Agriculture, Ecosystems and Environment 286 (2019) 106680

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Reducing nitrogen surplus and environmental losses by optimized nitrogen and water management in double rice cropping system of South China

Kaiming Liang[a,b], Xuhua Zhong[a,*], Junfeng Pan[a], Nongrong Huang[a], Yanzhuo Liu[a], Bilin Peng[a], Youqiang Fu[a], Xiangyu Hu[a]

[a] The Rice Research Institute of Guangdong Academy of Agricultural Sciences, Guangdong Key Laboratory of New Technology for Rice Breeding, Guangzhou 510640, China
[b] Guangdong Provincial Key Laboratory of Applied Botany, South China Botanical Garden, Chinese Academy of Sciences, China

ARTICLE INFO

Keywords:
Nitrogen use efficiency
N management
Water management
N surplus
Environmental N losses

ABSTRACT

Optimized agronomic management improves nitrogen (N) use efficiency in crop production. However, limited information exists about the effect of improved agronomic practices on the N surplus in double rice cropping system. In this study, we conducted field experiments to evaluate the N surplus for the prevailing farmers' practices (FP), optimized N management (OPT_N) and optimized N and water management (OPT_{NW}) during 2016–2017 in Guangdong province, South China. Grain yield, recovery efficiency (REN), partial factor productivity (PFPN) and agronomic efficiency (AE) of applied N in OPT_N and OPT_{NW} were substantially higher than FP. The yearly N surplus and environmental N loss in OPT_N were 29.4% and 26.2% lower than FP, respectively. The N surplus in OPT_{NW} was 32.1% lower than FP. Annual N losses resulting from runoff and leaching in OPT_{NW} were reduced by 45.0% and 17.4%, respectively, compared with OPT_N. Pooled data of 22 on-farm field trials from six sites in 2014–2017 showed that N input in OPT_N and OPT_{NW} was 16.2%–33.8% lower than FP. The tradable N output in OPT_N and OPT_{NW} was 9.9% and 9.0% greater than FP, respectively. The N efficiency of cropping systems (NUE_c) in OPT_N and OPT_{NW} was increased by 39.8% and 42.0%, respectively, compared with FP. N surplus notably increased with the increasing fertilizer N input, and decreased with the increasing tradable N output and NUE_c. These results suggest that through optimized N and irrigation management, N surplus and environmental risk can be practically reduced in a double rice cropping system without yield penalty.

1. Introduction

Rice (*Oryza sativa* L.) is consumed globally by more than 3 billion people, and is distinguished as one of the world's most essential crops. It is estimated that by the year 2025, rice production will have to increase 60% to meet the growing nutritional needs of the rising human population (GRiSP, 2013). Improvements in grain yields are strongly dependent on the fertilizer synthetic nitrogen (N). Over 55 million tonnes of N fertilizer are used in Chinese croplands. Of this, 20% is utilized in rice paddies on a national scale (Food and Agricultural Organization (FAO, 2016). The double rice cropping system is one of the most important rice production systems for assuring food security in China. It produces more than 35% of the country's rice grain (Ministry of Agriculture of China (MOA, 2017). The cropping system consists of two rice seasons, i.e. the early season from April to July and the late season from July to November. Previous studies have reported that in the early season, the use of N fertilizer for rice growth is 197 kg ha^{-1} on average, and for the late season, it is 191 kg ha^{-1}. The mean N recovery is 23% (Zhong et al., 2010), which is only half of the worldwide average of 46%, and is substantially lower than that in Europe or the USA (Liu et al., 2010; Deng et al., 2014).

The poor N efficiency can largely be credited to the misuse of N fertilizers. Rice growers usually input large amounts of synthetic N fertilizers to ensure higher crop yields. Over 80% of N fertilizer is used within the first 20 days after transplanting to boost tillering (Zhong et al., 2010). This use of N fertilizer leads to high residual N in the soil and elicits a number of environmental problems, including soil acidification (Guo et al., 2010), nitrate pollution in surface and groundwater (Gu et al., 2013) and increased gaseous N emissions (Zhang et al., 2013). Therefore, increasing yield with less input of N fertilizers has become a critical consideration for ensuring sustainability in rice production.

To minimize non-point source pollution, China seeks to achieve zero growth in the use of chemical fertilizers by 2020. For this purpose, N management practices need to be established that can sustain high yield and minimize loss of N to the environment. Various indicators have been proposed to estimate potential N losses to the environment within farming

* Corresponding author.
E-mail address: xzhong8@163.com (X. Zhong).

https://doi.org/10.1016/j.agee.2019.106680
Received 3 February 2019; Received in revised form 1 September 2019; Accepted 3 September 2019

systems – N input, NUE indices, soil mineral N and N surplus. Among these, N surplus analyses serve as an indicator of N accumulation in grains and soil and for quantifying eventual N losses to the environment. It helps provide guidelines for improvements in nutrient management within a specified boundary (De Notaris et al., 2018). Analyses of N surplus have been widely used for promoting sustainable nutrient management at various levels – for smallholder farms, regional, national, even global level (Zhang et al., 2019). A significant number of case studies have considered the effects of employing N surplus analysis in different cropping systems, including greenhouses and the addition of various vegetable and crop fields (Shi et al., 2012; Hartmann et al., 2014; Yao et al., 2018; Sela et al., 2019). These studies have contributed to the efficient agricultural management of N, and helped to restrict environmental degradation without sacrificing yields. Substantial improvements have been made to enhance the N use efficiency in rice cropping system in China. Many optimized N managements such as site-specific N management, balanced N fertilization, integrated N management, etc., have been shown to be effective to increase NUE and reduce fertilizer N input and N losses in cropping systems (Zhong et al., 2010; Xue et al., 2014). Besides N management, water-saving irrigation such as AWD (Alternative wetting and drying) irrigation, intermittent irrigation and control irrigation, etc., were found to be a promising option to mitigate environmental N losses while reducing irrigation water input in rice fields (Peng et al., 2015). Moreover, numerous studies demonstrated that agricultural regime with improved N and water management synergistically increased grain yield, NUE and water productivity, while reducing N losses to environment (Jiao et al., 2018). However, few, if any, studies have been conducted to assess N surplus in the double rice cropping system. The present study aims to offer a deep insight into N flows within intensive agricultural systems. In this regard, on-station field experiments were conducted along with multi-location on-farm trials to quantify N surplus and environmental N losses via different gaseous and hydrological pathways in the double-rice cropping system of South China. We aim to explore: 1) if optimized agronomic practices (in this case – the optimized management of N and the optimized management of water and N) achieve a lower surplus with sustained rice production and a reduction in N losses in comparison to current farmers' practice; 2) to identify the underlying causes of optimized agronomic practices in influencing N surplus and environmental N losses in double rice cropping system.

2. Methods and materials

2.1. On-station field experiments

Field experiments were conducted in the period 2016–2017 at Dafeng Experimental Station (113°20′E, 23°08′N) of the Guangdong Academy of Agricultural Sciences in Guangzhou, Guangdong, China. The field site has a humid, subtropical and monsoon climate. Data about weather patterns, acquired from the weather station, are shown in Fig. 1. The average temperature at the study site is 25.8 °C in the early season, from April to July, and 26.5 °C in late season, from August to November. The average recorded rainfall is 891.0 mm in early season and 444.8 mm in late season. Initial properties of the soil in the plough layer (0–20 cm) were analyzed by the Laboratory of Environmental Chemistry at the College of Natural Resources and Environment, South China Agricultural University. Briefly, the soil pH was measured in a 1:2.5 mixture of soil and distilled water using a pH probe. The soil organic matter content was determined by the potassium dichromate oxidation method. The total N content was determined by micro Kjeldahl digestion followed by distillation and titration. The available N was measured using alkaline hydrolysis diffusion method. The total P content was determined by the Mo-Sb antispectrophotography method. The available P content was determined by the Mehlich-3 extraction and colorimetric analysis. The total K content was measured using the sodium hydroxide melting-flame atomic absorption spectrophotometry. The available K content was determined by the ammonium acetate extraction-flame atomic absorption spectrophotometry. The soil properties are enlisted as follows: pH 6.0, organic matter 41.3 g kg^{-1}, total N 1.62 g kg^{-1}, total P 1.06 g kg^{-1}, total K 16.0 g kg^{-1}, available N 82.6 mg kg^{-1}, available P 40.4 mg kg^{-1} and available K 58.7 mg kg^{-1}. As a whole, the soil fertility at this site falls in the normal range of the study region (Ye et al., 2018).

2.1.1. Experimental design and field management

Four treatments in triplicate were employed in the experiment: 1) Zero nitrogen application (N0), no N input with farmers' water management; 2) Farmers' N and water management (FP); 3) Optimized N management with farmer's water management (OPT_N); 4) Optimized management of N in addition to optimized management of water (OPT_{NW}). Plots were established at 6.6 m × 4.8 m size. In order to preclude fertilizer leakage and the flow of water between adjoining plots, individual plots were all divided by 30 cm wide berms and covered by plastic film secured at 0.3 m in the soil.

N fertilizer used in different treatments is shown in Table 1. For FP, urea was utilized as N fertilizer at 180 kg N ha^{-1} in the early season and 210 kg N ha^{-1} in the late season, with 40% used as basal, 20% at recovering stage, 30% at early tillering and 10% at late tillering. In OPT_N and OPT_{NW}, a government-recommended technology, namely "three controls", was employed for N management. The N rate in the "three controls" technology is determined from the target yield and the yield without applied N, while P and K rates are estimated using a nutrient balance approach (Zhong et al., 2010). Total rate of fertilizer N was 150 kg N ha^{-1} in the early season and 180 kg N ha^{-1} in the late season. In the early season, N fertilizer was used at 50% as basal, 20% at mid-tillering (MT) and 30% at panicle initiation (PI) stage. In the late season, N was applied at 40% as basal, 20% at MT, 30% at PI and 10% at heading (HD) stage. Calcium superphosphate (45 kg P_2O_5 ha^{-1}) as P fertilizer and potassium chloride (135 kg K_2O ha^{-1}) as K fertilizer were used as basal.

In N0, FP and OPT_N, the water level of the field was maintained at 2–5 cm after transplanting. Subsequently, to manage excessive tiller growth, a mid-season drainage was carried out from around 25 to 45 days after transplanting (DAT). The water depth was maintained at 2–5 cm in the flowering stage, and shallow irrigation was employed after heading. Terminal drainage was done 7 days before harvest. In OPT_{NW}, the safe alternate wetting and drying technique (safe AWD), developed by the International Rice Research Institute, was adopted as the optimized water management. To properly implement the safe AWD, a perforated plastic tube (0.20 m in internal diameter and 0.25 m in height) was used as a tool to monitor the field water depth (Lampayanet al., 2015). The tube was installed in the field to a depth of 15 cm below the soil surface. To monitor the perched water-table level below ground, the soil inside the tube was removed. During the first 10 DAT, field water depth was maintained to a depth of 2–5 cm for the seedlings to recover and to suppress weeds. AWD cycles begin at 11 DAT. During the AWD cycles, the field is irrigated to a depth of 5 cm once the water level has dropped to 15 cm below the soil surface. When 10% of the panicles had emerged at the beginning of heading, the field was kept flooded with 2–5 cm water layer for 7 days to prevent spikelet sterility. The AWD cycles were then repeated until the terminal drainage at 7 days before harvest.

Prior to transplanting, all the plots were flooded and sufficiently tilled to about 20 cm in depth using a tractor with rototiller. Rice straw was manually removed from each plot after harvest. No agronomic practice was undertaken during winter-spring fallow season, and the field was allowed to dry for all treatments.

2.1.2. Evaluation of yield and N use efficiency

At maturity (MA), yield was ascertained for an area of 5 m^2 in every plot and expressed at a moisture content of 0.14 kg kg^{-1}. Twelve plant hills were sampled at random in each plot and dry weight and N uptake were measured. The samples of panicles, stems and leaves were first dried in an oven at 75 °C to make sure the weight was constant before weighed. The N concentration in the tissue was measured through micro-Kjeldahl digestion, titration and distillation (Bremner and

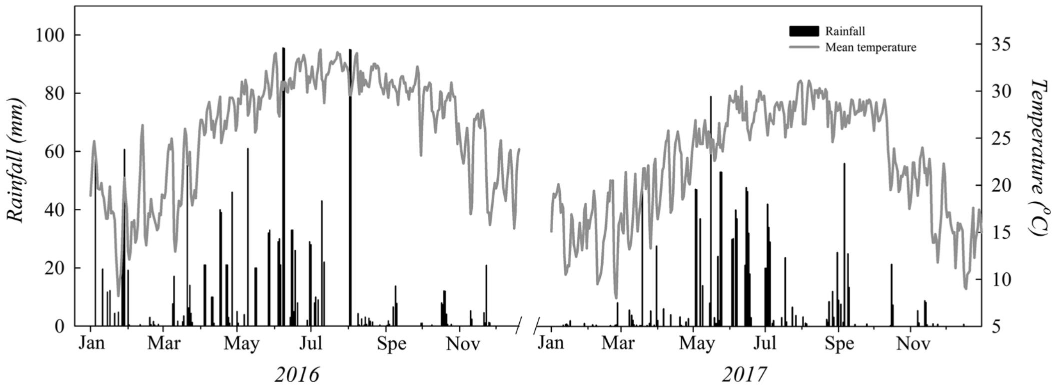

Fig. 1. Mean daily rainfall and temperature in the on-station field experiments conducted during 2016–2017 in Guangzhou, Guangdong province.

Table 1
The amount of fertilizer N applied to the treatments in the field experiments conducted at Guangzhou in 2016 and 2017.

Season	Treatment	Timing and rate of N fertilizer application (kg ha^{-1})							
		Total N	Basal Fertilizer	Recovering	Early tillering	Mid tillering	Late tillering	Panicle initiation	Heading
Early season	FP	180	72	36	54		18		
	OPT_N	150	75			30		45	
	OPT_{NW}	150	75			30		45	
Late season	FP	210	84	42	63		21		
	OPT_N	180	72			36		54	18
	OPT_{NW}	180	72			36		54	18

Mulvaney, 1982). The total N uptake of plants was established by calculating the total sum of N present in all of the components.

The partial factor productivity (PFPN), apparent N recovery efficiency (ARE), agronomic N use efficiency (AE) and physiological N use efficiency (IEN) of applied N were evaluated according to methodologies employed by Bandaogo et al. (2015). Following this methodology, PFPN was established by dividing the grain yield by the overall amount of N from fertilizer. The N uptake difference between plots that were fertilized and plots that were unfertilized was divided by the rate of N utilization in order to determine ARE. The difference in yield between fertilized treatments and zero N treatment was divided by the application rate of N in order to calculate AE. Yield was divided by the plant N uptake to determine IEN. The N efficiency in the cropping system (NUE_c) is mathematically defined as the ratio of N output from grains to total N input in a cropland, including fertilizer, seedlings, non-symbiotic N fixation, atmospheric deposition, and irrigation (Zhang et al., 2015).

2.1.3. Measurement of environmental N losses

The N loss via runoff was measured at each runoff event. The water outlets were equipped with flow meter sets to calculate the water outflow volume for each plot. Runoff samples were collected after each runoff event. For this purpose, a plastic bucket of 20 L was buried next to the plot to collect runoff water samples, using a piping system (Xue et al., 2014). The height of the hole for the runoff-collecting pipe was the same as for drainage ditch outlet. The drainage ditch outlet was 5 cm above the soil surface in OPT_{NW} for the whole periods. In FP and OPT_N, the height of drainage ditch outlet was 5 cm above soil surface for the whole periods except for mid-season drainage stage. During mid-season drainage, the height of drainage ditch outlet was set to ground level (0 cm above the soil surface) as standing water should be avoided at paddy field for controlling the number of unproductive tillers. After mid-season drainage stage, the height of drainage ditch outlet was returned to 5 cm above soil surface. In this way, water was collected in the collection buckets at each runoff event. The alkaline potassium persulfate oxidation-ultra spectrophotometer method was employed to establish the total amount of N in the water sample. The N concentration of the water sample was multiplied by the runoff volume in order to establish the N loss at each runoff event. In addition, the sum of event losses was used to establish the seasonal runoff loss of N.

The N loss as a result of leaching was measured on 1, 3, 5, 7 and 11 days after each N fertilizer application, and afterwards at 7 days' interval until rice harvest. Porous polyvinyl chloride pipes were used to collect percolation water (Li et al., 2008; Liang et al., 2017). Prior to this experiment, a lysimeter (a porous pipe with a sealed bottom) was vertically planted in the ground in every plot at a depth of 50 cm – the pipe was 70 cm in length and 18 cm in diameter; it had a 10 cm end formed with 200 pores bored together with a margin of 20 cm. To counteract sediment flow into the lysimeter, the lower part of the lysimeter was covered with nylon net (0.15 mm mesh size) and surrounded with quartz sand. The method outlined by Li et al. (2008) was used to arrive at an estimation of the quantity of N and water in the paddy fields. Briefly, the volume of soil contributing leaching water to each lysimeter was calculated, and the volume of water per volume of soil was extrapolated to calculate the leaching volume per hectare. The N loss from leaching was calculated by multiplying the TN concentration of the water sample by the measured leaching volume.

The N loss from ammonia volatilization (AV) was measured using the static chamber technique, which involved employing a sponge soaked in phosphoglycerol to absorb ammonia in an ammonia-trapping chamber (Xue et al., 2014; Liang et al., 2017). The AV was measured on 1, 3, 5, 7 and 11 days after each N fertilizer application, and afterwards at 7 days' interval until harvest. Chambers were constructed using PVC pipes that were 25 cm in length and 20 cm in diameter. Samples collected in the phosphoglycerol-soaked sponge using the PVC collectors were extracted by using 300 mL of 1.0 mol L^{-1} KCl. These were then appraised using a distillation and titration method. The AV rate was then determined using the calculation below:

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

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

2.1.4. Calculation of N surplus

The N surplus was defined as the difference between the total N inputs to the soil surface and the harvested N output with crop products at a given time period. It was calculated by the following formula (Oenema et al., 2003; Ju and Gu, 2017):

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

We calculated the theoretical N stored in soil ($N_{\Delta soil}$) by the following formula (Zhang et al., 2017; Liu et al., 2018):

$$N_{\Delta soil} = \text{total N inputs (fertilizer + seed + irrigation + rainfall + deposition + non-symbiotic N fixation) - total N outputs (tradable N output + runoff + ammonia volatilization + denitrification + leaching).} \quad (3)$$

$N_{\Delta soil}$ is an indicator to evaluate the sustainability of N management. A positive $N_{\Delta soil}$ indicates N contribution to the soil N stock, while a negative $N_{\Delta soil}$ indicates depletion of the soil N stock.

The tradable N output is the N output from tradable agricultural products that removed from the cropping system. In the field experiment, the tradable N output includes the N harvested in grain and straw as the rice straw was removed from the cropping system. In multi-location comparison trials, the tradable N output only includes the grain as rice straw was incorporated to the soil according to the policies of straw management in China. Atmospheric N deposition, both wet and dry, was estimated at 34 kg N ha^{-1} y^{-1} (Xu et al., 2015). In order to establish the N input in irrigation water, the total amount of irrigation water that was used was multiplied by the mean concentration of N in the irrigation water. N input from crop seeds was calculated at 1.8 kg N ha^{-1} in each cropping season (Hong et al., 2018). The estimated N input as a result of non-symbiotic N fixation was 32 kg N ha^{-1} y^{-1}, which is based on the mean value of the findings taken from published literature (Lu, 1998; Herridge et al., 2008; Liao et al., 2013). The N losses occurring as a result of leaching, ammonia volatilization and runoff under different treatments were obtained through actual measurement via on-station field experiments, while the N loss through denitrification in rice paddies was estimated to be 21.6% of N fertilizer input based on the mean value calculated from published literature (Zhao et al., 2011; Li et al., 2014; Xu and Cai, 2014; Dash et al., 2015).

2.2. On-farm multi-location comparisons

On-farm multi-location comparison trials (n = 22) were made in farmer's fields over a time period of four years, from 2014 to 2017. In the present study, six sites were selected in the main regions for rice production in Guangdong. Fertilizer inputs for FP, OPT_N and OPT_{NW} in different sites are listed in Table 2. Grain yield, PFPN and N surplus were evaluated using the same methods that were utilized in the on-station field experiment. In order to calculate the $N_{\Delta soil}$ in multi-location comparison trials, the environmental N losses as a result of leaching, ammonia volatilization and runoff in FP, OPT_N and OPT_{NW} were estimated based on values of coefficients obtained from on-station field experiments. The denitrification loss of N was estimated as 21.6% of the fertilizer N input. Because several N parameters were estimated in calculation of N surplus and $N_{\Delta soil}$ for on-farm multi-location comparison trails, a sensitivity analysis has been undertaken to evaluate the uncertainties by changing these N parameters. This was performed by changing the selected input and output parameters of N systemically in a certain range (± 0 to 40%), while holding other parameters unchanged.

2.3. Statistical analysis

The experiments were set up in a randomized complete block design with three replicates. The effects of the treatments were assessed through analysis of variance (ANOVA) using STATISTICA 9.0 (Stat Soft Inc., Tulsa, USA). Mean separation was performed using Fisher's Least Significant Difference method (LSD) at 0.05 probability level. Sigmaplot 12.0 was used to prepare the graphs.

3. Results

3.1. Grain yield and nitrogen use efficiency in different agronomic practices

3.1.1. Grain yield and nitrogen use efficiency in on-station field experiments

The grain yield and plant N uptake for each crop in N0 averaged 4725.2 kg ha^{-1} and 65.5 kg N ha^{-1}, respectively, across four cropping seasons. Grain yield for FP, OPT_N and OPT_{NW} in the field experiments in Guangzhou during 2016–2017 was 6616.6, 7532.8 and 7673.1 kg ha^{-1}, respectively (Fig. 2). Input of N fertilizer in FP was 18.2% higher than that in OPT_N and OPT_{NW}. Nevertheless, the grain yield in OPT_N and OPT_{NW} increased by 13.8% and 16.0%, and the total N uptake was 25.9% and 27.0% higher than that for FP. The averaged pooled data of AE, ARE and PFPN in FP listed as 21.8 kg kg^{-1}, 9.8% and 34.1 kg kg^{-1}, respectively. The AE, ARE and PFPN in OPT_N were 75.5%, 96.3% and 34.8% higher than FP, and those in OPT_{NW} were 83.9%, 98.6% and 37.2% higher than FP, respectively. In contrast to the AE, ARE and PFPN, the INE in FP was found to be higher than that for OPT_N and OPT_{NW}. This difference was significant in the late season of 2016 and early season of 2017. The grain yield and NUE indices for AE, ARE, PFPN and IEN showed no significant difference between OPT_N and OPT_{NW}.

3.1.2. Grain yield and nitrogen use efficiency in on-farm field trials

The systematic investigation conducted at six sites during the time period of 2014–2017 in Guangdong province revealed excessive use of N fertilizer in farmers' practice (Table 2). The average use of N fertilizer in FP was 199.3 kg N ha^{-1} in the early season, and 203.4 kg N ha^{-1} in the late season. Compared to N input in FP, the seasonal N input in OPT_N and OPT_{NW} was 16.7% to 33.8% lower during the early and late season, respectively. In FP, the yearly average input of N reached 403.9 kg N ha^{-1}. The average N input in OPT_N and OPT_{NW} was over 100 kg N ha^{-1} or 25% lower than that in FP. The aggregated data obtained from 22 on-farm field trials showed that the seasonal grain yield ranged from 4540.9 to 8665.5 kg ha^{-1}, with a mean value of 6548.8 kg ha^{-1} in FP (Fig.3A). For OPT_N and OPT_{NW}, the grain yield was recorded at 7198.8 kg ha^{-1} and 7139.3 kg ha^{-1}, respectively, and was respectively 9.93% and 9.02% higher than FP. The PFPN was 32.6 kg kg^{-1} for FP (Fig.3B). As compared to FP, the PFPN in OPT_N and OPT_{NW} increased by 48.6% and 50%, respectively. No statistical difference was observed in yield and PFPN between OPT_N and OPT_{NW} ($p > 0.05$).

3.2. N surplus in different agronomic practices

Pooled data acquired from field experiments showed N fertilizer as the dominant source of N, accounting for 79.4 to 82.9% of the total N input in the system (Table 3). Non-fertilizer N sources were estimated to be 84.6 kg ha^{-1} y^{-1} in FP and OPT_N, and 79.8 kg ha^{-1} y^{-1} in OPT_{NW}. The highest annual N input was in FP, which was 14.5% and 16.4% higher than in OPT_N and OPT_{NW}, respectively. In comparison to OPT_N, the input of N through irrigation in OPT_{NW} was reduced by 52.3%, due to less water input for irrigation in OPT_{NW} than in FP and OPT_N. But the total N input in OPT_{NW} decreased by only 1.6% in comparison to OPT_N, since the input of N from irrigation only accounted for a small fraction (< 5%) of the total N input. Total grain N uptake accounted for 35.6 to 55.2% of the total N output for all practices (Table 3). As compared to FP, the annual N input in OPT_N and OPT_{NW} was reduced by over 10%. However, there was a significant (21.7% and 22.8%, respectively) increase in the annual N uptake of the grain in OPT_N and OPT_{NW}. Seasonal N surplus ranged from 100.4 kg ha^{-1} to 165.1 kg ha^{-1}. In comparison to FP, the annual N surplus showed a significant decrease of 29.4% and 32.1% in OPT_N and OPT_{NW}, respectively. Without straw

Table 2
The fertilizer input of different treatments at on farm field trails in 6 sites in Guangdong during early and late season from 2014 to 2017.

Site	Year	Treatment	Early season			Late season		
			N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Qujiang Zhangshi village	2014	FP	180	100	120	180	54	153
		OPT_N	150	60	120	150	60	120
Yangjiang Kangzhou village	2016	FP	180	45	113	203	43	113
		OPT_N	150	36	113	138	36	113
		OPT_{NW}	150	36	113	138	36	113
Leizhou Beibian village	2015	FP	215	72	102	215	72	102
		OPT_N	148	60	117	148	48	117
	2016	FP	179	90	113	179	90	113
		OPT_N	150	60	117	150	30	120
Gaoyao Boxi village	2014	FP	204	45	81	204	43	81
		OPT_N	145	45	117	145	45	117
		OPT_{NW}	145	45	117	145	45	117
	2015	FP	204	43	81	204	43	81
		OPT_N	145	45	117	145	45	117
		OPT_{NW}	135	45	117	135	45	117
	2016	FP	204	43	81	204	43	81
		OPT_N	135	45	81	135	45	120
Gaoyao Baitu village	2016	FP	195	45	113	195	45	113
		OPT_N	135	36	113	150	36	113
		OPT_{NW}	135	36	113	150	36	113
	2017	FP	203	45	113	203	45	113
		OPT_N	150	36	113	150	36	113
		OPT_{NW}	150	36	113	150	36	113
Renhua Ziling village	2015	FP	218	45	90	240	45	90
		OPT_N	158	36	135	180	36	135
	2016	FP	210	41	101	210	41	101
		OPT_N	165	36	144	165	36	144
		OPT_{NW}	165	36	144	165	36	144

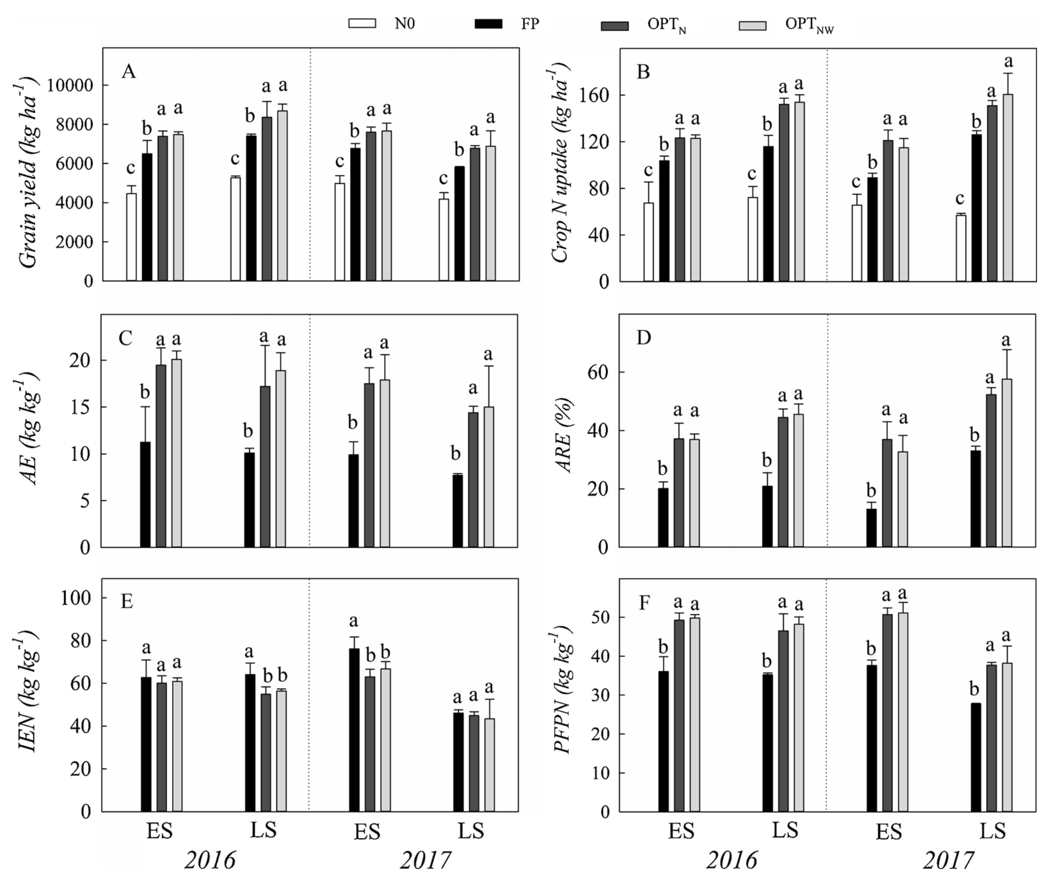

Fig. 2. Grain yield, crop N uptake, agronomic N use efficiency (AE), apparent N recovery efficiency (ARE), internal N use efficiency (IEN) and partial factor productivity (PFPN) of N in different treatments at field experiments conducted during 2016–2017 in Guangzhou.

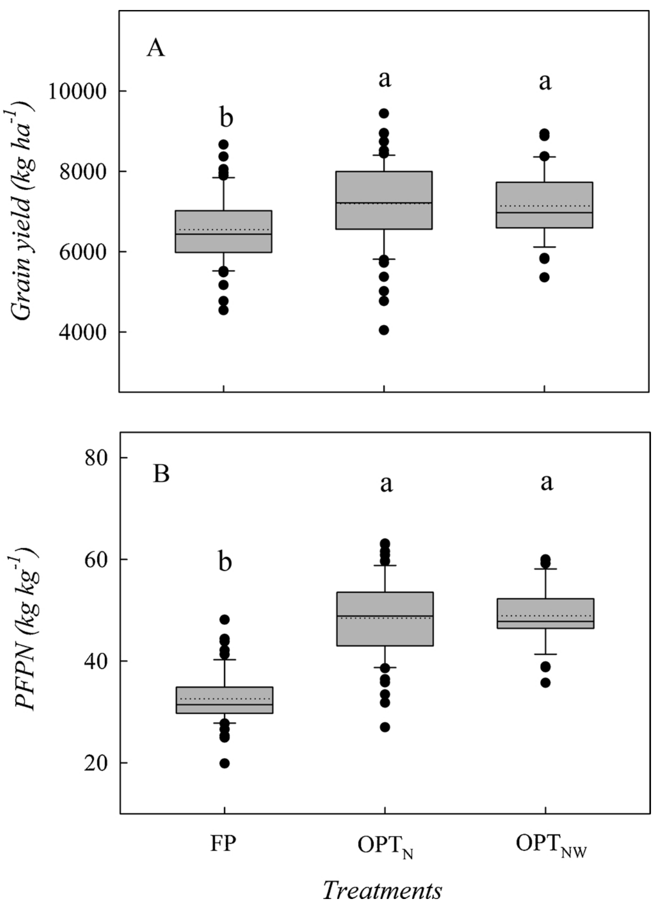

Fig. 3. The grain yield and PFPN under different treatments at on-farm multi-location comparison trials conducted during 2014–2017 in Guangdong province.

returning in field experiment, the value of N stored in soil ($N_{\Delta soil}$) displayed positive in FP and negative in OPT_N and OPT_{NW} for the two cropping seasons, ranging from −22.5 kg ha^{-1} to 9.27 kg ha^{-1}.

When averaged across the 22 on-farm field trials in different sites, the annual N input was recorded to be 21.5% lower in OPT_N and 23.5% lower in OPT_{NW} in comparison to FP (Table 4). The annual uptake of N by grain compared with FP was increased by 9.8% and 8.6% in OPT_N and OPT_{NW}, respectively, but there was no significant difference between OPT_N and OPT_{NW}. Because of the difference in N input and grain N uptake, remarkable differences in values of N surplus were observed for different treatments. Highest values for N surplus were recorded for FP. In comparison, annual N surplus was decreased by 33.6% in OPT_N, and by 36.0% in OPT_{NW}. Results obtained for the on-farm comparison trails conducted at multiple locations showed that most values for the N efficiency in the cropping system (NUE_c) in FP were below 0.35, whereas the majority of the values for NUE_c in OPT_N and OPT_{NW} ranged from 0.35 to 0.50 (Fig.4 B). N surplus notably increased with the increasing fertilizer N input (Fig.4 A) and decreased with the increasing tradable N output and NUE_c (Fig.4 C). These results suggested that lower N surplus in OPT_N and OPT_{NW} were linked to the improved NUE_c and reduced N fertilizer input.

3.3. Environmental N losses in response to N and water management

N losses from AV, runoff and leaching mainly occurred in the first month after transplanting (Fig.5). N loss from runoff was higher in early season than in late season due to the abundant rainfall during early season. N losses from AV, runoff and leaching were lower in OPT_N and OPT_{NW} relative to FP. No significant interaction effect between season

Table 3
Nitrogen surplus and N stored in soil (kg N ha^{-1}) in different treatments at field experiments during 2016–2017 at Guangzhou, Guangdong province.

	Early season			Late season			Annual scale		
	FP	OPT_N	OPT_{NW}	FP	OPT_N	OPT_{NW}	FP	OPT_N	OPT_{NW}
Input									
Fertilizer N	180.0 a	150.0 b	150.0 b	210.0 a	180.0 b	180.0 b	390.0 a	330.0 b	330.0 b
N deposition	*17.0*[c] a	*17.0* a	*17.0* a	*17.0* a	*17.0* a	*17.0* a	*34.0* a	*34.0* a	*34.0* a
Irrigation	4.00 ± 1.15 a[d]	4.00 ± 1.09 a	0.70 ± 0.30 b	8.50 ± 1.91a	8.80 ± 1.56 a	5.40 ± 1.49 b	12.5 ± 2.76 a	12.8 ± 2.34 a	6.10 ± 1.46 b
Seed	*1.80* a	*1.80* a	*1.80* a	*1.80* a	*1.80* a	*1.80* a	*3.60* a	*3.60* a	*3.60* a
Non-symbiotic N fixation	*16.0* a	*16.0* a	*16.0* a	*16.0* a	*16.0* a	*16.0* a	*32.0* a	*32.0* a	*32.0* a
Total input	218.8 ± 1.15 a	188.8 ± 1.09 b	185.5 ± 0.30 b	253.3 ± 1.91 a	223.6 ± 1.56 b	220.2 ± 1.49 b	472.1 ± 2.76 a	412.4 ± 2.34 b	405.7 ± 1.46 b
Output									
Tradable N output[a]	96.4 ± 8.82 b	122.1 ± 7.08 a	118.8 ± 7.12 a	121.0 ± 8.52 b	151.6 ± 4.28 a	157.2 ± 12.96 a	217.4 ± 7.53 b	273.7 ± 10.9 a	276.1 ± 15.2 a
Ammonia volatilization	40.8 ± 5.42 a	30.5 ± 7.00 b	28.4 ± 7.85 b	43.1 ± 9.03 a	29.1 ± 5.47 b	30.2 ± 1.63 b	83.9 ± 12.3 a	59.6 ± 10.3 b	58.6 ± 8.62 b
Runoff	22.9 ± 5.65 a	12.8 ± 3.94 b	7.3 ± 3.70 c	15.5 ± 2.21 a	10.1 ± 2.35 b	5.3 ± 2.28 c	38.4 ± 6.92 a	22.9 ± 3.87 b	12.6 ± 2.69 c
Leaching	17.9 ± 1.38 a	12.0 ± 3.45 b	10.3 ± 2.11 b	19.1 ± 2.10 a	13.9 ± 2.97 b	11.0 ± 3.44 b	37.0 ± 2.26 a	25.9 ± 3.63 b	21.3 ± 4.19 b
Denitrification	*38.9* a	*32.4* b	*32.4* b	*45.4* a	*38.9* b	*38.9* b	*84.2* a	*71.3* b	*71.3* b
Total output	216.9 ± 17.1 a	209.8 ± 9.65 ab	197.2 ± 12.1 b	244.0 ± 7.53 a	243.6 ± 4.14 b	242.7 ± 9.65 b	460.9 ± 16.5 a	453.4 ± 13.2 b	439.9 ± 14.8 b
N stored in soil[b]	1.87 ± 7.51 a	−21.0 ± 9.14 b	−11.7 ± 12.4 ab	9.27 ± 8.87 a	−20.0 ± 3.77 b	−22.5 ± 10.6 b	11.1 ± 16.2 a	−41.0 ± 12.7 b	−34.2 ± 14.6 b
Surplus	122.4 ± 8.72 a	66.7 ± 7.54 b	66.7 ± 7.63 b	132.3 ± 9.62 b	72.1 ± 4.58 b	63.0 ± 13.5 b	254.7 ± 8.47 b	138.8 ± 11.1 b	129.7 ± 15.6 b

[a] The tradable N output was calculated by multiplying the dry matter yields of grain and straw by the respective N concentration.
[b] The N stored in soil ($N_{\Delta soil}$) is the difference between total N inputs and total N outputs.
[c] The data of N input from N deposition, seed, non-symbiotic N fixation and N output from denitrification (represented in italic font) was estimated from published literature.
[d] Values are means ± standard deviations. Different lowercase letters indicate significant difference among treatments in each cropping season ($p < 0.05$).

Table 4
Nitrogen surplus and N stored in soil (kg N ha^{-1}) under different treatments at multi-location comparison trials during 2014–2017 in Guangdong province.

	Early season			Late season			Annual scale		
	FP	OPT_N	OPT_{NW}	FP	OPT_N	OPT_{NW}	FP	OPT_N	OPT_{NW}
Input									
Fertilizer N input	200.1 ± 12.3 a[b]	148.2 ± 8.40 b	146.6 ± 10.7 b	203.7 ± 15.6 a	150.6 ± 12.0 b	147.1 ± 10.1 b	403.9 ± 24.5 a	298.8 ± 18.8 b	293.7 ± 19.2 b
N deposition	*17.0*[c]a	*17.0 a*	*17.0 a*	*17.0 a*	*17.0 a*	*17.0 a*	*34.0 a*	*34.0 a*	*34.0 a*
Irrigation	*4.50 a*	*4.50 a*	*2.20 b*	*10.5 a*	*10.5 a*	*8.0 b*	*15.0 a*	*15.0 a*	*10.2 b*
Seed	*1.80 a*	*1.80 a*	*1.80 a*	*1.80 a*	*1.80 a*	*1.80 a*	*3.60 a*	*3.60 a*	*3.60 a*
Non-symbiotic N fixation	*16.0 a*	*16.0 a*	*16.0 a*	*16.0 a*	*16.0 a*	*16.0 a*	*32.0 a*	*32.0 a*	*32.0 a*
Total input	239.5 ± 12.3 a	187.6 ± 8.40 b	183.6 ± 10.7 c	249.0 ± 15.6 a	195.8 ± 12.0 b	189.9 ± 10.1 b	488.4 ± 24.5 a	383.4 ± 18.8 b	373.5 ± 19.2 c
Output									
Tradable N output[a]	70.2 ± 5.54 b	75.6 ± 6.04 a	73.5 ± 5.95 ab	66.1 ± 4.61 b	74.2 ± 6.72 a	75.1 ± 6.47 a	136.3 ± 5.91 b	149.6 ± 10.4 a	148.0 ± 8.61a
Surplus	169.2 ± 15.2 a	112.0 ± 11.7 b	110.1 ± 12.3 b	182.9 ± 18.7 a	121.6 ± 17.2 b	114.8 ± 9.70 b	352.1 ± 27.0 a	233.8 ± 23.7 b	225.5 ± 18.6 b

[a] The tradable N output was calculated by multiplying the dry matter yield of grain by N concentration in grain.
[b] Values are means ± standard deviations. Different lowercase letters indicate significant difference among treatments in each cropping season ($p < 0.05$).
[c] The data of N input from N deposition, seed, non-symbiotic N fixation (represented in italic font) was estimated from published literature.

and treatment was found on the seasonal N losses ($F = 0.30$, $p = 0.744$). Ammonia volatilization and denitrification were the primary pathways for N losses. The measured N loss from ammonia volatilization constituted 15.0% to 21.8% of the total N output (Table 3). N loss from denitrification was estimated as 21.6% of the fertilizer N input according to the mean value obtained from published literatures (Zhao et al., 2011; Li et al., 2014; Xu and Cai, 2014; Dash et al., 2015). It constituted 18.6% to 21.5% of the total N output in current study. Due to lower N fertilizer input, annual loss of N from denitrification for OPT_N and OPT_{NW} decreased by 15.3% within two years. In comparison to FP, the N loss from AV in OPT_N and OPT_{NW} was reduced by 25.2% and 30.4% respectively in the early season, and 32.5% and 29.9% in the late season ($p < 0.05$). N loss as a result of runoff accounted for 2.8% to 12.2% of the total output in rice cropping system. Furthermore, because of the lower N input of fertilizer compared to FP, the annual N runoff load in OPT_N was reduced by 40.4%. Because of the significant reduction of the runoff volume in OPT_{NW} (data not shown), the annual N runoff load was accordingly reduced by 67.2% and 45.0% respectively in comparison to OPT_N and FP. Annual N leaching loss in FP, OPT_N and OPT_{NW} accounted for 9.3%, 7.0% and 6.0% of the total N output, respectively (Table 3). N leaching loss in OPT_N was reduced by 30.0%, compared to that for FP, and in $OPT_{NW,}$ the loss of N through leaching was reduced by 17.8% in comparison to OPT_N. Based on the regression analysis using pooled data from on-station field experiments, the environmental N losses increased with the increase of total N input and N surplus, and decreased with the increase of plant N uptake, ARE, AE, and PFPN (Fig.6). These results indicated that NUE and crop N uptake played an integral role in mitigating environmental N losses. The pooled data obtained for the multi-location on-farm comparison trials clearly demonstrated the significant influence of adopted agronomic practice on N distribution in rice cropping systems (Fig.7). In OPT_N and OPT_{NW}, more N flows to grain rather than the environment or soil pool as compared to FP.

3.4. Sensitivity analysis of estimated N surplus and N stored in soil

The changes in calculated N surplus and $N_{\Delta soil}$ value were examined by changing the estimated N parameters by ± 40% at different treatments (Fig. 8). For input item, the ± 40% changes of N input from deposition resulted in changes of ± 3.86% to 6.03% in N surplus and ± 12.2% to 17.9% in $N_{\Delta soil}$ across all treatments. The ± 40% changes non-symbiotic N fixing resulted in changes of ± 3.63% to 5.68% in N surplus and ± 11.5% to 16.8% in $N_{\Delta soil}$. The increase of N input from irrigation and seed both resulted in insignificant increase in N surplus and $N_{\Delta soil}$. For output item, the ± 40% changes in denitrification led to changes of $N_{\Delta soil}$ by 30.2% to 33.8%. The ± 40% changes in AV led to changes of $N_{\Delta soil}$ by 23.6% to 27.7%. $N_{\Delta soil}$ showed less sensitivity to the parameters of runoff and leaching. The ± 40% changes in runoff led to changes of $N_{\Delta soil}$ by ± 4.84% to 14.6%. The ± 40% changes in leaching led to changes of $N_{\Delta soil}$ by ± 8.82% to 12.9%. These results indicated that the variations in the N parameters have small effects on the N surplus. The $N_{\Delta soil}$ was most sensitive to the N parameters of denitrification and AV.

4. Discussion

4.1. Grain yield and NUE in different agronomic practices

Farmers often utilize N fertilizers to maximize rice yield. However, continuous increase in N input does not ensure a sustainable increase in yield, because it leads to an increased loss of N from the system (Cassman et al., 2003). Value for AE in China was recorded at 5 to 10 kg kg^{-1} (Peng et al., 2006), much lower than the reported values for AE at 15 to 18 kg kg^{-1} worldwide (Cassman et al., 1996). Consistent with previous reports, AE averaged at 9.76 kg kg^{-1} in FP in current study as well. The values of AE, REN and PFPN was significantly increased in

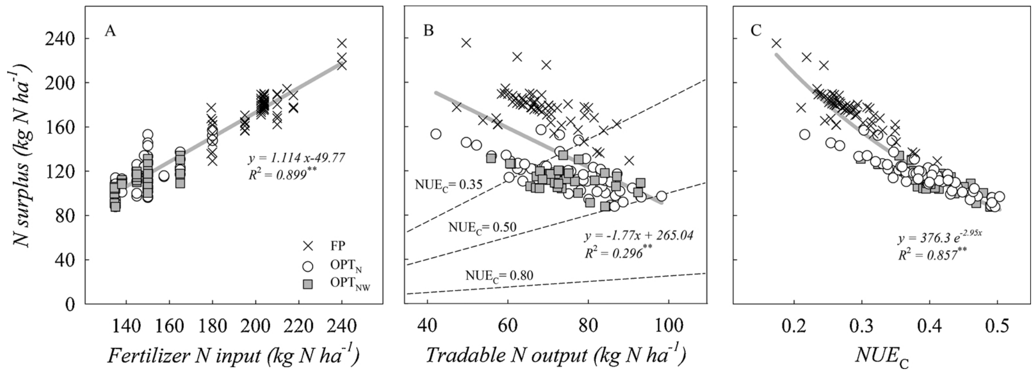

Fig. 4. The relationship between N surplus and fertilizer N input, tradable N output and N efficiency in cropping system (NUE_c) in the multi-location comparison trials during 2014–2017 in Guangdong province.

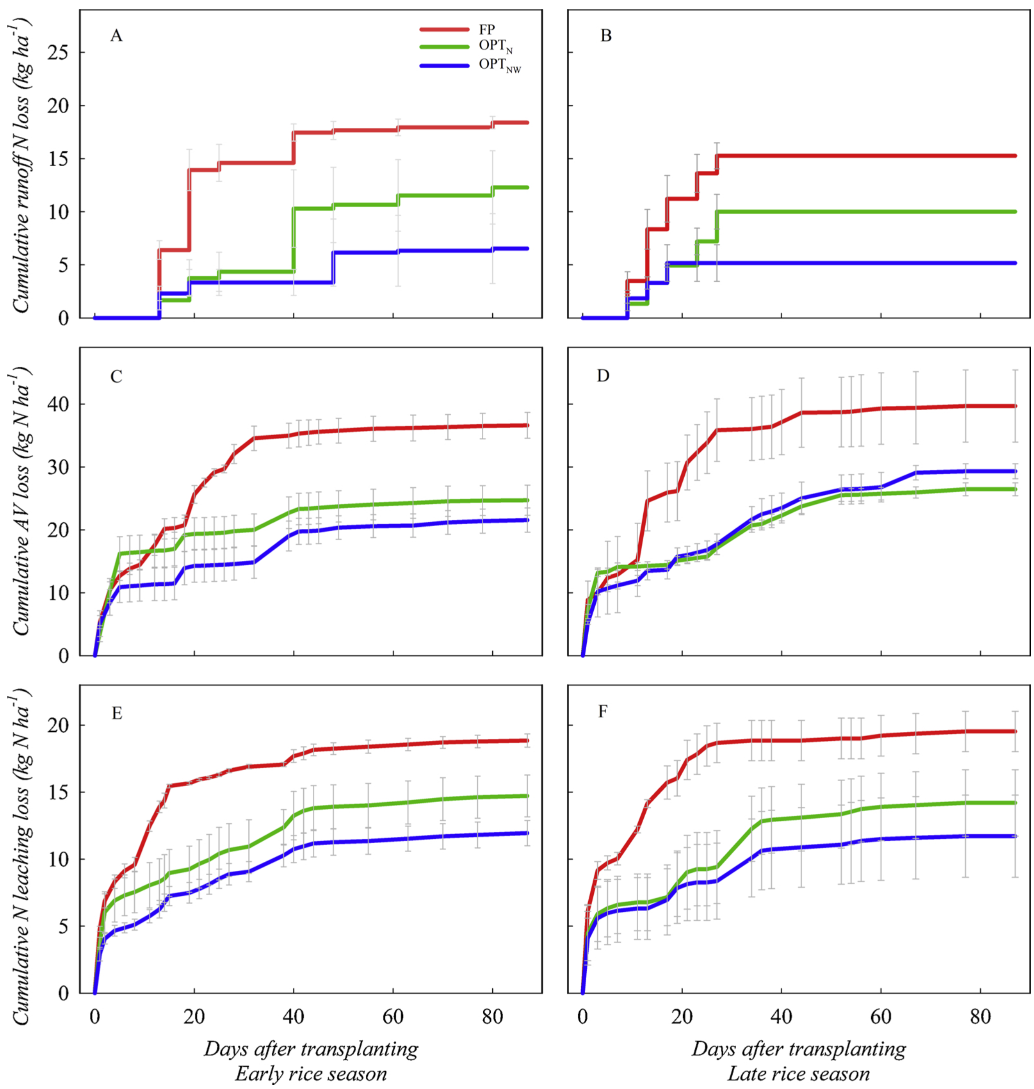

Fig. 5. Cumulative N losses from runoff, ammonia (NH_3) volatilization and leaching (mean ± SD) under different treatments in the field experiment at Guangzhou during early and late rice seasons of 2017.

OPT_N and OPT_{NW} due to lower rate of N input. Another factor that caused low NUE was the improper timing of N usage. In the current study, rice growers used large amount of N fertilizer during the early vegetative stage. High N rate in this stage promoted the production of a large number of unproductive tillers. According to our previous report, the productive tiller percentage was about 50% or even lower under farmers' practices. Half of the tillers in FP perish at PI and HD stages. Furthermore, these unproductive tillers wasted absorbed nutrients (Zhong et al., 2010). OPT_N and OPT_{NW} had a notable decrease in N fertilizer input, but the grain yields, crop N uptake, AE, ARE and PFPN improved considerably relative to FP (Fig.2). The primary reason for enhanced grain yield was a combination of proper N rate with proper timing of spilt application that was practiced in OPT_N and OPT_{NW}. In this regard, firstly, reduced N rate in the tillering stage resulted in fewer

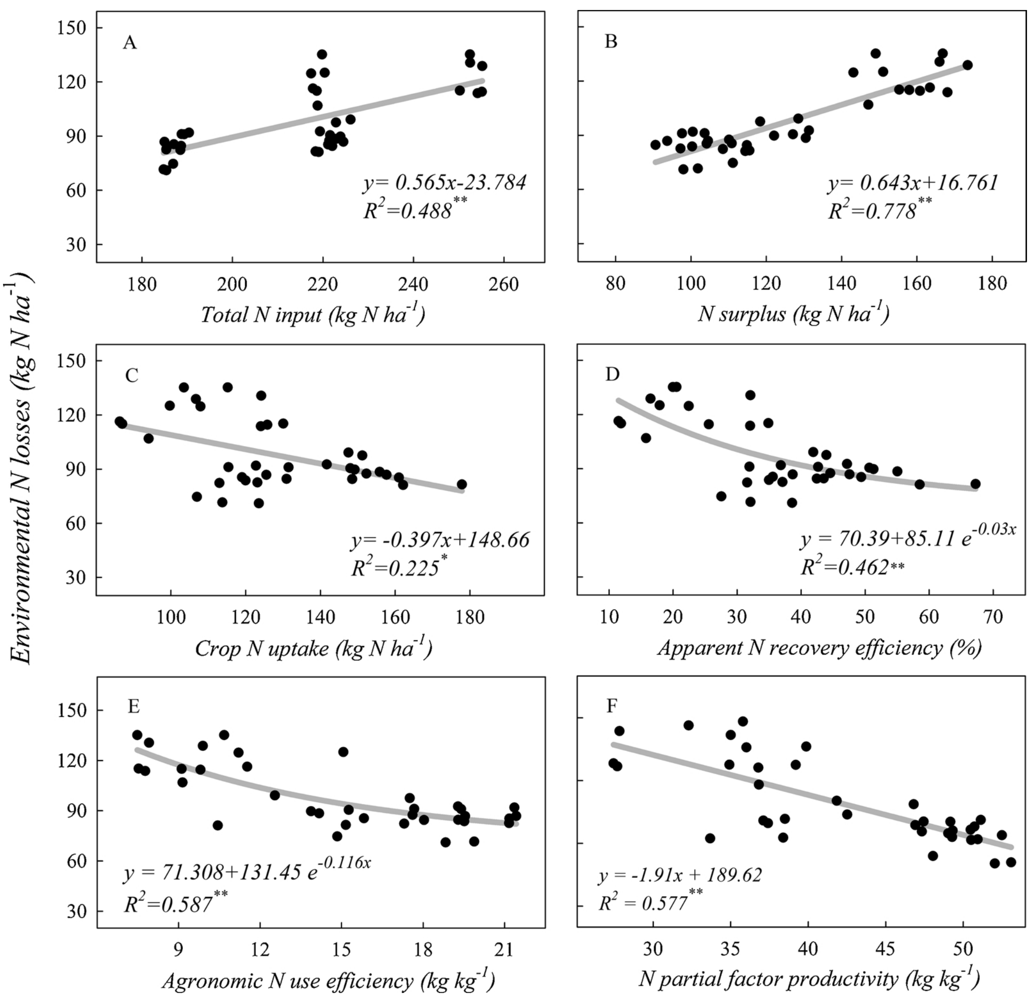

Fig. 6. Regression of environmental N losses to total N input, N surplus, crop N uptake, apparent recovery efficiency, agronomic use efficiency and partial factor productivity of applied N under different treatments in the field experiments at Guangzhou during 2016–2017.

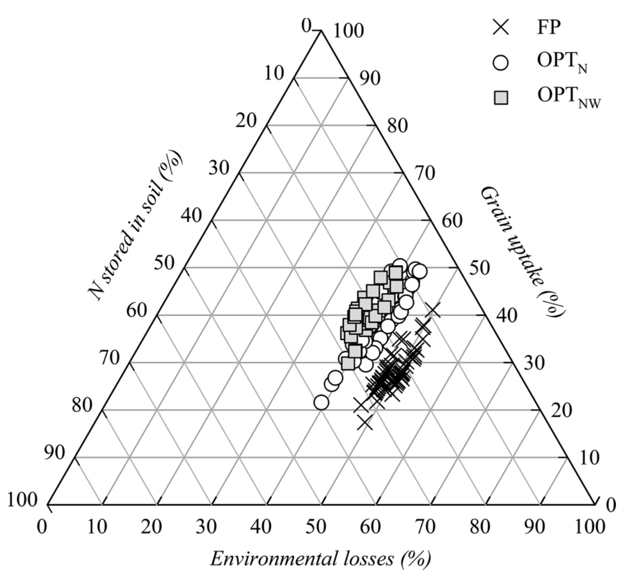

Fig. 7. The direction and proportion of total N inputs derived from different agronomic practices in the multi-location comparison trials during 2014 to 2017. The calculated N stored in soil ($N_{\Delta soil}$) was the difference between total N inputs and total N outputs, reflecting the contribution of N inputs to the soil nitrogen stock.

unproductive tillers. Secondly, a high proportion of N fertilizer was postponed and used in later growth stage in OPT_N and OPT_{NW}, with 30% top-dressed as panicle fertilizer at PI and, for late season, 10% at HD. N absorbed during panicle formation stage enhances spikelets per panicle, grain weight and grain filling, while top-dressing at HD prevents spikelet retrogression, thus laying a foundation for enhanced spikelet development (Zhong et al., 2010). Therefore, a combination of reduced N input with properly delayed split application improved NUE in double rice cropping system.

According to the report obtained from GRiSP, about 5–20 million ha of irrigated rice in Asia will be exposed to water shortage by 2025 (GRiSP, 2013). The irrigation water input is high in the farmers' irrigation practice (FWP), as the field were regularly irrigated to maintain 2–5 cm of surface water except a short mid-season drainage to control the number of unproductive tillers. The AWD technique was adopted in OPT_{NW}. Compared with FWP, the water input and irrigation frequency can be substantially reduced in AWD regime, as once seedlings have recovered from transplanting shock, field water is allowed to drop to 15 cm below the soil surface before irrigation is applied. For grain yield, it was observed that OPT_{NW} reduced field water use without compromising the overall yield. The 15 cm threshold is considered "safe" as soil water potential is greater than -10 k Pa, and allows rice to easily extract adequate water (Lampayan et al., 2015). Previous studies at Bangladesh demonstrated the lower irrigation cost for AWD adopters than the non-AWD adopters due to the lower frequency of irrigation application (Lampayan, et al., 2015). We suggested that AWD can act as a simple and practical water-saving technology for counteract the water

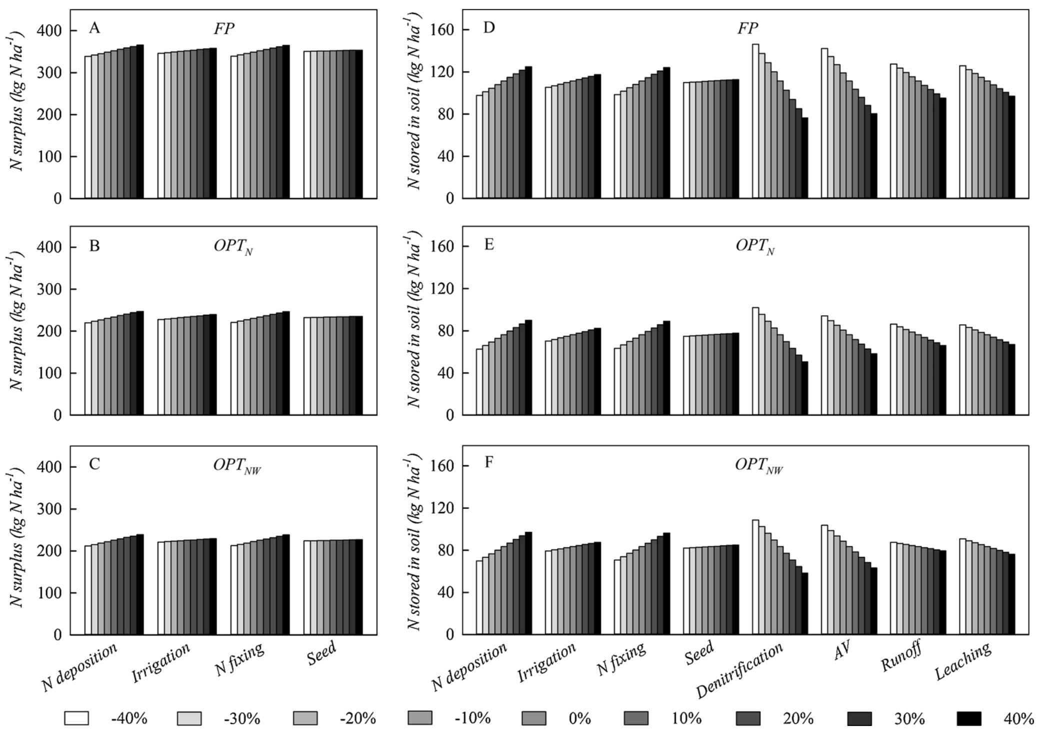

Fig. 8. Sensitivity of N surplus and calculated N stored in soil ($N_{\Delta soil}$) in response to the changes of N inputs and output parameters in the on-farm multi-location comparison trails. Different bars for each N item represent the values of N surplus and $N_{\Delta soil}$ in response to changes of the parameter in 10% increments from -40% (the left-most bar) to +40% (the right-most bar).

shortage in South China. But it is worth noting that despite the water input and irrigation frequency can be reduced by AWD technology, the water scarcity risk still exists if irrigation facility is not available for providing timely irrigation to the crops. Therefore, during the extension of AWD, assured irrigation facilities should also be developed, especially in drought- prone regions.

4.2. N surplus and NUE_c in soil-crop system

Generally, N input in a given soil-crop system comprises fertilizer, biological fixed N_2, atmospheric deposition, straw return, seeds and irrigation water. Based on systematic measurement of N input, crop N uptake, and hydrological and gaseous N losses, this study provides a comprehensive quantification of N surplus for different practices in double rice cropping system. In this study, N fertilizer accounted for 77.9 to 82.2% of total N input, while N input through deposition and non-symbiotic N fixing contributed to 13.5 to 17.7% of the total N input. To enhance NUE even further, accounting for N source from deposition and non-symbiotic N fixation should be recommended as a comprehensively designed strategy in a given soil-crop system.

Oenema et al advocated that a 100 kg ha^{-1} y^{-1} N surplus can serve as reference index for N management in arable land of clayey soils (Oenema et al., 2003). In this study, multi-location trails revealed that N surplus in FP was 352.1 kg ha^{-1} y^{-1} in double rice cropping system (Table 4). This is comparable with the maize/wheat double cropping system with N surplus estimated to be 349 kg N ha^{-1} y^{-1} in the North China Plain (Hartmann et al., 2014). This high level of N surplus primarily originated from exceedingly high level of N fertilizer input as well as through poor utilization of N for crops. For OPT_N and OPT_{NW}, N surplus was reduced by over 30% in comparison to FP. When considering fertilizer input of N solely, the N surplus in OPT_N and OPT_{NW} was 149.2 and 145.7 kg ha^{-1} y^{-1}, respectively, much closer to the reported values ranging from 68 to 192.7 kg ha^{-1} y^{-1} for various cropping systems in US and Europe (Sainju et al., 2018). Regression analysis indicates that N surplus was linearly increased with increasing fertilizer N rate (Fig.4 A) and was decreased with increasing tradable N output and NUE_c (Fig.4 B, C). This suggests that a lower N surplus is mainly attributed to lower N fertilizer input and higher N utilization through optimized N management.

Generally, a negative $N_{\Delta soil}$ indicates exhaustion of the soil pool in cropping system. Considering the sustainability of soil fertility, negative $N_{\Delta soil}$ should be avoided in N management to minimize the risk of soil N depletion. Results from on-station field experiment revealed that without straw incorporation, there were slight negative $N_{\Delta soil}$ in OPT_N and OPT_{NW}, indicating a potential risk of N deficit as consequence of higher crop N recovery under the condition of straw removal. But provided that the rice straw was returned to soil, seasonal $N_{\Delta soil}$ showed positive for OPT_N and OPT_{NW}, ranging from 14.2 to 29.8 kg ha^{-1}. Previous study demonstrated that straw return increased the $N_{\Delta soil}$ and improved the soil fertility due to reduced N output by harvest (Wang et al., 2019). We suggested that straw incorporation should be carried out in optimized N management to sustain long-term soil fertility under the high yielding conditions with reduced fertilizer N input. Fortunately, straw returning is now a national policy in China for crop production and is widely adopted by rice farmers (Zhao et al., 2018). This ensures the sustainability of the OPT_N and OPT_{NW} practices.

Sensitivity analysis for on-farm multi-location trials indicated that the N surplus and $N_{\Delta soil}$ were sensitive to the N input items of atmospheric N deposition and non-symbiotic N fixation. Previous studies considered atmospheric N deposition as an important N source in crop production in China (Zhang et al., 2015), as China is a global hotspot of N deposition at present (Xu et al., 2015). Liu et al. (2019) reported that N deposition accounted for 17–21% of the total N inputs in optimized N management, contributing to plant N uptake and influencing the apparent recovery efficiency of applied N. The N fixation was another important non-fertilizer N source for rice cropping systems due to the growth and activity of non-symbiotic N fixing organisms in the flooding condition (Herridge et al., 2008; Liao et al., 2013). Results from sensitivity analysis also revealed that $N_{\Delta soil}$ was most sensitive to the output parameters of denitrification and AV. Previous research demonstrated that AV and denitrification constituted the principal pathways for N loss in irrigated rice paddies (Li et al., 2014). Therefore, acquiring the precise field data of N deposition, non-symbiotic N fixing and the N losses from denitrification and AV could achieve a better quantification of N surplus and $N_{\Delta soil}$ for improving farm gate N management.

Many N use efficiency calculations in previous researches considered N inputs derived from chemical fertilizers, manures, or crop residues. In this study, NUE_c consisted of the N input items from fertilizer and non-fertilizer sources within crop-soil system, and the N output items from tradable out and environmental N losses were considered. This allowed elaboration of the relationship between crop production and N consumption at a farm level as well as the viability of N management at agricultural system level. According to previous research, ideal NUE_c should range from 0.5 to 0.9 in various agricultural systems (Ju and Gu, 2017). In FP, the NUE_c was 0.28, indicating that majority N input went to environment or soil pool. NUE_c of OPT_N and OPT_{NW} was 0.39 and 0.40, with an increase of about 39.8% and 42.0%, respectively, as compared to FP. Therefore, OPT_N and OPT_{NW} are clearly more efficient in using N resource. Zhang et al. (2015) reported that global NUE_c would need to increase from 0.4 to 0.7 between now and 2050 to ensure adequate food security and environmental safety. We believe that there remains great potential for achieving further improvement in NUE_c in the double rice cropping system.

4.3. N flows in response to N and irrigation management

Loss of N to the environment fluctuate based on the rate, timing, method of N use and climatic conditions. The current study has shown that N loss ranged from 48.4% to 59.6% of the total N input for different agronomic practices. Further, more than 30% of the total losses for different agronomic practices results from N loss to the environment via AV and denitrification. At the same time, N losses through runoff and leaching were lower, accounting for 7.7% to 19.0% of the total N losses (Table 4). Results from on-station field experiments showed that the annual loss of N to the environment in FP was 243.5 kg ha^{-1}, equivalent to 51.6% of the total N input in rice system (Table 3). Compared with FP, the environmental N losses in OPT_N and OPT_{NW} were markedly reduced. Generally, overuse of N fertilizer results in high concentration of N in floodwater and soil layer, which may elicit substantial losses of N through AV, denitrification and leaching. Optimum N rate was proposed as an effective practice to mitigate the environmental N losses due to a decrease of inorganic N concentration in soil and water (Zhao et al., 2009). The fertilizer N rate in OPT_N and OPT_{NW} was reduced by 16.6% to 33.8% relative to the current N rate in FP. It could be deduced that the lower fertilizer N rate in OPT_N and OPT_{NW} decreased the N concentrations in floodwater and soil layer, thus helping to mitigate the N losses to environment.

In addition to N, water is another determining factor for environmental N losses. Hydrological N loss through runoff and leaching is highly dependent on water management. Irrigated cropping system generally promotes N pollution in surface and ground water due to high water input. Farmers often use large amounts of fertilizer and frequent irrigation for rice fields. Since South China receives abundant rainfall, considerable N loss occurs via runoff and leaching. Compared with OPT_N, the gross loss of N via runoff and leaching was significantly reduced by 30.5% in OPT_{NW}. The lower hydrological N loss is related to the lower water input in AWD. N loss through leaching can be alleviated by reducing the volume of percolated water. Moreover, 'safe' AWD practice prolongs drainage period in paddy fields, thus helping to reduce loss of water via runoff by increasing the field buffering capacity. Therefore, reducing the input of irrigation water by adopting 'safe' AWD practice can be vital for decreasing N loss to the environment without compromising grain yield.

In a given crop-soil system, N amount is divided in plant pool, environmental losses and soil pool. Fertilizer N used in excess results in loss to aquatic and atmospheric environment, while increasing N uptakes in the crop helps to mitigate environmental N losses (Ju et al., 2009). Agronomic practices such as fertilizer usage and water management affect crop yield and N recovery, thus ultimately affecting N flows in the environment (Liu et al., 2018). N surplus has been classified as a primary source of N losses (De Notaris et al., 2018). Regression analysis revealed a 64.3 kg ha^{-1} reduction in N losses for each 100 kg ha^{-1} reduction of N surplus in rice paddies (Fig.6 B). Inefficient scheduling of N usage in FP exacerbated the effect of high N surplus because of asynchrony between crop demand and N supply, and further increased N losses to environment. In FP, the overuse of N fertilizer at early growth stage is particularly responsible for high N losses, since the under-developed rice plants lack a well-developed root system for N acquisition. It has been estimated that the N losses before PI accounted for over 70% of seasonal N losses (Liang et al., 2017). Previous study revealed that optimized N management increased the proportion of grain N removal to the total N input and reduced the proportion of environmental N loss as compared with conventional agronomic practices (Sainju et al., 2019). In OPT_N and OPT_{NW}, delayed N usage at panicle initiation increased N allocation to the plant pool by promoting the accumulation of dry matter. Subsequently, N was recovered in harvested crops, and relatively higher portion of N was allocated to grains rather than to environment or soil pool. Thus, our research suggests that when the current N rate is reduced, and when more N is utilized in the key stage of yield formation, a notable reduction in N surplus and N losses in intensive rice-cropping system can be achieved.

5. Conclusion

The current study has presented a systematic picture of the flow of N within crop and soil, including eventual N losses to the environment within double rice cropping systems in the central, south, north and east of Guangdong province, South China. The results have revealed significant benefits from optimized N and water management in improving NUE, reducing environmental N losses and N surplus at farm level. On average, OPT_N and OPT_{NW} increased grain yield (9.5%) with a significant reduction in N input (27%) relative to FP. Average NUE_c increased from around 0.28 to 0.40, while N surplus reduced from approximately 352.1 kg N ha^{-1} y^{-1} to below 250 kg N ha^{-1} y^{-1} due to the shift in agronomic practice from FP to OPT_N and OPT_{NW}. Lower N surplus in OPT_N and OPT_{NW} created a substantial reduction of N losses to the aquatic environment and atmosphere. Relative to OPT_N, OPT_{NW} reduced the N losses from leaching and surface runoff even more significantly. These results illustrate that OPT_N and OPT_{NW} methods ensure satisfactorily high grain yields while minimizing the N remaining in the soil and the environment at the same time.

Acknowledgments

This work is supported by the Special Fund for Agro-scientific Research in the Public Interest (201503106), the National High-tech Research and Development Program (863) (2014AA10A605), the National Key Research and Development Program of China (2016YFD0-300108-5), the Swiss Agency for Development and Cooperation through their funding for the Closing the Rice Yield Gaps in Asia (CORIGAP) project, the Science and Technology Program of Guangdong Province (2015B020231002), Guangdong Provincial Key Laboratory of Applied Botany, South China Botanical Garden, Chinese Academy of Sciences (AB2018013) and Modern Agriculture Industry Technology System for Rice in Guangdong Province (2016LM1066, 2017LM1066, 2018LM-1066). The authors are grateful to Prof. Xiaotang Ju, Prof. Lihong Xue, Dr. Xinsheng Niu and Dr. Chong Zhang for their helpful suggestions.

References

Bandaogo, A., Bidjokazo, F., Youl, S., Safo, E., Abaidoo, R., Andrews, O., 2015. Effect of fertilizer deep placement with urea supergranule on nitrogen use efficiency of irrigated rice in Sourou Valley (Burkina Faso). Nutr. Cycl. Agroecosyst. 102 (1), 79–89.
Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties. American Society of Agronomy, Madison, WI, pp. 595–624.
Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28, 315–358.
Cassman, K.G., Gines, H.C., Dizon, M.A., Samson, M.I., Alcantara, J.M., 1996. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and

applied nitrogen. Field Crops Res. 47, 1–12.
Dash, C.J., Sarangi, A., Singh, D.K., Singh, A.K., Adhikary, P.P., 2015. Prediction of root zone water and nitrogen balance in an irrigated rice field using a simulation model. Paddy Water Environ. 13, 281–290.
De Notaris, C., Rasmussen, J., Sørensen, P., Olesen, J.E., 2018. Nitrogen leaching: a crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agric. Ecosyst. Environ. 255, 1–11.
Deng, F., Wang, L., Ren, W.J., Mei, X.F., 2014. Enhancing nitrogen utilization and soil nitrogen balance in paddy fields by optimizing nitrogen management and using polyaspartic acid urea. Field Crops Res. 169, 30–38.
Food and Agricultural Organization (FAO), 2016. World Fertilizer Trends and Outlook to 2018. Food and Agriculture Organization of the United Nations, Rome, Italy Available from: www.fao.org/3/a-i4324e.pdf.
GRiSP (Global Rice Science Partnership), 2013. Rice Almanac. Web site:. fourth ed. International Rice Research Institute, Los Banos, Philippines, pp. 283. www.cgiar.org/rice-grisp.
Gu, B.J., Ge, Y., Chang, S.X., Luo, W., Chang, J., 2013. Nitrate in groundwater of China: sources and driving forces. Global Environ. Change 23 (5), 1112–1121.
Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010.
Hartmann, T.E., Yue, S.C., Schulz, R., Chen, X.P., Zhang, F.S., Muller, T., 2014. Nitrogen dynamics, apparent mineralization and balance calculations in a maize-wheat double cropping system of the North China Plain. Field Crops Res. 160, 22–30.
Herridge, D.F., Peoples, M.B., Boddey, R.M., 2008. Global inputs of biological nitrogen fixation in agricultural systems. Plant Soil 311, 1–18.
Hong, X., Gao, J.S., Luo, Z.Z., Zeng, X.B., Bai, L.Y., Luo, Z.Y., Yi, P., Chen, S.P., 2018. Effects of different fertilization regimes on nitrogen and phosphorus balance and eco-economic benefits in red paddy field. Chin. J. Appl. Ecol. 29 (1), 158–166 (in Chinese with English Abstract).
Jiao, J.G., Shi, K., Li, P., Sun, Z., Chang, D.L., Shen, X.S., Wu, D., Song, X.C., Liu, M.Q., Li, H.X., Hu, F., Xu, L., 2018. Assessing of an irrigation and fertilization practice for improving rice production in the Taihu Lake region (China). Agric. Water Manage. 201, 91–98.
Ju, X.T., Gu, B.J., 2017. Indexes of nitrogen management. Acta Pedol. Sin. 54 (2), 281–296 (in Chinese with English Abstract).
Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. U. S. A. 106, 3041–3046.
Lampayan, R.M., Rejesus, R.M., Singleton, G.R., Bouman, B.A., 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Res. 170, 95–108.
Li, C.F., Cao, C.G., Wang, J.P., Zhang, M., Yuan, W.L., Ahmad, S., 2008. Nitrogen losses from integrated rice-duck and rice-fish ecosystems in southern China. Plant Soil 307, 207–217.
Li, X.B., Xia, L.L., Yan, X.Y., 2014. Application of membrane inlet mass spectrometry to directly quantify denitrification in flooded rice paddy soil. Biol. Fert. Soils 50 (6), 891–900.
Liang, K.M., Zhong, X.H., Huang, N.R., Lampayan, R.M., Liu, Y., Pan, J., Peng, B.L., Hu, X.Y., Fu, Y.Q., 2017. Nitrogen losses and greenhouse gas emissions under different N and water management in a subtropical double-season rice cropping system. Sci. Total Environ. 609, 46–57.
Liao, Y.S., Zhuo, M.N., Li, D.Q., Guo, T.L., Li, J.J., Xie, Z.Y., 2013. Formulated fertilization for reducing nitrogen and phosphorus losses from paddy fields and increasing rice yield. Transat. Chin. Soci. Agric. Eng. 29 (1), 210–217.
Liu, J.C., You, L.Z., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. Proc. Natl. Acad. Sci. U. S. A. 17, 8035–8040.
Liu, Z., Gao, J., Gao, F., Dong, S.T., Liu, P., Zhao, B., Zhang, J.W., 2018. Integrated agronomic practices management improve yield and nitrogen balance in double cropping of winter wheat-summer maize. Field Crops Res. 221, 196–206.
Liu, J., Li, J.M., Ma, Y.B., Wang, E.L., Liang, Q., Jia, Y.H., Li, T.S., Wang, G.C., 2019. Crop productivity and nitrogen balance as influenced by nitrogen deposition and fertilizer application in North China. Sustainability 11 (5), 1347.
Lu, R.K., 1998. Principle and Apply Fertilizer of Soil-plant Nutrition. Chemical Industry Press, Beijing, pp. 152–208.
Ministry of Agriculture of China (MOA), 2017. http://www.zzys.moa.gov.cn, Accessed date: 18 August 2017.
Oenema, O., Kros, H., de Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20 (1), 3–16.
Peng, S.B., Buresh, R.J., Huang, J.L., Yang, J.C., Zou, Y.B., Zhong, X.H., Wang, G.H., Zhang, F.S., 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crops Res. 47, 243–252.
Peng, S.Z., He, Y.P., Yang, S.H., Xu, J.Z., 2015. Effect of controlled irrigation and drainage on nitrogen leaching losses from paddy fields. Paddy Water Environ. 13 (4), 303–312.
Sainju, U.M., Lenssen, A.W., Allen, B.L., Stevens, W.B., Jabro, J.D., 2018. Nitrogen balance in dryland agroecosystem in response to tillage, crop rotation, and cultural practice. Nutr. Cycl. Agroecosys. 110 (3), 467–483.
Sainju, U.M., Ghimire, R., Pradhan, G.P., 2019. Improving dryland cropping system nitrogen balance with no-tillage and nitrogen fertilization. J. Plant Nutr. Soil Sci. 182 (3), 374–384.
Sela, S., Woodbury, P.B., Marjerison, R., van Es, H.M., 2019. Towards applying N balance as a sustainability indicator for the US Corn Belt: realistic achievable targets, spatio-temporal variability and policy implications. Environ. Res. Lett. 14, 064015.
Shi, Z.L., Li, D.D., Jing, Q., Cai, J., Jiang, D., Cao, W.X., Dai, T.B., 2012. Effects of nitrogen applications on soil nitrogen balance and nitrogen utilization of winter wheat in a rice-wheat rotation. Field Crops Res. 127, 241–247.
Wang, L., Yuan, X.L., Liu, C., Li, Z.G., Chen, F., Li, S.Q., Wu, L.H., Liu, Y., 2019. Soil C and N dynamics and hydrological processes in a maize-wheat rotation field subjected to different tillage and straw management practices. Agric. Ecosyst. Environ. 285, 106616.
Xu, W., Luo, X.S., Pan, Y.P., Zhang, L., Tang, A.H., Shen, J.L., Zhang, Y., Li, K.H., Wu, Q.H., Yang, D.W., Zhang, Y.Y., Xue, J., Li, W.Q., Li, Q.Q., Tang, L., Lu, S.H., Liang, T., Tong, Y.A., Liu, P., Zhang, Q., Xiong, Z.Q., Shi, X.J., Wu, L.H., Shi, W.Q., Tian, K., Zhong, X.H., Shi, K., Tang, Q.Y., Zhang, L.J., Huang, J.L., He, C.E., Kuang, F.H., Zhu, B., Liu, H., Jin, X., Xin, Y.J., Shi, X.K., Du, E.Z., Dore, A.J., Tang, S., Collett, Jr.J.L., Goulding, K., Sun, Y.X., Ren, J., Zhang, F.S., Liu, X.J., 2015. Quantifying atmospheric nitrogen deposition through a nationwide monitoring network across China. Atmos. Chem. Phys. 15, 12345–12360.
Xu, Y.B., Cai, Z.C., 2014. Nitrogenous gas products of denitrification in subtropical soil. Ecol. Environ. Sci. 23 (6), 932–937 (in Chinese with English abstract).
Xue, L.H., Yu, Y.L., Yang, L.Z., 2014. Maintaining yields and reducing nitrogen loss in rice-wheat rotation system in Taihu Lake region with proper fertilizer management. Environ. Res. Lett. 9 (11), 115010.
Yao, Z.Y., Zhang, D.B., Yao, P.W., Zhao, N., Li, Y.Y., Zhang, S.Q., Zhai, B.N., Huang, D.L., Ma, A.S., Zuo, Y.J., Cao, W.D., Gao, Y.J., 2018. Optimizing the synthetic nitrogen rate to balance residual nitrate and crop yield in a leguminous green-manured wheat cropping system. Sci. Total Environ. 631, 1234–1242.
Zhang, C., Ju, X.T., Powlson, D., Oenema, O., Smith, P., 2019. Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. Environ. Sci. Tech. 53 (12), 6678–6687.
Zhang, W.F., Dou, Z.X., He, P., Ju, X.T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.L., Zhang, Y., Wu, L., Chen, X.P., Cassman, K.G., Zhang, F.S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Acad. Sci. 110 (21), 8375–8380.
Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51–59.
Zhang, X., Bol, R., Rahn, C., Xiao, G., Meng, F., Wu, W., 2017. Agricultural sustainable intensification improved nitrogen use efficiency and maintained high crop yield during 1980-2014 in Northern China. Sci. Total Environ. 596, 61–68.
Zhao, X., Zhou, Y., Wang, S.Q., Xing, G.X., Shi, W.M., Xu, R.K., Zhu, Z.L., 2011. Nitrogen balance in a highly fertilized rice-wheat double-cropping system in southern China. Soil Sci. Soc. Am. J. 76 (3), 1068–1078.
Zhao, X., Xie, Y.X., Xiong, Z.Q., Yan, X.Y., Xing, G.X., Zhu, Z.L., 2009. Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu lake region, China. Plant Soil 319 (1-2), 225–234.
Zhao, Y.C., Wang, M.Y., Hu, S.J., Zhang, X.D., Ouyang, Z., Zhang, G.L., Huang, B., Zhao, S.W., Wu, J.S., Xie, D.T., Zhu, B., Yu, D.S., Pan, X.Z., Xu, S.X., Shi, X.Z., 2018. Economics-and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. Proc. Natl. Acad. Sci. U. S. A. 115 (16), 4045–4050.
Zhong, X.H., Peng, S.B., Huang, N.R., Tian, K., Buresh, R.J., Singleton, G.R., 2010. The development and extension of three controls technology in Guangdong, China. In: Palis, F.G., Singleton, G.R., Casimero, M.C., Hardy, B. (Eds.), Research to Impact: Case Studies for Natural Resources Management of Irrigated Rice in Asia. International Rice Research Institute, Los Ban`os, Philippines, pp. 221–232.