Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area

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ABSTRACT

Agricultural activities are the main source of non-point pollution in the Taihu Lake region, and therefore reduction of nitrogen (N) fertilizer is imperative in this area. A two-year experiment was carried out in a paddy field of summer rice–winter wheat rotation in the Taihu Lake area, and the rice growing seasons were mainly concerned in this research. Grain yield, N accumulation at rice crucial stages, N use efficiency, as well as N losses via run off during rice growing season were determined under different N application rates. No significant differences were observed in grain yield under N fertilizer application rates of 135–270 kg N ha\(^{-1}\) (50–100\% of the conventional N application rate). Nitrogen accumulation before the heading stage (Pre-NA) accounted for 61–95\% of total nitrogen absorption in mature rice, and was positively correlated with straw dry matter at harvest. Positive correlations were found between Pre-NA and straw (0.53, \(p<0.05\)), and between grain yield and N accumulation after the heading stage (Post-NA) (0.58, \(p<0.05\)). Suggesting that increasing nitrogen accumulation after the heading stage is crucial for grain yield improvement. Poor agronomic efficiency of applied N (AE\(_N\)), partial factor productivity of applied N (PF\(_N\)) and internal utilization efficiency of applied N (IE\(_N\)) were observed for the higher soil fertility and a higher N fertilizer input; a simple N fertilizer reduction could significantly increase the nitrogen use efficiency in this region. Nitrogen loss via runoff was positively linearly related to N application rates and severely affected by rainfall events. The highest-yielding N rates were around 232–257 kg N ha\(^{-1}\), accounting for 86–95\% of the conventional N application rates for the rice season. To reduce N losses and enhance N use efficiency, the recommendable N fertilization rate should be lower than that of the highest yield rate for rice season. Our findings indicated that nitrogen fertilizer reduction in the Taihu Lake area is feasible and necessary for maintaining grain yield, enhancing nitrogen use efficiency, and reducing environmental impact. However, the longer-term yield sustainability for the proper N application rate needs to be further investigated.

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1. Introduction

According to the Food and Agriculture Organization of the United Nations, the increasing world population will require more intensive agricultural production (Lammel, 2007). For thousands of years, Chinese farmers used traditional organic materials and intensive care to maintain relatively high yields (Zhang et al., 2007). However, since chemical fertilizers were introduced in the 1950s, their consumption has continually and rapidly increased; the total consumption of chemical fertilizers in China exceeded 55.3 million tonnes (Mt) in 2005, accounting for 30\% of the global agricultural N consumption (National Bureau of Statistics of China, 2006).

As one of three major foodstuff production areas, the Taihu Lake region has been characterized by its intensive agriculture, which produces plentiful, affordable and healthy food for China. A summer rice–winter wheat double-cropping rotation with two crops per year is the main cultivation mode in this region. In summer rice season, farmers in the Taihu Lake region have applied as much as 300 kg N ha\(^{-1}\) (Cui et al., 2000), causing serious environmental pollution. However, the average fertilizer usage rate in China is only 228 kg N ha\(^{-1}\) per crop (Zhang et al., 2007). Researchers have already indicated that agricultural activities, which contribute 30\% P and 59\% N to the Taihu Lake eutrophication (Li and Yang, 2004), are the main source of non-point pollution of P (Ekholm et al., 2005) and N (Gao et al., 2004; Vitousek et al., 2009) and could lead to

Abbreviations: AE\(_N\), apparent recovery efficiency of applied N; AE\(_N\), agronomic efficiency of applied N; PF\(_N\), partial factor productivity of applied N; IE\(_N\), internal utilization efficiency of applied N; PE\(_N\), physiological efficiency of applied N; Pre-NA, pre-heading N accumulation in the aboveground biomass; Post-NA, post-heading N accumulation in the aboveground biomass; Pre-RE, pre-heading recovery efficiency of applied N.

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serious eutrophication in water systems (Wang et al., 2004b). Many research studies have been carried out to evaluate the behavior of nitrogen and its impact on water bodies (Jiao et al., 2007; Li et al., 2007, 2009; Song et al., 2009; Tian et al., 2007; Wang et al., 2006; Xiong et al., 2002). In addition, for particular areas, optimal nitrogen fertilizer rates exist, and overuse can cause grain yield decline (Wang et al., 2009). For example, Wang et al. (2004a) proposed that the optimal nitrogen fertilizer rates in Changshu in the Taihu Lake region are 225–270 kg N ha$^{-1}$ for rice and 180–225 kg N ha$^{-1}$ for wheat. In the study by Ju et al. (2009), the optimal nitrogen fertilizer rate for rice season could be reduced to 200 kg N ha$^{-1}$ in the Taihu Lake region.

Besides chemical N fertilizer, N input from atmospheric deposition and irrigation also contribute to the cropland in this area. According to observations conducted in Changshu city in the Taihu Lake region, the amount of atmospheric wet and dry N deposition reached up to about 37 kg N ha$^{-1}$ per year (Xie et al., 2007), and irrigation N was up to 56.3 kg N ha$^{-1}$ during the rice growing season (Xie et al., 2008). Considering such large amount environmental N input, using less N fertilizer per unit of food produced is considered to be at the forefront of measures to improve the global N balance (Liu et al., 2008).

Nitrogen use efficiency is a widely used index in assessing fertilizer management (Dobermann et al., 2002; Haefele et al., 2008; Peng et al., 2006; Rathke et al., 2006), and it can be further separated into different component indices to represent diverse aspects. The agronomic efficiency (AE$_N$) is an index to express the yield-increasing effect with applied N. The physiological efficiency of applied N (PE$_N$) and internal utilization efficiency of N (IE$_N$) are indices of the plant's ability to transform nutrients into economic yield. The partial factor productivity of N (PF$_N$), a useful measure in conventional cropping systems, can provide an integrative index of the total economic output in relation to the utilization of all N sources in the system (Cassman et al., 1998). The apparent crop recovery efficiency of applied nutrient (RE$_N$) is used to express the percentage of fertilizer nitrogen recovery in above-ground plant biomass. RE$_N$ is popularly used in field research to assess the contribution of fertilizer N (Zheng et al., 2007), and approximately 31% of fertilizer nitrogen is found in the final harvest in China (Dobermann and Cassman, 2002). Dobermann (2007) combined research from Europe, Asia, and the USA and proposed values for nitrogen use efficiency indices under good management practice: AE$_N$ (25–30 kg kg$^{-1}$), IE$_N$ (55–65 kg kg$^{-1}$), PF$_N$ (60–80 kg kg$^{-1}$), RE$_N$ (0.5–0.8 kg kg$^{-1}$), and PE$_N$ (50–60 kg kg$^{-1}$).

However, high rates of nitrogen use efficiency have not been achieved in most experiments in China and other areas. Consistent low agronomic efficiency of nitrogen (AE$_N$) was reported in conventional fertilizer applications in Wuxi (4.9–7.8 kg kg$^{-1}$) (Liu et al., 2006) and Hunan (3.2–4.8 kg kg$^{-1}$) (Zou et al., 2008) in China, and in eight districts in India (10.9 kg kg$^{-1}$) (Yadav, 2003). Low nitrogen use efficiencies have also been frequently reported in the Taihu Lake region. Peng et al. (2006) reported that the AE$_N$ was only 7 kg grain kg$^{-1}$ N in the high-fertility paddy field, while Huang et al. (2007) reported AE$_N$ to be 6–12 kg grain kg$^{-1}$ in the Taihu Lake region. Low nitrogen use efficiency with high N loss has already resulted in many environmental consequences in lakes and rivers. A report by Yan et al. (2009) showed that plants absorbed only 23.1% and 8.3% of the nitrogen in fertilizer applied at the tillering and pre-heading stages respectively. Thus, a great quantity of nitrogen is wasted and eventually enters the environment through runoff, leakage, and volatilization. There is an urgent need to improve N utilization for the sake of economic and environmental benefits. Many previous studies on N use efficiency have been mainly concerned with the final grain yields of crops, and few have addressed crucial growing stages. In order to achieve both high yield and efficiency of fertilizer application, it is necessary and imperative to optimize N fertilizer management at crucial growing stages.

Considering the negative impact of over-fertilization on grain yield, deterioration of the environment, decrease in use efficiency, and augmentation of atmospheric deposition that are caused by overuse of nitrogen fertilizers, it is necessary to significantly decrease nitrogen fertilizer use in agriculture. The objectives of this study are to (a) determine the feasibility of reducing nitrogen fertilizer use in the Taihu Lake region without a significant negative effect on crop yields; (b) assess the environmental impact of nitrogen fertilizer reduction; and (c) search a recommendable N fertilizer rate that can support high grain yield, minimize environmental impact, and improve nitrogen use efficiency.

2. Materials and methods

2.1. Study sites

The study was carried out at Yixing City, which is in the Taihu Lake region (30°5′–32°8′N, 119°8′–121°5′E) of Jiangsu Province, China. Yixing belongs to the northern subtropical humid climatic zone, with a mean annual temperature of 16 °C and annual rainfall of 1100–1400 mm (60–70% of which occurs from June to October, just during the rice growing season). The soil of the experimental site was developed from a lacustrine deposit, and is classified as Gleyed-stagnant Anthrosols according to the FAO soil taxonomy system. A summer rice and winter wheat double-crop rotation has been intensively cultivated in this region. Some selected properties of the top layer soil (0–15 cm) are as follows: organic matter 12.6 g kg$^{-1}$; total N 0.64 g kg$^{-1}$; total P 0.39 g kg$^{-1}$; total K 13.9 g kg$^{-1}$; mineral N 53.5 mg kg$^{-1}$; Olsen-P 42.6 mg kg$^{-1}$; NH$_4$OAc-extractable K 49.6 mg kg$^{-1}$; and pH 6.23. The soil texture was loamy clay.

2.2. Plot design

The experiment for the study has been described by Xue et al. (2009), which was set up in June 2008. Briefly, the area of each plot was 5.5 m × 5.5 m and the plots were arranged randomly with three replications for each treatment. The summer rice–winter wheat rotation was applied in all plots. The fertilizer rate applied was based on local farmers was 270 kg N ha$^{-1}$ for rice and 240 kg N ha$^{-1}$ for wheat. Seven treatments were designed at 0 (N$_0$), 135 (N$_1$), 189 (N$_2$), 216 (N$_3$), 243 (N$_4$), 270 (N$_5$) and 405 kg N ha$^{-1}$ (N$_6$) for the rice, and 0 (N$_0$), 120 (N$_1$), 168 (N$_2$), 192 (N$_3$), 216 (N$_4$), 240 (N$_5$), and 360 kg N ha$^{-1}$ (N$_6$) for the wheat, representing respectively 0%, 50%, 70%, 80%, 90%, 100% and 150% of the farmer's nitrogen application rate. This study was mainly focused on the rice growing season. All N treatments were fertilized with the same amount of P and K (81 kg P ha$^{-1}$, 81 kg K ha$^{-1}$), which were either from compound fertilizer (N 15%, P$_2$O$_5$ 15%, K$_2$O 15%) or from normal superphosphate (P$_2$O$_5$ 12%) and potassium chloride (K$_2$O 60%) or both from compound fertilizer, normal superphosphate and potassium chloride. The compound P and K fertilizer were all served as basal dressing and mixed with soil at puddling before the rice plants were transplanted. The tillering fertilizer and head dressing was urea, which was applied into the water as a supplemental fertilizer.

The rice season began on June 13 and ended on October 25 in 2008, and it was on June 15 and on October 23 in 2009 respectively. The monthly rainfall during rice growing season were 277.8, 165.1, 162.4, 120.1, 72.5 mm and 215.3, 226.6, 244.5, 55.3, 6.1 mm, in Jun, Jul, Aug, Sept and Oct 2008 and 2009, respectively.
2.3. Sampling and analysis

2.3.1. Plant

In the 2008–2009 experiment, the rice (Oryza sativa L.) cultivar (zhèn dào 10#) was selected. In the first year (2008), the rice was sown on May 20, and then transplanted on June 13 with a density of 20–25 hills m\(^{-2}\) and three seedlings per hill. Tillering and head dressing fertilization were carried out on July 3 and July 28, respectively. Seven hills of plants were sampled 10 days after tillering and heading fertilization were applied, and the dry weight of the above-ground biomass was measured. In the second year (2009), zhèn dào 10# was sown on May 18 and transplanted on June 15 with a density of 20–25 hills m\(^{-2}\) and four seedlings per hill. Tillering and head dressing fertilization were carried out on July 10 and August 1, respectively. Seven hills of plants were sampled 15 days after tillering and heading fertilizer were applied and the dry weight of plant biomass was measured.

At harvest, the above-ground portions of the plants were collected, and the oven-dry weights of straw and grain were measured separately. Subsamples of grain and straw were oven-dried at 70 °C for 24 h after heat-processing at 105 °C for 30 min, and were then ground and sieved to pass a 0.5 mm sieve for chemical analyses. The N in the plant samples was determined by the Kjeldahl method, the uptake of N was calculated by multiplying the concentration of N by the oven-dry weight, expressed in kg ha\(^{-1}\) (Lu, 2000).

2.3.2. Water

The surface water was gathered 1, 2, 3, 4, 5, 6, 7, 10, and 20 days after N fertilizer was applied for the N dynamic research. There were two ways for collecting the runoff water samples. First, the surface water in each plot was gathered before and after heavy rain events, which can cause water loss over the dam (10 cm lower than the ridge of field) at the outlet of each plot. The volume of water outflow was recorded using a flow meter set at the water outlet. Secondly, the surface water in each plot was collected before the dam at the outlet was open at tillering stage for the control of rice tillering, the volume of water drained was also recorded with a flow meter. Three random water samples in different position in each plot were collected, thoroughly mixed, and then immediately filtered and refrigerated at 4 °C for analysis. The concentrations of NH\(_4\)^+ - N, NO\(_3\)^- - N and Total N in the water were then determined colorimetrically using a continuous-flow auto analyzer (Traacs 800, Bran & Luebbe, Hamburg). The N losses via run off were calculated by multiplying the N concentrations (mean before and after water outflow for heavy rain events) in the water samples and the volume of the water outflow.

2.4. Nitrogen use efficiencies

\[
RE_N (\text{apparent recovery efficiency of applied N}) = \left( \frac{U_N - U_0}{F_N} \right) \times 100
\]

where \(U_N\) is the total N uptake (kg ha\(^{-1}\)) in grain and straw, \(U_0\) is the total N uptake measured without N application, and \(F_N\) is the rate of applied fertilizer N (kg ha\(^{-1}\)).

\[
AE_N (\text{agronomic efficiency of applied N}) = \frac{Y_N - Y_0}{F_N}
\]

where \(Y_N\) is the grain yield (kg ha\(^{-1}\)) at a certain level of applied fertilizer N, and \(Y_0\) is the grain yield (kg ha\(^{-1}\)) without N application.

\[
PFP_N (\text{partial factor productivity of applied N}) = \frac{Y_N}{F_N}
\]

![Fig. 1. Grain yields under different nitrogen rates in 2008 (solid circle) and 2009 (hole circle). Error bars presented standard deviations.](image)

Pre-NA: pre-heading N accumulation in the aboveground biomass (Novoa and Loomis, 1981; Cassman et al., 2002; Dobermann, 2007)  
Post-NA: post-heading N accumulation in the aboveground biomass  
Pre-RE: the ratio of N accumulation to the N fertilizer applied before heading stage  
Translocated N: the difference between N uptake in the whole above-ground plant at anthesis and N uptake in straw at maturity (Jiang et al., 2004)  
N-translocation efficiency: the ratio of translocated N to the N accumulation of the whole aboveground plant at anthesis.

2.5. Statistics

Statistical analyses of the data were performed using SPSS 13.0 with LSD to identify differences between the growing periods and Pearson correlation coefficients to test for significance between parameters.

3. Results

3.1. Grain yield

The mean grain yield of each treatment is shown in Fig. 1. Compared with no nitrogen application (\(N_0\)) in 2008, the grain yield with nitrogen application (from \(N_1\) to \(N_6\)) increased by 34.7%, 38.3% 39.2%, 34.7%, 42.2% and 18.4%, respectively. The differences between different nitrogen treatments were not significant except for \(N_4\), which had excessive N application rate. Interestingly, applying fertilizer at 50% of the conventional rate (\(N_1\)) did not significantly reduce the grain yield, whereas excessive fertilizer at 150% (\(N_6\)) of the conventional rate sharply decreased yield. Large N rate increment only results tiny increase in rice yield (0.40 tonnes ha\(^{-1}\), between the greatest yield and that of 135 kg ha\(^{-1}\) N application rate). A significant quadratic correlation between mean grain yield and nitrogen application existed \((y = -3.80E-005x^2 + 0.0177x + 5.29, r^2 = 0.97)\). For the year of 2009,
the yield increase was around 30.0%, compared with the control. No significant difference was found in grain yield among all the N treatments. A quadratic correlation between grain yield and nitrogen application rate was found ($y = -2.22E-005x^2 + 0.0114x + 5.09$, $r^2 = 0.81$). Compared with 2008, the rice grain yields for all N application treatments, except N6, were 8% lower in 2009.

3.2. N losses through runoff

The rainfalls in summer rice season in the Taihu Lake region were 797.9 and 747.8 mm separately in 2008 and 2009. In Jul and Aug, which belong to rice tillering and heading stages, the monthly rainfall in 2009 was greater than that in 2008. At three rice crucial stages (seedling, tillering and heading), the rainfall represents 75.9% and 91.8% of total rainfall during rice growing season in 2008 and 2009 respectively. Rainfall events always happened when the N content in surface water were higher especially at seedling and heading period in 2009 (Fig. 2).

Significant linear correlations between N application rates and N losses via runoff were observed (Fig. 3). N losses via surface runoff were 7.3, 8.9, 10, 12, 13, 15, and 21 kg N ha$^{-1}$ from control (N0) to N6 in the first year, whereas in the second year, the losses were 12, 26, 31, 47, 37, 57, and 65 kg N ha$^{-1}$, respectively. N loss through runoff increased with the N application rate. Compared with the control, N losses per unit N application were 0.01–0.03 kg N lost per kg N applied in 2008 and 0.10–0.17 kg N lost per kg N applied in 2009. N losses in the second year were 10 times higher than in the first year.

3.3. N accumulation

As the vegetative period was ending, the plant N uptake before the heading stage for all the treatments accounted for a great portion of N uptake for the whole plant growing period. In 2008, N accumulation before heading stage (Pre-NA) was 95–176 kg ha$^{-1}$, accounting for 61–95% of N absorption for the whole growing season (Fig. 4). Nitrogen accumulation post-heading (Post-NA) was
only 9–68 kg ha\(^{-1}\) (5–39% of the absorption for the whole growing season). The Post-NA was the highest for the N\(_2\) treatment and the lowest for N\(_0\). Compared with other nitrogen treatments, N\(_5\) had the lowest Post-NA (Fig. 4). In 2009, the Pre-NA was 83–191 kg ha\(^{-1}\), accounting for 70–94% of the total N uptake, while the Post-NA was 5–53 kg ha\(^{-1}\), accounting for 6–30% of whole absorption (Fig. 5). The greatest Post-NA levels were found in N\(_1\), N\(_2\), and N\(_3\). When the nitrogen application rate exceeded 216 kg ha\(^{-1}\), the Post-NA decreased to 20 kg ha\(^{-1}\) (Fig. 5). There was a tendency for Pre-NA to increase with the increasing N rate, but the increase was not significant, except for high nitrogen application rates such as N\(_5\) and N\(_6\) in the first year (Fig. 4). Nitrogen accumulation at harvest was found to increase with N inputs in the experiment.

N distribution in the aboveground parts of the plants at maturity is shown in Fig. 6. In 2008, the grain/straw N accumulation ratios were 1.85, 1.43, 1.53, 1.48, 1.13, and 0.77 respectively, from N\(_0\) to N\(_6\). In 2009, the grain/straw ratios showed a smooth decrease from N\(_0\) to N\(_6\), the ratios were 1.55, 1.35, 1.18, 1.12, 1.23, 1.03, and 0.99 respectively. Compared with the previous year, the differences in N accumulation in straw and grain among the N treatments were reduced in 2009. Interestingly, there appeared to be a threshold: when the N application rate exceeded the common farmers’ dosage of N\(_5\), N accumulation in straw was larger than that in grain, and vice versa (Fig. 6). This phenomenon was less obvious in 2009. In summary, the averaged N uptake of grain was 89 kg ha\(^{-1}\) in 2008 and 96 kg ha\(^{-1}\) in 2009, and the uptake for straw was 73 kg ha\(^{-1}\) in 2008 and 93 kg ha\(^{-1}\) in 2009.

Recovery efficiency before heading stage (Pre-RE) varied from 5% to 20% in 2008 and from 27% to 42% in 2009 (Table 1). The large

![Fig. 3](image1.png)

**Fig. 3.** N losses via runoff during rice season under different nitrogen rates in 2008 (solid circles) and 2009 (hole circles). Error bars presented standard deviations.

![Fig. 4](image2.png)

**Fig. 4.** N accumulation before (A) and after (B) heading period in 2008. Error bars presented standard deviations.

![Fig. 5](image3.png)

**Fig. 5.** N accumulation before (A) and after (B) heading period in 2009. Error bars presented standard deviations.
difference in Pre-RE between years might be due to higher plant density and a five-day delay in sampling time in the second year. No significant differences were found among N treatments in N-translocation efficiency in the first year, or in translocated N except for N2 and N5 treatments in the latter. However, significant differences in N-translocation efficiency were observed among the lower N application rates (N1, N2, N3), the high N application rates (N4, N5, N6), and the control (N0) in the second year (Table 1).

Correlation analysis showed that translocated N was positively correlated with Pre-NA in both years (Table 2). Grain yield was positively correlated with Post-NA, and straw was correlated with Pre-NA. No significant difference was found between translocated N and Post-NA (Table 2).

3.4. Nitrogen use efficiency

The nitrogen use efficiency indices all showed similar trends: nitrogen use efficiency was negatively correlated with nitrogen application rate (Table 3). Generally, IE_N was the highest in the control, and gradually decreased with increasing N rate. Overall, no significant difference in IE_N was observed between the conventional fertilizer treatment rates (N2) and the reduced rates. Compared with 2008, IE_N significantly decreased in 2009, except in the control. The range of IE_N was between 32.43 and 53.14 kg kg\(^{-1}\) for the first year and between 29.86 and 55.69 kg kg\(^{-1}\) for the second year.

The lowest AE_N was at the highest N rate of 405 kg ha\(^{-1}\) over both years. As N application was decreased from 405 to 135 kg ha\(^{-1}\), AE_N increased approximately 6 times in 2008, corresponding to 2.40 and 13.57 kg kg\(^{-1}\), while in the second year, AE_N ranged from 3.07 to 13.26 kg kg\(^{-1}\). Compared with the conventional fertilizer rate (N6), the N reduced fertilizer rates actually increased, but not significantly, the averaged value of AE_N, except for N1 treatment in the first year, and N1 and N2 in the second year. Notably, N1 (50% of the conventional fertilizer treatment rate) showed a significant increase in AE_N. There were also significant differences in AE_N for the N input treatments (N3, N4, and N5) between the two years.

In 2008, significant differences in PFP_N were observed among different N treatments, except for N3, N4, and N5. The N1 treatment displayed the highest PFP_N (52.62 kg kg\(^{-1}\)), while N6 had the lowest (15.24 kg kg\(^{-1}\)). Both N1 and N2 treatments had significantly higher PFP_N than the conventional fertilizer treatment rate. The average PFP_N of all nitrogen treatments was 32.53 kg kg\(^{-1}\). In 2009, significant differences in PFP_N were observed among all the N treatments. There was also a significant difference in PFP_N for the N treatments (N2, N4, and N5) between different years.

In 2008, N1 treatment had the highest REN among all nitrogen application rates. REN ranged from 27.14% to 40.56%, and the mean was 32.72%. There was no significant difference in REN among all nitrogen application rates except N1 and N2. Compared to 2008, the REN values for both N reduction and conventional N treatment rates were significantly increased in 2009. The mean value of REN in 2009 was 42.75%, 30% greater than in 2008. Contrary to the trend of REN, PFP_N decreased rapidly in the second year; PFP_N values averaged 27.03 kg kg\(^{-1}\) (6.11–33.49 kg kg\(^{-1}\)) for 2008 and 13.21 kg kg\(^{-1}\) (9.71–19.08 kg kg\(^{-1}\)) for 2009, indicating a 50% reduction.

Correlation analysis showed that translocated N was negatively correlated with all N use efficiency in 2009, and Pre-NA was negatively correlated with all N use efficiency in both years, except REN.

### Table 1

Translocated N and nitrogen recovery efficiency at heading stage.

<table>
<thead>
<tr>
<th>Treatment (kg N ha(^{-1}))</th>
<th>Year: 2008</th>
<th>Year: 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-translocation efficiency</td>
<td>Translocated N</td>
<td>Pre-RE</td>
</tr>
<tr>
<td>N0</td>
<td>0.63 ± 0.05a</td>
<td>59.76ab</td>
</tr>
<tr>
<td>N1</td>
<td>0.43 ± 0.09b</td>
<td>48.54ab</td>
</tr>
<tr>
<td>N2</td>
<td>0.34 ± 0.13b</td>
<td>36.29b</td>
</tr>
<tr>
<td>N3</td>
<td>0.43 ± 0.16b</td>
<td>51.35ab</td>
</tr>
<tr>
<td>N4</td>
<td>0.34 ± 0.05b</td>
<td>42.98ab</td>
</tr>
<tr>
<td>N5</td>
<td>0.48 ± 0.01ab</td>
<td>71.74a</td>
</tr>
<tr>
<td>N6</td>
<td>0.37 ± 0.05b</td>
<td>64.94ab</td>
</tr>
</tbody>
</table>

Means followed by different letters are significantly different at 0.05 probability level according to least significant difference (LSD) test.
Grain yield was positively correlated with $\text{AE}_\text{N}$, $\text{RE}_\text{N}$, and $\text{PE}_\text{N}$, while straw quantity was negatively correlated with $\text{IE}_\text{N}$ (Table 4).

4. Discussion

4.1. Nitrogen fertilizer reduction on grain yield

There were no significant differences in grain yield under nitrogen fertilizer application rates of 135–270 kg N ha$^{-1}$ (50–100% of the conventional fertilizer application rate) in the two-year experiment, and the grain yield declined with 150% of the conventional fertilizer application rate in both years. A similar result was also found in another study in a neighboring region (Wang et al., 2009). Dobermann (2007) stated that when yields come to a ceiling, incremental of nutrient do not result in significant increase of yield, because the nutrient is not one of main determinants for yield any more. The Taihu Lake area has suffered over-fertilization in the rice-wheat rotation with the aim of high yield for many years. After harvest, some crop residues were left in the topsoil, and mineral N content in 0–0.9 m soil profiles was frequently found to be between 50 and 100 kg N ha$^{-1}$ after the winter wheat harvest in the Taihu Lake region (Richter and Roelcke, 2000). The mineral N in the topsoil

Table 2
Correlation between nitrogen accumulation and yield in two-year experiment.

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameter</th>
<th>Pre-NA</th>
<th>Post-NA</th>
<th>Pre-RE</th>
<th>Grain</th>
<th>Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Translocated N</td>
<td>0.659*</td>
<td>-0.237</td>
<td>0.262</td>
<td>0.042</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>Pre-NA</td>
<td>-0.098</td>
<td>0.474</td>
<td>0.155</td>
<td>0.539</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>Post-NA</td>
<td>-0.395</td>
<td>0.525</td>
<td>0.014</td>
<td>0.642</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>Pre-RE</td>
<td>-0.441</td>
<td>0.102</td>
<td>0.250</td>
<td>0.533</td>
<td>0.488</td>
</tr>
<tr>
<td></td>
<td>Grain</td>
<td>-0.229</td>
<td>0.586</td>
<td>0.851</td>
<td>0.693</td>
<td>0.502</td>
</tr>
</tbody>
</table>

Pre-NA, Post-NA, Pre-RE stand for N accumulation before heading stage, N accumulation after heading stage, recover efficiency pre-heading stage, respectively.

* Significance at 0.05 probability.

** Significance at 0.01 probability.

Table 3
Indices of nitrogen use efficiency under varied nitrogen rates.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>$Y_0/Y_N$</th>
<th>$\text{IE}_\text{N}$ (kg kg$^{-1}$)</th>
<th>$\text{AE}_\text{N}$ (kg kg$^{-1}$)</th>
<th>PFP$_\text{N}$ (kg kg$^{-1}$)</th>
<th>RE$_\text{N}$ (%)</th>
<th>PE$_\text{N}$ (kg kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$N_0$</td>
<td>53.14 ± 0.83a</td>
<td>39.05</td>
<td>46.17 ± 0.71b</td>
<td>13.57 ± 1.20a</td>
<td>52.62 ± 1.20a</td>
<td>40.56 ± 4.30a</td>
</tr>
<tr>
<td></td>
<td>$N_1$</td>
<td>39.05</td>
<td>46.17 ± 0.71b</td>
<td>13.57 ± 1.20a</td>
<td>52.62 ± 1.20a</td>
<td>40.56 ± 4.30a</td>
<td>33.49 ± 0.66a</td>
</tr>
<tr>
<td></td>
<td>$N_2$</td>
<td>27.89</td>
<td>43.49 ± 1.47bc</td>
<td>10.69 ± 0.98b</td>
<td>38.59 ± 0.98b</td>
<td>36.27 ± 0.89b</td>
<td>29.53 ± 3.31a</td>
</tr>
<tr>
<td></td>
<td>$N_3$</td>
<td>24.41</td>
<td>43.70 ± 1.06bc</td>
<td>9.58 ± 0.96bc</td>
<td>31.56 ± 4.25c</td>
<td>31.20 ± 0.10c</td>
<td>30.69 ± 2.98a</td>
</tr>
<tr>
<td></td>
<td>$N_4$</td>
<td>21.70</td>
<td>44.04 ± 0.65c</td>
<td>7.53 ± 0.60c</td>
<td>29.23 ± 0.6c</td>
<td>31.47 ± 0.34c</td>
<td>23.93 ± 1.67b</td>
</tr>
<tr>
<td></td>
<td>$N_5$</td>
<td>19.53</td>
<td>41.78 ± 1.98bc</td>
<td>8.24 ± 1.82bc</td>
<td>27.76 ± 1.82c</td>
<td>29.68 ± 1.28c</td>
<td>24.79 ± 0.44b</td>
</tr>
<tr>
<td></td>
<td>$N_6$</td>
<td>13.02</td>
<td>32.43 ± 4.14d</td>
<td>2.40 ± 2.04d</td>
<td>15.42 ± 2.04d</td>
<td>27.14 ± 0.22c</td>
<td>6.11 ± 2.20c</td>
</tr>
</tbody>
</table>

Means followed by different letters are significantly different at 0.05 probability level according to least significant difference (LSD) test.

$Y_0/Y_N$: grain yield in $N_0$ divided by N rate; $\text{IE}_\text{N}$: internal efficiency of fertilizer N; $\text{AE}_\text{N}$: agronomic efficiency of fertilizer N; PFP$_\text{N}$: partial factor productivity; RE$_\text{N}$: apparent crop recovery efficiency of applied N; PE$_\text{N}$: physiological efficiency of applied N.

* Significant difference between different years for each parameter within the same treatment.

Table 4
Correlations among N-use efficiency, nitrogen accumulation and yield in two-year experiment.

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameter</th>
<th>Translocated N</th>
<th>Pre-NA</th>
<th>Post-NA</th>
<th>Pre-RE</th>
<th>Grain</th>
<th>Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$\text{IE}_\text{N}$</td>
<td>-0.102</td>
<td>-0.730</td>
<td>-0.105</td>
<td>-0.367</td>
<td>-0.210</td>
<td>-0.790</td>
</tr>
<tr>
<td></td>
<td>$\text{AE}_\text{N}$</td>
<td>-0.697</td>
<td>-0.533</td>
<td>-0.566</td>
<td>-0.452</td>
<td>-0.452</td>
<td>-0.138</td>
</tr>
<tr>
<td></td>
<td>PFP$_\text{N}$</td>
<td>-0.697</td>
<td>-0.533</td>
<td>-0.566</td>
<td>-0.452</td>
<td>-0.452</td>
<td>-0.138</td>
</tr>
<tr>
<td></td>
<td>$\text{RE}_\text{N}$</td>
<td>-0.028</td>
<td>-0.363</td>
<td>-0.351</td>
<td>-0.520</td>
<td>-0.592</td>
<td>-0.251</td>
</tr>
<tr>
<td>2009</td>
<td>$\text{IE}_\text{N}$</td>
<td>-0.514</td>
<td>-0.653</td>
<td>-0.625</td>
<td>-0.112</td>
<td>-0.714</td>
<td>-0.810</td>
</tr>
<tr>
<td></td>
<td>$\text{AE}_\text{N}$</td>
<td>-0.514</td>
<td>-0.653</td>
<td>-0.625</td>
<td>-0.112</td>
<td>-0.714</td>
<td>-0.810</td>
</tr>
<tr>
<td></td>
<td>PFP$_\text{N}$</td>
<td>-0.514</td>
<td>-0.653</td>
<td>-0.625</td>
<td>-0.112</td>
<td>-0.714</td>
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<td>-0.520</td>
<td>-0.592</td>
<td>-0.251</td>
</tr>
</tbody>
</table>

Pre-NA, Post-NA, Pre-RE stand for N accumulation before heading stage, N accumulation after heading stage, recover efficiency pre-heading stage, respectively. $\text{IE}_\text{N}$: internal efficiency of fertilizer N; $\text{AE}_\text{N}$: agronomic efficiency of fertilizer N; PFP$_\text{N}$: partial factor productivity; RE$_\text{N}$: apparent crop recovery efficiency of applied N; PE$_\text{N}$: physiological efficiency of applied N.

* Significance at 0.05 probability.

** Significance at 0.01 probability.
(0–15 cm) was 53.5 mg kg\(^{-1}\) soil before the rice cultivation in this research, suggesting sufficient available nutrition in the plow layer (120 kg N ha\(^{-1}\)). However, the high content of mineral N, present as NO\(_3\)–N, is harmful to the environment via leaching and/or denitrification during the preparation of paddy field for rice (Aulakh et al., 2001).

The experimental plots were newly established, and the soil nutrient contents were at the same level in all the plots. The presence of sufficient soil mineral N and the mineralization of organic nitrogen in soil may have mitigated the effect of applied nitrogen fertilizer. Richter and Roelcke (2000) also indicated that the high level of residual mineral nitrogen in the soil might have undermined the variation in grain yield caused by appropriate reduction of nitrogen fertilizer. In our research, excessive fertilizer application resulted in a low grain yield, which was only 1 tonnes ha\(^{-1}\) higher than control in the first year (Fig. 1). Nitrogen absorption was the highest at harvest under excessive fertilizer application, but the nitrogen was predominantly distributed in straw, rather than in grain (Fig. 6). Excess nitrogen absorption by the plant delayed maturity, and insufficient N translocation efficiency (Table 1) and especially lodging near rice harvest resulted in low grain yield. In fact there was lodging phenomenon for excessive N application rate especially when the bad weather accompanied near rice maturity in this experiment. In the first year, lodging only occurred in excessive N application rate (405 kg N ha\(^{-1}\)), while in the latter, the lodging status incoordinately appeared in all N application rates except for the 135 kg N ha\(^{-1}\) treatment. Thus, the sharp yield decrease was found comparing the two years results, but the decline for excessive N application rate (N0) was not significant (Fig. 1). A negative effect caused by excessive fertilizer application on plant growth and grain yield was also found using a model that established a relationship between nutrient application and growth yield (Cissé, 2007). Our results fit the model perfectly.

Deduced by the yield curve, the N application rate for the highest yield were 232 and 257 kg N ha\(^{-1}\) in 2008 and 2009 respectively, which represent 86% and 95% of the farmer’s conventional N application rate. Comparable research from a neighboring region showed that the N application rates for the highest yield were 200 kg N ha\(^{-1}\) (Feng et al., 2006) and 195–232 kg N ha\(^{-1}\) (Wang et al., 2009), which corresponded to 67% or 83–102% of conventional N application rate. For the sake of balance between environmental and economical purpose, the recommended fertilization rate should always be lower than that of the highest yield rate.

### 4.2. Nitrogen losses along with N fertilizer reduction

Nitrogen losses via runoff generally happen in the following situations: (a) drainage of the paddy field that occurs 10 days after the tillering stage dressing, and (b) rainfall events. Results from the same field showed that rainfall was the main reason for N loss through runoff in this region, especially during the N input period (Xue et al., 2009). Within 3–5 days after N application, ammonium N concentration was usually over 24 mg N L\(^{-1}\) in the surface water and total N exceeded 27 mg N L\(^{-1}\) in this experiment. When higher N contents in surface water coincided with a heavy rainfall event, N losses through runoff were generally serious in this area, especially during the 5 days after N tillering and heading dressing, which was a key period to control N entering the environment. In this study, N loss caused by precipitation accounted for 78–86% of total N losses via runoff for N application treatments in 2008 and 91–94% in 2009. Average N loss through soil drainage processes was no more than 20% in the two-year experiment. In 2009, heavy rain occurred during the seeding and heading stages. A precipitation event 1 day after the heading stage dressing with a duration of 1 day caused 37% of the total N losses for the entire rice season. Thus, heavy rain shortly after N application was the key reason for high N loss in 2009, and the higher N application rates resulted in greater N loss.

In addition to runoff, other mechanisms of N loss can severely affect the environment, and they should not be neglected. It has been reported that N losses by ammonia volatilization, leaching, and denitrification were all linearly and positively correlated with N application rates in the Taihu Lake region (Song et al., 2004; Xie et al., 2007; Zhu and Wen, 1992). Thus, reducing N application rates is necessary to lower the N environmental load.

### 4.3. Nitrogen fertilizer reduction on increase of nitrogen use efficiency

Translocated N represented the ability of plants to translocate accumulated N at anthesis to grains. There was no common trend in plant translocated N with different N application rates. However, correlation analysis showed that translocated N was negatively correlated with N use efficiency, and was positively correlated with Pre-NA and Pre-RE. No significant relationship was observed between translocated N and grain yield, but a positive correlation was found between yield and Post-NA (Table 2). It indicated that the final harvest yield increased with the accrual of Post-NA, implying that greater nitrogen accumulation after the heading stage would lead to a higher yield at harvest. This result was comparable with that from research conducted by Jiang et al. (2004), in which they also proposed that the improvement of nitrogen use efficiency should focus on Post-NA and dry matter accumulation. Pre-NA was negatively and significantly correlated with all nitrogen use efficiency (NUE) indices (n = 36, p < 0.05). The correlation between Pre-NA and straw dry matter (r\(^2\) = 0.539, p < 0.05) demonstrated that a high nitrogen accumulation during the heading stage would result in more straw at harvest.

According to Dobermann’s (2007) standard, none of the nitrogen fertilizer reduction treatments (N1–N4) in this study achieved best management practice status (Table 3), but N1 was relatively better than the other nitrogen application rates in terms of nitrogen use efficiency. On the base of the formula, nitrogen use efficiency indices largely depend on grain yield, N fertilizer input, and nitrogen accumulation. Experiments conducted in the Philippines (Dobermann and Gassman, 2002) and other countries in south and southeast Asia (Dobermann, 2007) showed low grain yields (3–4 tonnes ha\(^{-1}\)) in the control plots. In China, N-limited rice yields of 5–6 tonnes ha\(^{-1}\) are common in areas with substantial N inputs through atmospheric deposition and rainfall as well as with higher soil fertility (indigenous N supply) (Buresh and Witt, 2007).

In this experiment, the yield without fertilizer input was up to 5.27 tonnes ha\(^{-1}\) in the first year and 4.94 tonnes ha\(^{-1}\) in the second year. Compared to the zero-N input treatment, the yield increase with nitrogen application (135–270 kg ha\(^{-1}\)) was only 1.9–2.1 tonnes ha\(^{-1}\) in the first year and 1.4–1.8 tonnes ha\(^{-1}\) in the second year. The increase of nitrogen fertilizer input resulted in limited additions to the yield, and thus low AEN (averaging only 10.3 kg N ha\(^{-1}\)) were observed. Further increasing N fertilizer input led to lower AEN. From those trends, a good management AEN (25 kg kg\(^{-1}\)) could be achieved at an N fertilizer application rate of 135 kg ha\(^{-1}\) or lower. However, the good management index is not feasible at lower N input while considering yield decrease for the long run. The high yields on the control plots and high N fertilizer inputs are the main reasons for low nitrogen use efficiencies determined in China.

As one of the most important indices for grain growers, PFP\(_N\) directly reflects N input and economic income. Combined data from different areas of India (Yadav, 2003) showed a PFP\(_N\) range
of 21–62 kg kg⁻¹ with an average of 106 kg N ha⁻¹ input. PFPN was significantly influenced by soil organic carbon content (SOC) and positively correlated with available N. Our field was newly established, and had been treated with chemical fertilizer since the 1960s. The SOC and mineral N content were greater than those in Yadav’s study, but the PFPN values in this study were similar to those in Yadav’s experiment. The main reason for this was probably the relatively high N inputs (averaging 206 kg N) used in all the N treatments. A similar chemical N fertilizer reduction experiment in Hunan, China (Zou et al., 2008) showed an average PFPN ranging from 65 to 97 kg kg⁻¹ with 100–120 kg N ha⁻¹ input. Compared to conventional fertilizer treatment, double the level of PFPN was achieved with N₈ (50% of the conventional fertilizer application rate) in our study. Therefore, a simple reduction in N input could increase nitrogen use efficiency in this region.

The level of Iₑ₅ is dependent on rice genotype and environment (Dobermann, 2007). In our experiment, the Iₑ₅ in the control was closest to the optimal value for a rice field given by Dobermann (2007). The lower Iₑ₅ values for the other treatments indicated the rice variety’s poor ability to transform N into yield. In a comparable experiment, Peng et al. (2006) found that poor Iₑ₅ was usually associated with poor Pₑ₅, Aₑ₅, and yield, not with Rₑ₅. In this study, Iₑ₅ was significantly correlated with Pₑ₅ (r² = 0.940, p < 0.01) and Aₑ₅ (r² = 0.688, p < 0.01), but not with Rₑ₅. In addition, there was no significant difference in grain NA at maturity between all N application rates, suggesting that nitrogen uptake by rice was adequate in these N application rates for the two experimental years. The lack of significant differences in Rₑ₅ among N₂, N₄, N₆, and N₈ demonstrated that the N source in N₀ was sufficient for a potential high yield. The poor grain-filling percent of rice spikelets and low N translocation efficiency could be the reasons for low Iₑ₅ in high N accumulation treatments. Iₑ₅ has been shown to be strongly affected by indigenous nitrogen supply (Qi et al., 2008), and Hossain et al. (2005) proposed that low Aₑ₅ was caused by poor Iₑ₅, rather than low indigenous soil N supply, which was represented as yield in the zero-N control (3–5 tonnes ha⁻¹). In our study, the indigenous soil N supply (averaging 5.1 tonnes ha⁻¹) was high and the poor mean Iₑ₅ was correlated with a poor mean Aₑ₅ (y = 0.76x – 22.85, r² = 0.975, p < 0.01). Thus, our study firmly confirmed the conclusion proposed by Hossain et al. (2005).

5. Conclusions

Nitrogen fertilizer reduction is feasible in this area without significantly sacrificing grain yield. High levels of mineral N in the plow layer and substantial inputs of N through atmospheric deposition and irrigation water as well as N mineralization have greatly contributed to yield stability after N application reduction, but longer-term yield sustainability should be the main concern. Poor Aₑ₅, Pₑ₅, and Iₑ₅ were observed for the higher soil fertility and higher N fertilizer input. A simple N fertilizer reduction could significantly increase the nitrogen use efficiency in this region. Heavy rain events shortly after N application severely increase the N losses via runoff especially at the higher N application rates. The N application rate deduced from the yield curve for the highest yield were 232–257 kg N ha⁻¹, which occupied 86–95% of the farmers’ conventional N application rate for the rice season, the highest-yielding N rate would fall into this range. Taking the N losses and the N use efficiency into account, the recommendable N fertilizer rate should be lower than that of the highest yield rate for rice season. Future investigation should also focus on grain yield sustainability, improvement of nitrogen use efficiency, and reduction of nitrogen load in the environment.

Acknowledgements

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References


