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Agricultural Systems

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https://doi.org/10.1016/j.agsy.2022.103575

Agricultural Systems 205 (2023) 103575

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Can the advisory system Nutrient Expert® balance productivity, profitability and sustainability for rice production systems in China?

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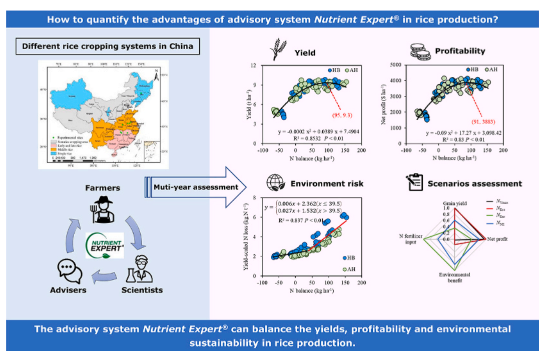
HIGHLIGHTS

- Smallholder rice growers in China apply too much nitrogen (N) fertilizer, given their realized yields.
- Using Nutrient Expert® (NE) as advisory system for scientific fertilization helps reduce economic loss and ecological risk.
- NE maintained rice yields, increased net profit while decreasing N loss.
- Sustainable N application rates were 122–214 kg ha^{-1} for rice.
- NE optimizes agronomic practice that balances yield, profitability and sustainability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jagadish Timsina

Keywords:
Environmental benefit
Nitrogen application rate
Nitrogen balance
Nitrogen loss
Oryza sativa
Sustainable agriculture

ABSTRACT

CONTEXT: To avoid excessive chemical-fertilizer application and improve agricultural productivity in rice, a fertilizer recommendation system called Nutrient Expert® (NE) was designed. However, the ability of NE to balance yield, profitability and environmental sustainability in rice production needs to be further evaluated, as it is still difficult for farmers to assess the proper nitrogen (N) application rate.

OBJECTIVE: The objective of this study was to demonstrate the advantages of the NE system in balancing yield, profitability and N loss in rice production, and recommend proper N application rates for different cropping seasons of rice.

METHODS: This study describes results from field experiments conducted in five main rice cropping provinces from 2017 to 2020 in China, to investigate any advantages of NE compared with local farmers' practice (FP), and to determine the proper N application rates for different cropping seasons of rice.

RESULTS AND CONCLUSIONS: Compared with FP, NE had 12.1% lower N-fertilizer application, but increased rice grain yield by 4.3% and net profit by 7.4%, and decreased yield-scaled N loss by 20.7%. We showed how yield, profitability and N loss were affected by N balance (i.e., N applied to the field minus N removed from the field by the harvested crop biomass), and quantified relationships between N balance and N application rate, and between N output and input. Based on relationships between N balance and N application rate, we recommend N

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https://doi.org/10.1016/j.agsy.2022.103575
Received 27 July 2022; Received in revised form 24 November 2022; Accepted 25 November 2022
Available online 1 December 2022
0308-521X/

application rates in a range from 122 to 214 kg ha^{-1}, depending on cropping seasons of rice. We demonstrated that NE can simultaneously improve yield, profitability and environmental sustainability.
SIGNIFICANCE: Our study provided quantitative support for NE-based recommendations on the N application rate for smallholders farming in different rice cropping systems, and these recommendations can serve as a reference for avoiding excessive N application rate in paddy fields in other regions with similar eco-environment.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important staple food crops and plays a dominant role in global food security. China is the largest rice producer in the world as it produces 30% of global rice on 18.5% of the world's cultivated area (FAO, 2020). In recent decades, rice yields have increased significantly in China, which has primarily been attributed to the genetic improvement and increase in input of inorganic fertilizers, especially nitrogen (N) fertilizers (Ju et al., 2009; Li et al., 2019). However, rice production in China needs to be further increased by 20% to feed the growing population by 2030 (Peng et al., 2015; Kamir et al., 2020).

N fertilizer plays a vital role in the pursuit of high rice yield and economic benefits, but it also results in significant effects on the environment and ecosystem when over-applied (Tilman et al., 2011; Yin et al., 2019a). Since the 1980s, the consumption of N fertilizer in China has increased by a threefold, and the rice yield only increased by 50% (National Bureau of Statistics of China, 2022). This was partly because most Chinese smallholder farmers generally believe that applying more inorganic fertilizer will achieve higher yields and economic benefits. Recent studies showed that the average N input in paddy fields in China was 209 kg ha^{-1} (Chen et al., 2014), while 300 kg N ha^{-1} was applied in paddy fields in Jiangsu province (Sui et al., 2013). These values are much higher than the world average and the crop needs. Such practices of excessive N fertilizer input combined with improper field management will not only cause a massive waste of resource and energy, and reduce N use efficiency (NUE), but also threatens the surrounding environments and ecosystems (Xia and Yan, 2011; Chai et al., 2019). In recent decades, a sharp increase in reactive N in farmland occurred due to a large amount of chemical N fertilizer applied to the agricultural system. The reactive N will inevitably enter the atmosphere and hydrosphere systems, through ammonia (NH_3) volatilization, nitrous oxide (N_2O) emissions, nitrate (NO_3^-) leaching and runoff (Vitousek et al., 1997; Zhang et al., 2011; Gu et al., 2015; Pittelkow et al., 2015; Zhang et al., 2021). How to increase grain production for coping with growing populations by proper management of inorganic N fertilizer, while maintaining environmental and agricultural sustainability is extremely challenging (Godfray et al., 2010; Foley et al., 2011; Stephens et al., 2018).

A science-based fertilization advisory has long been advocated (Fotyma and Pietras, 1981), such as those based on soil property and nutrient supply maps (Sarkadi and Várallyay, 1989) or based on the expected yield and nutrient balance (Várallyay et al., 1992). More recently, researchers have proposed several frameworks of nutrient management taking environmental sustainability into account, such as "nutrient management planning" (Beegle et al., 2000), "agricultural sustainability and intensive production practices" (Tilman et al., 2002), "ecological intensification" (Cassman, 1999), and "nutrient budgets" (Oenema et al., 2003). Chinese agronomists also proposed fertilizer recommendation strategies suitable for the agricultural economy of China. The aim of those strategies is to improve the agricultural productivity and profitability while reducing the environmental footprints, for instance, the integrated soil-crop system management (Zhang et al., 2011; Chen et al., 2014; Wu and Ma, 2015; Cui et al., 2018). Although such methods have been tested extensively, it is difficult for smallholder farmers to use these methods, due to the complexity of the assessment principle. Promoting crop yield, profitability and sustainability in a balanced way is still a daunting task in countries, such as China, India, Nepal, etc., where farming is mainly done by smallholder farmers. In view of spatial variability of crop field ecosystems associated with smallholder farming, a site-specific nutrient management decision support tool, *Nutrient Expert*® (NE), was developed. The NE system was designed based on the 4R nutrient stewardship (using fertilizers from the Right source, at the Right rate and at the Right time, and in the Right place) (Roberts, 2007; Pampolino et al., 2012; Xu et al., 2015; see the Supplementary text for additional information about NE). This NE system uses computer-based decision support technology and a questionnaire to provide a simple advice.

On-farm use of the NE-based fertilizer recommendation has been proven to significantly improve yield (Pampolino et al., 2012; Majumdar et al., 2016; Mandal et al., 2016; Dutta et al., 2020; Rurinda et al., 2020; Amgain et al., 2021), nutrient use efficiency (Pampolino et al., 2012; Rurinda et al., 2020; Amgain et al., 2021), farm profitability and soil health (Mandal et al., 2016; Amgain et al., 2021), while reducing environmental footprint of fertilizer use (Sapkota et al., 2021) in South and South-East Asia, and Sub-Saharan Africa. At present in China, NE has been successfully applied to rice (Xu et al., 2016a; Xu et al., 2017; Xu et al., 2019; Wang et al., 2020; Xu et al., 2022), maize (Xu et al., 2014a; Xu et al., 2014b; Xu et al., 2016b; Zhang et al., 2017a), wheat (Chuan et al., 2013) and tea (Tang et al., 2021). However, previous researches mainly focused on the comparison of rice grain yield and N usage between NE and farmers' practice (FP) by considering different cropping seasons as a whole. Little information is available on how N application rates based on NE balance agricultural productivity, profitability, and environmental sustainability across different cropping seasons of rice. Here, we hypothesize that the NE system maintains a balance between yield, profitability and environmental sustainability. To test this hypothesis, we conducted field experiments in five provinces in China from 2017 to 2020, covering four popular cropping seasons of rice in China. By analyzing the collected experimental data, we first aim to reveal whether, compared with FP, the NE system has advantages in balancing yield, profitability and N loss in different cropping seasons of rice. We also aim to recommend proper N application rates for different cropping seasons of rice in China, by establishing a set of quantitative relationships based on these data.

2. Material and methods

Field experiments were conducted from 2017 to 2020 with different N rates based on Nutrient Expert® (NE) recommendations. The rice grain yield, profitability, N loss, N uptake and N use were analyzed.

2.1. Experimental sites

Sites chosen for field experiments represent main rice producing areas in China (Fig. 1). In the light of the different cropping seasons, planting time and geographical locations, these areas can be classified into zones: (1) the double-cropping rice area, (2) the rice-wheat rotation area, and (3) the cropping area where the rice is grown as a single crop annually (Fig. 1). Our experimental sites were in five provinces: Jiangxi (JX), Hunan (HN), Hubei (HB), Anhui (AH), and Jilin (JL). A subtropical monsoon climate covers JX, HN and HB, with 16–18 °C of average annual air temperature, and 1200–1700 mm of average annual precipitation. Anhui has a warm temperate, semi-humid monsoon climate, with an average annual rainfall of about 800–1100 mm, and an average annual temperature of 16–17 °C. JL has a typical mid-temperate, subhumid monsoon climate, with an annual average temperature of 3–5 °C, and an average annual precipitation of 400–600 mm. Affected by the climates, planting histories and dietary habits, early and late rice are planted in JX and HN (i.e., the area of double-cropping rice, including early rice and late rice), the rice-wheat rotation is favored in HB and AH (where rice is called the middle rice in China), while the farmers of JL (the cold-season rice area) are used to plant single rice.

The experiments in JX, HB and JL were fixed-site experiments: the site in JX was Zhanggong town, Jinxian county, Nanchang city from 2017 to 2020, that in HB was Dianzishan village, Caihe town, Guangshui county, Suizhou city from 2017 to 2019, and that in JL was Xihe village, Gujiazi town, Lishu county, Siping city from 2017 to 2020. The data in HN was collected in Heshan district, Yiyang city in 2017, and in Baishiyuan village, Gaoqiao town, Changsha County, Changsha city from 2018 to 2019. The experimental sites in AH changed every year, with Qintai village, Ling town, Huoqiu county, Liuan city in 2017, Jiangji village, Jiangji town, Dingyuan county, Chuzhou city in 2018, and Shiba village, Shiba town, Mingguang county, Chuzhou city in 2019.

2.2. Experimental design

The experimental treatments included: (1) current farm practices (FP, the farmers' practices in the region but carried out in experimental plots); (2) Nutrient Expert (NE, fertilizer recommendations based on the NE for rice decision support tool); (3) N omission plots (N0, no N applied), and (4) a series of NE-based N rates which included different percentages of plus N (+N) or minus N (-N), expressed as NE ± 25%N and NE ± 50%N, to test the accuracy of the N rate based on NE. However, the N rates in JX from 2017 to 2019 were NE ± 15%N, NE ± 30%N and NE ± 45%N, and the experiments in JL had treatments for a series of NE-based N rates only in 2020 (but not from 2017 to 2019).

The randomized complete block experiments with three replications had individual plot sizes of 30 m^2 (5 m × 6 m) in JX, HN, HB and AH, and 40 m^2 (5 m × 8 m) in JL. The applied fertilizer rates and fertilizer basal-topdressing ratios of NE and FP treatments in each experimental site are shown in Table 1 and Table 2, respectively. N and K fertilizers were applied in splits at basal, tillering and booting stages, and all P fertilizer was applied as basal application (at one day before transplanting). The N, P and K fertilizer sources applied were urea (46.4% N), calcium-magnesium phosphate (18% P_2O_5) and potassium chloride (60% K_2O), respectively.

The rice cultivars chosen were the most cultivated in the experimental area (see Table S1 for details on rice cultivars). Before transplanting (see Table S2 for transplanting dates), 20-cm high earth banks were built on the paddy field to separate the experimental plots. These banks were covered with plastic films to prevent runoff of water and fertilizer. Rice straw was buried in the soil by ploughing after the harvest of each growing season in JX and HN, spread in the paddy field after grain harvest in HB, and removed from the field after grain harvest in AH and JL. No manure was applied. Pesticide and herbicide were sprayed manually before rice transplanting and regreening stage.

2.3. Sampling for yields and plant tissue analysis

At final harvest during each rice growing season, the rice grains of each plot were harvested manually, by collecting all plants in each plot, excluding the two border rows. The rice yields per hectare were standardized expressing them on the basis of a moisture content of 14%. Rice samples were dried in an oven set at 105 °C for 15 min, followed by further drying at 80 °C for 72 h until constant weight (Xiao et al., 2017). Sub-samples from the biomass samples were divided into vegetative organs (stems and leaves) and grains. These divided samples were crushed and passed through a 0.42-mm sieve to determine N concentrations using an element analyzer (Elementar vario MACRO cube, Germany). Aboveground dry biomass was determined from grain yield and the proportion of grain weight in the whole-plant weight of the subsample.

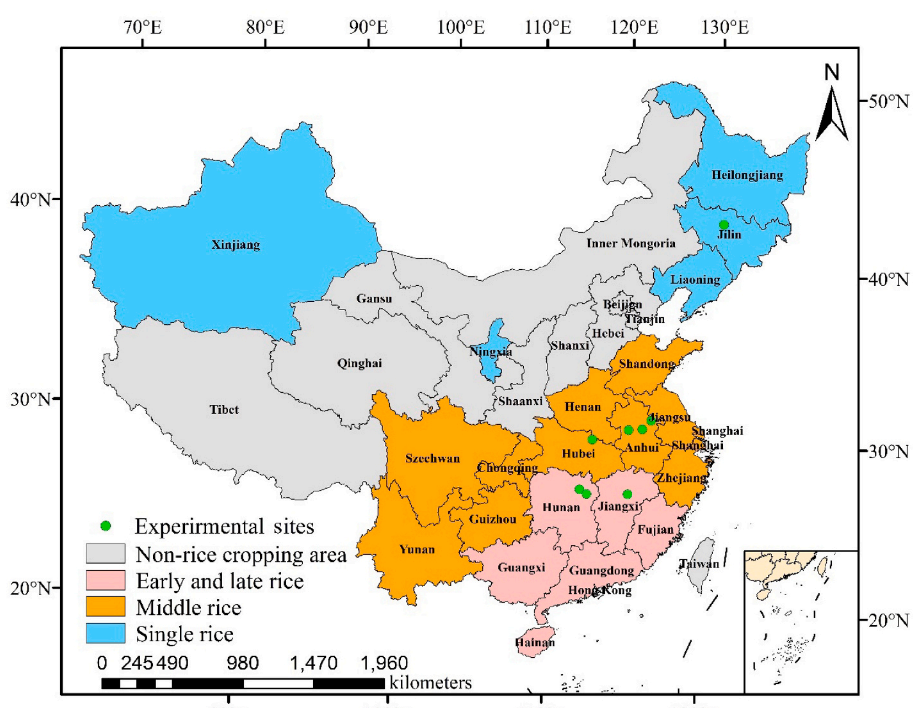

Fig. 1. Geographic locations of experimental sites (green dots) in different rice cropping areas in China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Fertilizer application rates based on recommendations by Nutrient Expert (NE) and farmers' practice (FP) treatments in Jiangxi (JX), Hunan (HN), Hubei (HB), Anhui (AH), and Jilin (JL) provinces from 2017 to 2020.

Site	Rice cropping season	Year	N rate (kg ha^{-1})		P_2O_5 rate (kg ha^{-1})		K_2O rate (kg ha^{-1})	
			NE	FP	NE	FP	NE	FP
JX	Early rice	2017–2020	139	159	48	90	43	80
	Late rice		140	205	53	101	56	236
HN	Early rice	2017 / 2018–2019[a]	140 / 146[a]	97 / 120[b]	65 / 77	68 / 80	81 / 118	56 / 80
	Late rice		146 / 143	180 / 180	68 / 54	68 / 100	108 / 91	56 / 80
HB	Middle rice	2017–2019	154	175	56	135	81	135
AH	Middle rice	2017/2018/2019	165/150 /186	201 / 189 / 210	63 / 54 / 57	79 / 68 / 60	114 / 54 / 60	79 / 68 / 72
JL	Single rice	2017–2020	169	200	60	75	84	105

[a] The numbers before and after the slashes represent the different experimental years, and the corresponding fertilizer input.
[b] The only case where N input was lower in FP than in NE.

Table 2
N and K fertilizer basal-topdressing ratio of fertilizer management recommended by Nutrient Expert (NE) and farmers' practice (FP) treatments in Jiangxi (JX), Hunan (HN), Hubei (HB), Anhui (AH), and Jilin (JL) provinces.

Site	N basal-topdressing ratio		–	K_2O basal-topdressing ratio	
	NE	FP		NE	FP
JX	4:3:3[a]	4:6:0		5:0:5	5:5:0
HN	4:4:2	4:6:0		4:4:2	10:0:0
HB	4:3:3	4:6:0		4:3:3	5:5:0
AH	5:2.5:2.5	4:6:0		5:2.5:2.5	10:0:0
JL	4:3.5:2.5	4:3:3		4:3.5:2.5	4:3:3

[a] The numbers separated by colons indicate the proportion of fertilization to the total fertilization application rate, and fertilizers were applied in splits as basal and topdressing at tillering and booting stages.

2.4. Calculations

2.4.1. Nitrogen balance

In this study, we attempted to determine how rice grain yield, profitability and N loss were affected by N balance, and then used N balance to deduce the appropriate N application rate in each rice planting area. N balance is the difference between N input through fertilizer application and N output through crop removal (Hartmann et al., 2014; Xu et al., 2015):

$$\text{N balance} = N_{\text{fert}} - N_{\text{harvest}} \quad (1)$$

where N_{fert} is the fertilizer N application rate (kg N ha^{-1}) and N_{harvest} is crop N removal at harvest (kg ha^{-1}), including both rice straw and grain.

2.4.2. Determination of nitrogen loss associated with yield

Total N loss from the rice field is the sum of ammonia volatilization (NH_3), nitrous oxide emission (N_2O), nitrate (NO_3^-) leaching and N runoff. We followed previous research of meta-analysis to quantify the total N loss in each rice planting area, calculated via applying an empirical model (Ding et al., 2020a, see Table S3 for detailed calculations). However, ensuring grain productivity while improving the environmental protection should consider N losses associated with food production (Pittelkow et al., 2014). We quantified N losses per unit rice grain yield, named yield-scaled N loss (Zhou and Butterbach-Bahl, 2014; Zhao et al., 2016):

$$\text{Yield scaled N loss}\left(\text{kg N t}^{-1}\right) = \text{N loss}/\text{Y} \quad (2)$$

where N loss is the sum of N loss via NH_3, N_2O, NO_3^- leaching and N runoff (kg ha^{-1}), and Y is rice grain yield at harvest (t ha^{-1}).

2.4.3. Calculation of profitability

In this study, profitability refers to the net benefit of gross income from rice grain yield after excluding the fertilizer cost, labor cost, and the cost of greenhouse gas damage due to global warming (C_{GHG}).

$$\text{Net profit} = \text{gross income} - \text{fertilizer cost} - \text{labor cost} - C_{GHG} \quad (3)$$

$$\text{Gross income} = P_R \times Y \quad (4)$$

$$\text{Fertilizer cost} = P_N \times F_N + P_P \times F_P + P_K \times F_K \quad (5)$$

where C_{GHG} was set at \$11.2 kg^{-1} N_2O-N (Schiermeier, 2009; Xia and Yan, 2011), P_R, P_N, P_P,and P_K are the average prices from 2017 to 2020 of rice grains, N fertilizer, P fertilizer and K fertilizer, respectively. P_R of early, late, middle, and single rice was defined as 0.45 \$ kg^{-1}, 0.48 \$ kg^{-1}, 0.48 \$ kg^{-1}, and 0.55 \$ kg^{-1}, respectively. P_N, P_P, and P_K were expressed as 0.70 \$ kg^{-1}, 1.15 \$ kg^{-1}, and 0.80 \$ kg^{-1}, respectively. F_N, F_P and F_K are the application rates of N fertilizer, P fertilizer and K fertilizer, respectively (for details on fertilizer application rate see Table 1).

2.4.4. Nitrogen output/input ratio

We introduced a mass balance-based N output/input ratio concept proposed and widely adopted by EU Nitrogen Expert Panel (2015). This ratio was used to assess the proper range of N application rate under the consideration of environmental N input.

In our study, in addition to the fertilizer N application rate, we also considered the N input through other sources, including biological N fixation, seeding, irrigation and deposition. N output was estimated by the plant N removal (grain and straw) from the field at harvest. Besides the fertilizer N application rate, other sources of N input were referred to a literature survey (Ding et al., 2021). This N output/input ratio can intuitively and clearly show the results through two-dimensional graphs. It is divided into three zones, namely the zone with a low ratio, the desired zone, and the zone with a high ratio (EU Nitrogen Expert Panel, 2015). The low-ratio zone indicates a low nutrient use efficiency and a potentially high N loss. The high-ratio zone means that the current management is mining the soil N resources and can easily lead to soil fertility depletion. According to the EU Nitrogen Expert Panel (2015), the desired ratio is between 0.5 and 0.9. Values lower than 0.5 lead to the risk of N pollution, and those >0.9 represent the risk of excessive N mining.

2.4.5. Assessing Nutrient Expert for rice and nitrogen application scenarios

The relationships between yield, net profit, yield-scaled N loss, and N balance were established. According to the robust linear relationship between N balance and N application rate, the corresponding N application rates for the maximum rice grain yield point, the maximum net profit point, and the environmental threshold point were derived thereof. We called these N application rates N_{Ymax} (the N application rate that results in the maximum rice grain yield), N_{Eco} (the N application rate that gives the maximum net profit) and N_{Env} (the N application rate that corresponds to the environmental threshold point), respectively. These points were used to compare with N application rate of NE and FP treatments (N_{NE} and N_{FP}) in terms of grain yield, net profit, environmental benefit and N fertilizer input in a radar chart.

2.5. Statistical analysis

Response models (quadratic or piece-wise linear models) were generated using Microsoft Excel™, and the regression analyses, three-way ANOVA and associated *t*-test, and the NLIN procedure for the obtained data were performed using SPSS Statistic 25 (SPSS Inc., Chicago, IL, USA), respectively.

3. Results

3.1. Grain yield in relation to nitrogen balance

The rice grain yields were significantly affected by the N balance (Fig. 2a–d, $P < 0.01$). The ranges of variation in grain yields in JX and HN provinces were 3.0–8.5 and 3.6–10.3 t ha^{-1} for early rice and late rice, respectively (Fig. 2a, b). The rice yields in the rice-wheat rotation system (middle rice) in HB and AH provinces varied from 4.1 to 9.9 t ha^{-1} (Fig. 2c), while the yields of single rice in the JL province ranged from 3.8 to 9.2 t ha^{-1} (Fig. 2d). The regression analyses showed that the rice grain yields of the four different cropping seasons of rice (early, late, middle, and single rice) increased quadratically with an increase in N balance. When the N balance of early, late, middle and single rice reached 67, 54, 95 and 90 kg ha^{-1}, respectively, maximum yields were achieved (6.3, 7.8, 9.3, and 8.6 t ha^{-1} in early, late, middle, and single rice, respectively). There were significant differences between years and types of management across different rice cropping seasons, and the average grain yield of the NE treatment was increased by 4.0% compared with the FP treatment (Fig. 2e).

3.2. Profitability in relation to nitrogen balance

The net profits were significantly influenced by N balance (Fig. 3a–d, $P < 0.05$). The ranges of variation in net profit of early, late, middle, and single rice were 886–3299, 1353–4416, 1535–4161, and 1643–4505 $

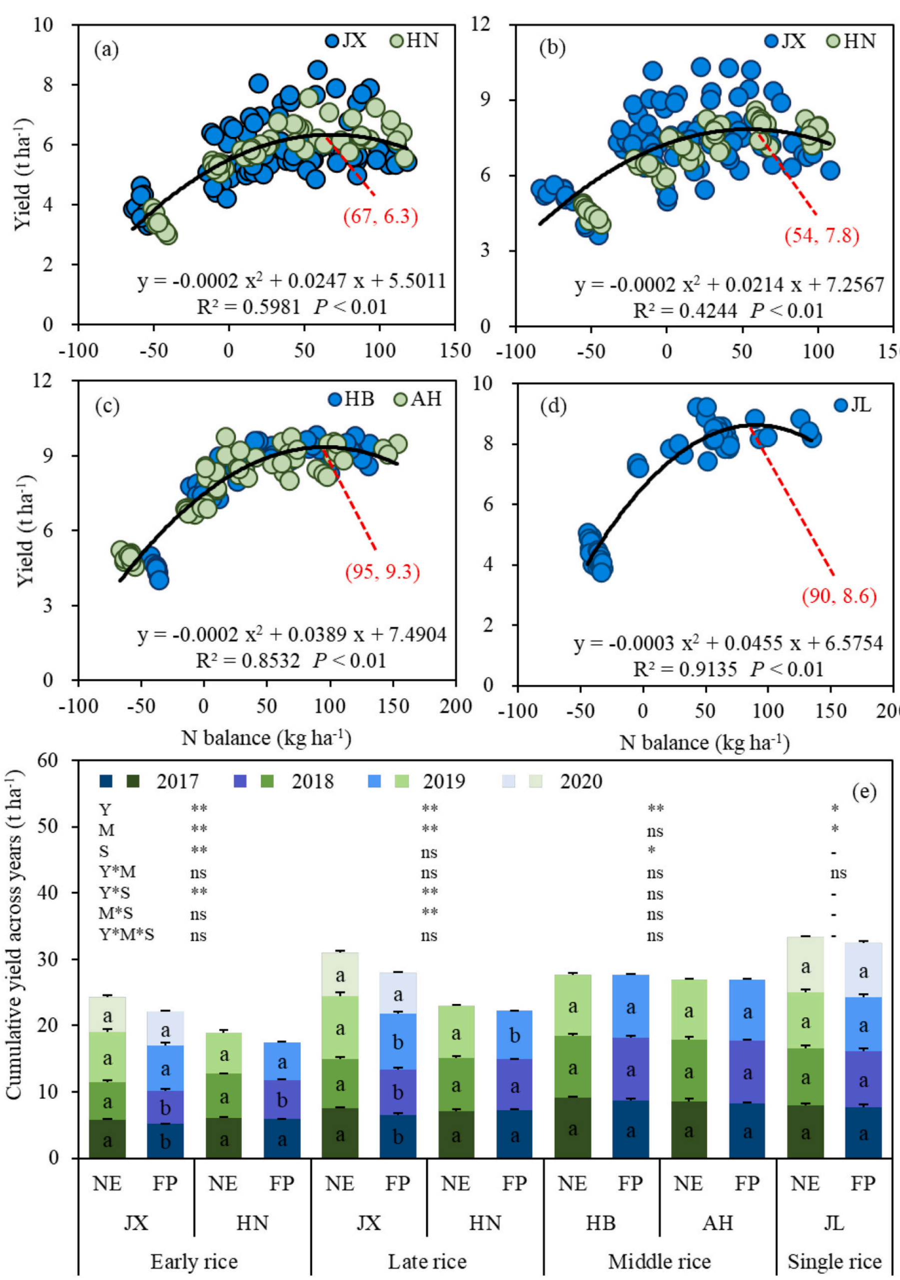

Fig. 2. Grain yield in relation to N balance in early (a), late (b), middle (c) and single (d) rice, and the comparison of rice grain yield between fertilizer management recommended by Nutrient Expert® (NE) and farmers' practice (FP) treatments (e). In (a) – (d), the solid curves are the regressed relationships between yield and N balance, and the numbers in parentheses represent the N balance (kg ha^{-1}) and the grain yield (t ha^{-1}) when the maximum yield was achieved. In (e), the series of green and blue bars represent NE and FP, respectively; three-way ANOVA analysis was conducted within the same rice cropping type, where the main variates are year (Y), management (M, that is NE and FP), and site (S), and the *t*-test was conducted thereof between NE and FP treatments within the same rice cropping type, in the same province and the same year (*, **, and ns indicate significant at $P < 0.05$, $P < 0.01$, and $P > 0.05$, respectively). JX, HN, HB, AH and JL indicate Jiangxi, Hunan, Hubei, Anhui and Jilin province, respectively. Note that, because single rice was only planted in JL (see the text), we conducted only two-way ANOVA analysis for single rice; thus, no effect of site can be found for it, which is indicated as - in panel (e) of the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

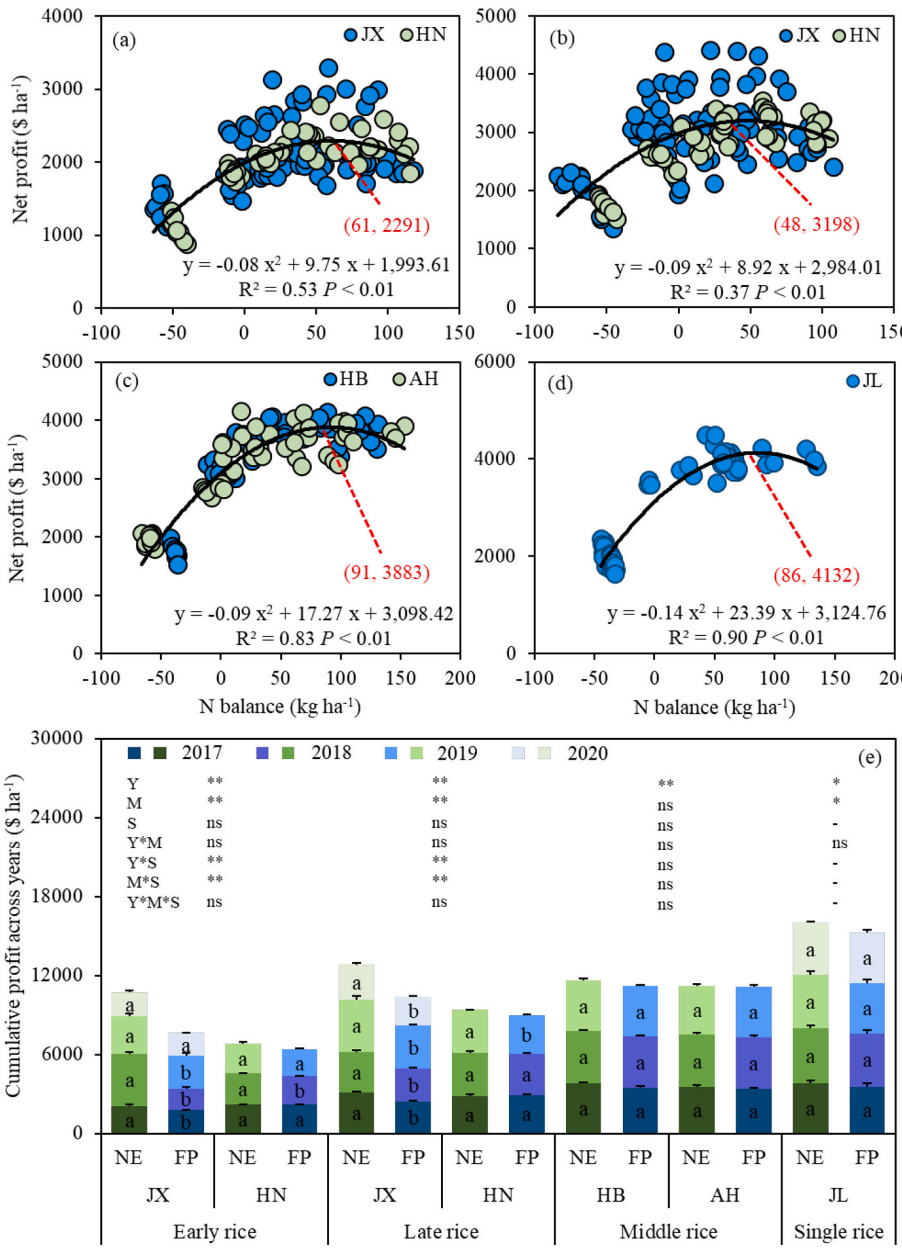

Fig. 3. Net profit in relation to N balance in early (a), late (b), middle (c) and single (d) rice, and the comparison of net profit between fertilizer management recommended by Nutrient Expert (NE) and farmers' practice (FP) treatments (e). In (a) – (d), the solid curves are the regressed relationships between net profit and N balance, and the numbers in parentheses represent the N balance (kg ha^{-1}) and the net profit ($ ha^{-1}) when the maximum profit was achieved. Further details as in Fig. 2.

ha^{-1}, respectively. The regression analysis indicated that the net profits of four different cropping seasons of rice first increased with the increase in N balance, and slightly dropped after reaching a certain value. The maximum values of early, late, middle, and single rice were 2291, 3198, 3883, and 4132 $ ha^{-1}, respectively, when the N balance reached 61, 48, 91 and 86 kg ha^{-1}. There were significant differences between years and types of management, and there were significant management × site interactions across different rice cropping seasons. The average net profit of the NE treatment increased by 7.4% compared with the FP treatment (Fig. 3e).

3.3. Quantification of nitrogen loss per unit of grain yield

With the increase in N balance, the yield-scale N loss increased nonlinearly (Fig. 4a–d). When the N balance exceeded a certain value, the yield-scale N loss increased with a greater pace. We called this turning point of N balance the environmental threshold point, which can help develop an environment threshold for N balance. A piece-wise linear model was established to estimate this threshold point.

The environmental threshold points of early, late, middle, and single rice were found where the N balance reached 30.2, 25.1, 39.5, and 66.1 kg ha^{-1}, respectively, and the yield-scale N losses at these points were 4.3, 2.5, 2.0, and 3.1 kg N t^{-1}. When the N balance exceeded these points, more N would not be taken up by the plants but readily lost to the environment. There were significant differences between years, types of management, and sites, while there were significant year × site interactions, and management × site interactions across different rice cropping seasons. The NE treatment resulted in an average reduction of 20.8% (significantly reduced by 5.5%, 36.3% and 22.7% in early, late and single rice, respectively) in the yield-scaled N losses compared with FP treatment (Fig. 4e).

3.4. Determination of nitrogen application rate ranges via nitrogen balance

As expected, N balance increased linearly with increasing N application rate (Fig. 5). The N balance values corresponding to the maximum grain yield, maximum profit, and environmental threshold

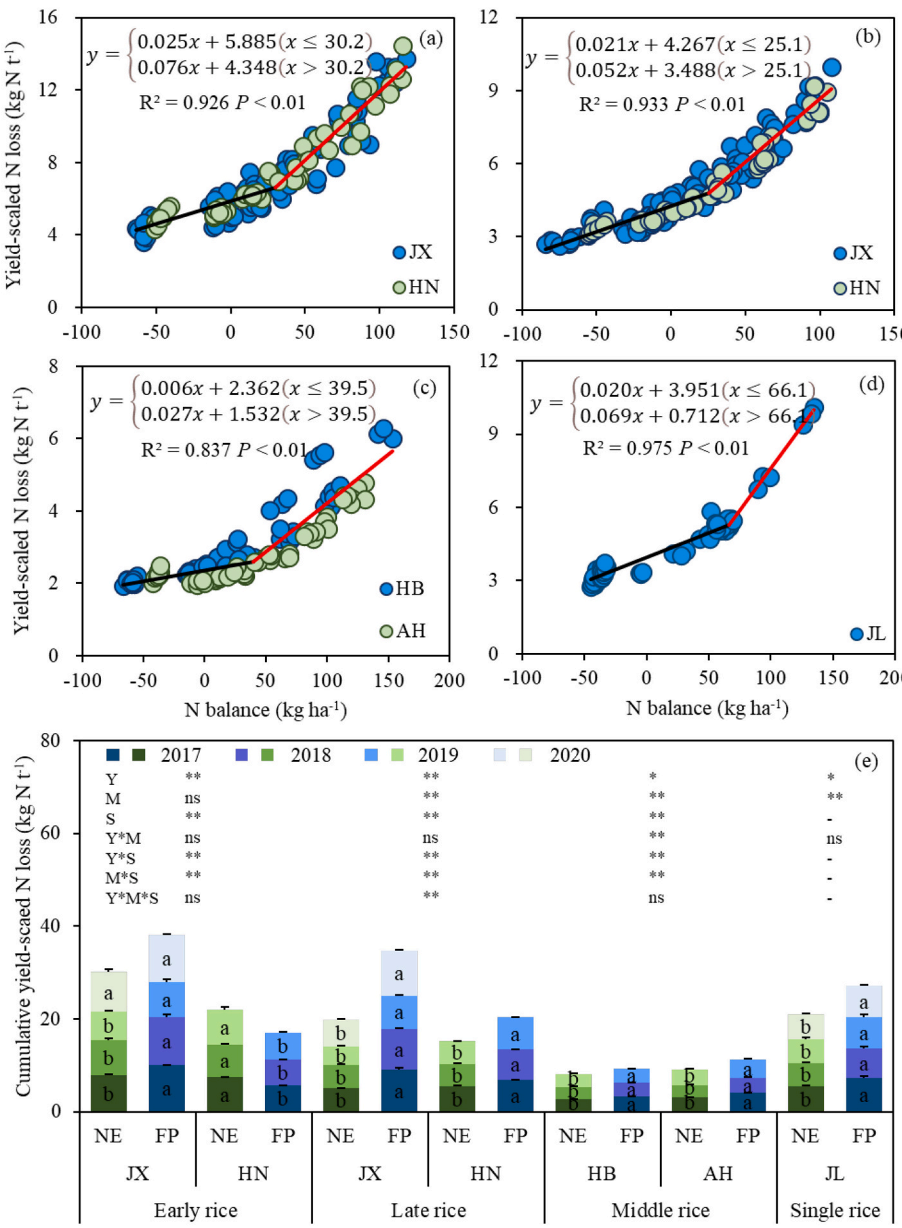

Fig. 4. N loss per unit of grain yield (or yield-scale N loss) in relation to N balance in early (a), late (b), middle (c) and single (d) rice, and the comparison of yield-scaled N loss between fertilizer management recommended by Nutrient Expert (NE) and farmers' practice (FP) treatments (e). In (a) – (d), the intersection of the blue and red lines represents the environment optimum point, beyond which the yield-scale N loss increases significantly. Further details as in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

point obtained from previous sections were introduced to the linear relationships in Fig. 5. In this way, the corresponding N application rate ranges could be obtained, which we consider as the range compromising rice productivity, profitability and environmental risk management.

When the maximum rice grain yields were achieved in early, late, middle, and single rice, the corresponding N application rates were 171, 172, 214, and 212 kg ha^{-1}, respectively. When the net profits were maximized, the corresponding N application rates were 164, 164, 209, and 205 kg ha^{-1}, respectively in early, late, middle, and single rice. The N application rate corresponding to the environmental threshold points in early, late, middle, and single rice were 122, 133, 138, and 163 kg ha^{-1}, respectively. Therefore, to compromise the yield, profitability and environmental benefits, the expected N application rate should be within the range of 122–171, 133–172, 138–214, and 163–212 kg ha^{-1} in early, late, middle, and single rice, respectively. The N application rates of the NE treatment (averaged 141, 142, 161, and 169 in early, late, middle, and single rice, respectively; Table 1) were within these ranges.

3.5. Evaluation of nitrogen application rate via nitrogen output/input ratio

We also evaluated the above calculated range of N application rate by using a conceptual framework based on the N output/input ratio. In addition to the fertilizer N and seed N (0.4–0.7 kg N ha^{-1}), N input also included N_2 fixation (22.1 kg N ha^{-1}), N deposition (15.4–19.4 kg N ha^{-1}) and N in irrigation water (7.9–27.5 kg N ha^{-1}), which were estimated by a literature survey (Ding et al., 2021). N output refers to the N removed by the plants, namely through crop N uptake by grain and straw.

On average, the N output/input ratio values of NE treatment in early, late, and middle rice (0.54, 0.62, and 0.53) were within the acceptable range indicated earlier (Fig. 6). But those in JL (0.47) and HB (0.48) were slightly lower than the lower limit, which may be mainly attributed to the rice cultivars grown and indigenous soil fertility, resulting in lower N output. Due to the lower N application rate (97–120 kg ha^{-1}) (Table 1), the N output/input ratio of early rice in HN (0.59) was the only one above 0.5 among the FP treatments, but with the lowest value

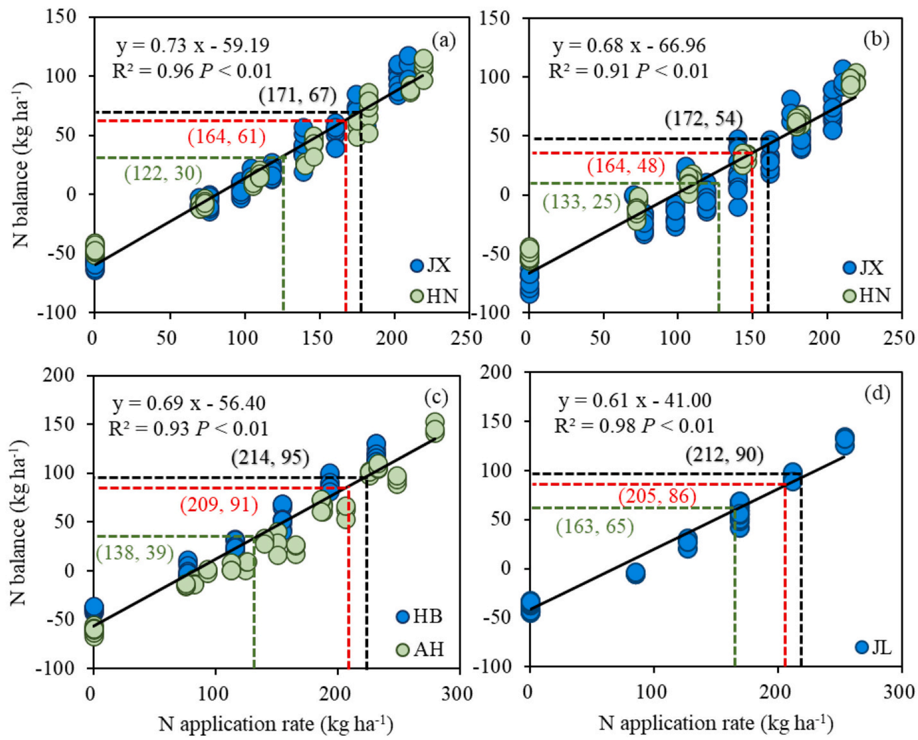

Fig. 5. N balance in relation to N application rate in early (a), late (b), middle (c) and single (d) rice. The black, red and green dotted lines represent the N application rate when the maximum yield (N_{Ymax}), maximum net profit (N_{Eco}) and the environmental threshold point (N_{Env}) were obtained, respectively. The numbers in parentheses represent the corresponding N application rate (kg ha^{-1}) and N balance (kg ha^{-1}). JX, HN, HB, AH and JL indicate Jiangxi, Hunan, Hubei, Anhui and Jilin province, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

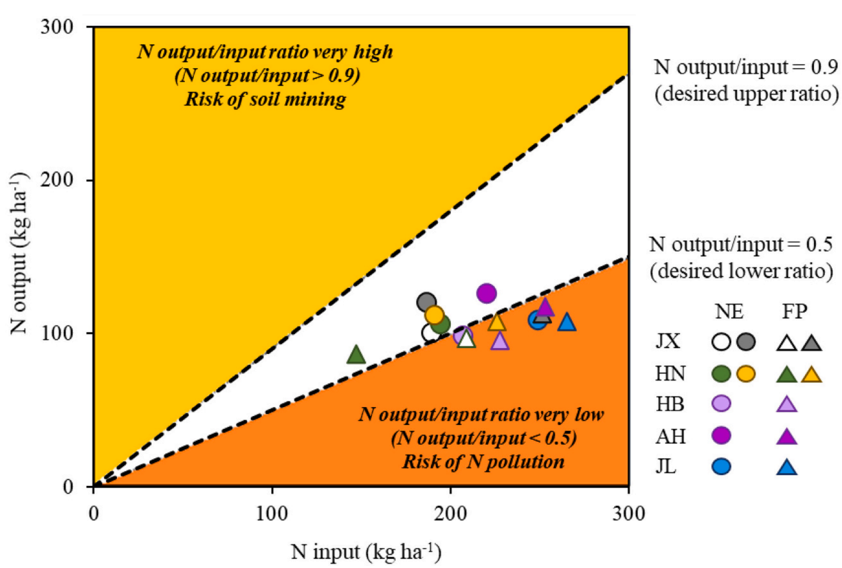

Fig. 6. N output in relation to N input in fertilizer management recommended by Nutrient Expert (NE) and farmers' practice (FP) treatments in Jiangxi (JX), Hunan (HN), Hubei (HB), Anhui (AH) and Jilin (JL) provinces. The N input includes N fertilizer, biological N fixation, seeding, irrigation, and deposition N, and N output includes N removals by harvested grain and straw from the field (see the text). The yellow and orange areas represent the areas where the N output/input ratio is higher than 0.9 and lower than 0.5, respectively (the range between 0.5 and 0.9 was considered as acceptable values by the EU Nitrogen Expert Panel, 2015). The circle and triangle legends with different colors respectively represent NE and FP treatments of different rice cropping seasons in various provinces: in JX and HN, double-cropping rice was grown with early and late rice represented by left and right legend symbols, respectively; HB and AH had middle rice while JL had the single rice. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

of N output (86.8 kg ha^{-1}) and lower grain yield as a cost.

3.6. *Assessing Nutrient Expert for rice and nitrogen application scenarios based on farmers' practice*

The advantages of various N application scenarios, N_{Ymax}, N_{Eco}, N_{Env} and N_{NE}, compared to the N input of farmers' practice (N_{FP}) in terms of grain yield, net profit, yield-scaled N loss, and N fertilizer input were assessed, as shown in Fig. 7. The values in the radar chart represent the degrees of relative advantage, based on the scoring that the values of FP were set at 0, and those of N_{Ymax} in terms of grain yield, of N_{Eco} in terms of net profit, and of N_{Env} in terms of environmental benefit or N fertilizer input were taken as 1. N_{Ymax} and N_{Eco} had little advantage in environmental benefit (0.03 and 0.17) and in N fertilizer input (both were negative values, indicating that the N fertilizer inputs were higher than N_{FP}). N_{Env} had a very low score in terms of yield (0.35) and profit (0.53). The NE had scores, in terms of grain yield, net profit, yield-scaled N loss, and N fertilizer input, of 0.61, 0.77, 0.81 and 0.54, respectively, suggesting that NE represented a good balance and compromise among grain yield, net profit, yield-scaled N loss and N fertilizer input.

4. Discussion

4.1. *Grain yield, profitability and environmental sustainability*

Our study showed that, compared with farmers' practice, Nutrient Expert® (NE) reduced the N-fertilizer application rate and N loss while ensuring the rice grain yield and profitability. Adopting NE as the field

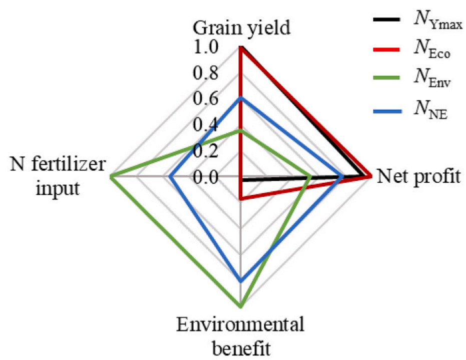

Fig. 7. The relative advantages of four fertilizer management scenarios, i.e., N application recommended by Nutrient Expert (N_{NE}), and N applications when the maximum yield maximum was achieved (N_{Ymax}), or when net profit was achieved (N_{Eco}), or when the environment optimum point of N loss was achieved (N_{Env}), compared with the N application of the farmers' practice (N_{FP}), in terms of grain yield, net profit, yield-scaled N loss (environmental benefit), and N fertilizer input. This was assessed in the following three steps. (i) The differences of each fertilization scenario (N_{NE}, N_{Ymax}, N_{Eco}, and N_{Env}) from N_{FP} was calculated in terms of grain yield; likewise, the differences of each scenario from N_{FP} was also calculated in terms of net profit, or yield-scaled N loss, or N fertilizer input. (ii) The values obtained at step (i) were divided by the corresponding maximum increase (decrease) in terms of grain yield, net profit, yield-scaled N loss, and N fertilizer input, respectively. (iii) The values obtained at step (ii) for N_{FP} in each aspect (grain yield, net profit, yield-scaled N loss, or N fertilizer input) were 0, while the values of N_{Ymax} in terms of grain yield, of N_{Eco} in terms of net profit, and of N_{Env} in terms of environmental benefit and N fertilizer input were equal to 1. Values of other fertilization scenarios in terms of each category are mostly between 0 and 1 and shown in the radar chart. If the value in the chart was positive but closer to 0, there was a smaller advantage compared to N_{FP}. Occasionally, the value was slightly negative, meaning that the advantage was negative, compared with N_{FP}.

management approach may minimize environmental risks and reduce the wastes caused by fertilization. This is an important result, given that a large proportion of farmers in China generally believe that the more fertilizer applied the more crop yield gained. As a consequence, the inorganic N fertilizers are always applied in large quantities to the farmland (Cui et al., 2010). In some rice areas in China, the N fertilizer application rate alarmingly reached 300 kg ha^{-1} or more (Sui et al., 2013; Chen et al., 2014), which undoubtedly posed great risks to the rice yield, profitability and environmental sustainability. Chinese farmers seemed to have a serious lack of basic knowledge about N demand of rice and the guidelines for N fertilizer management (Cui et al., 2010; Yin et al., 2019a). Much efforts have been made in the past studies, and the rice yields showed a trend of quadratic regression or linear-plateau with an increase in N application rate or N balance. For example, Ding et al. (2021) suggested that a higher rice yield could be obtained if the N balance of paddy fields could be controlled within the range of 50–75 kg ha^{-1}. Wu et al. (2015) proposed that the optimum N application rate varied from 114 to 224 kg ha^{-1} for different rice cropping areas, and the rice yield might experience negative effects if the N application rate exceeds this range. Our study showed that a yield increase can be maintained when the N balance is < 54–95 kg ha^{-1} for the different rice cropping seasons (Fig. 2). When the N balance is closer to these values, the yield response curve is flatter.

The N management is critical for agricultural profitability and environmental sustainability. The excessive N fertilizer input means the possibility of an imbalance in the N balance of farmland, which may lead to the direct or indirect negative influence on human health and agricultural profitability (Shibata et al., 2017). As the N balance increased in the paddy field, the profitability increased gradually, up to a certain value, beyond which the profitability did not increase statistically significantly or even declined rapidly (Fig. 3). When the N balance exceeded 25–66 kg ha^{-1} based on the different rice cropping seasons, the N loss would rise sharply by a factor 2–4 (Fig. 4), resulting in higher environmental risks. Through large-scale data analysis, Ying et al. (2017) and Yin et al. (2019a) found that the profitability had a quadratic relationship, while N loss had an exponential relationship, with N application rate. When N application rate exceeded a certain range, the profitability would decline rapidly with an increase in N application rate. Appropriate reduction of N fertilizer input had negligible impact on the profitability, but the N loss was significantly reduced. This is consistent with our results.

Our study showed that NE balanced rice productivity, profitability and sustainability. The recently reported integrated soil–crop system management program (Cui et al., 2018) had similar N fertilizer application rate, compared with the NE system, but with less yield and economic benefits. He et al. (2022) conducted 1534 field experiments in China, and compared NE-based management with farmers' practice as well as an N application approach based on soil testing. The result further showed that NE reduced the fertilizer input by 29.0% and 14.7%, compared with farmers' practice and soil testing approach, however, increased grain yield by 4.4% and profit by 5.8%, and reduced reactive N losses and greenhouse gas (GHG) emissions by 36.2% and 21.5%, respectively. Xu et al. (2022) found that NE improved the yield and NUE of double-cropping rice. They also found that NE enhanced the translocation of nutrients from source organs to sink organs. Furthermore, NE has shown its potential not only in China, but also in other Asian countries. Sapkota et al. (2021) evaluated a large number of on-farm trials in the Indo-Gangetic Plains, and confirmed that NE reduced N input by 15–35%, increased grain yield by 4–8%, and reduced global warming potential by 2–20% compared to FP. In the Terai regions of Nepal, known to have low productivities and high yield gaps, NE significantly increased the yields of rice, maize and wheat, net revenue and NUE, compared with farmers' fields and government's recommendations (Dahal et al., 2018; Amgain et al., 2021; Timsina et al., 2021). Timsina et al. (2022) also indicated a 90–97% agreement between actual rice yield and NE estimated yield. Moreover, NE had higher energy use efficiency, and reduced the greenhouse gas emission intensity. In our study, compared with farmers' practice, the NE system increased the rice grain yield by 4.3% (Fig. 2), and economic benefits by 7.4% (Fig. 3), and reduced the environmental risk by 20.7% (Fig. 4) and the N fertilizer application rate by 12.1% on average. Furthermore, developing countries dominated by smallholder farming have dramatic crop yield gaps (Zhang et al., 2016). The great significance of NE lies in simplifying the complex fertilizer recommendation process with an easy-to-use software program, and conducting the experiments in the farmers' fields. Therefore, farmers easily see the differences between NE and their own practices (FP), thereby facilitating farmers' acceptance of the science-based fertilizer recommendation (NE) to reduce the yield gaps. All these demonstrate that NE has positive effects on agricultural production, field management, and environmental health.

4.2. *Using nitrogen balance as the basis to quantify crop response to nitrogen management*

When the N balance is between 25 kg ha^{-1} and 95 kg ha^{-1} (depending on different rice cropping seasons), the balance of rice yield, profitability and environmental sustainability can be ensured. Response of crop production to N levels has traditionally been examined by relating yield as a function of N application rate. Recently, N balance has been increasingly used for examining the health and sustainability of plant-environment systems in agroecosystems, and its concepts include N input and output (Yang et al., 2007; Sainju, 2017). It is an important indicator to evaluate field management, apparent N loss and agricultural policies, and is widely used in many countries, regions and organizations (Salo and Turtola, 2006; Organisation for Economic Cooperation and Development (OECD), 2007; He et al., 2018). Some previous studies have explored the relationship between N loss and N balance and drew a linear or exponential relationship between the two parameters

(Korsaeth and Eltun, 2000; McLellan et al., 2018). However, it was still extremely ambiguous when setting the upper limit of N loss and making recommendation for the field management based on N balance. Based on the robust relationship of N loss as a function of N balance, Ding et al. (2021) proposed that a piecewise regression function can be used to determine the upper limit of N loss in Chinese rice to provide reliable recommendations for field management. Furthermore, in the context of the growing demand for food around the world, when formulating the agricultural policies, consideration should be given to achieving high crop yields while minimizing N loss for the sake of the environment. By doing so, a win-win situation for the agronomic and environmental goals can be promoted (Van Groenigen et al., 2010; Smith and Gregory, 2013). Therefore, we chose yield-scaled N loss as an important evaluation criterion. We found that N loss grew steadily and slowly with the increase of N balance before the environment threshold point, beyond which the N loss increased sharply (Fig. 4). The EU Nitrogen Expert Panel (2015) believes that a reasonable N balance should be controlled within 80 kg ha^{-1}, and excessive N balance will bring substantial N loss and environmental pollution. Our identified N balance for the environment optimum point was well below this value (Fig. 4a–d). He et al. (2018) reported that the average N balance of cropland in China was 76.9 kg ha^{-1}, but N loss was also considered a part of N output, so the N balance was likely to be higher than 80 kg ha^{-1} in China. In view of the current field N application levels in China, with which the average total N loss was 40–50% (Li et al., 2009; Gu et al., 2015), controlling soil N surplus is necessary to achieve a sustainable agricultural system. In our study, the N balance of only middle rice and single rice for yield and profit maximization (respectively averaged 95.4 and 89.9 kg ha^{-1} for maximum yield, and 90.9 and 86.1 kg ha^{-1} for maximum profit) exceeded this value of 80 kg ha^{-1}, as a result of a large amount N fertilizer applied for these two scenarios. The N balances of the NE treatments in early, late, middle, and single rice (respectively averaged 30.8, 21.4, 41.3, and 58.4 kg ha^{-1}) are all lower than this value. But it is worth noting that we might underestimate the N balance in the places where we adopted straw returning, e.g., JX, HN and HB. This is because we did not consider the nutrients released from the returned straw (ranging from 23.4 to 49.2 kg ha^{-1} based on different years and rice cropping seasons) in the last season in the calculation of the N balance. Although straw returning may increase N balance to some extent, the effect on the different pathways of N loss in the farmland may be minimal (Ding et al., 2020a). It has been proven that straw returning may have positive effects on agricultural productivity and soil fertility, and can compensate for the persistent consumption of soil indigenous N (He et al., 2018; Ding et al., 2020b).

4.3. Range of nitrogen application rates

We recommend N application rates in a range from 122 to 214 kg ha^{-1} (depending on the rice cropping seasons), which can help balance yield, profitability and sustainability of rice. Applying N fertilizer in a smart way can effectively provide necessary N for crop growth, increasing farmers' income, and maintain soil fertility (Zhang et al., 2017b; Bhatt et al., 2019). However, most Chinese farmers generally believe that applying more inorganic N fertilizer can further enhance yield and profit. This is mainly attributed to the deficient access to agricultural knowledge, and the difficulty of popularizing scientific fertilization technology among smallholder farmers. In pursuit of increasing grain production, the blind excessive use of nitrogen fertilizers has a certain negative impact on crop yield, farmers' income and ecological environment. It is of great benefit to provide suggestions and references for rice growers and agricultural policy makers. A reasonable agricultural policy can help reduce the environmental risk associated with the application of synthetic N fertilizer in agricultural production practices, and improve the profitability of agricultural production (Peng et al., 2010). At present, there are many studies on the restriction of N application rate for rice, but our study provided a new idea for determining the range of N application rate in rice, that is, using N balance and N input to determine the N fertilizer input range. Since there is a linearity between N balance and N application rate (Fig. 5), the relationship of rice grain yield, profitability and environment sustainability versus N balance can easily be converted into the range of N application rate for rice.

In this study, the ranges of N application rates following the analysis using N balance were 122–171 kg ha^{-1} in early rice, 133–172 kg ha^{-1} in late rice, 138–214 kg ha^{-1} in middle rice, and 163–212 kg ha^{-1} in single rice (Fig. 5). Zhang et al. (2018) investigated the overall fertilization status of rice in 1531 counties in China, and showed that the amount Chinese farmers apply is generally unreasonable. They suggested that the optimal N application rate of rice in China should be 169–199 kg ha^{-1}, which can effectively reduce the N loss in paddy fields, and guarantee $>$ 95% of the maximum rice grain yield. This range is close to the value we obtained for middle and single rice, and slightly higher than that for double-cropping rice. The yield potential of double-cropping rice is low, and most of the double-cropping rice planting areas adopt straw-returning, which can provide nutrients for the next season of rice. Therefore, there is no need to apply too much N fertilizer. Based on different climate and soil properties with 3896 measurements in rice-producing regions in China, Yin et al. (2019b) estimated that the N requirement of irrigated rice was 110–195 kg ha^{-1} in northern China and 164–262 kg ha^{-1} in southern China. Using statistical analysis and model simulation on multiple rice subspecies, varieties and cropping systems in nine provinces in southeastern China, Chen et al. (2011) indicated that the N application rate of rice was 180–285 kg ha^{-1} and 90–150 kg ha^{-1}, proposed from economic and ecological perspective, respectively. The N application rates of northern China and ecological aspects mentioned above were close to the proposed values by our study. However, the recommended N fertilizer rate for the rice in southern China by Chen et al. (2011) was much higher than our ranges. The N application rate in the southeast coastal area is very high, reaching about 300 kg ha^{-1} (Sui et al., 2013), which may easily cause N loss and environment pollution. Therefore, there is further room to reduce the N application rate. Wang et al. (2012) conducted 514 field experiments in Hubei Province, and according to the field conditions in different regions of Hubei province, the optimal N application rate they suggested was 138–165 kg ha^{-1}. Huang et al. (2008) conducted a two-year field experiment on two rice varieties using Site-specific Nutrient Management in Hubei Province, and concluded that the minimum N fertilizer input for these two rice varieties should be 120–150 kg ha^{-1}. The above recommended N application rate were similar to our study, all of which can reduce the environmental risk while ensure considerable rice grain yield.

4.4. Caveats of our study

This study systematically evaluated the impact of the NE system on rice grain yield, profitability and environmental benefits under different rice cropping systems through multi-year field experiments in five provinces of China. However, the used prices for calculating the net profit were average values across the whole country, and the N losses were obtained from empirical models in the literature. Different regions, climates and cultural practices created uncertainties in our evaluation. It is known that N losses vary significantly over time and space. For example, the N loss through ammonia volatilization is often difficult to determine and is affected by rainfall, temperature, soil texture, field N fertilizer management and other factors (Dattamudi et al., 2016; Li et al., 2021). Furthermore, rice is one of the major contributors to atmospheric nitrous oxide (N_2O). N_2O fluxes in paddy fields are affected by water management, soil conditions, microbial communities and algae (Bridgham et al., 2013; Nurulhuda et al., 2018; Timilsina et al., 2020), and the economic losses caused via N_2O emission are difficult to estimate accurately. Similarly, it is also difficult to quantify the N input from environment. For instance, atmospheric N deposition is significantly affected by rainfall, snowfall, temperature, the living and consumption conditions of human beings and the degree of urbanization and industrialization (Galloway et al., 2008; Wang et al., 2019). The N content of irrigation water is also influenced by N pollution of local water sources, field water management, and climate conditions. The investigations of N loss from ecosystem in relation to climate stability have always been inconsistent, and the estimated impacts are subject to great controversy and uncertainty (Mrozek and Taylor, 2002). Furthermore, rice cultivation is affected by many climate factors, like temperature, precipitation, and radiation, and the intensifying global climate change poses a huge threat to rice cultivation (Sarker et al., 2012; Shi et al., 2017; Yang et al., 2019; Hussain et al., 2020; Shao et al., 2021). Further research and field investigations are necessary to provide a better understanding of relevant processes, reduce the uncertainty of parameter values, and provide more accurate recommendations of nutrient management measures for various climate threat scenarios.

5. Conclusion

This study analyzed the data of field experiments conducted from 2017 to 2020 in five provinces with three different rice cropping systems. The ability of the Nutrient Expert® (NE) system to balance the rice grain yield, profitability, and environmental sustainability was examined, and the ranges of N application rate for rice was established. Compared with FP, NE significantly increased rice grain yield and net profit in early rice and late rice. Furthermore, it significantly reduced environmental risks of agricultural production by reducing the yield-scaled N loss. Based on the quantitative response curves that we established for different rice-based cropping systems, we recommend ranges of N application rate to be 122–171 kg ha^{-1} in early rice, 133–172 kg ha^{-1} in late rice, 138–214 kg ha^{-1} in middle rice, and 163–212 kg ha^{-1} in single rice. This study verified the advantages of the NE system in rice cropping systems. The NE system provides a favorable reference for scientific N fertilizer management in paddy fields, which has great significance for reducing the knowledge and yield gap, advocating the best fertilizer management decisions, efficiently intensifying fertilizer resources, and promoting green and sustainable agriculture development.

Declaration of Competing Interest

The authors declare no conflict of competing interests.

Data availability

Data used for the research described in the article could be obtained upon request.

Acknowledgements

This research was financed by the National Natural Science Foundation of China (No. 31471942) and National Key Research and Development Program of China (No. 2016YFD0200101). We acknowledge all those who provided local assistance or technical help to the Nutrient Expert Network in China. ZX thanks the China Scholarship Council for awarding him the PhD fellowship (No.202003250121) to study at Wageningen University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103575.

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