

Effects of Different Fertilization Methods on Rice Yield and Nitrogen Loss in Double-Cropping Rice Areas (Postprint)

Authors: Duan Ran, Tang Yuefeng, Wang Yanan, Wang Weizheng, Bai Lingyu, Wu Cuixia, Wen Jiong, Zeng Xibai

Date: 2017-11-08T00:00:00+00:00

Abstract

To ensure food security and reduce nitrogen fertilizer input in paddy ecosystems, improving nitrogen use efficiency and reducing nitrogen loss have become important agricultural and environmental measures. This study conducted a one-year field experiment with early and late rice at the Yueyang Agricultural Environmental Science Observation and Experimental Station of the Ministry of Agriculture, located in Yueyang, Hunan, comparing nutrient use efficiency, crop yield, and nitrogen loss under no fertilization (T1), conventional urea fertilization (T2, N application rate of $280 \text{ kg} \cdot \text{hm}^{-2}$, P_2O_5 $165 \text{ kg} \cdot \text{hm}^{-2}$, K_2O $120 \text{ kg} \cdot \text{hm}^{-2}$), conventional controlled-release fertilizer application (T3, N application rate of $230 \text{ kg} \cdot \text{hm}^{-2}$, P_2O_5 $165 \text{ kg} \cdot \text{hm}^{-2}$, K_2O $120 \text{ kg} \cdot \text{hm}^{-2}$), high-rate controlled-release fertilizer side-dressing (T4, N application rate of $230 \text{ kg} \cdot \text{hm}^{-2}$, P_2O_5 $138 \text{ kg} \cdot \text{hm}^{-2}$, K_2O $120 \text{ kg} \cdot \text{hm}^{-2}$), medium-rate controlled-release fertilizer side-dressing (T5, N application rate of $180 \text{ kg} \cdot \text{hm}^{-2}$, P_2O_5 $123 \text{ kg} \cdot \text{hm}^{-2}$, K_2O $120 \text{ kg} \cdot \text{hm}^{-2}$), and low-rate controlled-release fertilizer side-dressing (T6, N application rate of $140 \text{ kg} \cdot \text{hm}^{-2}$, P_2O_5 $123 \text{ kg} \cdot \text{hm}^{-2}$, K_2O $120 \text{ kg} \cdot \text{hm}^{-2}$), aiming to provide a theoretical basis for rational nitrogen utilization in paddy fields. The results indicated that side-dressing controlled-release fertilizer could effectively improve rice yield and its components, increase nitrogen use efficiency, and reduce non-point source loss. 1) Under conditions of reduced rice seedling numbers and nitrogen application rates, the early and late rice yields under T4 treatment increased by 13.17% and 4.72%, respectively, compared with T2 treatment, and also increased by 7.27% and 1.74%, respectively, compared with T3 treatment; 2) Side-dressing fertilization treatments effectively reduced nitrogen loss in paddy fields, with annual nitrogen loss of $0.466\text{--}0.673 \text{ kg} \cdot \text{hm}^{-2}$, reducing surface runoff nitrogen loss by 3.54%–29.36% compared with conventional fertilization treatments; 3) Side-dressing fertilization effectively improved nitrogen use efficiency, with the nitrogen use efficiency under T4 treatment being 1.70

times and 1.22 times that of T2 and T3 treatments, respectively. Therefore, adopting appropriate fertilization methods combined with suitable amounts of controlled-release nitrogen fertilizer can achieve higher output value and benefits. High-rate controlled-release fertilizer side-dressing (T4) represents the optimal fertilization model for the study area and holds significant importance for achieving high yield and efficiency, resource conservation, and ecological environmental protection in modern agricultural production.

Full Text

Effects of Different Fertilization Methods on Rice Yield and Nitrogen Loss in Double-Cropping Rice Systems

Duan Ran¹, Tang Yuefeng², Wang Yanan¹, Wang Weizheng², Bai Lingyu¹, Wu Cuixia¹, Wen Jiong², Zeng Xibai^{1*}

¹Institute of Agricultural Environment and Sustainable Development, Chinese Academy of Agricultural Sciences/Key Laboratory of Agricultural Environment and Climate Change, Ministry of Agriculture, Beijing 100081, China

²Yueyang Agricultural Sciences Institute, Yueyang 414000, China

Abstract: To ensure food security while reducing nitrogen fertilizer input in paddy ecosystems, improving nitrogen use efficiency and reducing nitrogen loss have become critical agricultural and environmental measures. This study conducted a one-year field experiment with early and late rice at the Yueyang Agricultural Environmental Science Observation Station in Hunan Province, comparing six fertilization treatments: no fertilizer (T1), conventional urea application (T2, N 280 kg · hm⁻²), controlled-release fertilizer with conventional method (T3, N 230 kg · hm⁻²), high-rate controlled-release fertilizer with side-bar application (T4, N 230 kg · hm⁻²), medium-rate controlled-release fertilizer with side-bar application (T5, N 180 kg · hm⁻²), and low-rate controlled-release fertilizer with side-bar application (T6, N 140 kg · hm⁻²). All treatments received P₂O₅ 123–165 kg · hm⁻² and K₂O 120 kg · hm⁻². The results demonstrated that side-bar application of controlled-release fertilizer effectively improved rice yield and its components, enhanced nitrogen use efficiency, and reduced non-point source nitrogen loss. Specifically: (1) Under reduced seedling density and nitrogen application rates, T4 increased early and late rice yields by 13.17% and 4.72%, respectively, compared with T2, and by 7.27% and 1.74% compared with T3; (2) Side-bar fertilization reduced annual nitrogen loss to 0.466–0.673 kg · hm⁻², decreasing surface runoff nitrogen loss by 3.54%–29.36% compared with conventional fertilization; (3) Side-bar fertilization significantly improved nitrogen use efficiency, with T4 achieving 1.70 and 1.22 times the efficiency of T2 and T3, respectively. Therefore, adopting appropriate fertilization methods with suitable controlled-release nitrogen fertilizer can achieve higher yields and economic returns. High-rate controlled-release fertilizer with side-bar application (T4) represents the optimal fertilization mode for this region, holding significant importance for realizing high yield and efficiency, resource conservation,

and ecological protection in modern agricultural production.

Keywords: Rice; Slow-release fertilizer; Side-bar fertilization; Nitrogen use efficiency; Nitrogen loss; Surface source loss rate; Dongting Lake

Introduction

Agricultural non-point source pollution constitutes one of the primary causes of water contamination, with over 60% of global surface water environmental issues attributed to agricultural activities [1]. The double-cropping rice region (28°44' -29°35' N, 111°53' -113°28' E) produces 30% of Hunan Province' s total grain output, predominantly rice. In recent years, excessive and improper nitrogen fertilizer application in this region has led to increasingly severe non-point source pollution and water eutrophication in the lake area [2]. The proportion of farmers applying excessive nitrogen in southern rice regions reaches 60%-90% [3], and studies using ¹⁵N-labeled nitrogen fertilizer indicate nitrogen loss rates of 30%-70% in paddy fields [4]. Such intensive agricultural practices not only reduce nutrient use efficiency and fertilization benefits but also increase nutrient concentrations in runoff water, thereby affecting downstream aquatic ecosystems and causing water quality degradation. Consequently, reducing nitrogen input into water bodies from the source represents the key to controlling agricultural non-point source pollution. Research in the Dongting Lake region has shown that substituting chemical fertilizers with equivalent amounts of organic manure can reduce nitrogen loss without significantly affecting rice yield [5]. Similarly, studies in the Taihu Lake region demonstrated that appropriately reducing nitrogen input does not decrease rice yield but can significantly improve nitrogen use efficiency and reduce nitrogen loss [6]. Slow/controlled-release fertilizers have emerged as an effective solution to these problems due to their high utilization efficiency and favorable nutrient release characteristics.

Numerous scholars domestically and internationally have dedicated efforts to the application and promotion of controlled-release nitrogen fertilizers. Research results indicate that slow-release urea application can increase root zone nitrogen content and enhance the activities of leaf glutamine synthetase, glutamine α -ketoglutarate aminotransferase, and nitrate reductase in rice plants. Under equivalent nitrogen application rates, slow-release urea achieves over 20% higher nitrogen use efficiency than conventional urea, while still producing 3%-5.9% higher yields even with 30% reduced application rates [7]. Zheng et al. [8] reported that appropriate sulfur coating can improve soil Ca and Mg activation, increase rice nitrogen uptake and utilization efficiency, and boost yield. Using ¹⁵N tracer technology, Ji et al. [9] investigated controlled-release nitrogen fertilizer utilization and nitrate leaching loss during early rice cultivation, finding that single basal application of controlled-release nitrogen fertilizer increased grain yield by over 7.0% compared with split urea application, with nitrogen utilization efficiency 35.9% higher and nitrate nitrogen loss reduced by

27.1%. Additionally, Xu et al. [10] found that nitrogen loss through ammonia volatilization in paddy fields under controlled-release fertilizer combined with non-flooding irrigation management was $23.73 \text{ kg(N)} \cdot \text{hm}^{-2}$, significantly lower than in flooded paddies with conventional fertilization.

Regarding application methods, controlled-release fertilizers are typically broadcast or uniformly deep-incorporated using conventional techniques. Although controlled-release fertilizers can slowly release nutrients according to crop demand, they cannot achieve spatially intensive utilization. Side-bar fertilization technology represents a comprehensive nutrient management system encompassing seedling cultivation, pre-transplanting preparation, transplanting with fertilization, and post-planting management [11]. Its core principle involves mechanized operations that optimize planting density while applying slow-release fertilizer 3–4 cm lateral to seedlings at a depth of 3–5 cm. Due to its significant advantages in promoting yield and conserving nutrients, this technology is being piloted and promoted on a large scale in Hunan, Ningxia, and Heilongjiang provinces. Liu et al. [12] demonstrated in Ningxia's Yellow River irrigation region that side-bar fertilization technology significantly increased aboveground nitrogen uptake and nitrogen partial factor productivity while reducing apparent nitrogen loss. Currently, research remains limited on the application of controlled-release fertilizers through rice side-bar fertilization technology and its effects on rice yield, fertilizer utilization efficiency, and soil nutrient runoff losses, particularly in major rice-producing regions adjacent to important lake areas in China. Addressing nitrogen surplus issues in rice production in the Dongting Lake region, this study conducted field plot experiments using side-bar fertilization technology in a double-cropping rice system to investigate the effects of different fertilizer side-bar application techniques on crop yield, fertilizer utilization efficiency, soil nutrients, and field runoff water, aiming to provide scientific basis and technical support for rational fertilization, regional agricultural non-point source pollution control, and water environment protection in the Dongting Lake region.

1.1 Study Area Overview

The experiment was conducted at the Yueyang Agricultural Environmental Science Observation Station (112°44' 14" E, 28°57' 11" N), Ministry of Agriculture, located in a subtropical region with warm and humid climate, adequate sunlight, and moderate rainfall. The area has an average annual temperature of 17 °C, mean annual precipitation of 1,400 mm, and annual sunshine duration of 1,722.1–1,816 h. The experimental soil was alluvial soil developed from Dongting Lake sediments with a clay-loam texture, pH 5.67, organic matter content of $36.3 \text{ g} \cdot \text{kg}^{-1}$, total nitrogen $1.4 \text{ g} \cdot \text{kg}^{-1}$, total phosphorus $0.6 \text{ g} \cdot \text{kg}^{-1}$, and available potassium $98 \text{ mg} \cdot \text{kg}^{-1}$.

1.2.1 Experimental Design

Based on conventional fertilization practices in the region, the field plot experiment included the following treatments: (1) No fertilizer, T1; (2) Conventional fertilization, T2; (3) Controlled-release fertilizer with conventional method, T3; (4) High-rate controlled-release fertilizer with side-bar application, T4; (5) Medium-rate controlled-release fertilizer with side-bar application, T5; (6) Low-rate controlled-release fertilizer with side-bar application, T6. Specific fertilizer application rates for each treatment are shown in Table 1. The controlled-release fertilizer, produced by Shandong Shikefeng Chemical Co., Ltd., contained 15.0% N, 15.0% P_2O_5 , and 15.0% K_2O . Conventional fertilization used urea (N, 46%), calcium magnesium phosphate fertilizer (P_2O_5 , 14%), and potassium chloride (K_2O , 60%). All controlled-release fertilizer was applied as basal fertilizer during transplanting. The T3 treatment received basal application during field preparation, while T4, T5, and T6 treatments employed side-bar fertilization using a Japanese-made Minoru four-wheel, four-row transplanter-fertilizer applicator during transplanting, with fertilizer placed 5 cm deep and 5 cm lateral to the root system at row spacing of 33 cm and plant spacing of 14 cm. For conventional fertilization treatments, 80% of nitrogen and all phosphorus and potassium fertilizers were applied as basal fertilizer during field preparation, with the remaining 20% nitrogen topdressed as broadcast application at the tillering stage (May 10 for early rice, August 6 for late rice).

The rice varieties were ‘Yueyou 27’ for early rice and ‘Yueyou 9113’ for late rice. Early rice seedlings were cultivated starting March 30, transplanted on April 30, and harvested on July 20. Late rice seedlings were cultivated starting June 28, transplanted on July 25, and harvested on October 27. Planting densities were 16 cm \times 20 cm for early rice and 20 cm \times 25 cm for late rice in T1, T2, and T3 treatments, and 12 cm \times 33 cm for early rice and 14 cm \times 33 cm for late rice in T4, T5, and T6 treatments. Each experimental plot measured 15 m in length and 5.2 m in width (fertilizer applicator width 1.3 m \times 4 rows = 5.2 m), with an area of 78 m². All plots were isolated with double-layer plastic film (30 cm underground depth, 30 cm aboveground ridge height) to minimize lateral seepage and cross-flow between plots. Each plot had independent drainage and irrigation inlets, with three replications per treatment arranged in a randomized complete block design (Table 1).

1.2.2 Observation Indicators and Measurement Methods

During the rice growing season (excluding the midseason aeration period), precipitation events causing changes in surface water height were considered effective precipitation. Surface water samples were collected using a small spoon at five random points in a quincunx pattern within each plot, with 1,000 mL total volume stored in mineral water bottles. Samples were immediately refrigerated below 5 °C. At harvest, crops in each plot were harvested separately for yield determination and grain quality analysis. Mature plant samples were divided into aboveground vegetative parts and grains. Aboveground plant parts were

killed at 105 °C for 30 minutes, then dried to constant weight at 70 °C. Simultaneously, five soil samples (0–20 cm depth) were collected from each plot using quincunx sampling, mixed, and analyzed for nitrate nitrogen content in fresh subsamples. Approximately 0.5 kg of remaining soil was air-dried, ground, and passed through a 2-mm sieve for storage. Throughout the growing season, five precipitation events generating runoff were successfully captured. Soil nitrate nitrogen was extracted with 1 mol · L⁻¹ KCl solution and measured by dual-wavelength UV spectrophotometry correction. Total soil nitrogen and phosphorus were determined by semi-micro Kjeldahl method and HClO₄-H₂SO₄ digestion-molybdenum antimony colorimetry, respectively. Water samples were analyzed for total nitrogen by potassium persulfate oxidation-UV spectrophotometry and total phosphorus by potassium persulfate oxidation-molybdenum blue colorimetry [13].

1.3 Data Calculation and Statistical Analysis

Grain yield was calculated based on air-dried grain weight at 13% moisture content. Nitrogen loss was calculated as the sum of pollutant concentrations in each runoff (or leachate) event multiplied by the corresponding water volume. Total annual runoff represents the sum of losses during effective precipitation events throughout the year. The calculation formulas are as follows:

$$\text{Nitrogen loss amount} = \Sigma(C \times V) \quad (1)$$

where P is the pollutant loss amount, C is the nitrogen or phosphorus concentration in the i-th runoff (or leachate) event, and V is the water volume of the i-th runoff event.

$$\text{Fertilizer uptake} = \text{Content in grain} + \text{Content in straw} \quad (2)$$

$$\text{Nitrogen use efficiency} = (\text{Uptake in fertilized plot} - \text{Uptake in control plot}) / \text{Fertilizer application rate} \quad (3)$$

All data were subjected to multiple comparison tests using SPSS 13.0 software.

2.1 Changes in Rice Yield Under Different Fertilization Treatments

The effects of different fertilization treatments on rice grain yield are shown in Figure 1 [Figure 1: see original paper]. All fertilization treatments promoted rice yield improvement. Although statistical analysis showed no significant difference in yield between early and late rice under the same application rate (T3 and T4), the T5 treatment (controlled-release fertilizer with 18% nitrogen reduction and side-bar application) showed no significant difference from the T3 treatment (controlled-release fertilizer without nitrogen reduction and conventional application), demonstrating that side-bar fertilization technology can maintain rice yield while reducing nitrogen application. Furthermore, in terms

of average yield, T4 treatment was 7.28% higher than T3 in the early rice season and 1.75% higher in the late rice season. Compared with conventional urea fertilization (T2), side-bar fertilization technology maintained rice yield even with $40 \text{ kg} \cdot \text{hm}^{-2}$ reduced controlled-release fertilizer application (T6), with no significant changes in early rice ($5,356.94 \text{ kg} \cdot \text{hm}^{-2}$) or late rice ($7,073.39 \text{ kg} \cdot \text{hm}^{-2}$) yields.

Rice yield components are primarily affected by panicles per plant, grains per panicle, and 1,000-grain weight. Due to lower planting density in side-bar fertilization treatments, effective panicle numbers were lower than in T2 and T3 (Table 2). Treatment T3 (conventional farmer practice) achieved the highest final panicle numbers, reaching $326.1 \times 10^4 \cdot \text{hm}^{-2}$ and $315.9 \times 10^4 \cdot \text{hm}^{-2}$ in early and late rice seasons, respectively—substantially higher than the three side-bar fertilization treatments. However, side-bar fertilization treatments showed higher grains per panicle and slightly increased 1,000-grain weight, compensating for the lower effective panicle numbers and achieving yield component balance with conventional fertilization. No significant differences in yield components were observed between T2 and T3 treatments.

2.2 Effects of Different Fertilization Treatments on Paddy Soil Nitrogen Content

Table 3 shows that different fertilization treatments had no significant effect on soil total nitrogen, though all were significantly higher than the no-fertilizer treatment, with no significant difference between early and late rice seasons. Effects on soil nitrate nitrogen and ammonium nitrogen varied with season and fertilization treatment. In early rice soil samples, T4 showed the highest nitrate and ammonium nitrogen contents, significantly different from the other two side-bar fertilization treatments (T5 and T6) but not from conventional fertilization treatments (T2 and T3). For late rice soil samples, T4 nitrate nitrogen content was significantly higher than T2 and T3. Except for T1 and T5, early rice soil nitrate nitrogen content was significantly higher than late rice, while ammonium nitrogen content was higher in early rice than late rice across all treatments. The highest late rice ammonium nitrogen content was only $1.71 \text{ mg} \cdot \text{kg}^{-1}$ (T5), whereas the highest early rice ammonium nitrogen content was 8.14 times greater (T4).

2.3 Non-Point Source Loss Rates of Fertilizer Nitrogen Under Different Treatments

Comprehensive analysis revealed that all fertilization treatments were accompanied by nitrogen transfer from soil to water (Figure 2 [Figure 2: see original paper]), with side-bar fertilization technology significantly outperforming conventional and controlled-release fertilizer applications in reducing nitrogen loss. The primary nitrogen release occurred within 20 days after fertilization. Calculated as release proportion, early rice total nitrogen release during the first 20 days accounted for 66.44% (T6) to 84.20% (T2) of the entire growing period,

ammonium nitrogen 70.56% (T6) to 82.84% (T2), nitrate nitrogen 81.27% (T5) to 87.30% (T3), and organic nitrogen 45.36% (T5) to 83.81% (T2). For late rice, the ranges were: total nitrogen 77.30% (T6) to 91.52% (T2), ammonium nitrogen 79.86% (T4) to 92.42% (T2), nitrate nitrogen 88.67% (T2) to 94.82% (T3), and organic nitrogen 63.59% (T6) to 91.35% (T2).

In terms of absolute loss amounts (Figure 3 [Figure 3: see original paper]), T2 showed the highest loss, with total nitrogen loss reaching $9.57 \text{ kg} \cdot \text{hm}^{-2}$ and ammonium nitrogen loss of $3.74 \text{ kg} \cdot \text{hm}^{-2}$. The lowest loss occurred in T6 treatment. Side-bar fertilization technology effectively reduced nitrogen loss in paddy fields, with annual nitrogen loss of only $4.66\text{--}6.73 \text{ kg} \cdot \text{hm}^{-2}$, decreasing surface runoff nitrogen loss by 3.54%–29.36% compared with conventional fertilization. Nitrogen loss was primarily related to fertilization timing, with rainfall also exerting influence, mainly affecting total nitrogen, ammonium nitrogen, and organic nitrogen. Rainfall events occurring within 20 days after nitrogen application significantly increased nitrogen loss from paddy fields.

2.4 Nitrogen Fertilizer Utilization Under Different Fertilization Treatments

Nitrogen use efficiency under different fertilization treatments is shown in Figure 4 [Figure 4: see original paper]. Except for T6, no significant difference in nitrogen use efficiency existed between early and late rice, though significant differences were observed among fertilization treatments. Both side-bar and conventional fertilization technologies showed that high-rate controlled-release fertilizer application achieved higher average nitrogen use efficiency than conventional urea fertilization (T2). In terms of nitrogen application rate, conventional urea fertilization (T2) achieved nitrogen use efficiencies of 22.79% and 21.28% for early and late rice, respectively, while low-rate controlled-release fertilizer with side-bar application (T6) achieved 21.18% for early rice and 34.28% for late rice. The T4 treatment reached 38.82% nitrogen use efficiency for early rice, while T5 treatments showed higher efficiencies than T3 for both early (37.25%) and late rice (38.18%). These data demonstrate that side-bar fertilization enhances nitrogen use efficiency in paddy systems.

Discussion

Excessive nitrogen application in paddy soils typically causes surface water eutrophication, groundwater nitrate nitrogen exceedance, increased greenhouse gas N_2O emissions, and low nitrogen utilization efficiency. Side-bar fertilization technology combined with slow-release fertilizer has become a primary approach to mitigate these environmental issues in paddy fields. Previous studies have shown that compared with conventional surface broadcasting, deep nitrogen placement not only reduces nitrogen loss but also creates a high-concentration fertilizer zone around the root system, largely achieving root-zone fertilization re-

quirements [14] that stimulate root growth and nutrient uptake, thereby increasing crop yield [15]. Additionally, deep placement of large granular controlled-release nitrogen fertilizer can reduce nitrogen application rates, improve nitrogen use efficiency [16], and decrease ammonia volatilization and surface runoff loss [17–18]. For instance, Inubushi et al. [19] reported that deep placement (15 cm) of controlled-release nitrogen fertilizer in paddy fields improved nitrogen utilization efficiency up to 71.9%, substantially higher than the 26.0% achieved with conventional ammonium chloride application. Ji et al. [9] demonstrated that controlled-release nitrogen fertilizer application increased nitrogen use efficiency by 35.9% and reduced nitrate nitrogen leaching loss by 27.1% compared with urea, while increasing grain yield by over 7.0%. In this study, the high-rate controlled-release fertilizer with side-bar application (T4) achieved nitrogen use efficiency 1.70 times that of conventional urea fertilization (T2) and 1.22 times that of conventional controlled-release fertilizer application (T3). Moreover, using side-bar fertilization technology with $20 \text{ kg} \cdot \text{hm}^{-2}$ and $30 \text{ kg} \cdot \text{hm}^{-2}$ nitrogen reduction for early and late rice, respectively, increased yields by 13.17% and 4.72% compared with T2, and by 7.27% and 1.74% compared with T3. Furthermore, the T6 treatment, with 53% reduced nitrogen application compared with T2 in late rice production, still achieved comparable yield levels, and even with nearly one-third reduced seedling numbers, obtained grain yields equivalent to T2 and T3 treatments with slightly increased 1,000-grain weight. These results indicate that in double-cropping rice regions, side-bar fertilization technology can reduce chemical fertilizer input while ensuring rice yield and improving nitrogen use efficiency, representing an advantageous rice fertilization technique. Additionally, significant correlations ($P < 0.05$) among different nitrogen forms in paddy water (ammonium nitrogen, nitrate nitrogen, soluble organic nitrogen, and total nitrogen) suggest that nitrogen transformation across treatments was primarily influenced by local soil physicochemical properties rather than fertilization methods.

The combination of side-bar fertilization technology with slow-release fertilizer can significantly enhance aboveground nitrogen uptake and fertilizer use efficiency while reducing environmental pollution from fertilizer loss. Zhang et al. [19] reported that side-bar application of high-rate slow-release fertilizer reduced nitrogen input by approximately 40% compared with conventional fertilization while maintaining equivalent rice yield, achieving nitrogen recovery rates of 54.5%–63.5%, higher than the 36.9% from conventional fertilization, with total nitrogen leaching loss of $14.86 \text{ kg} \cdot \text{hm}^{-2}$. Liu et al. [12] found that side-bar fertilization achieved nitrogen partial factor productivity of $39.1\text{--}67.8 \text{ kg} \cdot \text{kg}^{-1}$, significantly higher than the $23.7 \text{ kg} \cdot \text{kg}^{-1}$ from conventional fertilization, with apparent nitrogen loss of $23.2\text{--}61.9 \text{ kg} \cdot \text{hm}^{-2}$, substantially lower than the $174.2 \text{ kg} \cdot \text{hm}^{-2}$ from conventional fertilization. In this study, side-bar fertilization effectively reduced nitrogen loss in runoff water, with consistent trends between early and late rice seasons, achieving annual nitrogen loss of only $0.466\text{--}0.673 \text{ kg} \cdot \text{hm}^{-2}$ and reducing surface runoff nitrogen loss by 3.54%–29.36% compared with conventional fertilization. These results align with Li et al. [21], who reported

annual nitrogen loss of 0.22–0.48 kg · hm⁻² and surface runoff nitrogen reduction of 12.54%–28.68% in Dongting Lake upland maize with reduced fertilization.

Post-fertilization nutrient release rates in paddy soils depend on fertilizer type, application rate, timing, and placement. The first nine days after conventional fertilization represent a critical period for nitrogen loss, whereas side-bar fertilization extends the nitrogen release period to 30 days [20]. Controlled-release nitrogen fertilizer significantly reduces nitrogen concentrations in surface water and runoff during this period, thereby substantially decreasing total nitrogen runoff loss throughout the rice growing season. The maximum release amounts of different nitrogen forms from controlled-release fertilizer follow the same pattern as their cumulative release, with surface water total nitrogen and ammonium nitrogen concentrations peaking 15–30 days after fertilization before rapidly declining [22–23]. High surface water nitrogen concentrations within 15 days after fertilization mean that rainfall-runoff events occurring within 20 days post-application significantly increase nitrogen loss [23]. Therefore, this study confirms that rainfall-runoff effects on nitrogen loss from paddy fields are primarily related to the interval between fertilization and rainfall, with nitrogen release concentrated within 20 days after application. These findings are consistent with comparative studies on urea and controlled-release nitrogen fertilizer in double-cropping rice paddies in the Dongting Lake region [24]. This research demonstrates that side-bar fertilization technology effectively reduces farmland nutrient loss, though further research is needed on microbial transformation of side-bar applied fertilizers in soil and their effects on root systems.

Field soil fertility management should comprehensively consider crop growth patterns and nutrient requirements to achieve nutrient supply-demand balance and reduce fertilizer input. The combination of slow-release fertilizer with side-bar fertilization technology, as an effective measure to improve fertilizer use efficiency and reduce non-point source pollution, has been piloted and promoted in Hunan, Ningxia, and Heilongjiang provinces, with Hunan establishing technical regulations for side-bar fertilization application. This study fully demonstrates the advantages of side-bar fertilization technology in improving nitrogen use efficiency, reducing non-point source pollution, and increasing rice yield, indicating broad application prospects for future rice cultivation.

Conclusions

1. Compared with conventional urea fertilization, all reduced-nitrogen controlled-release fertilizer treatments (including side-bar and conventional application) showed no significant difference in rice yield, except for the low-nitrogen side-bar application treatment. Controlled-release fertilizer combined with side-bar application technology can appropriately reduce nitrogen input while maintaining yield. Additionally, data on various nitrogen forms in surface water during the growing season

demonstrated that side-bar fertilization technology effectively reduces surface runoff nitrogen loss and improves nitrogen use efficiency.

2. Soil nitrogen data indicated that side-bar fertilization technology plays a positive role in maintaining or increasing soil fertility levels while ensuring rice yield and reducing fertilizer input.
3. As farmland represents an important source of non-point source pollution, side-bar fertilization technology can reduce nitrogen input and loss from paddy fields, thereby decreasing non-point source pollution risk.

Nitrogen transformation in paddy fields involves not only physicochemical processes but also microbially mediated biogeochemical processes that have long been a research focus. Side-bar fertilization technology alters the distribution and diffusion patterns of fertilizers in conventional application methods, and whether a “micro-fertilizer domain” effect [14] exists and its influence on microbial nitrogen transformation processes warrant further investigation.

References

- [1] Tim U S, Jolly R. Evaluating agricultural nonpoint-source pollution using integrated geographic information-systems and hydrologic/water quality model[J]. *Journal of Environmental Quality*, 1994, 23(1): 25-35
- [2] Quan W M, Yan L J. Effects of agricultural non-point source pollution on eutrophication of water body and its control measure[J]. *Acta Ecologica Sinica*, 2002, 22(3): 291-299
- [3] Zhang Z F, Zhang W F. The situation and trend of fertilizer application in China[J]. *Phosphate & Compound Fertilizer*, 2008, 23(6): 9-12
- [4] Zhu Z L. Loss of fertilizer N from plants-soil system and the strategies and techniques for its reduction[J]. *Soil and Environmental Sciences*, 2000, 9(1): 1-6
- [5] Xiang X Y, Liu Q, Rong X M, et al. Effects of combined application of organic manures and inorganic fertilizers on early-rice and late-rice in Northern Hunan[J]. *Hunan Agricultural Sciences*, 2012, (7): 59-61
- [6] Qiao J, Yang L Z, Yan T M, et al. Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area[J]. *Agriculture, Ecosystems & Environment*, 2012, 146(1): 103-112
- [7] Yang Y C, Zhang M, Li Y C, et al. Controlled release urea improved nitrogen use efficiency, activities of leaf enzymes, and rice yield[J]. *Soil Science Society of America Journal*, 2012, 76(6): 2307-2317
- [8] Zheng L, Zhang M, Yang Y C, et al. Effects of controlled release fertilizer and sulfur-coating left from SCU on rice growth and soil property[J]. *Journal of Soil and Water Conservation*, 2009, 23(2): 193-197
- [9] Ji X H, Zheng S X, Nie J, et al. Nitrogen recovery and nitrate leaching from a controlled release nitrogen fertilizer in an irrigated paddy soil[J]. *Chinese Journal of Soil Science*, 2007, 38(3): 467-471

- [10] Xu J Z, Peng S Z, Yang S H, et al. Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements[J]. *Agricultural Water Management*, 2012, 104: 184-192
- [11] Duan R, Bai L Y, Zeng X B. One season rice transplanting and side bar fertilization technical regulations (HNZ027-2013) [S], Agricultural Department of Hunan Province, 2013.
- [12] Liu R L, Li Y H, Wang F, et al. Effect of slow-release fertilizer side bar fertilization technology on rice yield and nitrogen use efficiency[J]. *Journal of Agricultural Resources and Environment*, 2014, (1): 45-49
- [13] Bao S D. *Soil and Agricultural Chemistry Analysis*[M]. Beijing: Agricultural Publishing House of China, 2000
- [14] Wang H Y, Zhou J M. Root-zone fertilization –A key and necessary approach to improve fertilizer use efficiency and reduce non-point source pollution from the cropland[J]. *Soils*, 2013, 45(5): 785-790
- [15] Wu J M, Yao Y M, Chen Y F, et al. Effect of deep fertilization on rice field and fertilizer management[J]. *Chinese Journal of Soil Science*, 1999, 30(3): 110-112
- [16] Gaudin R, Dupuy J. Ammoniacal nutrition of transplanted rice fertilized with large urea granules[J]. *Agronomy Journal*, 1999, 91(1): 33-36
- [17] Zhu Z L. Research on soil nitrogen in China[J]. *Acta Pedologica Sinica*, 2008, 45(5): 778-783
- [18] Duan L, Duan Z Q, Chang J. Effect of surface management and fertilization mode on nitrogen runoff from upland in Taihu Lake region[J]. *Journal of Agro-Environment Science*, 2007, 26(3): 813-818
- [19] Inubushi K, Acquaye S, Tsukagoshi S, et al. Effects of controlled-release coated urea (CRCU) on soil microbial biomass N in paddy fields examined by the ^{15}N tracer technique[J]. *Nutrient Cycling in Agroecosystems*, 2002, 63(2/3): 291-300
- [20] Zhang A P, Liu R L, Yang S Q, et al. Effect of side bar fertilization technology based on slow-release fertilizer on rice yield and nitrogen losses[J]. *Journal of Agro-Environment Science*, 2012, 31(3): 555-562
- [21] Li E Y, Qiu Y Q, Peng P Q, et al. The ecological interception technology and effects on maize yield and surface runoff in red soil slopes of Dongting Lake[J]. *Chinese Agricultural Science Bulletin*, 2011, 27(9): 137-142
- [22] Zheng S X, Xiao J, Yi G Y. Kinetics and mathematic simulation of nutrient release from coated controlled release fertilizer under the condition of flooded paddy soil[J]. *Phosphate & Compound Fertilizer*, 2005, 20(4): 8-11
- [23] Dong Y, Wang Z Y. Study on release characteristics of different forms of nitrogen nutrients of slow/controlled release compound fertilizer[J]. *Scientia Agricultura Sinica*, 2006, 39(5): 960-967
- [24] Ji X H, Zheng S X, Lu Y H, et al. Dynamics of floodwater nitrogen and its runoff loss, urea and controlled release nitrogen fertilizer application regulation in rice[J]. *Scientia Agricultura Sinica*, 2006, 39(12): 2521-2530

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.