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Evaluation of fertilizing schemes for direct-seeding rice fields in Taihu Lake Basin, China

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Abstract: Field experiments were performed to identify an effective fertilizing scheme for direct-seeding rice (DSR) fields in the Taihu Lake Basin in east China. Based on local traditions, 3 typical fertilizing schemes (FS-1, FS-2, and FS-3) were evaluated, in consideration of ensuring a certain rice yield and relatively low nitrogen (N) loss. The base, seedling, tillering, jointing, and panicle fertilizers for FS-1 were all 20% of 270 kg N ha^{-1}, those for FS-2 were 30%, 30%, 0%, 25%, and 15% of 270 kg N ha^{-1}, and 15%, 20%, 25%, 20%, and 20% of 220 kg N ha^{-1} for FS-3, respectively. The results show that the majority of fertilizer N for DSR should be applied as topdressing fertilizer and not as base fertilizer as in transplanted rice cultivation. Increasing base fertilizer would not significantly improve the growth or yield of rice due to the low uptake of N during the seedling stage, and in turn would lead to greater N loss. Under FS-1, FS-2, and FS-3, N loss was 91.4, 103.1, and 70.5 kg ha^{-1}, respectively, via surface runoff, volatilization, and leaching. Furthermore, using different fertilizer N methods during the rice growing season led to different N uptake by rice plants. In the present study N uptake by rice was measured at 108, 91, and 102 kg N ha^{-1} under FS-1, FS-2, and FS-3, respectively. At the same time, the rice yield with FS-1, FS-2, and FS-3 was 8530, 7780, and 8620 kg ha^{-1}, respectively. In modern agricultural management an effective fertilizer scheme should simultaneously benefit both rice yield and the water environment. As a result, FS-3 was used in this study for DSR cultivation in the Taihu Lake Basin, which resulted in good rice yield and totally reducing N loss of 20.9-32.6 kg N ha^{-1}.

Key words: Rice, direct-seeding, fertilizing scheme, nitrogen loss

Introduction

Paddy fields are a major contributor to the human food supply (Brohi et al. 1998; Singh et al. 2002; Feng et al. 2004; Yoon et al. 2004). In Asia transplanting is the most popular crop establishment method; nevertheless, direct seeding has been adopted as a more efficient method of planting rice in many developed countries in which the labor pool is limited (Schnier et al. 1990; Naklang et al. 1996). Compared with traditional transplanted rice, direct-seeding rice (DSR) grows in the same paddy fields without the transplanting process or the turn-green stage (Ikeda et al. 2008). This accelerates the growth of rice, saving manpower and time. At the same time DSR has more seedlings that distribute evenly in paddy fields (Yadav et al. 2007). Without the transplanting process the

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roots of DSR are located in the shallow surface soil, which results in a relatively low uptake of nitrogen (N) (Zhang and Wang 2002).

As such, fertilizing schemes for DSR have become the focus of new studies to ensure rice yield and to reduce the environmental influence on water bodies. Zhang and Wang (2002) studied optimal N application for direct-seeding early rice at the city of Jinhua, Zhejiang province, China, and reported that site-specific nutrient management was related to improved splitting and timing of fertilizer N application, which led to a more balanced supply of N nutrition for rice growth than common fertilizer practice. Sharma (1995) compared the cultivation of DSR and transplanted rice in lowlands of South and Southeast Asia, and suggested that DSR should be cultivated via optimal combinations of agronomic practices, including seeding, irrigation, and fertilizing at a reasonable time to ensure its yield and improve the N utilization rate. Schnier et al. (1990) evaluated the effect of the timing and method of fertilizer N application on grain yield and N use efficiency in transplanted and direct-seeded flooded rice using ^{15}N-labeled urea.

At present, the DSR paddy in the Taihu Lake Basin still has not a uniform fertilizing scheme. The fertilization method for transplanted rice, which applies most N as base fertilizer (40%-60% of total fertilizer–N), is inherited in the present DSR without improvement (Yin et al. 2004). This easily leads to a low use efficiency of N by rice and a high rice production cost. Further, excessive fertilizer increases the chances that N will be discharged into the water resources (Antonopoulos and Wyseure 1998; Kara 2000; Cao 2003). High yields of a crop need optimum N availability in the root zone. A reasonable fertilizing scheme is important to control N cycling in water bodies (Aulakh and Bijay-Singh 1997). Therefore, more studies on fertilizing scheme in DSR paddy are necessary to establish a proper fertilizer management practice that would minimize environmental pollution and maximize rice yield.

With the deterioration of water quality, and both industrial and domestic sewage increasing in Taihu Lake Basin, the attention of governments and researchers has gradually focused on agricultural pollution. According to farmers' experiences with DSR cultivation, applying more fertilizer does not always increase rice yield. The arrange rate of base and topdressing fertilizers is more important than only increasing the total quality of fertilizer to some extent, which not only results in good yield, but also protects the local water environment. The present study aimed to identify an effective fertilizing scheme for DSR cultivation based on local conventional fertilization traditions in the Taihu Lake Basin, in consideration of ensuring rice yield and reducing N loss. The local traditional irrigation scheme for DSR was directly adopted and 3 typical fertilizing schemes were tested in our field experiments.

Materials and Methods

Experimental field description

A field experiment was carried out in 1350 m^2 (13.5 m × 100 m) paddy fields located in the upstream region of Taihu Lake Basin, which drains agricultural water into Taihu Lake through adjacent ponds and rivers. The basin area is about 36,900 km^2 and the rice paddy field accounts for 34.8% of this area. Annual precipitation is 1010-1400 mm year^{-1}, of which 35%-40% occurs between June and August. Mean seasonal maximum and minimum temperature during the 2007season was 16.5 and 41.0 °C. The study site is classified as a flood plain due to the frequent flooding of the Yangtze River. The ground surface layer is classified as silt or loam. The groundwater table is at a depth of about 120 cm below field surface, which varies with the irrigation and precipitation events in the agricultural fields. The physical and chemical properties of the soil in the experimental field are listed in Table 1.

Experimental design

The paddy field was divided evenly into 3 plots (each about 13.5 m × 33.3 m), as shown in Figure 1, and each plot was divided into 3 sub-plots (each about 150 m^2) for replicated experiments. The field was evenly dry-seeded with 75 kg of seed ha^{-1} (Wuxiangjing 14, Japonica rice) on 21 June 2007 without standing water, and harvested on 20 November 2007 (153 days after sowing). Irrigation water was supplied from a river east of the study site. The irrigation scheme was completely based on the local tradition for DSR cultivation. Precipitation was

Table 1. Physical properties of the tested soil in Taihu Lake Basin, China.

Depth (cm)	Particle size distribution (%) Sand (> 0.05 mm)	Silt (0.002-0.05 mm)	Clay (< 0.002 mm)	Bulk Density ($g\ cm^{-3}$)	pH (H_2O)	Organic matter ($g\ kg^{-1}$)	Total nitrogen ($g\ kg^{-1}$)
0-20	7.01	73.70	19.29	1.42	6.65	5.12	1.52
20-40	0.02	81.01	18.97	1.56	6.85	5.40	0.64
40-60	18.53	72.83	8.64	1.51	6.85	3.70	0.31
60-100	14.35	81.60	4.05	1.43	6.80	3.40	0.38

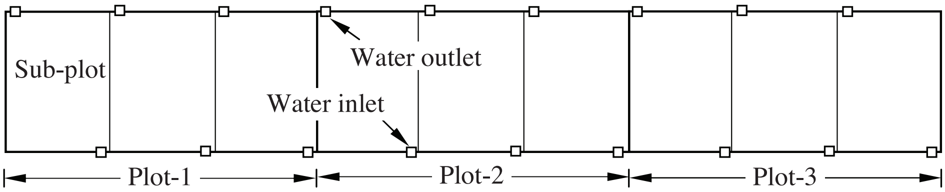

Figure 1. Layout of the experimental paddy field in Taihu Lake Basin, China.

forcibly drained during the period of seed germination (about 15 days after sowing). Total irrigation during the rice growing season was about 600 mm, and each time about 50 mm of water was irrigated. Total rainfall was about 630 mm. A controlled soil drying stage occurred from day 49 to 62 after rice seeding.

In the experimental field DSR had been cultivated for 3 years before our experiment started. Total fertilizer N applied in this paddy field was about 210-230 kg N ha^{-1} during each previous rice growing season. In our experiment the fertilization dates for the 3 plots were the same, although the amounts of fertilizer used were different. As listed in Table 2, 3 fertilizing schemes (FS-1, FS-2, and FS-3) were designed for plot 1, plot 2, and plot 3. FS-1 and FS-2 are screened out from the present local fertilizing traditions in this region. FS-3, which is an improvement over the ration of base and topdressing fertilizer of the customary fertilizing scheme in this paddy field, was designed to optimize the fertilizing scheme for DSR. Total quantity of N for FS-1, FS-2, and FS-3 during the rice growing season was 270, 270, and 220 kg N ha^{-1}, respectively. Base fertilizer (BF), a compound fertilizer (containing about 15% nitrogen, phosphorus, and potassium), was applied with rice seeds on 21 June, and then the surface soil was plowed to a depth of about 50 mm. The topdressing fertilizers (seedling, tillering, jointing, and panicle fertilizers, abbreviated as SF, TF, JF, and PF, respectively) and urea (about 46% nitrogen) were broadcast by hand 4 times with standing water in the paddy field. The details of the timing and rate of fertilizer application are listed in Table 2.

Table 2. Nitrogen fertilizer schemes for direct-seeded rice in Taihu Lake Basin, China (kg N ha^{-1}).

Fertilizing schemes	Base fertilizer (1st day)	Seedling fertilizer (16th day)	Tillering fertilizer (31st day)	Jointing fertilizer (45th day)	Panicle fertilizer (77th day)	Total
FS-1 (plot 1)	54.0 (20%)	54.0 (20%)	54.0 (20%)	54.0 (20%)	54.0 (20%)	270
FS-2 (plot 2)	71.0 (30%)	71.0 (30%)	0	67.5 (25%)	40.5 (15%)	270
FS-3 (plot 3)	33.0 (15%)	44.0 (20%)	55.0 (25%)	44.0 (20%)	44.0 (20%)	220

Monitoring and analysis methods

During the field experiment daily rainfall data were obtained from an adjacent agro-meteorological station. Total irrigation water and surface runoff were individually measured using flow-meters at inlet and outlet points of each sub-plot (Figure 1). Total water leaching was calculated by measuring the difference in the level of water in a cylinder (250 mm in diameter) with a glass bottle placed underground in each sub-plot for 24 h, and is expressed as a mean value of the 3 sub-plots in each plot.

Irrigation water samples were periodically collected directly from the irrigation inlet point. Surface runoff water samples were collected hourly from the outlet point of each sub-plot when it was raining or during draining. Soil solutions were collected weekly throughout the rice growing season using porous ceramic cups. The porous ceramic cups (60 mm long) were installed in each sub-plot at a depth of 100 cm (position of cup center) below the soil surface before rice seeding. The porous ceramic cups, connected to glass bottles, were initially evacuated (to 80 kPa) by a vacuum pump with a tensiometer. All water samples and soil solutions were filtered through a 0.2-μm membrane filter. The ammonium-N (NH_4^+–N) and nitrate-N (NO_3^-–N) concentrations were analyzed using the indo-phenol blue method and HPLC, respectively. Inflow and outflow of N were determined by multiplying the N concentration by the transported water volume, which consisted of irrigation, percolation, and surface drainage.

Ammonia (NH_3) volatilization was measured by the H_2SO_4 trap method (Sarkar et al. 1991; Kyaw et al. 2005). Rice growth parameters were measured 15, 30, 45, 60, 75, 90, 105, 120, and 153 days after seeding. The rice plants were separated into grain, straw, and roots, and then oven dried at 70 °C. The dried samples were weighed, ground, and prepared for chemical analysis. Total N content in the plant samples was determined by automatic combustion in tin (Sn) capsules and analyzed using a stable isotope mass spectrometer. N uptake was determined by multiplying the dry matter yield by the N content in the corresponding tissues (Kyaw et al. 2005). Floodwater pH was measured with a portable pH meter using a combined calomel glass electrode assembly. At harvest, the grains from two 2-m^2 sample areas per sub-plot were weighed separately and expressed at about 145 g kg^{-1} moisture.

Data were subjected to analysis of variance (ANOVA) using OriginPro v.8.0 software. Differences were considered significant at $P < 0.05$ and treatment means that were significantly different were separated by least significant differences at $P < 0.05$.

Results

Ammonia volatilization

Ammonia volatilization is a major cause of N loss from fertilizer N applied to flooded rice. Generally, increasing fertilizer N led to higher volatilization rates, as shown in Figure 2. The peak ammonia volatilization rate (AVR) values after BF under 3 fertilizing schemes were relatively small due to the lack of standing water. Until the first rainfall on the 7th day after BF the AVR appeared at a peak value of 2.16, 2.93, and 1.55 kg ha^{-1} day^{-1} under FS-1, FS-2, and FS-3, respectively. Rain water accelerated the hydrolysis reaction of the remaining fertilizer in the soil. After SF was applied a typhoon that dumped 23 cm of rainfall greatly decreased the concentration of NH_3 in the standing water, which slowed the volatilization flux, even though a high rate of fertilizer was applied. The greatest AVR (3.45 kg ha^{-1} day^{-1}), which was about 1.9-fold that in plot 3, was observed

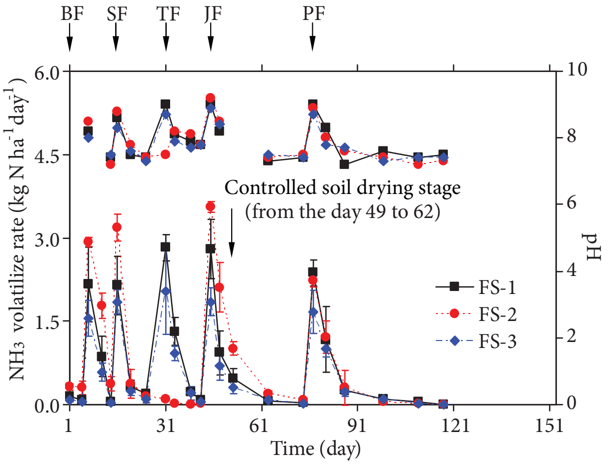

Figure 2. Measured ammonia volatilization rate and pH value in field water in plot 1 (FS-1), plot 2 (FS-2), and plot 3 (FS-3), corresponding to the fertilization events.

in plot 2 when JF was applied. During the late stage AVR decreased when PF was applied in plot 1 and plot 3, as compared to when JF was applied, although the same quantity of fertilizer and application method were used. The AVR in plot 2 was maximal after base and 3 topdressing fertilizer applications (days 16, 45, and 77) were applied. The peak values of AVR occurred 1-2 days after topdressing fertilizers were applied. About 8-11 days after fertilizer was applied, AVR drastically decreased (near zero) in the 3 plots. Higher NH_3 flux was observed after fertilization, coinciding with higher floodwater pH values (8.3-9.3) (Figure 2). In addition, the hydrolysis of urea proceeded rapidly, especially when the temperature was high (June-August).

Different allocations of fertilizer, although with the same total amount, would produce dissimilar N loss through NH_3 volatilization when comparing FS-1 and FS-2. When a high rate of fertilizer is applied during the early stage of growth, low uptake of N by rice seedlings easily leads to high NH_3 volatilization. In the present study mean AVR values were 70.5, 78.4, and 54.3 kg N ha^{-1} in plot 1, plot 2, and plot 3, which accounted for about 26.1%, 29.0%, and 24.7% of their total fertilizer N, respectively.

Nitrogen loss through surface runoff

The quantity of N loss via surface runoff depends primarily on the quantity of surface runoff and its concentration of N. As shown in Figure 3, in our paddy field surface runoff occurred mostly during the rainy season. During the rice germination stage (days 1-15), rainfall was forcibly drained, keeping the rice seeds from rotting, which led to some residual fertilizer N being discharged into the soil. In particular, the 230 mm of rainfall due to a typhoon that occurred on 6-9 July (just after SF was applied), carried a lot of N outside along with the surface runoff. Although the concentration of N in the surface runoff was low, the NH_4^+–N content accounted for about 68% of total N. This indicates that the hydrolysis reaction was proceeding when the surface runoff drained. As a consequence, the SF greatly contributed to the quantity of N drained through the surface runoff. Similarly, the forced drainage during the controlled soil drying stage took some N outside of the paddy field. No obvious surface runoff was observed during the other stages of growth.

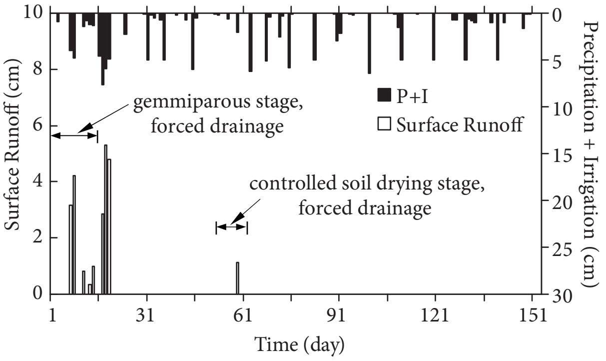

Figure 3. Mean value of surface runoff in the 3 plots under precipitation and irrigation in Taihu Lake Basin, China (P+I: precipitation + irrigation).

The quantity of surface runoff from plot 1, plot 2, and plot 3 was about 224, 216, and 225 mm, respectively. The mean concentration of total N in the surface runoff from plot 1, plot 2, and plot 3 was 4.3, 5.7, and 3.2 mg L^{-1}, respectively. The N carried by surface runoff from plot 1, plot 2, and plot 3 was 9.7, 12.3, and 7.1 kg N ha^{-1}, which accounted for about 3.6%, 4.6%, and 3.2% of their total fertilizer N, respectively. Among them, NH_4^+–N and NO_3^-–N accounted for about 53.5% and 46.5%.

Bottom leakage of nitrogen

Bottom leakage of N was predominantly influenced by precipitation and irrigation events. The relatively low hydraulic conductivity of the plow pan (15-25 cm) controlled the infiltration flux of water. As shown in Figure 4, it is evident that the wetting and drying stages occurred alternately during the entire rice growing season. In total, NH_4^+–N leaching was minimal during the controlled soil drying stage in the 3 plots. N leaching at a depth of 100 cm below the surface significantly slowed about 12 days after fertilizer was applied. In the 3 plots the greatest NH_4^+–N leaching losses were observed during the prophase, soon after fertilization, which then gradually decreased with time as shown in Figure 4a. NH_4^+–N leaching primarily occurred after TF was applied. Although PF was applied, the leaching of NH_4^+–N decreased gradually due to good N uptake by the rice during this stage. Figure 4b shows the leaching flux of NO_3^-–N, which occurred primarily during the middle stage of growth after TF and JF were applied. The

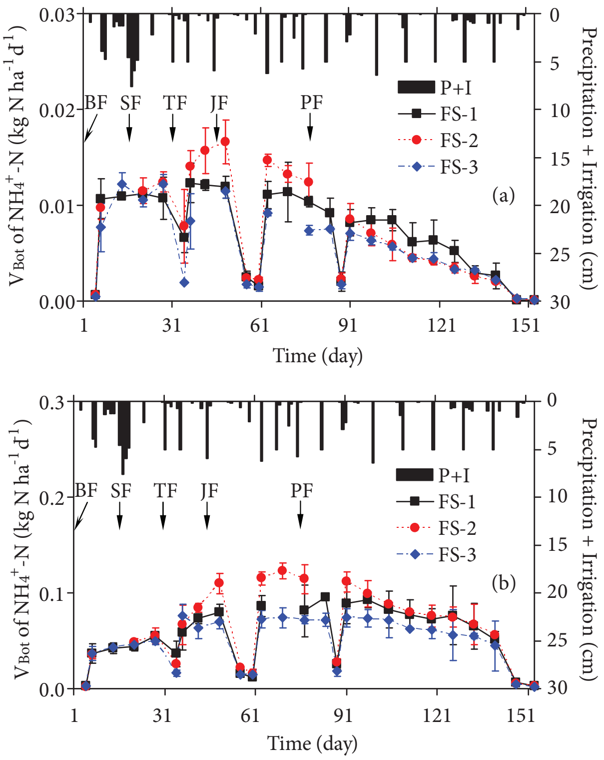

Figure 4. Measured bottom (at depth of 100 cm) leakage flux of NH_4^+–N (a) and NO_3^-–N (b) corresponding to the precipitation/irrigation and fertilization events during the rice growing season (BF: base fertilizer; SF: seedling fertilizer; TF: tillering fertilizer; JF: jointing fertilizer; PF: panicle fertilizer; controlled soil drying stage: from the day 49 to 62; P+I: precipitation + irrigation).

greatest leaching flux of NO_3^-–N was about 0.12 kg ha^{-1} day^{-1}, which occurred in plot 2 after JF (67.5 kg N ha^{-1}) was applied. Moreover, the nitrification process may have increased during the controlled soil drying stage, which led to the leaching of a large quantity of NO_3^-–N under irrigation/precipitation. During the entire growing season the mean concentration of NO_3^-–N at a depth of 100 cm was 0.054, 0.063, and 0.048 mg L^{-1} in plot 1, plot 2, and plot 3, respectively. The mean concentration of NO_3^-–N in soil solutions was about 7.6-fold that of NH_4^+–N.

The quantity of N leaching from plot 1, plot 2, and plot 3 was 11.2, 12.4, and 9.1 kg of N ha^{-1}, which accounted for about 4.1%, 4.6%, and 4.1% of total fertilizer N, respectively. Among of them, mean NH_4^+–N and NO_3^-–N leaching loss in the 3 plots accounted for 10.7% and 89.3%, respectively.

Rice uptake of nitrogen

The efficient use of N by flooded rice is a major concern for agriculture. In our experiment total N uptake in plot 1 was greater than in plot 2 and plot 3, as shown in Figure 5. Generally, a high N supply leads to relatively high N uptake by rice. However, high N supply during the early growth phase did not result in vigorous vegetative plant growth, which inversely resulted in N loss through surface runoff, volatilization, and leaching in plot 2. After TF and JF were applied, N uptake by rice increased quickly due to the thick root mat that developed in the surface soil. The absence of TF in plot 2 might have influenced the uptake of N by rice, even though some N was supplied via mineralization. Uptake of the initially applied N was slow and was almost complete 13 days after panicle initiation, after which time no significant fertilizer N uptake occurred.

As shown in Figure 5, total N uptake by rice plants were calculated at 108, 91, and 102 kg N ha^{-1} in plot 1, plot 2, and plot 3, respectively. Excessive N supply during the late stage did not benefit the growth of rice, but resulted in more field stalk lodging in plot 2 and plot 1. Under a certain N uptake by rice, an increase in N fertilizer would decrease the utilization rate of N in the paddy field, and simultaneously result in additional N discharged into water or the atmosphere.

Rice yield under 3 fertilizing schemes

Rice yield may be the most important factor to farmers. Actually, rice production also reflects the field fertilizer management system, to some extent. In

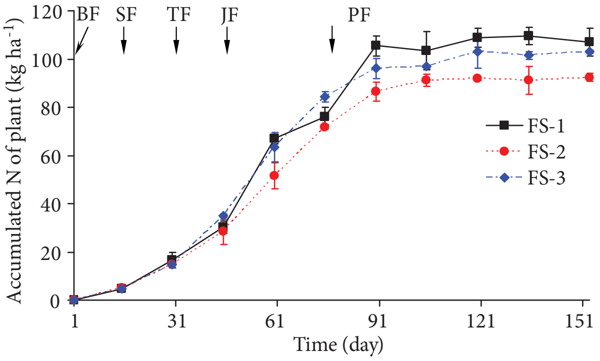

Figure 5. Measured accumulated nitrogen in rice root uptake in plot 1 (FS-1), plot 2 (FS-2), and plot 3 (FS-3) (BF: base fertilizer; SF: seedling fertilizer; TF: tillering fertilizer; JF: jointing fertilizer; PF: panicle fertilizer).

our field experiment the mean rice yield in plot 1 (FS-1), plot 2 (FS-2), and plot 3 (FS-3) were 8530, 7780, and 8620 kg ha^{-1}, respectively. Thus, the difference in rice yield between plot 2 and plot 3 is obvious, and the yield of plot 1 was similar to that of plot 3. In fact, the field stalk lodging part of rice in plot 2 influenced the rice yield, to a certain extent.

Discussion

Under an acceptable yield of DSR the environmental and economic benefits may receive more attention. In recent years the yield of DSR in Taihu Lake Basin was 6000-9000 kg ha^{-1}, which was influenced by local weather, except for the field management. Plot 1 and plot 3 had small differences in rice yield, which were acceptable to local farmers; however, FS-2 in plot 2 influenced the rice yield, which was low in the local region. The absence of TF under FS-2 might have influenced rice growth due to the demand for N at this time (Naklang et al. 1996; Yin et al. 2004). Furthermore, during the late stage of rice growth, the amount of N applied in plot 2 caused more field stalk lodging, which influenced harvesting by agricultural machinery. Using a certain quantity of fertilizer it is key to arrange the fertilizer rate at appropriate times (Roberts, 2008). The appropriate reduction in BF and increase in topdressing fertilizers during the middle stage ensured the rice yield for DSR (Yin et al. 2004); therefore, it is crucial that farmers manage their fertilizing schemes to best match application with the peak demands of their crops (Baligar et al. 2001).

In terms of agricultural, economic, or environment protection, lower total fertilizer N is an advantage. A good economic effect in plot 3 was obtained due to the high rice yield and low total added fertilizer, as compared to plot 2. Improving the N utilization rate of plants may significantly reduce the total added fertilizer (Yan et al. 2005). Nutrients should be applied at the right rate, time, and place, as a best management practice for achieving optimum nutrient efficiency (Schnier et al. 1990; Roberts 2008). The more nutrients that are used, the less opportunity there will be for loss (Roberts 2008). The fertilization rate and time may be the most critical factors in determining fertilizer uptake efficiency and crop yield. When N is added near the time of maximum growth crops are able to efficiently use the nutrients (Mosier et al. 2004). FS-2 (270 kg N ha^{-1}) is a traditional fertilization method for transplanted rice, in which the main portion of fertilizer (60%) is applied during the prophase stage, after the rice has been transplanted (Yin et al. 2004). More N loss occurred in plot 2 during the prophase of the rice season. FS-1, with an even allocation of fertilizer, is good for rice N uptake, although the same fertilizer was applied as in plot 2. Actually, as shown in Figure 5, the rice seedlings in plot 1 and plot 2 did not absorb more N than those in plot 3. Instead, more N was lost through NH_3 volatilization, surface runoff, and leaching. Generally, only increasing BF under a certain total quantity cannot improve growth or yield of rice due to the low uptake of N at the seedling stage. The N utilization rate in plot 1, plot 2, and plot 3 was about 40.0%, 33.7%, and 46.4%, respectively. These results are higher than those reported by Schnier et al. (1990) (about 38%). This is primarily because the quantity of N through rainfall, irrigation, and mineralization was not considered. Correspondingly, the rice in plot 3 had good N utilization; more fertilizer was applied as topdressing fertilizer when rice growth required more N. Excessive application increased both the cost to the grower and the potential contamination of surface and groundwater (Mosier et al. 2004). The main demand for nutrients by DSR occurs during the middle stage of its growing season (Yin et al. 2004).

Due to the continuous deterioration of the water environment over the last 20 years, the non-point pollution from agriculture fields is too high to control the blue algae eruption in Taihu Lake (Gao et al. 2002; Zhu et al. 2004). As a whole, low total fertilizer N in DSR fields would be beneficial to the local surface and groundwater environments (Schnier et al. 1990; Zhu et al. 2004). Compared with the present fertilization method (FS-1 and FS-2), FS-3 in plot 3 reduced total fertilizer N to 50 kg N ha^{-1} and correspondingly decreased N loss of 20.9-32.6 kg N ha^{-1} via NH_3 volatilization, surface runoff, and leaching. Low added fertilizer also decreased N loss through denitrification of NO_3^-–N in soil (Reddy et al. 1990; Xing et al. 2002; Yoon et al. 2004) under the same field management conditions, and N remained in the soil profile (Lian et al. 2003; Zhu et al. 2004).

Both rice yield and influences on the environment should be considered at the same time in modern agricultural cultivation activities. According to our field experiment, the FS-3 fertilizing scheme for DSR cultivation in Taihu Lake Basin, which applied BF, SF, TF, JF, and PF of 15%, 20%, 25%, 20%, and 20% of 220 kg N ha^{-1}, respectively, is presented in this study, considering rice yield at a certain extent and relative low N loss into environments.

Acknowledgements

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