Science of the Total Environment 609 (2017) 46–57

Contents lists available at ScienceDirect

Science of the Total Environment

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

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

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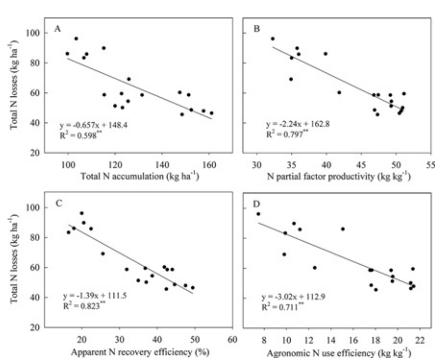
HIGHLIGHTS

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

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 May 2017
Received in revised form 11 July 2017
Accepted 12 July 2017
Available online 19 July 2017

Keywords:
Nitrogen losses
Methane emission
Nitrous oxide emission
South China

ABSTRACT

Nitrogen non-point pollution and greenhouse gas (GHG) emission are major challenges in rice production. This study examined options for both economic and environmental sustainability through optimizing water and N management. Field experiments were conducted to examine the crop yields, N use efficiency (NUE), greenhouse gas emissions, N losses under different N and water management. There were four treatments: zero N input with farmer's water management (N0), farmer's N and water management (FP), optimized N management with farmer's water management (OPT_N) and optimized N management with alternate wetting and drying irrigation (OPT_N + AWD). Grain yields in OPT_N and OPT_N + AWD treatments increased by 13.0–17.3% compared with FP. Ammonia volatilization (AV) was the primary pathway for N loss for all treatments and accounted for over 50% of the total losses. N losses mainly occurred before mid-tillering. N losses through AV, leaching and surface runoff in OPT_N were reduced by 18.9–51.6% compared with FP. OPT_N + AWD further reduced N losses from surface runoff and leaching by 39.1% and 6.2% in early rice season, and by 46.7% and 23.5% in late rice season, respectively, compared with OPT_N. The CH_4 emissions in OPT_N + AWD were 20.4–45.4% lower than in OPT_N and FP. Total global warming potential of CH_4 and N_2O was the lowest in OPT_N + AWD. On-farm comparison confirmed that N loss through runoff in OPT_N + AWD was reduced by over 40% as compared with FP. OPT_N and OPT_N + AWD significantly increased grain yield by 6.7–13.9%. These results indicated that optimizing water and N management can be a simple and effective approach for enhancing yield with reduced environmental footprints.

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http://dx.doi.org/10.1016/j.scitotenv.2017.07.118
0048-9697/

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_2O, but evidence is mounting that high N rate promotes N_2O emissions (Cai et al., 1997; Zou et al., 2005). Seasonal N_2O flux from rice paddies in China have increased from 0.32 kg N_2O-N ha^{-1} in the 1950s to 1.00 kg N_2O-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 fields after the water level has reached to 15 cm below the soil surface is one of the most commonly practiced water-saving techniques in Asia, and was introduced by us into South China in recent years. This practice is known as safe alternate wetting and drying (AWD15). A previous study in double season rice cropping system demonstrated that AWD15 outperformed the farmer's practice of midseason drainage in reducing water input and 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_2O) emission and N losses were systematically evaluated under different water and N management practices. Our objectives were to explore 1) if optimized N management could improve N use efficiency and reduce N loss and GHG emission; and 2) if integrating water-saving technology into the optimized N management could further improve NUE and reduce environmental footprints.

2. Materials and methods

2.1. On-station field experiment

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

2.1.1. Treatments and design

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

In farmers' N management, N fertilizer (urea, 46% N) was applied with 40% as basal, 20% at rooting stage, 30% at early tillering stage and 10% at late tillering stage for both seasons. The N rate was 180 kg N ha^{-1} in early rice season and 210 kg N ha^{-1} in late rice season. In 'three controls' N management, N rate was 150 kg N ha^{-1} in early rice season and 180 kg N ha^{-1} in late rice season. For early rice season, N fertilizer was applied with 50% as basal, 20% at mid-tillering (MT) and 30% at panicle initiation (PI). For late rice season, N was applied with 40% as basal, 20% at MT, 30% at PI and 10% at heading (HD). For all treatments, potassium (135 kg K_2O ha^{-1} as potassium chloride) and phosphorus (45 kg P_2O_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 OPT_N, field water layer was continuously kept at 2–5 cm after transplanting, and then around 25 DAT, midseason drainage was carried out to control