm{N}_2$), and 270 ($\mathrm{N}_3$) kg N ha^{-1}, to determine the effects of water regimes and $\mathrm{N}_{\mathrm{app}}$ rates on rice yield, total water productivity (WP_{i+r}) and nitrogen recovery efficiency (NRE). The results demonstrated that the water regime, $\mathrm{N}_{\mathrm{app}}$ rate and their interaction showed significant effects on rice yield, WP_{i+r} and NRE and similar variations were observed in 2017 and 2018. The rice grain yield and WP_{i+r} (or the water productivity of irrigation, WP_{i}) significantly increased from N_0 to N_2 treatments but varied little between N_2 and N_3 treatments. The rice yield under $\mathrm{AWD}_{\mathrm{safe}}$ was higher than that under $\mathrm{AWD}_{\mathrm{severe}}$, whereas their WP_{i+r} and WP_i values showed the opposite trends. The WP_i values in 2018 were substantially higher than those in 2017 due to the lower irrigation amount in 2018. The highest rice NRE occurred with the combination of N_2 with the CF and $\mathrm{AWD}_{\mathrm{safe}}$ conditions, and it was significantly higher than that under $\mathrm{AWD}_{\mathrm{severe}}$. The dualistic and quadric regression equations of water and $\mathrm{N}_{\mathrm{app}}$ rate showed that rice yield, WP_{i+r} and NRE could not be maximized simultaneously. Based on the maximum likelihood method, it was demonstrated that maintaining the water quantity and $\mathrm{N}_{\mathrm{app}}$ rate at 11,000 $\mathrm{m}^3\ \mathrm{ha}^{-1}$ and 160 kg N ha^{-1} can serve as a suitable strategy to achieve maximal comprehensive benefits for rice grain yield, WP_{i+r} and NRE in certain regions with water shortage. The optimization model can save approximately 17.0% of water input and 11.1% of $\mathrm{N}_{\mathrm{app}}$ rate, respectively, compared to the traditional strategy. However, further research should validate and adapt these technologies in larger-scale fields.

Introduction

As a major rice planting country, China accounts for approximately 19% of the world's rice planting area and 32% of total rice production globally. Over the past 50 years, China's rice sector has used higher amounts of irrigation water and chemical fertilizer compared to other countries worldwide (Peng et al. 2009; FAO 2019). Although fertilizer application, especially nitrogen (N), plays an important role in maintaining continuous yield increases, its excessive application and improper management result in poor N utilization efficiency, thus causing detrimental effects on ecology, environment and human health (Ju et al. 2009; Peng et al. 2009). With global challenges imposed by the increasing population and the negative impacts of climate change, the shortage and inefficient utilization of water resources have become important factors limiting rice grain yield in the irrigation-based production system (Ye et al. 2015; Mekonnen

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and Hoekstra 2016). Therefore, the exploring approaches to producing more rice with high N recovery efficiency (NRE) and water productivity (WP) is vital to ensure food security and rice crop system sustainability.

Since the 1980s, many water-saving technologies, such as aerobic cultivation (Lampayan et al. 2010; Sudhir-Yadav et al. 2011), intensification cultivation (Uphoff et al. 2011), nonflooded mulching cultivation (Tao et al. 2006), and alternate wetting and drying (AWD) irrigation (Bouman and Tuong 2001; Sudhir-Yadav et al. 2012; Ye et al. 2013; Carracelas et al. 2019), have been implemented to reduce water input and the associated irrigation costs. However, many studies have reported conflicting results on grain yields, due to the significant variations of water management or other factors (Humphreys et al. 2005; Parent et al. 2010; Sudhir-Yadav et al. 2012). Based on a meta-analysis, Carrijo et al. (2017) found that a soil water potential at root depth of > -20 kPa or a 15 cm water depth threshold below the soil surface can serve as a safe AWD strategy to maintain the relatively higher rice yields (https://www.knowledgebank.irri.org/step-by-step-production/growth/water-management#for-safe-alternate-wetting-and-drying). This safe AWD method has been introduced and widely applied in different Asian countries (Tuong et al. 2005) and has other potential benefits, such as increases in farmer incomes (Lampayan et al. 2015a), reduced methane emission (Liang et al. 2016; Tarlera et al. 2016; Linquist et al. 2015) and decreased the risks of pest and disease damage (Zhuang et al. 2019). Additionally, AWD can reduce arsenic accumulation in rice grain (Linquist et al. 2015; Carrijo et al. 2017) compared to the continuous flooding (CF) technique.

Water and N are important inputs for rice production, and may interact with each other to produce a coupling effect. Their positive interactions on rice growth and yield determined through coordination of the source-sink relationship have been widely reported, especially during the grain filling stage (Yang and Zhang 2006; Badr et al. 2012; Wang et al. 2016; Aziz et al. 2018). Some authors attributed the increase in the yield sink capacity to the improvement of agronomic and physiological performance, including a greater productive tiller percentage, higher spikelet number, chlorophyll and soluble protein contents, and higher photosynthetic rate (Sun et al. 2012; Liu et al. 2013; Cao et al. 2017). Under the AWD condition, the main nutrition source changes from NH_4^+ under flooding condition to a mixture of NH_4^+ and NO_3^- (Fierer and Schimel 2002). Previous studies demonstrated that the mixture of NH_4^+ and NO_3^- can effectively alleviate the negative effects of water stress on plant growth relative to the use of NO_3^- alone (Cao et al. 2018, 2019). Water-saving technology also creates a healthy environmental condition for root growth and N uptake by increasing the rhizosphere redox potential and microbial community (Yang et al. 2018; Abbas et al. 2019). However, others have argued that the adoption of AWD technology reduces plant N accumulation and N use efficiency, because it could stimulate the N losses via increasing the ammonia volatilization, nitrification and denitrification of paddy soils (Belder et al. 2004; Tao et al. 2006; Zou et al. 2007). Sincik et al. (2013) suggested that the effects of the N application rate on plant growth and N use efficiency should be in accordance with the soil water condition. However, evidence quantitatively determining the water and N application amounts in different regions is still scarce (Bouman 2009).

Considering the significant synergistic effects of irrigation and N fertilizer, to optimize water use and N_{app} rates for rice production, WP and NRE are critical for sustainable agricultural management. Studies on the effects of different water-saving management, N-saving management, site-specific N management and integrative crop management strategies on yields and NRE have been widely reported (Sun et al. 2012; Liu et al. 2013; Zhang et al. 2018). These practices provide the potential for greater rice production in water-scarce areas and indicate that N_{app} rates can be adjusted within certain limits to improve crop yield and WP. The optimal N_{app} and irrigation regimes for simultaneously obtaining better crop growth, higher yield and improved quality in rice (Liu et al. 2019), maize (Gheysari et al. 2009), and tomato (Zotarelli et al. 2009) have previously been investigated. Therefore, establishing reasonable water-N-yield, water-N-WP or water-N-NRE functions through systematic and experimental research is an important theoretical basis and scientific premise for implementing optimized irrigation and N management strategies, especially considering the lack of sufficient water for irrigation, high N fertilizer use and environmental concerns.

Thus, this study was conducted with the following objectives: (1) to quantify and describe the responses of rice yield, WP and NRE to the different water regimes and N_{app} rates; and (2) to determine the optimal water-N strategy to achieve comprehensive benefits of higher rice yields, WP and NRE according to a 2-year field experiment.

Materials and methods

Site description

The field experiment was conducted at the research farm of the China National Rice Research Institute, Fuyang area, Zhejiang Province, China (30°03′ N, 119°57′ E) during the entire rice growing season (May to October) in 2017–2018. The soil was a bluish-purple clay with 6.85 pH, 2.65 g kg^{-1} total N, 36.8 g kg^{-1} organic matter, 142 mg kg^{-1} alkali hydrolysable N, 17.0 mg kg^{-1} Olsen-phosphorus, and 54.1 mg kg^{-1} exchangeable potassium as described in Cao et al. (2017). The site was under a water-N management strategy for 2 years for rice cultivation prior to initiation of the experiment.

Weather data

The daily rainfall, solar radiation intensity, sunshine hour and the average temperature during the growth duration from transplantation to physiological maturity were provided by the Fuyang Meteorological Observatory of Zhejiang Province (https://www.hzqx.com/hztq/index.html), China, which is approximately 1500 m away from our experimental field. Thus, the data should be accurate for representing the natural conditions of the field.

Field experiment

The experiment was established in a split-plot design with the water regime as the main plot and N_{app} rate as the subplot. Three water regimes and four N_{app} rates were tested with three replicates, and 36 subplots (4.4 m × 5 m) were established in field. The main plot consisted of three water regimes: (1) continuous flooding (CF) irrigation; (2) safe alternate wetting and drying (AWD_{safe}) irrigation; and (3) severe alternate wetting and drying (AWD_{severe}) irrigation. After transplanting, the field was flooded to a water depth of 3–4 cm for the first 10 days to promote seedling establishment and to control weeds. Then, different water regimes were imposed as described in Table 1.

In the CF regime, field water was kept at 3–4 cm until the tiller number reached 80% of the expected panicle number at harvest, and midseason drainage was imposed to depress the excessive growth of tillers until 10 days after visible panicle initiation occurred. Subsequently, the field was re-flooded, the water was maintained at 3–4 cm during the entire heading stage, and then shallow wetting irrigation was conducted. Whenever the water disappeared in the field, 3–4 cm of water was applied to re-flood the field. Seven days before harvest, the field was allowed to dry. Except for the midseason drainage, the fields were not irrigated until the soil water potential reached from − 15 to − 20 kilopascal (kPa) and − 35 to − 40 kPa at a depth between 15 and 20 cm under the AWD_{safe} and AWD_{severe} regimes, respectively. At initial flowering (when 10% of the panicles had fully emerged from the boot), the AWD_{safe} and AWD_{severe} treatments were suspended and the water was maintained at a depth between 1 and 2 cm to reduce the risk of spikelet sterility caused by water-deficit stress at this sensitive stage.

The soil water potential was monitored at the 15–20 cm soil depth with a tension meter consisting of a sensor with a length of 5 cm. Four tension meters were installed in each plot of AWD_{safe} and AWD_{severe} regimes, and readings were recorded at 12:00 each day. Under the AWD_{safe} and AWD_{severe} regimes, the timing of irrigation was based on the soil water potential in

Table 1 Water management under the different irrigation regimes

Deep of water (mm)		Growth stage								Irrigation water (m^3 ha^{-1})		Total water input (m^3 ha^{-1})	
		Turning green	Early tillering	Middle tillering	Late tillering	Jointing-booting	Heading-flowering	Grain-filling	Yellow-ripe	2017	2018	2017	2018
CF[a]	Max. level	30	35	35	Field drying	35	35	35	0	8240	5465	13,045	13,463
	Min. Level	20	15	15	Field drying	15	15	15	0				
AWD_{safe}	Max. level	30	15	10	Field drying	20	20	10	0	5050	2980	9855	10,978
	Min. Level	15	0 (− 17 kPa)[b]	0 (− 17 kPa)	Field drying	10	0 (− 17 kPa)	0 (− 17 kPa)	0				
AWD_{severe}	Max. level	30	15	10	Field drying	20	20	10	0	2775	1224	7580	9222
	Min. Level	20	0 (− 37 kPa)	0 (− 37 kPa)	Field drying	10	0 (− 37 kPa)	0 (− 37 kPa)	0				

[a] *CF* continuous flooding, AWD_{safe} safe alternate wetting and soil drying; AWD_{severe} severe alternate wetting and soil drying

[b] The values of soil water potential, − 17 and − 37 kPa, indicate that fields were not irrigated until soil water potential reached these values in AWD_{safe} and AWD_{severe} regimes, respectively

each plot. Thus, the irrigation time and frequency varied across the different treatments. When the soil water potential reached the threshold, a flood with a 1–2 cm water depth was applied. The irrigation was controlled and monitored using a flow meter (LXSG-50 Flow meter, Shanghai Water Meter Manufacturing Factory, Shanghai, China) installed in the irrigation pipelines. The seasonal total water input was the sum of all irrigation water and rainfall from the transplanting to harvesting stages. Each plot was irrigated or drained independently.

The N_{app} treatments consisted of four N_{app} rates, including 0, 90, 180, and 270 kg N ha^{-1}, which represented the zero amount (N_0), low amount (N_1), normal amount (N_2), and high amount (N_3) treatments, respectively. To prevent water and fertilizer flow between neighboring plots, the plots were separated by 100 cm wide bund using plastic film inserted into the soil to a depth of 30 cm, and the height of the ridge was 40 cm. N as urea was applied at the pre-transplantation, early tillering, panicle initiation and spikelet differentiation stages in proportions of 40, 20, 20 and 20%, respectively. Potassium (120 kg K_2O ha^{-1} as KCl) was applied in two equal splits as basal and panicle fertilizer, and phosphorus (60 kg P_2O_5 ha^{-1} as single superphosphate) was applied as basal fertilizer (Table S1).

Crop management

The indica rice (*Oryza sativa* L.) cultivar "Zhongzheyou 1", which was widely cultivated in the local region, was grown in the field from 2017 to 2018. Weeds, insects, and diseases were intensively controlled by a 50% pretilachlor emulsifiable concentrate (1500 ml ha^{-1}), 40% chlorothiamethoxam (150 g ha^{-1}) and a 27% suspension of tricyclazole and hexazolidol (1050 ml ha^{-1}), respectively, to avoid yield loss.

Rice tillers were recorded in a 5.0 m^2 subarea delimited during seedling establishment, where ten plants were tagged. The tiller dynamics of each treatment was monitored weekly from the active tillering stage to the heading stage, and the maximum tillers were investigated. Tiller efficiency was calculated as the number of productive tillers divided by the maximum tiller number. Yield- and yield-related traits, i.e., effective panicle number, spikelet number, grain filling rate, and 1000-grain weight were determined from three single plants randomly sampled from each plot. Grain yields were normalized to 13.5% moisture. The tissue N content was subjected to Micro-Kjeldahl digestion, distillation, and titration to calculate the aboveground N uptake (Yoshida et al. 1976).

Calculation of WP_{i+r}, WP_i and NRE

Total water productivity (WP_{i+r}) and irrigation water productivity (WP_i) were calculated using the Eqs. (1) and (2) (Bouman et al. 2007):

$$\mathrm{WP}_{i+r} = Y_{\mathrm{grain}} / W_{i+r} \tag{1}$$

$$\mathrm{WP}_{i} = Y_{\mathrm{grain}} / W_{i} \tag{2}$$

where W_{i+r} is the amounts of irrigation water (W_i) plus rainfall (W_r), and Y_{grain} is the rice grain yield (moisture percentage, 13.5%).

Nitrogen recovery efficiency (NRE) was estimated as the difference in N uptake in plants among fertilized and unfertilized N plots divided by total N amount in applied N fertilizer according to the Eq. (3).

$$\mathrm{NRE} = \left(\mathrm{N}_{\mathrm{fert.}} - \mathrm{N}_{\mathrm{unfert.}}\right) / \mathrm{N}_{\mathrm{app}} \tag{3}$$

where $N_{fert.}$ and $N_{unfert.}$ represent the plant N contents of the aboveground parts under the $N_1/N_2/N_3$ and N_0 treatments, respectively; $N_{app.}$ represents the N_{app} rates under the N_1, N_2 or N_3 treatments.

Model development and optimization of the water-N management strategy

Using the total water amount and N_{app} rate as the independent variables, rice yield, WP_{i+r} and NRE were employed as the response variables. Based on the least-squares method, a binary quadratic regression equation was established to calculate the irrigation amount and N_{app} rate required to maximize the grain yield, WP_{i+r} and NRE according to Dai et al. (2019).

The fitting formulation is expressed as Eq. (4):

$$Z = a + bx + cy + dx^2 + ey^2 + fxy \tag{4}$$

where Z is the value of rice yield, WP_{i+} or NRE; x and y are the total water input amount (irrigation water plus rainfall) and N_{app} rate, respectively; and a, b, c, d, e and f are the parameters of the Eq. (4).

Subsequently, binary quadratic regression equations were established using MATLAB (V.8.3, MATLAB Inc., 2014) to investigate the optimal water input and N_{app} rates required to obtain higher rice yield, WP_{i+r} and NRE simultaneously based on the least-squares method. As described in Table 4, the rice grain yield, WP_{i+r} and NRE could not be maximized simultaneously in our field experiment. However, a suitable strategy for water and N_{app} management that can maximize comprehensive benefits must exist, because they had significant interaction effects on the rice grain yield, WP_{i+r} and NRE. Therefore, combinations of likelihood functions were used for parameter estimation, where C_1 was the addition combination, C_2 was the multiplication combination, and C_3 was the mean square root combination according to a previous study (He 2008). These parameters were calculated as follows:

$$C_1 = \frac{1}{K}\left(\sum_{i=1}^{k} Y_i\right) \tag{5}$$

$$C_2 = \prod_{i}^{K} Y_i \tag{6}$$

$$C_3 = \left(\frac{1}{K}\sum_{i=1}^{k} Y_i^2\right)^{1/2} \tag{7}$$

where Y_i is the relative yield, WP_{i+r} or NRE, and K is the number of targets (three for this test, including the yield, WP_{i+r} and NRE).

The yield, WP_{i+r} and NRE have different units; therefore, these different parameters cannot be directly compared. We normalized the values of the three parameters to obtain the relative yield, WP_{i+r} and NRE according to the methods described in Dai et al. (2019). Assume that the yield, WP_{i+r} and NRE have the same weight for the three combinations (Eqs. (5)–(7)); thus, the water investment, N_{app} rate and the targets of C_1, C_2 and C_3 can be obtained.

Statistical analysis

All statistical data, including analysis of variance (ANOVA) results, interaction effects and least significant means, were derived using the SPSS system for Windows, version 14.0 (SPSS Inc. IBM Corp., Armonk, NY, USA). The significance of the treatment effect was determined using the Tukey-test, and comparisons of means were carried out using the least significant method (LSD) at the 5% level of significance. Figures were drawn using Origin v. 8.0 (OriginLab Corp., Northampton, MA, USA).

Results

Water used under the different irrigation regimes

Compared with the AWD_{safe} and AWD_{severe} regimes, traditional CF irrigation required the highest water input. From rice transplanting to maturity, the amounts of irrigation water under the CF, AWD_{safe} and AWD_{severe} regimes were 824.0, 505.0 and 277.5 mm in 2017, and 546.5, 298.0 and 122.4 mm in 2018, respectively (Table 1). The rainfall recorded from rice transplanting to harvesting was 480.5 mm in 2017 and 799.8 mm in 2018, and their amounts and distribution showed significant seasonal differences between the 2 years (Fig. 1). In 2018, rainfall was distributed from the rice transplanting to maturity stages, while in 2017 rainfall was mainly concentrated at the early tillering and grain-filling stages. The mean daily temperature was higher in 2017 than in 2018 (Fig. S1), especially in the panicle differentiation and grain filling stages. However, the average daily sunshine time from transplanting to harvest was 6.04 h in 2017, which was lower than that of 6.80 h in 2018.

Rice grain yield and yield components

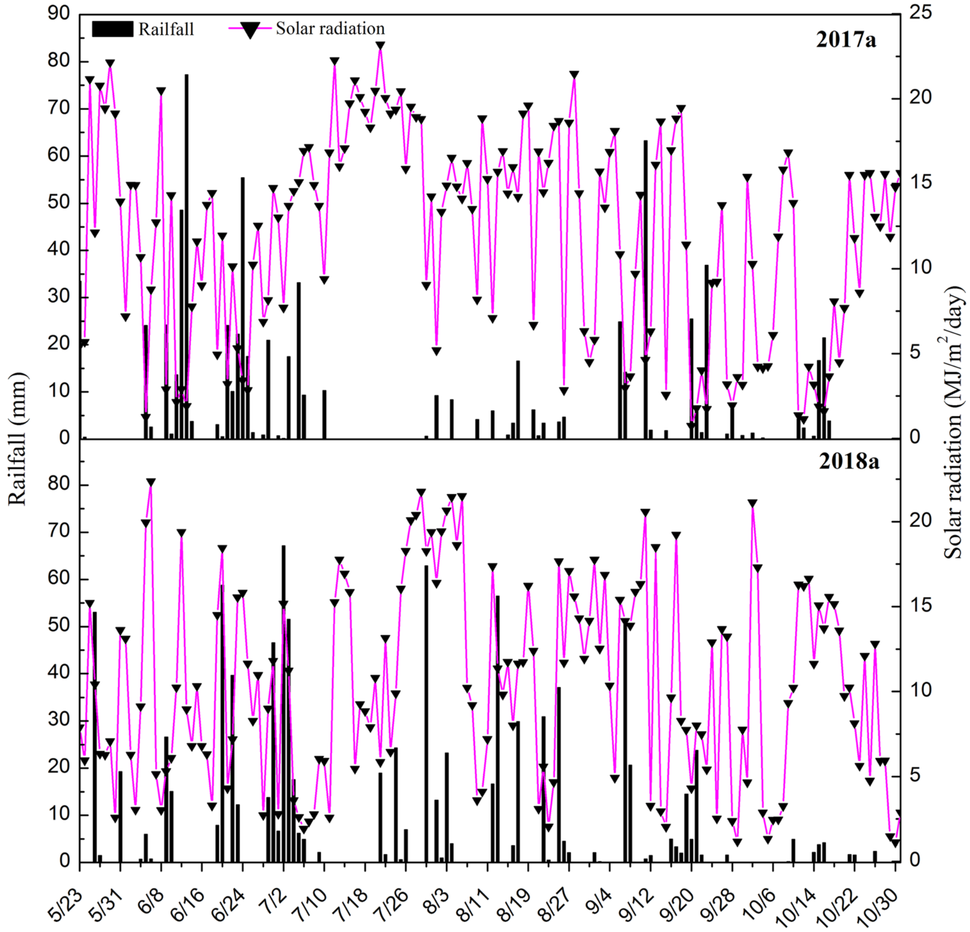
In 2017 and 2018, rice grain yields were significantly increased from the N_0 to N_2 rates under the three different water regimes (except N_0 and N_1 under CF in 2017, Fig. 2). Higher yields occurred with the N_2 and N_3 rates under the AWD_{safe} regime, and the values were 9631 and 9206 kg ha^{-1} in 2017 and 2018, respectively; however, significant differences were not observed between the N_2 and N_3 rates. Under the same N_{app} rate conditions, the rice grain yields under the AWD_{safe} regime were significant higher than that under the AWD_{severe} regime.

The rice yield components, including the effective panicle and spikelet numbers, were significantly increased when the N_{app} rates increased from N_0 to N_2 under the three water regimes (Table 2). In contrast, the grain filling rate decreased with an increasing N_{app} rate. Compared with the AWD_{safe} regime, the AWD_{severe} regime significantly inhibited the spikelet number but increased the effective panicle number. The main effects of N and water (W) and their interaction showed significant effects on rice grain yield (Table S2). An ANOVA of the yield components demonstrated similar main effects with respect to the effective panicle number, spikelet number, grain filling rate and 1000-grain weight, while only the N × W interaction presented the significant effects on the effective panicle and spikelet numbers.

Water productivity (WP_{i+r} and WP_i)

The water-N treatments had significant effects on WP_i and WP_{i+r}, and the responses showed similar variations in 2017 and 2018 (Fig. 3). With decreasing total water consumption, WP_{i+r} increased from 0.60 to 1.18 kg m^{-3} in 2017 and from 0.55 to 0.95 kg m^{-3} in 2018 between the CF and AWD_{severe} regimes (Fig. 3), whereas WP_i ranged from 0.95 to 3.23 kg m^{-3} in 2017 and from 1.37 to 7.12 kg m^{-3} in 2018. The WP_i values in 2018 were substantially higher than those in 2017 due to the large reduction in the irrigation amount in 2018. In contrast, WP_{i+r} and WP_i significantly increased when the N_{app} rates ranged from N_0 to N_3, and their values under the AWD_{safe} and AWD_{severe} regimes were significantly higher than those under the CF regime. However, WP_{i+r} and WP_i varied little between the N_2 and N_3 rates. Compared with those under the CF regime, WP_{i+r} and WP_i under the AWD_{safe} regime increased on average by 39.3 and 71.5% in 2017 and by 27.4 and 89.8% in 2018, respectively.

Fig. 1 Daily rainfall and solar radiation during the rice growing seasons in 2017 and 2018



Nitrogen recovery efficiency (NRE)

Generally, the variation in NRE gradually increased and then decreased with increasing N_{app} rates under the three different irrigation regimes (Fig. 4). The NRE was highest with the N_2 rate under the CF and AWD_{severe} regimes, and the values were approximately 45.0 and 45.6% in 2017 and 45.0 and 44.9% in 2018, respectively. Under the same N_{app} rate, the NRE varied little between the CF and AWD_{safe} regimes but was significantly higher than that under the AWD_{severe} regime.

Optimizing the water-N_{app} strategy based on comprehensive benefits

Here, the optimal water quantity and N_{app} rate needed to obtain a highest rice yield, WP_{i+r} and NRE were analyzed according to the binary quadratic regression equations as described in Table 3. The results demonstrated that the fitted equations showed significant correlations between the measured and predicted data ($R^2 > 0.71$, $P < 0.05$). The maximum rice yield, WP_{i+r} and NRE were achieved under different water inputs and N_{app} rates (Table 4, Fig. 5). The maximum rice yields of 9619.5 and 9602.4 kg ha^{-1} were achieved with 10,411 m^3 ha^{-1} of water and 283.2 kg ha^{-1} of N in 2017 and with 11,620 m^3 ha^{-1} of water and 264.0 kg ha^{-1} of N in 2018, respectively. WP_{i+r} was maximized at 1.18 and 1.19 kg m^{-3} with the lowest water input (7580 m^3 ha^{-1} in 2017 and 9200 m^3 ha^{-1} in 2018) and 240.0 kg ha^{-1} of N in 2017 and 2018. The highest NRE values of 46.7 and 46.8% were obtained with 11,157 and 12,178 m^3 ha^{-1} of water and 163.0 and 153.3 kg ha^{-1} of N in 2017 and 2018, respectively.

Combinations of likelihood functions demonstrated that the optimal water amount and N_{app} rate were not achieved in 2017 according to the C_3 combination (Table 5). Due to the large difference in precipitation, the amounts of applied water in the C_1 combination showed large differences between 2017 and 2018. Therefore, the C_1 and C_3 combinations are not suitable for predicting the optimal water-N_{app}-yield/WP_{i+r}/NRE functions. In contrast, the difference in the optimal water amount and N_{app} rate in the C_2 combination was within 2.2% and the yield, WP_{i+r}, and NRE were simultaneously maximized in 2017 and 2018. Therefore, the multiplication combination (C_2) can be reasonably considered to be better. The suitable strategy for water-N_{app} management is to control the total water input at 11,000 m^3 ha^{-1} and N_{app}

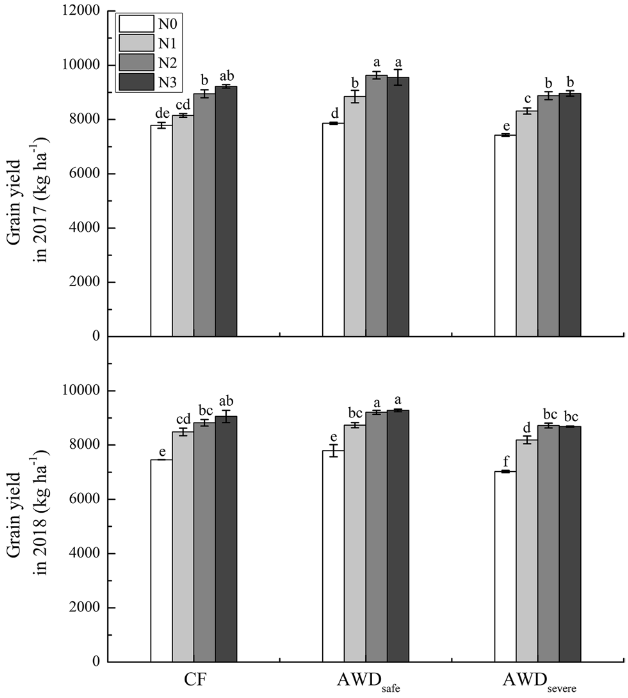


Fig. 2 Rice grain yields under the different water regimes and nitrogen application rates in 2017 and 2018

rate at 160 kg ha^{-1}, and this combination may achieve the multiple targets of water and N fertilizer conservation and yield increases in rice cultivation (Table 5, Fig. 6).

Discussion

Improving the productivity of water and N resources is becoming increasingly important in rice production due to the shortage of water resources and the serious non-point source pollution caused by the irrational fertilization-irrigation management (Ju et al. 2009; Peng et al. 2009). Based on a 2-year field experiment, this study concluded that optimized water-N management with 11,000 m^3 ha^{-1} of total water input (including irrigation and rainfall) and 160 kg ha^{-1} of N can serve as an optimal strategy for rice cultivation to achieve the targets of water and fertilizer conservation and yield increases.

Effects of irrigation and N_{app} rate on water used and WP_{i+r}/WP_i

Water and its interaction with the N_{app} rate had significant effects on rice grain yield and WP_{i+r}/WP_i ($P < 0.05$, Table S2). Compared with 2017, less irrigation water was applied in 2018 due to the more abundant rainfall. The AWD_{safe} and AWD_{severe} treatments required less irrigation compared to the CF treatment despite different rainfall amounts and distributions due to lower seepage (Sudhir-Yadav et al. 2012) and runoff losses (Sudhir-Yadav et al. 2011). More than 3,200 and 2,480 m^3 hm^{-2} (38.7% and 45.5%) of irrigation water under the AWD_{safe} regime were saved in 2017 and 2018, respectively, in comparison to the CF regime. The large irrigation water saving is consistent

Table 2 Effects of water regimes and nitrogen application rates on yield components of rice in 2017 and 2018

Treatment		Effective panicle ($\times 10^4 \cdot ha^{-1}$)		Spikelet (No. $panicle^{-1}$)		Grain filling rate (%)		1000-grain weight (g)	
		2017	2018	2017	2018	2017	2018	2017	2018
CF[†]	N_0[‡]	165.2d[§]	163.4e	191.1f	182.0ef	87.9a	89.5a	27.0d	27.3e
	N_1	187.6bc	189.0bcd	204.4cde	192.5d	86.8a	88.3ab	27.3 cd	28.4c
	N_2	197.9bc	202.4bc	232.2ab	219.1ab	86.1ab	87.3abc	27.5 cd	28.9a
	N_3	191.4bc	189.3bcd	212.9c	203.1c	81.2 cd	83.8de	28.0ab	28.7abc
AWD_{safe}	N_0	164.0d	162.2e	186.1f	174.7f	87.5a	89.7a	27.5 cd	27.8d
	N_1	176.8 cd	174.9de	206.3 cd	194.9 cd	87.3a	89.2a	27.7bc	28.5bc
	N_2	193.2bc	196.8bcd	240.7a	226.0a	86.3ab	88.5ab	27.7abc	29.1a
	N_3	180.5 cd	182.8cde	227.7b	216.5b	83.3bc	86.3bcd	28.1ab	28.8ab
AWD_{severe}	N_0	179.6 cd	181.6cde	175.2 g	164.2 g	86.0ab	87.2abc	27.0d	27.4e
	N_1	189.2bc	192.0bcd	195.1ef	183.6ef	85.0ab	85.8bcd	27.4 cd	28.5bc
	N_2	206.6ab	208.5ab	208.1 cd	194.7 cd	83.2bc	84.6 cd	28.4a	29.0a
	N_3	220.8a	225.0a	202.8de	191.7de	78.5d	80.4f	28.2a	28.7abc

[†] *CF* continuous flooding, AWD_{safe} safe alternate wetting and drying, AWD_{severe} severe alternate wetting and drying. N and W represents the N application rates and water regimes, respectively

[‡] N_0, N_1, N_2, N_3 represents zero N (0 kg N ha^{-1}), low N (90 kg N ha^{-1}), normal N (180 kg N ha^{-1}) and high N (270 kg N ha^{-1}), respectively

[§] Different letters within columns are significant different with a probability of $P < 0.05$

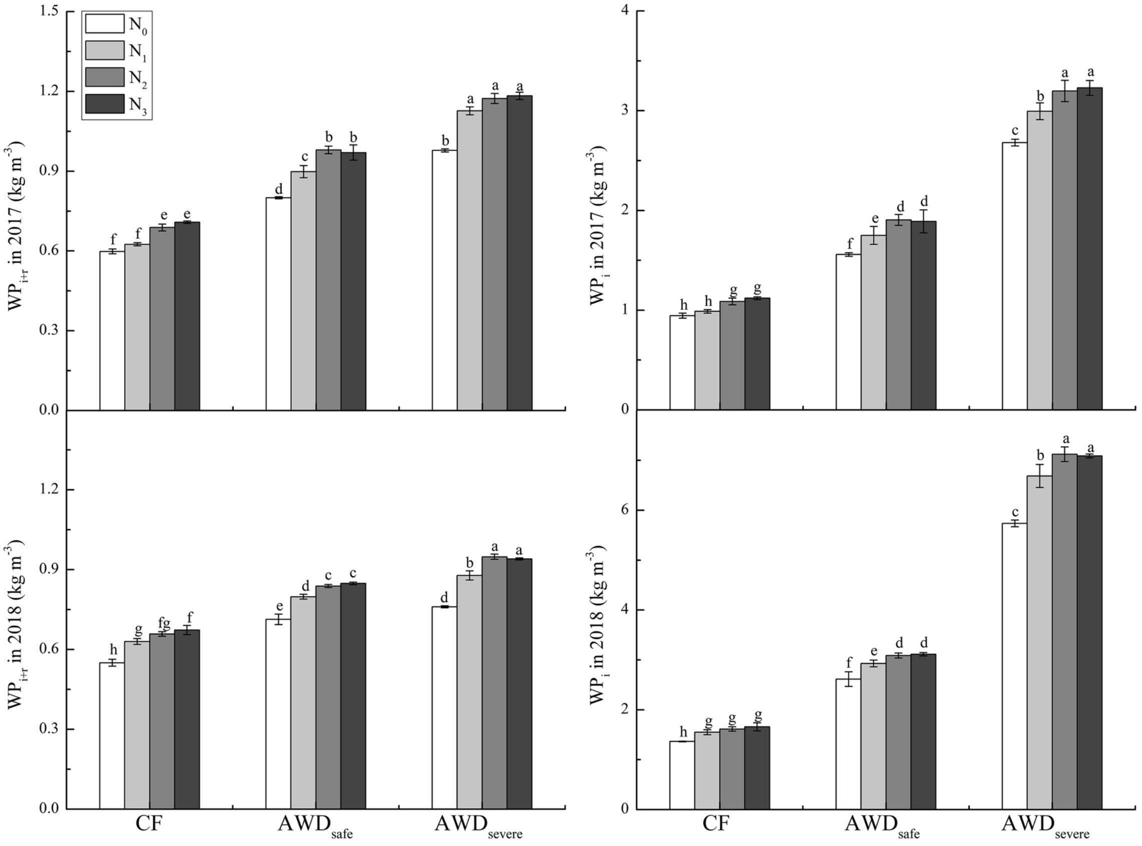


Fig. 3 Total water productivity (WP_{i+r}) and irrigation water productivity (WP_i) under the different water regimes and nitrogen application rates in 2017 and 2018. Bars represent the standard errors of the means. Different lowercase letters indicate significant differences ($P < 0.05$)

with the findings of many other studies reviewed by Humphreys et al. (2010), who found a 15–40% water-saving rate with AWD compared to CF.

The results from this paper also agree with international work and show that AWD irrigation management has significant potential to increase WP_{i+r} and WP_i (Bouman et al. 2007; Sudhir-Yadav et al. 2012). WP_{i+r} increased with decreasing total water consumption, ranged from 0.55 to 0.60 kg m^{-3} under the CF regime and from 0.95 to 1.18 kg m^{-3} under the AWD_{severe} regime in the 2 years. The WP_{i+r} values were also very good compared with the ranges reported internationally, e.g., 0.2–0.4 kg m^{-3} in India, 0.3–1.1 kg m^{-3} in Philippines and 0.7–1.4 kg m^{-3} in southeastern Australia (Bouman and Tuong 2001; Sudhir-Yadav et al. 2012; Dunna and Gaydon 2011). On average, the WP_{i+r} under the AWD_{safe} regime was increased by 39.3% in 2017 and by 27.4% in 2018 compared to that under the CF regime, indicating that the AWD_{safe} regime can fulfil the physiological water demand of rice through rational control of the water supply during key growth stages. The usage of irrigation water is significantly decreased while WP_{i+r} is increased (Table 3). However, the rice WP_i in 2018 ranged from 1.37 to 7.12 kg m^{-3} and was significantly higher under the three different water regimes than that in 2017. Their values were all substantially higher than those in previous studies (Carracelas et al. 2019; Aziz et al. 2018). The high degree of variation in WP_i was likely related to the differences of rice cultivar, irrigation timing, and the duration and severity of drying with this technique.

With increasing N_{app} rates, the rice WP_{i+r} and WP_i significantly increased from the N_0 to N_2 treatments but decreased or stabilized from the N_2 to N_3 treatments, indicating that only a reasonable N_{app} rate can improve the WP, while an excessive N_{app} rate not only reduces the WP but also strengthens the possibility of agricultural non-point source pollution. Similar results have been found for other crops, including potato (Badr et al. 2012), onion (Patel and Rajput 2009) and tomato (Ismail et al. 2008).

Effects of irrigation and N_{app} rate on rice grain yield and yield components

Although reports have indicated that different water-saving technologies can significantly increase the WP_{i+r}, whether AWD irrigation can increase rice grain yield remains debatable (Yang et al. 2007; Yao et al. 2012; Liu et al. 2013;

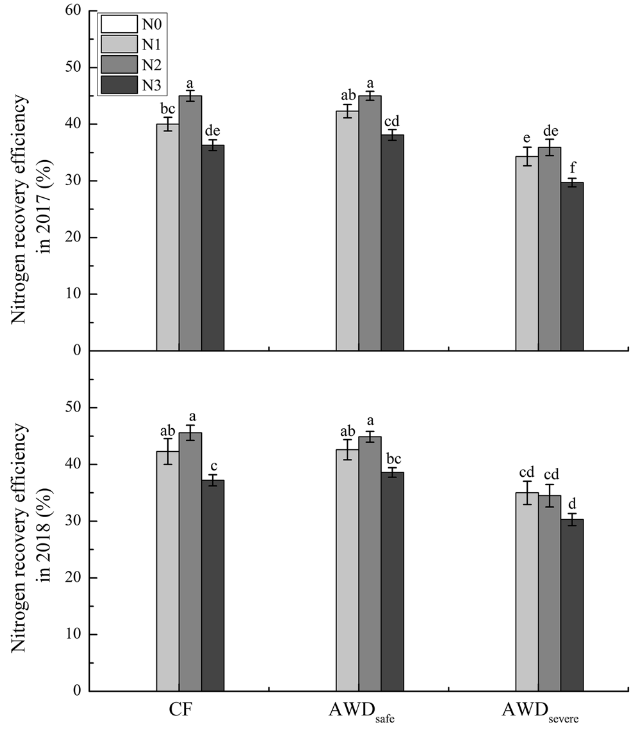


Fig. 4 Nitrogen recovery efficiency (NRE) of rice under the different water regimes and nitrogen application rates in 2017 and 2018. Bars represent the standard errors of the means. Different lowercase letters indicate significant differences ($P < 0.05$)

Humphreys et al. 2005; Carracelas et al. 2019). Our results demonstrated that rice grain yields increased gradually along with the N_{app} rates and were highest with the N_2 rate under the AWD_{safe} regime, which may be attributed to the fact that the appropriate N_{app} rate can effectively increase leaf photosynthesis, promote the optimal distribution of crop photosynthetic products in source-sink systems, and ultimately increase crop yields (Zhong et al. 2019a, b). However, the benefits of applying N for photosynthesis are partially offset by a lower Rubisco activation state under higher N conditions (Li et al. 2009). The AWD_{safe} regime significantly increased the grain yield compared to the CF regime, indicating that the conventional irrigation system is not essential for attaining higher grain yields. However, too little water under the AWD_{severe} regime may compromise the N fertilizer effect due to a significant reduction in the rice yield compared to that under the AWD_{safe} regime. The similar yield reduction induced by the severe water deficit was also confirmed in Sudhir-Yadav et al. (2011) and Carrijo et al. (2017). These results strongly showed that the roles of N and water are not independent of each other. The better rice yield under the AWD_{safe} regime indicated that the soil water potential (− 20 kPa at a soil depth of 15–20 cm) can be used as an index for a safe AWD model to achieve a higher yield. However, this threshold needs to be tested over a wider range of seasonal and site conditions.

Previously, studies demonstrated that the positive results and increased grain yields under AWD are associated with increases in the effective panicle number, spikelet number or grain weight (Yang et al. 2007; Wang et al. 2015; Carrijo

Table 3 Investment of irrigation and N_{app} rate, and their regression equations for yield (kg ha^{-1}), total water productivity (WP_{i+r}, kg m^{-3}) and nitrogen recovery efficiency (NRE, %)

Year	Variable	Regression equation	R^2	P
2017	Grain yield	$Z = 77.748 + 11.725x + 1.514y - 0.0202x^2 - 0.0000723y^2 - 0.0000294xy^a$	0.833	<0.001
	WP_{i+r}	$Z = 1.663 + 0.00184x - 0.0000981y - 0.00000227x^2 + 0.00000000112y^2 - 0.0000000600xy$	0.976	<0.001
	NRE	$Z = -63.536 + 0.199x + 0.00169y - 0.000640x^2 - 0.000000763y^2 + 0.000000867xy$	0.819	<0.01
2018	Grain yield	$Z = -7144.470 + 14.689x + 2.548y - 0.0259x^2 - 0.000109y^2 - 0.0000853xy$	0.891	<0.001
	WP_{i+r}	$Z = 2.135 + 0.00210x - 0.000144y - 0.00000227x^2 + 0.00000000209y^2 - 0.0000000773xy$	0.976	<0.001
	NRE	$Z = -145.377 + 0.160x + 0.0296y - 0.000493x^2 - 0.00000121y^2 - 0.000000744xy$	0.705	<0.05

[a] Z is the maximum of rice yield, WP_{i+r} or NRE; x and y are the amounts of total water input and N application rate

Table 4 Maximum yield (kg ha^{-1}), total water productivity (WP_{i+r}, kg m^{-3}) and nitrogen recovery efficiency (NRE, %) and their corresponding water input amounts and N_{app} rates

Year	Target	N application rate (kg N ha^{-1})	Total water (m^3 ha^{-1})	Grain yield (kg ha^{-1})	WP_{i+r} (kg m^{-3})	NRE (%)
2017	Max. Yield	283.2	10,411.0	9619.5	0.93	37.5
	Max. WP_{i+r}	240.0	7580.0	8998.6	1.18	33.0
	Max. NRE	163.0	11,157	9290.6	0.84	46.7
2018	Max. Yield	264.0	11,620	9602.4	0.90	40.4
	Max. WP_{i+r}	240.0	9200.0	8945.6	1.19	32.6
	Max. NRE	153.3	12,178	9254.9	0.82	46.8

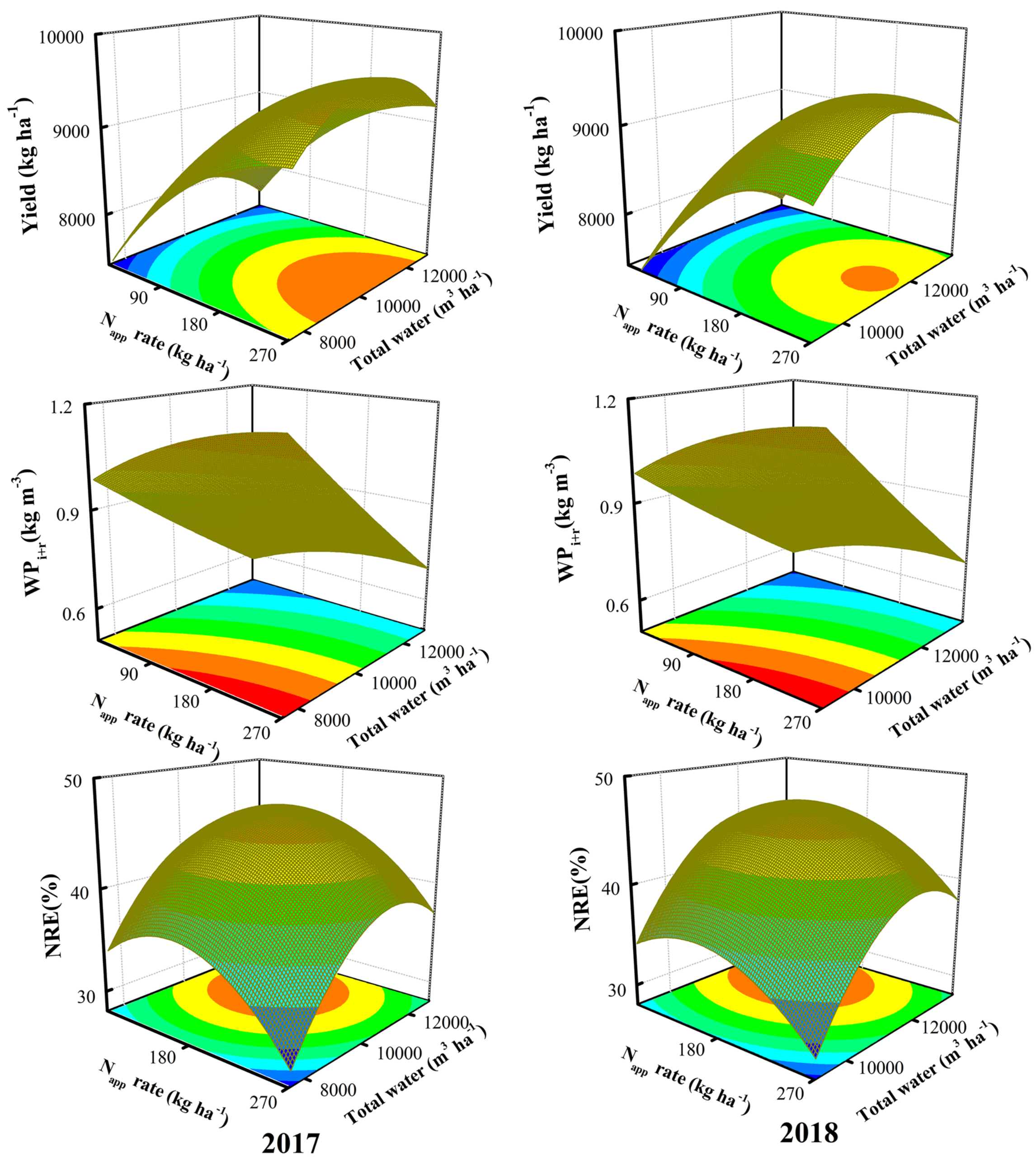


Fig. 5 Relationship among the N application rate (N_{app}), total water input, rice yield, water productivity (WP_{i+r}) and nitrogen recovery efficiency (NRE) in 2017 and 2018. Bars represent the standard errors of the means. Different lowercase letters indicate significant differences ($P < 0.05$)

Table 5 Maximum targets of C_1, C_2, C_3 and their corresponding water input amounts and N_{app} rates

Year	Target	N_{app} rate (kg N ha^{-1})	Total water (m^3 ha^{-1})	Grain yield (kg ha^{-1})	WP_{i+r}[a] (kg m^{-3})	NRE (%)
2017	C_1	185.8	9550	9372.1	0.99	44.4
	C_2	165.6	11,061	9312.4	0.85	46.8
	C_3	–	–	–	–	–
2018	C_1	188.0	11,041	9411.6	0.95	44.7
	C_2	162.0	11,256	9314.0	0.92	45.8
	C_3	175.5	11,298	9384.6	0.92	45.7

[a] WP_{i+r}, total water productivity; NRE, nitrogen recovery efficiency

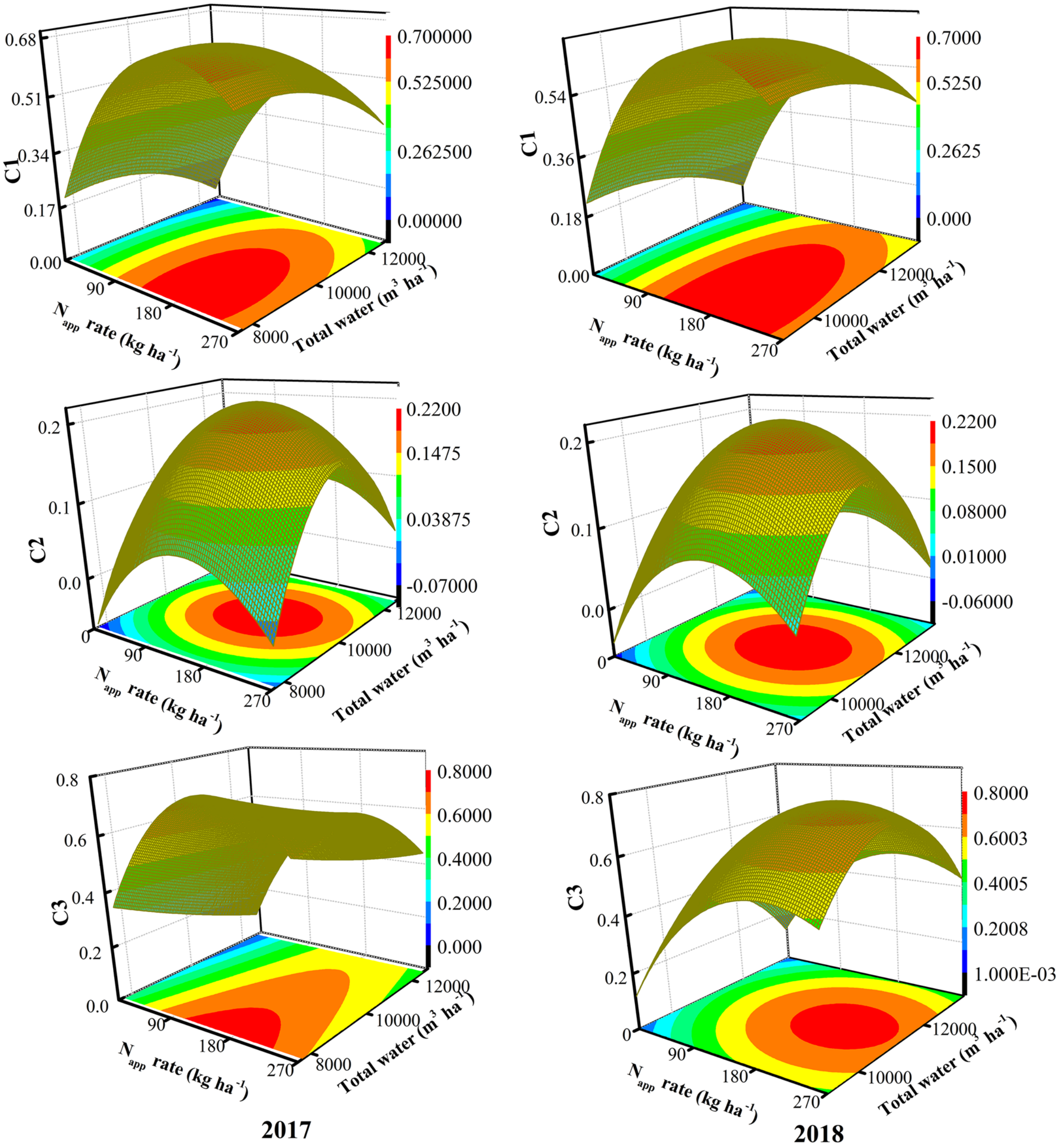


Fig. 6 Relationships between the water investment and N_{app} rate for rice and the targets of C_1, C_2 and C_3

et al. 2017). Compared with the CF and AWD_{severe} regimes, the spikelet number (sink size) under the AWD_{safe} regime significantly increased at different N_{app} rates, which is beneficial for improving the "pulling force" of sink size and enhancing the grain yield (Yang and Zhang 2006, 2010; Wang et al. 2016). With an increasing N_{app} rate, the number of spikelets significantly increased from the N_0 to N_2 rates but decreased at the N_3 rate, which was consistent with the variations of rice yield. Reis et al. (2018) demonstrated that rice yield components, including the spikelet number, are strongly correlated with N uptake. In the AWD_{safe} regime, the aerobic soil conditions are associated with a higher N mineralization rate, resulting in potentially higher N uptake (Dong et al. 2012; Kader et al. 2013). However, an excessive N_{app} rate induces spikelet sterility in rice (Gunawardena and Fukai 2004; Huang et al. 2008). Compared with the AWD_{safe} regime, the AWD_{severe} regime significantly increased the rice maximum tillers and effective panicles but inhibited the percentage of productive tillers (effective panicles/maximum tillers), especially at the higher N_{app} rate (Table 2, Fig. S2). The redundant vegetative growth correspondingly inhibited the effectiveness of the nutrients and water applied (Yang and Zhang 2010). The failure of pollination induced by severe water stress under the AWD_{severe} regime also caused spikelet sterility and a reduced grain yield (Liang et al. 2016). In contrast, AWD_{safe} regime combined with an optimal N_2 rate could suppress noneffective tillers and alleviate the detrimental effects of an excessive N_{app} rate on rice growth by accelerating plant senescence and remobilizing of carbohydrates and N compounds (Wang et al. 2016).

Effects of irrigation and N_{app} rate on rice NRE

Our study further demonstrated that proper water and N management can improve rice NRE. The higher rice biomass and NRE are evidence of the efficient utilization of N fertilizer influenced by AWD. The rice NRE was improved under the AWD_{safe} regime compared with that under the $\text{AWD}_{\text{severe}}$ regime, and it had N_1, N_2, and N_3 values of 22.6, 27.7 and 27.8%, respectively. This result may be attributed to the following two reasons: (1) with moderate wetting and drying cycles, AWD_{safe} strengthens air exchange and accelerates soil organic matter mineralization, which not only increases soil fertility but also stimulates N uptake (Dong et al. 2012; Kader et al. 2013); and (2) the reduced surface water runoff and increased water storage capacity under the AWD_{safe} regime efficiently inhibit soil total N loss by minimizing ammonium and total N leaching (Gao et al. 2009; Tan et al. 2013). The AWD_{safe} regime combined with an appropriate N_{app} rate also provides a better environment for root growth and canopy development, thus achieving higher N uptake and NRE (Bhattarai et al. 2008; Abuarab et al. 2013; Chu et al. 2014). In contrast, greater N loss occurred under the $\text{AWD}_{\text{severe}}$ regime because this strategy likely reduced the plant N accumulation and NRE (Cabangon et al. 2011), indicating that the safe AWD regime can increase the yield and NRE under suitable irrigation amounts. Similar results under the moderate AWD have been reported previously (Chu et al. 2014; Sudhir-Yadav et al. 2012; Wang et al. 2016; Carracelas et al. 2019).

Irrigation-N management strategy based on the comprehensive benefits

In the process of sustainable agriculture, the optimal use of water and nutrient resources is urgently required for rice cultivation. Under the three water regimes and four N_{app} rates, when the yield was highest in 2017 and 2018, the WP_{i+r} was reduced by 26.9 and 32.2% compared with the maximum WP_{i+r} while the NRE was reduced by 24.5 and 15.8% compared with the maximum NRE, respectively (Tables 3, 4). Increasing the water input and N_{app} rate above these rates did not improve the rice yield, the opposite effect was observed for WP_{i+r} and NRE in some cases. Therefore, the strategy for water-N_{app} management must be determined based on economic and environmental benefits. Previously, some authors suggested that the maximum likelihood method can be used to solve the problem of comprehensive benefits (Wu et al. 2015), which was also confirmed by this study. The models developed in this study show that maintaining the total water input at 11,000 $\text{m}^3\ \text{ha}^{-1}$ and the N_{app} rate at 160 kg N ha^{-1} may achieve the multiple targets of water conservation, fertilizer conservation and yield increases (Fig. 6, Table 5). Compared with traditional water-N management, approximately 2,254 $\text{m}^3\ \text{ha}^{-1}$ (17.0%) of total water input and 20 kg ha^{-1} (11.1%) of N were saved with our optimized model. Importantly, the grain yield, WP_{i+r} and NRE were all significantly and synergistically increased. Previous, Liu et al. (2019) suggested that irrigation water and N_{app} rates could be adjusted within certain limits to improve crop yield and grain quality and the optimal N_{app} rate and water consumption ranged from 80 to 140 kg N ha^{-1} and 5000 to 8000 $\text{m}^3\ \text{ha}^{-1}$, respectively. Based on the average amounts of rainfall in the last decade, we suggest that approximately 5,200 $\text{m}^3\ \text{ha}^{-1}$ of irrigation water input with the AWD technique is an achievable target with no yield penalties for rice in this region.

The models obtained here can be used as a reference for performance optimization under the similar climatic conditions. However, other climatic factors, including temperature and light intensity, also affect the precision of this model. Lampayan et al. (2015b) found that rice performs better when grown under longer sunshine duration and thus more solar radiation. Further research should also validate and adapt these technologies in larger-scales fields. These challenges require an integrated decision tool that enables efficient water and fertilization management and continuous monitoring, reporting and verification of management practices.

Conclusions

This study established functions revealing the water-N-yield, water-N-WP_{i+r} and water-N-NRE relationships of rice in the form of quadratic models. Our results demonstrated that water quantities and N_{app} rates showed significant main and interaction effects on the rice yield, WP_{i+r} and NRE. The rice grain yield and WP_{i+r} significantly increased from the N_0 to N_2 treatments but varied little between the N_2 and N_3 treatments. The rice yield under the AWD_{safe} regime was higher than that under the $\text{AWD}_{\text{severe}}$ regime, whereas the WP_{i+r} values showed the opposite trend. Rice NRE was highest at the N_2 rate combined with the CF and AWD_{safe} regimes and significantly higher than that under the $\text{AWD}_{\text{severe}}$ regime.

The dualistic and quadric regression equations of water input and the N_{app} rate showed that the maximum rice yields of 9619.5 and 9602.4 kg ha^{-1} were achieved with 10,411 $\text{m}^3\ \text{ha}^{-1}$ of water input and 283.2 kg ha^{-1} of applied N in 2017, and 11,620 m^3 ha^{-1} of water input and 264.0 kg ha^{-1} of applied N in 2018, respectively. The maximum WP_{i+r} was between 1.18 and 1.19 kg m^{-3} with the lowest water input and 240.0 kg ha^{-1} of applied N, while the maximum NRE was between 46.7 and 46.8% with 11,157–12,178 m^3 ha^{-1} of total water and 153.3–163.0 kg ha^{-1} of N in 2017 and 2018. However, the rice yield, WP_{i+r} and NRE cannot be simultaneously maximized under the given N_{app} and water regimes. According to the maximum likelihood method, maintaining an 11,000 m^3 ha^{-1} water input and a 160-kg ha^{-1} N_{app} rate can be considered the best strategy for water-N_{app} management in this region. This combination can result in maximal comprehensive benefits of higher yield, WP_{i+r} and NRE, with reductions of 17.0% in total water and 11.1% in N use, compared to traditional water-N management.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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