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Mitigation of environmental N pollution and greenhouse gas emission from double rice cropping system with a new alternate wetting and drying irrigation regime coupled with optimized N fertilization in South China

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ABSTRACT

Reducing greenhouse gas (GHG) emission and nitrogen (N) pollution are essential for sustainable crop production. An alternate wetting and drying irrigation management ('safe' AWD) was invented and implemented to reduce water input and GHG emission in many Asian countries. The 'safe' AWD allows the soil to dry and re-irrigated when water level reaches 15 cm below soil surface and is called 'safe' as it will not cause yield decline in most cases. To further improve water productivity (WPT) and reduce GHG emission and N pollution, a modified AWD irrigation (MAWD) was developed in current study. Field experiment was carried out to evaluate the GHG emission and N losses under different irrigation and N management during 2017–2020. The treatments were: (i) zero N application with farmers' irrigation practice, (ii) farmers' N fertilization and irrigation practice (FP), (iii) farmer's irrigation practice with optimized N fertilization (OPTN), (iv) 'safe' AWD with optimized N fertilization (OPTN+AWD), and (v) MAWD with optimized N fertilization (OPTN+MAWD). Compared with FP, grain yield in OPTN, OPTN+AWD and OPTN+MAWD was increased by 12.1%, 13.6% and 14.4%, respectively. The OPTN, OPTN+AWD and OPTN+MAWD were comparable in plant N accumulation and grain yield, suggesting that irrigation did not have detectable effects on yield. Water input in OPTN+MAWD was 3.68–26.0% lower than OPTN+AWD. N losses loading was positively correlated with water input. Relative to OPTN, OPTN+AWD and OPTN+MAWD reduced N loss through leaching and surface runoff due to lower water input and enhanced rainwater storage capacity. N losses loading in OPTN+MAWD was 20.5% lower than OPTN. Greenhouse gas intensity and net GWP were lowest in OPTN+MAWD. CH_4 emission in OPTN+MAWD was 16.2% lower than OPTN+AWD. MAWD irrigation increased the N_2O emission, but the net GWP was 13.9% lower than OPTN+AWD due to reduced CH_4 emission. Our results suggested that integrating MAWD with optimized N fertilization could synergistically improve grain yield and reduced GWP and N pollution in rice production of South China.

1. Introduction

Rice (*Oryza sativa* L.) is an essential cereal crop consumed by about half of the world's population. With the global population ever increasing, rice production is likely to be increased by as much as 25% by 2025 (Fahad et al., 2018). Water resources has become a limiting factor in rice production. For more than a decade, over 61% of freshwater in China was utilized by agriculture (exceeding 360 billion m^3 in each year) and around 70% of the irrigation water is utilized for rice cultivation (National Bureau of Statistics, 2022). With the increasing population and non-agricultural water consumption, freshwater resource is increasingly scarce in rice production. It is necessary to produce more grains with less irrigation to meet the escalating food demand. N fertilizer is another important factor in rice production. More than 3.0×10^{10} kg N fertilizer was used on China's cropland in each year (FAO, 2019). Meanwhile, seasonal fertilizer N input for rice growth was generally higher than 190 kg N ha^{-1}. The average N recovery was lower than the global average level (Zhong et al., 2010; Deng et al., 2014).

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Excessive water and N fertilizer input has resulted in greenhouse gas emission (GHG) and non-point N pollution. Environmental N losses loading in rice production was estimated to be about 2.6×10^9 kg per year during 2011–2015 (Huang et al., 2020). Rice is a non-negligible source of CH_4, accounting for about 11% of global CH_4 emission associated with the anthropogenic activity (Runkle et al., 2019). The emissions of CH_4 and N_2O from rice fields were estimated to be 4.80–11.40 Tg CH_4 yr^{-1} and 31.1 Gg N_2O-N yr^{-1}, respectively, in China (Wang et al., 2021; Yue et al., 2018). To minimize non-point source pollution and GHG emission, China seeks to achieve zero growth in chemical fertilizers use by 2020 and to achieve carbon peaking by 2030 and carbon neutrality by 2060. Varieties of efforts have been devoted to enhance the fertilizer N and irrigation water use efficiency in China during the past two decades. Several optimized N fertilization practices such as the balanced N fertilization, the precise and quantitative N application and the site-specific N management, etc., have been proven to increase NUE and reduce fertilizer N input in cropping systems effectively (Zhong et al., 2010; Liu et al., 2013; Ling et al., 2005). In South China, the 'three controls' technology with reduced total N input and increased panicle N application was developed and officially introduced to rice producers as optimized N management practice by the Ministry of Agriculture and Rural Affairs of China (OPTN) (http://dara.gd.gov.cn/sztjs/content/post_3554120.html).

Various water-saving technologies have been managed in rice paddy fields, including 'ditch irrigation', controlled irrigation, intermittent irrigation and 'safe' alternative wetting and drying irrigation (Deng et al., 2020; Wei et al., 2022; Peng et al., 2011; Wang et al., 2020; Cheng et al., 2022). The 'safe' alternative wetting and drying technology ('safe' AWD) is an easy-to-follow and low-cost irrigation technology recently developed by the International Rice Research Institute. It was widely used in many Asian countries and performed well for reducing irrigation water without yield penalty (Bouman et al., 2007; Lampayan et al., 2015; Ishfaq et al., 2020; Feng et al., 2021; Leon et al., 2022).

To reduce the environmental N losses and the emissions of GHG from rice paddies, the 'safe' AWD irrigation was introduced into South China. Previous studies demonstrated that the 'safe' AWD irrigation effectively reduced irrigation water input and GHG emission in double rice cropping system at South China (Liang et al., 2017). Mid-season drainage was a typical practice at South China. In this practice, about 2 weeks' drainage was imposed at the late tillering stage. The mid-season drainage was effective in suppressing unproductive tillers and promoting root activity and root growth through increasing soil oxygen supply. Moreover, mid-season drainage substantially reduced CH_4 emission relative to permanent flooding (Zou et al., 2005; Itoh et al., 2011; Liang et al., 2016). Based on the beneficial characteristics of the mid-season drainage irrigation, a modified AWD irrigation technology (MAWD) was developed in current study. In this regime, the mid-season drainage was integrated into the 'safe' AWD irrigation. Furthermore, optimized N management was integrated with the MAWD to reduce the environmental footprints in double rice cropping system. To systematically assess the grain yield, water productivity, GHG emissions and environmental N losses and under different agronomic practices, a six-season field experiment was conducted in this study. We aim to: (i) identify if the integration of mid-season drainage and mild AWD regime (MAWD) further improve water productivity while maintaining yield in comparison to the 'safe' AWD; (ii) evaluate the performance of optimized N and MAWD irrigation in yield, water and N use efficiency, GHG emission and environmental N loss in rice field; (iii) explore the underlying mechanisms of these agronomic practices in influencing the environmental footprints in double rice cropping system.

2. Methods and materials

2.1. Site description

Field experiment was carried out during 2017–2020 at Dafeng Experimental Station for Guangdong Academy of Agricultural Sciences (113°20'E, 23°08'N) in Guangzhou, China. The field site has a subtropical continental monsoon climate with rainy summers and dry winters. The meteorological data during the experiment years from 2017 to 2020 were obtained from the weather bureau of Guangzhou. Monthly trends of rainfall and air temperature are shown in Fig. 1. The annual air temperature during the cropping season from 2017 to 2020 averaged 22.6 ℃. The annual rainfall averaged 2008.7 mm, of which 60.9% occurred in April to July. Paddy soil is classified as clay loam soil in the field site. The bulk density of the soils was 1.29 g cm^{-3} and the average field water capacity of the soils was 31.6%. Soil properties of 0–20 cm depth are: pH 6.0, organic matter 41.3 g kg^{-1}, total nitrogen (N) 1.62 g kg^{-1}, available N 82.6 mg kg^{-1}, total phosphate (P) 1.06 g kg^{-1}, available P 40.4 mg kg^{-1}, total potassium (K) 16.0 g kg^{-1}, and available K 58.7 mg kg^{-1}.

2.2. Experimental design and water and N management

Field experiment was conducted using randomized complete block design in three replications. The treatments were: (1) zero N application (N0), practice of farmers' water management (mid-season drainage) was used and no N fertilizer was applied; (2) farmers' N fertilization with farmers' water management (FP); (3) optimized N fertilization with mid-season drainage (OPTN); (4) optimized N fertilization with 'safe' AWD irrigation management (OPTN+AWD); (5) optimized N fertilization with MAWD irrigation management (OPTN+MAWD). Each plot was 15.1 m^2 in area. Plots were separated from each other by double bands of 30 cm width and covered by plastic film secured at 30 cm in the soil. Hybrid rice variety Tianyou3618 was used in 2017 and 2018. Inbred rice variety Huanghuazhan was used in 2019 and 2020. The two varieties are high-yielding cultivars and widely used in Guangdong province. The agronomic management in different treatments was shown in the supplementary Table S1.

In plots of FP, N rate was 180 kg N ha^{-1} at the early cropping season and 210 kg N ha^{-1} at the late cropping season. N fertilizer (urea, 46% N) was applied with 40% as basal fertilizer, 20% as seedling recovering fertilizer at 3–5 days after transplanting (DAT), 30% at the stage of early tillering (8–10 DAT) and 10% at the stage of late tillering (20–25 DAT) for promoting tillering. For all treatments, phosphorus and potassium were applied as basal fertilizer at the rate of 45 kg P_2O_5 ha^{-1} and 135 kg K_2O ha^{-1}, respectively. Optimized N management was applied in OPTN, OPTN+AWD and OPTN+MAWD. In the early season, the fertilizer N rate was 150 kg N ha^{-1}, with 50% as basal, 20% at mid-tillering stage (MT) and 30% at panicle initiation stage (PI). In the late season, the fertilizer N rate was 180 kg N ha^{-1}, with 40% as basal, 20% at the stage of MT, 30% at the stage of PI and 10% at the stage of heading (HD) (Except for late season in 2018, when N was applied at the rate of 160 kg N ha^{-1}, with 40% as basal and 60% at the stage of PI).

To record the field water level under the ground in each plot, a

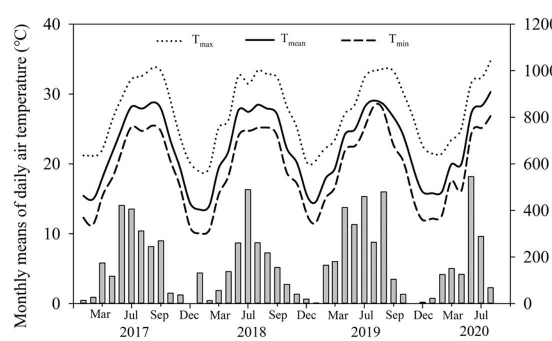

Fig. 1. Monthly means of daily maximum temperature (T_{max}), mean temperature (T_{mean}), minimum temperature (T_{min}) and rainfall in the field experiments during 2017-2020 in Guangzhou, Guangdong province, South China.

perforated tube was installed to a depth of 15 cm below ground. The soil inside of the tube was removed. Filed water depth of each plot was recorded daily. Field water management under different irrigation regimes was shown in the supplementary Fig. S1. In farmers' irrigation practice, the water layer maintained at 2–5 cm after the transplantation. When rice tiller number reaches 80% of the projected final panicle number, mid-season drainage was imposed. Field was re-flooded when the 2nd top leaf appeared. During the heading stage, water layer was kept at 2–5 cm in order to prevent the sterility of spikelet. After heading, field water layer was irrigated to a depth of 2–3 cm above soil surface when the visible water layer disappeared. Terminal drainage was done one week before harvest. In the AWD irrigation regime, water layer kept at a depth of 2–5 cm at the first 10 DAT for recovering of the seedlings. Then field was allowed to dry and timing and amount of irrigation depended on the water level in the tube. When the ponded water disappeared in the bottom (15 cm under the surface of soil), field water layer was irrigated to 5 cm depth. At beginning of heading, field was re-flooded for one-week to prevent spikelet sterility and hereafter AWD cycles repeated. In the MAWD irrigation regime, field was flooded at the first 10 DAT and hereafter AWD cycles commenced. The field soil was allowed to dry and irrigation was applied when water layer reach the threshold at 15 cm under soil surface. A mid-season drainage was imposed when the number of tiller reaches 80% of the projected final number of panicle. When the 2nd top leaf appear, field was re-flooded and AWD cycle repeated. At the beginning of heading, field was flooded for a week. Hereafter AWD cycle was repeated until the final drainage.

2.3. Measurement of yield, yield components, crop N uptake and nitrogen use efficiency

Grain yield was measured taking 5 m^2 plant samples at maturity (excluding the border plants) from each plot. Grain yield was adjusted to a standard moisture content of a 0.14 kg H_2O kg^{-1} fresh grain weight. Twelve hills of rice plants adjacent to the harvest area were sampled in each plot to determine yield components (percent of filled spikelets, density of panicle, thousand grain weight, and the number of spikelets per panicle).

Twelve rice plants were randomly selected to determine the biomass and the N uptake at the stage of MT, PI, HD and maturity (MA) from each plot. The growth rate of crop (CGR) was determined as CGR = (W_2-W_1) / (T_2-T_1), W_1 and W_2 are the aboveground dry weight at times of T_1 and T_2. The N content of the crop tissue was measured by the method of Kjeldahl digestion and distillation (Bremner and Mulvaney, 1982). The difference of the total aboveground plant N between sampling times of T_1 and T_2 was used to evaluated the N uptake rates for a specific interval (Peng and Cassman, 1998). The various indicators of N use efficiency were calculated as follows: Internal use efficiency of applied N (IE_N, kg kg^{-1}) = yield/total crop N uptake. Apparent recovery efficiency of applied N (ARE, kg kg^{-1}) = (N uptake of fertilized plot - N uptake of unfertilized plot)/applied N rate × 100. Agronomic use efficiency of applied N (AE, kg kg^{-1}) = (yield in fertilized plot - unfertilized plot)/applied N rate. Partial factor productivity of applied N (PFP_N) = yield/N rate.

2.4. Measurement of crop water productivity

Plots were irrigated by underground water from a reservoir. Irrigation water input of each plot was recorded by a flow meter. The precipitation data in field was recorded from a rain gauge (HOBO Event, Onset Computer, Massachusetts, USA). The water productivity of crop (WPT) was evaluated by dividing the yield by the total water consumption.

2.5. Measurement of environmental N losses through runoff, leaching, and ammonia volatilization

Water samples of surface runoff were taken during each event of runoff loss. A plastic bucket of 20 L was set beside the plots in order to collect the samples from runoff water via pipes system (Xue et al., 2014). Other runoff water entered the drainage ditch via a runoff collection pipe set at the water outlet of the plot. The height of the drainage outlet in local farmer's field was generally set at 3–5 cm, so the hole of the water inlet of the runoff collection pipe was set at 5 cm above soil surface. While the hole of the water outlet of the pipe was set at 20 cm below the soil surface. Runoff water discharged into the drainage ditch through water outlet of the pipe automatically due to the gravity caused by the height difference. A flow meter was equipped at the water outlet of the pipe at the lower end to measure the volume of runoff water. Total N content (TN) in water sample was measured by the method of alkaline potassium persulfate oxidation-ultra spectrophotometry. The runoff N loss was determined by multiplying the TN of water sample by the runoff volume recorded by the collection bucket and flow meter.

N loss via leaching and ammonia volatilization (AV) were evaluated at 1, 3, 5, 7 and 11 d after each N application and then at one-week interval. N leaching sample of percolation water was collected by a lysimeter made of porous PVC pipe with length and inner diameter of 70 cm and 16 cm, respectively. The lysimeter is sealed in the bottom. The lower end of the lysimeter has 200 pores to allow the infiltration of leaching water. To avoid the sediment flowing into the pipe, each lysimeter was surrounded with nylon net and quartz sand (Li et al., 2008; Ye et al., 2015). The lysimeter was inserted into soil at 50 cm depth. Before sampling, the leaching water was pumped out from the lysimeter and the leaching water volume was recorded. The soil volume contributing leaching water to lysimeter was determined by the method described by Li et al. (2008). Leaching volume per soil volume was extrapolated to calculate the leaching volume per hectare. N leaching loss was determined by multiplying the TN of water sample by the leaching volume.

N loss from AV was measured by the static chamber method (Xue et al., 2014; Liang et al., 2017). Sample was collected by sponge soaked in phosphoglycerol to absorb ammonia in an ammonia-trapping chamber. The chamber was made by transparent PVC pipe with length of 25 cm diameter of 20 cm. Samples collected by the sponge were extracted by KCl solution (1.0 mol L^{-1}) of 300 mL. The TN of the samples was measured by the method of distillation and titration. AV flux was determined by the calculation below:

$$\text{AV rate (kg N ha}^{-1}\text{ d}^{-1}) = [M / (A \times D)] \times 10^{-2}, \quad (1)$$

where M stands for the AV amount (in mg) collected, A stands for the area of the cross-sectional of the chamber (m^2), and D stands for the time interval (d).

2.6. Calculation of N surplus and N balance

N surplus was defined as the difference between the total N inputs to the cropping system and the harvested N output of crop (Oenema et al., 2003; Ju et al., 2017):

$$\text{N surplus} = \text{total N inputs (fertilizer + seed + irrigation + rainfall + deposition + non-symbiotic N fixation) - crop N output} \quad (2)$$

N balance was expressed by subtracting the N output from the N input (Li et al., 2013; Grzebisz et al., 2018; Lee et al., 2020; Nguyen et al., 2020):

$$\text{N balance} = \text{total N inputs (fertilizer + seed + irrigation + rainfall + deposition + non-symbiotic N fixation) - total N outputs (crop N output + runoff + AV + leaching)} \cdot \quad (3)$$

N input from irrigation was the product of the irrigation water amount and the TN concentration in the water. Atmospheric N deposition was estimated as 34 kg N ha^{-1} y^{-1} (Xu et al., 2015a). N input of non-symbiotic N fixation was estimated as 32 kg N ha^{-1} $year^{-1}$ (Lu et al., 1998; Herridge et al., 2008; Liao et al., 2013). N input from rice seeds was estimated as 1.8 kg N ha^{-1} in each season (Hong et al., 2018). Crop N output included the grains and straws.

2.7. CH_4 and N_2O emission measurement

The emissions of CH_4 and N_2O were measured by the method of static opaque chamber at 7-d intervals. Samples were corrected between 9:00 am to 11:00 am. Chamber was 60 cm in width. The chamber's height was 60 cm until PI stage and was adjusted to 120 cm thereafter to accommodate the plant height. Samples were withdrawn into a vacuumed tub. The contents of CH_4 and N_2O was analyzed on an Agilent 7890 A gas chromatograph (Agilent Technologies, USA). The emission flux of CH_4 or N_2O was calculated by the calculation below (Zheng et al., 1998):

$$F=\rho\times h\times[273/(273+T)]\times dC/dt, \quad (4)$$

where F stands for the gas flux of CH_4 (mg m^{-2} h^{-1}) or N_2O (μg m^{-2} h^{-1}), ρ stands for the density of CH_4 (0.71 kg m^{-3}) or N_2O (1.964 kg m^{-3}) at standard state, h stands for the height of chamber above the soil. T stands for the air temperature (°C) in the chamber. C stands for the concentration of gas mixing-ratio (mg m^{-3}), dC/dt stands for the concentration change of CH_4 (mg m^{-3} h^{-1}) or N_2O (μg m^{-3} h^{-1}). The net GWP of CH_4 and N_2O was expressed in CO_2 equivalents (CO_2 −eq) by multiplying the emissions of CH_4 by 25 and N_2O by 298 (IPCC, 2007). Greenhouse gas intensity (GHGI) expressed in CO_2 −eq kg^{-1} grain yield was used to evaluate the GHG emissions per unit of yield (Zhang et al., 2016).

2.8. Statistical analysis

Statistical analyses were performed by STATISTICA 9.0 (StatSoft Inc., Tulsa, OK, USA). The significance of the treatment effect was determined by F-test. The means among treatments were compared by the Turkey's test at 5% level of probability. The figures were created by Sigmaplot 12.5 (Systat Software, Inc.).

3. Results

3.1. Field water depth, irrigation water input and water productivity

As shown in Fig. 2, field water level fluctuated between 0 and 5 cm in OPTN and FP for most stages except for mid-season drainage. While in OPTN+AWD and OPTN+MAWD, the water level fluctuated from 5 to − 15 cm. The number of AWD cycle in FP, OPTN, OPTN+AWD and OPTN+MAWD was 2.94, 2.83, 5.53 and 5.4, respectively, when averaged across the six cropping seasons. Compared with OPTN+AWD, drainage period in OPTN+MAWD was increased by 10–15 days. Relative to early seasons, AWD cycles number under OPTN+AWD and OPTN+MAWD was increased by 2–3 times in late seasons due to lower rainfall.

The total water input, irrigation water input and irrigation frequency were significantly reduced in OPTN+AWD and OPTN+MAWD, relative

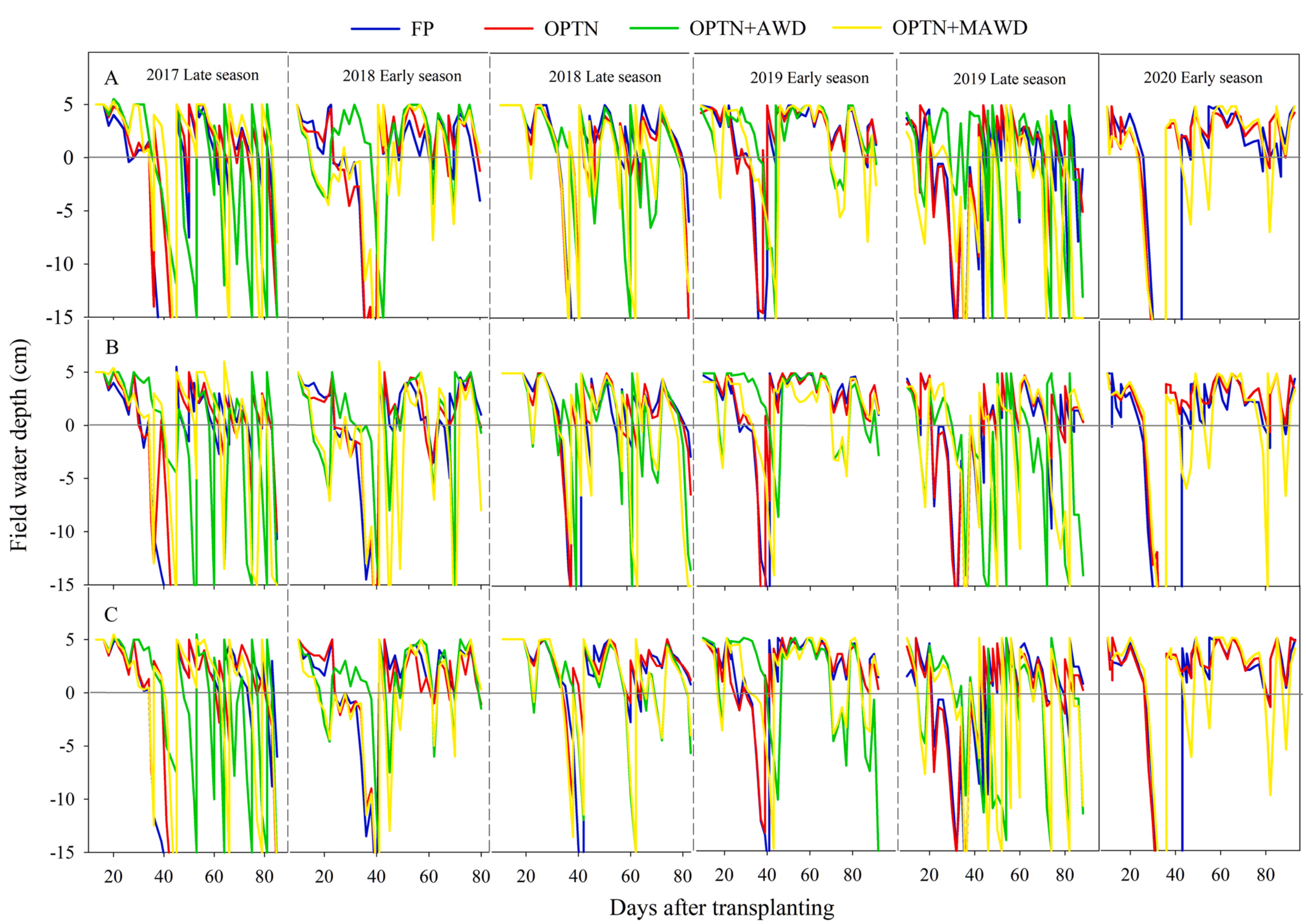

Fig. 2. Changes in field water depth under different treatments in the field experiments conducted during 2017–2020 in Guangzhou, Guangdong province, South China. The field water depth under different treatments was demonstrated by single replication group. A, B, C: replication 1, 2, 3, respectively.

to those of FP and OPTN (Table 3). Relative to OPTN, the input of irrigation water was reduced by 40.9–91.8% in OPTN+MAWD. Compared with OPTN+AWD, the average irrigation water input under OPTN+MAWD was reduced by 19.0%. The water productivity was increased by 2.8–19.6% in OPTN+AWD and 1.5–25.7% in OPTN+MAWD, compared with OPTN. Overall, the WPT was not significant different between OPTN+AWD and OPTN+MAWD, except in early season of 2020 while the WPT of OPTN+MAWD was significantly increased by 6.25% compared with OPTN+AWD.

3.2. Crop growth

Rice variety Tianyou3618 was used in 2017–2018 cropping seasons. Rice variety Huanghuazhan was used in 2019–2020 cropping seasons. The CGR, N uptake rate and N accumulation of rice plant were significantly affected by N management. Overall, the N uptake rate and N accumulation were highest in FP for both rice varieties in MT-PI period (Fig. 3). While in PI-HD period, the CGR, N uptake rate and N accumulation in OPTN, OPTN+AWD and OPTN+MAWD were higher than those in the FP for both rice varieties. During 2017–2018 cropping seasons, the average CGR of Tianyou3618 in OPTN, OPTN+AWD and OPTN+MAWD was 9.4%, 16.9% and 16.0% higher than that of FP, respectively. The average N uptake rate of Tianyou3618 in OPTN, OPTN+AWD and OPTN+MAWD was increased by 105.7%, 95.4% and 117.1%, respectively. Similar result was observed in the value of N accumulation. During 2019–2020 cropping seasons, the average CGR of Huanghuazhan in OPTN, OPTN+AWD and OPTN+MAWD in PI-HD period were increased by 32.4%, 38.5% and 34.4%, respectively, compared with FP. The N uptake rate and N accumulation of Huanghuazhan in OPTN, OPTN+AWD and OPTN+MAWD were increased by 173.9–203.9%, respectively. For most period, there were no significant difference on CGR, N uptake rate, and N accumulation of crop among OPTN, OPTN+AWD and OPTN+MAWD for both rice varieties ($p > 0.05$).

3.3. Grain yield, yield components and N use efficiency

Grain yield was lowest in N0 treatment, varying from 4181.7 to 5066.6 kg ha^{-1} (Table 1). The panicle number, spikelets per panicle and thousand grain weight were lowest in N0 treatment. The yield averaged 6413.7 kg ha^{-1} for FP, varying from 5807.5 to 7064.4 kg ha^{-1}. Relative to FP, the 3-season average yield of Tianyou3618 in OPTN, OPTN+AWD and OPTN+MAWD was increased by 12.8%, 13.8% and 15.4%, respectively. The 3-season average grain yield of Huanghuazhan in OPTN, OPTN+AWD and OPTN+MAWD was 11.4%, 11.6% and 11.5% higher than that of FP. Overall, there were no significant differences in seed setting rate and panicle number per unit area among FP, OPTN, OPTN+AWD and OPTN+MAWD (p>0.05). Relative to FP, the grain weight in OPTN, OPTN+AWD and OPTN+MAWD was slightly increased but the differences did not reach statistical significance (p>0.05). While

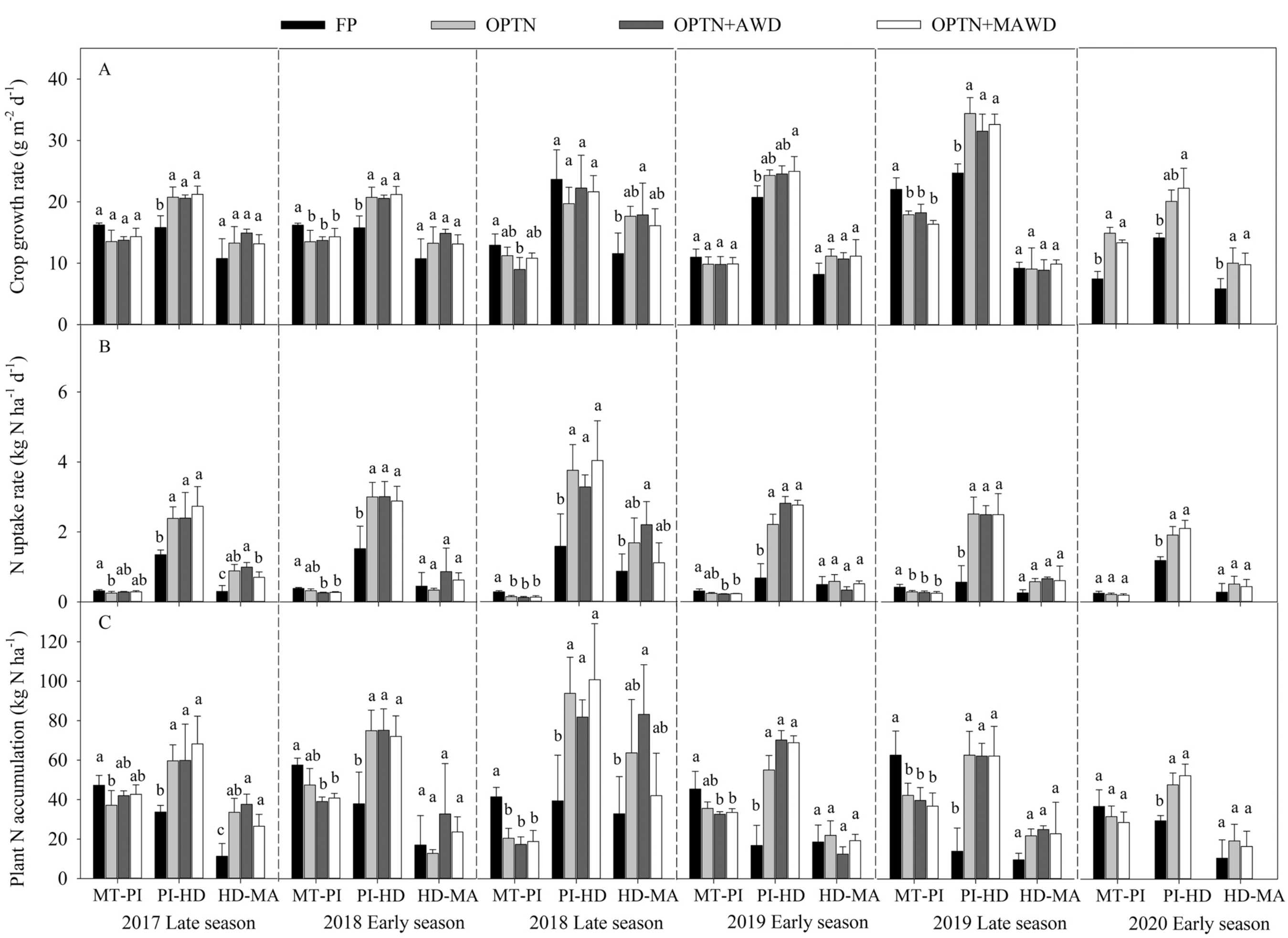

Fig. 3. Crop growth rate, N uptake rate and plant N accumulation in the stage from mid-tillering to panicle initiation (MT-PI), panicle initiation to heading (PI-HD) and heading to maturity (HD-MA) under different treatments at the field experiment conducted during 2017–2020 cropping season in Guangzhou, Guangdong province, South China. Hybrid rice variety Tianyou3618 was used in 2017 and 2018. Inbred rice variety Huanghuazhan was used in 2019 and 2020. Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (Turkey's test).

Table 1
Grain yield and yield components of rice under different treatments in the field experiment conducted during 2017–2020 cropping season in Guangzhou, Guangdong province, South China.

Year /Season	Treatment	Panicle number (no. m^{-2})	Spikelets per panicle	Seed setting rate (%)	Thousand grain weight (g)	Yield (kg ha^{-1})
Late season of 2017	N0	225.0 b	152.5 b	78.5 a	19.3 b	4181c
	FP	304.2 a	163.1 b	78.5 a	19.8 ab	5808 b
	OPTN	321.7 a	160.6 ab	80.0 a	20.3 a	6781 a
	OPTN+AWD	330.8 a	164.1 ab	79.3 a	20.2 a	6875 a
	OPTN+MAWD	324.2 a	177.5 a	78.5 a	19.9 ab	6925 a
Early Season of 2018	N0	201.7 b	144.1 b	83.6 a	19.8 a	5067c
	FP	273.3 a	156.1 b	78.9 a	20.4 a	7064 b
	OPTN	275.0 a	160.0 ab	81.8 a	20.3 a	8273 a
	OPTN+AWD	270.8 a	164.6 ab	80.4 a	20.7 a	8373 a
	OPTN+MAWD	266.7 a	168.2 a	79.4 a	20.3 a	8559 a
Late Season of 2018	N0	154.9 b	139.3 b	86.0 a	19.2 b	4226 b
	FP	236.1 a	155.3 ab	86.7 a	19.5 ab	6934 ab
	OPTN	241.7 a	164.7 a	87.6 a	19.6 ab	7282 a
	OPTN+AWD	233.3 a	175.7 a	88.1 a	20.2 a	7285 a
	OPTN+MAWD	237.5 a	164.5 a	89.1 a	20.2 a	7380 a
Early Season of 2019	N0	220.0 b	158.5 a	85.2 a	18.1c	4949c
	FP	267.5 ab	162.3 a	86.5 a	18.4 bc	6320 b
	OPTN	290.0 a	167.6 a	88.3 a	18.6 ab	7151 a
	OPTN+ AWD	281.7 a	173.5 a	87.7 a	18.8 a	7074 ab
	OPTN+MAWD	295.8 a	168.8 a	86.6 a	18.5 abc	6972 ab
Late Season of 2019	N0	216.0 b	144.2 a	75.9 b	18.5 a	4391 b
	FP	279.2 a	150.7 a	78.9 ab	18.9 a	6115 b
	OPTN	283.3 a	158.6 a	80.8 ab	19.2 a	6821 a
	OPTN+AWD	284.0 a	155.8 a	82.1 ab	19.2 a	6825 a
	OPTN+MAWD	282.6 a	153.1 a	82.6 a	19.6 a	6838 a
Early season of 2020	N0	220.0 b	121.3 b	87.1 a	18.8 a	4455c
	FP	295.8 a	130.2 ab	88.8 a	19.1 a	6242 b
	OPTN	305.8 a	146.3 a	86.1 a	19.3 a	6831 ab
	OPTN+MAWD	304.2 a	142.1 ab	87.1 a	19.5 a	7031 a

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to Turkey's test (0.05).

the number of spikelets per panicle in OPTN, OPTN+AWD and OPTN+MAWD was 4.4–9.0% higher than that of FP. Therefore, higher yield in OPTN, OPTN+AWD and OPTN+MAWD generally resulted from the greater number of spikelets per panicle. The number of spikelets per panicle, panicles per unit area, seed setting rate, thousand grain weight and yield was not significantly different among OPTN, OPTN+AWD and OPTN+MAWD (p>0.05), indicating that irrigation did not have detectable effects on grain yield. Relative to FP, crop N uptake in OPTN was significantly increased by 15.9–44.5%. No significant difference of crop N uptake was observed among OPTN, OPTN+AWD and OPTN+MAWD in all the cropping seasons during 2017–2020 (Table 2). Except for IE_N, the PFP_N, ARE and AE under OPTN, OPTN+AWD and OPTN+MAWD were significantly higher than FP (p<0.05). No significant differences were observed between OPTN, OPTN+AWD and OPTN+MAWD for N use efficiencies indices (IE_N, AE, ARE and PFP_N) during 2017–2020 cropping seasons (p>0.05), indicating that irrigation did not have significant effect on N use efficiencies under the same fertilization treatment.

3.4. Environmental N losses and N surplus analysis

The N losses loading by AV in different treatments accounted for 52.6–62.6% of the total environmental N loss. The environmental N loss via AV was mainly occurred within the first month after transplanting (Fig. 4 A, B). Relative to FP, N loss loading from AV was decreased by 26.1–38.8% under OPTN, OPTN+AWD and OPTN+MAWD. No significant difference of AV loss loading was found between OPTN, OPTN+AWD and OPTN+MAWD.

The N loss loading from surface runoff in different treatments accounted for 14.6–23.8% of the total environmental N loss. The runoff event was greater in the early cropping season than that of the late cropping season. For FP and OPTN treatments, the runoff loss loading in early cropping season was 34.8% and 59.5% higher than that in late cropping season. The water management had significant effect on the N runoff loading. Relative to OPTN, the N runoff loading in OPTN+AWD and OPTN+MAWD was reduced by 50.4% and 49.1% in the early season, and 48.3% and 36.8% in the late season, respectively (p < 0.05).

The N loss loading by leaching in different treatments accounted for 22.3–23.7% of the total environmental N loss. N leaching loss mainly occurred in the stage from MT to PI after transplanting in FP (Fig. 4 E, F). Compared with FP, N leaching loss loading in OPTN was significantly reduced by 16.9% in early cropping season and 27.3% in late cropping season. Relative to OPTN, N leaching loss loading under OPTN+AWD and OPTN+MAWD was respectively reduced by 17.5% and 23.6% in early cropping season, and 18.7% and 25.4% in late cropping season. Table 3.

The total N losses loading from AV, surface runoff and leaching in FP, OPTN, OPTN+AWD and OPTN+MAWD was averaged for 75.1, 54.3, 45.2 and 43.1 kg N ha^{-1}, respectively, across the early and late cropping seasons (Table 4). Compared with FP, the seasonal N losses loading under OPTN, OPTN+AWD and OPTN+MAWD was reduced by 23.6–44.4% (Table 4). Compared with OPTN, the total N losses loading under OPTN+AWD and OPTN+MAWD was significantly reduced by 16.8% and 20.5%, respectively (p < 0.05). The total N losses loading was not significantly different between the treatments of OPTN+AWD and OPTN+MAWD (p > 0.05).

Compared with FP, seasonal fertilizer N input of OPTN, OPTN+AWD and OPTN+MAWD was reduced by 14.3–16.7%. Reversely the crop N output in OPTN, OPTN+AWD and OPTN+MAWD was 15.0–30.1% higher than FP. The N surplus of FP were 86.8 kg N ha^{-1} and 122.5 kg N ha^{-1}, respectively, for early and late season. Seasonal N surplus in different treatment averaged from 22.5 kg ha^{-1} to 122.6 kg ha^{-1} (Table 4). Compared with FP, N surplus in OPTN, OPTN+AWD and OPTN+MAWD was significantly decrease by 55.0–74.1%. The N surplus and N balance were not significantly different between OPTN, OPTN+AWD and OPTN+MAWD (p > 0.05). Regression analysis indicated that total N losses was linearly increased with increasing N surplus and irrigation water input (Fig. 5 A, D) and decreased with increasing

Table 2
The total crop N uptake, internal N use efficiency (IE_N), agronomic N use efficiency (AE), apparent recovery efficiency of N (ARE), and partial factor productivity of applied N (PFP_N) under different treatments in the field experiment conducted during 2017–2020 in Guangzhou, Guangdong Province, China.

Year /Season	Treatment	Crop N uptake (kg N ha^{-1})	IE_N (kg kg^{-1})	AE (kg kg^{-1})	ARE (%)	PFP_N (kg kg^{-1})
Late season of 2017	FP	129.2 b	45.0 a	7.74 b	34.5 b	27.7 b
	OPTN	158.0 a	42.9 a	14.4 a	56.2 a	37.7 a
	OPTN+AWD	168.1 a	41.5 a	15.0 a	61.8 a	38.2 a
	OPTN+MAWD	163.3 a	42.7 a	15.2 a	59.2 a	38.5 a
Early Season of 2018	FP	132.8 b	53.3 a	11.1 b	25.1 b	39.2 b
	OPTN	153.8 ab	53.8 a	21.4 a	44.2 a	55.2 a
	OPTN+AWD	163.8 a	51.4 a	22.0 a	50.9 a	55.8 a
	OPTN+MAWD	152.7 ab	56.1 a	23.3 a	43.4 a	57.1 a
Late Season of 2018	FP	136.2 b	50.9 a	12.9 b	26.9 b	33.0 b
	OPTN	193.2 a	38.4 b	19.1 a	70.9 a	45.5 a
	OPTN+AWD	196.9 a	37.3 b	19.1 a	73.3 a	45.5 a
	OPTN+MAWD	177.5 ab	41.7 ab	19.7 a	61.1 a	46.1 a
Early Season of 2019	FP	96.8 b	65.5 a	7.6 b	14.7c	35.1 b
	OPTN	124.2 a	57.7 ab	14.7 a	35.9 a	47.7 a
	OPTN+AWD	126.9 a	55.9 ab	14.2 a	37.7 a	47.2 a
	OPTN+MAWD	134.3 a	51.7 b	13.3 a	42.6 a	46.2 a
Late Season of 2019	FP	109.5 b	53.1 a	7.7 b	22.6 b	27.7 b
	OPTN	139.9 a	48.5 a	14.4 a	43.2 a	37.7 a
	OPTN+AWD	141.4 a	48.5 a	15.0 a	44.1 a	38.2 a
	OPTN+MAWD	136.2 a	51.2 a	15.2 a	41.2 a	38.5 a
Early season of 2020	FP	87.4 b	61.6 a	9.93 b	15.5 b	34.7 b
	OPTN	108.0 a	54.8 a	15.8 a	32.4 a	45.5 a
	OPTN+MAWD	107.6 a	56.6 a	17.2 a	32.2 a	46.9 a

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to Turkey's test (0.05).

crop N uptake and ARE (Fig. 5 B, C). A reduction of 100 kg N ha^{-1} of N surplus leads to reduction of 67.1 kg N ha^{-1} of total N losses from rice paddies (Fig. 5 C), indicated the environmental N pollution was decreased in OPTN, OPTN+AWD and OPTN+MAWD as more fertilizer N was absorbed by crops and less N was lost to environment or remained in paddy soil.

3.5. CH_4 and N_2O emissions and the global warming potential

CH_4 emission was significantly influenced by irrigation. In early cropping season, CH_4 fluxes under FP and OPTN showed an increasing trend and then suppressed by mid-season drainage. While when the paddy re-flooded, the CH_4 re-emission commenced and resumed to a high level (Fig. 6 A). At late season, the CH_4 fluxes generally maintained at low rate at heading stage due to the descending temperature. The CH_4 fluxes under OPTN+AWD and OPTN+MAWD were substantially reduced by the mid-season drainage and AWD cycles and were kept at a low level. The CH_4 emissions was not significantly different between FP and OPTN. When averaged across the six cropping seasons during 2017–2020, CH_4 emission under OPTN+AWD was 19.8% lower than that of OPTN. The average CH_4 emission in OPTN+MAWD was further reduced by 16.0% than that of OPTN+AWD. N_2O emission was significantly influenced by N fertilization and irrigation. The large amount of basal and tillering N significantly promoted N_2O fluxes at seedling stage, especially for FP (Fig. 6 B). The N_2O emission in OPTN was 25.3–51.1% lower than that of FP. Relative to OPTN, the 6-season average N_2O emission increased by 25.9% in OPTN+AWD and 33.0% in OPTN+MAWD. While compared with FP, the N_2O emission was decreased by 18.1% in OPTN+AWD and 13.4% in OPTN+MAWD, respectively.

Seasonal net GWP under FP, OPTN, OPTN+AWD and OPTN+MAWD was 9110.1, 8416.7, 6988.1 and 6033.3 kg CO_2 −eq ha^{-1}, respectively. No significant difference exists between FP and OPTN with respect to the net GWP, while lower GHGI was obtained in OPTN, which can be predominantly attributed to the higher grain yield in OPTN. The GWP of CH_4 accounted for 86.3–92.7% of the net GWP among various treatments, indicated that CH_4 was consistently the dominant factor of GWP from rice paddies. The GHGI in FP, OPTN, OPTN+AWD and OPTN+MAWD averaged for 1.42, 1.18, 0.96 and 0.84 kg CO_2 −eq kg^{-1} grain yield respectively. Compared with OPTN+AWD, the GWP and GHGI in OPTN+MAWD was decreased by 13.9% and 13.4%, respectively.

Correlation analysis using pooled data across different management practices revealed that net GWP and GHGI were positively correlated with irrigation water input and were negatively correlated with the WPT (Fig. 7 A, B, D and E). The GHGI was negatively correlated with grain yield (Fig. 7 F), indicating that lower greenhouse gas intensity was linked to increased water productivity and grain yield with reduced water input. For FP and OPTN adopting the mid-season drainage, there was statistically a highly positive relationship between net GWP and yield. While in OPTN+AWD and OPTN+MAWD using the water saving irrigation, no correlation was found between the net GWP and the grain yield (Fig. 7 C).

4. Discussion

4.1. Effects of optimized crop management on grain yield and utilization of water and N fertilizer

Grain yield, N uptake, NUE and WPT in OPTN, OPTN+AWD and OPTN+MAWD were substantially greater than those of FP. The reduction of the basal and tiller N application under OPTN had no effect on the final effective panicles number. Higher yields in OPTN, OPTN+AWD and OPTN+MAWD were predominantly attributed to the increased spikelets per panicle. Panicle N topdressing has greater N recovery efficiency than basal and tiller N fertilizer (Sui et al., 2013). Postponing N application and increasing the panicle N helps to prevent excessive growth of tillers and avoid waste of N nutrient by unnecessary vegetative growth (Zhong et al., 2010; Huang et al., 2017), while the biomass accumulation in grain-filling period increased (Xu et al., 2015b; Zhou et al., 2022). When more than 30% of fertilizer N was applied at PI and HD, the CGR, N uptake rate and plant N accumulation during the spikelet differentiation and grain-filling stage were substantially increased in optimized N management (Fig. 3). This helps to increase the differentiated spikelet number and prevent spikelet retrogression. Therefore, the increased panicle N ratio with reduced basal and tiller N ratio is responsible for the improved grain yield and NUE.

The 4-year field study demonstrated that the OPTN+AWD and OPTN+MAWD remarkably reduced the irrigation water input without yield loss in comparison with FP and OPTN. Grain yield and NUE were not significantly different between OPTN+AWD and OPTN+MAWD. Literature so far does not reach a consensus on the effect of the AWD

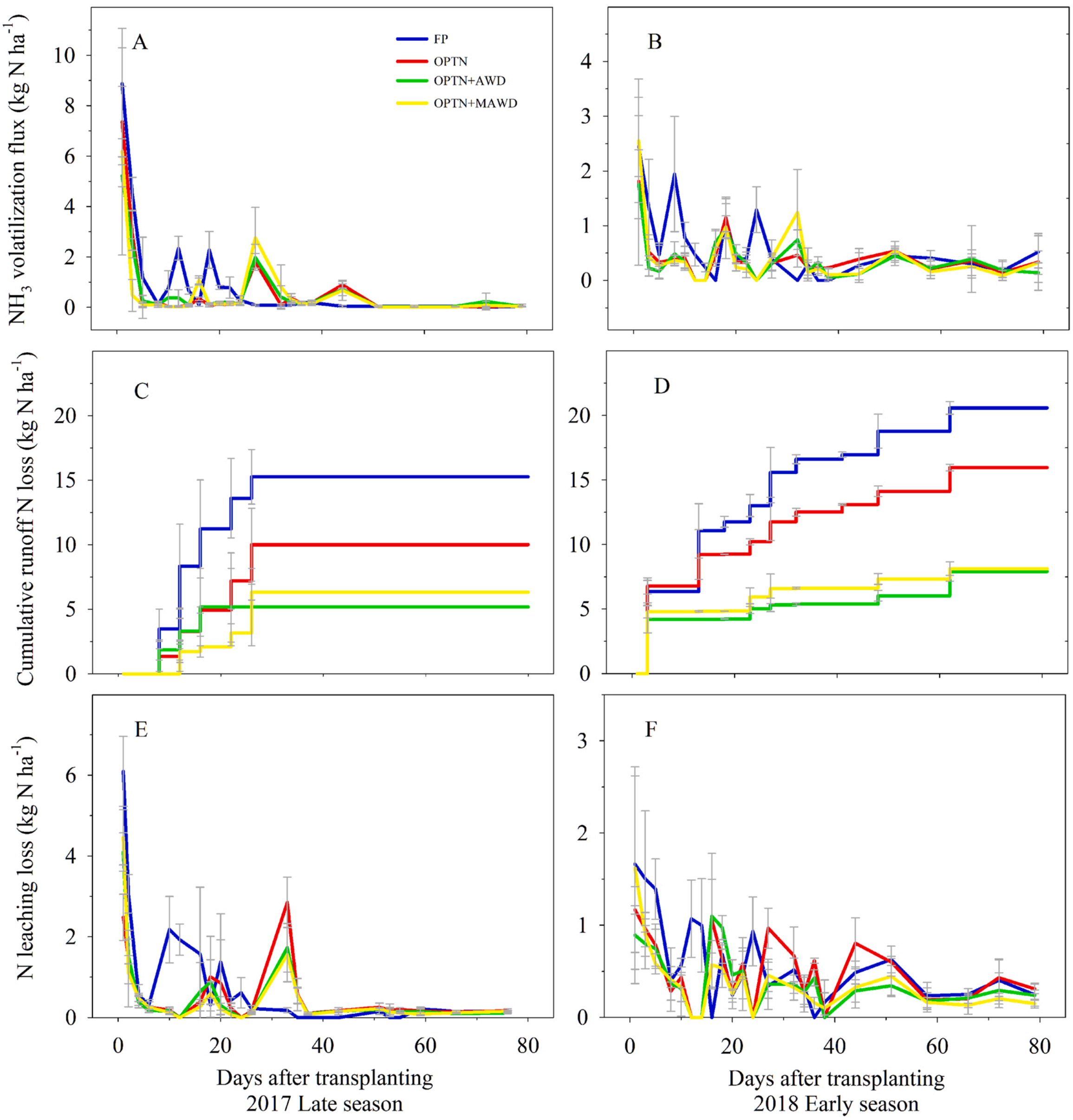

Fig. 4. Dynamics of NH_3 volatilization, N loss from runoff and N leaching under different treatments in the field experiment during 2017–2020 in Guangzhou, Guangdong province, South China.

irrigation on grain yields. Several studies reported yield reduction under AWD (Lagomarsino et al., 2016; Feng et al., 2021), whereas others reported that AWD saved water without yield loss or even increased yield (Carrijo et al., 2018; Setyanto et al., 2018; Ullah et al., 2018). The discrepancy could be attributed to the factors such as the specification of the AWD, variety, weather, soil types and hydrological conditions of the study site. The 'safe' AWD irrigation has been proposed as a cost-effective method to save irrigation water in several Asian countries (Bouman and Tuong, 2001; Chu et al., 2014). It is reported that rice can extract the water in the root zone easily if the groundwater level did not drop to 15 cm underground (Carrijo et al., 2017). In current study, OPTN+AWD saved irrigation water without yield loss as compared with OPTN and the results were consistent across the six cropping seasons, indicating that the threshold of water level ≤ 15 cm could be proposed for maintaining the rice yield at South China.

To further improve the WPT, a severe AWD were evaluated in previous study. For severe AWD, the irrigation management followed the same procedure as safe AWD except that field was re-irrigated when groundwater level dropped to 30 cm below soil surface. Although the severe AWD saved water by 12.8–29.7% as compared with the mid-season drainage and safe AWD, but the yield was decreased by 3.07–9.82% (Liang et al., 2016). Therefore, irrigation threshold of 30 cm below soil surface may not suitable for many rice varieties or soil types in South China. Study also revealed that a water depth ≤ 20 cm below soil surface was safe for rice, thus possibility exist to further reduce the irrigation water use without compromising yield in clay loam soil condition (Liang et al., 2016). This is in accordance with other observations suggested that the re-irrigating threshold of soil water potential at − 10 kPa at − 15 to − 20 cm soil depth could meet of the water demand of rice even at the panicle and flowering stages which are sensitive to water stress (Ishfaq et al., 2020).

Due to the different sensitivity of rice plant to water stress at different stages, the irrigation thresholds can be adapted to a specific period. Numerous studies reported that rice plants in late tillering stage were less sensitive to water deficit, while mid-season drainage in this period increased yields mainly due to prevention of the root-rot, the controlling of unproductive tillers, and reduced lodging because of better root anchorage and removal of anaerobic toxins (Bouman and Tuong, 2001;

Table 3
The rainfall, irrigation, total water input and water productivity under different irrigation treatments in field experiment conducted during 2017 – 2020 cropping season in Guangzhou, Guangdong province, South China.

Year /Season	Treatment	Rainfall (m^3 ha^{-1})	Irrigation water input (m^3 ha^{-1})	Total water input (m^3 ha^{-1})	Irrigation frequency (No. per season)	Water productivity (kg grain m^{-3})
Late season of 2017	FP	4970.0	2188.3 a	7158.3 a	6.3 ab	0.81 b
	OPTN	4970.0	2326.0 a	7296.0 a	6.7 a	0.93 b
	OPTN+AWD	4970.0	1203.6 bc	6173.6 bc	4.3 b	1.11 a
	OPTN+MAWD	4970.0	947.1c	5917.1c	4.7 b	1.17 a
Early Season of 2018	FP	7140.0	2687.2 a	9827.2 a	7.3 a	0.72 b
	OPTN	7140.0	2154.3 a	9294.3 a	7.3 a	0.89 b
	OPTN+AWD	7140.0	815.7 b	7955.5 b	3.3 b	1.05 ab
	OPTN+MAWD	7140.0	682.0 b	7821.9 b	2.7 b	1.10 a
Late Season of 2018	FP	5931.0	1359.2a	7290.2 a	5.3 a	0.95 b
	OPTN	5931.0	1343.4 a	7274.4 a	5.7 a	1.00 ab
	OPTN+AWD	5931.0	823.7 b	6754.7 b	4.0 a	1.08 ab
	OPTN+MAWD	5931.0	793.4 b	6724.4 b	4.0 a	1.10 a
Early Season of 2019	FP	12978.0	541.7 a	13519.7 a	2.7 a	0.47 b
	OPTN	12978.0	579.2 a	13557.2 a	4.0 a	0.53 a
	OPTN+AWD	12978.0	74.4 b	13052.4 b	0.7 b	0.54 a
	OPTN+MAWD	12978.0	47.7 b	13025.7 b	0.3 b	0.54 a
Late Season of 2019	FP	5369.0	2667.5 a	8036.5 a	11.3 a	0.76c
	OPTN	5369.0	2351.4 ab	7720.4 ab	9.7 ab	0.89 bc
	OPTN+AWD	5369.0	1508.2 bc	6877.2 bc	6.3 bc	1.00 ab
	OPTN+MAWD	5369.0	1115.6c	6484.6c	4.7c	1.05 a
Early season of 2020	FP	9822.0	1382.3 a	11204.3 a	6.7 a	0.56 b
	OPTN	9822.0	862.7 ab	10684.7 ab	5.0 b	0.64 b
	OPTN+MAWD	9822.0	537.8 b	10359.8 b	2.3c	0.68 a

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to Turkey's test (0.05).

Table 4
Nitrogen surplus in different treatments at field experiments during 2017–2018 cropping seasons at Guangzhou, Guangdong province.

	2017 late season				2018 early season			
	FP	OPTN	OPTN+AWD	OPTN+MAWD	FP	OPTN	OPTN+AWD	OPTN+MAWD
Input								
Fertilizer N	210.0 a	180.0 b	180.0 b	180.0 b	180.0 a	150.0 b	150.0 b	150.0 b
N deposition	17.0 a	17.0 a	17.0 a	17.0 a	17.0 a	17.0 a	17.0 a	17.0 a
Irrigation	6.99 a	6.99 a	4.04 b	3.74 b	4.81 a	4.81 a	1.53 b	1.45 b
Seed	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Non-symbiotic N fixation	16.0 a	16.0 a	16.0 a	16.0 a	16.0 a	16.0 a	16.0 a	16.0 a
Total input	251.8 a	221.8 b	218.8c	218.5c	219.6 a	189.6 b	186.3c	186.2c
Output								
Crop N output	129.2 b	158.0 a	168.1 a	163.3 a	132.8 b	153.8 a	163.8 a	152.7 ab
Ammonia volatilization	39.7 a	26.5 b	29.3 ab	24.3 b	41.6 a	30.6 ab	27.1 b	28.3 b
Runoff	15.3 a	10.0 ab	5.17 b	6.32 b	20.6 a	16.0 a	7.91 b	8.13 b
Leaching	19.5 a	14.2 ab	11.71 b	10.84 b	13.5 a	11.2 ab	9.13 b	8.38 b
Total output	203.7 a	208.7 a	214.3 a	204.8 a	208.5 a	211.6 a	207.9 a	197.5 a
N balance	48.1 a	13.1 b	4.53 b	13.8 b	11.2 a	-22.0 a	-21.61 a	-11.26 a
Surplus	122.6 a	63.8 b	50.7 b	55.2 b	86.8 a	35.8 b	22.5 b	33.5 b

Values are means of three replications. Within each row, means followed by the same letter are not significantly different according to Turkey's test (0.05). The crop N output was calculated by multiplying the dry matter yields of grain and straw by the respective N concentration. N balance is the difference between total N inputs and total N outputs, including the possible errors associated with the determination of the items for N inputs and outputs. The data of N input from N deposition, seed, non-symbiotic N fixation was estimated from published literature.

Wang et al., 2013; Zheng et al., 2018). Fu et al. (2021) reported that the sink size, panicle number and grain yield are highly associated with the CGR and N uptake in the stages of PI and HD in double rice system. In current study, the CGR and N uptake rate under MAWD were comparable to those of OPTN and OPTN+AWD in PI-HD and HD-MA stages. No significant differences were observed in CGR and crop N accumulation between OPTN, OPTN+AWD and OPTN+MAWD. When mid-season drainage was imposed, the irrigation water input in OPTN+MAWD was 3.68~26.0% lower, and the 6-season average WPT was 3.1% higher than that of OPTN+AWD. While the grain yield and crop N accumulation were not significant different between OPTN+AWD and OPTN+MAWD. Therefore, in comparison with AWD, MAWD could further reduce water input without negative impact on rice growth and grain yield.

4.2. *Effects of integrated irrigation and N management on N surplus and environmental N losses*

N surplus benchmark are widely used indicators to evaluated the environmental performance for fertilization within a specified boundary at various level, e.g., smallholder farms, national, regional and global scale. Annual N surplus for rice system in the region of Yangtze River was 225 kg N ha^{-1} y^{-1} under farmers' conventional N practice (Zhang et al., 2019). In current study, seasonal N surplus in South China was 86.8–122.6 kg N ha^{-1} under farmers' conventional fertilization and irrigation practice. Relative to FP, N surplus was substantially reduced by optimized fertilization and water saving irrigation in OPTN+AWD and OPTN+MAWD.

Superfluous N rate results in a greater N surplus that can remain in soil or move to the environment by the paths of gaseous emission, leaching and surface runoff. N losses in the first 30 DAT averaged

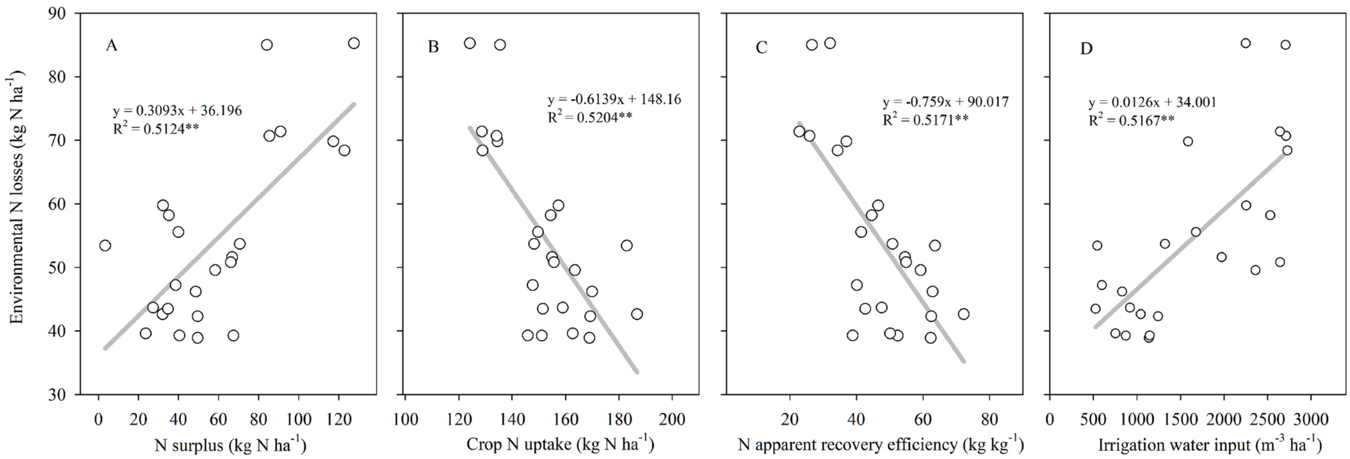

Fig. 5. Regression of environmental N loss to N surplus, crop N uptake, N apparent recovery efficiency and irrigation water input in different treatments during 2017–2020.

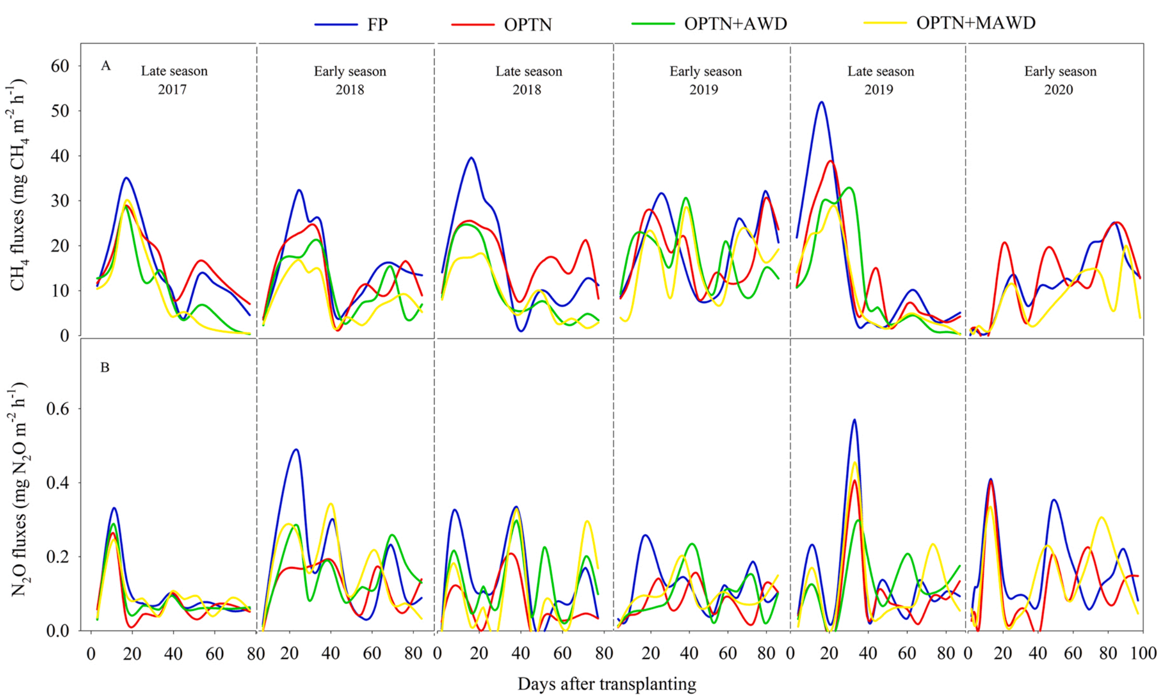

Fig. 6. The CH_4 and N_2O emissions from rice field under different treatments in the field experiment conducted during 2017–2020 in Guangzhou, Guangdong province, South China.

46.9 kg N ha^{-1} in FP, accounted for 87.4% of seasonal N loss. Therefore, environmental N losses mainly occurred at early growth stage. Excess basal and tiller N fertilizer not only increases the unproductive tillers but also increase the N surplus as most of N fertilizer was lost to environment owing to the imperfect root system at early stage. Lin et al. (2014) reported that merely 14.5% of base and tillering N was absorbed by crops, while 26% of the panicle N was taken up by crops. Wu et al. (2021) suggested that basal fertilizer proportion should be reduced and the N topdressing should be postponed for rice in the region of middle reaches of Yangtze River. For the treatment of OPTN, the total N rate was reduced by 14.3–23.8% and the basal and tiller N was reduced by up to 40% relative to FP. In current study, the total N losses loading in OPTN at the first 30 DAT was 28.0 kg N ha^{-1}, being 59.6% lower than that of FP. Therefore, reducing the N ratios in the early stage can reduce environmental N loss, as the plant roots in early stage uptake limited N. When suitable N ratio was postponed to the PI stage, N accumulation at reproductive growth stage could be substantially increased, as the developed root systems at late growth stage give the rice plants a greater opportunity to compete against environmental N loss. It is worth notice that optimized N management substantially increased AE, ARE, PFP_N and crop N uptake under treatments of OPTN, OPTN+AWD and OPTN+MAWD, but did not enhance the IE_N. Therefore, the increases of grain yield were not higher than the increases of N uptake by plants in optimized N management with delayed N topdressing. To further improve the NUE, optimized N management should aim to increase the yield per unit of absorbed N.

N runoff loss in South China was probably four times than that in north China (Hou et al., 2016, 2018). Irrigation significantly influenced the surface runoff and leaching loss in current study. The total N losses loading depict a significant and negative correlation with irrigation water input (Fig. 5 D). Relative to OPTN, runoff volume in OPTN+AWD and OPTN+MAWD was reduced by 56.7–61.0% and 46.8–69.1%, while

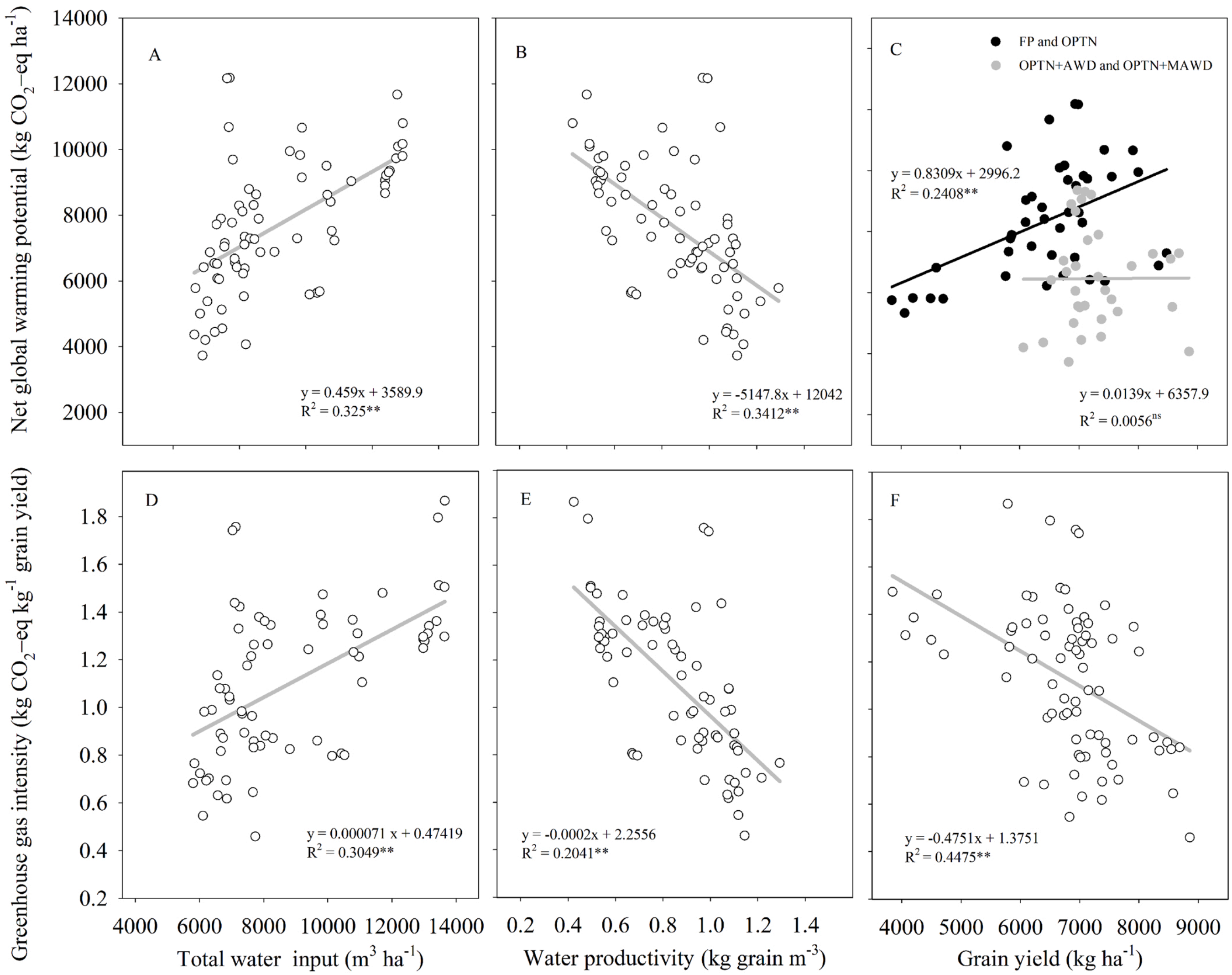

Fig. 7. The net global warming potential (GWP) and greenhouse gas intensity (GHGI) as affected by the total water input, water productivity and grain yield in the field experiment during 2017–2020 in Guangdong province, South China.

runoff loss of N was reduced by 48.3–50.4% and 36.8–49.1%, respectively. Intermittent irrigation enhanced the storage capacity of rice field because the dried paddy soil may act as "buffer" to reduce surface runoff induced by extreme precipitation (Liu et al., 2021). Therefore, the increased drainage intensity in AWD and MAWD not only enhanced the storage capacity of rainfall water to save irrigation water but also reduce the N runoff loss. As the height of the runoff collection pipe was set at 5 cm for all treatments in this study, runoff event still occurred in AWD and MAWD when ponding water layer in field exceed 5 cm under heavy rainfall. To further reduced the environmental N losses through the path of surface runoff in AWD and MAWD, it would be necessary to avoid fertilizing or increase the height of drainage outlet reasonably before the arrival of heavy rainfall.

It is reported that 25–85% of the irrigation water was lost via leaching while leaching water volume was influenced by soil condition and irrigation pattern (Hafeez et al., 2014; Moallim et al., 2018). In current study, leaching loss of N in MAWD was reduced by 17.5% and 23.6% compared with FP and OPTN. Reduced irrigation water input and percolation volume could be the critical factors for lowering the leaching loads in OPTN+AWD and OPTN+MAWD. Works done so far did not reach a consensus on the effects of water management on the amount of N loss via AV. Several studies suggested that AV was greater in intermittent irrigation as less water input resulted in shallow water layer and higher ammonium concentration (Win et al., 2009). While others reported that intermittent irrigation reduced AV loss as the amount of ammonium binding in the soil was increased (Zhu et al., 1988). Results from this study suggesting that irrigation did not have detectable effects on AV. This is possibly due to the fact that water layer between treatments was not remarkably different within 3–5 days after the application of fertilizer N, as the field was irrigated before fertilization for all treatments. By reducing the N losses from AV, leaching and surface runoff, the environmental N losses was substantially reduced by 40.8–44.4% under OPTN +MAWD in comparison to FP. Therefore, our study demonstrated that the combination of optimized N management and MAWD was effective to improve NUE and to reduce N loss, thus reducing agricultural pollution.

4.3. Effects of integrated water and N management on greenhouse gas emission

The CH_4 was dominant contributor to GWP in double rice cropping system, which contributed more than 80% of total GWP across different treatments (Table 5). It is reported that seasonal CH_4 emissions under farmers' practice in middle of the Yangtze River region was 90.7–238.4 kg CH_4 ha^{-1} (Li et al., 2018; Yang et al., 2019). Seasonal CH_4 emissions under FP ranged between 226.2 and 404.6 kg CH_4 ha^{-1} in current study. The greater CH_4 emissions under rice paddies of South China could associated with high temperature and frequent rain events

Table 5
The net global warming potential (GWP) and greenhouse gas intensity (GHGI) under different treatments in the field experiment conducted during 2017–2020 in Guangzhou, Guangdong Province, China.

Year /Season	Treatment	N_2O emissions (kg ha^{-1})	CH_4 emissions (kg ha^{-1})	Net GWP (kg CO_2 −eq ha^{-1})	GHGI (kg CO_2 −eq kg^{-1} grain yield)
Late season of 2017	FP	1.89 a	266.2 a	7219.8 a	1.24 a
	OPTN	1.40 a	274.3 a	7273.2 a	1.07 a
	OPTN+AWD	1.61 a	175.3 b	4860.4 b	0.71 b
	OPTN+MAWD	1.70 a	164.7 b	4624.7 b	0.66 b
Early Season of 2018	FP	4.69 a	339.2 a	9878.2 a	1.40 a
	OPTN	3.06 b	285.2 ab	8042.5 ab	0.98 ab
	OPTN+AWD	3.85 ab	237.7 ab	7090.5 ab	0.85 b
	OPTN+MAWD	4.03 ab	177.0 b	5624.8 b	0.66 b
Late Season of 2018	FP	2.53 a	372.1 a	10055.0 a	1.45 a
	OPTN	1.23 b	375.0 a	9742.1 a	1.35 ab
	OPTN+AWD	2.37 a	248.3 ab	6914.1 ab	0.95 b
	OPTN+MAWD	2.03 ab	204.5 b	5717.4 b	0.77 b
Early Season of 2019	FP	2.48 a	404.6 a	10854.4 a	1.72 a
	OPTN	1.66 b	376.1 a	9898.6 ab	1.39 b
	OPTN+AWD	1.99 ab	344.7 ab	9210.3 b	1.30 b
	OPTN+MAWD	2.06 ab	333.8 b	8959.1 b	1.28 b
Late Season of 2019	FP	3.10 a	296.3 a	8331.5 a	1.36 a
	OPTN	1.84 b	261.7 ab	7092.1 ab	1.04 ab
	OPTN+AWD	2.79 ab	241.3 ab	6865.2 ab	1.01 ab
	OPTN+MAWD	2.75 ab	192.8 b	5638.8 b	0.83 b
Early season of 2020	FP	3.76 a	288.0 a	8321.8 a	1.33 a
	OPTN	2.81 a	304.5 a	8451.7 a	1.23 a
	OPTN+MAWD	3.43 a	184.5 b	5634.9 b	0.80 b

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to Turkey's test (0.05).

in this region. Before mid-season drainage, rice paddies were generally under flooding condition for seedling growth and promoting tillering. During rice growth, root incorporation and stubble retained in soil increased the amount of carbon pool in the soil and provided methanogens with an abundant carbon substrate. Therefore, the abundant carbon substrate and anaerobic condition before mid-season drainage favored the growth of methanogens in paddy soil, leading to a high CH_4 emission. Although the CH_4 emission was reduced during mid-season drainage in FP and OPTN, but obvious re-emission of CH_4 was observed after mid-season drainage (Fig. 6). Accumulation of the substrate and microbial biomass before mid-season drainage could promote methane production under re-flooding condition at later growth stage. Intermittent drainage is a practical option to mitigate the emission of CH_4 (Li et al., 2002; Liao et al., 2020; Toma et al., 2021). In current study, seasonal CH_4 emissions averaged 249.5 kg ha^{-1} for OPTN+AWD, being 20.2% lower than that of OPTN. Relative to OPTN+AWD, the seasonal CH_4 emission under OPTN+MAWD was further reduced by 16.0%. We suggested that combination of mid-season drainage and AWD cycles in MAWD irrigation helped to inhibit the activity of methanogen and reduced the CH_4 emissions.

Seasonal N_2O emission averaged 3.07 kg N_2O ha^{-1} in FP. While relative to FP, N_2O emission was reduced by 34.9% in OPTN. An exponential relationship was found between fertilizer N rate and N_2O emission in current study, which can be quantitatively described as $y = 0.945\ e^{0.0053x}$ ($R^2 = 0.297$, $p < 0.01$), indicated that emission of N_2O was significantly affected by the N rate. It has been proven that excess N fertilizer in soil leads to great amount of inorganic N and overgrowth of nitrification and denitrification related microbes, while the lower soil moisture during intermittent drainage periods encouraged overproduction of N_2O (Hu et al., 2015; Xia et al., 2017; Zeng et al., 2019). Excess N fertilizer applied in the earlier growth stage in the practice of FP lead to great amount of N surplus at soil, while greater soil-N induced overproduction of N_2O during drainage episode. Reducing N rate was proven to be practical to reduce the emission of N_2O (Zou et al., 2005; Lan et al., 2020; Kong et al., 2021). Relative to FP, the basal and tiller N rate under OPTN, OPTN+AWD and OPTN+MAWD was reduced by 30–60%, while the N_2O emissions was reduced by 13.3–34.9%. We suggested that beside the reduction of N fertilizers inputs, reducing N ratio at early growth period while increasing the panicle N ratio also helped to decrease N_2O emissions. Seasonal N_2O emission was significantly influenced by water inputs (Table 5). Relative to OPTN, N_2O emissions in AWD and MAWD was increased by 25.9% and 33.2%, respectively, indicating that wet-dry cycles in AWD and MAWD impose a trade-off between emissions of N_2O and CH_4. Compared with constant aerobic or anaerobic conditions, the anaerobic and aerobic cycling normally promotes N_2O emissions through nitrification and denitrification (Dang Hoa et al., 2018; Fertitta-Roberts et al., 2019). Therefore, it is still a main task to mitigate N_2O emissions under water saving irrigation regime.

The GWP in FP and OPTN were positively correlated with grain yield. We hypothesize that higher yield with greater shoot and root biomass may increase carbon products, as greater carbon products released from root system in anaerobic condition could enhanced root exudation and the substrate utilized by methanogens, which eventually elicit greater CH_4 emission (Das et al., 2008). Relative to OPTN+AWD, the combination of mid-season drainage and AWD cycles in MAWD increased the N_2O emission, however, MAWD further reduced the GWP and GHGI as the mitigation of CH_4 emissions outweighed the increase of the N_2O emission. Both GWP and GHGI had positive correlation with the total water input and negative correlation with WPT. Average GWP and GHGI ranged from high to low were in the order FP, OPTN, OPTN+AWD, and OPTN+MAWD. In OPTN+AWD and OPTN+MAWD, the net GWP showed minimal response to the increasing of grain yield (Fig. 7 C), suggesting that improving WPT by AWD and MAWD irrigation effectively mitigate GWP in double rice cropping systems while maintaining grain yield. Relative to farmers practice of irrigation and fertilization, integration of optimized N management and MAWD irrigation significantly increased the grain yield and reduced the net GHG emission and GHGI, the results were consistent across the six cropping seasons. Therefore, we suggested that integrating MAWD with optimized N fertilization can synergistically improve the rice yield and reduced the GWP in rice paddies. It worth notice that water management and N application rate could interact with each other to produce coupling effect. Therefore, the interaction effect of different water management and N rate on GHG emissions should be explored in future.

5. Conclusion

Optimized N management with reduced total N input and increased panicle N application (OPTN) was effective to reduce environmental N losses and N_2O emissions while improving grain yield and NUE. Compared with FP, OPTN+MAWD significantly increases N and water use efficiencies and reduced N surplus, environmental N losses and GWP. Relative to OPTN+AWD, the irrigation water input, CH_4 emission and GWP in OPTN+MAWD was reduced by 19.0%, 16.0% and 13.7%, respectively. Yield and crop N accumulation in OPTN+MAWD were comparable with those of OPTN+AWD. Integration of optimized N management and MAWD can be a practical approach to enhance grain yield and reduce N losses and GHG emission synergistically.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108282.

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