



Nitrogen losses and greenhouse gas emissions under different N and water management in a subtropical double-season rice cropping system



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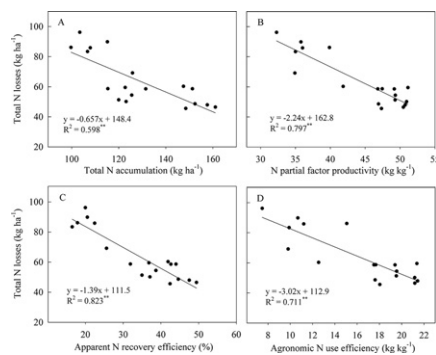
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HIGHLIGHTS

- Optimized N and water management reduced environmental footprints without yield penalty.
- Reduced amount and delayed timing of N application helped to improve NUE and reduce N losses.
- Increasing N and water use efficiency can reduce greenhouse gas emission and N losses.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrogen non-point pollution and greenhouse gas (GHG) emission are major challenges in rice production. This study examined options for both economic and environmental sustainability through optimizing water and N management. Field experiments were conducted to examine the crop yields, N use efficiency (NUE), greenhouse gas emissions, N losses under different N and water management. There were four treatments: zero N input with farmer's water management (N0), farmer's N and water management (FP), optimized N management with farmer's water management (OPT_N) and optimized N management with alternate wetting and drying irrigation (OPT_N + AWD). Grain yields in OPT_N and OPT_N + AWD treatments increased by 13.0–17.3% compared with FP. Ammonia volatilization (AV) was the primary pathway for N loss for all treatments and accounted for over 50% of the total losses. N losses mainly occurred before mid-tillering. N losses through AV, leaching and surface runoff in OPT_N were reduced by 18.9–51.6% compared with FP. OPT_N + AWD further reduced N losses from surface runoff and leaching by 39.1% and 6.2% in early rice season, and by 46.7% and 23.5% in late rice season, respectively, compared with OPT_N. The CH₄ emissions in OPT_N + AWD were 20.4–45.4% lower than in OPT_N and FP. Total global warming potential of CH₄ and N₂O was the lowest in OPT_N + AWD. On-farm comparison confirmed that N loss through runoff in OPT_N + AWD was reduced by over 40% as compared with FP. OPT_N and OPT_N + AWD significantly increased grain yield by 6.7–13.9%. These results indicated that optimizing water and N management can be a simple and effective approach for enhancing yield with reduced environmental footprints.

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1. Introduction

To feed 22% of the world population with 9% of the world's arable land, nitrogen (N) fertilizer has been intensively used in rice production and rice yield has been substantially improved for the past decades in China. Today, China has become the largest synthetic N fertilizer consumer in the world with >30% of global consumption (FAO, 2015). Meanwhile, the N recovery efficiency in China is considerably lower than world average (Deng et al., 2014). Zhang et al. (2008) reported that the agronomic efficiency of N (AE) in China's rice production is 10.4 kg grain kg⁻¹ N, which is about 50% lower than the AE under appropriate fertilization management. The low N use efficiency is largely caused by the inappropriate timing and rate of N application (Zeng et al., 2012). Most farmers apply N fertilizer as basal and then topdressing after regreening (Jiang et al., 2012). Inappropriate use of N fertilizer results in serious non-point source pollution to the environment via ammonia (NH₃) volatilization (AV), leaching and runoff (Juan et al., 2005; Liu et al., 2016). In China, one study reported that over 30% of the collected groundwater samples had nitrate concentrations that exceeded the safety standard (Zhao et al., 2007), another study reported 42% of sampled lakes to be contaminated by N and other chemicals (Jin et al., 2005).

Greenhouse gas (GHG) emission is another environmental problem in rice production. The annual methane (CH₄) emission from rice paddies has been estimated to be 6.15 million tons, accounting for 17.9% of the total CH₄ emission (Shi et al., 2010). Due to anaerobic conditions, rice fields were previously considered to be a less important source of N₂O, but evidence is mounting that high N rate promotes N₂O emissions (Cai et al., 1997; Zou et al., 2005). Seasonal N₂O flux from rice paddies in China have increased from 0.32 kg N₂O-N ha⁻¹ in the 1950s to 1.00 kg N₂O-N ha⁻¹ in the 1990s (Zou et al., 2009). Therefore, establishing reliable agronomic practices to mitigate N losses and GHG emissions in rice paddies are of national significance.

Optimized N fertilizer management has been shown to be effective to reduce N losses in cropping systems (Xue et al., 2014). Aside from N management, water-saving techniques also help to reduce CH₄ emissions and N losses that occur via runoff and leakage in rice fields (Tyagi et al., 2010; Peng et al., 2015; Liang et al., 2016). A number of studies have focused on mitigation of N losses from single-season rice cropping systems in the Yellow River region (Liu et al., 2012) and rice/wheat rotational cropping systems in the Yangtze River region in central China (Wu and Hu, 2010; Zhang et al., 2011a; Xue et al., 2014). In South China, however, N losses and GHG emissions in the double-season rice cropping system remains unclear. Furthermore, few studies have systematically assessed the effectiveness of integrated N and water management in mitigating both GHG emissions and N losses via runoff, leaching and AV. The potential to mitigate N losses and GHG emissions from paddy field in this cropping system needs to be explored.

Recently, a new nutrient management technology, namely, 'three controls' technology, has been developed and officially recommended to rice farmers in China. The technology includes three components: (1) control of fertilizer-N application to improve NUE; (2) control of unproductive tillers to improve canopy quality; and (3) control of diseases and insects to reduce pesticides use (Zhong et al., 2010). Compared with farmers' practice, 'three controls' technology typically reduces 20% of fertilizer-N input and achieves 10% increase in grain yield (Zhong et al., 2010). The recovery of N fertilizer is increased by 10%. After early tillering of rice, the practice of only re-irrigating fields after the water level has reached to 15 cm below the soil surface is one of the most commonly practiced water-saving techniques in Asia, and was introduced by us into South China in recent years. This practice is known as safe alternate wetting and drying (AWD15). A previous study in double season rice cropping system demonstrated that AWD15 outperformed the farmer's practice of midseason drainage in reducing water input and CH₄ emission under different N levels (Liang et al., 2016). To further improve the water and N use efficiency, integrated

management that combines AWD15 and the 'three controls' technology has been implemented recently in South China (Pan et al., 2017). Yet, an assessment of the environmental impacts from the integration of 'three controls' and AWD15 regimes is still lacking. In the present study, the crop productivity, GHG (CH₄ and N₂O) emission and N losses were systematically evaluated under different water and N management practices. Our objectives were to explore 1) if optimized N management could improve N use efficiency and reduce N loss and GHG emission; and 2) if integrating water-saving technology into the optimized N management could further improve NUE and reduce environmental footprints.

2. Materials and methods

2.1. On-station field experiment

On-station field experiments were conducted in the early and late rice seasons during 2016 at the Dafeng Experimental Station of the Guangdong Academy of Agricultural Sciences (113°20'E, 23°08'N), Guangzhou, Guangdong province, China. The study site is in a subtropical humid monsoon climate zone. Weather data were obtained from the weather bureau of Guangdong province, China and was shown in Fig. 1. In Guangzhou, the mean temperature is 26.3 °C in early rice season from April to July and 25.8 °C in the late rice season from August to November. The paddy soil had pH of 6.0 and contained 41.3 g kg⁻¹ organic matter, 1.62 g kg⁻¹ total N, 1.06 g kg⁻¹ total P, 16.0 g kg⁻¹ total K, 82.6 mg kg⁻¹ available N, 40.4 mg kg⁻¹ available P, and 58.7 mg kg⁻¹ available K.

2.1.1. Treatments and design

The field experiment was laid out in a randomized complete block design with three replications. Four treatments were employed: (1) zero nitrogen application (N0), which followed the farmers' practice of water management, while no N fertilizer was applied during the growing season; (2) farmer's practice (FP), which followed the practice of farmers' water and N management; (3) optimized N management (OPT_N), which included the farmers' practice for water management and 'three controls' technology for optimized N management; (4) optimized N and water management (OPT_N + AWD), which integrate the 'three controls' N management and AWD15 irrigation. The rice variety used was Tianyou 3618 (TY3618), a super hybrid rice variety widely planted in South China. Thirty-day-old (early rice season) or eighteen-day-old (late rice season) seedlings were transplanted at a hill spacing of 20 cm × 20 cm with two seedlings per hill. To prevent water flow between plots, the plots were separated with double bunds that were covered with plastic film buried to a depth of 30 cm.

In farmers' N management, N fertilizer (urea, 46% N) was applied with 40% as basal, 20% at rooting stage, 30% at early tillering stage and 10% at late tillering stage for both seasons. The N rate was 180 kg N ha⁻¹ in early rice season and 210 kg N ha⁻¹ in late rice season. In 'three controls' N management, N rate was 150 kg N ha⁻¹ in early rice season and 180 kg N ha⁻¹ in late rice season. For early rice season, N fertilizer was applied with 50% as basal, 20% at mid-tillering (MT) and 30% at panicle initiation (PI). For late rice season, N was applied with 40% as basal, 20% at MT, 30% at PI and 10% at heading (HD). For all treatments, potassium (135 kg K₂O ha⁻¹ as potassium chloride) and phosphorus (45 kg P₂O₅ ha⁻¹ as calcium superphosphate) was applied as basal in both seasons.

Irrigation treatments were started at the 10th day after transplanting (DAT). Field water depth was kept at 2–5 cm during the first 10 DAT to facilitate seedling recovery. A perforated field water tube was installed to a depth of 15 cm below the soil surface in each plot, with the soil removed from inside of the tube to monitor the water level above and below the soil surface. In N0, FP and OPT_N, field water layer was continuously kept at 2–5 cm after transplanting, and then around 25 DAT, midseason drainage was carried out to control

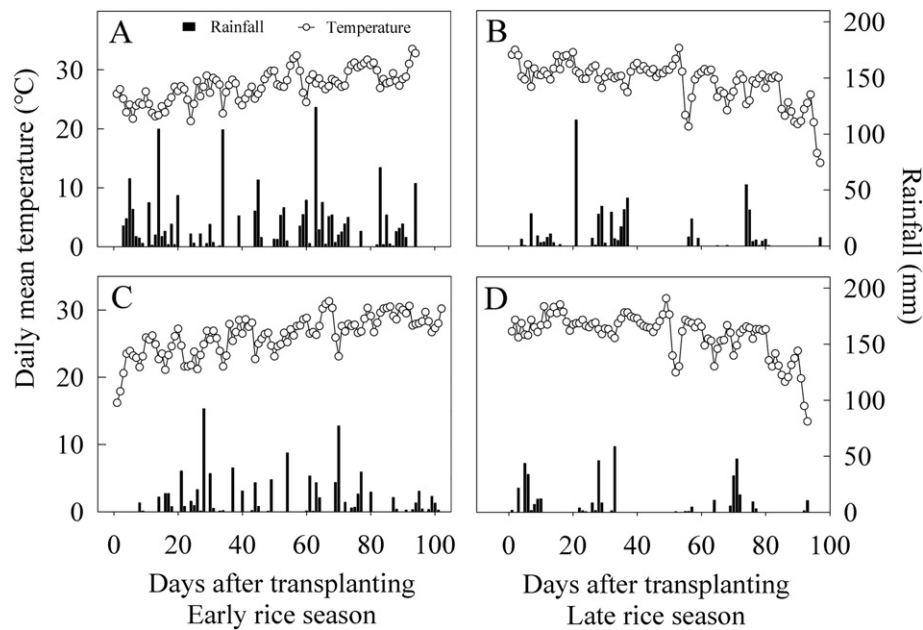


Fig. 1. Daily mean temperature and rainfall during 2016 early and late season at Guangzhou and Gaoyao, Guangdong province. A and B: Guangzhou. C and D: Gaoyao.

excessive growth of tillers until 10 days after visible panicle initiation occurred. The water layer was kept at 2–5 cm at flowering stage to avoid spikelet sterility. Shallow wetting irrigation was carried out after heading. Watering was halted 7 days before harvesting to allow the field to dry. In AWD15, the field was allowed to dry 10 DAT. The next irrigation occurred when the water depth in the field water tube was 15 cm from the surface. The plot was re-irrigated to a depth of 5 cm above the soil surface. At the beginning of heading (when 10% of the panicles had emerged), the field was re-flooded for 7 days to reduce the risk of spikelet sterility. Hereafter AWD15 cycles were repeated until terminal drainage. Field water depth was recorded between 4:00 pm–5:00 pm every other day.

2.1.2. Determination of N uptake, grain yield and nitrogen use efficiency

Twelve hills of plant samples were randomly taken from each plot at MT, PI, HD and physiological maturity (MA) to determine aboveground dry weight and the amount of N uptake of plants. The samples were separated into leaves and stems (including panicles, if any), oven-dried at 75 °C to constant weight, and then weighed. Total aboveground dry weight (TDW) was the sum of the dry matter of leaves and stems (including panicles, if any). Crop growth rate (CGR) was calculated as $CGR = (W_2 - W_1) / (T_2 - T_1)$, where W_1 and W_2 are the TDW at times T_1 and T_2 , respectively. Tissue N concentration was determined by micro-Kjeldahl digestion, distillation, and titration (Bremner and Mulvaney, 1982). Plant N accumulation was calculated by summing the N in each above ground components. The difference in total aboveground N accumulation between sampling times was used to calculate N uptake rates for a specific interval (Peng and Cassman, 1998). At physiological maturity, grain yield was determined from a 5 m² area of each plot and adjusted to a 0.14 kg kg⁻¹ moisture content basis. The nitrogen use efficiencies were evaluated according to Bandaogo et al. (2015): partial factor productivity of applied N ($PPFN = \text{grain yield} / \text{N application rate}$). Apparent N recovery efficiency (ARE) = (N uptake in fertilized plot – unfertilized plot) / N application rate × 100. Agronomic N use efficiency (AE) = (grain yield in fertilized plot – unfertilized plot) / N application rate. Internal N use efficiency ($IE_N = \text{grain yield} / \text{total N uptake}$).

2.1.3. Determination of water input and water productivity

The water input in each plot was measured by a flow meter. Rainfall data were collected by a rain gauge equipped with event data logger (HOBO Event, Massachusetts, USA). Total water productivity (WPT)

was calculated as the grain yield per unit of total water input including irrigation and rainfall (Mahajan et al., 2009).

2.1.4. Measurement of runoff, leaching, and ammonia volatilization

Water samples from runoff loss were collected during each runoff event. Before the experiment, a 20 L plastic bucket was buried beside each plot to collect the sample of runoff water through a piping system as described by Xue et al. (2014). Other runoff from the plot flowed into a drainage ditch through the water outlet. The runoff volume for each plot was recorded by a flow meter set at the water outlet. The height of the hole for the runoff collection pipe was with the same as the height of the outlet to the drainage ditch in each plot. Water from collection buckets was sampled after each runoff event. Total N in a water sample was measured using the alkaline potassium persulfate oxidation-ultra spectrophotometer method. Total N loss from runoff was calculated by multiplying the N concentration of water sampled by the total runoff volume.

The N losses from leaching and AV were measured at 1, 3, 5, 7 and 11 d after fertilizer application and then at intervals of one week until rice harvest. The percolation water was collected by porous polyvinyl chloride pipes (Li et al., 2008a; Ye et al., 2015). Before the experiment, porous pipes were vertically inserted into soil at a depth of 0.5 m in each plot. The pipe was 16 cm in diameter and 70 cm in length, and the bottom was sealed. About 200 pores were bored to form a 10 cm end of pipe with 20 cm margin. To prevent sediment flowing into the column, the bottom of the PVC column was surrounded with quartz sand and covered by nylon net (0.15 mm mesh size). A plastic pellicle was tightly wrapped at 20 cm beneath the soil surface and extended horizontally to 20 cm to prevent floodwater leaking along the pipe. Prior to the sampling, the water in the pipe was pumped out and the volume of leach water was recorded. The amount of water and N in paddy fields was estimated according to the method of Li et al. (2008a). The diameter of the lysimeter and distance between the top of the porous surface and soil zone were 18 and 30 cm, respectively. The part of the PVC lysimeter between the soil surface and the top of porous zone can be abstracted as a hemi-ellipsoid with a 24 cm ($30/2 + 18/2$) diameter and a 30 cm long axes. The volume of hemi-ellipsoid was 0.00904 m³. The leaching of water and N from the hemi-ellipsoid corresponded to those from the lysimeter, therefore the soil with a depth of 30 cm and an area of 1 ha contained 331,573 hemi-ellipsoids.

The ammonia volatilization loss from a field was measured by a semi open-static system using an ammonia-trapping chamber with a phosphoglycerol soaked sponge as the absorbent (Xue et al., 2014). The chamber was constructed with PVC pipe 20 cm in diameter and 25 cm tall. The base of the chamber was inserted 5 cm into the soil. The lower sponge was used to absorb ammonia volatilized from the soil while an upper sponge was used to prevent the lower sponge absorbing ammonia from outside. The ammonia in the upper sponges was then extracted by 300 mL of 1.0 mol L⁻¹ KCl and was evaluated by a distillation and titration method. Ammonia flux was calculated by the following equation:

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

where M is the ammonia volatilization amount collected by the collector (mg), A is the cross-sectional area of the collector (m²), and D is the sampling interval (d).

2.1.5. Measurement of CH₄ and N₂O emission

The CH₄ and N₂O emission were simultaneously measured at 7-d intervals by the static chambers method (Wang et al., 2012). The chamber was square in cross section and was made of PVC with an area of 60 cm × 60 cm. The chamber was wrapped with sponge and aluminum foil to minimize temperature changes inside. An electric fan was installed in the chamber for gas mixing. During the sampling, one chamber was placed on the base frame fixed in each plot, and then gas samples were collected with a sealed and pre-evacuated tube. Gas samples were taken between 9:00 am–11:00 am and analyzed by a gas chromatograph (Agilent 7890A, Agilent Technologies, USA). The water depth and air temperature in the chamber were recorded during sampling. The CH₄ and N₂O emission fluxes were calculated by the following equation (Zheng et al., 1998):

$$F = \rho \times h \times [273/(273 + T)] \times dC/dt, \quad (2)$$

where F is the gas flux (mg m⁻² h⁻¹ for CH₄, μg m⁻² h⁻¹ for N₂O), ρ is the density at the standard state (0.714 kg m⁻³ for CH₄, 1.964 kg m⁻³ for N₂O), h is the height of the chamber above the soil (40 cm at early tillering stage, 60 cm at MT, 120 cm at PI and thereafter), T is the mean air temperature (°C) inside the chamber; dC/dt is the gas accumulation rate with time (t) in the chamber (mg m⁻³ h⁻¹ for CH₄, μg m⁻³ h⁻¹ for N₂O).

The net effect of CH₄ and N₂O emissions expressed in CO₂-equivalents was obtained by multiplying the cumulative emissions of CH₄ and N₂O by 21 and 310, respectively (IPCC, 2007).

2.2. On-farm comparisons

In 2016, on-farm comparison trials were conducted in the early and late rice seasons at farm land (113°19′, 23°14′N) in Baitudong village of Gaoyao county, Guangdong province during 2016. The mean temperature in the site was 26.2 °C in early rice season (April to July) and 26.3 °C in the late rice season (August to November). Total rainfall was 770.4 mm for the early rice season and 406.1 mm for the late rice season (Fig. 1C and D). The field soil was waterloggogenic paddy soil, which had pH of 4.8 and contained 26.8 g kg⁻¹ organic matter, 1.98 g kg⁻¹ total N, 116.0 mg kg⁻¹ available N, 25.3 mg kg⁻¹ available P, and 51.6 mg kg⁻¹ available K.

The comparison trials were performed with three treatments and three replications. The treatments were FP, OPT_N and OPT_N + AWD. In FP, N fertilizer (urea) was applied with 40% as basal, 20% at rooting stage, 30% at early tillering stage and 10% at late tillering stage. Total N rate was 202.5 kg N ha⁻¹ according to the local average level. Fertilizer K (potassium chloride) was applied at the rate of 112.5 kg K₂O ha⁻¹ with 50% at early tillering stage and 50% at late tillering stage. Fertilizer P (calcium superphosphate) was applied as basal dressing at the rate of 45 kg P₂O₅ ha⁻¹.

In OPT_N and OPT_N + AWD, total N rate was 150 kg N ha⁻¹ in both seasons. In early rice season, N fertilizer was applied with 50% as basal, 20% at MT and 30% at PI. In late rice season, N was applied with 40% as basal, 20% at MT, 30% at PI and 10% at HD. Fertilizer K was applied at the rate of 112.5 kg K₂O ha⁻¹ with 50% at MT and 50% at PI. All fertilizer P was applied as basal at the rate of 36 kg P₂O₅ ha⁻¹. Water management of FP and AWD15 were the same as those of the on-station experiment in Guangzhou. The rice varieties used were Shuangzhensimiao (inbred) in early rice season and Shenyou 9516 (hybrid) in late rice season. The seedlings were transplanted manually at a hill spacing of 20 cm × 20 cm. The number of irrigations was recorded. The runoff loss was measured followed the same method as that in the on-station field experiment. Grain yield was measured at harvest and adjusted to 14.0% moisture content.

2.3. Statistical analysis

The significance of the treatment effect was determined using F-test. When ANOVA indicated that there was a significant difference, multiple comparisons of means were performed using the Least Significant Difference method (LSD) at 0.05 probability level.

3. Results

3.1. On station field experiment

3.1.1. Water input and productivity

Field water depths in N0, FP and OPT_N were maintained at 0–5 cm for most periods except for the midseason drainage (Fig. 2). In OPT_N + AWD plots, the field water depth fluctuated from 5 to –15 cm, and the seasonal drainage period was increased by 9–14 days as compared with N0, FP and OPT_N for both seasons. In late rice season, more AWD cycles occurred in OPT_N + AWD due to lower rainfall.

The rainfall was 8952 m³ ha⁻¹ for the early rice season and 3926 m³ ha⁻¹ for the late rice season (Table 1). Under the same treatment, irrigation water input and the number of irrigation were higher, while the total water input was lower in late rice season. The irrigation water input and total water input were lowest in OPT_N + AWD, while there were no significant differences between FP and OPT_N. The irrigation water input and total water input in OPT_N + AWD compared with OPT_N was decreased by 89.4% and 11.9% in early rice season, and by 30.6% and 12.8% in late rice season, respectively. WPT in OPT_N and OPT_N + AWD were both higher than in FP. Owing to the lower water input in AWD15, the WPT in OPT_N + AWD was increased by 13.9% in early rice season and 18.4% in late rice season compared with OPT_N.

3.1.2. Crop growth, grain yield, plant N uptake and N use efficiency

The crop growth rate was lowest in TR-MT and highest in PI-HD for all treatments (Fig. 3). In terms of N uptake accumulation, the highest N uptake rate and N accumulation amount for FP were observed in MT-PI. While for OPT_N and OPT_N + AWD, highest N uptake rate and N accumulation amount were observed in PI-HD. Due to delayed N application, OPT_N and OPT_N + AWD had greater N uptake rate and N accumulation than FP during PI-HD for both seasons. OPT_N and OPT_N + AWD were comparable in grain yield and total N uptake at harvest (Table 2). Compared with FP, the grain yield under OPT_N and OPT_N + AWD treatments was significantly increased by 13.0–17.3%, while the total N uptake of rice plants increased by 18.5–32.9% across the two cropping seasons. The NUE indices including PFP_N, ARE and AE (except for IE_N) were significantly higher than those of FP. No significant difference of NUE indices were found between OPT_N and OPT_N + AWD in both seasons (Table 2).

3.1.3. N losses through runoff, leaching, and ammonia volatilization

The N runoff loss in FP, OPT_N and OPT_N + AWD averaged 21.6, 11.8 and 6.80 kg N ha⁻¹ across the two seasons, respectively. Approximately 56.4–76.6% of N runoff loads were observed in the early rice season across the treatments (Fig. 4 and Table 3), mainly due to the temporal

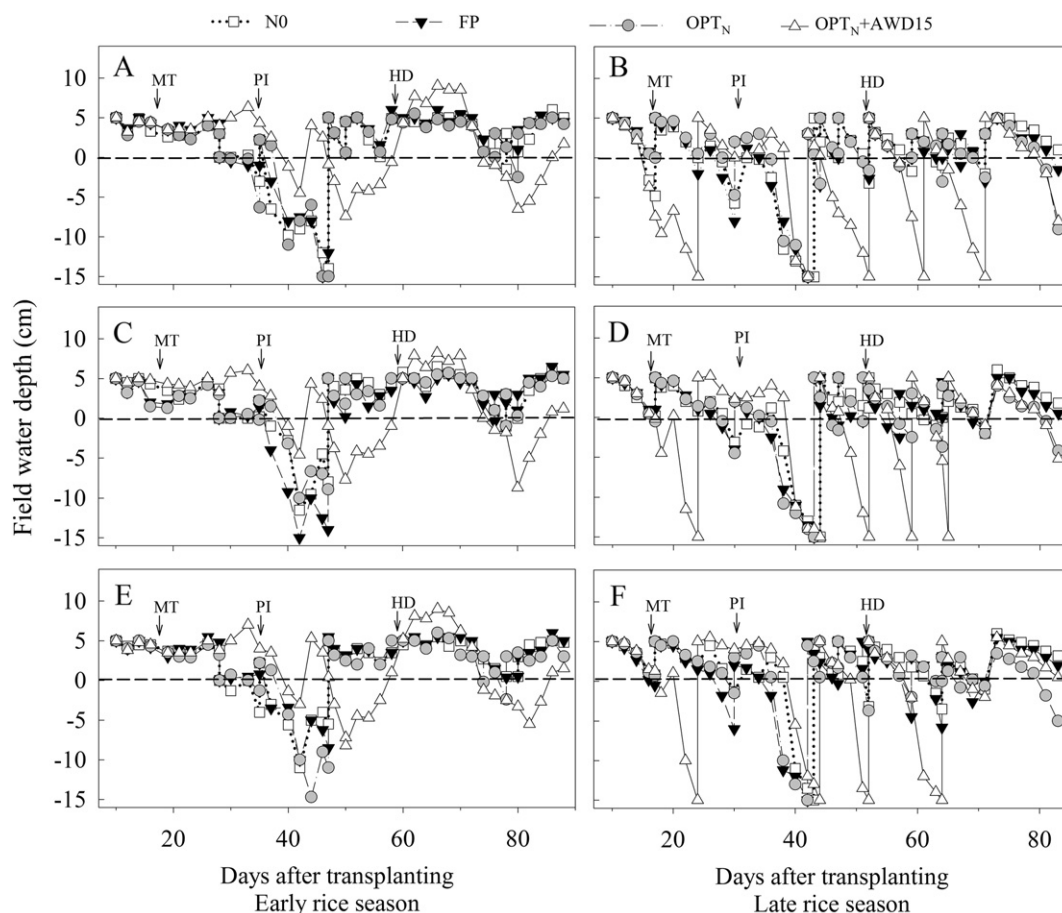


Fig. 2. Changes in field water depth under different treatments in the on-station field experiments conducted during 2016 early and late seasons in Guangzhou. The field water depth under different irrigation treatments was demonstrated by single replication group. A, C, E: replication 1, 2, 3 of early season. B, D, F: replication 1, 2, 3 of late season, respectively.

distribution of rainfall. For all fertilized treatments, the N runoff loss mainly occurred in the TR-MT, amounting to >60% of the runoff for the whole season (Fig. 5). Compared with FP, the N runoff loss in OPT_N was reduced by 51.6% in early rice season and 34.4% in late rice season (Table 3). Compared with OPT_N, the runoff event in OPT_N + AWD was significantly reduced, N runoff losses were consequently reduced by 39.1% in early rice season and 46.7% in late rice season.

The N loss via AV contributed to over 50% of the total N losses for all treatments (Table 3). The highest peak of fluxes of AV rate appeared on the first day after each split of urea application and rapidly decreased to a negligible level (Fig. 4). Across the two seasons, the AV loss for FP, OPT_N

and OPT_N + AWD treatments averaged 45.7, 34.1 and 33.1 kg N ha⁻¹, respectively (Table 3). Both OPT_N and OPT_N + AWD had a significantly decreased AV loss relative to FP ($p < 0.05$), with a mean reduction of 25.5% and 27.6%, respectively. In FP, AV losses mainly occurred in the stage of TR-MT, accounting for 44.4% of the seasonal AV loss for early rice season and 76.2% of late rice season (Fig. 5). In OPT_N and OPT_N + AWD, AV loss mainly occurred in the TR-MT and PI-HD, accounting for 62.8%–85.7% of the seasonal AV loss.

The N leaching loss in FP, OPT_N and OPT_N + AWD averaged 17.6, 11.4 and 9.55 kg N ha⁻¹ across the two seasons, respectively (Table 3). In FP, the N leaching loss mainly occurred in TR-PI (Fig. 5). N leaching amount in OPT_N was reduced by 45.9% in early rice season and 26.9% in late rice season compared with FP. N leaching loss in OPT_N + AWD was reduced by 6.2% in early rice season and 23.5% in late rice season compared with OPT_N. In OPT_N + AWD, N loss from leaching was greater than that from runoff in late season.

Across the two seasons, the mean N losses loading in FP, OPT_N and OPT_N + AWD was 85.1, 57.3 and 49.5 kg N ha⁻¹, respectively (Table 3). In FP, the total N losses loading accounted for 49.6% of fertilizer N input in the early rice season and 38.5% in late rice season. The total N losses loading in OPT_N + AWD was reduced by 34.1% in early rice season and 31.2% in late rice season compared with FP. The total N losses loading in OPT_N + AWD was reduced by 11.8% in early rice season and 15.7% in late rice season compared with OPT_N, mainly due to the lower runoff amount of N under the AWD15 regime. Total N losses in the stage of TR- MT in FP, OPT_N and OPT_N + AWD was 52.1, 23.5 and 22.1 kg N ha⁻¹ for early rice season and 55.3, 28.4 and 25.0 kg N ha⁻¹ for late rice season, respectively, accounting for 39.8–68.2% of seasonal N losses (Fig. 5). Therefore, TR-MT was the critical stage for losses of N during both rice cropping seasons.

Table 1

The rainfall, water input and water productivity (WPT) during the growing season under different treatments in the on-station field experiment conducted during 2016 early and late season in Guangzhou, Guangdong province, China.

Season	Treatment	Rainfall (m ³ ha ⁻¹)	No. of irrigations	Irrigation water input (m ³ ha ⁻¹)	Total water input (m ³ ha ⁻¹)	WPT (kg m ⁻³)
Early rice	NO	8952	2.7 ab ^a	878.7 a	9830.7 a	0.45 d
	FP	8952	4.0 a	1280.3 a	10,232.3 a	0.63 c
	OPT _N	8952	5.7 a	1372.2 a	10,324.2 a	0.72 b
	OPT _N + AWD	8952	1.0 b	146.1 b	9098.1 b	0.82 a
Late rice	NO	3926	6.0 b	2094.6 bc	6020.6 bc	0.88 c
	FP	3926	8.0 a	2757.4 ab	6683.4 ab	1.11 b
	OPT _N	3926	8.0 a	2827.0 a	6753.0 a	1.25 b
	OPT _N + AWD	3926	4.3 b	1963.1 c	5889.1 c	1.48 a

Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (LSD).

^a Values are means of three replications.

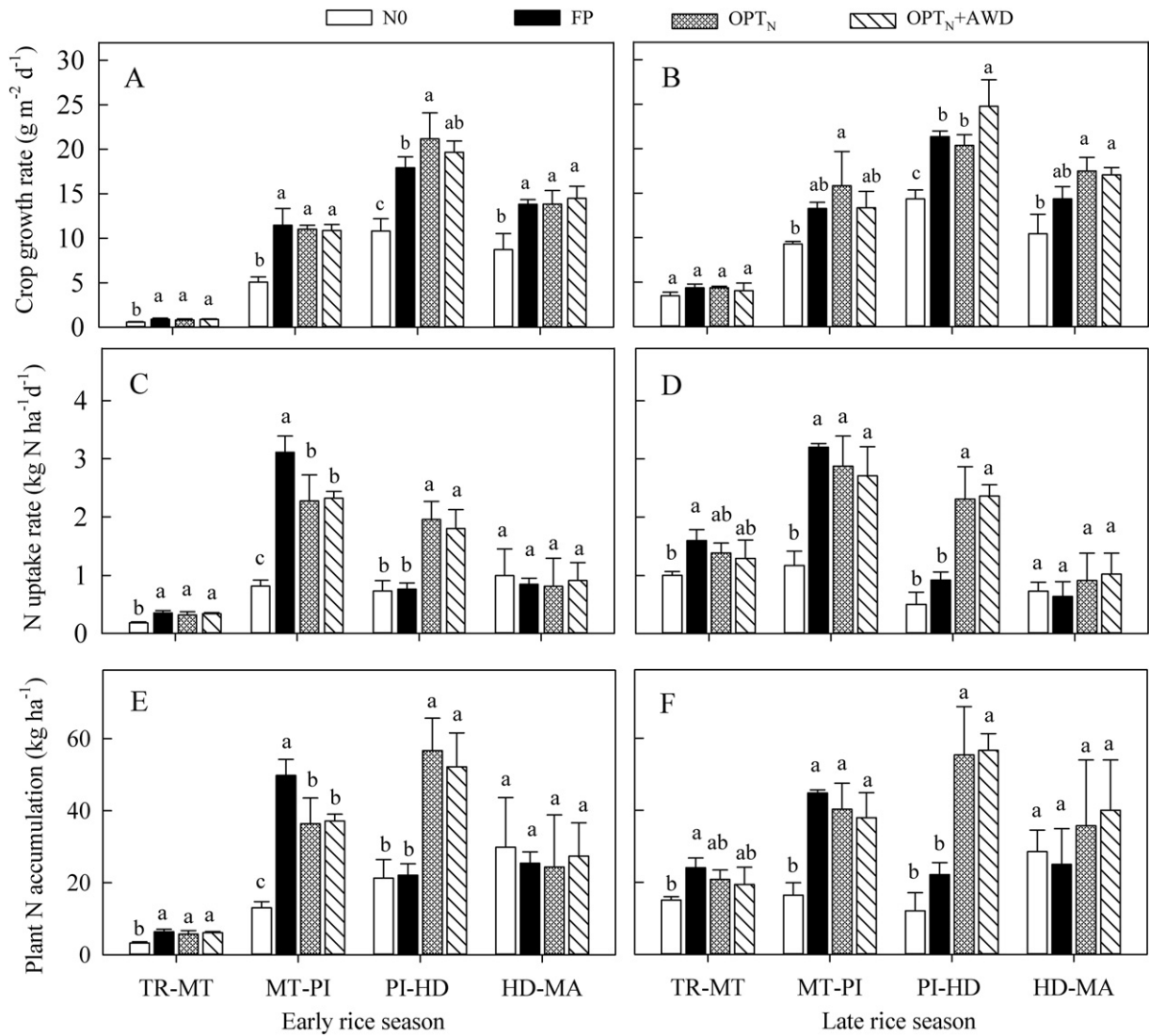


Fig. 3. Crop growth rate, N uptake rate and plant N accumulation from transplanting to mid-tillering (TR-MT), mid-tillering to panicle initiation (MT-PI), panicle initiation to heading (PI-HD) and heading to maturity (HD-MA) under different treatments at the on-station field experiment conducted during 2016 early and late seasons in Guangzhou. Values are means + SD for three replications. Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (LSD).

3.1.4. CH₄ and N₂O emissions

In early rice season, CH₄ emissions were initially high and decreased during midseason drainage in farmers' practice or during AWD cycles. However, after the field was re-flooded in FP and OPT_N, the CH₄ emission resumed and was maintained at a high level during HD-MA. In late rice season, the CH₄ fluxes in NO, FP and OPT_N reached a peak at late tillering stage, then decreased at midseason drainage and thereafter maintained a low level due to

the descending air temperature (Fig. 6A and B). The CH₄ fluxes in OPT_N + AWD were significantly decreased after the AWD cycles and were the lowest for all treatments. The seasonal CH₄ emission in FP, NO, OPT_N and OPT_N + AWD averaged 194.3, 158.4, 187.0 and 126.2 kg CH₄ ha⁻¹ across the two seasons, respectively (Table 4). There were no statistical differences in CH₄ emission between FP and OPT_N, but lower total GWPs per unit grain yield was obtained in OPT_N due to higher yield. The CH₄ emission in OPT_N + AWD was

Table 2

The grain yield, total 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 on-station field experiment conducted during 2016 early and late seasons in Guangzhou, Guangdong Province, China.

Season	Treatment	Grain yield (kg ha ⁻¹)	Total N uptake (kg ha ⁻¹)	IE _N (kg kg ⁻¹)	ARE (%)	AE (kg kg ⁻¹)	PFP _N (kg kg ⁻¹)
Early rice	NO	4465.4 c	67.5 c	68.0 a	—	—	—
	FP	6491.0 b	103.7 b	62.7 a	20.1 b	11.3 b	36.1 b
	OPT _N	7387.0 a	123.2 a	60.1 a	37.1 a	19.5 a	49.2 a
	OPT _N + AWD	7476.7 a	122.9 a	60.9 a	36.9 a	20.1 a	49.8 a
Late rice	NO	5273.2 c	72.1 c	74.1 a	—	—	—
	FP	7400.0 b	115.9 b	64.1 ab	20.9 b	10.1 b	35.2 b
	OPT _N	8361.9 a	152.1 a	54.9 b	44.5 a	17.2 a	46.5 a
	OPT _N + AWD	8682.6 a	154.0 a	56.4 b	45.5 a	18.9 a	48.2 a

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

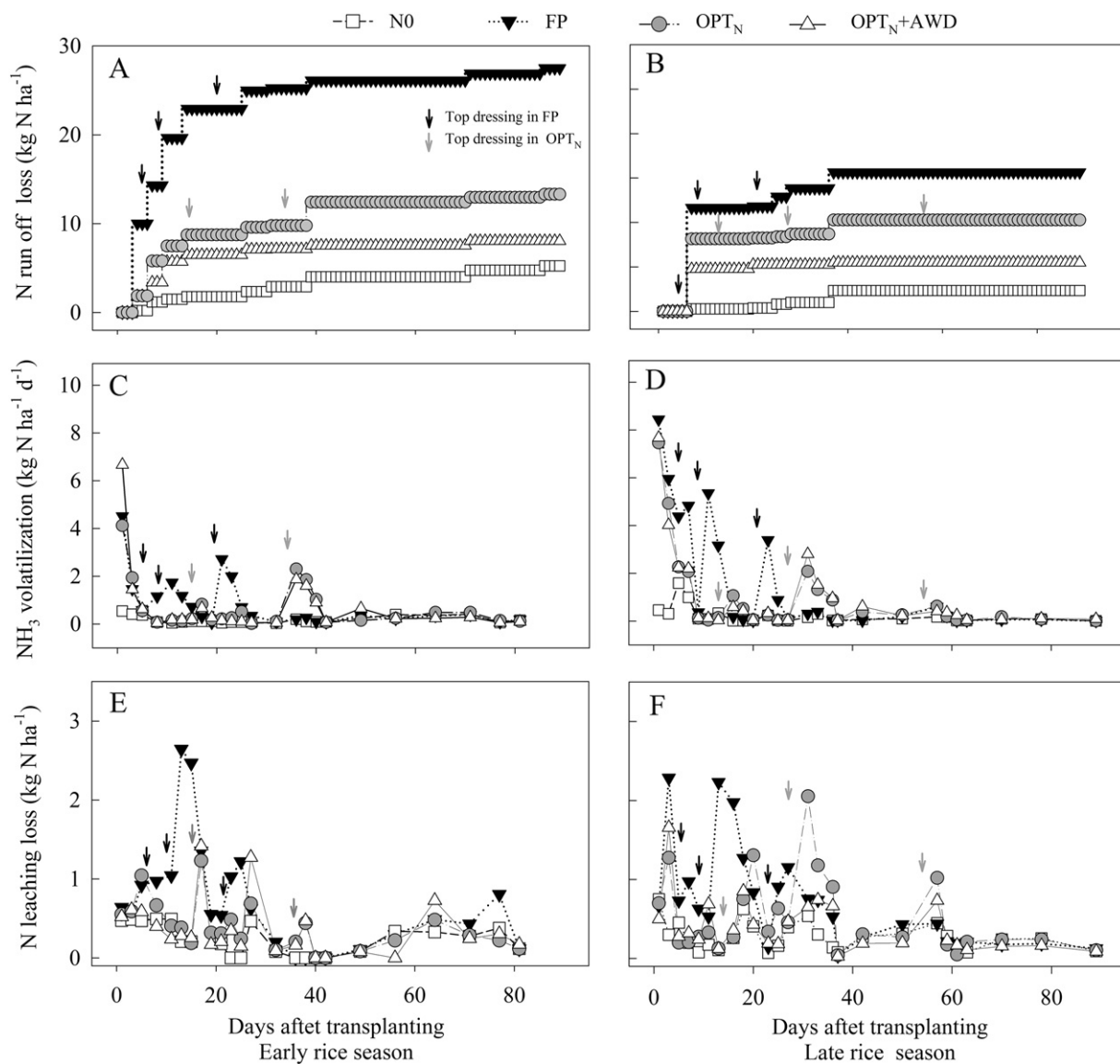


Fig. 4. Dynamics of runoff, ammonia (NH_3) volatilization and leaching losses of N under different treatments at the on-station field experiment conducted during 2016 early and late seasons in Guangzhou.

reduced by 21.1% and 20.5% in early rice season, and by 45.4% and 42.0% in late rice season, respectively, compared with FP and OPT_N .

Table 3

The N losses from run-off, leaching and ammonia volatilization under different treatments in the on-station field experiment conducted during 2016 early and late seasons in Guangzhou, Guangdong Province, China.

Season	Treatment	Run-off (kg N ha ⁻¹)	Leaching (kg N ha ⁻¹)	Ammonia volatilization (kg N ha ⁻¹)	Total N losses (kg N ha ⁻¹)
Early rice	N0	5.3 c	5.08 c	16.5 c	26.8 c
	FP	27.5 a	17.13 a	44.9 a	89.4 a
	OPT_N	13.3 b	9.26 b	36.4 b	58.9 b
	OPT_N + AWD	8.1 c	8.69 b	35.2 b	52.0 b
Late rice	N0	1.62 c	7.1 d	8.99 c	17.7 c
	FP	15.7 a	18.6 a	46.5 a	80.8 a
	OPT_N	10.3 b	13.6 b	31.7 b	55.6 b
	OPT_N + AWD	5.49 c	10.4 c	31.0 b	46.9 b

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

The seasonal N_2O emission was significantly influenced by fertilizer management practices. The application of basal N fertilizer significantly promoted N_2O fluxes. The highest N_2O fluxes appeared in FP due to the large amount of N topdressing in seedling stage (Fig. 6C and D). The N_2O emission in OPT_N and OPT_N + AWD was decreased by 31.8% and 26.0% in early rice season, and by 30.7% and 22.1% in late rice season, respectively, compared with FP. Compared with OPT_N , the N_2O emission was slightly increased in OPT_N + AWD plots, but with no statistical significance.

Across the two seasons, the total GWP in FP, N0, OPT_N and OPT_N + AWD was 5017.1, 3524.1, 4569.8 and 3367.7 kg CO_2 ha⁻¹, respectively. No statistical difference was detected in GWPs between FP and OPT_N in both seasons. Whereas the GWP in OPT_N + AWD was reduced by 22.0% in early rice season and 40.7% in late rice season ($p < 0.05$), respectively, compared with FP.

3.1.5. Correlation analysis in N losses and CH_4 emission

There was a positive linear relationship between seasonal GWP of CH_4 (y, kg CO_2 ha⁻¹) and irrigation water input (x, m³ ha⁻¹). The regression equation, $y = 0.622x + 3122.7$ yielded significant R^2 ($R^2 = 0.337$, $p < 0.05$). Correlations analysis using pooled data across two seasons in OPT_N and OPT_N + AWD revealed that the N loss by runoff (y_1 , kg

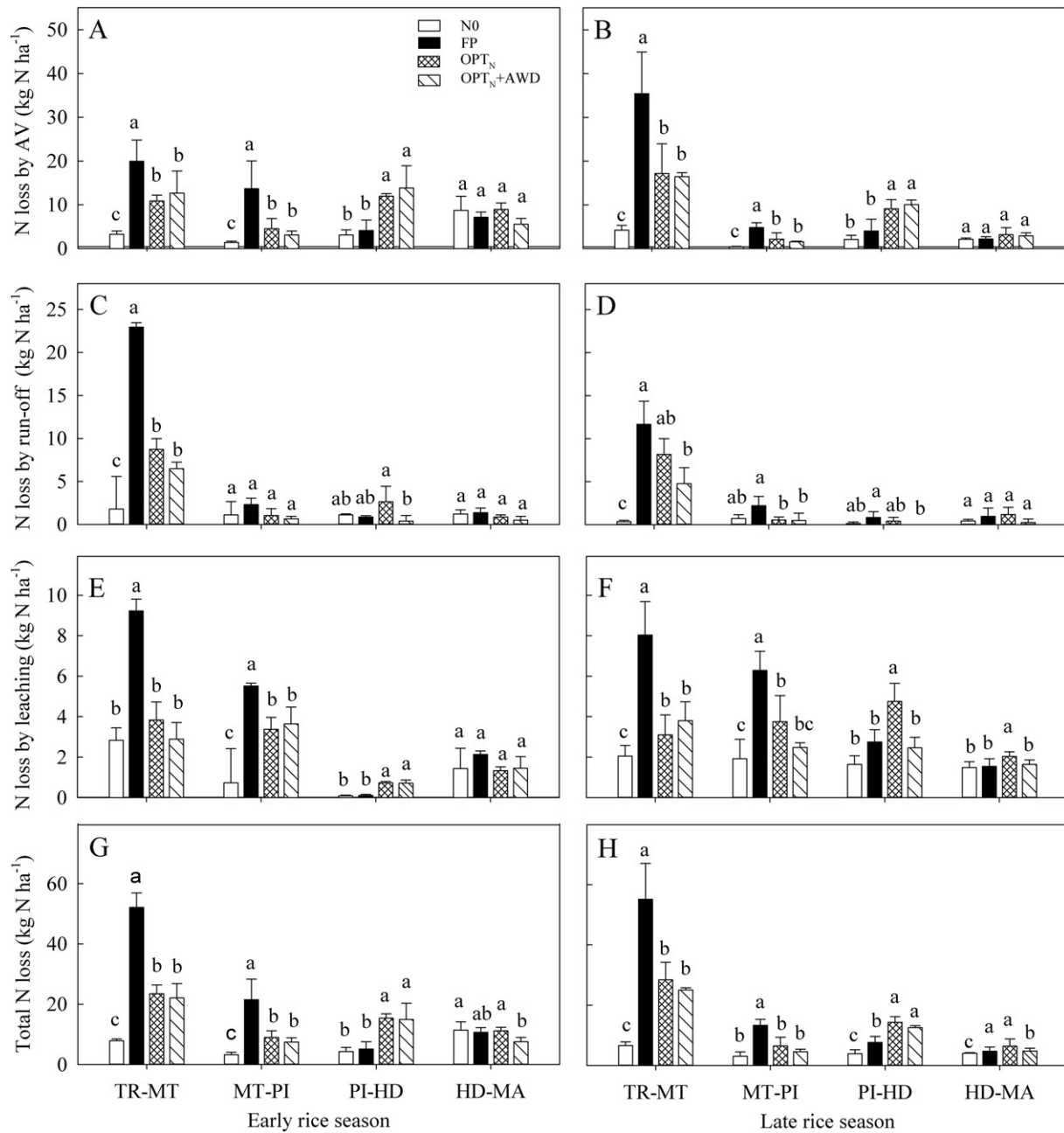


Fig. 5. The N losses through surface run-off, leaching and ammonia volatilization from transplanting to mid-tillering (TR-MT), mid-tillering to panicle initiation (MT-PI), panicle initiation to heading (PI-HD) and heading to maturity (HD-MA) under different treatments. Values are means + SD for three replications. Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (LSD).

N ha^{-1}) and the total N losses (y_2 , kg N ha^{-1}) were both significantly correlated with the total water input (x , $\text{m}^3 \text{ha}^{-1}$). The resulting regression equations were $y_1 = 0.0011x + 0.770$ ($R^2 = 0.357$, $p < 0.05$) and $y_2 = 0.0018x + 39.3$ ($R^2 = 0.345$, $p < 0.05$), respectively. This indicated that under the same N management, N losses can be mitigated by a systematic reduction of water input. In FP, OPT_N and OPT_N + AWD, the total N losses were negatively correlated with N accumulation and NUE indices including PFP_N, ARE and AE (Fig. 7), indicating a great opportunity for reducing N losses associated with higher plant N uptake and NUE under optimized N and water management.

3.2. Performance of OPT_N and AWD in on-farm comparison trials

Our on-farm comparison trials in farmer's field indicated that OPT_N and OPT_N + AWD increased grain yield by 6.7–13.9% as compared

with FP. The PFP_N was significantly increased in OPT_N and OPT_N + AWD plots in both cropping seasons. Runoff N loss was significantly affected by water and N management, being highest in FP and lowest in OPT_N + AWD (Table 5). Compared with FP, the runoff N loss in OPT_N + AWD was reduced by 52.3% in early rice season and 42.1% in late rice season.

4. Discussion

4.1. Crop yield, N uptake and NUE in relation to N and water management

Rice farmers traditionally apply over 80% of N fertilizers at basal and the rest top-dressed within the first 10–20 DAT to promote early tillering (Zhong et al., 2010; Jiang et al., 2012). Large amount of N fertilizer applied at the early growth stages, however, resulted in poor

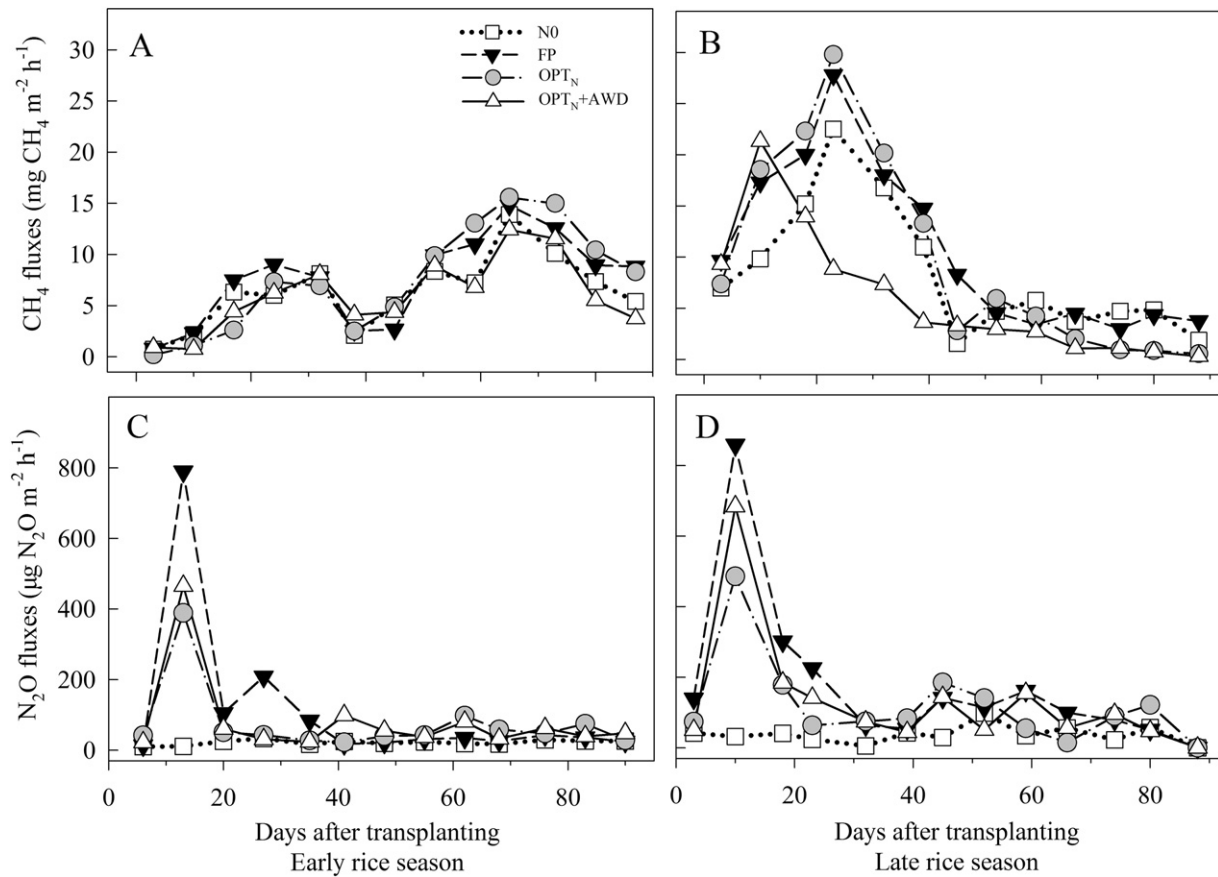


Fig. 6. The CH_4 and N_2O emissions from rice field under different treatments in the on-station field experiment conducted during 2016 early and late seasons in Guangzhou.

synchronization between N supply and crop demand, leading to low NUE and large numbers of unproductive tillers (Zhong et al., 2010; Zhang et al., 2011b). Although N input was significantly reduced in OPT_N and $\text{OPT}_N + \text{AWD}$, the grain yields, crop N uptake and NUE indices in OPT_N and $\text{OPT}_N + \text{AWD}$ were significantly increased (Table 2). The delay of N input in ‘three controls’ technology helps to reduce unproductive tillers through avoiding luxury crop N uptake in tillering stage. In addition, high proportion of panicle N fertilizer was adopted in this technology. It has been proven that N absorbed during panicle formation makes the most contribution to spikelet production (Sun et al., 2012; Zhong et al., 2010). Moreover, under the denser plant root systems in later growth stage, plants could more effectively use the N fertilizer.

Table 4

Global warming potential (GWP) of CH_4 and N_2O from rice field under different treatments in the on-station field experiment conducted during 2016 early and late seasons in Guangzhou, Guangdong Province, China.

Season	Treatment	CH_4 emissions (kg ha ⁻¹)	N_2O emissions (kg ha ⁻¹)	Total GWP (kg CO ₂ ha ⁻¹)	Total GWP per unit grain yield (kg CO ₂ kg ⁻¹ grain yield)
Early rice	NO	139.3 b	0.47 c	3069.1 b	0.69 a
	FP	166.1 a	2.23 a	4181.1 a	0.65 a
	OPT_N	164.7 a	1.52 b	3928.8 a	0.53 b
	$\text{OPT}_N + \text{AWD}$	131.0 b	1.65 b	3262.8 b	0.44 c
Late rice	NO	177.5 ab	0.81 c	3979.1 b	0.75 a
	FP	222.5 a	3.81 a	5853.0 a	0.79 a
	OPT_N	209.2 a	2.64 b	5210.7 a	0.63 a
	$\text{OPT}_N + \text{AWD}$	121.4 b	2.97 b	3472.6 b	0.40 b

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

Our previous study showed that AWD15 can be easily extended to rice growers as field water level can be managed with simple guidelines coupled with simple instrumentation (Liang et al., 2016; Pan et al., 2017). This technique outperformed the farmer’s water management practice with mid-season drainage on grain yield and WPT under various N input levels (Pan et al., 2017). Results from current study also showed that the grain yield in $\text{OPT}_N + \text{AWD}$ was comparable as OPT_N with higher WPT (Table 1). The trend was the same for both seasons, and the on-farm comparison trials at Gaoyao confirmed the observations in Guangzhou (Table 5). The maintenance in grain yield under AWD15 with lower water input can be attributed to the sufficient water supply even the field water falls to 15 cm below the soil surface. At 15 cm threshold, the soil water potential at 15 cm depth is higher than -10 k Pa, and rice can still take up enough water from the saturated soil and the perched water in root zone (Liang et al., 2016).

4.2. N losses loading in relation to N and water management

The climate in South China is characterized by the overlap of the high temperature and the abundant rainfall (Xiang and Griffiths, 1988). These may trigger considerable CH_4 emissions and N losses through runoff and AV from paddies. The FP is representative of the majority of farmers’ N and water management practice in South China. When large amounts of N were applied during the seedling stage in FP, considerable N losses by AV and runoff occurred when the high amount of applied N coincided with heavy rainfall events or high temperature. Although the study was carried out only in one year, the results from the two-seasons (early rice season and late rice season) in Guangzhou both showed that OPT_N and $\text{OPT}_N + \text{AWD}$ significantly reduced N loss from AV, runoff and leaching (Table 3). On-farm experiment conducted in Gaoyao also showed that N loss through runoff in OPT_N and $\text{OPT}_N + \text{AWD}$ was reduced by 10.2–61.4% as compared with

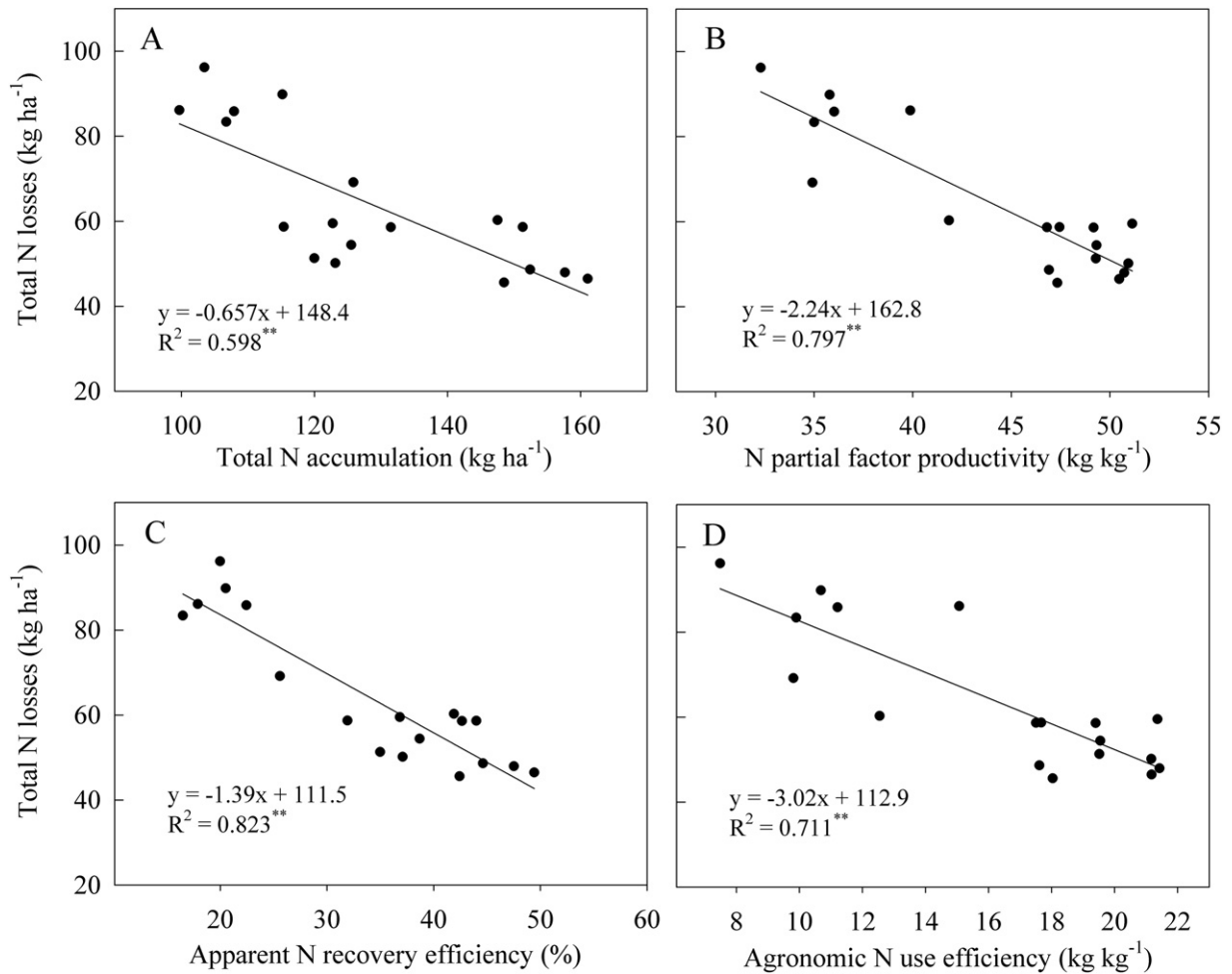


Fig. 7. Correlation between the total N loss and total N accumulation, partial factor productivity, apparent recovery efficiency, and agronomic N use efficiency of applied N under different treatments in the on-station field experiment conducted during 2016 early and late seasons in Guangzhou. The double asterisks (**) denote significantly correlated at the 0.01 probability level.

FP (Table 5). Through the paths of AV, runoff and leaching, the FP treatment released 89.4 kg ha^{-1} of N to the environment in early rice season and $80.8 \text{ kg N ha}^{-1}$ in late rice season (Table 3). By adopting the 'three controls' technology in OPT_N , the N input was reduced by 14.3% in early rice season and 16.7% in late rice season as compared with FP. The average N loss through AV, runoff and leaching was reduced by 45.4%, 36.0% and 25.5%, respectively. Except cutting the N input, postponing N application should also have contributed to reduce N losses in the rice field. In FP, the runoff N losses mainly occurred in the stage of TR-PI, when the rainfall in this period accounted for >40% of seasonal rainfall (Fig. 5). Whereas in the 'three controls' technology, N topdressing was adjusted to PI and HD, and this helped to avoid serious rainfall events. Generally, the ratio of AV process increases with the wind speed, radiation, air temperature and ammonia concentrations in water (Sommer et al., 2004). Li et al. (2008b) reported that N loss via AV in South

China can be as high as 40% of the total applied N due to the strong solar radiation and high temperature. The current study also showed that AV is the primary pathway for N loss, accounting for over 50% of the total loss of N regardless of treatments and season (Table 3). By reducing and postponing N application in OPT_N , AV loss was remarkably reduced. Although a high flux pulse of AV occurred after the topdressing at PI, this level was significantly lower than after basal dressing (Fig. 4C and D). We assumed that the larger canopy in PI-HD may have helped reduce AV loss by reducing the temperature and air movement above the water surface.

Flood irrigation with midseason drainage is a traditional practice in South China, but heavy rainfall often triggers considerable runoff of N (Yao et al., 2015). Compared with OPT_N , adopting AWD15 in the OPT_N + AWD treatments reduced losses of N from runoff and leaching by 42.4% and 16.5%, respectively, across the two seasons. This can be

Table 5

The grain yield, partial factor productivity (PFP_N) and run off loss of N in the on-farm comparison trials conducted during 2016 early and late season at Gaoyao, Guangdong province, China.

Season	Variety	Treatment	Grain yield (kg ha ⁻¹)	PFP _N (kg kg ⁻¹ N)	N loss from run off (kg N ha ⁻¹)
Early rice	Shuangzhensimiao	FP	7092.7 a	35.5 b	10.3 a
		OPT_N	8075.6 a	53.8 a	8.33 a
		OPT_N + AWD	7568.6 a	50.5 a	3.97 b
Late rice	Shenyou9516	FP	7339.1 b	36.7 b	5.79 a
		OPT_N	8117.4 ab	54.1 a	5.20 a
		OPT_N + AWD	8355.5 a	55.7 a	3.01 a

Values are means for three replications. Within a column at each location, the different lowercase letters indicate significant differences for treatment at $p < 0.05$.

attributed to the large reduction in water input, as AWD15 allows the floodwater to drop at 15 cm below the soil surface, and total volume of surface runoff and water leakage were consequently reduced.

Previous research does not provide a consensus on the influence of irrigation on AV rates. It was suggested that AV was higher in AWD than under flood irrigation because lower water input under AWD resulted higher ammonium concentration in the paddy water (Win et al., 2009). On the other hand, intermittent irrigation was reported to reduce AV due to enhanced ammonium binding in the soil (Zhu et al., 1988). In the current study, the AV loss was not significantly different between OPT_N and OPT_N + AWD treatments, suggesting that the water regime had little effect on AV. This can be accounted for by the fact that the field was irrigated to 2–3 cm before fertilization in both water regimes. Hence, water status was not significantly different among treatments within 3 days after fertilization, a period when loss of AV is highest.

A fundamental principle of reducing losses of N in fields is to maximize the amount of fertilizer used by the crop, in other words, to increase the crop NUE in intensive vegetable production (Venterea et al., 2012). Therefore, good agronomic practices should lead to higher NUE and lower losses of N. We found that in FP, the N losses loading in TR-MT accounted for 58.3–68.4% of seasonal N losses loading, mainly due to the large input of N fertilizer at early growth stage when the rice seedlings do not have a well-developed root system. Proper timing of N application is crucial to improve N use efficiency and minimize N losses. Fageria and Baligar (2001) suggested that split or delayed top-dressing produce higher recoveries by giving the rice plant a better chance to compete against N losses to the environment. Correlation analysis in this study revealed that the total N losses was negatively correlated with the NUE indices of rice, indicating a great opportunity for reducing N losses associated with higher NUE and increased effectiveness of absorption of N by rice plants via optimized N and water management. In rice-soil systems, fertilizer N is partitioned between crop uptake, N immobilization in soil and N losses in the paddy field. Since the plant uptakes of N in paddy soil compete against the losses, the effectiveness of the plant to absorb N critically influences the N losses. Higher NUE indices of PPP_N, ARE and AE indicate more nutrient utilization by plant growth and lower N loading to the environment. In OPT_N and OPT_N + AWD, optimal timing of N top-dressing in coordination with rapid plant N uptake rate not only increased the NUE indices, but also reduced the seasonal N losses through better synchronization between crop demand and N supply.

4.3. GHG emission in response to N and water management

CH₄ was the dominant contributor to the net GWPs in rice paddies, contributing 73.5–95.3% to the net GWPs for all treatments. Usually the highest air temperature occurs in June to August in South China. In FP and OPT_N treatments which employed farmers' water management, the highest fluxes of CH₄ were observed during the flooding stage in HD-MA (June to July) in early rice season (Fig. 6). While in late rice season, the highest fluxes occurred during flooding at the Tr-MT stages (early to mid-August). This indicated that the fluctuation of CH₄ emission was strongly affected by temperature under flood condition. Usually the soil Eh lower than –150 mV is a requirement for the production of CH₄ (Wang et al., 1993). But by adopting intermittent irrigation, soil aeration and soil Eh can be improved, resulting in lower CH₄ emissions (Cai et al., 1997). By adopting AWD, the CH₄ emission in OPT_N + AWD was 20.4–45.4% lower than OPT_N and FP (Table 4). Even during PI-MA of early rice season and TR-PI of late rice season, the CH₄ fluxes were significantly suppressed by alternate wetting and drying cycles (Fig. 6). This revealed that AWD15 outperformed the midseason drainage with regard to CH₄ mitigation, because paddy soils become more aerobic by more frequent wetting and drying cycles.

Reducing N application rate is a practical option to mitigate N₂O emissions (Zhong et al., 2016). Compared with FP, the fertilizer input

was reduced by 14.3%–16.7% in OPT_N and OPT_N + AWD, while the N₂O emission was notably decreased by 22.0%–31.8% (Table 4). We assume that other than reducing the N application rate, the delayed timing of N topdressing may also have contributed to the N₂O mitigation. The rapid N uptake in PI and HD can reduce the N accumulation in soil, resulting in lower seasonal N₂O emission. In contrast to CH₄, the N₂O emissions were slightly increased in OPT_N + AWD as compared with OPT_N (Table 4). Our conclusion was consistent with previous researches that a trade-off between CH₄ and N₂O emissions occurs. CH₄ tends to be generated under anaerobic conditions, while N₂O emission tends to be promoted by the shift from anaerobic to aerobic condition (Cai et al., 1997). Therefore, simultaneous minimization of CH₄ and N₂O by water management is difficult. However, the net GWP was substantially reduced in OPT_N + AWD because the decrease of CH₄ emissions far outweighed the increase of N₂O in CO₂-equivalents. Therefore, combining AWD with OPT_N can further reduce greenhouse gas emissions. The seasonal GWP of CH₄ was significantly and positively correlated with irrigation water input, suggesting that the mitigation of CH₄ can be achieved by reasonable reduction of water input.

5. Conclusion

N losses mainly occurred before mid-tillering regardless of treatments and seasons. The AV is the primary pathway for N losses and accounts for over 50% of the total N loading. Runoff N loss was higher in early season than in late season. N losses loading in FP and OPT_N averaged 85.1 and 57.3 kg N ha⁻¹, respectively. Reduced amount and delayed timing of N application in OPT_N helps to improve NUE and reduce N losses. By adopting AWD15, the N losses loading and net GWPs in OPT_N + AWD was reduced by 13.6% and 26.3%, respectively, as compared with OPT_N. Total N loss was positively correlated with total water input, and was negatively correlated with crop N accumulation and NUE indices. Therefore, increasing N and water use efficiency can translate into mitigation of GHG emissions and N losses loading. As an easy-to-use integrated technique, OPT_N + AWD15 could be recommended to farmers in the subtropical double-season rice cropping system. This is the first comprehensive evaluation of N losses loading and GHG emissions under different water and N management in subtropical double-season rice cropping system.

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