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

Kaiming Liang, Xuhua Zhong, Nonrong Huang, Rubenito M. Lampayan, Yanzhuo Liu, Junfeng Pan, Bilin Peng, Xiangyu Hu, Youqiang Fu

A The Rice Research Institute of Guangdong Academy of Agricultural Sciences/Guangdong Key Laboratory of New Technology for Rice Breeding, Guangzhou 510640, China
B International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines
C College of Engineering and Agro-Industrial Technology, University of the Philippines Los Banos, College, Laguna, Philippines

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

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 (OPTN), and optimized N management with alternate wetting and drying irrigation (OPTN + AWD). Grain yields in OPTN and OPTN + 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 OPTN were reduced by 18.9–51.6% compared with FP. OPTN + 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 OPTN. The CH4 emissions in OPTN + AWD were 20.4–45.4% lower than in OPTN and FP. Total global warming potential of CH4 and N2O was the lowest in OPTN + AWD. On-farm comparison confirmed that N loss through runoff in OPTN + AWD was reduced by over 40% as compared with FP. OPTN + AWD significantly increased grain yield by 6.7–13.3%. These results indicated that optimizing water and N management can be a simple and effective approach for enhancing yield with reduced environmental footprints.

© 2017 Published by Elsevier B.V.
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 (NH$_3$) 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 (CH$_4$) emission from rice paddies has been estimated to be 6.15 million tons, accounting for 17.9% of the total CH$_4$ emission (Shi et al., 2010). Due to anaerobic conditions, rice fields were previously considered to be a less important source of N$_2$O, but evidence is mounting that high N rate promotes N$_2$O emissions (Cai et al., 1997; Zou et al., 2005). Seasonal N$_2$O flux from rice paddies in China have increased from 0.32 kg N$_2$O-N ha$^{-1}$ in the 1950s to 1.00 kg N$_2$O-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 CH$_4$ 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 water input and CH$_4$ 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 (CH$_4$ and N$_2$O) 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 (OPTn), which included the farmers’ practice for water management and ‘three controls’ technology for optimized N management; (4) optimized N and water management (OPTn + AWD), which integrate the ‘three-control’ 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 K$_2$O ha$^{-1}$ as potassium chloride) and phosphorus (45 kg P$_2$O$_5$ 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 OPTn, field water layer was continuously kept at 2–5 cm after transplanting, and then around 25 DAT, midseason drainage was carried out to control
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:

\[ \text{CGR} = \frac{W_2 - W_1}{T_2 - T_1} \]

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 (Bremmer 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 (PFPN) = grain yield/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 (IEN) = grain yield/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 mol L⁻¹ KCl and was evaluated by a distillation and titration method. Ammonia flux was calculated by the following equation:

\[ AV = \frac{M}{(A \times D)} \times 10^{-2}, \]  

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 \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emission

The \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) 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 \( \times \) 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 \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emission fluxes were calculated by the following equation (Zheng et al., 1998):

\[ F = \rho \times h \times \left[ 273/(273 + T) \right] \times dC/dt, \]  

where \( F \) is the gas flux (mg m⁻² h⁻¹ for \( \text{CH}_4 \), mg m⁻² h⁻¹ for \( \text{N}_2\text{O} \)), \( \rho \) is the density at the standard state (0.714 kg m⁻³ for \( \text{CH}_4 \), 1.964 kg m⁻³ for \( \text{N}_2\text{O} \)), \( h \) 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 \( \text{CH}_4 \), mg m⁻³ h⁻¹ for \( \text{N}_2\text{O} \)).

The net effect of \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions expressed in \( \text{CO}_2 \)-equivalents was obtained by multiplying the cumulative emissions of \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) 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′′W, 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 waterlogged 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, OPTN, and OPTN + AWD. In FP, N fertilizer (urea) was applied with 40% as basal, 20% at resting stage, 30% at early tilling stage and 10% at late tilling 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 tilling stage and 50% at late tilling stage. Fertilizer P (calcium superphosphate) was applied as basal dressing at the rate of 45 kg P₂O₅ ha⁻¹. In OPTN and OPTN + 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 OPTN were maintained at 0–5 cm for most periods except for the midseason drainage (Fig. 2). In OPTN + 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 OPTN for both seasons. In late rice season, more AWD cycles occurred in OPTN + 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 OPTN + AWD, while there were no significant differences between FP and OPTN. The irrigation water input and total water input in OPTN + AWD compared with OPTN 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 OPTN and OPTN + AWD were both higher than in FP. Owing to the lower water input in AWD15, the WPT in OPTN + AWD was increased by 13.9% in early rice season and 18.4% in late rice season compared with OPTN.

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 OPTN and OPTN + AWD, higher N uptake rate and N accumulation amount were observed in PI-HD. Due to delayed N application, OPTN and OPTN + AWD had greater N uptake rate and N accumulation than FP during PI-HD for both seasons. OPTN and OPTN + AWD were comparable in grain yield and total N uptake at harvest (Table 2). Compared with FP, the grain yield under OPTN and OPTN + 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 PFPn, ARE and AE (except for IEAN) were significantly higher than those of FP. No significant difference of NUE indices were found between OPTN and OPTN + AWD in both seasons (Table 2).

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

The N runoff loss in FP, OPTN and OPTN + AWD averaged 21.6, 11.8 and 6.80 kg N ha⁻¹ across the two seasons, respectively. Approximately 56.4–76.8% of N runoff loads were observed in the early rice season across the treatments (Fig. 4 and Table 3), mainly due to the temporal
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 OPTN was reduced by 51.6% in early rice season and 34.4% in late rice season (Table 3). Compared with OPTN, the runoff event in OPTN + AWD was significantly reduced, N runoff losses was 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, OPTN and OPTN + AWD treatments averaged 45.7, 34.1 and 33.1 kg N ha$^{-1}$, respectively (Table 3). Both OPTN and OPTN + 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 OPTN and OPTN + 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, OPTN and OPTN + AWD averaged 17.6, 11.4 and 9.55 kg N ha$^{-1}$ across the two seasons, respectively (Table 3). N leaching amount in OPTN was reduced by 45.9% in early rice season and 26.9% in late rice season compared with FP. N leaching loss in OPTN + AWD was reduced by 6.2% in early rice season and 23.5% in late rice season compared with OPTN. In OPTN + 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, OPTN and OPTN + 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 OPTN + AWD was reduced by 34.1% in early rice season and 31.2% in late rice season compared with FP. The N losses loading in OPTN + AWD was reduced by 6.2% in early rice season and 23.5% in late rice season compared with OPTN. In OPTN + 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, OPTN and OPTN + 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 OPTN + 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 OPTN + AWD was reduced by 11.8% in early rice season and 15.7% in late rice season compared with OPTN. In OPTN + 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, OPTN and OPTN + 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 OPTN + 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 OPTN + AWD was reduced by 11.8% in early rice season and 15.7% in late rice season compared with OPTN. In OPTN + 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, OPTN and OPTN + 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 OPTN + 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 OPTN + AWD was reduced by 11.8% in early rice season and 15.7% in late rice season compared with OPTN. In OPTN + AWD, N loss from leaching was greater than that from runoff in late season.

### Table 1
The rainfall, water input and water productivity (WPT) during the growing season under different treatments in the on-station field experiments conducted during 2016 early and late season in Guangzhou, Guangdong province, China.

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Rainfall (m$^3$ ha$^{-1}$)</th>
<th>No. of irrigations</th>
<th>Irrigation water input (m$^3$ ha$^{-1}$)</th>
<th>Total water input (m$^3$ ha$^{-1}$)</th>
<th>WPT (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early rice</td>
<td>N0</td>
<td>8952</td>
<td>2.7 ab</td>
<td>878.7 a</td>
<td>9530.7 a</td>
<td>0.45 d</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>8952</td>
<td>4.0 a</td>
<td>1280.3 a</td>
<td>10,232.3 a</td>
<td>0.63 c</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>8952</td>
<td>5.7 a</td>
<td>1372.2 a</td>
<td>10,324.2 a</td>
<td>0.72 b</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>8952</td>
<td>1.0 b</td>
<td>146.1 b</td>
<td>9098.1 b</td>
<td>0.82 a</td>
</tr>
<tr>
<td>Late rice</td>
<td>N0</td>
<td>3926</td>
<td>6.0 b</td>
<td>2094.6 bc</td>
<td>6020.6 bc</td>
<td>0.88 c</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>3926</td>
<td>8.0 a</td>
<td>2757.4 ab</td>
<td>6683.4 ab</td>
<td>1.11 b</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>3926</td>
<td>8.0 a</td>
<td>2827.0 a</td>
<td>6753.0 a</td>
<td>1.25 b</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>3926</td>
<td>4.3 b</td>
<td>1963.1 c</td>
<td>5889.1 c</td>
<td>1.48 a</td>
</tr>
</tbody>
</table>

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

* Values are means of three replications.
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 N₀, 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, N₀, 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).

![Fig. 6A and B. 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).]

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Grain yield (kg ha⁻¹)</th>
<th>Total N uptake (kg ha⁻¹)</th>
<th>IEN (kg kg⁻¹)</th>
<th>ARE (%)</th>
<th>AE (kg kg⁻¹)</th>
<th>PFPN (kg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>N₀</td>
<td>4465.4 c</td>
<td>67.5 c</td>
<td>68.0 a</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>6491.0 b</td>
<td>103.7 b</td>
<td>62.7 a</td>
<td>20.1 b</td>
<td>11.3 b</td>
<td>36.1 b</td>
</tr>
<tr>
<td></td>
<td>OPT_N</td>
<td>7387.0 a</td>
<td>123.2 a</td>
<td>60.1 a</td>
<td>37.1 a</td>
<td>19.5 a</td>
<td>49.2 a</td>
</tr>
<tr>
<td></td>
<td>OPT_N + AWD</td>
<td>7476.7 a</td>
<td>122.9 a</td>
<td>60.9 a</td>
<td>36.9 a</td>
<td>20.1 a</td>
<td>49.8 a</td>
</tr>
<tr>
<td>Late</td>
<td>N₀</td>
<td>5273.2 c</td>
<td>72.1 c</td>
<td>74.1 a</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>7400.0 b</td>
<td>115.9 b</td>
<td>64.1 ab</td>
<td>20.9 b</td>
<td>10.1 b</td>
<td>35.2 b</td>
</tr>
<tr>
<td></td>
<td>OPT_N</td>
<td>8361.9 a</td>
<td>152.1 a</td>
<td>54.9 b</td>
<td>44.5 a</td>
<td>17.2 a</td>
<td>46.5 a</td>
</tr>
<tr>
<td></td>
<td>OPT_N + AWD</td>
<td>8652.6 a</td>
<td>154.0 a</td>
<td>56.4 b</td>
<td>45.5 a</td>
<td>18.9 a</td>
<td>48.2 a</td>
</tr>
</tbody>
</table>

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

The seasonal N2O emission was significantly influenced by fertilizer management practices. The application of basal N fertilizer significantly promoted N2O fluxes. The highest N2O fluxes appeared in FP due to the large amount of N topdressing in seedling stage (Fig. 6C and D). The N2O emission in OPTN and OPTN + 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 OPTN, the N2O emission was slightly increased in OPTN + AWD plots, but with no statistical significance.

Across the two seasons, the total GWP in FP, N0, OPTN and OPTN + AWD was 5017.1, 3524.1, 4569.8 and 3367.7 kg CO2 ha$^{-1}$, respectively. No statistical difference was detected in GWPs between FP and OPTN in both seasons. Whereas the GWP in OPTN + 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 CH4 emission

There was a positive linear relationship between seasonal GWP of CH4 ($y$, kg CO2 ha$^{-1}$) and irrigation water input ($x$, m$^3$ 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 OPTN and OPTN + AWD revealed that the N loss by runoff ($y_1$, kg

---

**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.

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Run-off (kg N ha$^{-1}$)</th>
<th>Leaching (kg N ha$^{-1}$)</th>
<th>Ammonia volatilization (kg N ha$^{-1}$)</th>
<th>Total N losses (kg N ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>N0</td>
<td>5.3 c</td>
<td>5.08 c</td>
<td>16.5 c</td>
<td>26.8 c</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>27.5 a</td>
<td>17.13 a</td>
<td>44.9 a</td>
<td>89.4 a</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>13.3 b</td>
<td>9.26 b</td>
<td>36.4 b</td>
<td>58.9 b</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>8.1 c</td>
<td>8.69 b</td>
<td>35.2 b</td>
<td>52.0 b</td>
</tr>
<tr>
<td>Late</td>
<td>N0</td>
<td>1.62 c</td>
<td>7.1 d</td>
<td>8.99 c</td>
<td>17.7 c</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>15.7 a</td>
<td>18.6 a</td>
<td>46.5 a</td>
<td>80.8 a</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>10.3 b</td>
<td>13.6 b</td>
<td>31.7 b</td>
<td>55.6 b</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>5.49 c</td>
<td>10.4 c</td>
<td>31.0 b</td>
<td>46.9 b</td>
</tr>
</tbody>
</table>

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to LSD (0.05).
N ha⁻¹) and the total N losses (y₂, kg N ha⁻¹) were both significantly correlated with the total water input (x, m³ ha⁻¹). The resulting regression equations were y₁ = 0.0011x + 0.770 (R² = 0.357, p < 0.05) and y₂ = 0.0018x + 39.3 (R² = 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, OPTN and OPTN + AWD, the total N losses were negatively correlated with N accumulation and NUE indices including PFPN, 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 OPTN and AWD in on-farm comparison trials

Our on-farm comparison trials in farmer’s field indicated that OPTN and OPTN + AWD increased grain yield by 6.7–13.9% as compared with FP. The PFPN was significantly increased in OPTN and OPTN + AWD plots in both cropping seasons. Runoff N loss was significantly affected by water and N management, being highest in FP and lowest in OPTN + AWD (Table 5). Compared with FP, the runoff N loss in OPTN + 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
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 OPTN and OPTN + AWD, the grain yields, crop N uptake and NUE indices in OPTN and OPTN + 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.

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 OPTN + AWD was comparable as OPTN 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 $-10$ kPa, 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 OPTN and OPTN + 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 OPTN and OPTN + AWD was reduced by 10.2–61.4% as compared with

### Table 4

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>CH$_4$ emissions (kg ha$^{-1}$)</th>
<th>N$_2$O emissions (kg ha$^{-1}$)</th>
<th>Total GWP (kg CO$_2$ ha$^{-1}$)</th>
<th>Total GWP per unit grain yield (kg CO$_2$ kg$^{-1}$ grain yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early  rice</td>
<td>N0</td>
<td>139.3 b</td>
<td>0.7 c</td>
<td>3069.1 b</td>
<td>0.69 a</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>166.1 a</td>
<td>2.2 a</td>
<td>4181.1 a</td>
<td>0.65 a</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>164.7 a</td>
<td>1.5 b</td>
<td>3928.8 a</td>
<td>0.53 b</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>131.0 b</td>
<td>1.65 b</td>
<td>3262.8 b</td>
<td>0.44 c</td>
</tr>
<tr>
<td>Late  rice</td>
<td>N0</td>
<td>177.5 ab</td>
<td>0.81 c</td>
<td>3979.1 b</td>
<td>0.75 a</td>
</tr>
<tr>
<td></td>
<td>FP</td>
<td>222.5 a</td>
<td>3.81 a</td>
<td>5853.0 a</td>
<td>0.79 a</td>
</tr>
<tr>
<td></td>
<td>OPTN</td>
<td>209.2 a</td>
<td>2.64 b</td>
<td>5210.7 a</td>
<td>0.63 a</td>
</tr>
<tr>
<td></td>
<td>OPTN + AWD</td>
<td>121.4 b</td>
<td>2.97 b</td>
<td>3472.6 b</td>
<td>0.40 b</td>
</tr>
</tbody>
</table>

Values are means of three replications. Within a column, means followed by the same letter are not significantly different according to LSD (0.05).
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 kg N ha\(^{-1}\) in late rice season (Table 3). By adopting the ‘three controls’ technology in OPTN, 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 OPTN, 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 OPTN, adopting AWD15 in the OPTN + 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>
<thead>
<tr>
<th>Season</th>
<th>Variety</th>
<th>Treatment</th>
<th>Grain yield (kg ha(^{-1}))</th>
<th>PFPN (kg kg(^{-1}) N)</th>
<th>N loss from run off (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>Shuangzhensimiao</td>
<td>FP</td>
<td>7092.7 a</td>
<td>35.5 b</td>
<td>10.3 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPTN</td>
<td>8075.6 a</td>
<td>53.8 a</td>
<td>8.33 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPTN + AWD</td>
<td>7568.6 a</td>
<td>50.5 a</td>
<td>3.97 b</td>
</tr>
<tr>
<td>Late</td>
<td>Shenyoud9516</td>
<td>FP</td>
<td>7339.1 b</td>
<td>36.7 b</td>
<td>5.79 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPTN</td>
<td>8117.4 ab</td>
<td>54.1 a</td>
<td>5.20 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPTN + AWD</td>
<td>8355.5 a</td>
<td>55.7 a</td>
<td>3.01 a</td>
</tr>
</tbody>
</table>

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., 2016). Compared with FP, the fertilizer input son, the highest emissions (Zhong et al., 2016). Compared with FP, the fertilizer input into the soil was 20.4–45.4% lower than OTR in, 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 topdressing 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 FPR, AOE and AE indicate more nutrient utilization by plant growth and lower N loading to the environment. In OTR, N and OTR + 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 OTR 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 OTR + AWD was 20.4–45.4% lower than OTR 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 OTR and OTR + 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 OTR + AWD as compared with OTR (Table 4). Our conclusion was consistent with previous research 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 OTR + AWD because the decrease of CH₄ emissions far outweighed the increase of N₂O in CO₂-equivalents. Therefore, combining AWD with OTR 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 OTR averaged 85.1 and 57.3 kg N ha⁻¹, respectively. Reduced amount and delayed timing of N application in OTR helps to improve NUE and reduce N losses. By adopting AWD15, the N losses loading and net GWPs in OTR + AWD was reduced by 13.6% and 26.3%, respectively, as compared with OTR. 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, OTR + 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.

Acknowledgments

This work is supported by the Special Fund for Agroscientific Research in the Public Interest (201503106), the Swiss Agency for Development and Cooperation through their funding of CORIGAP, the Guangdong Agricultural Non-Point Source Pollution Control Project (0724-1610A08N11125), the National High-Tech R&D Program (863) (2014AA10A605), the Guangdong Modern Agricultural Industry Technology System (2016LM1066), and the Science and Technology Program of Guangdong Province, China (No. 20138050800014, Yueke Guicaizi No. [2014]208).

References


