Maintaining yields and reducing nitrogen loss in rice–wheat rotation system in Taihu Lake region with proper fertilizer management

Lihong Xue, Yingliang Yu and Linzhang Yang

Institute of Agricultural Resources and Environment, Jiangsu Academy of Agricultural Sciences, Zhongling Street 50, Nanjing, 210014, People’s Republic of China

E-mail: njxuelihong@gmail.com and lzyang@issas.ac.cn

Received 5 May 2014, revised 19 October 2014
Accepted for publication 22 October 2014
Published 18 November 2014

Abstract
In the Taihu Lake region of China, heavy nitrogen (N) loss of rice–wheat rotation systems, due to high fertilizer-N input with low N use efficiency (NUE), was widely reported. To alleviate the detrimental impacts caused by N loss, it is necessary to improve the fertilizer management practices. Therefore, a 3 yr field experiments with different N managements including organic combined chemical N treatment (OCN, 390 kg N ha$^{-1}$ yr$^{-1}$, 20% organic fertilizer), control–released urea treatment (CRU, 390 kg N ha$^{-1}$ yr$^{-1}$, 70% resin-coated urea), reduced chemical N treatment (RCN, 390 kg N ha$^{-1}$ yr$^{-1}$, all common chemical fertilizer), and site-specific N management (SSNM, 333 kg N ha$^{-1}$ yr$^{-1}$, all common chemical fertilizer) were conducted in the Taihu Lake region with the ‘farmer’s N’ treatment (FN, 510 kg N ha$^{-1}$ yr$^{-1}$, all common chemical fertilizer) as a control. Grain yield, plant N uptake (PNU), NUE, and N losses via runoff, leaching, and ammonia volatilization were assessed. In the rice season, the FN treatment had the highest N loss and lowest NUE, which can be attributed to an excessive rate of N application. Treatments of OCN and RCN with a 22% reduced N rate from FN had no significant effect on PNU nor the yield of rice in the 3 yr; however, the NUE was improved and N loss was reduced 20–32%. OCN treatment achieved the highest yield, while SSNM has the lowest N loss and highest NUE due to the lowest N rate. In wheat season, N loss decreased about 28–48% with the continuous reduction of N input, but the yield also declined, with the exception of OCN treatment. N loss through runoff, leaching and ammonia volatilization was positively correlated with the N input rate. When compared with the pure chemical fertilizer treatment of RCN under the same N input, OCN treatment has better NUE, better yield, and lower N loss. 70% of the urea replaced with resin-coated urea had no significant effect on yield and NUE improvement, but decreased the ammonia volatilization loss. Soil total N and organic matter content showed a decrease after three continuous cropping years with inorganic fertilizer application alone, but there was an increase with the OCN treatment. N balance analysis showed a N surplus for FN treatment and a balanced N budget for OCN treatment. To reduce the environmental impact and maintain a high crop production, proper N reduction together with organic amendments could be sustainable in the rice–wheat rotation system in the Taihu Lake region for a long run.
Keywords: nitrogen use efficiency, N loss, soil fertility, grain yield, rice–wheat rotation, organic amendments

1. Introduction

Rice and wheat are the world’s two most important cereal crops contributing about 45% of the digestible energy and 30% of total protein in the human diet. Rice–wheat production systems occupy 24 million ha of cultivated land in the Asian subtropics and about 13 million ha in China and constitute about 72% of total cereal production. Rice–winter wheat double-cropping rotation with two crops per year is a main cultivation mode in the Taihu Lake region, which is one of the three major crop production areas in China. To meet the food demand for the increasing population, chemical fertilizers have been increasingly applied to the fields in China since the 1980s, especially in more developed regions. According to the investigation data by Wang et al., the average nitrogen (N) fertilizer input in the Taihu Lake region in 2008 is 352 kg ha\(^{-1}\) in rice season and 244 kg ha\(^{-1}\) in wheat season, respectively [1]. However, the researchers in the Taihu Lake region showed that the optimum economic N rate for high yield ranged from 225 to 300 kg ha\(^{-1}\) for rice and 180 to 225 kg ha\(^{-1}\) for wheat [2–6]. The excessive use of N fertilizers may actually not only decrease N utilization efficiency (NUE) by crops, but also increase N loss to the environment through runoff, leaching, ammonia volatilization, and N\(_2\)O emission forming pollution in atmosphere and water systems [7].

With the increasing concerns on the non-point pollution from agricultural fields in recent years, N loss into the environment through runoff, leaching, ammonia volatilization in rice–wheat rotation systems in the Taihu Lake region has been fully evaluated [3, 8–11]. N runoff, leaching, and ammonia volatilization from crop field were positively related with total N application rate [9–13] and accounted for about 10%, 3% and 17% of the applied N, respectively [3, 8]. Some practices have also been explored to reduce the N loss to the environment from rice–wheat rotation systems, such as reducing the amount of N the farmer applies [11,12], using controlled–released fertilizer [13,14], and combining fertilization with organic and chemical fertilizer [15]. Experiments showed no significant differences in grain yield under N fertilizer application rates between 135 and 270 kg N ha\(^{-1}\), but N loss via runoff was reduced significantly [11]. Control–released N fertilizer can reduce ammonia volatilization loss significantly compared with common urea [12–14] and can also decrease the amount of runoff N when runoff occurred within 15 days after urea application [13,14]. Substitution of chemical fertilizer by organic manure can improve the yield and soil nutrient supply as well as reduce the N loss [15,16]. In order to further increase the NUE of irrigated rice and enhance the yield, the site-specific N management (SSNM) system has proven to be effective [17] and has already gained popularity in the rice production regions [18–22]. The practice of SSNM in China has shown that similar or more rice yield could be achieved with 30–50% less N fertilizer and NUE can be improved and N loss decreased significantly compared with the farmer’s practice [12,18–22]. The N rate in SSNM in Taihu lake region ranged from 120 to 162 kg ha\(^{-1}\) [12,18–20], in accordance with the range of ecologically optimum N rate suggested by Wang et al. and Deng et al. [5,6]. There is a consensus that proper N reduction in the Taihu Lake region can sustain high yields, improve the NUE, and reduce the N escape from fields to the environment [6, 11,12]; nevertheless, it is difficult to reach an overall conclusion on which practice can be sustainable for a long run in rice–wheat rotation systems.

Sustainability implies that both high yields can be maintained and agricultural practices are acceptable to the environmental impacts for a long run [23]. How can the negative environmental impacts be minimized at the same time that the crop yield is increased or maintained? One of the keys is to improve the efficiency of fertilizer and to maintain the soil fertility. The balance of inputs and outputs to the system could be a measure of sustainability or efficiency of the management practices without long-term experiment [24]. Several studies indicated that soil fertility is declining due to intensive cultivation of rice crops [25]. Most of previous study in Taihu Lake region was focused on the influences of N reduction on crop yields, NUE and N loss to the environment, while little attention was given on the soil fertility and limited information was on the N balance with N reductions. Since N input is essential for high crop yields and N-induced negative environmental impacts are inevitable, the fertilizer N rates that maintain high crop yields while minimizing N loss are of great concern. In recent years, the government of China has actively extended prescription fertilization based on soil testing and yield potential, which resulted in an increase in grain yield and a reduction in fertilizer inputs. In the Taihu Lake region, N fertilizer rate for rice decreased a little and 270–300 kg ha\(^{-1}\) was more common in the farmer’s practice according to the recent investigation (data not published). More research is still needed to comprehensively evaluate the different N management practices from the viewpoint of sustainability to achieve a balance between crop production and environmental impacts. For this reason, four previously recommended N management practices including different fertilizer type (slow released fertilizer, organic fertilizer and chemical fertilizer) and different N rates (the suggested ecological optimum N rate and the economic optimum N rate for rice) were compared alongside the ‘farmer’s N’ (FN) practice (the control) in a field in the Taihu Lake region for three successive years from 2009 to 2012. The objective of this study was to: (1) compare the yield, NUE and N loss of different N management schemes for the rice–wheat rotation system in the Taihu Lake region; (2) to evaluate the soil fertility after three-year’s N reduction; and (3) to determine which practice could be sustainable according to the partial N balance analysis.
urea management (CRU), and zero N treatment (N0). In the combined chemical N management (OCN), control reduced chemical N application (RCN), SSNM, organic management schemes were designed: FN management, with three replications. Six treatments for different N fertilizer The experiment was a completely randomized block design of organic matter (oxidation with potassium dichromate); and the soil in

Field experiments included three rice–wheat crop years, conducted from May 2009 to May 2012, at Longyan county (31°31′N, 120°06′E), Hudai town, Wuxi city, Jiangsu province, China. The site was located in the Taihu Lake region of Changjiang river delta. The annual mean temperature in this region is 15.7 °C and annual mean rainfall is 1177 mm [8]. Rice–wheat rotation is the typical cropping system in this area. The soil is a hydric paddy soil (silt loam, mixed, mesic Mollic Endoaquepts). The topsoil (0–20 cm) with pH 6.99 contained 1.88 g kg\(^{-1}\) of total N (Kjeldahl digestion–distillation method), 188 mg kg\(^{-1}\) of alkali-hydrolysable N, 0.61 g kg\(^{-1}\) of total P (molybdenum blue color method), 37.9 mg kg\(^{-1}\) of Olsen-P, 118 mg kg\(^{-1}\) of Avail K, 32 g kg\(^{-1}\) of organic matter (oxidation with potassium dichromate); and the soil infiltration rate is 0.62 cm d\(^{-1}\) determined in situ by WS-55 type of soil-leaking-measuring instrument.

| Treatments | Base N (kg N ha\(^{-1}\)) | Rice season | Wheat season | Total N per crop year |
|------------|-----------------------------|-------------|--------------|-----------------------|
| FN         | 81                          | 81          | 108          | 270                   |
| RCN        | 63                          | 63          | 84           | 210                   |
| SSNM       | 63                          | 45          | 45           | 153                   |
| OCN        | 42 + 21                     | 63          | 84           | 210                   |
| CRU\(^*\)  | 147                         | 0           | 63           | 210                   |
| N0         | 0                           | 0           | 0            | 0                     |

\[^{*}\] N in commercial organic fertilizer.

\[^{\#}\] N in control–released urea.

### 2. Materials and methods

#### 2.1. Site description

Field experiments included three rice–wheat crop years, conducted from May 2009 to May 2012, at Longyan county (31°31′N, 120°06′E), Hudai town, Wuxi city, Jiangsu province, China. The site was located in the Taihu Lake region of Changjiang river delta. The annual mean temperature in this region is 15.7 °C and annual mean rainfall is 1177 mm [8]. Rice–wheat rotation is the typical cropping system in this area. The soil is a hydric paddy soil (silt loam, mixed, mesic Mollic Endoaquepts). The topsoil (0–20 cm) with pH 6.99 contained 1.88 g kg\(^{-1}\) of total N (Kjeldahl digestion–distillation method), 188 mg kg\(^{-1}\) of alkali-hydrolysable N, 0.61 g kg\(^{-1}\) of total P (molybdenum blue color method), 37.9 mg kg\(^{-1}\) of Olsen-P, 118 mg kg\(^{-1}\) of Avail K, 32 g kg\(^{-1}\) of organic matter (oxidation with potassium dichromate); and the soil infiltration rate is 0.62 cm d\(^{-1}\) determined in situ by WS-55 type of soil-leaking-measuring instrument.

### 2.2. Experiment design

The experiment was a completely randomized block design with three replications. Six treatments for different N fertilizer management schemes were designed: FN management, reduced chemical N application (RCN), SSNM, organic combined chemical N management (OCN), control–released urea management (CRU), and zero N treatment (N0). In the SSNM, a fixed time and varied N rate approach was adopted in rice season; the basal N was the same as the RCN, but the topdressing N rate was applied at the leaf chlorophyll (SPAD) value. In wheat season, the SSNM was the same as the RCN. In the OCN, 20% of N was from organic fertilizer and applied as basal. The commercial organic fertilizer is made of dairy manure by Jiangsu Tianiang Agricultural Technology Corporation with the organic matter content of 45.07%, the total N content of 1.86%, total phosphorus content of 3.11%, total potassium content of 0.85%, and water content of 36.2%. In the CRU treatment, a resin-coated urea containing 43% of N was used. The N release time is about 90 days while the growth days of rice after transplanting and wheat in the Taihu Lake region is about 130 days and 168 days, respectively. In order to ensure N supply in the late growth stage and maintain high yields, only 70% of N was applied as basal with resin-coated urea; and 30% of N was top-dressed with synthetic urea at the panicle initiation stage according to a preliminary experiment result. The total N rate of OCN, RCN and CRU was the same and set as the recommend N amount (210 kg N ha\(^{-1}\) for rice and 180 kg N ha\(^{-1}\) for wheat) based on previous studies [2, 4, 11]. The details of N application are shown in table 1. The amount of super phosphate (65 kg P\(_2\)O\(_5\) ha\(^{-1}\) for rice and 36 kg P\(_2\)O\(_5\) ha\(^{-1}\) for wheat) and the amount of potassium chloride (90 kg K\(_2\)O ha\(^{-1}\) for rice and 36 kg K\(_2\)O ha\(^{-1}\) for wheat) were the same for all treatment and applied basally in both seasons in all plots. Only the basal fertilizers were incorporated into the plowed layer; and the other fertilizers were surface-applied. In rice season, N fertilizer was distributed at three times, 30% at the basal stage, 30% at tillering and 40% at panicle initiation stage. In wheat season, half of N fertilizer was applied as basal and half at jointing stage. There were total 18 plots with 80.4 m\(^2\) (12 m × 6.7 m) per plot. Ridges, 300–350 mm wide at the base and 200 mm high, covered with plastic sheets that were inserted into the soil plow layer to a depth of 150 mm to prevent hydrological interaction between plots. Rice season began in the middle of May. Seedlings (genotypes Wuyunjing 19) were transplanted with a density of 0.3 m × 0.13 m in the end of June. When rice was harvested at the end of October, winter wheat (genotypes Yangmai 8) was seeded directly onto soil surface. The flooded water was maintained at a depth of 5 cm in all plots during the rice season except for mid-season aeration and final drainage. There was no irrigation during the period of wheat growth and rainwater was the only source of water supply to soil moisture.

### 2.3. Sampling and measurements

#### 2.3.1. Crop measurements

The crops were manually harvested at physiological maturity. Grain and crop residues within 2 m\(^2\) were then sampled and oven-dried at 70 °C to a constant mass, weighed, and ground into a powder (<0.149 mm fragments) for total N analyses. N concentration in plant samples was analyzed by the micro-Kjeldahl method. Plant N uptake (PNU) was determined by multiplying dry matter yield by the total N content. Grain yield was determined for each plot at maturity by harvesting 20 m\(^2\) and adjusted to a moisture content of 13.5%.
2.3.2. Soil measurement. At the end of the experiment, five soil cores (from 0 to 20 cm) were collected from each plot and mixed to make one composite soil sample. The soil samples were air dried to a constant weight and then ground to pass a 0.149 mm sieve for soil organic matter and total nitrogen analyses. Soil organic matter was determined by the potassium dichromate method. Total nitrogen was analyzed using an elemental analyzer (Flash EA 1112 series; Thermo Finnegan, Elk Grove Village, IL).

2.3.3. Runoff, leaching, and NH$_3$ volatilization measurements. Before the experiment started, eighteen 301 plastic buckets were buried beside each plot to collect runoff water from 2 m$^2$ of the plot through a piping system. Other runoff from the plot flowed into the drainage ditch. During rice season, the floodwater was primarily maintained at a depth of 3–5 cm in the field. The height of the local drainage hole was approximately 10 cm, so the hole for the runoff collection pipe was set at 10 cm above the soil surface. During the wheat season, small drainage ditches (20 cm in depth and 10 cm in width, usually spaced 1.5–2 m apart) were mechanically dug in the field to ensure the crop was not damaged by water-logging. In this case, the hole for the runoff collection pipe was set at 20 cm below the soil surface. An electromagnetic flow meter was equipped to measure the runoff volume at the drainage ditch outlet for the whole field. Meanwhile, the amount of rainfall was recorded daily by an automated rainfall collector (Watchdog 2000, America). Water from the collection buckets was sampled after each rainfall, immediately filtered, and refrigerated at −5 °C for analysis. Runoff N was measured with an auto analyzer (Traacs 800, Bran & Luebbe, Hamburg). Runoff was measured for the three successive years.

To monitor N leaching, porous pipes made of polyvinyl chloride were installed at different soil depths (20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm) to collect percolation water (detailed porous pipes schematics view can be seen in Zhao et al [8]). Leachate was collected 1, 3, 5, and 7 d after fertilizer application in paddy season and after rain events in wheat season with a vacuum pump. Leachate volumes were calculated as the product of flooding days and filtration rate in rice season, and directly obtained with the field undisturbed tension-free monolith lysimeters in wheat season [8]. N concentrations in leachate were determined with a continuous-flow analyzer (BRAN+LUEBBE, AA3, Hamburg, Germany) using a Cd reduction method. Total N leached for different seasons were calculated by multiplying the average N concentration of four depths by the total leachate volume. Leaching was measured for two crop years from 2009 to 2011.

NH$_3$ volatilization losses from the plots of the rice fields were measured via ventilation method using 20 cm height PVC collectors with phosphoglycerol soaked sponges as absorbents [26]. The samples were collected daily after the N fertilizer application for first week, collected at 2–3 d intervals for the next week, they were later collected at a weekly interval until the next fertilizer application or rice harvest. The samples collected in the phosphoglycerol soaked sponges from the rice fields were immediately immerged in 300 ml of 1.0 mol$^{-1}$ KCl solution in 500 ml containers and were shaken on a reciprocating shaker before the extracted solutions were measured with a continuous-flow analyzer (BRAN+LUEBBE, AA3, Hamburg, Germany). After which, the AV rate was calculated using the following equation:

$$\text{NH}_3\text{ volatilization rate (kg N ha}^{-1}\text{ d}^{-1}) = \frac{M}{(A \times D)} \times 10^{-2},$$

where $M$ is NH$_3$ volatilization amount captured by the PVC collector (mg), $A$ is the cross sectional area of PVC collector ($m^2$), $D$ is the interval for NH$_3$ volatilization sample collection (d). NH$_3$ volatilization was only measured in the 2010 rice season.

2.4. Data analysis

NUE were calculated using the differences between N-fertilized treatments and the 0-N plots, as described by Cassman et al [27]. Terms used are AEN, the agronomic efficiency of applied N (kg grain yield increase per kg N applied) and REN, the apparent recovery efficiency of applied N (kg N taken up per kg N applied).

By definition, N balances are the differences between N gains and losses. The inputs include N coming from fertilizers including the organic fertilizer, returned crop residues, irrigation, atmospheric N deposition, and biological N fixation. The outputs include removal through harvested biomass, runoff, leaching, ammonia volatilization and N$_2$O discharge. N balance can be developed at different scales, including plot, field, farm or catchment, district, province, and country scale, and for different purposes [28]. A complete study of N balances is very complicated, so most assessment is composed of partial analysis of input and output data [29]. In this study, the N balance at a pilot scale was calculated according to the difference between N input including fertilization, irrigation and rainfall and output (N removal by plant harvest, runoff, and leaching and ammonia volatilization). N$_2$O discharge was not considered due to its low value of no more than 2% of N rate [3]. When the balance is negative, there is a nutrient input deficit and the N stock becomes depleted. When the balance is positive, there is a N input surplus and the N application should be reduced to prevent environmental risks.

Analysis of variance (ANOVA) and multiple comparisons in SPSS 13.0 software package (SPSS, Chicago) were used to evaluate the N management effects on grain yield, PNU, NUE, N losses, soil total N and organic matter.

3. Results and discussions

3.1. Crop productivity

Table 2 showed the grain yield of rice and wheat under five different N managements in successive three years. Although there was no significant difference in the yield
between the five different N managements in the first three crop seasons when the N rate was reduced from 510 kg ha\(^{-1}\) yr\(^{-1}\) of FN to 333 kg ha\(^{-1}\) of SSNM, there was significant yield loss in SSNM in the last three crop seasons. An increase in both rice and wheat yields was seen under OCN treatment, while the RCN showed a slight but no significant decline in yield when compared with FN treatment. In this experiment, although the rice N rate for FN has already decreased to 270 kg ha\(^{-1}\), it is still over applied and can be reduced further without yield losses, consistent with the previous result [5, 6, 11]. OCN treatment maintained similar yield levels as FN treatment but with less N input of 360 kg ha\(^{-1}\) in three years. Moreover, OCN treatment produced 4% more yield than RCN and significantly higher yield (7–10% more) than CRU treatment with the same N rate in the second and third crop years. This is mainly due to the increase of soil nutrient availability brought from the organic emendation along with the chemical fertilizer, which is shown in the table 4. A study of long-term rice–wheat experiment in India also showed that farmyard manure application in rice production could not only promote the rice yield but had a significant residual effect on the consequent wheat yield [30]. A yield decline of 3–5% was also observed in SSNM in rice–wheat rotation system in Taihu Lake region in Xu’s study when N rate decreased from 403 kg ha\(^{-1}\) of farmer’s practice to 162 kg ha\(^{-1}\) of SSNM [12]. However, a yield increase of SSNM was observed with a N reduction of 120–140 kg ha\(^{-1}\) from the FN rate in Peng’s study in Jiangsu province in China [19]. The significant yield decline in SSNM in the third rice season in this study could be because the N rate was not adjusted according to the real growth status. In this experiment, the N rate of SSNM was only determined based on the leaf color at the first rice season; the same N rate was used in the succeeding two rice seasons. In fact, soil N supply may be depleted under the continuous N reduction in both rice and wheat season and the real crop N demand may be increased in the following two rice seasons. This can be verified from the study of Peng et al that the N rate of SSNM in the second year was 20–30 kg ha\(^{-1}\) higher than the first year and a yield increase was observed [19]. Also, a relatively high rate of basal fertilizer (63 kg ha\(^{-1}\)) could be another reason for the lower yield of SSNM in this study compared with the 50 kg ha\(^{-1}\) in Peng’s study [19].

Improper input of excessive N fertilizer to rice field could result a low return due to the high loss [4–6]. This can be verified from the dry matter production (figure 1). Total 84.87 t dry matters were produced per hectare in FN in three years with total N input of 1530 kg. The dry matter production per kg N fertilizer was 0.055 t for FN treatment, 0.067–0.068 t kg\(^{-1}\) for OCN, RCN and CRU treatments, and further increased to 0.074 t kg\(^{-1}\) for SSNM treatment when the N application decreased by about 35%.

### 3.2. PNU and NUE

In rice season, PNU of FN treatment was the highest but NUE including AEN and REN was the lowest among the five N management schemes, with a value of 7.73 kg kg\(^{-1}\) for AEN and 0.38 kg kg\(^{-1}\) for REN (table 3). Similar results were also observed in the study of Doberman et al in China [31]. Reduced N application was shown to improve NUE. The average AEN and REN of the rice production in the three years were highest in the SSNM treatment when the lowest N is applied, with the value of 10.87 kg kg\(^{-1}\) and 0.60 kg kg\(^{-1}\) respectively (table 3). Previous studies on SSNM in rice in China and other countries also showed increased NUE and reduced N fertilizer with a similar or increased grain yield compared with farmers’ practices [18–20, 31]. These studies suggested that SSNM is a matured technology for optimizing the fertilizer management in irrigated rice systems. AE of SSNM in this study was lower than the value of 19–23 kg kg\(^{-1}\) reported in Peng’s study in Jiangsu province, China, which was mainly due to the different rice variety used. An indica/indica hybrid rice variety, Shanyou 63, which is used in Peng’s study has higher yield potential than Wuyunjing 19 in this study. The higher proportion of basal N rate in this study was partly contributed to the lower NUE because the RE of basal N fertilizer was very low (0.09–0.23 kg kg\(^{-1}\)), far less than that (0.54–0.82 kg kg\(^{-1}\)) of the topdressing N at panicle initiation stage based on the N15 tracer experiment [32].

Under the same N rate, OCN treatment can improve PNU and NUE compared with pure chemical urea treatment (RCN) and CRU treatment, though the difference was not significant (table 3). Similar result was also reported in the Taihu Lake region [33, 34], and the organic carbon accumulation in paddy field was thought to be a main reason [33]. Liu

![Table 2. Grain yield (t ha\(^{-1}\)) of rice and wheat under different N management.](image-url)

| Treatments | First crop year | Second crop year | Third crop year |
|------------|----------------|-----------------|----------------|
|            | Rice | Wheat | Total | Rice | Wheat | Total | Rice | Wheat | Total |
| FN         | 9.06 a | 3.12 a | 12.18 a | 8.23 a | 3.92 a | 12.14 ab | 7.58 ab | 3.94 ab | 11.52 ab |
| RCN        | 8.93 a | 2.99 a | 11.92 a | 8.06 a | 3.74 ab | 11.79 ab | 7.54 ab | 3.87 ab | 11.41 ab |
| SSNM       | 8.79 a | 3.06 a | 11.84 a | 7.77 a | 3.23 b | 11.00 c | 7.04 b | 3.42 c | 10.46 c |
| OCN        | 9.00 a | 3.16 a | 12.16 a | 8.34 a | 4.00 a | 12.34 a | 7.76 a | 4.12 a | 11.87 a |
| CRU        | 8.91 a | 3.03 a | 11.94 a | 7.71 a | 3.48 ab | 11.20 bc | 7.47 ab | 3.58 bc | 11.05 bc |
| N0         | 7.14 b | 0.96 b | 8.10 b | 5.64 b | 1.72 c | 7.36 d | 5.83 c | 0.94 d | 6.77 d |

Different letters in the same column means significant at 0.05 level based on Duncan’s multiple comparisons test.
explored the mechanisms for the increased fertilizer NUE of rice under the combined fertilization from the viewpoint of microbiology and found that organic combined inorganic fertilizer promoted the propagation of soil microbes, and caused more immobilized mineral N in soil at rice early growth stage, and then gradually released at the mid and late growth stages, making a better balance of soil N supply and rice N demand [34].

In wheat season, the AEN and REN of the FN treatment was still the lowest. Similarly, OCN treatment had higher REN and AEN compared to the pure chemical fertilizer treatment with the same N rate (table 3). Yaduvanshi also found that OCN treatment resulted in similar NUE in rice as compared with inorganic fertilizer treatment under the same N rate, but NUE was increased in wheat [16]. The improved grain yield and PNU caused by the residual effect of organic manures was the main reason.

### 3.3. N losses to environment

Runoff was mainly dependent on the precipitation and water management. Ten and seven runoff events occurred in the first and third crop year, while only three in the second crop year due to the relative low precipitation (figure 2). There was considerable temporal variability in the TN concentration of runoff water for each runoff event throughout the experiment; and the N concentration ranged from 0.24 mg l$^{-1}$ to 39.54 mg l$^{-1}$ depending on the occurrence time of runoff (figure 2). The N concentration in runoff in wheat season was higher than that in rice season. This is mainly due to the dilution effect with flooded water in rice season. The N loss from runoff ranged from 4.89 to 9.08 kg ha$^{-1}$ in the rice season and from 4.82 to 27.50 kg ha$^{-1}$ in the wheat season in the first crop year. The higher runoff in wheat season in 2009 was attributed to the higher precipitation of 542.3 mm compared to that in 2010 and 2011. In the second and third years,

### Table 3. Plant nitrogen uptake (PNU), Agronomic efficiency (AEN) and recovery efficiency (REN) of nitrogen of rice and wheat under different N managements in 2009–2012.

| Crop Year | N Rate | PNU (kg ha$^{-1}$) | AEN (kg kg$^{-1}$) | REN (kg kg$^{-1}$) |
|-----------|--------|--------------------|--------------------|--------------------|
| Rice 2009 | FN     | 198.6a             | 7.12b              | 0.35b              |
|           | RCN    | 191.9a             | 8.55ab             | 0.42ab             |
|           | SSNM   | 193.1a             | 10.78a             | 0.58a              |
|           | OCN    | 194.3a             | 8.84ab             | 0.43ab             |
|           | CRU    | 179.8a             | 8.45ab             | 0.36b              |
|           | N0     | 103.5b             | —                  | —                  |
| 2010      | FN     | 219.2a             | 9.57b              | 0.39c              |
|           | RCN    | 207.8a             | 11.50ab            | 0.45b              |
|           | SSNM   | 200.8a             | 13.92a             | 0.58a              |
|           | OCN    | 120.1a             | 12.86a             | 0.46b              |
|           | CRU    | 195.3a             | 9.83b              | 0.40bc             |
|           | N0     | 112.4b             | —                  | —                  |
| 2011      | FN     | 232.5a             | 6.49a              | 0.41c              |
|           | RCN    | 228.2a             | 8.15a              | 0.51b              |
|           | SSNM   | 217.6a             | 7.91a              | 0.63a              |
|           | OCN    | 232.7a             | 9.19a              | 0.53b              |
|           | CRU    | 230.5a             | 7.79a              | 0.52b              |
|           | N0     | 120.9b             | —                  | —                  |
| Wheat 2010| FN     | 144.6ab            | 9.00b              | 0.37b              |
|           | RCN    | 120.5b             | 11.28a             | 0.37b              |
|           | SSNM   | 122.9b             | 11.64a             | 0.38b              |
|           | OCN    | 148.6a             | 12.17a             | 0.52a              |
|           | CRU    | 118.0b             | 11.50a             | 0.35b              |
|           | N0     | 54.6c              | —                  | —                  |
| 2011      | FN     | 148.8a             | 9.17b              | 0.39b              |
|           | RCN    | 128.7b             | 10.83ab            | 0.41b              |
|           | SSNM   | 118.5b             | 8.39b              | 0.36c              |
|           | OCN    | 138.6ab            | 12.67a             | 0.46a              |
|           | CRU    | 122.6b             | 9.78b              | 0.40b              |
|           | N0     | 55.4c              | —                  | —                  |
| 2012      | FN     | 153.5a             | 11.42b             | 0.38b              |
|           | RCN    | 149.5ab            | 13.28b             | 0.49b              |
|           | SSNM   | 142.7ab            | 12.33b             | 0.45b              |
|           | OCN    | 165.9a             | 16.22a             | 0.58a              |
|           | CRU    | 144.8ab            | 13.22b             | 0.46b              |
|           | N0     | 61.4c              | —                  | —                  |

Means followed by different letters in the same row are significantly different at 0.05 probabilities according to Duncan’s multiple comparisons test.
the runoff N loss was relative lower than that in 2009 and was only 10–25% of that of 2009. N loss from runoff increased with the increasing N rate in all three years and was the highest in FN treatments. Runoff N loss in the CRU treatment was higher than that in RCN treatment in both rice and wheat seasons in the first two crop years, but was lower in the third crop year (table 4). The inconsistent phenomena were also reported in literature; Wang et al observed that coated urea have lower runoff than uncoated urea [13], while another study in the upland found that N concentration in runoff water of control–released fertilizer treatment decreased at early growth stage but increased at the late growth stage compared with the chemical compound fertilizer treatment [35]. Those phenomena could be related with the time that runoff occurred. If runoff events occurred within 7–10 d after the fertilizer application, the N concentration of the runoff would be higher in the chemical fertilizer treatment. On the other hand, if runoff events occurred 10 d after fertilizer application, the N concentration in the surface water of the urea treatment declined rapidly to a very low value [11], which would result in higher runoff N loss in the controlled–releasing fertilizer treatment due to its continuous release of N. These can also be seen from figure 2. The N concentration in runoff in wheat season under CRU was lower than that in RCN and OCN just after fertilizer application, but was higher at the late stage. N concentration in drainage water of the CRU treatment in the rice season during mid-season aeration stage was also higher than that of other treatments. In addition, runoff N loss of OCN treatment was relative higher in 2009 compared with that of RCN treatment under the same N rate. This also implied that fertilizer with slowly continuous-released N might have high risk of runoff loss when the precipitation occurred at the late stage of fertilizer application. N runoff loss was positively related with N rate and can be minimized

|                  | Rice season | Wheat season |
|------------------|-------------|--------------|
|                  | 2009 | 2010 | 2011 | 2009–2010 | 2010–2011 | 2011–2012 |
| Runoff (kg N ha⁻¹) |      |      |      |          |          |          |
| FN               | 8.75a | 4.49a | 1.84a | 27.50a    | 1.75a    | 2.11a     |
| RCN              | 7.45bc| 3.67b | 1.63a | 17.70bc   | 0.89c    | 1.67a     |
| SSNM             | 7.25c | 3.31b | 1.56a | 16.46c    | 0.75c    | 2.02a     |
| OCN              | 8.15b | 3.55b | 1.32b | 20.53b    | 0.94c    | 1.30ab    |
| CRU              | 9.08a | 3.90b | 1.34b | 18.87bc   | 1.28b    | 1.56a     |
| N0               | 4.89d | 2.02c | 1.11b | 4.82d     | 0.75c    | 1.06b     |
| Leaching(kg N ha⁻¹) |      |      |      |          |          |          |
| FN               | 3.74a | 4.18a | —    | 3.27a     | 0.51a    | —         |
| RCN              | 3.35ab| 2.37b | —    | 2.65b     | 0.39c    | —         |
| SSNM             | 2.61c | 1.90c | —    | 2.03b     | 0.41bc   | —         |
| OCN              | 3.24b | 1.87c | —    | 2.41b     | 0.45b    | —         |
| CRU              | 3.07b | 2.57b | —    | 2.03b     | 0.55a    | —         |
| N0               | 2.36d | 1.30c | —    | 1.39c     | 0.38c    | —         |

Means followed by different letters in the same column are significantly different at 0.05 probabilities according to Duncan’s multiple comparisons test.
— Data not collected.
by reduction of N application [8, 9, 11]. It was evident that N runoff loss was the lowest in the SSNM treatment due to the lowest N rate and decreased by about 33% compared with that in FN treatment while RCN, OCN and RCU mitigated 22%–28% of runoff N loss with the N reduction of 24%.

N leaching loss was mainly influenced by N rate of application and increased with the raised N rate in both rice and wheat seasons in the first two crop years (table 4) and agreed with other reports in the literature [2, 4, 9]. Variation of leaching loss across cropping years in rice seasons was little due to the water flooding management. N leaching losses in rice seasons ranged from 1.30 to 4.18 kg ha$^{-1}$ and consisted only 1–3% of the total N applied in both years from 2009 to 2011. N leaching in wheat season is closely related to the precipitation, thus the N leaching loss was higher in 2009–2010 than that in 2010–2011. The spatial and temporal variability of N leaching was also observed in other studies [2, 8, 16, 36]. Site-specific nutrient management has been proposed widely for reducing N leaching in recent years and proved that nitrate leaching loss was cut by 25% after executing a site-specific nutrient management plan [37]. In this study, N loss from leaching was the lowest in the SSNM treatment among the five treatments and was about 44–55% in the rice seasons and 20–38% in the wheat seasons compared to that in the FN treatment. In addition, OCN and CRU treatments can reduce the risk of N leaching compared with the RCN treatment.

Ammonia volatilization was only measured in the 2010 rice season and ranged from 40.04 kg N ha$^{-1}$ in the N0 treatment to 75.85 kg N ha$^{-1}$ in the FN treatment (figure 3). Ammonia volatilization, due to the flooding condition in the field and the strong sunlight and high temperature in summer, contributed to significant N loss during the rice season [38]. Ammonia volatilization loss was much greater than runoff and leaching [2] and accounted for 23–32% of applied N rate and comparable to the other published results [2, 10, 12]. The amount of ammonia volatilization loss is correlated to the N fertilizer types and N application methods in flooding paddy [12]. Compared with the common urea, coated urea can reduce ammonia volatilization significantly [12–14]. In this study, ammonia volatilization loss during a week after basal fertilizer application was reduced from 20.4 kg ha$^{-1}$ of the urea treatment to 16.9 kg ha$^{-1}$ of the coated urea treatment. But the total ammonia volatilization loss of the CRU treatment only reduced about 2% compared with that of the RCN treatment, which is mainly due to the chemical urea application at panicle initiation stage. OCN treatment significantly reduced ammonia volatilization loss about 19% compared with the RCN treatment under the same applied N rate (figure 3). In addition, N rate reduction can also decrease the ammonia volatilization loss, which is consistent with the reports from literature [13, 39]. In wheat season, ammonia volatilization was limited and only 0.2% and 0.85% of applied N rate at Hokkaido, North Japan and the Taihu Lake region, China, respectively [2, 40]. Thus, ammonia volatilization loss in wheat season may be ignored compared with the amount from runoff loss due to the open-drainage system in wheat season.

According to the total N loss collected in the field, nitrogen application reduction significantly reduced the N loss, but did not change the N loss ratio to the total N application. About 23.5%–42.7% of N reduction in application could mitigate about 24.8%–33.8% of N loss (table 4). SSNM can mitigate about 32.5% of N loss, which is consistent with the report by Ju in the Taihu Lake region and with the report by Pampolino in India, Philippines and Southern Vietnam [21, 41]. It is therefore recommended that the ecologically optimum N application rate is 150–180 kg N ha$^{-1}$ for rice production in the Taihu Lake region to maximally reduce N loss while to minimally affect on the decline of rice yields. [2, 4–6] The N rate of the SSNM treatment (153 kg N ha$^{-1}$) in rice season in this study coincided with the ecological N rate recommended, thus the lowest N loss was observed. From the view of whole crop rotation system, OCN in both rice and wheat production could be the optimum N management scheme.

3.4. Soil fertility

Fertile soils with good physical and chemical properties to support root growth are essential for sustainable agriculture. Continuous cropping without adequate replacement of removed nutrients in harvested materials, nutrient lost through erosion, leaching, and gaseous emission deplete soil fertility and causes soil organic matter level to decline [15, 42]. The soil total nitrogen content of all treatments declined slightly after three continuous cropping years except for OCN, although there were no significant differences except for the treatment of N0 (figure 4), which decreased significantly from 1.88 g kg$^{-1}$ to 1.38 g kg$^{-1}$. As a result, obvious yield decline was also observed for wheat in the N0 treatment and 63% of FN’s yield in the first crop year and then declined to 44% and 31% in the following two years.

The same trends were also observed in soil organic matter; compared to the original value of 32 g kg$^{-1}$, the only treatment with improved values was OCN. This is due to the continuous application of organic fertilizer, which agreed with the results from Pan et al [33]. The improvement of organic matter and the total nitrogen content in soil

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**Figure 3.** Ammonia volatilization losses under different N management schemes in 2010 rice season.
contributed to incremental grain yield [43]. The organic matter and nitrogen contents of those treatments with only inorganic fertilizer application all declined, although the total N input of FN was higher than that of OCN. The results of two long-term rice–wheat experiments also showed (1) that the current practice of inorganic fertilization alone could not maintain soil quality capable of sustaining crop productivity and (2) that organic manures to supplement inorganic fertilizers must be optimized to increase C and N accumulations in the soil and avoid negative effects on crop yield [42]. This suggested that proper organic supplementation was very important to maintain soil fertility and crop yield.

### 3.5. N balance

N input through irrigation in rice season was 19.11 kg ha$^{-1}$ in 2009 and 22.66 kg ha$^{-1}$ in 2010, respectively, covering 6–8% of the total N input in rice season. The high irrigation input was related with the high N concentration in the irrigation water (1.21–5.9 mg N l$^{-1}$), which is the result of the eutrophication of rivers and lakes in recent years. Furthermore, wet deposition in the Taihu Lake region is also an important N source with an annual value of 27 kg N ha$^{-1}$ in 2003–2005 and 30.49–37.37 kg N ha$^{-1}$ in 2010–2011 [44, 45]. Wet decomposition in rice season averaged 25.83 kg N ha$^{-1}$, synonymous to about 56 kg urea, and therefore, contributed to about 10% of the total of N input. Together with the fertilizer N input, the average total N input was about 191–309 kg ha$^{-1}$ in rice season and 185–245 kg ha$^{-1}$ in wheat season. Crop harvest was the main output of N, and ranged from 157.1 to 355.8 kg ha$^{-1}$, accounting for 70–83% of the total N output. The annual N export through runoff and leaching ranged from 29.71 to 43.26 kg ha$^{-1}$ in the first rice–wheat rotation year, accounted for about 8–9% of the total N fertilizer input; whereas, in the second crop year, the annual N export decreased to 3.32 to 8.67 kg ha$^{-1}$, due to low precipitation (569 mm in the 2010 rice season and 186 mm in 2010–2011 wheat season). Considering the other results in Taihu Lake region, N runoff and leaching loss was positively related with the N rate [3, 4, 8, 9], and 10% and 3% was taken to calculate the annual runoff and leaching loss, separately. Ammonia volatilization loss in wheat season was set as 1% of the N fertilizer input according to the results in the same region as this research [3]. Positive N balance was only observed in FN treatment, and N surplus was 44.3 kg ha$^{-1}$ (figure 5). When considering the biological N$_2$ fixation during the rice season (40 kg ha$^{-1}$ N according to Cassman et al 1998 [46]), the N surplus can be 88.3 kg ha$^{-1}$, which demonstrated that the N rate of FN was more than sufficient and should be reduced to prevent environmental risks. N balance of OCN was $-5.4$ kg ha$^{-1}$, almost near zero, suggested that OCN maybe sustainable and should be a good N management. Negative N budgets can impair the resource sustainability of agriculture through soil degradation and soil mining, which resulting in a decline of soil fertility. Thus, soil TN and OM declined in RCN, CRU and SSNM treatments, and soil fertility and yield declined significantly in the N0 treatment (figure 4 and table 2). From the view of the whole crop rotation system, OCN treatment is predicted to be the optimal N management, and the use of crop residues and other organic manures is an important part of nutrient management in rice based cropping systems.
4. Conclusion

Optimizing N management can improve crop yield and NUE and can reduce N loss from field. Reducing about 25% of N application rate from farmer’s practice of 270 kg ha$^{-1}$ in rice season has no significant effect on PNU and final yield of rice and improved the NUE and mitigated N loss by 23–47%. SSNM had the lowest N loss, the highest NUE in rice season and improved the NUE and mitigated N loss by 23–47% with the continuous reduction of N input, but the yield also significantly decreased only with the exception of the OCN treatment. OCN management produced similar yield levels with FN with less N input and N loss to environment in both rice and wheat production and was superior to the pure chemical fertilizer (RCN) treatment and the control–released fertilizer (CRU) treatment with the same N input. Soil TN and organic matter contents tended to decline with only inorganic fertilization application, however, improved when using the OCN treatment. In order to reduce negative environmental impacts while maintaining crop productivity, proper N reduction alongside the addition of organic amendments is predicted to be the optimal N management strategy in the rice–wheat rotation system in the Taihu Lake region. With more restricted implementation of environmental protection policy and relatively abundant organic resources from agricultural waste, the strategy may be welcomed in the region.

Acknowledgements

This work was partially supported by National Natural Science Foundation (No.41171235), Major Science and Technology Program for Water Pollution Control and Treatment of China (No. 2012ZX07101-004) and Special Fund for Environmental Research in the Public Interest (No. 201309035-7).

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