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Grain yield, water productivity and nitrogen use efficiency of rice under different water management and fertilizer-N inputs in South China

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ABSTRACT

The increasing scarcity of irrigation water necessitates the development of water-saving technology in rice production. Our previous studies have shown that "safe" alternate wetting and drying irrigation (AWD15) can effectively save water, improve water productivity while maintain grain yield compared to continuous flooding (CF) and farmer's water management practice (FP) under a single fertilizer-N input. The objectives of this study are (1) to investigate the superiority of this novel water management practice compared with FP; and (2) to examine whether there is an interaction between water and N input and whether fertilizer-N input needs to be adjusted under AWD15. Two field experiments were conducted during the late cropping seasons of 2014 and 2015. A hybrid rice variety Tianyou3618 was grown under two water management (AWD15 and FP) and four fertilizer-N rates (0, 90, 180, 270 kg N ha^{-1}). Grain yield, water productivity and nitrogen use efficiency were determined. Compared to that of FP, irrigation water input of AWD15 was reduced by 24.1% in 2014 and 71.4% in 2015. The number of irrigations decreased and water productivity increased significantly. No significant differences existed between AWD15 and FP in grain yield, biomass, leaf area index and nitrogen use efficiency. Nitrogen input level had significant effects on yield, biomass, harvest index and nitrogen use efficiency in both years. Grain yield increased with N rate and the optimal N rate was 180 kg N ha^{-1}. No significant interaction was found between water and nitrogen rate regarding biomass production and grain yield. Our results demonstrated that no change in N input is needed under AWD15 condition and AWD15 is advantageous over farmer's water management practice under all N levels investigated in South China. This is the first report on the performance of AWD15 under different fertilizer-N levels in South China.

1. Introduction

Water and nitrogen are important inputs for rice production. The scarcity of fresh water resources now threatens rice production in China (Yao et al., 2014). South China is one of the major rice-producing regions in the country, with a total planting area of 5 Mha. More than 80% of cereal food produced comes from rice (National Bureau of Statistics of China, 2015). Two rice crops are grown annually under irrigation in this region. Although there is abundant rainfall in South China, water shortage is still a major problem for rice production because of the uneven distribution of the rainfall among seasons and regions (Liu et al., 2011). Moreover, climate change has brought an alarming situation to agricultural production, such as an increase in the occurrence of periods of water scarcity. Global warming is likely to result in a 24% greater demand for water in the double-cropping areas of rice in South China (Ye et al., 2015).

In rice production, farmers often apply more N fertilizers than the minimum required for maximum crop growth to maximize grain yield (Peng et al., 2002). Water scarcity, environmental

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pollution caused by excessive application of fertilizers, and the high costs of irrigation and fertilizers, demand for greater increase than ever in grain yield of rice with less water and less fertilizers (N fertilizer in particular) in China (Peng et al., 2002, 2006). Thus, there is an increasing need to develop water-saving and N-fertilizer efficient technologies for economical and environment-friendly production of rice.

For rice, water-saving technologies include alternate wetting and drying (AWD) irrigation, saturated soil culture, and aerobic rice, etc. (Bouman et al., 2007b). AWD has been used in many countries in Asia since being developed by IRRI since 1990s. The practice provides a chance of more rice production in water scarce areas. "Safe" AWD (AWD15), with a threshold of 15 cm in water depth below the soil surface, also has other potential benefits, such as (1) increase in farmers' income (Lampayan et al., 2015b), (2) reduction in lodging of rice plants because of better rooting system and better control of some pests and diseases such as golden apple snail (Bouman et al., 2007b), and (3) reduction of methane (a greenhouse gas) emissions (Yagi et al., 1996; Liang et al., 2016). Up to now, AWD15 has become one of the most commonly practiced water-saving irrigation technologies in Asia (Tuong et al., 2005; Lampayan et al., 2015b; Liang et al., 2016). However, this technology was introduced by us into South China only in recent years. More information is needed to validate its adaptability to this region and its superiority over local farmers' water management practice.

Water and nutrient may interact with each other to produce a coupling effect. Some studies (Wang et al., 2004; Sun et al., 2009, 2010) indicated that there was a significant interaction between nitrogen application and water management on nitrogen absorption and utilization and grain yield in rice. However, other studies have found no significant interaction between them (Yang et al., 2008; Yao et al., 2012). Under the growing conditions of lowland rice in South China, the interaction between water management practice (AWD15 and FP) and nitrogen input has not been documented yet and needs to be investigated. When AWD15 is practiced, continuous standing water will not be observed in the field except for the first 10 days after transplanting and during the flowering stage. The field will alternately experience flooding and drying conditions. We speculate that nutrient loss (nitrogen in particular) caused by water runoff from the field may be reduced considerately, resulting in an indirect improvement in nitrogen use efficiency under AWD15. In addition, non-point source pollutants (nitrogen in particular) may be reduced due to less water runoff (Xue et al., 2013). Furthermore, if an interaction exists between water management practice and nitrogen rate, then the N input will have to be changed under AWD15.

Water management with a midseason drainage is a common practice widely used nowadays by farmers to control the unproductive tillers in China. Continuous flooding (CF) was widely used by rice farmers until the 1980s but has been gradually replaced by the present midseason drainage (regarded as farmer's practice or FP in this paper) (Zou et al., 2009; Liang et al., 2016). A direct comparison between AWD15 and FP is more meaningful, but previous studies on AWD15 by other researchers were based on a comparison between AWD15 and CF. In our previous studies, we found that AWD15 was advantageous over both CF and FP in saving water (Liang et al., 2016). However, more evidences are needed to confirm the superiority of AWD15 to FP. In the current study, we grow rice under two water management (AWD15 and FP) and four fertilizer-N rates (0, 90, 180, 270 kg N ha^{-1}) to determine the effect of water and N input on grain yield, water productivity and nitrogen use efficiency. We hypothesize that rice yield, water productivity and nitrogen use efficiency will be higher under AWD15 and would be optimal at a certain N input level.

2. Material and methods

2.1. Experimental site description

The experiments were conducted at the Baiyun Experimental Farm of Guangdong Academy of Agricultural Sciences in Guangzhou (113°23′E, 23°17′N, altitude of 41.0 m), Guangdong, China, during 2014 and 2015 late seasons (August to November). The field had been continuously cropped with puddled rice twice a year and was surrounded by flooded rice fields during the two cropping seasons. The field soil had pH of 5.5 and contained 23.1 g kg^{-1} organic matter, 13.6 mg kg^{-1} available P, and 82.9 mg kg^{-1} available K. Mean rainfall (from 1992 to 2015) was 1106 mm in the early cropping season (April–July), and 577 mm in the late season (August–October). The area has a mean temperature of 21–23 °C, relative humidity of 75%, and solar radiation of 12.4 MJ m^{-2} day^{-1}.

2.2. Experimental treatments and design

The experiment was laid out in a split-plot design with water regime (W) as the main plot and nitrogen (N) treatment as the subplot. Two W and four N treatments were tested with three replicates and 24 subplots (4.2 m × 6.8 m) were established in the field. The W treatments were farmers' irrigation practice with midseason drainage (FP) and safe AWD at the −15 cm threshold level for irrigation (AWD15). The N treatments were 0, 90, 180, and 270 kg N ha^{-1}, respectively. All plots were separated each other with bunds and had a separate draining outlet to drain water into ditches. The bunds were covered with plastic film (0.15 mm) which was inserted to 40 cm depth below soil surface to minimize seepage between plots. In order to reduce or avoid the residual effect of precropping fertilizers, rice was grown and no fertilizers was applied in the same field in the previous season of both years. The field was irrigated with underground water which came from a depth of 126 m below ground surface and was pumped into a water storage tank. The water inflowed into each plot directly through PVC pipeline. The variety in this experiment was Tianyou3618, which is recognized as a super hybrid rice by the Ministry of Agriculture of China and has been widely planted in South China.

In both water treatments, the field was flooded to a water depth of 3–5 cm for the first 10 days after transplanting to promote seedling establishment and control weeds. Two water treatments were imposed afterwards. In the FP treatment, field water was kept at 2–5 cm until the tiller number reached 80% of the expected panicle number at harvest, a midseason drainage (about 25 DAT) was imposed to depress excessive growth of tillers until 10 days after the visible panicle initiation occurred. The field was re-flooded and the water was kept at 2–5 cm during the entire heading stage. After heading, shallow wetting irrigation was carried out. Whenever the water disappeared in the field, 2–3 cm of water was applied to re-flood the field. At 7 days before harvest, the field was allowed to dry. In the AWD15 treatment, timing of irrigation was based on the water depth in the field water tube installed in each plot (Lampayan et al., 2015a). Irrigation time and frequency thus varied slightly across replicates. The tubes were installed in the field to 15 cm depth below the soil surface. When the ponded water disappeared in the water tubes, then irrigation was applied to re-flood the field up to 5 cm above the surface. At initial flowering (when 10% of the panicles had fully emerged from the boot), AWD15 treatment was suspended and water depth was maintained at 2–5 cm depth to reduce the risk of spikelet sterility caused by water-deficit stress at this sensitive stage. After completion of the flowering stage, the AWD15 cycles were repeated until 7 days before harvest.

Nitrogen in the form of urea was applied four times: 30% as basal, 30% at 25–27 DAT, 30% at 40–45 DAT, and 10% at heading. Seeds were sown in the seedbed on 21 July in 2014 and 20 July in

Table 1
Cumulative rainfall and pan evaporation, mean daily maximum and minimum temperatures, and mean daily sunshine duration at the experimental field from transplanting (TR) to maturity (MAT) at Guangzhou, Guangdong Province, China in 2014 and 2015.

Growth stage	Rainfall (mm)		Evaporation (mm)		T_{max} (°C)		T_{min} (°C)		Sunshine duration (h)	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
TR-PI	250.6	257.2	106.4	105.8	36.6	36.3	23.9	23.9	6.6	5.3
PI-HD	25.2	36.0	63.5	63.5	36.1	35.4	22.9	22.1	6.8	6.4
HD-MAT	3.8	2.2	115.0	111.9	35.7	32.5	18.6	13.6	6.1	5.5

2015. Transplanting was done on 7 August in 2014 and 8 August in 2015 at a hill spacing of 13.3 cm × 30 cm with two seedlings per hill. Potassium (135 kg K_2O ha^{-1} as KCl) was applied in two equal splits (as basal and at 25–27 DAT), and phosphorus (45 kg P_2O_5 ha^{-1} as single super-phosphate) was applied as basal. Both basal K and P fertilizer were incorporated in the field one day before transplanting. Pests, diseases, and weeds were intensively controlled to avoid yield loss.

2.3. Measurements and calculations

A network of pipes was installed in the experimental plots to facilitate irrigation and measurement of water flow. Irrigation water applied in each plot was measured using a flow meter attached between the pump and the distribution pipe. The seasonal water input per treatment from transplanting to harvesting was the sum of all irrigation water applied and total rainfall. Soil moisture tension at 15-cm soil depth was monitored using SR1075 tensiometers installed in all plots. Daily standing water depths (aboveground) and perched water depths (below ground) in all plots were monitored manually by measuring the water level inside the field water tubes (Lampayan et al., 2015a) with a meter stick. In FP plots, water tubes also were installed to monitor daily ponded water depths as done in AWD15, but its irrigation application followed its own mode regardless of change of water depth. Daily groundwater dynamics were monitored using 200-cm-long PVC pipes with a diameter of 5 cm, whose lower circular surface (120 cm) was perforated with 0.5 cm holes at 2 cm intervals. The groundwater tubes were installed in the center of the main experimental field to a depth of 150 cm from the soil surface (Yao et al., 2012). Water table readings were taken at 0900–1000 h every 2–3 days depending on weather condition and water depth of the field.

Plant samples were taken at mid-tillering (MT), panicle initiation (PI), heading (HD), and physiological maturity (MAT) to determine aboveground biomass and leaf area index (LAI) during the season. At each sampling, a total of eight plants (0.32 m^2) were sampled and brought to the laboratory for biomass and leaf area measurements. Plants were partitioned into green leaf blade, stem plus leaf sheath, dead leaves (if any), and panicles (if any). The area of the green leaves was measured using a leaf area meter (Licor™ LI3100) and the LAI was determined. Biomass was determined after oven-drying of plant samples at 70 °C for 3 days. Grain yields were determined at maturity by taking 5 m^2 plant samples at the center of each plot. Grains were separated from the rachis, filled and unfilled grains were separated, and the total weight of filled grains was determined. Filled grains were dried in an oven at 70° to a stable weight, and grain yield was calculated at 14% moisture content. Plant samples were taken for the determination of yield components (panicle density, number of spikelets per panicle, 1000-grain weight, and percent filled spikelets) from 12 hills (0.48 m^2) adjacent to the harvest area. Total water productivity (WPT) was calculated as kg grain m^{-3} total water input (rainfall and the sum of all irrigations, excluding land preparation and water consumption during the first 10 days after transplanting). Tissue N concentration was determined by micro Kjeldahl protocol of digestion, and titration (Bremner and Mulvane, 1982) to calculate aboveground total N uptake. The various parameters of nitrogen use efficiency below were evaluated according to Bandaogo et al. (2015). Physiological N use efficiency (PE) was calculated as grain yield divided by total N uptake. The apparent recovery efficiency of N (ARE) was estimated based on the increase in plant N uptake at maturity divided by the fertilizer N rate. Agronomic N use efficiency (AE) was calculated as the increase in grain yield per kg N applied. Partial factor productivity of applied N (PFP) was calculated as grain yield divided by total N applied.

Weather data were logged using a Vantage Pro2™ Weather Station (Davis Instruments, USA) throughout the year. Seasonal means and sums were reported over the growth duration from transplanting to physiological maturity.

2.4. Data analysis

Data analysis was carried out using the balanced analysis of variance (ANOVA) and the linear mixed model of STATISTICA 9.0 (StatSoft Inc., Tulsa, OK, USA) for a split-plot design with water as the main factor and nitrogen as the sub-factor. Mean comparison among treatments was based on the least significant difference (LSD) test at the 5% probability level.

3. Results

3.1. Weather

The rainfall during all the growth stages of the late season rice was 279.6 mm in 2014 and 295.4 mm in 2015. The rainfall from transplanting to PI accounted for more than 85% of total rainfall during the crop growth period in both years. Mean daily maximum temperature was higher in 2014 than that in 2015 (Table 1). Cumulative evaporation in 2014 was also higher than in 2015. Mean daily

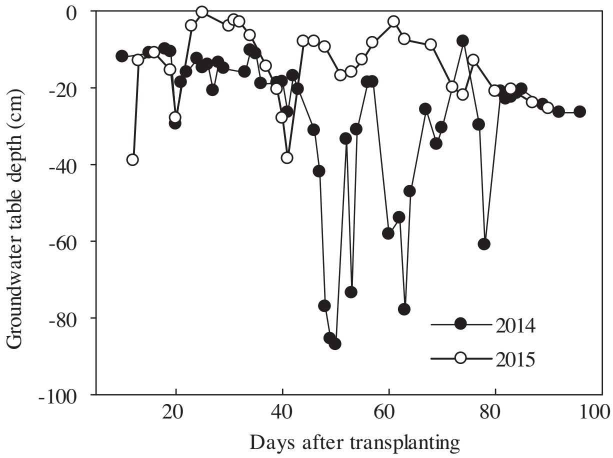

Fig. 1. Daily groundwater levels of experimental field at Guangzhou, Guangdong Province, China in 2014 and 2015.

sunshine from transplanting to harvest was 6.1–6.8 h in 2014, also higher than in 2015 (5.3–6.4 h).

3.2. Hydrological conditions and water level changes

In 2014, mean groundwater depth (before terminal drainage was imposed) was 48 cm below the ground surface, with fluctuations from 8 to 87 cm in the season (Fig. 1). The average groundwater in the 2015 experimental field, however, was shallow and the depth fluctuated from about 1 to 39 cm below the ground surface, with a seasonal mean depth of 20 cm (before terminal drainage was imposed).

We collected water depth data in all 24 subplots, but here only two subfigures of typical irrigation system under N2 (180 kg ha^{-1}) treatment were presented for each year (Fig. 2). The water depth of the FP plots dropped to −10 cm below the soil surface only at mid-season in both years (Fig. 2). In other periods, the water level was higher than that of AWD15. As expected, more irrigations were needed for FP (4 more irrigations than AWD15) in both years.

Soil water tension dynamics under different water treatments was significantly correlated with field water level dynamics. When groundwater level became deeper, soil water tension at 15 cm became higher (Fig. 3). In both years, soil water tension in the FP plots was higher than that of the AWD15 plots. The mean soil water tensions in 2014 were higher than those in 2015 because of more drying events in 2014.

3.3. Water consumption and productivity

Total water input was higher in 2014 than in 2015 (Table 2). Total water input across water treatments ranged from 326.8 to 430.8 mm in 2014 and from 54.3 to 189.2 mm in 2015. The irrigation water input and the total water input of FP were significantly higher than that of AWD15 each year.

In both years, there were neither significant W × N interactions nor significant effects of N, with respect to irrigation water input, total water input, and number of irrigations. Water treatments significantly affected all those parameters in both years (Table 2). Total rainfall from transplanting to maturity (279.6 mm in 2014 and 295.4 mm in 2015) represented approximately 43% and 73% of total water input during the same period in 2014 and 2015, respectively (Table 2). The irrigation water input in FP plots was 104 mm and 135 mm higher than in AWD15 plots in 2014 and 2015, respectively. On average, AWD15 saved 24% irrigation water in 2014 and 71% in 2015 compared with FP. In 2014, AWD15 received 5 fewer irrigations than FP from 10 DAT to maturity. Fewer irrigations were applied for both W treatments in 2015 due to more abundant rainfall for both FP and AWD15.

The total water productivity (WPT) in AWD15 plots was significantly higher than in FP plots in both years, being 15.6% and 40.9% higher in 2014 and 2015, respectively. WPT was also significantly affected by N across the two years. Higher WPT were observed in plots that received more N-fertilizer (N2 and N3). The difference in WPT was not significant between N2 and N3. There was no significant W × N interaction on WPT in both years of the experiment.

3.4. Crop growth and development

In general, LAI increased from the mid-tillering to heading stage (Table 4). In both years, there was no significant interaction between W and N treatments on LAI. The LAI at all measured growth stages was not significantly affected by W, but it was significantly affected by N. Across N treatments in both years, LAI tended to increase with N-fertilizer rate, and N3 was highest among the treatments at MT, PI and HD, although N3 was not significantly different with other nitrogen treatments at MT in 2015.

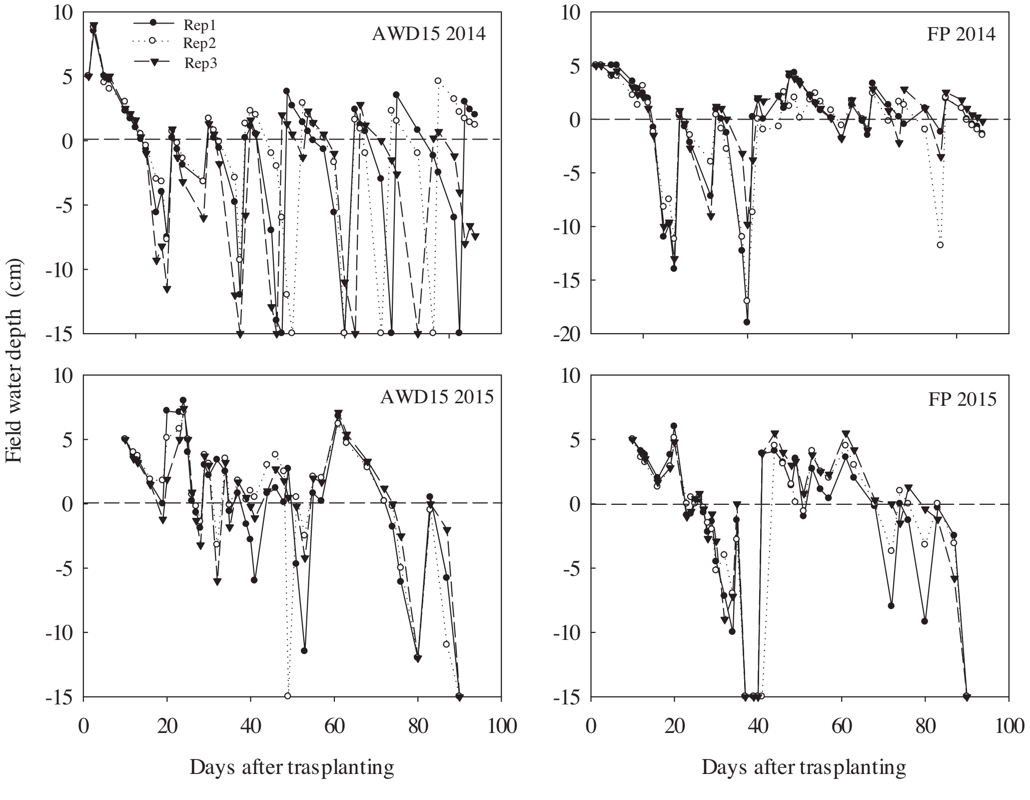

Fig. 2. Daily perched water level under different water treatments at Guangzhou, Guangdong Province, China in 2014 and 2015. Only data from N2 (180 kg N ha^{-1}) treatment are shown.

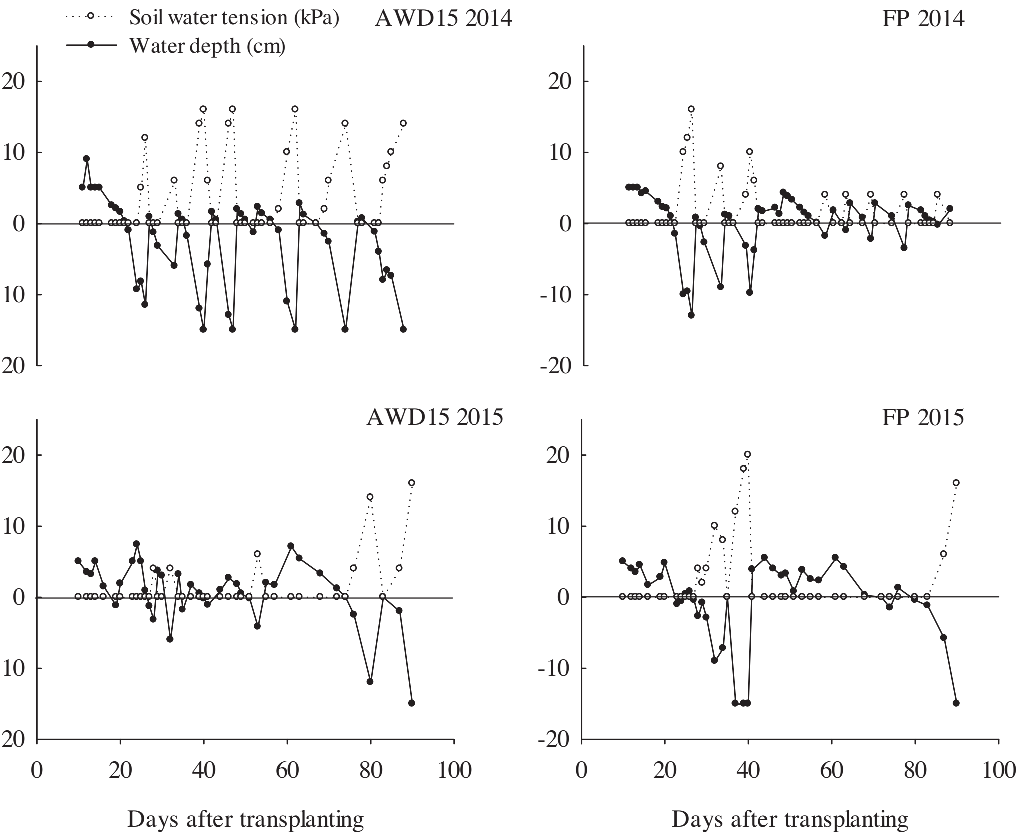

Fig. 3. Soil water tension at 15 cm depth and field water depth under different water treatments at Guangzhou, Guangdong Province, China in 2014 and 2015. Only data from replicate 3 of N2 treatment are shown.

Similarly, there were no significant W × N interactions for the crop growth rate (CGR). W treatments exerted no significant effect on CGR during MT-PI, PI-HD, and HD-MAT periods, but CGR was significantly affected by N in each year (Table 3). Across N treatments in both years, the trends of CGR values at different growth stages were consistent: N3 was highest among the treatments at MT-PI and PI-HD periods. During HD-MAT stage, N2 was highest, although the difference was not significant between N2 and N3. No significant interactions between W and N were found on the aboveground dry biomass (Table 4). Only N significantly affected

Table 2
Irrigation and total water input (irrigation plus rainfall) during the growing period under different water and nitrogen managements at Guangzhou, Guangdong Province, China in 2014 and 2015.

Year	Treatment	Irrigation water input (mm)	Total water input (mm)	No. of irrigations	WPT (kg m^{-3})
Water (W)					
2014	AWD15	326.8 b	606.3 b	5.7 b	1.18 a
	FP	430.8 a	710.4 a	10.5 a	1.02 b
2015	AWD15	54.3 b	349.7 b	1.8 b	1.90 a
	FP	189.2 a	484.6 a	5.7 a	1.35 b
Nitrogen (N)					
2014	N0	336.6 a	616.2 a	7.2 b	0.854c
	N1	384.4 a	664.0 a	8.3 ab	1.074b
	N2	366.7 a	646.2 a	8.0 ab	1.218 ab
	N3	427.5 a	707.2 a	8.8 a	1.253 a
2015	N0	105.8 b	401.2 b	3.5 b	1.275 c
	N1	122.3 ab	417.7 ab	3.7 ab	1.606 b
	N2	116.2 ab	411.6 ab	3.5 b	1.853 a
	N3	142.6 a	438.0 a	4.3 a	1.755 a
ANOVA					
2014	W	*	*	**	**
	N	ns	ns	ns	**
	W × N	ns	ns	ns	ns
2015	W	*	*	*	*
	N	ns	ns	ns	**
	W × N	ns	ns	ns	ns

Means in a column followed by the same letter are not significantly different ($P < 0.05$) for each year. ns means not significant ($P > 0.05$), * means significant ($P < 0.05$), ** means highly significant ($P < 0.01$).
N0 = zero N, N1 = 90 kg N ha^{-1}, N2 = 180 kg N ha^{-1} and N3 = 270 kg N ha^{-1}.

Table 3
Total aboveground dry weight at mid-tillering (MT), panicle initiation (PI), heading (HD) and physiological maturity (MAT) under different water and nitrogen treatments at Guangzhou, Guangdong Province, China in 2014 and 2015.

Year	Treatment	Total aboveground dry weight (Mg ha^{-1})			
		MT	PI	HD	MAT
Water (W)					
2014	AWD15	0.31 a	2.13 a	6.79 a	10883 a
	FP	0.33 a	2.01 a	6.90 a	10718 a
2015	AWD15	0.41 a	1.62 a	6.59 a	11201 a
	FP	0.45 a	1.68 a	6.58 a	10918 a
Nitrogen (N)					
2014	N0[a]	0.25 d	1.50 d	5.13 c	7.90 c
	N1	0.30 c	1.91 c	6.95 b	10.68 b
	N2	0.34 b	2.17 b	7.34 ab	12.20 a
	N3	0.40 a	2.71 a	7.97 a	12.41 a
2015	N0	0.39 a	1.37 c	4.9 d	8.32 c
	N1	0.43 a	1.60 bc	6.54 c	11.03 b
	N2	0.43 a	1.69 ab	7.02 b	12.26 a
	N3	0.47 a	1.93 a	7.85 a	12.62 a
ANOVA					
2014	W	ns	ns	ns	ns
	N	**	**	**	**
	W × N	ns	ns	ns	ns
2015	W	ns	ns	ns	ns
	N	ns	**	**	**
	W × N	ns	ns	ns	ns

ns = not significant ($P > 0.05$), * means significant ($P < 0.05$), ** means highly significant ($P < 0.01$).

[a] N0 = zero N, N1 = 90 kg N ha^{-1}, N2 = 180 kg N ha^{-1} and N3 = 270 kg N ha^{-1}.

the above ground biomass, which increased with higher nitrogen application. There were no insignificant differences between FP and AWD15 in aboveground dry biomass at all measured growth stages.

3.5. Grain yield and yield components

In both years, there were neither significant W × N interactions nor significant effect of W on grain yield and yield components. N significantly affected grain yield, panicle number, spikelets per panicle, and filled spikelets in both years. However, 1000-grain weight was only significantly affected by N in 2015 (Table 5). Grain yield was highest with N3 (although not significantly different from N2) in both years, and lowest with N0 in both years. The number of filled spikelets was generally increased by the N application rate, with lowest values in N0 in both years. There was a significant difference between N1 and N3 in 2014, while in 2015, there were no significant difference among N1, N2 and N3. W had no significant effect on any yield components.

Table 4
Leaf area index and crop growth rate of rice at different growth stages under different water and nitrogen treatments at Guangzhou, Guangdong Province, China in 2014 and 2015.

Year	Treatment	Leaf area index			Crop growth rate (g m^{-2} d^{-1})		
		MT[a]	PI	HD	MT-PI[c]	PI-HD	HD-MAT
Water (W)							
2014	AWD15	0.408 a	1.708 a	3.433 a	9.56 a	24.575 a	10.767 a
	FP	0.442 a	1.700 a	3.608 a	8.85 a	25.742 a	10.042 a
2015	AWD15	0.458 a	1.725 a	3.72 a	8.60 a	21.62 a	10.99 a
	FP	0.475 a	1.742 a	3.57 a	8.82 a	21.33 a	10.31 a
Nitrogen (N)							
2014	N0[b]	0.317 c	0.983 d	1.767 d	6.567 d	19.13 b	7.317 c
	N1	0.400 b	1.483 c	2.950 c	8.483 c	26.53 a	9.817 b
	N2	0.467 a	1.933 b	4.050 b	9.60 b	27.25 a	12.783 ab
	N3	0.517 a	2.417 a	5.317 a	12.17 a	27.72 a	11.70 a
2015	N0	0.450 a	1.25 c	1.88 d	7.00 c	15.50 c	8.07 b
	N1	0.433 a	1.65 b	3.22 c	8.40bc	21.48 b	10.68 ab
	N2	0.467 a	1.83 b	4.23 b	9.00 ab	23.17 b	12.48 a
	N3	0.517 a	2.20 a	5.23 a	10.43 a	25.73 a	11.37 a
ANOVA							
2014	W	ns	ns	ns	ns	ns	ns
	N	**	**	**	**	**	**
	W × N	ns	ns	ns	ns	ns	ns
2015	W	ns	ns	ns	ns	ns	ns
	N	ns	**	**	**	**	*
	W × N	ns	ns	ns	ns	ns	ns

ns = not significant ($P > 0.05$), * means significant ($P < 0.05$), ** means highly significant ($P < 0.01$).

[a] MT: Mid-tillering, PI: panicle initiation, HD: heading, MAT: physiological maturity.

[b] N0 = zero N, N1 = 90 kg N ha^{-1}, N2 = 180 kg N ha^{-1} and N3 = 270 kg N ha^{-1}.

[c] MT-PI: Mid-tillering to panicle initiation, PI-HD: panicle initiation to heading, HD-MAT: heading to physiological maturity.

Table 5
Yield components and harvest index under different water and nitrogen treatments at Guangzhou, Guangdong Province, China in 2014 and 2015.

Year	Treatment	Panicles ($\times 10^4$ ha^{-1})	Spikelets (no. panicle^{-1})	Filled spikelets (%)	1000-grain weight (g)	Grain yield (Mg ha^{-1})
Water (W)						
2014	AWD15	220.5 a	171.2 a	86.8 a	24.28 a	7.14 a
	FP	230.3 a	164.7 a	85.2 a	24.15 a	7.13 a
2015	AWD15	231.0 a	170.2 a	83.6 a	24.16 a	6.64 a
	FP	241.0 a	169.0 a	79.7 a	23.73 a	6.51 a
Nitrogen (N)						
2014	N0	170.2c	145.7b	92.8 a	24.48 a	5.20 c
	N1	209.8b	178.2 a	86.4b	24.27 ab	7.08 b
	N2	257.7 a	172.0 a	83.3 bc	24.25 ab	8.03a
	N3	263.9 a	175.7 a	81.5 c	23.86 b	8.24 a
2015	N0	189.3 c	149.3 c	85.9 a	23.95 ab	4.96 c
	N1	237.6 b	169.2 b	81.5 b	24.32a	6.52 b
	N2	254.2ab	178.6 a	80.2 b	23.84 b	7.41 a
	N3	262.9 a	181.4 a	79.2 b	23.68 b	7.42 a
ANOVA						
2014	W	ns	ns	ns	ns	ns
	N	**	**	**	ns	**
	W × N	ns	ns	ns	ns	ns
2015	W	ns	ns	ns	ns	ns
	N	**	**	**	*	**
	W × N	ns	ns	ns	ns	ns

ns = not significant ($P > 0.05$), * means significant ($P < 0.05$), ** means highly significant ($P < 0.01$).
N0 = zero N, N1 = 90 kg N ha^{-1}, N2 = 180 kg N ha^{-1} and N3 = 270 kg N ha^{-1}.

Table 6
Total N uptake, physiological N use efficiency (PE), agronomic N use efficiency (AE), apparent recovery efficiency of N (ARE), and partial factor productivity of applied N (PFP) under different water and nitrogen treatments at Guangzhou, Guangdong Province, China in 2014 and 2015.

Year	Treatment	Total N uptake (kg ha^{-1})	PE (kg kg^{-1})	ARE (%)	AE (kg kg^{-1})	PFP (kg kg^{-1})
Water (W)						
2014	AWD15	107.0 a	50.1 a	32.3 a	15.8 a	51.3 a
	FP	108.5 a	50.1 a	31.7 a	16.1 a	51.2 a
2015	AWD15	120.5 a	34.5 a	35.9 b	12.3 a	47.4 a
	FP	118.3 a	32.4 a	44.9 a	14.4 a	46.6 a
Nitrogen (N)						
2014	N0	65.0 d	–	–	–	–
	N1	93.2 c	66.8 a	31.3 ab	20.9 a	78.6 a
	N2	128.2 b	44.9 b	35.1 a	15.7 ab	44.6 b
	N3	144.7 a	38.6 b	29.5 b	11.3 b	30.5 c
2015	N0	67.0 d	–	–	–	–
	N1	107.2 c	40.8 a	44.6 a	17.3 a	72.5 a
	N2	142.2 b	33.2 ab	41.8 a	13.6 b	41.2 b
	N3	161.1 a	26.4 b	34.9 a	9.1 c	27.5 c
ANOVA						
2014	W	ns	ns	ns	ns	ns
	N	**	*	ns	*	**
	W × N	ns	ns	ns	ns	ns
2015	W	ns	ns	**	ns	ns
	N	**	ns	ns	**	**
	W × N	ns	ns	ns	ns	ns

ns = not significant ($P > 0.05$), * means significant ($P < 0.05$), ** means highly significant ($P < 0.01$).
N0 = zero N, N1 = 90 kg N ha^{-1}, N2 = 180 kg N ha^{-1} and N3 = 270 kg N ha^{-1}.

3.6. N-use efficiency

In both years, total N uptake increased significantly with increased N-fertilizer rates. In general, physiological N use efficiency (PE), apparent recovery efficiency of N (ARE), agronomic N use efficiency (AE), and partial factor productivity of applied N (PFP) decreased in both years as the rate of N application increased, but the significance of the difference was inconsistent between different treatments. No significant differences were observed between AWD15 and FP in both years in all other parameters for in total N uptake, and N use efficiencies (PE, ARE, AE, and PFP), except for ARE in 2015 which was significantly lower in AWD15 than in FP (Table 6). There was no significant interaction effect between W and N on the total N uptake and other parameters of N use efficiencies over the two years of study (Table 6).

4. Discussion

The hydrological conditions of our experimental site are representative for many large-scale irrigated lowland rice areas in South China. The groundwater table of this area is comparable to that of other places in Hubei, Zhejiang and Guangdong provinces where relevant experiments were previously conducted (Cabangon et al., 2004; Yao et al., 2012; Liang et al., 2016). In addition, the sum and distribution of rainfall during the rice growing seasons in 2014 and 2015 are similar to those in the past 24 years in Guangzhou (data not shown). So conclusions about water and N-fertilizer management drawn from this study are applicable for rice production in South China.

Across the two years, grain yield in 2014 was higher than in 2015 by about 0.560 Mg ha^{-1} probably due to the longer sunshine duration in 2014. Rice performs better when grown under longer sunshine duration and thus more solar radiation (Zhao and Li, 1993; Lampayan et al., 2015a). Across the two water treatments, the grain yield of AWD15 is comparable to that of FP in the late cropping season in South China. Even for super rice hybrid variety Tianyou3618, which consumes more water for high grain yield, AWD15 is still a better choice to save water and maintain high yield. Similar results of grain yield under AWD have been reported previously (Cabangon et al., 2004; Yao et al., 2012; Liang et al., 2016). The stability of yield under AWD15 may be attributed to adequate water supply even if the water table of field falls to −15 cm below the soil surface. At a threshold of 15 cm in water depth below the soil surface, the soil water potential is more than −20 kPa, and the lower parts of the rice roots (generally extending 15–20 cm deep) will still be able to take up enough water from the saturated soil and the perched water in the root zone (Bouman et al., 2007b; Lampayan et al., 2015a; Carrijo et al., 2017). Our previous study similarly showed that the soil water potential (−20 kPa) during the rice-growing season was usually not a limitation factor for plant growth and yield formation when AWD15 was practiced (Liang et al., 2016).

Positive results with increase in grain yield under AWD15 (compared with CF) also was reported, which was associated with an increase in panicle number, more spikelets per panicle or higher grain weights (Yang et al., 2007; Wang et al., 2015; Carrijo et al., 2017). These findings contrast with a survey on the application of AWD in Southeast Asian countries conducted by Bouman and Tuong (2001). They reported that AWD displayed yield reduction ranging from 0 to 70% in most experiments if compared with continuously flooded controls. The large variability in the performance of AWD was attributed to differences in the irrigation interval, monitoring tools and standards across the experiments. The use of the generic term “AWD” has led to the confusion that AWD reduced yields, and therefore Bouman et al. (2007a) suggested to emphasize the terminology of “safe” AWD. Therefore, precaution should be taken by properly defining the AWD being practiced. Also, other factors such as hydrological conditions, and weather should be considered carefully. In particular, strict regulations, such as maintaining the threshold of water depth, must be carried out to guarantee its safe use. Besides the on-station experiments for two years, our on-farm experiments in several areas in Guangdong province also demonstrated the effectiveness of AWD15 in saving water and maintaining grain yield (Liang et al., 2016). Although the experiments were conducted in the late cropping season in both years, it can be postulated that comparable or even better results could be obtained in the early cropping season because of more rainfall, more humid weather and higher groundwater table in the early season. As shown in this study, the AWD15 further saved irrigation water by about 20% and enhanced water input productivity by about 30% in comparison with FP. Up to now, all evidence we accumulated confirms that AWD15 is a safe irrigation regime and is appropriate for wide adoption in the rice-planting areas in South China.

In both years there were neither significant W × N interaction nor significant effects of W, with respect to grain yield, leaf area index, crop growth rate, and biomass, implying that the growth and grain yield of rice plants is not impeded by water stress under AWD15.

Application of N significantly increased both irrigation water input and water productivity in comparison with N0 (Table 2). Plant growth and photosynthetic ability have been repeatedly demonstrated to increase with N supply. The increased irrigation water input under higher N rate was caused by increased water absorption, and the increased water productivity was due to much higher grain yield under N application condition in rice (Ren et al., 2015).

In both years, the highest yield was obtained when nitrogen fertilizer application was 180 kg N ha^{-1}. We did not find significant W × N interaction on total N uptake at maturity (Table 6), which is in line with previous studies (Yang et al., 2008; Yao et al., 2012). At the zero N level (N0), AWD15, on average, increased plant N accumulation from heading to maturity in 2014 and 2015 by 11% and 64%, respectively (data not shown). We also found that the leaves turned green unexpectedly again during late ripening stage under this condition. This can explain that ARE (apparent recovery efficiency of N) was significantly lower under AWD15 in 2015 (Table 6). This phenomenon was not observed under other treatments. One possible reason may be that the elongation of roots of rice plants and the absorption of nitrogen from soil can be promoted under low nitrogen and water saving conditions (Chu et al., 2014; Sun et al., 2014). This merits further investigation.

Sun et al. (2012) found that there was significant interaction effect between different irrigation modes and N application strategies on grain yield and NUE of rice, but the grain yield and NUE were higher under intermitted irrigation (like AWD15) than under other water treatments. They also suggest that the combination of water alternation mode with application of panicle N fertilizer should be widely adopted in China to solve the problems of water shortage and low NUE in China (Sun et al., 2012). Recently, panicle N fertilization was recommended for rice production in China to increase grain yield and improve NUE in the field (Sun et al., 2012; Zhong et al., 2007). High proportion of panicle N fertilizer was adopted in this experiment. Under such N management strategy, the grain yield was not affected by irrigation mode, indicating the AWD15 water-saving technology can be safely used without changing existing fertilizer management recommendations in South China.

The tool used in AWD15 is the perforated field water tube. It is simple and practical and it can be fabricated with cheap materials such as polyvinyl chloride (PVC) pipe, bamboo, plastic water bottles, or even tin cans (Lampayan et al., 2015b). In addition to its convenience, AWD15 technology can be widely used in irrigated lowland soil types, such as clay (Cabangon et al., 2011), loam (Cabangon et al., 2003), soil clay (Lampayan et al., 2015a), silty clay/clay loam (Cabangon et al., 2004). In Guangdong province almost 90% of irrigated rice land belongs to the above soil types (Lin et al., 2005), and therefore, are suitable for AWD15 practices. In rice production, irrigation water input and the labor cost can be reduced by applying AWD15 technology. In 2014, the annual planting area of rice in the South China region (Guangdong, Guangxi, Fujian, and Hainan province) amounts to 5.04 Mha, accounting for 17% of the total planting area of China, and the total water consumption of rice is about 2343 × 10^{8} m^{3} in this region (Yao et al., 2014; National Bureau of Statistics of China, 2015). If AWD15 can be widely adopted in this region, as much as 1.12 × 10^{11} m^{3} (nearly half of water input) irrigation water could be saved annually. A 10% reduction in water used in irrigated rice would free up to 150,000 million m^{3}, corresponding to about 25% of the total fresh water used globally for non-agriculture purposes (Klemm, 1999). In Asia, lowland rice is grown on more than 30% of the irrigated land and accounts for 50% of irrigation water (Barker et al., 1999). Freeing a small portion of water from rice areas can have large social and environmental effects if this conserved water is used for urban, industrial, or environmental purposes.

In rice production of China, continuous flooding irrigation (CF) had once been widely used by rice farmers until 1980s. It was gradually replaced by the present farmer's practice (FP), which keeps continuous standing water before heading except 15–20 days of mid-season drainage for controlling unwanted tillers (Zou et al., 2009). After heading, irrigation is applied when water disappears from the soil surface. Up to now, midseason drainage practice is still dominant in the lowland irrigated rice production in China. Compared with CF, FP water management practice can reduce irrigation water input and increase water use efficiency (Zou et al., 2009;

Liang et al., 2016). When AWD15 is practiced, continuous standing water will not be observed in the field except for the first 10 days after transplanting and during the flowering stage. The field will alternately experience flooding and drying conditions. For FP, the timing of reflooding is judged with experiences. For AWD15, reflooding begins when water depth (monitored accurately by water table tubes) reaches threshold value of −15 cm. As standing water exists for shorter periods in the field, water loss from runoff or evaporation can be reduced under AWD15 regime. The advantage of AWD15 over CF in water saving has been documented by many researchers (Carrijo et al., 2017). However, a direct comparison between AWD15 and FP is more meaningful. Only if AWD15 is better than FP, rather than CF, will farmers be willing to adopt this new technology. In our previous study, we found the superiority of AWD15 over FP under a single N input level (Liang et al., 2016). This study demonstrated that AWD15 is advantageous over FP in a range of N levels. As a third generation of watering technology after CF and FP, AWD15 is expected to be widely applied in the rice production in China for saving water and protecting environment.

5. Conclusions

Even compared to farmer's water management practice with mid-season drainage (FP), AWD15 can still save 24%–71% of irrigation water and reduce 4–5 irrigation applications without yield loss under different N levels. No significant interaction effect between W and N application rates was found on grain yield and NUEs in both years. The optimal nitrogen rate was 180 kg N ha^{-1} under both water management regimes. The current recommended nitrogen rate under the conventional water management is applicable under AWD15 irrigation practice and AWD15 can replace FP to further increase water use efficiency in South China.

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