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Mechanical side-deep fertilization mitigates ammonia volatilization and nitrogen runoff and increases profitability in rice production independent of fertilizer type and split ratio

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ABSTRACT

A combination of nitrogen (N) fertilizer side-deep placement and mechanical transplanting of rice seedling (MSDF) has been recommended as an effective alternative technique to conventional broadcasting of fertilizer. However, its comprehensive interactions with N-fertilizer type, split ratio, environmental impact, and profitability are unclear. A three-year field experiment was conducted using MSDF and three fertilizer types (NPK briquette, F1; NPK briquette with nitrification inhibitor, F2; and controlled-released N fertilizer, F3) with 200 kg N hm^{-2} at two split ratios (a one-time basal application (N200) and basal plus supplementary application at the rice tillering stage (N140 + 60)). Conventional fertilization (conventional fertilizer using NPK briquettes by broadcasting with 270 kg N hm^{-2} at three split ratios (CF1N270)) and a no-N-added treatment were established as two controls. Directly reducing the N-application rate by 26% (CF1N200) decreased grain production by 13.1%. However, MSDF management (MF1N200, MF2N200, MF3N200, MF1N160 + 40, MF2N160 + 40, MF3N160 + 40) maintained high yield, increased NUE by 24.8–40.9%, and decreased NH_3 volatilization and total N concentration in runoff by 39.0–65.6% and 29.1–59.3%, respectively. Moreover, there was no difference with fertilizer type and split ratio design among these MSDF treatments. When using a lower N-application rate (200 kg N hm^{-2}), compared with CF1N200, MSDF treatments increased NUE by 43.6% and net economic benefit by 74.9%, and decreased NH_3 volatilization and total runoff N concentration by 35.2% and 78.4%, respectively. MSDF at a reduced N-application rate minimizes NH_3 volatilization and N runoff and increases profitability, independent of fertilizer type and split ratio.

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for more than 50% of the world's total population (FAO, 2020). In China, paddy fields occupy over 30% of the total arable land area and provide rice for nearly 70% of Chinese residents (Li et al., 2020). Due to the high demand for food as result of its continuously increasing population, China is experiencing greater challenges than many other countries in agricultural production and environmental degradation (Zhu et al., 2019). Nitrogen (N) fertilizer is indispensable to achieve high crop grain yields to match the population growth (Kronzucker et al., 2000; Glass et al., 2001; Sun et al., 2020). In some particular cases, more than 300 kg N hm^{-2} was applied into paddy soils during the rice growth season (Hofmeier et al., 2015). Nevertheless, excessive chemical fertilizer-N input brings with it both lower agronomic N-use efficiency (NUE) (Liu et al., 2018) and threats to the human habitat and the environment (Sun et al., 2015; Miah et al., 2016; Coskun et al., 2017a/b).

Ammonia (NH_3) volatilization, a major N-loss pathway from rice systems, on average accounts for 17% of applied N during the rice season (Cui et al., 2014; Paulot et al., 2014; Sun et al., 2015), and is greater than from other crop systems (Huang et al., 2016). NH_3 emission can lead to surface non-point source pollution and PM 2.5 breakout in cities via NH_3

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deposition (Gu et al., 2012; Behera et al., 2013). Moreover, considering the total N directly exported to aquatic environments, >80% derive from runoff N losses (accounting for ~4.1% of total N applied) (Zhao et al., 2012b). Therefore, to simultaneously reduce N pollution of the environment and improve rice production, landholders can increase the number of split N applications, adjust optimal N rate and application time, add inhibitors, biochar, and other amendments (Xu et al., 2012; Li et al., 2018; Sun et al., 2019; Feng et al., 2020). However, the increased labor or training requirements associated with advanced N-management techniques and the higher economic cost of improved N fertilizers and biochar have limited more wide-spread application of these techniques, particularly on a larger scale (Zhang et al., 2015; Yao et al., 2018).

China's urbanization has accelerated in recent years, which has led to a rapid decline in the agricultural labor force. To solve this issue in rice production systems, changing manual to machine transplanting has become a popular alternative in China (Huang et al., 2018; Chen et al., 2019). Conventional surface broadcasting of fertilizer N is often ineffective for intensive rice production (Nkebiwe et al., 2016). Studies have also shown that urea deep placement can improve NUE by 50–70% and thereby increase rice grain production by 15–20%, compared with urea surface broadcasting (Alam et al., 2013; Miah et al., 2016). However, manual application requires 3–4 times more time compared to the classic two split broadcast applications of urea, which limits the adoption of urea deep placement (Liu et al., 2020). Recently, placement machinery that overcomes these difficulties has been developed (Ke et al., 2018; Zhu et al., 2019). Synchronously, when transplanting rice seedling, fertilizers can be incorporated side-deep, at 5–6 cm of soil depth near rice roots (Ke et al., 2018; Zhu et al., 2019). Therefore, mechanical side-deep fertilization (MSDF) technique has potential to realize a synchronous effect of reducing reactive N (Nr) losses while ensuring high rice production. Zhu et al. (2019) demonstrated that MSDF increased rice NUE and yield by 24.4–91.6% and 6.2–13.1%, respectively. However, few studies have paid attention to the responses of the Nr losses via NH_3 volatilization and runoff following the adoption of MSDF in paddy fields.

Both the type and application method of N fertilizer strongly affects Nr cycling (Yan et al., 2001; Zhang and Yu. 2020). Recently, many novel N fertilizers have been emerging, including controlled-released N fertilizers and stabilized fertilizer containing urease and nitrification inhibitors, and these novel fertilizers with traditional manual surface broadcasting can increase rice N uptake and yield as well as decrease Nr losses (Ke et al., 2017; Min et al., 2021; Tian et al., 2021). Therefore, the deep placement of innovative fertilizers potentially exerts better effects in enhancing NUE and reducing Nr losses than deep placement of traditional urea fertilizer (Kapoor et al., 2008). However, deep placement studies have been mostly focused on urea (Gaihre et al., 2015; Yao et al., 2018), and it is unknown whether novel fertilizers can increase the effectiveness of MSDF. In common practice in rice production systems, to achieve high grain yield, N fertilizer has been split-applied by manual broadcasting as basal and one or two times of supplementary fertilizer (Sun et al., 2015; Li et al., 2018). This is because a single basal application of N by broadcasting is typically not sufficient to meet the nutrient requirements over the whole growth cycle of rice (Huda et al., 2016; Ke et al., 2018). Thus, from the view of reducing labor cost, it is necessary to study whether reducing the frequency of supplementary fertilization can achieve stable yield and reduce environmental impacts when deploying MSDF. While reducing labor cost, MSDF increased the consumption of energy. Combined with MSDF's effects on rice production, we therefore compared the net profitability of rice production under different treatments pertaining to MSDF.

Therefore, a three-year plot-scale field trial was established in 2017, 2019, and 2020, in Taihu Lake region, China, a typical rice growing region. The specific objectives of the current study were: 1) to clarify how MSDF comprehensively affects rice NUE and yield, NH_3 volatilization as well as runoff N losses from paddy soil, and 2) to evaluate whether these effects are consistent across varied novel fertilizer types and frequencies of split N application.

2. Materials and methods

2.1. Field experiment site and materials

The field experiment was conducted in Gaocheng Town, Yixing City, Jiangsu Province (31.4° N, 119.8° E), China, a typical rice production system in the subtropical climatic zone with (annual mean temperature 16.6 °C and precipitation 1387 mm. According to FAO classification, the tested soil is a typical Gleyi-stagnic Anthrosol. The surface layer (0–20 cm) of the soil is a silt loam texture with 9.2% of sand, 75.7% of silt, and 15.1% of clay, and with a bulk density of 1.40 g cm^{-3}. The daily precipitation and air temperature during three rice growth cycles are presented in Fig. 1. The pH (H_2O: soil = 5: 1) of the topsoil sampled at the initiation of experiment was 6.25, and the soil contained 1.2 g kg^{-1} total N, 21.4 mg kg^{-1} NH_4^+-N, 56.3 mg kg^{-1} NO_3^--N, 27.4 mg kg^{-1} Olsen-P, 39.3 mg kg^{-1} available K, and 22.7 g kg^{-1} organic matter.

Jiangsu Academy of Agricultural Sciences provide 'Nanjing 46' rice seedlings for the current work. An imported rice transplanter (PZ640, Iseki Agricultural Machinery Co., Ltd., Japan) performed the MSDF management. The three types of N fertilizer used were NPK briquettes with an N:P:K ratio of 16:8:16 (conventional fertilizer for rice production), NPK briquettes with the nitrification inhibitor 2-chloro-6-(trichloromethyl)-pyridine 0.1% (*w/w*), and control-released fertilizer with 20% N from common urea and 80% N from two polymer-coated urea (2% and 4% (*w/w*) coating, at a ratio of 1:1). The rice transplanter was equipped with a side-deep fertilization apparatus.

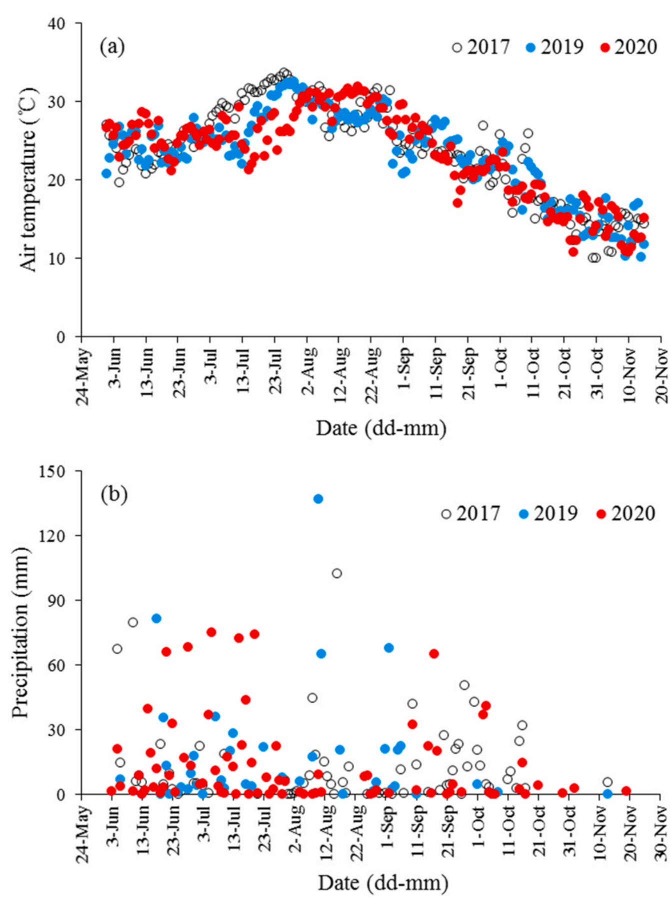

Fig. 1. The daily air temperature (a) and the precipitation (b) observed under there rice growth cycles in 2017, 2019, and 2020.

2.2. Field experiment design and management

Field trials were conducted over three rice growth cycles in 2017, 2019, and 2020. In total, 9 treatments (each with 3 replicates) were established as follows: N0 (a control with no N fertilizer), CF1N270 (NPK briquette broadcasting, 270 kg N hm^{-2}, split into three applications), CF1N200 (NPK briquette broadcasting, 200 kg N hm^{-2}, split into three applications), MF1N200 (NPK briquette MSDF, 200 kg N hm^{-2}, one-time), MF2N200 (NPK briquette with nitrification inhibitor MSDF, 200 kg N hm^{-2}, one-time), MF3N200 (controlled-released N fertilizer MSDF, 200 kg N hm^{-2}, one-time), MF1N160 + 40 (NPK briquette MSDF, 200 kg N hm^{-2}, split into two applications), MF2N160 + 40 (NPK briquette with nitrification inhibitor MSDF, 200 kg N hm^{-2}, split into two applications), MF3N160 + 40 (controlled-released N fertilizer MSDF, 200 kg N hm^{-2}, split into two applications). The rates and timing of N fertilizations for each treatment in each year are summarized in Table 1. Rice seedling transplantation and basal fertilization occurred on 11 June 2017, 13 June 2019, and 14 June 2020, respectively. All treatments equally received 50 kg P_2O_5 hm^{-2} and 150 kg K_2O hm^{-2}, both as basal fertilizers with N incorporated into the topsoil before transplanting in three rice growth cycles. The first supplementary fertilizer at the tillering stage was applied on July 19, 2017, 1 July 2019, and 30 June 2020. The second supplementary fertilizer at the panicle stage was applied on 6 August 2017, 13 August 2019, and 30 July 2020. Ridges, covered with a plastic film, were constructed between each plot (50 m × 10 m), to separate the plots and prevent water and nutrient exchange (Supplementary Figure 1). During the most intense rice growth period, surface floodwater was maintained by river water irrigation at a 3–7 cm depth, except for midseason aerations and 20 days before rice physiological maturity for harvesting work.

2.3. Plant, soil sampling and analysis

2.3.1. Plant measurement

The mature rice plants from each whole plot were harvested to determine rice NUE and grain yields on 3 November 2017, 1 November 2019, and 11 November 2020. Rice straw and panicles were separated and oven-dried at 105 °C for 30 min firstly and then at 80 °C to a constant weight for biomass determination. We thereafter weighed, ground, and sieved the rice plant samples through a 0.5-mm sieve for N-content measurement. Nitrogen contents of rice straw and grain were determined by the Kjeldahl method (Bremner and Jenkinson, 1960). The percentage of applied fertilizer N recovered in shoot biomass minus that of N0 treatment was calculated as the rice NUE.

2.3.2. Ammonia volatilization and runoff N measurements

Ammonia volatilization was measured by a modified continuous-airflow-enclosure method using a chamber (20 cm inner diameter, 15 cm height) (Sun et al., 2015). The air exchange rate was 15–20 chamber volumes per minute to flow through the NH_3 absorbent. The NH_3 absorbent was constituted with 2% (*v:v*) H_3BO_3 (AR) and mixed indicators of ethanol, bromocresol green, and methyl red. We investigated the NH_3 volatilization rate from 7:00 a.m. to 9:00 a.m. and from 13:00 p.m. to 15:00 p.m. until there was no color change in the NH_3 absorbent. The NH_3 absorbent solutions from the 2-h intervals were titrated with H_2SO_4 (0.01 mol L^{-1}). Cumulative volatilized NH_3–N losses were the sum of daily emissions over the investigation periods for each rice growth cycle. The cumulative NH_3–N losses from the N-amended treatments were calculated as the subtraction of the cumulative NH_3–N volatilizations from the N amended treatments and that from the N0 treatment.

Runoff water samples of the three rice growth seasons were taken at the drainage outlet when the drainage or runoff events occurred (Tian et al., 2007). We stored the runoff water samples with 250 mL plastic bottles in a freezer at −20 °C. Runoff water total N (TN) concentration was determined by a continuous-flow N analyzer (Skalar Scan^{++}, Netherlands, with a detection limit of 0.2 mg N L^{-1} and analytic error ± 3.9%).

2.3.3. Net economic benefit (NEB)

Net economic benefit (NEB) can provide a scientific basis to authorities and farmers for formulating policies to adopt environmental friendly approaches related to MSDF. We calculated NEB using the following equations:

$$NEB\ (RMB\ hm^{-2}\ season^{-1}) = EB_{yield}\ (RMB\ hm^{-2}\ season^{-1}) - EB_{production\ cost}(RMB\ hm^{-2} season^{-1}) \quad (1)$$

where

$$EB_{yield} = \text{rice grain yield}\ (kg\ hm^{-2}) \times v\ (RMB\ kg^{-1}) \quad (2)$$

v refers to the rice price, and mean prices of 3.0, 2.4, and 3.0 RMB kg^{-1} for 2017, 2019, and 2020, respectively, were used (National Bureau of Statistics of China, 2017, 2019, and 2020; same below).

$$EB_{production\ cost} = \Sigma\ [\text{Production cost}\ (h\ hm^{-2}/\ L\ hm^{-2}/\ kg\ hm^{-2}) \times p\ (RMB\ h^{-1}\ /\ RMB\ L^{-1}\ /\ RMB\ kg^{-1})] \quad (3)$$

Table 1
Experimental design and N-fertilization management.

Treatment	2017					2019					2020				
	Basal fertilization			Topdressing (kg N hm^{-2})		Basal fertilization			Topdressing (kg N hm^{-2})		Basal fertilization			Topdressing (kg N hm^{-2})	
	Methods	Types	N rate (kg N hm^{-2})	I	II	Methods	Types	N rate (kg N hm^{-2})	I	II	Methods	Types	N rate (kg N hm^{-2})	I	II
N0	–	–	0	0	0	–	–	0	0	0	–	–	0	0	0
CF1N270	SB	F1	94.5	103.5	72	SB	F1	94.5	103.5	72	SB	F1	94.5	103.5	72
CF1N200	SB	F1	70	80	50	–	–	–	–	–	–	–	–	–	–
MF1N200	MSDF	F1	200	–	–	MSDF	F1	200	–	–	–	–	–	–	–
MF2N200	MSDF	F2	200	–	–	MSDF	F2	200	–	–	–	–	–	–	–
MF3N200	–	–	–	–	–	MSDF	F3	200	–	–	–	–	–	–	–
MF1N140 + 60	MSDF	F1	140	–	60	MSDF	F1	140	–	60	MSDF	F1	140	–	60
MF2N140 + 60	MSDF	F2	140	–	60	MSDF	F2	140	–	60	MSDF	F2	140	–	60
MF3N140 + 60	–	–	–	–	–	MSDF	F3	140	–	60	MSDF	F2	140	–	60

Note: SB, surface broadcasting; MSDF, mechanical side-deep fertilization; F1, NPK briquette with a ratio of 16:8:16; F2, NPK briquette with nitrification inhibitor; F3, controlled-release N fertilizer. All treatments received 150 kg K_2O hm^{-2} and 50 kg P_2O_5 hm^{-2} as basal fertilizer. The fertilizer used for topdressing was urea and applied by broadcasting. Basal fertilization occurred at the same time as used in rice transplanting, I refers to tillering topdressing on July 19, 2017, 1 July 2019, and 30 June 2020; II refers to panicle topdressing on 6 August 2017, 13 August 2019, and 30 July 2020.

where *p* refers to the current price of each production costed, and prices of 280 RMB h^{-1}, 7.0 RMB L^{-1}, 15 RMB kg^{-1}, 2.3 RMB kg^{-1}, 3.55 RMB kg^{-1}, and 2.8 RMB kg^{-1} for labor (h hm^{-2}), fuel (L hm^{-2}), pesticide (kg hm^{-2}), NPK briquettes (kg hm^{-2}), controlled-release N fertilizer (kg hm^{-2}), and NPK briquettes with nitrification inhibitor (kg hm^{-2}), respectively, were used.

2.4. Statistical analysis of data

We used SPSS 16.0 (SPSS Inc., Chicago, IL, USA) to perform the analysis of variance (one-way or two-way ANOVA), and determined the differences between individual treatments by Tukey multiple comparison tests at $P < 0.05$.

3. Results

3.1. Rice grain yield and NUE

The impact of MSDF on grain yields over the three rice growing seasons is presented in Fig. 2. When fertilizer N-input rate was reduced from 270 kg N hm^{-2} to 200 kg N hm^{-2} under conventional broadcasting management, rice grain yield significantly decreased ($P < 0.05$) by 13.1% (Fig. 2 a). Interestingly, by changing conventional fertilizer management to MSDF, the treatments with 200 kg N hm^{-2} yielded 7.7–8.4 t hm^{-2}, with the same grain yield to that recorded under CF1N270 in 2017 (Fig. 2 a). For the fertilization strategies with MSDF management, the averaged grain yields on different N types under the treatments of all N applied by basal fertilization (100% basal, MF1N200, MF2N200) and 70% basal plus 30% topdressing (MF1N140 + 60, MF2N140 + 60) were 8.07 and 8.13 t hm^{-2}, respectively, and there was no significant difference between these two fertilization strategies in 2017 (Fig. 2 a). However, the grain yield of MF1N200 treatment was significantly decreased ($P < 0.05$) by 7.5%, compared with CF1N270 in 2019 (Fig. 2 b), and the average yield with the 100% basal fertilization strategy was 10.14 t hm^{-2}, which was 5.5% lower than that with the 70% basal plus 30% topdressing treatment (Fig. 2 b). For the three fertilizer types with MSDF management, there was no significant difference ($P > 0.05$) in rice grain production among synthetic compound fertilizer alone (MF1N140 + 60) and its two counterparts, i.e. synthetic compound fertilizer plus nitrification inhibitor (MF2N140 + 60) and controlled release fertilizer (MF3N140 + 60) in 2019 and 2020 (Fig. 2 b, c), with equal grain yield to that recorded under CF1N270.

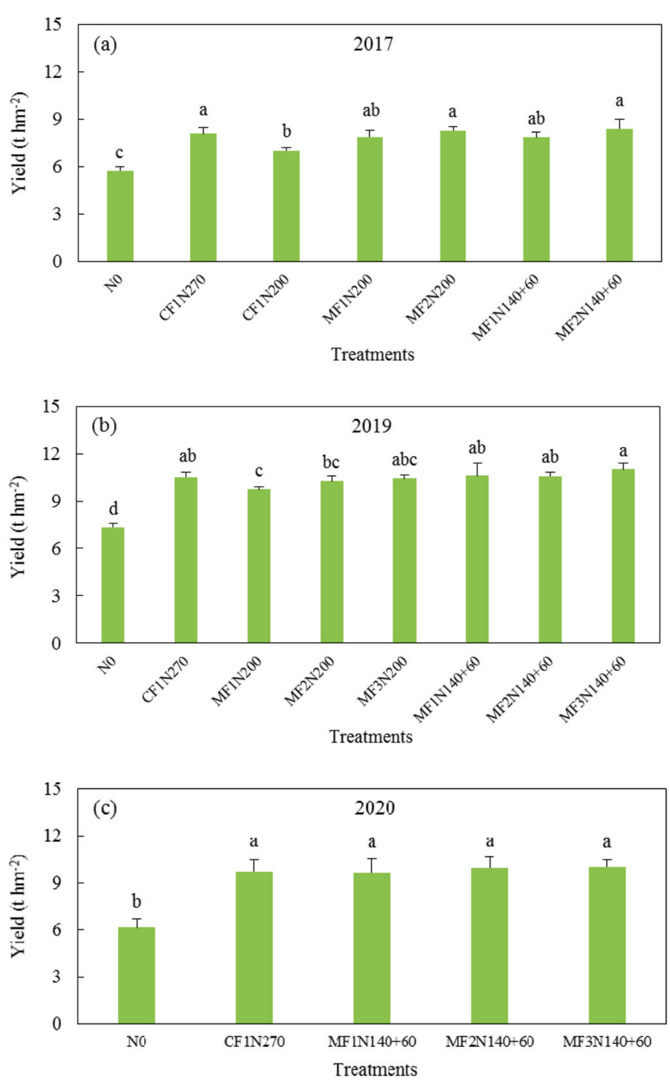

Fig. 2. The impact of mechanical side-deep fertilization (MSDF) on rice yields in 2017 (a), 2019 (b), and 2020 (c). *Error bars* represent the standard deviations (SD) of the mean ($n = 3$) and *different letters* above columns indicate significant differences among treatments, according to Tukey's multiple-comparison test ($P < 0.05$).

Nitrogen-use efficiencies of rice crops receiving 200 and 270 kg N hm^{-2} via conventional broadcasting management were almost identical, with 35.3% and 33.4%, respectively (Fig. 3 a). NUE was similar under the same fertilization strategies with MSDF management based on three-year field trials, and average NUE with the 100% basal fertilization strategy (MF1N200, MF2N200, MF3N200) was 44.5% and 43.9% in 2017 and 2019, respectively, and no significant improvement relative to the conventional broadcasting management was observed, while average NUE with 70% basal plus 30% topdressing treatment (MF1N140 + 60, MF2N140 + 60, MF3N140 + 60) over three years was 47.7%, which was significantly ($P < 0.05$) higher (by 36.1%) than that with CF1N270 (Fig. 3 a, b, c).

3.2. Ammonia volatilization loss

The peak value of NH_3 volatilization appeared after each fertilization under the conventional broadcasting management (CF1N270) in all three years (Fig. 4 a, c, e). With CF1N200, a 31.2% lower ($P < 0.05$) NH_3 volatilization was recorded compared to CF1N270, mainly as result of reduction of 70 kg N hm^{-2} in fertilizer input (Fig. 4 b). For the N200 addition treatments, cumulative NH_3 volatilization loads were from 17.7 to 30.4 kg N hm^{-2} in 2017, from 19.2 to 24.0 kg N hm^{-2} in 2019, and from 5.3 to 8.4 kg N hm^{-2} in 2020, which accounted for approximately 8.9–15.2%, 9.6–12.0% and 2.6–4.2% of current seasonal urea N input in 2017, 2019, and 2020, respectively (Fig. 4 b, d, f). In all cases (both N fertilizer type and split ratio), MSDF decreased total NH_3 volatilization loads over the rice growing season. Ammonia volatilization was significantly reduced ($P < 0.05$) with MSDF by 51.0–54.1% and 58.2–62.8% when 200 kg N hm^{-2} was applied one-off (MF1N200, MF2N200, MF3N200) or as basal and supplementary fertilizer in the form of urea (MF1N140 + 60, MF2N140 + 60, MF3N140 + 60).

3.3. Nitrogen runoff loss

There were 6 runoff events observed during the 2017 rice growth season and 11 events during both the 2019 and 2020 rice growth seasons. The peak values in runoff TN concentration appeared after ear fertilization both in 2017 and 2019, but after basal fertilizer application in 2020 (Fig. 5 a, b, c). In comparison with CF1N270, CF1N200 significantly ($P < 0.05$) decreased runoff TN concentration by 34% (Fig. 5 a). In particular for N200 addition treatments, MSDF decreased ($P < 0.05$) runoff TN concentration by 78.4% associated with the fourth runoff event (on 16th Aug. 2017) compared with broadcasting (CF1N200). There was no significant difference ($P > 0.05$) in TN concentrations among treatments during other runoff events, although MSDF

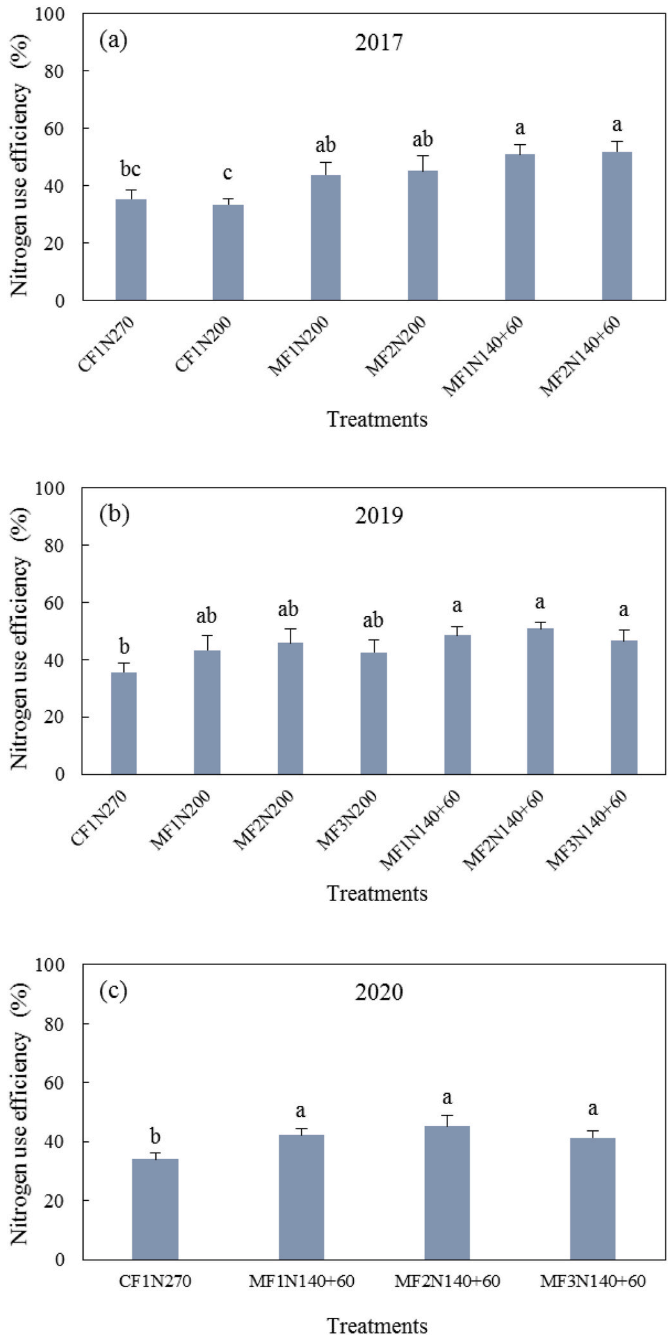

Fig. 3. The impacts of mechanical side-deep fertilization (MSDF) on rice N-use efficiency (NUE) in 2017(a), 2019 (b), and 2020 (c). *Error bars* represent the standard deviation (SD) of the mean (n = 3); *different letters* above columns indicate significant differences among treatment according to Tukey's multiple-comparison test ($P < 0.05$).

treatments led to relatively lower TN concentration (Fig. 5 a). The average TN concentration in runoff samples collected over the three rice seasons was 7.43 mg L^{-1} under CF1N270 treatment, which was reduced to 3.12–4.77 mg L^{-1} when receiving 200 kg N hm^{-2} with MSDF. On average, rice plots received 200 kg N hm^{-2} with MSDF decreased TN concentration by 35.5% (a range of 7.7–50.9% was recorded) (Fig. 5 a, b, c). However, N fertilizer type and split ratio had no significant impact ($P > 0.05$) on TN concentration reduction under MSDF management.

4. Discussion

4.1. MSDF can mitigate N losses via NH_3 volatilization and runoff in rice paddy fields

In the context of agriculture's potentially negative impacts on aquatic and atmospheric environments, N management in rice paddy soils must aim at reducing volatilized NH_3 and runoff N losses in order to achieve low-emission agricultural production (Coskun et al., 2017a/b). In the present work, cumulative NH_3 losses from N270-treated rice plots ranged from 16.9 to 47.5 kg N hm^{-2} in a three-year observation. These losses accounted for 6.3–17.6% of seasonally applied fertilizer N, which is lower than the results in Liu et al. (2015) (18–33% in 2012 and 22–36% in 2013), but is confirmed by Zhao et al. (2012b) (17%) and Zhang et al. (2011) (13–18%) and other workers who measured NH_3 volatilization in typical Chinese rice paddy fields (Xu et al., 2012). Fertilization practices affect fertilizer N fate by influencing Nr transformations including NH_3 volatilization, N_2O emission, and N leaching (Zhang et al., 2011; Min and Shi, 2018). Of these management techniques for rice production, conventional broadcasting is probably the most inefficient one, due to extensive Nr losses and low NUE. The MSDF method reduces total NH_3 volatilizations by 26.2–41.9% relative to conventional N broadcasting at the equal N applied rate (Fig. 4 b). To mitigate NH_3 volatilization, previous works focused on controlled-release N fertilizer application (–20–32%) (Tian et al., 2021), and biofertilizer and biochar co-application (−12.3%) (Sun et al., 2020). Moreover, according to Liu et al. (2015), deep placement of fertilizer N suppressed cumulative NH_3 volatilization because of both decreases in floodwater pH (–2–4%) and NH_4^+-N concentration (–29–98%), compared with traditional N broadcasting. Deep-placed urea is always hydrolyzed in the first eight days after fertilization, but the NH_4^+-N produced during this hydrolysis process is absorbed by the soil particles, and, thus, NH_4^+ flow from the urea placement site was slow and restricted by a limited soil volume with only 4–13 cm depth (Yao et al., 2018). In addition, daily floodwater NH_4^+-N amounts with side-deep fertilization treatments were not dissimilar to those without N fertilizer treatment over the full rice season, indicating that NH_4^+ diffusion upward into surface water was only a small quantity Kapoor et al. (2008); Huda et al. (2016); this, in turn, reduces NH_3 volatilization.

Runoff from rice paddy fields gives rise to large risks to adjacent waterbodies (Zhao et al., 2012a), due to frequent draining associated with midseason aeration and heavy rainfall during the summer rice growth season (Tian et al., 2007), and this loss can be both in the forms of oxidised and reduced N (Kronzucker et al., 2000; Kirk and Kronzucker, 2005). Our study found that high TN concentrations were detected in runoff, particularly shortly after N fertilization. Meanwhile, there was great inter-seasonal variation in TN concentrations in runoff water samples during each rice season (Fig. 5), which was mainly governed by fertilization regime and rainfall events, as seen in previous reports (Kim et al., 2006; Yoshinaga et al., 2007). The TN concentration of runoff water varied from 2.8 to 11.7 mg L^{-1} (Fig. 5). The peak value in TN concentration from runoff in the 2017 and 2019 seasons was during the heading stage, which could be attributed to heavy precipitation events recorded during these time intervals (102.5 mm on 16^{th} Aug. 2017, 137.1 mm on 10^{th} Aug. 2019, Figs. 1 and 5 a, b) followed by the ear-fertilization stage, while the peak in TN concentration was reached in the tillering stage in 2020, due to the frequency of rainfall events in that season coinciding with basal fertilization (Figs. 1 and 5 c). In the current field experiment, MSDF management significantly decreased ($P < 0.05$) TN concentration from 14.8 mg L^{-1} to 3.2 mg L^{-1} for individual runoff events under equal N application levels compared with broadcasting, and the reduction (78.4%) was very substantial (Fig. 5a). Similar with broadcasting management, deep N placement reduced floodwater NH_4^+ concentration from 34.3% to 51.4% (Ke et al., 2018), likely representing the main reason for the N-runoff reduction by MSDF.

Interestingly, NH_3 volatilization losses varied greatly among the

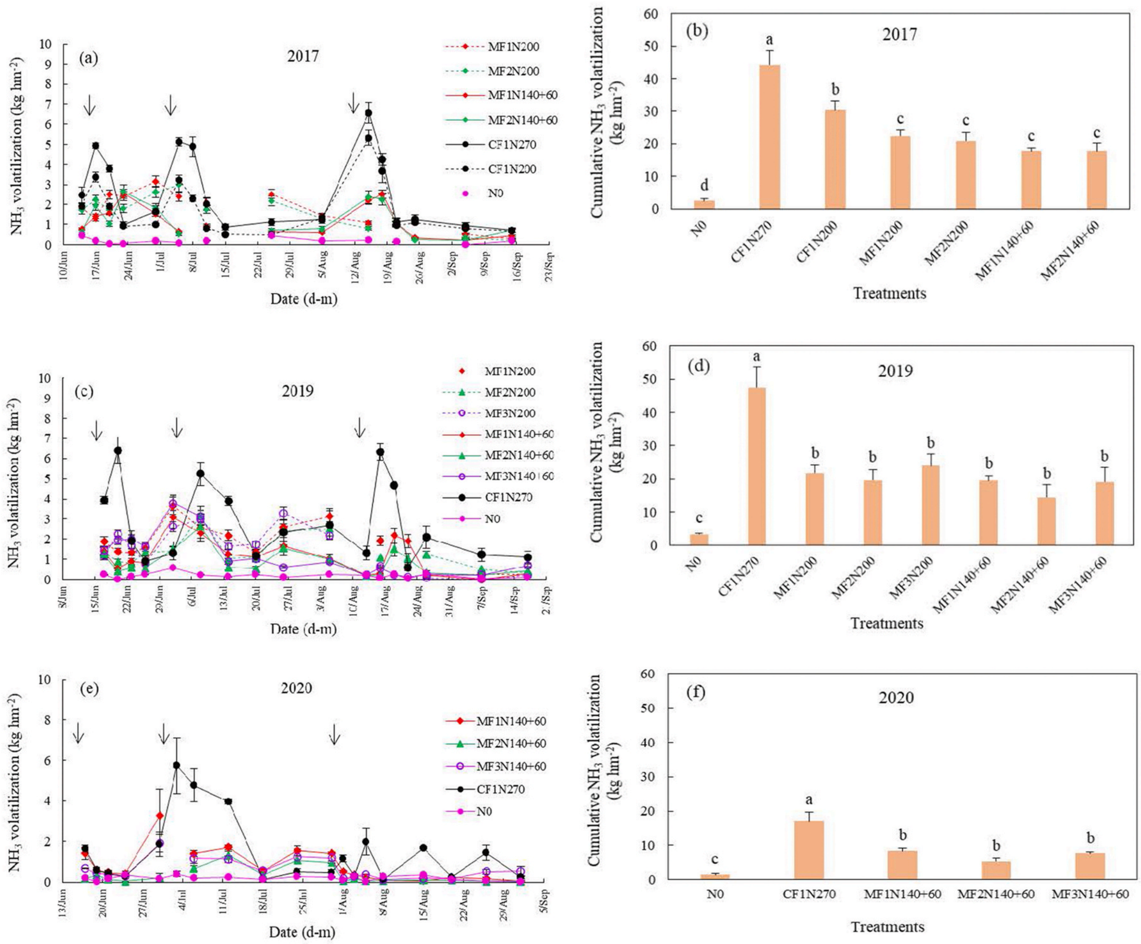

Fig. 4. The impact of mechanical side-deep fertilization (MSDF) on NH_3 volatilization fluxes for each sampling in a) 2017, c) 2019, and e) 2020, and cumulative NH_3 volatilization losses in b) 2017, d) 2019, and f) 2020. Arrows denote the fertilization time, June 8, July 19, and August 6 in 2017, and June 13, July 1, and August 13 in 2019, and June 14, 30 and July 30 in 2020 for basal, first and second supplementary fertilization, respectively.

years studied. For instance, volatilization losses in 2020 were on average 63% lower than those in 2017 and 2019. Nevertheless, the average TN concentration from runoff in 2020 was 52% and 57% higher than that in 2017 and 2019, respectively, particularly during the basal fertilizer period, which was also the period of highest proportional application. Therefore, more N lost via runoff might have led to the lower NH_3 volatilization in 2020. According to previous reports, deep placement of N fertilizers can increase N leaching (Ke et al., 2018) and can reduce N_2O emission, relative to broadcasting (Liu et al., 2020). Therefore, MSDF in the current study may contribute to greenhouse gas reduction, and future studies should pay attention to the carbon footprint by MSDF.

4.2. Overall evaluation of environmental impact, energy consumption, and economic benefit of MSDF

Enhancing NUE, and thereby crop yield, is important to achieving environmental sustainability and the food security (Coskun et al., 2017a/b; Chen et al., 2019). Over the three rice-growing seasons studied here, MSDF treatments significantly increased ($P < 0.05$) rice NUE by 24.2–47.1% in 2017, 19.3–42.3% in 2019, and 36.1–47.7% in 2020, compared with conventional fertilizer management, i.e. CF1N270 (Fig. 3). High NUE obtained under MSDF management in the current study is confirmed by findings from several previous studies focusing on side-deep placement of N (Kapoor et al., 2008; Liu et al., 2015). Side-deep placement of fertilizer into the anaerobic soil layer increases soil-fertilizer contact and stability and decreases Nr losses via NH_3 volatilization and runoff, which was confirmed by our result that NH_3 volatilization and runoff TN concentrations both decreased by 35.2% and 78.4%, respectively (Figs. 4 and 5). At the same time, MSDF promotes the N uptake of rice and thereby improves its NUE (Fig. 3). Moreover, side-deep placement could supply more N to the deep rhizosphere compared with traditional N broadcasting management, which might promote rice root growth and NUE (Liu et al., 2015). Furthermore, side-deep placement prolongs fertilizer N availability and stimulates biological N fixation, both of which help reduce tillering and facilitate productive tillers and larger panicles (Savant and Stangel, 1990).

In the current field experiment, rice grain yield significantly decreased ($P < 0.05$), by 13.1%, when N-input rate was reduced from 270 kg N hm^{-2} (CF1N270) to 200 kg N hm^{-2} (CF1N200) under broadcasting management (Fig. 2a). Interestingly, by changing conventional broadcasting to MSDF, there was no grain yield loss, while the N-application rate was reduced by 26% (Fig. 2). MSDF increases direct energy consumption compared with manual broadcasting, given that the technique relies on machinery that is energy-intensive and may, therefore, not be suitable for sustainable full-scale use in rice production. Therefore, the energy consumption associated with MSDF was appraised compared with conventional broadcasting in the current work. We estimate that MSDF increased gasoline consumption by 11.25 L hm^{-2}, and using a coefficient of conversion to standard coal per liter of gasoline of 1.46 (GB/T 2589, China), this is equivalent to 16.4 kg standard coal per hectare. However, MSDF allowed for the reduction in urea application by 152 kg hm^{-2} (N rate by 70 kg N hm^{-2}), and using a standard coal consumption coefficient for urea production of 1.5 (GB/

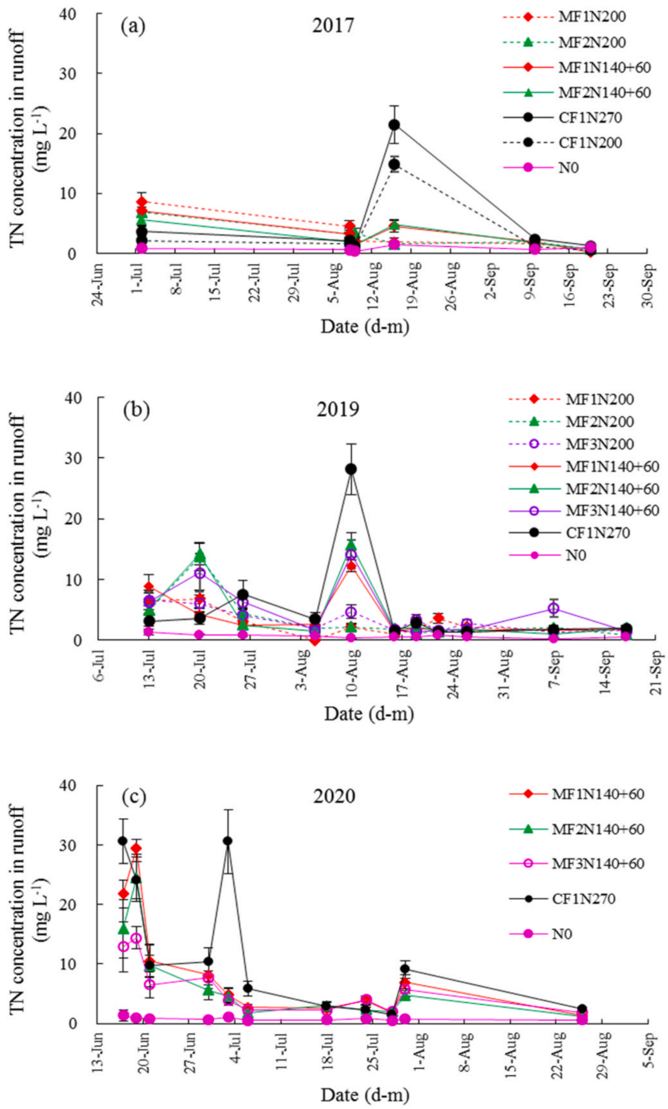

Fig. 5. The impact of mechanical side-deep fertilization (MSDF) on runoff total N (TN) losses for each observation in a) 2017, b) 2019, and c) 2020.

T 21344, China), this is equivalent to 228 kg standard coal per hectare. Therefore, the net energy consumption is −211.6 kg standard coal per hectare when the increased direct energy consumption is subtracted from the indirect energy consumption due to the reduction of urea application. Thus, MSDF emerges as an energy-saving and emission-reducing technique, compared with traditional forms of management. Moreover, mechanical application of basal fertilizer also saves labor costs, saving 1500–2250 RMB per hectare (Table 2). Overall, MSDF, with an N input of 200 kg N hm^{-2}, increased net economic benefit (NEB) by 11.2%, whereas the production value increased by 0.4%, while the production cost decreased by 5.8% compared with CF1N270, on average, based on the data gathered over three seasons of rice cultivation (Table 2).

4.3. The positive effects of MSDF are independent of N-fertilizer type and split ratio

In our current study, MSDF is shown to have a positive role in improving NUE and reducing NH_3 volatilization and runoff TN concentration. More importantly, these positive effects of MSDF are independent of fertilizer type and split ratio, as evident in the result that there were no significant differences between N-fertilizer type (NPK briquette, controlled-released N fertilizer, and stabilized fertilizer with urease and nitrification inhibitor) and split ratio (one-time basal, and basal plus panicle fertilizer) at an identical application rate. Soil texture may affect Nr losses and, thus, alter the effectiveness of applied fertilizer N (Yao et al., 2018). The current study is based on sandy loam soil, so further research of novel fertilizers under deep placement is also needed on sandy and clay soils. In rice production areas where MSDF is not available, novel fertilizer application may also increase rice NUE and the profitability of rice production. When manually broadcast, controlled-release fertilizer can slowly release N nutrients into the soil, to meet the N demand of the crop at different growth stages (Tian et al., 2021). Previous studies in China have found that controlled-release N fertilizer could improve stable crop production (Yang et al., 2012; Zheng et al., 2016). In addition, Chen et al. (2010) and Ke et al. (2017) demonstrated that a mixture of compound synthetic fertilizer and controlled-release N fertilizers with conventional broadcasting management can increase rice grain production, via increasing panicle number and grain number per panicle (Li et al., 2017; Liu et al., 2018). Moreover, although the grain yield of rice was increased by 13.5%, NH_3 volatilization was increased by 25.1% with the combination of urea and a nitrification inhibitor (Sun et al., 2015). To pursue high grain yield, N fertilizer had been traditionally split-applied during three growth stages of rice, with basal, tillering, and panicle fertilizer being applied by broadcasting (Xie et al., 2019). However, some work has shown that one-time application of N fertilizer through side-deep placement may be sufficient to meet the N requirements of the whole growth cycle for high grain yield (Pan et al., 2017; Yao et al., 2018), similar to the conclusions reached from our data. Therefore, the independence of the positive effects of MSDF from N-fertilizer type and split ratio indicates that, as long as the fertilizer is suitable for deep placement (i.e. does not easily float and wash out), there is no strict requirement for modern fertilizer types, such as controlled-release formulas or those that offer combinations with nitrification inhibitors. In addition, the MSDF technique offers savings on fertilizer as well as labor costs, rendering it conducive to more widespread adoption.

Future research should carefully evaluate the carbon footprint of MSDF to determine its potential contribution to carbon reduction, and match the MSDF technique with the soil's innate N-supply capacity, the

Table 2
Effects of mechanical side-deep fertilization (MSDF) on EB and NEB (RMB hm^{-2} $season^{-1}$).

Treatments	2017			2019			2020		
	EB_{yield}	$EB_{production\ cost}$	NEB[a]	EB_{yield}	$EB_{production\ cost}$	NEB	EB_{yield}	$EB_{production\ cost}$	NEB
CF1N270	24 205	16 500	7705	25 272	16 650	8622	29 217	17 565	11 652
CF1N200	21 041	16 200	4841	–	–	–	–	–	–
MF1N200	23 597	15 240	8357	23 377	15 300	8077	–	–	–
MF2N200	24 865	15 780	9085	24 607	15 840	8767	–	–	–
MF3N200	–	–	–	25 016	15 375	9641	–	–	–
MF1N140 + 60	23 581	15 960	7621	25 441	16 035	9406	28 959	16 260	12 699
MF2N140 + 60	25 192	16 395	8797	25 399	16 410	8989	29 957	15 765	14 192
MF3N140 + 60	–	–	–	26 412	16 095	10 317	30 112	16 095	14 017

[a] NEB (RMB hm^{-2} $season^{-1}$) = EB_{yield} (RMB hm^{-2} $season^{-1}$) C $EB_{production\ cost}$ (RMB hm^{-2} $season^{-1}$).

crop N requirement, and the environment adjacent to agricultural fields (e.g. proximity to water bodies). In addition, current deep-fertilizer application equipment is installed on transplanters, which slows down the speed of transplanting, reducing the enthusiasm of farmers to adopt the technology more readily. For future, larger-scale applications, the MSDF equipment will need to be improved to enhance its speed and power, to overcome the reduced efficiency of transplanting, and it will be necessary to develop both larger and smaller-sized, lower-cost deep fertilizer applicators to promote their wider application in rice-growing regions.

5. Conclusions

Our study over three rice seasons shows that changing the fertilization method from surface broadcasting to MSDF can reduce chemical N fertilizer input by 26% without any reductions in grain yield, while increasing NUE by nearly 30% and reducing NH_3 volatilization and runoff N losses at a near-identical 200 kg N hm^{-2} N-application rate. These positive effects of MSDF are independent of N-fertilizer type and split ratio, eliminating the strict requirement for more expensive fertilizer types, favoring larger-scale applications of MSDF. Additionally, a single basal application may meet the N demand of rice to maintain grain yield. Although afflicted by higher direct energy consumption requirements, MSDF emerges as an energy-saving technique overall, as it permits a significant reduction in urea input, which indirectly reduces the energy consumption related to fertilizer production. Furthermore, MSDF has a higher benefit-cost ratio, attributable to its higher total return but lower production cost, suggesting that the MSDF technique could be effective to achieve higher economic profitability by lowering labor requirements, and to afford greater environmental protection by reducing Nr losses from rice production systems. MSDF, therefore, presents itself as a strong technical choice for rice-planting areas that are in needs of both yield improvement and environmental protection.

CRediT authorship contribution statement

Ju Min: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing. **Haijun Sun:** Formal analysis, Data curation, Writing. **Yuan Wang:** Resources, Investigation. **Yunfeng Pan:** Resources, Investigation. **Herbert J. Kronzucker:** Writing – review & editing. **Dongqing Zhao:** Resources. **Weiming Shi:** Conceptualization, Validation, Writing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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