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European Journal of Agronomy

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https://doi.org/10.1016/j.eja.2022.126513

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European Journal of Agronomy 137 (2022) 126513

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Simultaneously improving yield and nitrogen use efficiency in a double rice cropping system in China

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ARTICLE INFO

Keywords:
Aboveground biomass
Nitrogen uptake
Nitrogen management
Nutrient recovery efficiency
Nutrient translocation

ABSTRACT

The Nutrient Expert system (NE) has been proposed to improve yield and nitrogen (N) use efficiency (NUE) in the double rice cropping systems in China. However, the advantage of the NE system has yet to be quantified experimentally. A four-year field experiment was conducted in a double rice cropping system in China, to evaluate the ability of NE in improving yield and NUE. The experimental treatments consisted of NE based fertilization, current farmers' practices (FP) and soil test based fertilizer recommendation (ST), and a series of nitrogen (N) rate treatments. The NUE decreased with increasing N application, while the yield did not increase significantly beyond N application rates of about 140 kg ha^{-1} (corresponding to the amount proposed by NE) in both early and late rice. NE increased grain yield (by 10.3% and 6.3%) and N uptake (by 5.7% and 4.0%) compared with FP and ST, respectively. NE significantly increased NUE compared with FP, and decreased the N surplus in comparison to FP and ST. The N dilution curve was $Nc = 34.50\ W^{-0.55}$ for early rice and $Nc = 37.71\ W^{-0.59}$ for late rice (where Nc is the N concentration in g kg^{-1}, and W is the dry matter accumulation in t ha^{-1}). The relationship between relative yield and the nitrogen nutrition index derived from the dilution curves confirmed that NE offered an optimum N application rate (approximately 140 kg ha^{-1}) for both early and late rice. Carbon (C) and N translocation from vegetative organs to grains was enhanced with increasing N rate, while NE significantly increased C and N translocation compared with FP. Overall, the NE system ensured a high rice yield, increased N uptake and NUE. Therefore, the NE, as a user-friendly tool, is a sustainable fertilizer recommendation approach suitable for double rice cropping system, especially when soil testing is not available or timely for smallholders.

1. Introduction

Nitrogen (N) is considered to play a crucial role in high-yielding production of rice (*Oryza sativa* L.) (Kiba and Krapp, 2016). In recent decades, the rice yield has increased significantly in China; this is primarily attributed to the genetic gain and increase in input of inorganic fertilizers, especially N fertilizers (Ju et al., 2009; Miao et al., 2010; Li et al., 2019). However, applying N fertilizer should aim to obtain both higher yields and better N use efficiency (NUE) (Mueller et al., 2012). A smart N supply can provide a high NUE and considerable economic benefits (Pan et al., 2012). Farmers, however, apply N in hope for high productivities, and often tend to over-fertilize, leading to low NUE of rice production in China (Vitousek et al., 2009; Peng et al., 2010). Over-fertilization is detrimental to plant development, reproduction, and grain quality (Mikkelsen and Hartz, 2008). Moreover, over-fertilization causes a series of environmental issues, e.g.,

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Abbreviations: AB_N, apparent balance of nitrogen; AE_N, agronomic efficiency of nitrogen; C, carbon; FP, farmers' practices; HI, harvest index; K, potassium; LAI, leaf area index; N, nitrogen; N0, nitrogen omission; Nc, N concentration; NE, Nutrient Expert; NHI, nitrogen harvest index; NNI, nitrogen nutrition index; NUE, nitrogen use efficiency; P, phosphorus; PFP_N, partial factor productivity of nitrogen; PNB_N, partial nutrient balance of nitrogen; RE_N, recovery efficiency of nitrogen; RE_{Nac}, accumulated recovery efficiency of nitrogen; ST, soil testing.

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https://doi.org/10.1016/j.eja.2022.126513
Received 10 February 2022; Received in revised form 23 March 2022; Accepted 2 April 2022

greenhouse gas emissions (Kahrl et al., 2010; Liu et al., 2015), soil fertility degradation (Reidsma et al., 2012), and ground and surface water pollution (Letey and Vaughan, 2013).

To increase grain yield without creating environmental problems, fertilizer recommendation based on soil testing (ST) has been implemented in China since 2005, and promoting this activity at a large scale has yielded positive results (He et al., 2009; Yusuf et al., 2009). Although this activity has reduced the inappropriate use of fertilizers, the correlations between soil testing values and crop yields are very low especially for rice (Dobermann et al., 1995). Moreover, soil testing entails a cumbersome process, takes a long time and is expensive, and is therefore not accessible to smallholder farmers (Tang et al., 2021). A site-specific nutrient management method based on yield response and agronomic efficiency was jointly developed by the Institute of Agricultural Resource and Regional Planning, Chinese Academy of Agricultural Sciences, China (IARRP, CAAS) and the International Plant Nutrition Institute (IPNI) to surmount above limitations. These institutes developed the so-called Nutrient Expert (NE) system for rice (Xu et al., 2017).

This NE system uses computer-based decision support technology and a questionnaire to provide a simple advice despite the complexity of the principles behind fertilization (He et al., 2022; Xu et al., 2017). The NE system aims to provide 4 R nutrient stewardship (using fertilizers with the Right source, at the Right rate and at the Right time, and in the Right place) based on a field management method for farmer fields. The NE system has been widely used in rice production, especially in terms of right fertilizer sources and fertilization places that are supported by the local agricultural extension system. Yet, the ability of the NE system in improving rice grain yield and NUE needs experimental confirmation. Moreover, there are still no reports on the physiological bases of increasing grain yield and NUE by NE. Here, we hypothesize that the NE system promotes the translocation of nutrients from source organs to sink organs during grain filling, thus increasing rice grain yield and NUE.

It is well-known that the analysis of NUE of any fertilization strategies such as NE or ST must refer to the crop N demand and then assess if crop N demand is fully satisfied by N supply. The more this N demand is satisfied, the less will be the response of the crop to N fertilization. There is a well-established method for estimating the extent of crop N demand satisfaction: the Nitrogen Nutrition Index, NNI (Lemaire et al., 2008; Lemaire and Ciampitti, 2020). The NNI values can be derived from the known fact that the N concentration (Nc) in a crop decreases with an increase in shoot biomass (Greenwood et al., 1990). This decrease in N concentration can be expressed as a power function called the “critical N-dilution curve” (Lemaire et al., 2008), i.e, the curve for the minimal concentration of total N in shoots that produced the maximum aerial dry matter. The N dilution curve helps dynamically diagnosing the N status in the crop’s vegetative stages, which is crucial to evaluate plant N demand, predict crop yield and optimize N management. The NNI can be obtained by dividing the actual plant N concentration by the Nc value determined by the N dilution curve, and NNI can be used as a practical diagnostic tool for analyzing N status in plant (Lemaire and Meynard, 1997; Ziadi et al., 2008). So far, there is a lack of data on the evaluation of NUE using the N dilution curve and the NNI to assist in evaluating the fertilizer management performance of the NE system.

The objectives of this study are: (i) to demonstrate the ability of the NE system in improving rice grain yield and NUE, (ii) to use the “critical dilution curve-NNI” framework to confirm the validity of the NE system, and (iii) to analyze the crop physiological basis of the simultaneous improvement of yield and NUE. We do so by determining grain yield, N uptake dynamics, NUE and nutrient translocation of rice under various nutrient management scenarios and N application rates, based on a four-year experiment with early and late rice planting, thus encompassing eight growing seasons in China.

2. Material and methods

2.1. Experimental site

A four-year field experiment was carried out in a double rice cropping system, i.e. with early and late rice planting (in total eight growing seasons) on an experimental field at Jiangxi Institute of Red Soil (166.17 N, 28.35 E) from 2017 to 2020 in Zhanggong town, Jinxian County, Jiangxi province, China. The experimental site is situated in the south bank of the middle and lower reaches of the Yangtze River. The climate is subtropical, humid, monsoonal, warm and rainy. The average annual sunshine hours, air temperature, surface evaporation, and precipitation are 1809.5 h, 17.7 ℃, 1318 mm and 1700 mm, respectively. More than 50% of the precipitation is concentrated in the period from April to June. The daily precipitation and air temperature throughout the experimental period are shown in Fig. 1. The soil properties (0–20 cm) of the experimental field were determined from soil samples collected before the experiment. The soil is a red paddy soil with an organic matter content of 20.88 g kg^{-1}, total N of 1.32 g kg^{-1}, alkali-N of 160.58 mg kg^{-1}, Olsen-P of 47.65 mg kg^{-1}, NH_4OAc-K of 114.70 mg kg^{-1}, pH of 5.34, and a soil bulk density of 1.21 g cm^{-3}. Irrigation was implemented whenever needed to avoid any drought.

2.2. Experimental design

The experimental treatments included: (1) current farm practices (FP, the farmers’ practices in the region but managed in experimental plots); (2) soil testing (ST, fertilizer recommendation based on soil testing given by local researcher or technician); (3) Nutrient Expert (NE, fertilizer recommendation based on Nutrient Expert decision support tool); (4) N omission plots (N0, no N applied), which was conducted to calculate recovery efficiency of N (REN) and agronomic efficiency of N (AEN), and series of N rates based on which included different percentages of plus N (+N) and minus N (-N) expressed as NE ± 15%N, NE ± 30%N and NE ± 45%N to test the accuracy of N rate based on NE, and to assess the N transformation and translocation from source to sink organs. In 2020, the NE-based N rate was slightly adjusted using NE ± 25%N to replace NE ± 15%N and NE ± 30%N, and using NE ± 50%N to replace NE ± 45%N, respectively. A randomized complete block experiment with three replications was conducted on the plot size of 30 m^2 (5 m × 6 m). Fertilizer N-P_2O_5-K_2O rate produced by NE was 139–48–43 kg ha^{-1} for early rice, and 140–53–53 kg ha^{-1} in late rice. Comparatively, fertilizer N-P_2O_5-K_2O rate applied by ST was 135–78–120 for early rice, and 180–60–63 for late rice, while that applied by FP was 159–90–80 for early rice, and 205–101–101 for late rice, respectively. The N and K basal-topdressing ratios were 4:3:3 and 5:0:5 for NE, 4:3:3 and 5:5:0 for ST, and 4:6:0 and 5:5:0 for FP, respectively. The above N and K fertilizers were applied in splits at basal, tillering and booting stage, 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 among the most cultivated in the experimental area, and detailed information about rice cultivars, sowing date, transplanting date and harvesting date of each rice planting season from 2017 to 2020 is listed in Table 1. Before transplanting, 20-cm high earth banks were built artificially on the paddy field to separate the experimental plots, and 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. No manure fertilizer was applied. The planting density was 25 hills m^{-2}. Pesticide and herbicide were sprayed manually before rice transplanting and regreening stage. There was no obvious weed, pest or disease stress during the entire experiment. But in 2020, there was an extreme rainstorm during the early summer, and a continuous low temperature in the autumn, which led to an early harvest of the early rice and a delayed harvest of

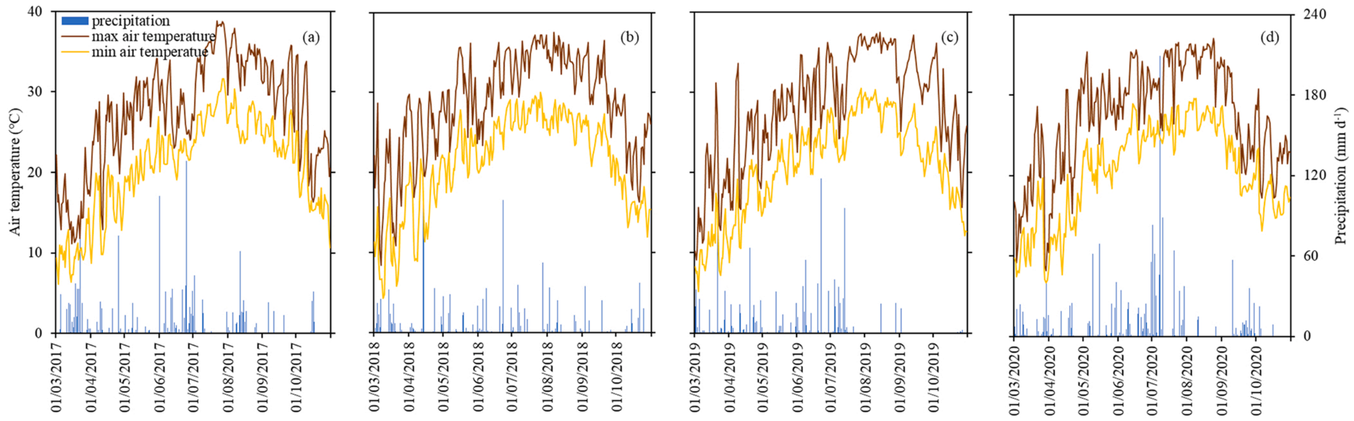

Fig. 1. Daily air temperature and precipitation throughout the rice growing seasons. (a), (b), (c) and (d) indicate the rice growing seasons from March to October in 2017, 2018, 2019, 2020, respectively, and share the same legends.

Table 1
Rice cultivars and dates of sowing, transplanting and harvesting during each growing season from 2017 to 2020.

Growing season		Rice cultivar	Date (date/month/year)		
			Sowing	Transplanting	Harvesting
2017	Early rice	Yihe9	29/03/2017	26/04/2017	26/07/2017
	Late rice	Zhengcheng456	05/07/2017	29/07/2017	27/10/2017
2018	Early rice	Yihe9	26/03/2018	22/04/2018	25/07/2018
	Late rice	Zhengcheng456	05/07/2018	28/07/2018	30/10/2018
2019	Early rice	Yihe9	31/04/2019	27/04/2019	21/07/2019
	Late rice	Zhengcheng456	03/07/2019	31/07/2019	25/10/2019
2020	Early rice	Tanliangyou83	01/04/2020	29/04/2020	14/07/2020
	Late rice	Jiyou3	07/07/2020	30/07/2020	02/11/2020

the late rice.

2.3. *Sampling and analyses*

In 2019 and 2020, flowering date was recorded when 50% of anthers protruded out of the glumes. Six hills were collected at tillering, stem-elongating, flowering, and grain-filling stages to determine aboveground biomass and N concentration. At rice sampling, aboveground biomass was determined by collecting samples of 1 m^2 area of rice crop near the center of each plot. Samples were dried in an oven set at 105 ℃ for 15 min to de-activate enzymes followed by further drying at 80 ℃ for 72 h until constant weight. Sub-samples from the biomass samples were divided into vegetative and grain parts, and were crushed and passed through a 0.42-mm sieve to determine N concentrations using an element analyzer (Elementar vario MACRO cube, Germany). At final harvest during each of the eight seasons, the rice grains of each plot were harvested manually, by collecting all plants in each plot, excluding the two most marginal lines and the sampling areas for intermediate harvests. The rice yields per hectare were standardized expressing them on the basis of a moisture content of 14%.

Leaf area index (LAI) was assessed manually in 2019 and 2020 at stem-elongating, flowering, and grain-filling stages via collecting plants of three hills in the middle rows and measuring all leaf area. The leaf area was measured as the length of green leaf (from leaf base to leaf tip) multiplied by the maximum width of the blade and an empirical shape factor of 0.75 (Palaniswamy and Gomez, 1974).

2.4. *Calculations*

2.4.1. *Harvest index*

Harvest index (HI) and N harvest index (NHI) are quantified as follows (Hay, 1995; Lu et al., 2015):

$$\mathrm{HI} = B_G \,/\, B_A \tag{1}$$

$$\mathrm{NHI} = U_G \,/\, U_A \tag{2}$$

where B_G and B_A are the rice grain biomass (t ha^{-1}) and the aboveground biomass (t ha^{-1}) at the final harvest, respectively; U_G and U_A are the N present in the rice grain biomass (kg ha^{-1}) and in the aboveground biomass (kg ha^{-1}) at the final harvest, respectively.

2.4.2. *Nitrogen use efficiency*

Several parameters were regarded as important components of NUE (He et al., 2009; Yang et al., 2017). First, the recovery efficiency (RE_N) reflects how much applied fertilizer N in the current season was taken up by the crops, and accumulated recovery efficiency (RE_{Nac}) describes the percentage of total applied fertilizer N that was taken up by crops in a continuous planting land.

$$\mathrm{RE_N}\ (\%) = (U - U_0) \,/\, F_{inp} \tag{3}$$

$$\mathrm{RE_{Nac}}\ (\%) = (U_{ac} - U_{0ac}) \,/\, F_{inpac} \tag{4}$$

where U_0 and U are the seasonal N uptake in the aboveground crop biomass in the N0 plots and N-treated plots (kg ha^{-1}); U_{0ac} and U_{ac} are the total accumulated N uptake of all rice growing seasons in the aboveground crop biomass in the N0 plots and N-treated plots (kg ha^{-1}); F_{inp} and F_{inpac} are the seasonal N fertilizer input (kg ha^{-1}) and total accumulated N fertilizer input of all rice growing seasons (kg ha^{-1}).

Secondly, agronomic efficiency (AE_N) and partial factor productivity (PFP_N) represent the ability of applied fertilizer N to improve grain yield.

$$\mathrm{AE_N}\ (\mathrm{kg\ kg^{-1}}) = (Y - Y_0) \,/\, F_{inp} \tag{5}$$

$$\mathrm{PFP_N}\ (\mathrm{kg\ kg^{-1}}) = Y \,/\, F_{inp} \tag{6}$$

where Y_0 and Y are the seasonal rice grain yield at harvest in the N0 plots and N-treated plots (kg ha^{-1}).

Thirdly, partial nutrient balance (PNB_N) and apparent balance (AB_N) of the N applied indicate whether nutrient management treatments are depleting or enriching soil N.

$$\mathrm{PNB_N}\ (\mathrm{kg\ kg^{-1}}) = N_{out} \,/\, N_{inp} \tag{7}$$

$$\mathrm{AB_N}\ (\mathrm{kg\ ha^{-1}}) = N_{inp} - N_{out} \tag{8}$$

where N_{inp} is seasonal N input (kg ha^{-1}, including fertilizer N input and N content of rice straw in the previous season), and N_{out} is the seasonal N removal from rice harvest (kg ha^{-1}). Note that seasonal N removal only included the rice grain N content, but not straw N at harvest because, as stated earlier, straw was incorporated into the soil after grain harvest.

2.4.3. *Carbon and nitrogen translocation efficiency*

Carbon (C, expressed in dry matter, DM) formation of grain can be calculated as (He et al., 2004):

$$\text{Grain C mobilized from vegetative organs (t ha}^{-1}) = DM_{\mathrm{vf}} - DM_{\mathrm{vm}} \quad (9)$$

$$\text{Grain C from postflowering photosynthesis (t ha}^{-1}) = DM_{\mathrm{gm}} - (DM_{\mathrm{vf}} - DM_{\mathrm{vm}}) \quad (10)$$

$$\text{C translocation efficiency (\%)} = (DM_{\mathrm{vf}} - DM_{\mathrm{vm}}) / DM_{\mathrm{vf}} \times 100\% \quad (11)$$

where DM_{vf} and DM_{vm} are the dry matter of vegetative organs at flowering stage and maturity (t ha^{-1}), DM_{gm} is the dry matter of grain at maturity (t ha^{-1}). Likewise, equivalent values for N can be calculated as (He et al., 2004):

$$\text{Grain N mobilized from vegetative organs (kg ha}^{-1}) = N_{\mathrm{vf}} - N_{\mathrm{vm}} \quad (12)$$

$$\text{Grain N from postflowering uptake (kg ha}^{-1}) = N_{\mathrm{gm}} - (N_{\mathrm{vf}} - N_{\mathrm{vm}}) \quad (13)$$

$$\text{N translocation efficiency (\%)} = (N_{\mathrm{vf}} - N_{\mathrm{vm}}) / N_{\mathrm{vf}} \times 100\% \quad (14)$$

where N_{vf} and N_{vm} are the N content of vegetative organs at flowering stage and maturity (kg ha^{-1}), and N_{gm} is the N content of grain at maturity (kg ha^{-1}).

2.4.4. *Critical nitrogen dilution curve*

As stated earlier, for 2019 and 2020, we had plant materials sampled at various stages and we used these data to construct the critical N curves based on the method of Justes et al. (1994). The data points were first divided into two groups, namely (a) the N-limiting group, where increasing N supply significantly increased plant dry matter and N concentration, and (b) the non-N-limiting group, where further N added did not result in an increase in plant dry matter and N concentration. The N concentrations as the Y-axis were plotted against aboveground dry matter in the X-axis for both groups. For each sampling stage, the N concentrations of the N-limiting group were linearly regressed versus the aboveground dry matter, while the mean of all data points of the non-N-limiting group was taken to draw a line vertical to the X-axis. The intersection of the fitted regression line of the N-limiting group and the vertical line of the non-N-limiting group was considered as the theoretical critical N concentration at that sampling stage, and the intersection points of all sampling stages were then connected. This procedure allows to construct the critical N dilution curve covering a wide range of aboveground biomass values, which is commonly described by an allometric relationship as (Lemaire and Ciampitti, 2020):

$$\mathrm{Nc} = a\mathrm{W}^{-b} \quad (15)$$

where Nc is the N concentration (g kg^{-1}), W is the dry matter accumulation in the crop (t ha^{-1}). The coefficient a (g kg^{-1}) represents the value of Nc for $\mathrm{W} = 1$ t ha^{-1}, and the coefficient b is dimensionless, together quantifying the relationship between the decrease in N concentration and the increase in aboveground dry matter. Strictly speaking, the above allometric relationship should be written as $\mathrm{Nc} = a(\mathrm{W}/\mathrm{W}_0)^{-b}$ in order to make the exponent b dimensionless (see Yin et al., 2021), thereby the coefficient a referring to the value of Nc when W equals W_0. Eq. (15) does not have the W_0 term as W_0 is implicitly set to be 1 t ha^{-1}. Note that the data points with shoot dry matter < 1 t ha^{-1} are usually not used in assessing the N dilution curve (Lemaire and Gastal, 1997; Herrmann and Taube, 2004), because with a shoot dry matter < 1 t ha^{-1}, the critical N concentration is constant. After generating the N dilution curves of early rice and late rice, we performed an F test to verify whether the two curves were significantly different. To this end, we estimated two sets of parameters using the SAS package: set 1: assuming early and late rice had different parameter values; set 2: assuming they had common parameter values. Then the F test was constructed based on the degree of freedom and the sum of squares of the residual term of the two sets.

2.4.5. *Nitrogen nutrition index and relative yield*

The N nutrition index (NNI) has been used as a diagnostic tool for analyzing and explaining the variations in yield by differences in crop N status (Lemaire and Meynard, 1997):

$$\mathrm{NNI} = \mathrm{Na} / \mathrm{Nc} \quad (16)$$

where Na is the actual crop N concentration, and Nc is the crop N concentration from the N dilution curve. If $\mathrm{NNI} = 1$, N nutrition is considered optimum, while $\mathrm{NNI} > 1.0$ means that N nutrition supply excesses the crop's demand and $\mathrm{NNI} < 1$ indicates N deficiency.

In addition, to identify a threshold NNI value for high yield using data across treatments and seasons (see the Results), we expressed yield data in relative yield:

$$\text{Relative yield} = \text{grain yield / maximum grain yield} \quad (17)$$

where maximum grain yield refers to the maximum yield value observed among all the treatments in a given season.

2.5. *Statistical analysis*

The significance of differences in rice yield, aboveground biomass, NUE, HI, C and N translocation and other parameters between NE, FP and ST treatments were performed by an analysis of variance (ANOVA) using SPSS Statistics 18.0 package. The treatment means were separated using the least significant difference (LSD) at $P < 0.05$. The regression analyses were performed using SPSS. Response models (quadratic or linear-plateau models) were generated using Excel (2016) and the NLIN procedure in SPSS, respectively.

3. Results

3.1. *Grain yield, biomass and harvest index*

The rice grain yield and biomass were significantly affected by N application (Fig. 2, $P < 0.05$). The average yield and biomass of early rice ranged from 3.4 to 7.7 t ha^{-1} and 6.5–12.8 t ha^{-1}, while those of late rice were 3.9–9.6 t ha^{-1} and 7.0–16.2 t ha^{-1}. In most growing seasons, no significant yield and biomass increases were observed beyond an N application rate of early rice of 139, and of late rice of 140 kg ha^{-1}. There was no significant difference in biomass among NE, FP and ST strategies. But NE significantly increased grain yield of early rice by 10% compared with FP, and increased grain yield of late rice by 11% and 7% compared with FP and ST, respectively. The higher grain yield of NE was mainly attributed to a higher HI (Table 2, averages 0.48, 0.47, and 0.47 for NE, FP, and ST, respectively, in early rice, and 0.50, 0.47, and 0.50 in late rice, respectively).

3.2. *Nitrogen uptake and harvest index of nitrogen*

N uptake increased with an increase in N application rate (Fig. 2). The N uptake of early and late rice ranged from 54.9 to 113.8 kg ha^{-1} and from 51.3 to 140.8 kg ha^{-1}, respectively. In most growing seasons, N uptake did not further increase significantly when N application rate of early rice exceeded 139 kg ha^{-1} and for late rice exceeded 140 kg ha^{-1}. The difference in NHI among treatments was not significant in 2017–2019 (Table 2), but in the 2020 late rice, NE increased NHI by 10% compared with FP, with an average of 0.66 vs. 0.60, which

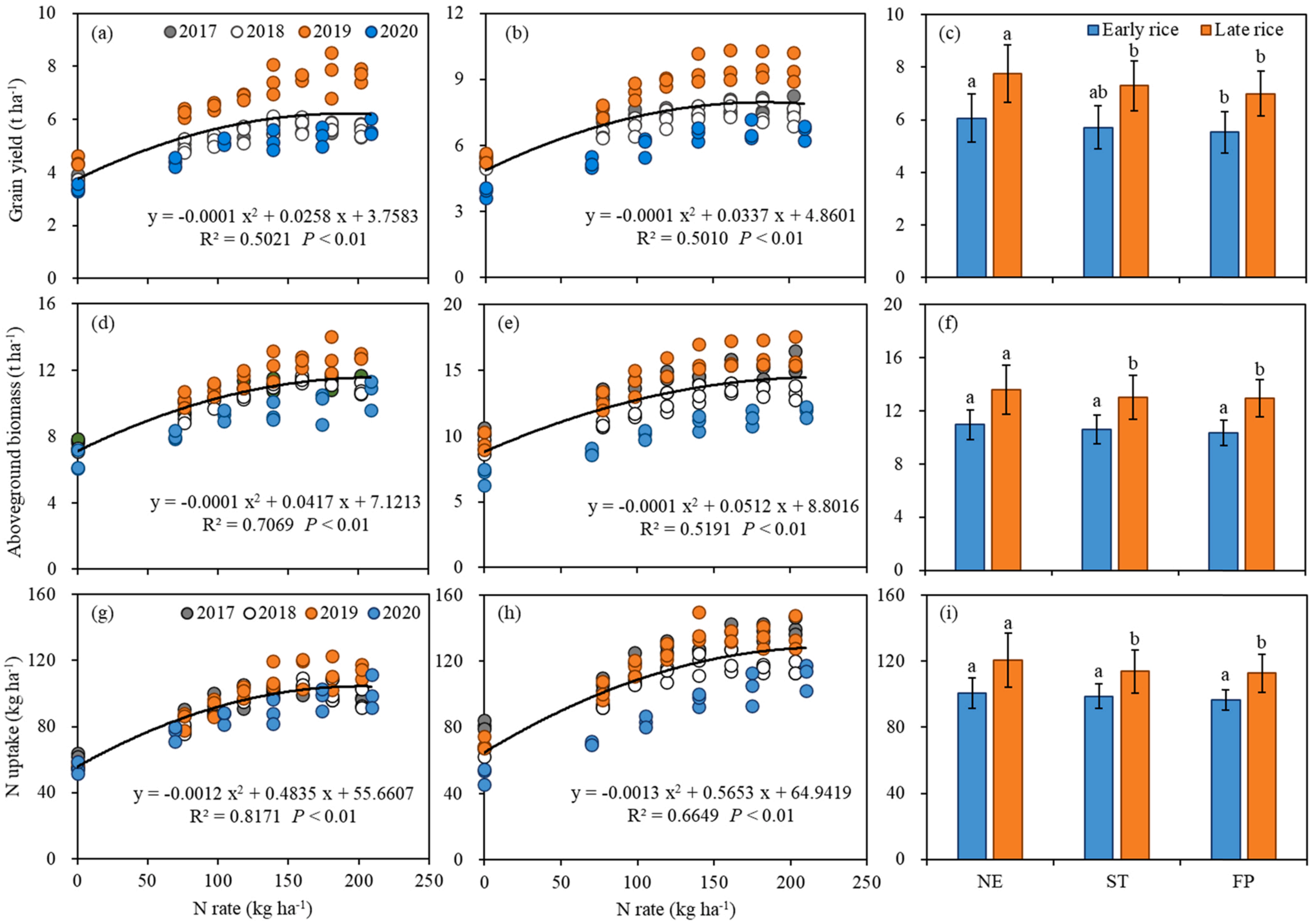

Fig. 2. The relationship between rice grain yield (a, b), aboveground biomass (d, e), N uptake (g, h) and N application rate for early rice (a, d, g) and late rice (b, e, h) from 2017 to 2020, with the four-year average rice grain yield (c), aboveground biomass (f), and N uptake (i) given in the right column for the three nutrient management methods (NE, ST and FP). Detailed seasonal parameters of the three nutrient management methods are given in the Appendix Table A.1 and A.2.

means that a higher proportion of N was accumulated in grains in NE. Over the four years, NE significantly increased N uptake of late rice by 6.8% and 5.8% compared with FP and ST, with averages of 112.9, 114.0, and 120.6 kg ha^{-1}, respectively, while the N uptake among the treatments in early rice was similar.

3.3. *Nitrogen use efficiency*

The RE$_N$ of early and late rice ranged from 18.7% to 37.5% and from 17.6% to 49.5%, and decreased beyond a certain N application rate (Fig. 3). In most growing seasons, NE–15% (averaged 33.4% and 38.2% in early and late rice, respectively) and NE (averaged 31.1% and 37.4% in early and late rice, respectively) showed the highest RE$_N$. Over the four years, NE significantly increased RE$_N$ (by 6.6% and 15.7% point of RE$_N$ in early and late rice, respectively), compared with FP (averaged 24.5% and 21.7% in early and late rice, respectively), and 12.1% point in late rice compared with ST treatment (25.3%). RE$_{Nac}$ significantly declined with an increase in N application rate, and overall, showed an upward trend from season to season (Fig. 4, $P < 0.05$). The RE$_{Nac}$ of NE was 10.3% and 4.6% point significantly higher than that of FP and ST, with an average of 32.5% vs. 22.2% vs. 27.9%.

AE$_N$, PFP$_N$ and PNB$_N$ were significantly impacted by N application rate; the regression analyses showed that AE$_N$, PFP$_N$ and PNB$_N$ decreased with an increase in N application rate (Fig. 3, $P < 0.05$). Over the four years, AE$_N$ ranged from 8.3 to 24.2 and from 6.0 to 30.8 kg kg^{-1}; PFP$_N$ ranged from 27.1 to 93.6 and from 30.2 to 98.7 kg kg^{-1}; PNB$_N$ ranged from 0.19 to 0.62 and from 0.24 to 0.60 kg kg^{-1}, in early and late rice, respectively. NE significantly increased AE$_N$ by 50.0% and 100.0%, PFP$_N$ by 25.3% and 62.0% and PNB$_N$ by 24.1% and 51.9% in early and late rice compared with FP. NE also significantly increased AE$_N$, PFP$_N$ and PNB$_N$ by 55.0%, 36.8%, and 32.2% in comparison to ST treatment in late rice.

Seasonal AB$_N$ of early and late rice ranged from –30.4–219.0 kg ha^{-1} and from –14.5–187.2 kg ha^{-1}, respectively (Fig. 3). Except for N0 treatment (averaged –8.9 and –14.3 kg ha^{-1} in early and late rice), other N application treatments showed positive N balance (i.e., N input > output). Over the four years, NE significantly decreased AB$_N$ in early rice compared with FP, with an average of 119.6 vs. 140.2 kg ha^{-1}, and in late rice in comparison to FP and ST, with an average of 108.9 vs. 179.6 vs. 153.1 kg ha^{-1}.

3.4. *Critical nitrogen dilution curve and nitrogen nutrition index*

Aboveground biomass of early rice and late rice ranged from 0.65 to 14.01 t ha^{-1} and from 0.83 to 17.60 t ha^{-1}, respectively, from tillering stage to maturity, depending on N application rate, management, sampling date and year. The aboveground biomass increased with increasing N application rates across all sampling dates during 2019 and 2020 (Fig. A.1). N concentration always decreased with growth: N concentration ranged from 7.56 to 36.31 g kg^{-1} for early rice and from 7.25 to 36.40 g kg^{-1} for late rice (Fig. A.2).

Across the years, eight points between 3.66 and 12.45 t ha^{-1} in early rice and 10 points between 1.51 and 15.66 t ha^{-1} in late rice of aboveground biomass were used to derive the theoretical critical N

Table 2
Harvest index (HI) and N harvest index (NHI) at maturity under different N treatments during each rice growing season from 2017 to 2020.

Year	Treatments	Early rice		Late rice	
		HI	NHI	HI	NHI
2017	N0	0.44 a[a]	0.51 a	0.45 ab	0.54 a
	NE–45%	0.46 a	0.55 a	0.48 a	0.57 a
	NE–30%	0.44 a	0.53 a	0.46 ab	0.55 a
	NE–15%	0.45 a	0.53 a	0.46 ab	0.56 a
	NE	0.45 a	0.55 a	0.46 ab	0.53 a
	NE+15%	0.44 a	0.54 a	0.45 b	0.53 a
	NE+30%	0.44 a	0.55 a	0.45 b	0.53 a
	NE+45%	0.44 a	0.55 a	0.44 bc	0.53 a
	ST	0.43 a	0.56 a	0.42 c	0.52 a
	FP	0.44 a	0.55 a	0.42 c	0.52 a
2018	N0	0.43 a	0.50 a	0.50 a	0.61 a
	NE–45%	0.47 a	0.52 a	0.52 a	0.65 a
	NE–30%	0.45 a	0.54 a	0.50 a	0.63 a
	NE–15%	0.46 a	0.54 a	0.50 a	0.62 a
	NE	0.46 a	0.55 a	0.50 a	0.62 a
	NE+15%	0.45 a	0.53 a	0.50 a	0.63 a
	NE+30%	0.44 a	0.53 a	0.48 a	0.63 a
	NE+45%	0.45 a	0.52 a	0.48 a	0.62 a
	ST	0.43 a	0.51 a	0.51 a	0.62 a
	FP	0.43 a	0.51 a	0.48 a	0.63 a
2019	N0	0.52 a	0.62 a	0.50 b	0.61 a
	NE–45%	0.54 a	0.66 a	0.53 ab	0.63 a
	NE–30%	0.53 a	0.65 a	0.53 ab	0.63 a
	NE–15%	0.52 a	0.64 a	0.52 ab	0.63 a
	NE	0.53 a	0.65 a	0.52 ab	0.62 a
	NE+15%	0.53 a	0.64 a	0.52 ab	0.64 a
	NE+30%	0.53 a	0.65 a	0.52 ab	0.64 a
	NE+45%	0.52 a	0.63 a	0.51 ab	0.62 a
	ST	0.52 a	0.62 a	0.54 a	0.65 a
	FP	0.51 a	0.63 a	0.50 ab	0.63 a
2020	N0	0.46 b	0.59 b	0.49 a	0.63 bcd
	NE–50%	0.48 a	0.58 b	0.52 a	0.68 a
	NE–25%	0.49 a	0.65 a	0.52 a	0.66 ab
	NE	0.49 a	0.61 ab	0.52 a	0.65 abc
	NE+25%	0.48 a	0.60 ab	0.51 a	0.63 bcd
	NE+50%	0.47 a	0.63 ab	0.49 a	0.60 d
	ST	0.50 a	0.65 a	0.51 a	0.63 bcd
	FP	0.49 a	0.61 ab	0.49 a	0.60 cd

[a] Average; values followed by different letters in the same column within a year are significantly different at $P < 0.05$.

points (Fig. 5). The critical N dilution curves for early and late rice were estimated as:

$$Nc = 34.50W^{-0.55} \tag{18}$$

$$Nc = 37.71W^{-0.59} \tag{19}$$

where Nc is N concentration (g kg^{-1}) in the shoot, and W is the aboveground biomass (t ha^{-1}). The model of Eqs. (18) and (19) accounted for 97% and 94% of the total variance in early rice and late rice, respectively (Fig. 5).

The F-test suggested that the two curves obtained for early and late rice did not differ significantly ($P > 0.05$). Therefore, a generic N dilution curve was also generated using pooled data points (Fig. 5c):

$$Nc = 36.94W^{-0.58} \tag{20}$$

However, we continued to use season-specific equations for further analysis as they were more tailored to the growth pattern of early rice and late rice, which experienced different climatic and edaphic conditions and had different biomass levels.

Significant differences were observed for NNI across N application rates at different sampling dates. The NNI values ranged from 0.57 to 1.17 and from 0.59 to 1.04 for early rice, and ranged from 0.54 to 1.19 and from 0.57 to 1.14 for late rice, in 2019 and 2020, respectively. The NNI value decreased slightly from tillering to flowering, and then increased slightly towards maturity. The NNI increased with N application rate in the same growth stage, and generally decreased at flowering stage, but all data points of late rice in 2019 increased with the growth of rice (Fig. A.3).

Across-stage average NNI showed an upward trend with an increase in N application rate, but reached a plateau (NNI = 1.0 in both early rice and late rice) when N application rate reached 150 and 146 kg ha^{-1} in early rice and late rice, respectively (Fig. 6). NNI did not change significantly when N application rate exceeded 140 kg ha^{-1} in both early rice and late rice. This indicated that the optimal N application rate of early rice and late rice should not be less than 140 kg ha^{-1}, and if the N application rate was less than 140 kg ha^{-1} this would mean N deficiency. But a continuous increase in the N application rate did not result in a significant luxurious N uptake. Except the NE+45% (+50%) treatment, all values of NNI in 2020 were lower than 1, which might be caused by low N uptake or high nitrogen loss in cold and rainy climates.

Based on the maximum yields, which were 8.5 t ha^{-1} and 6.0 t ha^{-1} for early rice (NE+30% and NE+50% treatments) and 10.3 t ha^{-1} and 7.2 t ha^{-1} for late rice (NE+15% and NE+25% treatments) in 2019 and 2020, respectively, we derived relative yields (see Eq. 17). With an increase in NNI, the relative yield increased first and then remained stable (Fig. 7). Relative yields of early rice and late rice were 0.87 and 0.90 when the value of NNI reached 0.98 and 0.96, and relative yield did not increase significantly once NNI exceeded those values, indicating that the data points reached seasonal high yields (for significance analysis of the relationship between N application rate and relative yield, see Table A.5). In this study, the average relative yield of NE treatment (averaged 0.87 and 0.91 for early rice and late rice, respectively, see Table A.5) was closest to this data point.

3.5. *Carbon and N translocation*

The translocation of carbon (C) and N from vegetative organs to grains, the accumulated grain C through post-flowering photosynthesis, and grain N from post-flowering uptake could be described by quadratic relationships with increasing N application rates in most growing seasons (Fig. 8). From 2019–2020, the C translocation ranged from 0.20 to 1.99 t ha^{-1}; N translocation ranged from 15.3 to 42.4 kg ha^{-1}, grain C from post-flowering photosynthesis ranged from 2.5 to 7.2 t ha^{-1}, and grain N from post-flowering uptake ranged from 5.2 to 52.9 kg ha^{-1}, respectively. In most growing seasons, C and N translocation, grain C from post-flowering photosynthesis and N from post-flowering uptake no longer changed significantly beyond an N application rate in early and late rice of 139 and 140 kg ha^{-1} (NE, averaged respectively 1.33 t ha^{-1}, 34.1 kg ha^{-1}, 4.96 t ha^{-1} and 36.3 kg ha^{-1}). No significant difference of C and N translocation efficiency was observed among different N application treatments in 2019 (Table 3). In the early season of 2020, C and N translocation efficiencies of treatments with more N applied than in NE were significantly higher than those of treatments with less N applied than in NE, with an average of 12.8% vs. 10.8% and 44.0% vs. 41.3%, while the late season of 2020 showed an opposite trend, with an average of 18.7% vs. 21.5% and 58.0% vs. 44.9%. The C translocation and the C from post-flowering photosynthesis were significantly higher in NE than in FP, with an average of 1.3 vs. 1.2 t ha^{-1} and 5.0 vs. 4.6 t ha^{-1}, while there was no significant difference between NE and ST. A significant difference among NE, FP and ST in N translocation was observed, with an average of 32.0 vs. 26.5 vs. 29.9 kg ha^{-1}, and NE significantly increased C and N translocation efficiencies by 1.8% and 4.3%, respectively, compared with FP, with an average of 18.3% vs. 16.5% and 44.3% vs. 40.0%.

4. Discussion

4.1. *Fertilization, grain yield, N uptake and N use efficiency*

Grain yield can be significantly increased by applying N fertilizer (Min et al., 2012; Zhang et al., 2017; Zhang et al., 2021). In our four-year

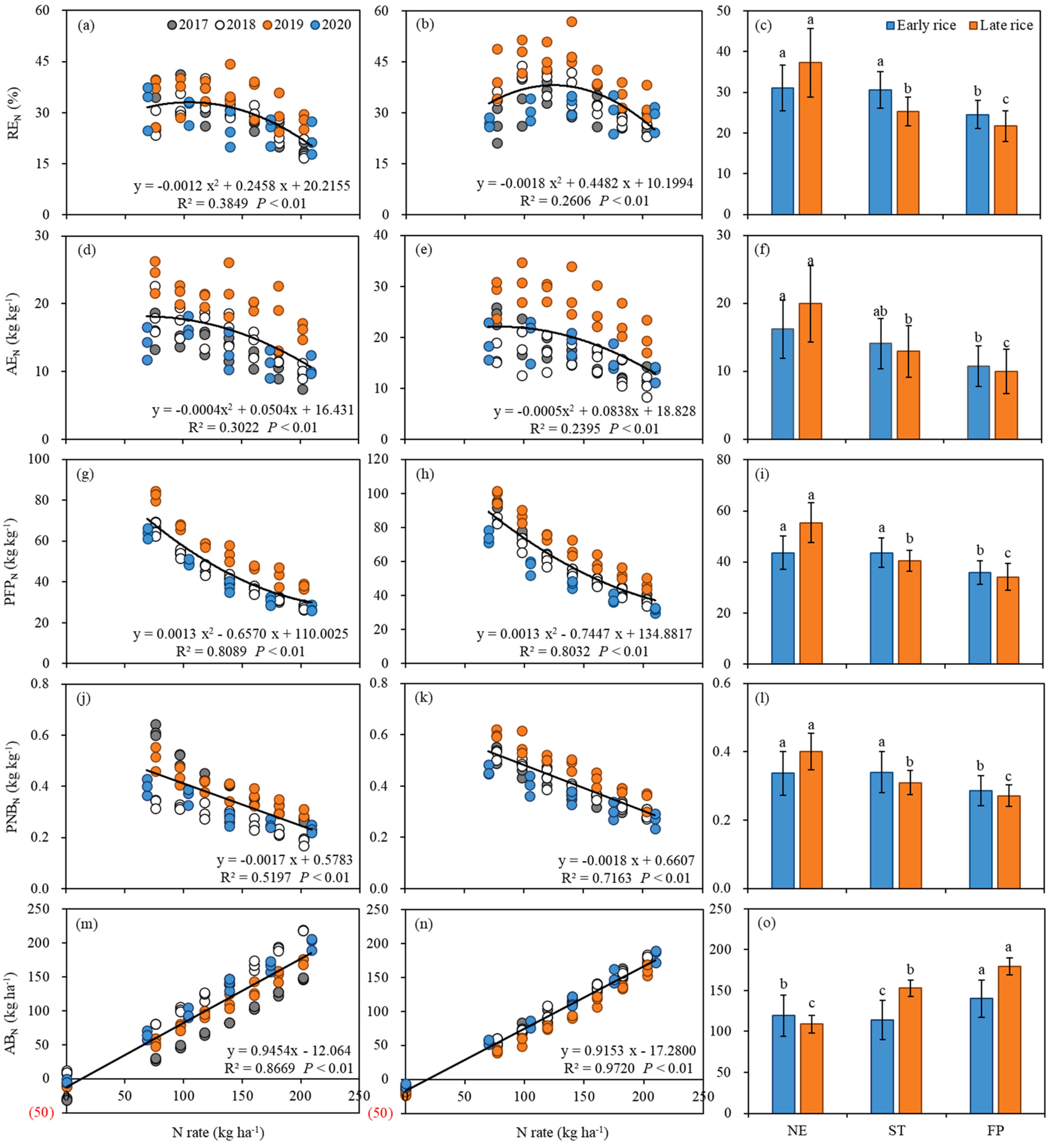

Fig. 3. The relationship between recovery efficiency (RE$_N$, a, b), agronomic efficiency (AE$_N$, d, e), partial factor productivity (PFP$_N$, g, h), partial nutrient balance (PNB$_N$, j, k), apparent balance (AB$_N$, m, n) and N application rate for early rice (a, d, g, j, m) and late rice (b, e, h, k, n), and the average RE$_N$ (c), AE$_N$ (f), PFP$_N$ (i), PNB$_N$ (l), AB$_N$ (o) of the three nutrient management methods (NE, ST and FP) from 2017 to 2020. Detailed seasonal parameters of the three nutrient management methods are given in the Appendix Table A.1 and A.2.

field experiment, however, in most growing seasons, the grain yield did not increase beyond an N application rate of 139 or 140 kg ha^{-1} (NE) in early and late rice, respectively. When the N input exceeds a certain threshold value, the crop yield generally does not increase significantly (Tilman et al., 2002; Yang et al., 2017). Excessive N input will not further improve crop yield, instead, it may reduce the quality of soil, air and water (Liu et al., 2016; Yan et al., 2010). As reported in most field researches, the relationship between N application rate and grain yield followed a quadratic regression or a linear-plateau model (Qiu et al., 2015; Zhao et al., 2010). In this study, the N application rate of NE was between the linear-plateau model (122 and 120 kg ha^{-1} in early and late rice, Fig. 9) and the recommended N application rate to produce the maximum grain yield described by the quadratic regression model (194 and 163 kg ha^{-1} in early and late rice, Fig. 9). Although there were

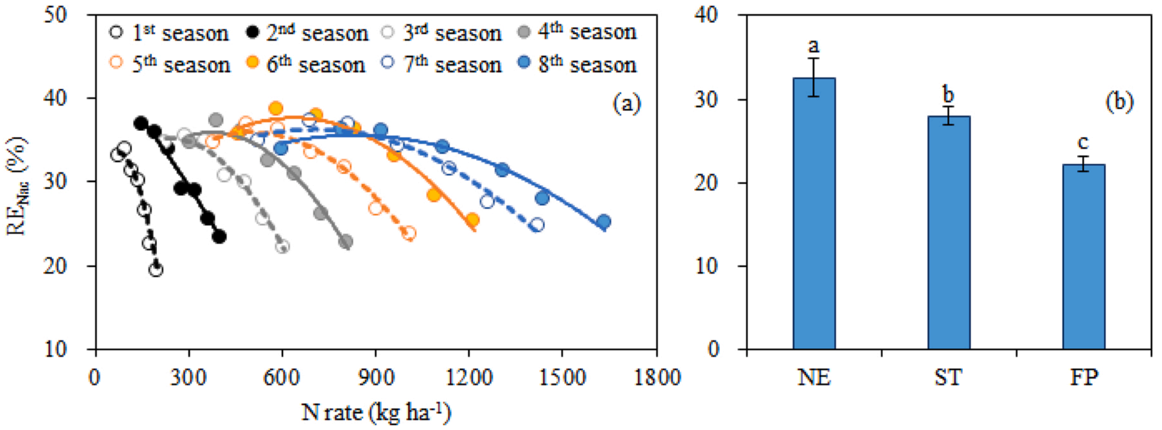

Fig. 4. The relationship between accumulated N recovery efficiency (RE_{Nac}, a) and accumulated N application rate of rice growing seasons, and the average RE_{Nac} (b) of the three nutrient management methods (NE, ST and FP) from 2017 to 2020. The eight seasons arose from the combination of four years (2017–2020) and two seasons (i.e. early rice and late rice) per year. Black, gray, orange, blue trend lines indicate 2017 (the 1st and 2nd seasons), 2018 (3rd and 4th seasons), 2019 (5th and 6th seasons), and 2020 (7th and 8th seasons), respectively. Dotted line and solid line represent the odd seasons (early rice) and even seasons (late rice), respectively. Equations and regression analyses are given in the Appendix Table A.3. Detailed seasonal parameters of the three nutrient management methods are given in the Appendix Table A.4.

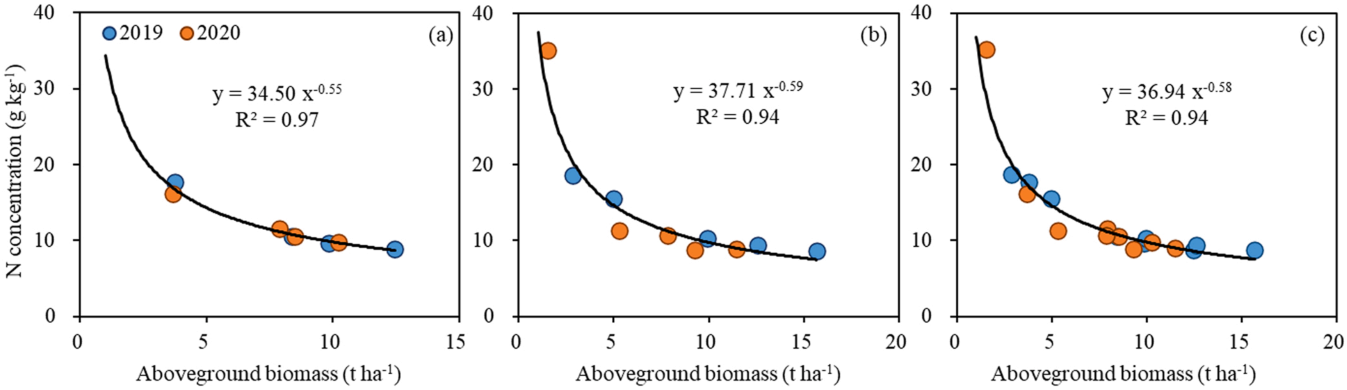

Fig. 5. Data points used to determine the critical N dilution curves for early rice (a) and late rice (b) in 2019 and 2020, and (c) the generic N dilution curve generated in a wide range of conditions based on both early rice and late rice.

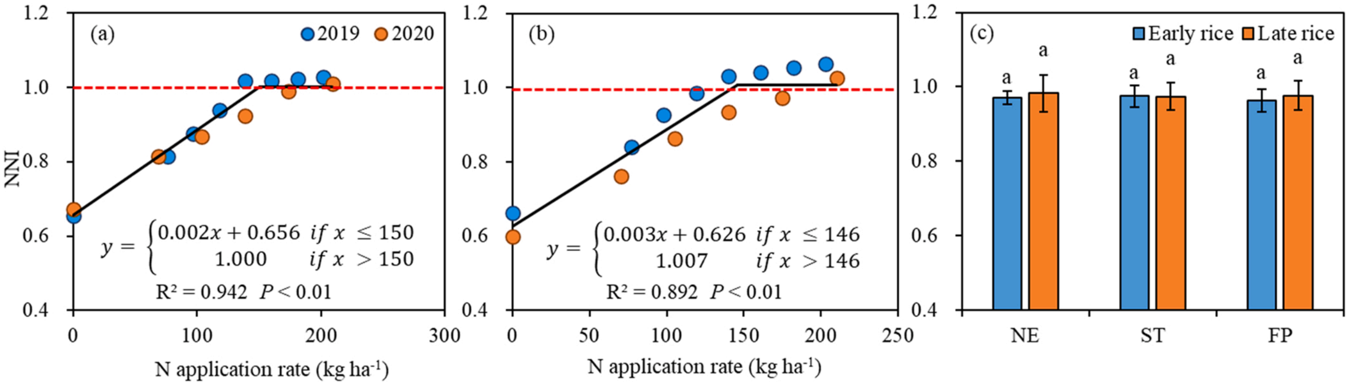

Fig. 6. The relationships between application rate (kg ha^{-1}) and average N nutrition index (NNI) for early rice (a) and late rice (b), and the average NNI of three nutrient management methods (NE, ST and FP) (c) in 2019 and 2020. The red dotted line represents the value of NNI = 1.

differences between the optimized N application rates identified by the two models and the NE application rate, no significant differences were observed between their yields and the yield of NE in most growing seasons. Moreover, the N application rate of NE was closer to the N application rate fitted by the linear-plateau model. The N application rate of ST (135 and 180 kg ha^{-1} in early and late rice, respectively) was rational in early rice, close to that of NE, but in late rice it was much higher than that recommended by linear-plateau model. This may be because the soil testing recommends the fertilzier rate by most local technicians according to the level of soil mineral N, which varies greatly with soil water content, soil temperature and sampling time (Khan et al., 2001). This leads to challenges for N recommendation and thus

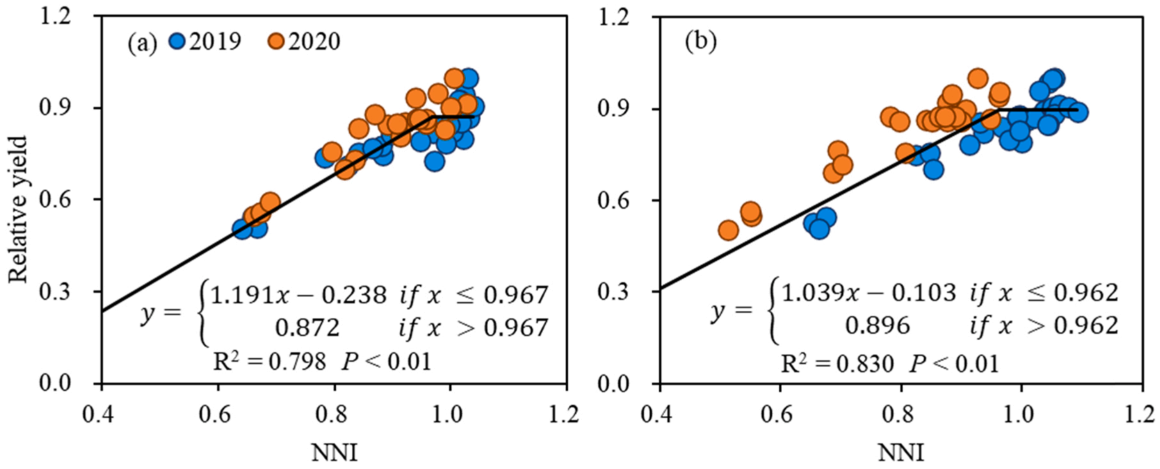

Fig. 7. The relationships between Relative yield and N Nutrition Index (NNI) for early rice (a) and late rice (b) in 2019 and 2020.

sometimes N recommendation produced by local experts is based on past experiences or just follows farmers' traditional habits. Therefore, soil testing often takes little account of the influence of the environmental factors on the crop growth; as a result, the correlation between soil testing value and crop yields may be low. The N fertilizer rate of FP reached 159 and 205 kg ha^{-1} in early and late rice, respectively, which was 14% and 46% higher than that of NE. However, there was no yield increase observed, and FP even caused some yield decline instead (Fig. 2). When the excessive N fertilizer was accumulated in the soil profile, part of it may enter into the environment through leaching, runoff, NH_3 volatilization or nitrification and denitrification (Xu et al., 2012; Cameron et al., 2013; Ding et al., 2020). In addition, many farmers, who often pursue for off-farm work to earn extra income, tend to apply all N fertilizer within two weeks after transplanting (Fan et al., 2007). Such concentrated N fertilizer application is prone to loss (Fan et al., 2009). Therefore, numerous researchers suggested strategies to optimize N distribution to improve crop yield and NUE, such as split fertilization or fertilization time postponement (Cassman et al., 1998; Abbasi et al., 2013; Kelling et al., 2015). The FP in this study adopted the most commonly used N distribution rate by the local farmers, that is, 40% of N fertilizer was applied one day before rice transplanting, and 60% of that was applied at tillering. As a result of this irrational N distribution, the early N supply substantially exceeded the demand of crops, which led to low NUE (Bijay-Singh et al., 2012). In NE, N fertilizer was applied at transplanting, tillering, and booting stages, respectively, with a basal-topdressing ratio of 4:3:3. It optimized the N distribution and application time, reduced the N input at the initial stage, and satisfied the N demand for the growth from vegetative to reproductive periods. In addition, excessive N input may disorder the physiological metabolism of crops, and reduce the N remobilization and grain-filling rate, and eventually reduce yield (Fait et al., 2008; Kong et al., 2017). Therefore, NE effectively coordinated the N fertilizer application rate and time, the components of 4 R nutrient stewardship, to synchronize soil N supply and rice plant N demand and thus raised the yields of both early and late rice.

Increasing NUE is conducive to reducing the negative influence of fertilization on environment (Abbasi et al., 2012). In general, NUE decreases with an increase in N application rate (Gu et al., 2017; Zhang et al., 2021). But in our study, the relationship between N application rate and RE_N or AE_N changed, with a general trend of increasing initially and declining subsequently (Fig. 3). Luo et al. (2018) and Qiu et al. (2015) got similar results for cotton and maize, respectively. The RE_N and AE_N were calculated from the difference between N application and omission treatments (see Eqs. (3) and (5)). If the grain yield and N uptake of N omission treatment were high, the RE_N and AE_N of N application treatments inevitably decreased. In this study, the grain yield and N uptake of N0 were high, which might be attributed to an enormous amount of residual N in the cropland soils (Yan et al., 2014). This N may be released in the form of mineralized organic N, and absorbed by crops (López-Bellido et al., 2014). The N deposition in the Jiangxi province was considerable, which has been estimated to contribute to the yield increase of 12.5 – 240.0 kg ha^{-1} in early rice, and of 232.5 – 315.0 kg ha^{-1} in late rice (Wang et al., 2019a, 2019b). Under the N limited condition, the N deposition in the atmosphere can enhance crop yields. Furthermore, in our field experiment, the rice straw was returned to the field. Because of the hot and humid climate conditions, the rice straw in the paddy field decayed fast, which was conducive to the uptake of released nutrients by the next season crop (Nakajima et al., 2016; Yan et al., 2019). Thus, the NUE of FP in the early and late rice planting systems was extremely low, especially in late rice, which was often supplied with excessive N fertilizer. In comparison, with a lower N input, NE obtained ideal yield, N uptake, and HI, and improved agronomic and environmental benefits, namely, the yield and NUE were simultaneously increased.

4.2. *The support of the NE system by the "N nutrition index" framework*

Our data of 2019 and 2020 seasons allowed to construct the N critical dilution curves (Fig. 5). The coefficient *a* values of the dilution curves of Indica and Japonica rice were reported to be 52.0 (Sheehy et al., 1998) and 35.0 (Ata-Ul-Karim et al., 2013), respectively (here, the values in the references were converted to the same units as in our study). In this study, early rice and late rice were both Indica hybrid type, and the *a* values were 34.5 and 37.7, respectively. The differences from the literature values may have been caused by various different factors, including field management, crop genotypes (Gastal et al., 2014), crop growth stages (Ata-Ul-Karim et al., 2013), and environment conditions (Lemaire and Ciampitti, 2020). However, the F-test showed no significant difference between our two curves of early and late rice, in line with the results of Makowski et al. (2020) and Ciampitti et al. (2021) for maize genotypes grown under different environment and management conditions.

The average NNI value derived from the dilution curve for NE and NE+15% treatments were closest to 1, and there was no significant difference in N uptake between NE and NE+ 15% treatments in most rice planting seasons, showing that the N application rate of NE was more appropriate. In most rice growing seasons of this study, the NNI value decreased to a certain extent from tillering to flowering; after that, it increased from flowering to maturity (Fig. A.3). This was due to the long interval between two topdressings at tillering and booting stages. Before the booting period, some treatments were in N deficit, and after topdressing, nitrogen was supplemented. Thus, it can be seen that NNI at

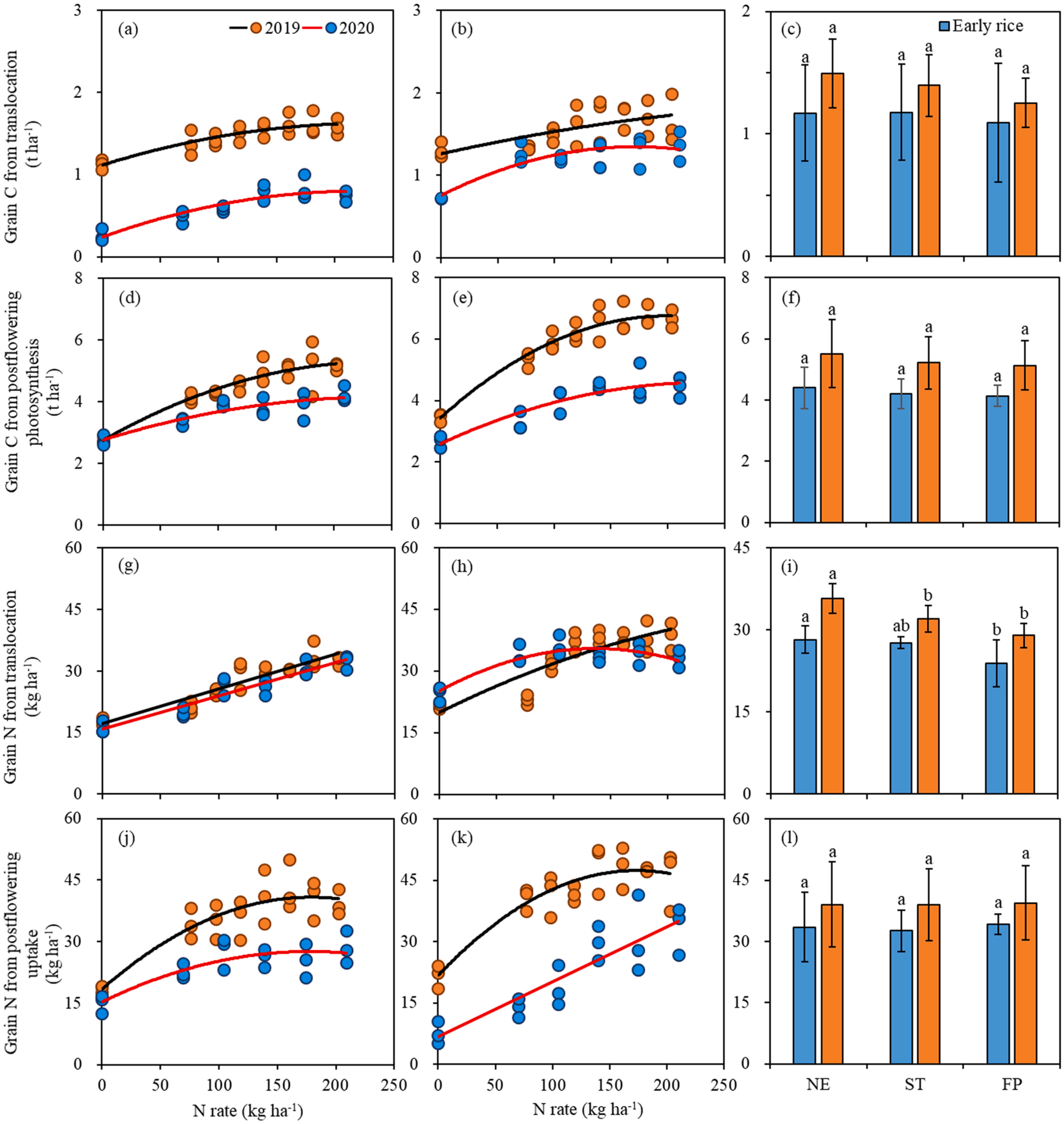

Fig. 8. Contribution of different C (a, b, d, e) and N (g, h, j, k) sources to grain sink during grain filling under different N application rates for early rice (a, d, g, j) and late rice (b, e, h, k), and the comparison between the three nutrient management methods (NE, ST and FP) (c, f, i, j) from 2019 to 2020. Equations and regression analyses in the scatter charts are given in the Appendix Table A.6.

given intervals during crop vegetative growth period could help optimize the nitrogen application time and rate (Lemaire et al., 2008). Zhao et al. (2020) also used the NNI value at flowering to explain the grain number, and interpret the grain yield via the NNI value of panicle at harvest. Ata-Ul-Karim et al. (2016) estimated the relationship between relative yield of rice and NNI under N-limiting and non-N-limiting conditions, and they found that NNI accurately explained the variation in relative yield. In our study, when the average NNI values of early rice and late rice reached 0.98 and 0.96 respectively, the relative yield reached a plateau (Fig. 7), indicating that the NNI values could effectively explain the seasonal rice yield. The average NNI values of the NE treatment were 0.97 and 0.98 in early rice and late rice, and the corresponding relative yields were 0.87 and 0.91, respectively, which were close to the optimal NNI threshold. Thus, it was proven that NE optimized N uptake in the early and late rice systems, and obtained reasonable yields.

4.3. Relationship between C/N translocation and N application rate

Source and sink coordinate to co-determine crop yield (Li et al.,

Table 3
Translocation efficiency of C and N under different treatments in 2019 and 2020.

Year	Treatment	Mobilized C (%)		Mobilized N (%)	
		Early rice	Late rice	Early rice	Late rice
2019	N0	23.7 a[a]	21.4 a	44.9 ab	44.0 ab
	NE–45%	22.5 ab	18.2 ab	42.6 bc	38.0 c
	NE–30%	21.8 ab	18.3 ab	43.3 ab	42.6 ab
	NE–15%	21.5 ab	18.3 ab	44.9 ab	44.4 a
	NE	21.4 ab	18.4 ab	44.1 abc	42.0 ab
	NE+ 15%	21.7 ab	18.4 ab	42.4 bc	43.7 ab
	NE+ 30%	21.1 b	17.8 b	45.9 a	43.9 ab
	NE+ 45%	20.6 b	17.3 b	43.9 abc	42.8 ab
	ST	21.7 ab	19.5 ab	42.3 c	42.9 ab
	FP	21.8 ab	16.4 b	43.1 bc	38.9 c
2020	N0	7.0 e	16.7 cd	40.5 b	56.4 b
	NE–50%	10.5 d	23.1 a	37.0 c	60.2 a
	NE–25%	11.0 cd	19.9 b	45.6 a	55.7 b
	NE	13.9 abc	19.4 bc	41.5 b	49.4 c
	NE+ 25%	14.0 ab	19.0 bcd	42.9 ab	47.1 cd
	NE+ 50%	11.6 bcd	18.3 bcd	45.0 a	42.6 e
	ST	14.8 a	18.1 bcd	44.9 a	46.0 d
	FP	11.6 bcd	16.2 d	35.2 c	42.1 e

[a] Average; values followed by different letters in the same column within a year are significantly different at $P < 0.05$.

1998; Shao et al., 2020). The assimilates of grains principally come from post-flowering photosynthesis of canopy and the translocation of non-structural carbohydrates reserved primarily during the pre-anthesis period (Yang and Zhang, 2006; Ehdaie et al., 2008). Likewise, the grain N come from post-flowering N uptake from the soil and translocation of pre-anthesis N assimilates from vegetative organs to the sink organ (Mueller and Vyn, 2016). During the vegetative stage, a good source capacity means that rice can accumulate sufficient nutrients in the stems and leaves, but the grain-filling period is a decisive phase for rice grain yield (Yang et al., 2008). Generally, to obtain a higher grain yield, more nutrients need to be transferred from the stems and leaves to the grains during the grain-filling period (Buerkert and Hiernaux, 1998). While leaf area index (LAI) can frequently be used to assess the source capacity of crop, it also reflects the accumulation of C and N in vegetative organs (Plénet and Lemaire, 1999; Li et al., 2009). In this study, we also measured the LAI at elongating, flowering and grain-filling stages of each rice growing season from 2019 to 2020. FP always had the highest LAI with an average of 6.1, 6.5 and 5.1 at stem-elongating, flowering and grain-filling stages (Table 4). Higher LAI represents more nutrients stored in the source organs, as LAI is highly dependent on canopy leaf N (Yin et al., 2003). The average LAI of NE treatment was 5.5, 5.2 and 3.8 at stem-elongating, flowering and grain-filling stages, but the grain yield of NE was significantly higher than that of FP with an average of 6.1 vs. 5.5 t ha^{-1} and 7.8 vs. 7.0 t ha^{-1} in early and late rice, respectively, and there was no significant difference between NE and NE+ treatments. This is because increasing the N application rate can obviously promote the source capacity of rice, but the grain yield of rice and other cereals is usually limited by sink capacity (Reynolds et al., 2005; Fischer, 2007; Li et al., 2016). If the crop grows with a limited sink capacity, the grain yield would be critically restricted (Venkateswarlu and Visperas, 1987). In this regard, NE could definitely optimize the relationship between source and sink of early and late rice planting system.

Ample N supply enhanced the photosynthetic capacity and N uptake from soil, and stored more nutrients in vegetative organs, thereby reducing the translocation efficiency of C and N (He et al., 2004). Effectively optimizing the non-structural reserves and N assimilates stored in stems and leaves can be achieved by a smart N supply, and the photosynthetic competence will also be improved, while excessive N

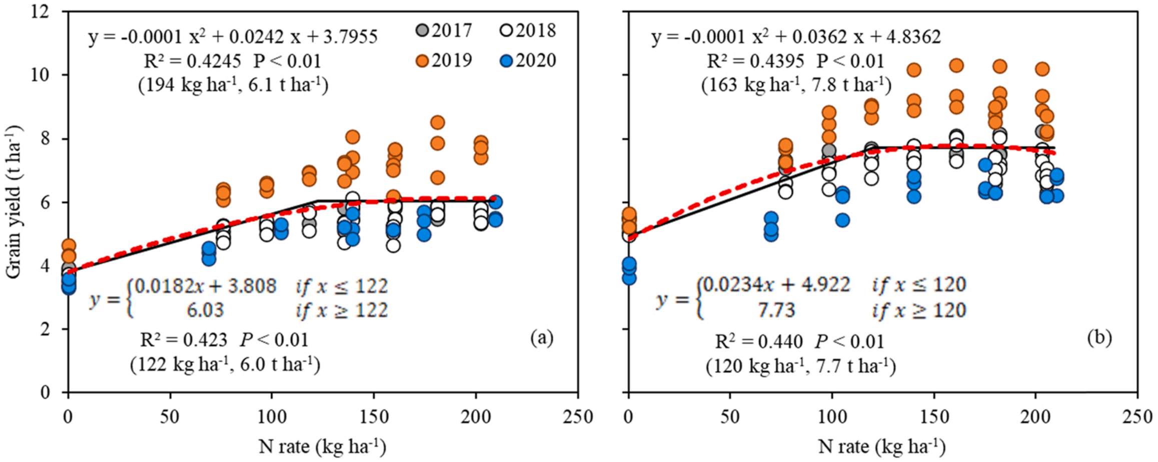

Fig. 9. Grain yield of early rice (a) and late rice (b) as functions of N application rate. The numbers between brackets under the linear equation represent the minimum N rate required to produce the maximum grain yield and corresponding grain yield; those under the quadratic equation represent the N rate required to produce the maximum grain yield and corresponding grain yield.

Table 4
Leaf area index (LAI) dynamics at rice stem-elongating, flowering and grain-filling stages under different N management methods (NE, ST and FP) for early and late rice from 2019 and 2020.

Year	Treatment	Early rice			Late rice		
		Elongating	Flowering	Grain-filling	Elongating	Flowering	Grain-filling
2019	NE	5.3 ± 0.3b[a]	5.8 ± 0.5b	4.4 ± 0.2b	5.4 ± 0.1b	3.9 ± 0.4b	3.0 ± 0.1c
	ST	6.1 ± 0.4a	6.5 ± 0.3ab	4.5 ± 0.3b	6.0 ± 0.5ab	4.1 ± 0.3b	3.9 ± 0.2b
	FP	6.2 ± 0.2a	7.5 ± 0.6a	6.0 ± 0.3a	6.5 ± 0.2a	5.1 ± 0.3a	4.5 ± 0.2a
2020	NE	4.6 ± 0.2ab	4.5 ± 0.4ab	2.7 ± 0.2b	6.5 ± 0.2a	6.6 ± 0.3a	4.9 ± 0.2b
	ST	4.4 ± 0.2b	4.3 ± 0.2b	2.7 ± 0.2b	6.3 ± 0.2a	6.7 ± 0.1a	5.6 ± 0.3b
	FP	5.0 ± 0.1a	4.9 ± 0.2a	3.4 ± 0.2a	6.6 ± 0.2a	7.5 ± 0.3b	6.4 ± 0.4a

[a] Average ± SE; values followed by different letters in the same column within a year are significantly different at $P < 0.05$.

supply will only increase the nutrient reserve in vegetative organs (Li et al., 2016). This is similar to the results in our study. The average translocation of C and N of NE was 1.33 t biomass ha^{-1} and 32.0 kg N ha^{-1}, and the translocation efficiency of those of NE were 18.3% and 44.3%, respectively, which had no significant difference compared with the NE+ and NE– treatments. Similarly, although the N application rate of FP was higher than that of NE, C and N translocation of FP were remarkably lower than those of NE. This may be due to the 4 R nutrient stewardship that was employed in NE, which optimized the nutrient application rate and time, improved the synergistic effect between nutrients, and synchronized the nutrient supply and crop demand (Dobermann et al., 2002; Pasuquin et al., 2014; Wang et al., 2007). Previous studies have also shown that a rational nutrient management, such as Site-specific Nitrogen Management, can fruitfully improve grain yield and nitrogen accumulation of rice at maturity (Pampolino et al., 2007; Sun et al., 2012).

5. Conclusion

In this study, NE increased both grain yield and NUE by improving C and N translocation from source organ to sink organ in the early and late rice cropping systems under the reduced N application rate, as compared with FP. The N dilution curves of early and late rice were derived, which can be used to serve as an N diagnosis and management tool. Through the analysis of the relationship between NNI and relative yield, the optimum N application rate of both early and late rice was about 140 kg ha^{-1}, similar to the amount as in NE. Excessive N application with FP may obtain higher dry matter accumulation, but it cannot effectively increase HI and NHI at rice maturity. On the contrary, it will reduce NUE, increase N surplus, result in luxurious vegetative growth, reduce the nutrient translocation efficiency, and result in a low NNI value. Both NE and ST realized an improvement of agronomic and environmental benefits. However, compared with ST, NE has the advantage of convenience, quickness and low costs to customize a rational nutrient management strategy for the smallholders, without consuming much human and material resources, and supposed to be a promising fertilizer recommendation approach for the regions with smallholder farmers.

CRediT authorship contribution statement

Zhuo Xu: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Ping He:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Xinyou Yin:** Methodology, Writing – review & editing, Supervision. **Paul C. Struik:** Writing – review & editing, Supervision. **Wencheng Ding:** Writing – review & editing. **Kailou Liu:** Investigation, Resources. **Qiuhong Huang:** Writing – review & editing.

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.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 31471942), and the Double Thousand Plan in Jiangxi Province of China (No. JXSQ2020102116).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126513.

References

Abbasi, M.K., Tahir, M.M., Sadiq, A., Iqbal, M., Zafar, M., 2012. Yield and nitrogen use efficiency of rainfed maize response to splitting and nitrogen rates in Kashmir. Pak. Agron. J. 104, 448–457.

Abbasi, M.K., Tahir, M.M., Rahim, N., 2013. Effect of N fertilizer source and timing on yield and N use efficiency of rainfed maize (Zea mays L) in Kashmir-Pakistan. Geoderma 195–196, 87–93.

Ata-Ul-Karim, S.T., Yao, X., Liu, X., Cao, W., Zhu, Y., 2013. Development of critical nitrogen dilution curve of Japonica rice in Yangtze River reaches. Field Crops Res. 149, 149–158.

Ata-Ul-Karim, S.T., Liu, X., Lu, Z., Yuan, Z., Zhu, Y., Cao, W.X., 2016. In-season estimation of rice grain yield using critical nitrogen dilution curve. Field Crops Res 195, 1–8.

Bijay-Singh, Varinderpal-Singh, Yadvinder-Singh H.S., Thind, Kumar, A., Gupta, R.K., Kaul, A., Vashistha, M., 2012. Fixed-time adjustable dose site-specific fertilizer nitrogen management in transplanted irrigated rice (Oryza sativa L.) in South Asia. Field Crops Res 126, 63–69.

Buerkert, A., Hiernaux, P., 1998. Nutrients in the West African Sudano-Sahelian zone: Losses, transfers and role of external inputs. J. Plant Nutr. Soil Sci. 164, 365–383.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil-plant system: A review. Ann. Appl. Biol. 162, 145–173.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., Singh, U., 1998. Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56, 7–38.

Ciampitti, I., Fernandez, J., Tamago, S., Zhao, B., Lemaire, G., Makowski, D., 2021. Does the critical N dilution curve for maize crop vary across genotype x environment x management scenarios? - A Bayesian analysis. Eur. J. Agron. 123, 126202.

Ding, W., He, P., Zhang, J., Liu, Y., Xu, X., Ullah, S., Cui, Z., Zhou, W., 2020. Optimizing rates and sources of nutrient input to mitigate nitrogen, phosphorus, and carbon losses from rice paddies. J. Clean. Prod. 206, 120603.

Dobermann, A., Cassman, K.G., Sta Cruz, P.C., Neue, H.U., 1995. Dynamic soil test for rice. In: Rothschild, G., Zeigler, R.S. (Eds.), Fragile Lives in Fragile Ecosystems. Proceedings of The International Rice Research Conference. International Rice Research Institute, Los Baños, pp. 343–365.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C., Adviento, M.A.A., 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res. 74, 37–66.

Ehdaie, B., Alloush, G.A., Waines, J.G., 2008. Genotypic variation in linear rate of grain growth and contribution of stem reserves to grain yield in wheat. Field Crops Res. 106, 34–43.

Fait, A., Fromm, H., Walter, D., Galili, G., Fernie, A.R., 2008. Highway or byway: The metabolic role of the GABA shunt in plants. Trends Plant Sci. 13, 14–19.

Fan, M., Lu, S., Jiang, R., Liu, X., Zeng, X., Goulding, K.W.T., Zhang, F., 2007. Nitrogen input, ^{15}N balance and mineral N dynamics in a rice-wheat rotation in southwestern China. Nutr. Cycl. Agroecosystems 79, 243–253.

Fan, M., Lu, S., Jiang, R., Liu, X., Zhang, F., 2009. Triangular transplanting pattern and split nitrogen fertilizer application increase rice yield and nitrogen fertilizer recovery. Agron. J. 101, 1421–1425.

Fischer, R.A., 2007. Understanding the physiological basis of yield potential in wheat. J. Agr. Sci. 145, 99–113.

Gastal, F., Lemaire, G., Durand, J.L., Louarn, G., 2014. Quantifying Crop Responses to Nitrogen and Avenues to Improve Nitrogen-use Efficiency. Crop Physiology. Academic Press, pp. 161–206.

Greenwood, D.J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., Neeteson, J.J., 1990. Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann. Bot. 66, 425–436.

Gu, B., Ju, X., Chang, S., Ge, Y., Chang, J., 2017. Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection. Reg. Environ. Change 17, 1217–1227.

Hay, R.K.M., 1995. Harvest index: A review of its use in plant breeding and crop physiology. Ann. Appl. Biol. 126, 197–216.

He, P., Zhou, W., Jin, J., 2004. Carbon and nitrogen metabolism related to grain formation in two different senescent types of maize. J. Plant Nutr. 27, 295–311.

He, P., Li, S., Jin, J., Wang, H., Li, C., Wang, Y., Cui, R., 2009. Performance of an optimized nutrient management system for double-cropped wheat-maize rotations in North-Central China. Agron. J. 101, 1489–1496.

He, P., Xu, X., Zhou, W., Smith, W., He, W., Grant, B., Ding, W., Qiu, S., Zhao, S., 2022. Ensuring future agricultural sustainability in China utilizing an observationally validated nutrient recommendation approach. Eur. J. Agron. 132, 126409.

Herrmann, A., Taube, F., 2004. The range of the critical nitrogen dilution curve for maize (Zea mays L.) can be extended until silage maturity. Agron. J. 96, 1131–1138.

Ju, X., Xing, G., Chen, X., Zhang, S., Zhang, L., Liu, X., Cui, Z., Yin, B., Christie, P., Zhu, Z., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. 106, 3041–3046.

Justes, E., Mary, B., Meynard, J.M., Machet, J.M., Thelier-Huche, L., 1994. Determination of a critical nitrogen dilution curve for winter wheat crops. Ann. Bot. 74, 397–407.

Kahrl, F., Li, Y., Su, Y., Tennigkeit, T., Wilkes, A., Xu, J., 2010. Greenhouse gas emissions from nitrogen fertilizer use in China. Environ. Sci. Policy 138, 688–694.

Kelling, K.A., Arriaga, F.J., Lowery, B., Jordan, M.O., Speth, P.E., 2015. Use of hill shape with various nitrogen timing splits to improve fertilizer use efficiency. Am. J. Potato Res. 92, 71–78.

Khan, S.A., Mulvaney, R.L., Hoeft, R.G., 2001. A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci. Soc. Am. J. 65, 1751–1760.

Kiba, T., Krapp, A., 2016. Plant nitrogen acquisition under low availability: Regulation of uptake and root architecture. Plant Cell Physiol. 57, 707–714.

Kong, A., Xie, Y., Hu, L., Si, J., Wang, Z., 2017. Excessive nitrogen application dampens antioxidant capacity and grain filling in wheat as revealed by metabolic and physiological analyses. Sci. Rep. 7, 43363.

Lemaire, G., Ciampitti, I., 2020. Crop mass and N status as prerequisite covariables for unraveling nitrogen use efficiency across genotype-by-environment-by-management scenarios: A review. Plants 9, 1309.

Lemaire, G., Gastal, F., 1997. N uptake and distribution in plant canopies. In: Lemaire, G. (Ed.), Diagnosis of the Nitrogen Status in Crops. Springer, Berlin, Heidelberg, pp. 3–43.

Lemaire, G., Meynard, J.M., 1997. Use of the nitrogen nutrition index for analysis of agronomical data. In: Lemaire, G. (Ed.), Diagnosis on the Nitrogen Status in Crops. Springer, Berlin, Heidelberg, pp. 45–55.

Lemaire, G., Jeuffroy, M., Gastal, F., 2008. Diagnosis tool for plant and crop N status in vegetative stage. Theory Pract. Crop N. Manag. Eur. J. Agron. 28, 614–624.

Letey, J., Vaughan, P., 2013. Soil type, crop and irrigation technique affect nitrogen leaching to groundwater. Calif. Agr. 67, 231–241.

Li, G., Xue, L., Gu, W., Yang, C., Wang, S., Ling, Q., Qin, X., Ding, Y., 2009. Comparison of yield components and plant type characteristics of high-yield rice between Taoyuan, a 'special eco-site' and Nanjing, China. Field Crops Res 112, 214–221.

Li, R., Li, M., Ashraf, U., Liu, S., Zhang, J., 2019. Exploring the relationships between yield and yield-related traits for rice varieties released in China from 1978 to 2017. Front. Plant Sci. 10, 543.

Li, W., Xiong, B., Wang, S., Deng, X., Yin, L., Li, H., 2016. Regulation effects of water and nitrogen on the source-sink relationship in potato during the tuber bulking stage. PLoS ONE 11, e0146877.

Li, Z., Pinson, S.R.M., Stansel, J.W., Paterson, A.H., 1998. Genetic dissection of the source-sink relationship affecting fecundity and yield in rice (Oryza sativa L.). Mol. Breed. 4, 419–426.

Liu, H., Wang, Z., Yu, R., Li, F., Li, K., Cao, H., Yang, N., Li, M., Dai, J., Zan, Y., Li, Q., Xue, C., He, G., Huang, D., Huang, M., Liu, J., Qiu, W., Zhao, H., Mao, H., 2016. Optimal nitrogen input for higher efficiency and lower environmental impacts of winter wheat production in China. Agric. Ecosyst. Environ. 224, 1–11.

Liu, Y., Zhou, Z., Zhang, X., Xu, X., Chen, H., Xiong, Z., 2015. Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil-crop system management: a three-year field study. Atmos. Environ. 116, 92–101.

López-Bellido, L., Muñoz-Romero, V., Fernández-García, P., López-Bellido, R.J., 2014. Ammonium accumulation in soil: The long-term effects of tillage, rotation and N rate in a Mediterranean Vertisol. Soil Use Manag. 30, 471–479.

Lu, D., Lu, F., Pan, X., Cui, Z., Zou, C., Chen, X., He, M., Wang, Z., 2015. The effects of cultivar and nitrogen management on wheat yield and nitrogen use efficiency in the North China Plain. Field Crops Res 171, 157–164.

Luo, Z., Liu, H., Li, W., Zhao, Q., Dai, J., Tian, L., Dong, H., 2018. Effects of reduced nitrogen rate on cotton yield and nitrogen use efficiency as mediated by application mode or plant density. Field Crops Res. 218, 150–157.

Makowski, D., Zhao, B., Ata-Ul-Karim, T.S., Lemaire, G., 2020. Analysing uncertainty in critical nitrogen dilution curves. Eur. J. Agron. 118, 126076.

Miao, Y., Stewart, B.A., Zhang, F., 2010. Long-term experiments for sustainable nutrient management in China. A review. Agron. Sustain. Dev. 1–18.

Mikkelsen, R., Hartz, T., 2008. Nitrogen sources for organic crop production. Better Crop 92, 16–19.

Min, J., Zhang, H., Shi, W., 2012. Optimizing nitrogen input to reduce nitrate leaching loss in greenhouse vegetable production. Agric. Water Manag. 111, 53–59.

Mueller, N., Gerber, J., Johnston, M., Ray, K., Ramankutty, N., Foley, J., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.

Mueller, S.M., Vyn, T.J., 2016. Maize plant resilience to N stress and post-silking N capacity changes over time: a review. Front. Plant Sci. 7, 53.

Nakajima, M., Cheng, W., Tang, S., Hori, Y., Yaginuma, E., Hattori, S., Hanayama, S., Tawaraya, K., Xu, X., 2016. Modeling aerobic decomposition of rice straw during the off-rice season in an Andisol paddy soil in a cold temperate region of Japan: Effects of soil temperature and moisture. Soil Sci. Plant Nutr. 62, 90–98.

Palaniswamy, K.M., Gomez, K.A., 1974. Length-width method for estimating leaf area of rice. Agron. J. 66, 430–433.

Pampolino, M.F., Manguiat, I.J., Ramanathan, S., 2007. Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems. Agr. Syst. 93, 1–24.

Pan, S., Huang, S., Zhai, J., Wang, J., Cao, C., Cai, M., Zhan, M., Tang, X., 2012. Effects of N management on yield and N uptake of rice in Central China. J. Integr. Agr. 11, 1993–2000.

Pasuquin, J.M., Pampolino, M.F., Witt, C., Dobermann, A., Oberthür, T., Fisher, M.J., Inubushi, K., 2014. Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. Field Crops Res. 156, 219–230.

Peng, S., Buresh, R., Huang, J., Zhong, X., Zou, Y., Yang, J., Wang, G., Liu, Y., Hu, R., Tang, Q., Cui, K., Zhang, F., Dobermann, A., 2010. Improving nitrogen fertilization in rice by site-specific N management. A review. Agron. Sustain. Dev. 30, 649–656.

Plénet, D., Lemaire, G., 1999. Relationships between dynamics of nitrogen uptake and dry matter accumulation in maize crops. Determ. Crit. N. Conc. Plant Soil 216, 65–82.

Qiu, S., He, P., Zhao, S., Li, W., Xie, J., Hou, Y., Grant, C.A., Zhou, W., Jin, J., 2015. Impact of nitrogen rate on maize yield and nitrogen use efficiencies in Northeast China. Agron. J. 107, 305–313.

Reidsma, P., Feng, S., Van Loon, M., Luo, X., Kang, C., Lubbers, M., Kanellopoulos, A., Wolf, J., Van Ittersum, M., Qu, F., 2012. Integrated assessment of agricultural land use policies on nutrient pollution and sustainable development in Taihu basin, China. Environ. Sci. Policy 18, 66–76.

Reynolds, M.P., Pellegrineschi, A., Skovmand, B., 2005. Sink-limitation to yield and biomass: A summary of some investigations in spring wheat. Ann. Appl. Biol. 146, 39–49.

Shao, L., Liu, Z., Li, H., Zhang, Y., Dong, M., Guo, X., Zhang, H., Huang, B., Ni, R., Li, G., Cai, C., Chen, W., Luo, W., Yin, X., 2020. The impact of global dimming on crop yields is determined by the source-sink imbalance of carbon during grain filling. Glob. Change Biol. 27, 689–708.

Sheehy, J.E., Dionora, M.J.A., Mitchell, P.L., Peng, S., Cassman, K.G., Lemaire, G., Williams, R.L., 1998. Critical nitrogen concentrations: Implications for high-yielding rice (Oryza sativa L.) cultivars in the tropics. Field Crops Res. 59, 31–41.

Sun, Y., Ma, J., Sun, Y., 2012. The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China. Field Crops Res. 127, 85–98.

Tang, S., Zheng, N., Ma, Q., Zhou, J., Sun, T., Zhang, X., Wu, L., 2021. Applying *Nutrient Expert* system for rational fertilisation to tea (*Camellia sinensis*) reduces environmental risks and increases economic benefit. J. Clean. Prod. 305, 12797.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Venkateswarlu, B., Visperas, R.M., 1987. Source-sink relationships in crop plants. Int. Rice Res. Inst. Pap. Ser. 125, 1–19.

Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L., Holland, E.A., Johnes, J.P., Katzenberger, K., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D.S., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A., Zhang, F., 2009. Nutrient imbalances in agricultural development. Science 324, 1519–1520.

Wang, G., Zhang, Q., Witt, C., Buresh, R.J., 2007. Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang province, China. Agric. Syst. 94, 801–806.

Wang, J., Yi, X., Cui, J., Chang, Y., Yao, D., Zhou, D., Yang, J., Zhou, J., Chan, A., Wang, W., Yin, X., 2019a. Nonlinear effects of increasing nitrogen deposition on rice growth and heavy metal uptake in a red soil ecosystem of southeastern China. Sci. Total Environ. 609, 1060–1067.

Wang, Z., Zhang, X., Liu, L., Wang, S., Wu, X., Zhang, W., Zhao, L., Lu, X., Zhao, X., 2019b. Evaluating the effects of nitrogen deposition on rice ecosystems across China. Agric. Ecosyst. Environ. 285, 106617.

Xu, X., He, P., Yang, F., Ma, J., Pampolino, M.F., Johnston, A.M., Zhou, W., 2017. Methodology of fertilizer recommendation based on yield response and agronomic efficiency for rice in China. Field Crops Res. 206, 33–42.

Xu, Z., Yang, Z., Ju, M., Wang, S., Xing, G., 2012. Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China. Agric. Ecosyst. Environ. 156, 1–11.

Yan, C., Yan, S., Jia, T., Dong, S., Ma, C., Gong, Z., 2019. Decomposition characteristics of rice straw returned to the soil in northeast China. Nutr. Cycl. Agroecosystems 114, 211–224.

Yan, W., Mayorga, E., Li, X., Seitzinger, S.P., Bouwman, A.F., 2010. Increasing anthropogenic nitrogen inputs and riverine DIN exports from the Changjiang River basin under changing human pressures. Glob. Biogeochem., GB0A06. Cycles 24.

Yan, X., Ti, C., Vitousek, P., Chen, D., Leip, A., Cai, Z., Zhu, Z., 2014. Fertilizer nitrogen recovery efficiencies in crop production systems of China with and without consideration of the residual effect of nitrogen. Environ. Res. Lett. 9, 095002.

Yang, J., Zhang, J., 2006. Grain filling of cereals under soil drying. N. Phytol. 169, 223–236.

Yang, W., Peng, S., Dionisio-Sese, M.L., Laza, R.C., Visperas, R.M., 2008. Grain filling duration: A crucial determinant of genotypic variation of grain yield in field-grown tropical irrigated rice. Field Crops Res. 105, 221–227.

Yang, X., Lu, Y., Ding, Y., Yin, X., Raza, S., Tong, Y., 2017. Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). Field Crops Res. 206, 1–10.

Yin, X., Lantinga, E.A., Schapendonk, A.H.C.M., Zhong, X., 2003. Some quantitative relationships between leaf area index and canopy nitrogen content and distribution. Ann. Bot. 91, 893–903.

Yin, X., Struik, P.C., Goudriaan, J., 2021. On the needs for combining physiological principles and mathematics to improve crop models. Field Crops Res. 271, 108254.

Yusuf, A., Waddington, S., Timsina, J., Hodson, D., Dixon, J., 2009. Maize-rice cropping systems in Bangladesh: Status and research needs. J. Agr. Sci. Tech. 3, 35–53.

Zhang, B., Li, Q., Cao, J., Zhang, C., Song, Z., Zhang, F., Chen, X., 2017. Reducing nitrogen leaching in a subtropical vegetable system. Agric. Ecosyst. Environ. 241, 133–141.

Zhang, J., He, P., Ding, W., Ullah, S., Abbas, T., Li, M., Ai, C., Zhou, W., 2021. Identifying the critical nitrogen fertilizer rate for optimum yield and minimum nitrate leaching in a typical field radish cropping system in China. Environ. Pollut. 268, 115004.

Zhao, B., Niu, X., Ata-Ul-Karim, S.T., Wang, L., Duan, A., Liu, Z., Lemaire, G., 2020. Determination of the post-anthesis nitrogen status using ear critical nitrogen dilution curve and its implications for nitrogen management in maize and wheat. Eur. J. Agron. 113, 125967.

Zhao, C., Hu, C., Huang, W., Sun, X., Tan, Q., Di, H., 2010. A lysimeter study of nitrate leaching and optimum nitrogen application rates for intensively irrigated vegetable production systems in Central China. J. Soils Sediments 10, 9–17.

Ziadi, N., Brassard, M., Bélanger, G., Cambouris, A.N., Tremblay, N., Nolin, M.C., Claessens, A., Parent, L., 2008. Critical nitrogen curve and nitrogen nutrition index for corn in eastern Canada. Agron. J. 100, 271–276.