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Effects and potential of optimized fertilization practices for rice production in China

Yanhua Zhuang^{1,2} · Shuhe Ruan^{1,2} · Liang Zhang^{1,2} · Jingrui Chen³ · Sisi Li¹ · Weijia Wen^{1,2} · Hongbin Liu⁴

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Abstract

Optimized fertilization practices are a promising management strategy for sustainable rice production. Green manuring, straw incorporation, postponing nitrogen (N) application, formula fertilization, combined application of organic and inorganic fertilizers, reducing fertilization, deep fertilization, slow/controlled-release fertilizers (S/CRFs), and biochar addition are nine frequently used optimized fertilization practices in China. The nitrogen use efficiency (NUE) improvement, yield increase, and N loss-reducing effects of these practices were analyzed based on multisite studies across China. An index system considering the applicability and effects of various practices was developed to identify their potential distributions. The results indicated that 76.5% of all paddies in China are overfertilized regions under the current rice yields. Optimized fertilization practices were mainly adopted in central and eastern China regions with serious water pollution and excessive fertilization. Postponing N application, S/CRFs, and formula fertilization had wide applicability nationwide, suitable for 100% of all paddies, followed by straw incorporation (98.8%), deep fertilization (81.4%), green manuring (67.0%), reducing fertilization (44.0%), biochar addition (33.7%), and combined application of organic and inorganic fertilizer (23.4%). Overall, except for reducing fertilization, which decreased yields by an average -2% , most practices increased yield by more than 5% and reduced total N losses by more than 15%. Reducing fertilization, postponing N application, S/CRFs, straw incorporation, and green manuring are five eco-friendly practices with wide distribution, low inputs, and good effects. By fully implementing the recommended combination scenarios based on the five preferred practices at the country level, the total yield increasing rate and N loss-reducing rate were 3–9% and 15–35%, respectively. Optimized fertilization in China has noticeable potential to alleviate agricultural non-point source pollution while ensuring rice yield.

Keywords Rice paddy · Optimized fertilization practices · Yield increase · Nitrogen use efficiency (NUE) · Non-point source (NPS) pollution · Sustainable agriculture

1 Introduction

Rice production not only consumes large amounts of irrigation water and fertilizer, but also poses a high risk of water pollution by delivering nitrogen (N) through surface runoff, which is the principal cause of agricultural non-point source pollution in major rice-producing regions (Liu et al. 2021b; Zhang et al. 2021a; Zhuang et al. 2020). Rice paddies in China account for 1/5 of the world's planting regions (FAO 2019). To meet the demand of an expanding population in China, chemical fertilizers, especially N fertilizers, have been extensively applied in paddy fields to maintain high rice yields. Excessive use of N fertilizers and traditional fertilization methods have become major challenges for sustainable and intensive agriculture (Liu et al. 2021a). Nitrogen use efficiency (NUE), defined as the ratio of crop N uptake to the total

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input of N fertilizer, is one of the most critical concerns in rice cultivation to reduce N losses, increase yields, and improve crop management (Gil-Ortiz et al. 2020; Zhang et al. 2014a). In China, NUE is approximately 35% in paddy systems, and a considerable portion of N is discharged into water via surface runoff and leaching (Bai et al. 2020; Ju et al. 2009; Qi et al. 2020). Determining optimum N management and reducing environmental harm are critical in Chinese agriculture (Shi et al. 2020; Yao et al. 2018).

Agronomic measures, such as fertilization, irrigation, and tillage, can reduce N loss by affecting the NUE, the N concentration in paddy surface water and soil, and the N conversion process (Jiang et al. 2021; Zhuang et al. 2019). N fertilizer is usually supplied via multiple applications during rice production in China (Ye et al. 2019). Similar to water saving irrigation, optimized fertilization practices are an important source-control solution to mitigating pollution and eutrophication from paddy fields (Wu et al. 2020). Green manuring, straw incorporation, postponing N application, formula fertilization, reducing fertilization, deep fertilization, and combined application of organic and inorganic fertilizers, have been applied across China (Fig. 1) (Liu et al. 2015; Xia et al. 2020a; Xia et al. 2020b). As a traditionally sustainable source of nutrients, the appropriate substitution of green manuring for N fertilizers (e.g., 20–40%) is beneficial for improving the productivity and sustainability of paddy fields (Islam et al. 2019; Li et al. 2021; Xie et al. 2016). Straw incorporation is increasingly recommended due to its ability to increase the soil organic carbon (SOC) stock and improve soil fertility after microbial decomposition (Ku et al. 2019). Postponing N application optimizes the split proportion of N fertilizers in different growing stages according to the N demand of rice mainly by reducing the fertilizer amount in the basal period and increasing the fertilizer amount in the tillering stage and booting stage (Bai et al. 2020). Rational formula fertilization can efficiently restore and improve soil fertility, and increase nutrient uptake (Xiao et al. 2019). Reducing fertilization often reduces the N fertilizer application rate by 10–30% to decrease the risk of N runoff on the basis of cost savings and yield maintenance (Xu et al. 2020). Compared to broadcast application, deep fertilization can promote nutrient uptake by rice roots (Zhong et al. 2021b). The combined application of organic and inorganic fertilizers can maintain high soil productivities and high NUE to improve not only rice yield but also yield sustainability in low-productivity paddy soil (Jabbar et al. 2008; Mi et al. 2018; Qaswar et al. 2020). Meanwhile, some new optimized fertilization types, such as slow/controlled-release fertilizers (S/CRFs) and biochar addition, have shown good applied effects for reducing N losses, and enhancing NUE and rice yields (Liu et al. 2020; Lu et al. 2020; Shen et al. 2021; Sun et al. 2020). S/CRFs present the advantage of better matching the plants' need for nutrients over time under current agricultural practice to decrease the

environmental impact caused by fertilizer doses applied in excess of the plants' uptake rate (Gil-Ortiz et al. 2020). Biochar application in farmland can effectively increase soil organic carbon content and improve soil properties (Chen et al. 2021). The management strategies and advantages of the nine common fertilization practices are listed in Table 1.

Coordinating grain production and environmental protection through improved NUE will be a key step in achieving sustainable rice production in Chinese agriculture (Jiao et al. 2016). In China, the three major rice planting regions are the Northeast Plain, Yangtze River Basin, and Southeast Coast, with approximately 14.9%, 63.5%, and 19.7% of the total rice planting areas, respectively. In recent years, optimized fertilization practices have been vigorously pursued nationwide. However, the potential effects and distribution of various practices for paddy fields in China are not clear, which hinders the popularization of efficient practices. The objectives of this study are to (1) compare different optimized practices in terms of their effects on yield increase, NUE improvement, and N loss reduction by analyzing of published data from multisite field studies; (2) identify the suitable application regions of optimized fertilization practices for paddy fields across China; and (3) estimate the potential overall effects under full implementation of optimized fertilization practices for rice production at the country level.

2 Data and methods

2.1 Data sources

To analyze the general effects of common fertilization practices in paddy fields, research data from multisite studies were collected from the Chinese National Knowledge Infrastructure (CNKI). To ensure representativeness and comparability of the data, only data that satisfied the following criteria were regarded as effective and used in subsequent analysis: (1) the control treatment must involve conventional fertilization; (2) the study period must cover the whole rice-growth season; (3) field monitoring (excluding laboratory experiments and pot experiments); (4) standardized monitoring method; and (5) the crop N uptake for NUE includes the above- and belowground plant biomass. The relevant studies covered 24 provinces/territories and 367 study sites in China during 1997–2021 (Fig. 2). Original data were extracted by WebPlot-Digitizer-3 from multidata studies.

Data on N fertilizer application, rice yields, precipitation, land use and cover change (LUCC), digital elevation model (DEM), and livestock were collected to analyze the suitable distribution of various fertilization practices. Information on N fertilizer application was recorded from the literature, which comprised 242 site-year data points for rice paddy fields and can be considered representative of the amount applied by

Table 1 Strategies and advantages of common optimized fertilization practices. NUE nitrogen use efficiency.

Fertilization practices	Strategy	Main advantages
Postponing N application	Reduce N application rate at basal stage, apply large amounts of fertilizer at the tillering stage and booting stage	<ul style="list-style-type: none"> • Improve the NUE • Increase rice yield • Reducing N losses • Reduce labor input (Zhang et al. 2014a)
Slow/controlled-release fertilizers	Manufactured from mineral fertilizers encapsulated into a synthetic polymer matrix or coated by a polymer layer	<ul style="list-style-type: none"> • Control nitrogen release • Reduce chemical fertilizer applications • Reduce nutrient losses • Simplify field operations (Achilea et al. 2010) • Reduce agricultural costs by decreasing fertilization frequency (Solihin et al. 2019)
Formula fertilization	Determine the optimum fertilizer rate and ratio of N-P-K fertilizer through soil testing	<ul style="list-style-type: none"> • Improve the NUE • Increase rice yield • Reduce fertilizer applications (Xiao et al. 2019)
Biochar addition	Add biochar in fields, which is the solid byproduct derived from biological organic material pyrolysis in an anaerobic or hypoxic environment.	<ul style="list-style-type: none"> • Enhance soil fertility • Increase rice yield • Improve soil physical and chemical properties (Yang et al. 2018) • Enhance water-retention capacity (Madari et al. 2017) • Alleviate soil acidification (Zhang et al. 2018)
Reducing fertilization	Reducing 10–30% of N fertilizer application rates according to the current fertilizer application rates and crop demand.	<ul style="list-style-type: none"> • Reduce chemical fertilizer applications • Reduce N losses (Xu et al. 2020)
Green manuring	Green manure is ploughed under the soil to improve soil fertility.	<ul style="list-style-type: none"> • Enhance soil fertility • Increase rice yield (Zhou et al. 2020) • Reduce chemical fertilizer applications (Raheem et al. 2019) • Improve soil structure and properties • Enhance water-retention capacity (Choi et al. 2014) • Adjust soil pH (Gao et al. 2015)
Straw incorporation	Straw is returned to the fields by ploughing.	<ul style="list-style-type: none"> • Enhance soil fertility • Adjust soil pH (Liu et al. 2021) • Lower residue • Decrease rice culture management costs (Han and He 2010)
Deep fertilization	Chemical fertilizer is applied under the surface soil at about 6 to 10 cm.	<ul style="list-style-type: none"> • Improve the NUE • Increase rice yield • Improve deep root growth • Increase available N content (Zhong et al. 2021)
Combined application of organic and inorganic fertilizers	Organic materials (such as manure) partially replace chemical fertilizers.	<ul style="list-style-type: none"> • Enhance soil fertility • Improve soil health (Jabbar et al. 2008) • Alleviate soil acidification (Zhai et al. 2011)

farmers in China (Hou et al. 2018). The local recommendations for N fertilizer amounts with special planting patterns and yield levels were obtained from the Ministry of Agriculture and Rural Affairs of the People's Republic of China (local recommendations of fertilizer amounts 2016). Rice yields in 2019 were obtained from the National Bureau

of Statistics (Rice yield, 2019); precipitation, and LUCC were obtained from the Resource and Environment Data Cloud Platform, Chinese Academy of Sciences (RESDC) (Precipitation and LUCC data 2020); annual frost-free season was calculated based on the daily minimum temperature with an inclusive 2 °C threshold from China Meteorological Data

Fig. 1 Application scenes of typical optimized fertilization practices in paddy fields in China: (a) straw incorporation, (b) green manuring, and (c) slow/controlled release fertilizers. Photographs a and b by Dr. Jingrui Chen. Photograph c courtesy of Pr Yufeng Wang.



Service Centre (Frost-free season, 2016–2020) (Tang and Niu 2011); DEM was obtained from the Geospatial Data Cloud to calculate the slope (DEM, 2019); soil conditions were calculated from soil property data of the FAO Harmonized World Soil Database (HWSD) (Soil property data 2018); and the number of livestock (total of large animals, hogs, sheep and goats) in 2019 was obtained from the China Statistical Yearbook in 2020 (Number of livestock, 2020). All data were unified into grid-scale images with a resolution of 1000 m in ArcGIS 10.2.

2.2 Methods

2.2.1 Analysis of the effects of various optimized fertilization practices

The load of total nitrogen (TN), lost from paddy fields via runoff in the whole growth period, was selected as the proxy

indicator to estimate the loss risk of N from paddy fields (Zhuang et al. 2019). Based on the multisite studies collected from the CNKI, the NUE-improving rate (NIR, %), yield-increasing rate (YIR, %), and N loss-reducing rate (NLRR, %) of each study site were calculated by Equations 1–3.

$$\text{NIR} = \text{NUE}_{\text{opt}} - \text{NUE}_{\text{conven}} \quad (1)$$

$$\text{YIR} = (\text{Y}_{\text{opt}} - \text{Y}_{\text{conven}}) / \text{Y}_{\text{conven}} \cdot 100 \quad (2)$$

$$\text{NLRR} = (\text{NL}_{\text{conven}} - \text{NL}_{\text{opt}}) / \text{NL}_{\text{conven}} \cdot 100 \quad (3)$$

where NUE_{opt} is the NUE at specific optimized practice (%); $\text{NUE}_{\text{conven}}$ is the NUE at conventional practice (%); Y_{opt} is the rice yield at specific optimized fertilization practice (kg/ha); Y_{conven} is the rice yield at conventional practice (kg/ha); $\text{NL}_{\text{conven}}$ is the TN loss load at conventional practice (kg/ha); and NL_{opt} is the TN loss load at special optimized practice (kg/ha).

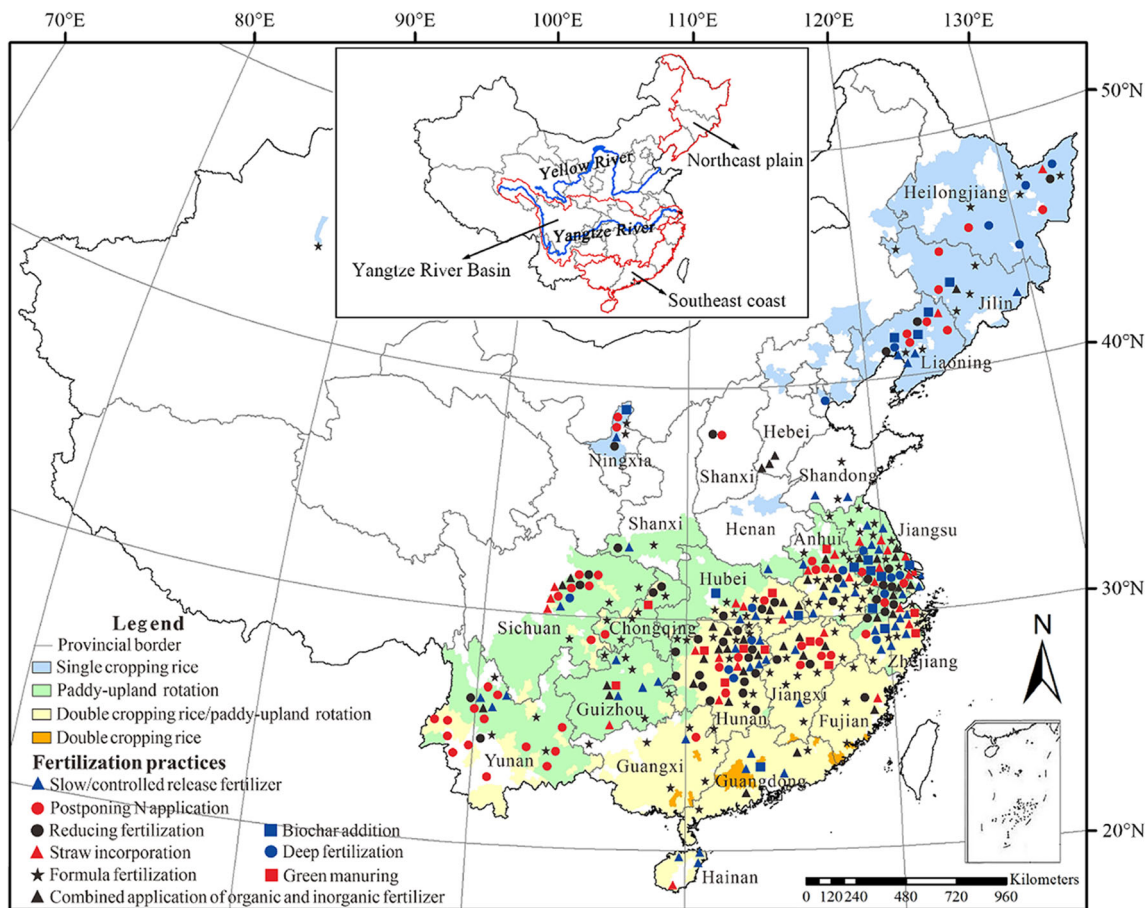


Fig. 2 Surveyed research sites of optimized fertilization practices in paddy fields in China.

Furthermore, these data were used to calculate the mean and standard deviation (SD) of YIR, NIR, and NLRR by specific fertilization practices. The differences in NUE increasing, yield increasing, and N loss-reducing effects between various practices were analyzed.

2.2.2 Analysis of fertilizer application status of paddy fields in China

Referring to the local recommendations of fertilizer application rates under specific yields, we first calculated the overapplied fertilizer amounts at the current rice yields in the local regions by Eq. (4), and further identified the overfertilized regions. The identification and visualization of overfertilized regions were finished in ArcGIS.

$$F_{\text{Over}} = F_{\text{local}} - F_{\text{recom}} \quad (4)$$

where F_{Over} is the overapplied fertilizer amount of N (kg/ha) used in the local regions; F_{local} is the actual fertilizer amount of N in the local regions (kg/ha); and F_{recom} is the recommended fertilizer amount of N at a specific yield level in the local regions (kg/ha). The overfertilized regions of paddies in China were divided into five levels based on the F_{Over} :

- Not excessive
- $F_{\text{Over}} \leq 50 \text{ kg/ha}$
- $50 \text{ kg/ha} < F_{\text{Over}} \leq 100 \text{ kg/ha}$
- $100 \text{ kg/ha} < F_{\text{Over}} \leq 150 \text{ kg/ha}$
- $F_{\text{Over}} > 150 \text{ kg/ha}$

2.2.3 Identification of the potential distribution of optimized fertilization practices at the country level

First, we analyzed the application conditions of various fertilization practices and identified the critical factors affecting their distribution across China by a literature survey (Hong et al. 2019; Liu et al. 2015; Zhang et al. 2014a; Zhou et al. 2020). Considering the applicability of various practices and the representativeness and measurability of the indices, these critical factors were selected as indicators to establish a new index system for fertilization practice selection, as shown in Table 2. The indices included five regional attribute factors (including soil condition, hydrothermal condition, terrain, current fertilization condition, and scale of livestock and poultry breeding) and two reference indicators (including labor and cost input effects). The reference factors are chosen as

Table 2 Index system and corresponding criteria for optimized fertilization practice selection of paddy systems in China. /, no special requirement; *, the practice needs to be given priority in this region; lower/higher, labor and cost inputs to increase/reduce compared to conventional fertilization practice; #, actual inputs depend on mechanization level. NLR, N loss-reducing; NI, NUE-improving; YI, yield-increasing.

Fertilization practices	I. Soil		II. Hydrothermal conditions			III. Terrain	IV. Fertilization condition	V. Livestock and poultry breeding	VI. Labor and cost inputs		VII. Effects
	Soil texture	Soil fertility	Soil acidity	Climate (precipitation)	Frost-free season				Labor	cost	
Postponing N application	/	/	/	/	/	/	/	/	Lower	Lower	NLR, NI, YI
Slow/controlled-release fertilizers	/	/	/	/	/	/	/	/	Lower	Lower	NLR, NI, YI
Formula fertilization	/	Medium, low*	/	/	/	/	Over-fertilized area*	/	Higher	Lower	NLR, NI, YI
Reducing fertilization	Clay, loam	/	/	/	/	/	Over-fertilized area	/	Lower	Lower	NLR
Green manuring	Sandy*	Medium, low*	pH≤5.5, PH>8.5*	Humid, semi-humid	>210 days	/	/	/	Lower	Lower	YI, NI
Straw incorporation	Sandy*	Medium, low*	pH≤5.5, PH>8.5*	Humid, semi-humid	/	/	/	/	Lower	Lower	YI, NI
Biochar addition	Sandy*	Medium, low*	pH≤6.5	Humid, semi-humid	/	/	/	/	Higher	Higher	NLR, YI, NI
Deep fertilization	Clay, loam	/	/	/	/	Plain paddy	/	/	Lower	Higher#	NI, YI, NLR
Combined application of organic and inorganic fertilizers	Sandy*	Medium, low*	pH≤5.5, PH>8.5*	/	/	Plain paddy*	/	Concentrated areas	Higher	Lower	NLR, YI

alternative indicators when the regional attributes related to optimized practices are similar.

The soil condition is subdivided into soil texture, soil fertility, and soil acidity. An American triangular chart for soil texture classification was used to classify soil texture as sandy, loamy, or clayey. In China, N surplus caused by excessive fertilization is common for cropping systems (Zhang et al. 2019); meanwhile, the fertility of most soils depends on the level of soil organic matter (SOM) (Adejuyigbe and Kodaolu 2012; Xie et al. 2021). Therefore, SOM was estimated to represent the soil fertility based on the topsoil organic carbon (T_OC), and topsoil pH (T_pH) was selected as indicative of soil acidity (Zhuang et al. 2019). The precipitation and frost-free season were selected to approximately express the hydrothermal conditions. In China, the growth periods of rice and green manure are approximately 110–160 days and 50 days, respectively, and the frost-free season of 210 days was determined to be the minimum requirement to assess whether the region is suitable to plant green manure. According to the terrain, paddy fields were divided into plain paddy (slope $\leq 6^\circ$), hilly paddy ($6^\circ < \text{slope} \leq 15^\circ$), mountainous paddy ($15^\circ < \text{slope} \leq 25^\circ$), and sloping paddy fields ($> 25^\circ$). The number of livestock was used to analyze the scale of livestock and poultry breeding, which directly impacts the combined application of organic and inorganic fertilizers.

The potential distribution of optimized fertilization practices in China was simulated according to the new index system by spatial analysis in ArcGIS 10.2. The actual distribution of fertilization practices, acquired by survey, was used to verify the identification results.

2.2.4 Analysis of potential effects of optimized fertilization practices at the country level

According to the simulation results of the potential distribution of specific optimized fertilization practices, the spatial distribution of recommended scenarios was identified. Furthermore, based on the effects of a single optimized fertilization practice, the overall effects under recommended scenarios at the grid level and the country level were estimated successively. For each grid (i), the local yield-increasing rate (YIR_{local}) and N loss-reducing rate ($NLRR_{\text{local}}$) were calculated by Equations (5) and (6); then, the rice yield and the fertilizer amount in various regions were used as weights to calculate the total yield-increasing rate (YIR_{total}) and N loss-reducing rate ($NLRR_{\text{total}}$) at the country level by Equations (7) and (8).

$$YIR_{\text{local}} = 1 - \prod_{j=1}^n (1 - YIR_{i,j}) \quad (5)$$

$$NLRR_{\text{local}} = 1 - \prod_{j=1}^n (1 - NLRR_{i,j}) \quad (6)$$

where $YIR_{i,j}$ is the yield-increasing rate of j th single practice for i th grid (%); $NLRR_{i,j}$ is the N loss-reducing rate of j th single practice for i th grid (%); i is the i^{th} grid at the country level; j is the j^{th} optimized fertilization practice for the specific grid; and n is the number of all practices under the recommended scenario applied locally.

$$YIR_{\text{total}} = \sum(YIR_{\text{local}} \times Y_{\text{local}}) / \sum Y_{\text{local}} \quad (7)$$

$$NLRR_{\text{total}} = \sum(NLRR_{\text{local}} \times F_{\text{local}}) / \sum F_{\text{local}} \quad (8)$$

where YIR_{total} is the yield-increasing rate of combined optimized fertilization practices at the country level (%); Y_{local} is the rice yield in the local regions (kg/ha); $NLRR_{\text{total}}$ is the N loss-reducing rate of combined optimized fertilization practices at the country level (%); and F_{local} is the amount of N fertilizer used in the local regions (kg/ha).

The potential effects of optimized fertilization practices at the country level were estimated by applying Eqs. (5–8) and visualized by raster calculator and zonal statistics in ArcGIS 10.2.

3 Results and discussion

3.1 Fertilizer application status of paddy fields in China

The local recommendations for fertilizer amounts specified the standard N fertilizer amounts under high, medium, and low yields; overall, with higher yields, the required fertilizer amounts were greater, which explained to a certain extent why overfertilization occurs when pursuing high yields for a long time. The overfertilized regions for rice production under current yields in China are identified in Fig. 3.

Under the current yields at the country level, 76.5% of all paddies in China were in overfertilized regions. Among these overfertilized regions, the regions with more than 150 kg/ha excessive N fertilizer cover 6.9%, scattered in Jiangsu, Hunan, Guangxi, Yunnan, Jilin, and Hebei Provinces; the regions with an excessive N fertilizer range of 100 to 150 kg/ha cover 8.3%, scattered in Jiangsu, Jiangxi, Yunnan, and Jilin Provinces; and 61.3% of all paddies had excessive N fertilizer less than 100 kg/ha, mainly distributed in Anhui, Jiangsu, Hunan, Sichuan, and Jiangxi of central China. Overall, the overfertilized regions were mainly concentrated in the Yangtze River Basin, which exhibits severe eutrophication (Shi et al. 2020). On the one hand, among the three main rice-producing areas, the Yangtze River Basin has an absolutely dominant position in terms of planting area and rice yield; on the other hand, the national investigation of water and N fertilizer use in paddy fields implied that non-point source pollution of N is expected to continue increasing, especially in the Yangtze River Basin (Liu et al. 2021b). Widespread overfertilization is the primary cause of TN losses and underutilization of N fertilizer. To

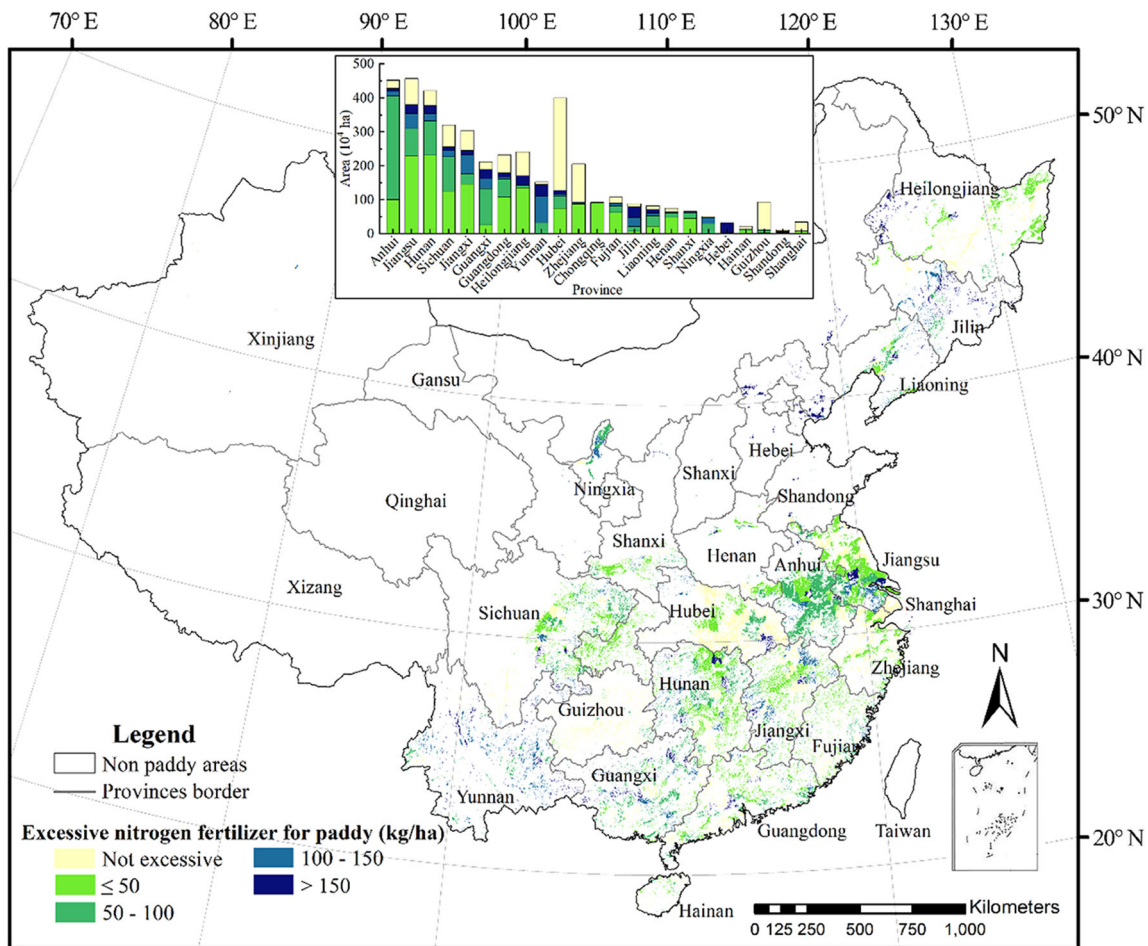


Fig. 3 Spatial distribution of overfertilized regions at current rice yield levels in China.

change the current fertilization status, optimized fertilization with high NUE is necessary.

3.2 Individual effects of optimized fertilization practices for rice production in China

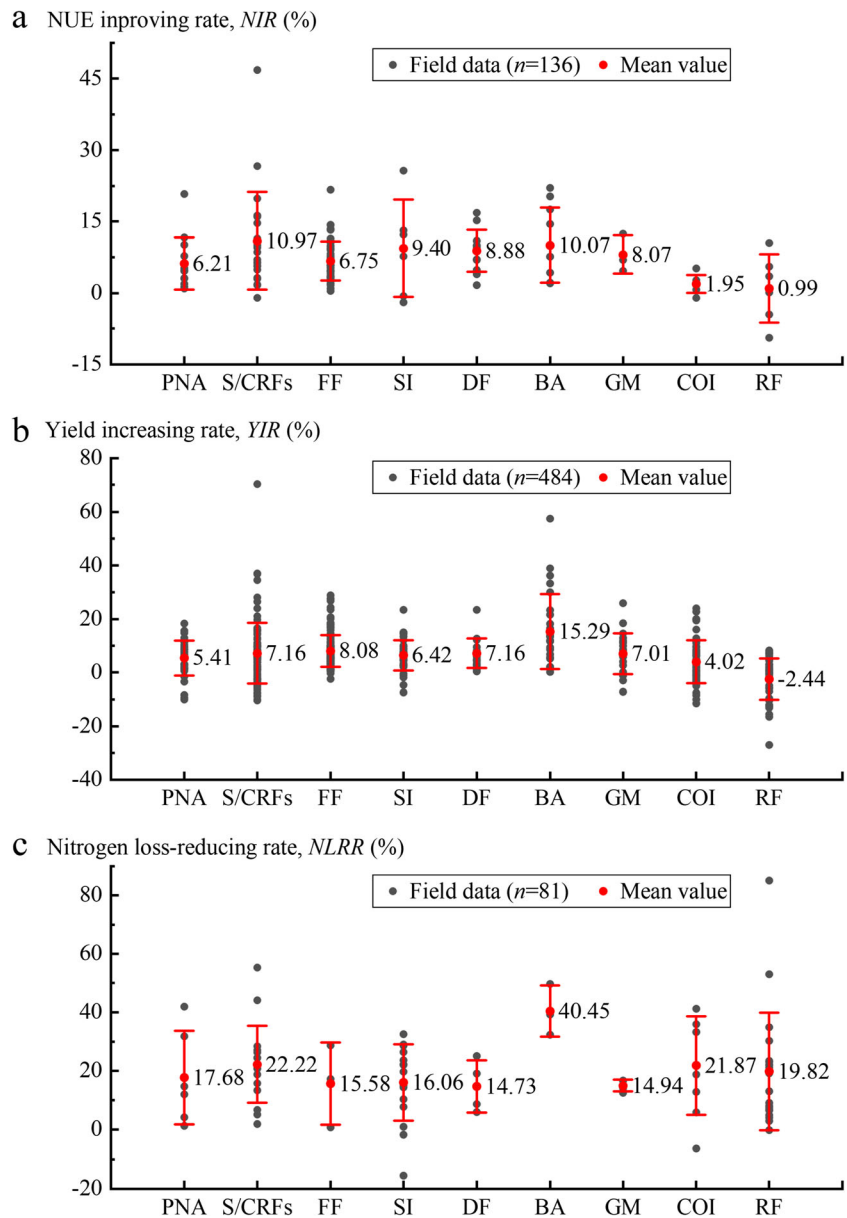
According to the spatial distribution of multi-research sites, most studies are clustered together in central and eastern China, such as Jiangsu, Zhejiang, Anhui, Hubei, Hunan, and Jiangxi provinces, which belong to the paddy-upland rotation area located in the Yangtze River Basin of central China; relatively few studies are scattered in the single cropping rice area of Northeast China and the double cropping paddy area of South China. In addition to increasing rice yield, environmental pollution control is another prime motivator to implement optimized fertilization practices. The effects of various fertilization practices on enhancing NUE, increasing yield, and reducing TN loss, as extracted from the literature data, are shown in Fig. 4.

In terms of NUE enhancing effects, the range of the average NIR of nine optimized fertilization practices was 1~11%. S/CRFs had the highest average NIR of 11%, followed by

biochar, straw incorporation, and deep fertilization; the combined application of organic and inorganic fertilizers and the reducing fertilization had a relatively low NUE enhancing effect with the average NIR of 2% and 1%, respectively. Overall, optimized fertilization increased the NUE. S/CRFs and biochar addition increase the NUE by controlling the N release rate according to the N demand of rice in different growing stages (Solihin et al. 2019); postponing N application increases the NUE by selecting a reasonable time and frequency of fertilization to promote N uptake (Bai et al. 2020); and deep fertilization potentially increases the NUE by promoting root absorption (Zhao et al. 2021). Because of the different mechanisms, the NIR varied among fertilization practices. Due to the good NUE-improving effects, optimized fertilization practices, such as slow/controlled-release fertilizers, formula fertilization, and green manuring, can reduce N fertilizer amounts under the premise of ensuring stable and increasing rice yields to some extent (Achilea et al. 2010; Raheem et al. 2019; Xiao et al. 2019).

In terms of yield-increasing effects, the range of the average YIR of nine optimized fertilization practices was ~2~15%. Reducing fertilization had the lowest average YIR

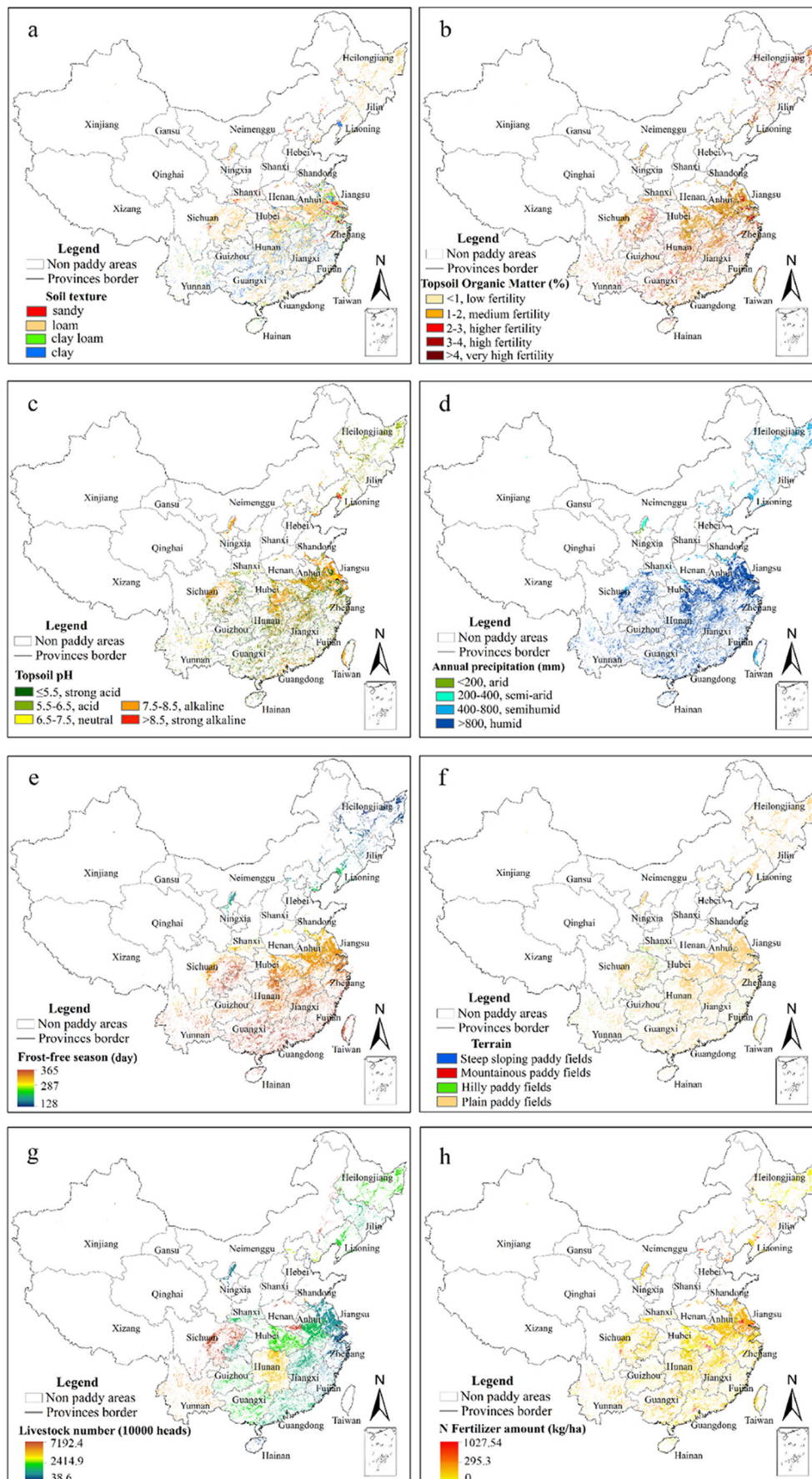
Fig. 4 Effect analysis of optimized fertilization practices: (a) NUE-improving rate (NIR), (b) yield-increasing rate (YIR), and (c) nitrogen loss-reducing rate (NLRR). PNA postponing N application; S/CRFs slow/controlled-release fertilizers; FF formula fertilization; SI straw incorporation; DF deep fertilization; BA biochar addition; GM green manuring; COI combined application of organic and inorganic fertilizer; RF reducing fertilization.



of -2% ; biochar addition had the highest average YIR of 15%, followed by formula fertilization (8%), S/CRFs (7%), deep fertilization (7%), green manuring (7%), straw incorporation (6%), postponing N application (5%), and combined application of organic and inorganic fertilizers (4%). The improvement of NUE and soil fertility is the important reason for the yield-increasing effects of most optimized fertilization practices. In addition, biochar addition increased crop yield by improving soil structure to reduce mechanical resistance to crop root growth and enhance water-retention capacity (Madari et al. 2017; Yang and Lu 2021; Yang et al. 2018); green manure improves paddy soil fertility and ecology through nitrogen fixation while improving soil structure (Ma et al. 2020). The main goal of reducing fertilization is to reduce the excessive fertilizer input under the premise of stable

yield. Reducing fertilization may lead to negligible effects on yield increases and even yield reductions when the amount of fertilizer is probably less than the optimum fertilization rate.

In terms of the N loss-reducing effect, the range of the average NLRR of nine optimized fertilization practices was 15~40%. Biochar addition had the highest average NLRR of 40%, followed by S/CRFs, organic and inorganic fertilizer, and reducing fertilization. Overall, the NLRR of most fertilization practices was more than 15%. Biochar addition, organic and inorganic fertilizer, green manuring, and straw incorporation reduce TN losses mainly by improving soil structure and fertility; moreover, biochar also has strong absorbability and a larger ion exchange capacity with good void structure, which is observed to significantly reduce the TN contents of paddy surface water after fertilization, and has a high NLRR



◀ **Fig. 5** Regional attribute factors of paddy systems in China: (a) soil texture, (b) soil fertility, (c) soil pH, (d) annual precipitation, (e) frost-free season, (f) slope, (g) number of livestock, and (h) N fertilizer amount.

(Lu et al. 2020; Ni et al. 2021). On the basis of conventional fertilization, reducing fertilization can control the fertilizer amount from the source and effectively reduce the TN losses via surface runoff from paddy fields (Xu et al. 2020). Under the current conditions of excessive fertilization in China, reducing fertilization has huge potential for use.

NIR and YIR were positively correlated ($r = 0.728$, $p = 0.026$). In general, the higher the NIR was, the higher the YIR; the correlation between NIR and NLRR was not significant. NUE improvement directly promoted the yield increase, but the N loss-reducing effects did not only depend on NUE improvement. For a specific fertilization practice, a relatively large standard deviation (SD) of NIR, YIR, and NLRR arose. Between various practices, the variability of effects was mainly dependent on the fertilization strategy and mechanism. For example, biochar has strong absorbability and can enhance water-retention capacity, so its NLRR is apparently higher than that of S/CRFs, under a similar NIR (Madari et al. 2017). For the same practice, the variability of effects is mainly dependent on specific fertilization regimes and environmental factors, such as specific fertilization time, fertilizer amount and types, soil condition, precipitation, rice variety, and local planting habit. For example, the effectiveness of various N stabilizers of S/CRFs on rice yield and NUE varies greatly (Liu et al. 2020), and the effect of biochar application on soil N varies with biochar application mode, N form, and rice growth period (Lu et al. 2020).

3.3 Potential distribution of optimized fertilization practices for rice production in China

Fertilizing regimes vary in not only agronomic effects but also environmental impact factors, labor and cost inputs, technology maturity, etc. The spatial distribution of key factors that affect the applicability of optimized fertilization practices is shown in Fig. 5, and the index system and corresponding criteria for optimized fertilization practice selection of paddy systems in China are shown in Table 2.

In terms of soil conditions, soil texture, soil fertility, and soil acidity are the main factors. Only 14.1% of paddy fields are sandy soils in China. Highly permeable sandy soil often has a low holding capacity for nutrients and moisture (Yang et al. 2008). Deep fertilization is not suitable for use in sandy soils because of possible leaching loss of nutrients (Phongchanmixay et al. 2019). Straw incorporation, green manuring, and the combined application of organic and inorganic fertilizers are beneficial for rice cultivation in sandy soil by improving soil structure and properties while enhancing

water-retention capacity (Barros et al. 2017; Jabbar et al. 2008; Choi et al. 2014). Strongly acidic soil covers approximately 25.3% of total paddy fields and soil acidification is relatively serious in paddy fields in central and southern China. Biochar can ameliorate soil acidification by providing a liming effect and strong nutrient adsorption (Madari et al. 2017; Dai et al. 2017). Straw incorporation, green manure, and organic fertilizer have the potential to adjust soil pH by changing the microbial communities and improving soil properties (Zhang et al. 2018; Gao et al. 2015; Zhai et al. 2011).

Rich water and heat resources represent that the region has good water and temperature conditions, such as abundant precipitation and a long frost-free season, which are beneficial for straw degradation and green manure planting (Tomasek et al. 2017; Zhang et al. 2021b). Most of China's paddy fields occur in areas with precipitation exceeding 400 mm year⁻¹ and a relatively short frost-free season results in green manure not having enough time to grow in the single-cropping rice region of Northern China (Zhang et al. 2014b). N runoff loss is predominantly governed by the fertilization rate (Xu et al. 2020), and reducing fertilization is an effective way to mitigate runoff pollution in overfertilized regions. According to terrain data, paddy fields in China are mainly distributed across both plains and hills, and only 4.2% of paddy fields are scattered in mountainous regions such as Guizhou, Yunnan, and Sichuan Provinces. Hilly or mountainous terrain is usually not beneficial for deep fertilization. Moreover, in China, planting and breeding are always separated, which results in a low utilization rate of livestock and poultry manure. Therefore, the combined application of organic and inorganic fertilizers has vast potential in well-developed livestock and poultry breeding regions, but the most optimum fertilization ratio needs to be identified to form a sustainable agricultural development pattern by combining the local breeding industry and planting mode.

In terms of labor and cost inputs, reducing fertilization, postponing N application, S/CRFs, straw incorporation, and green manuring can decrease the cost input by reducing chemical fertilizer application and simplifying rice culture management (Achilea et al. 2010; Xu et al. 2020; Han and He 2010; Solihin et al. 2019). Accordingly, high labor and cost inputs will restrict the application of other fertilization practices. Given the high labor requirement for deep fertilization, mechanical fertilization technology is necessary to overcome this difficulty (Liu et al. 2015; Su et al. 2015). Formula fertilization and biochar addition require constant technical support to determine the optimal fertilization scheme (Lu et al. 2020).

Based on the new regional attributes of various fertilization practices (Table 2), the potential distribution of appropriate fertilization practices for paddy systems in China was simulated based on the new index system, as shown in Fig. 6, which is consistent with the investigation results (Fig. 2).

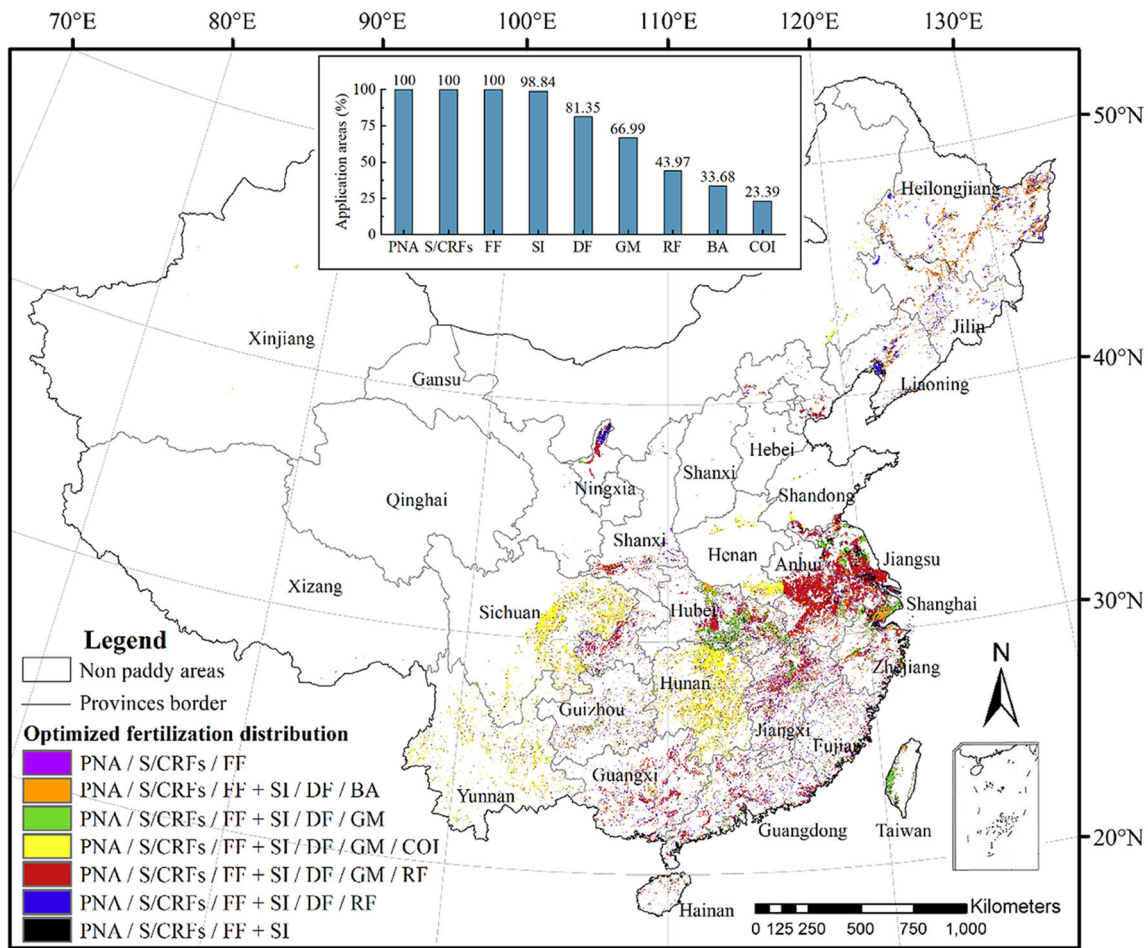


Fig. 6 Potential distribution of appropriate optimized fertilization practices for rice production in China. PNA postponing N application; S/CRFs slow/controlled-release fertilizers; FF formula fertilization; SI

straw incorporation; DF deep fertilization; BA biochar addition; GM green manuring; COI combined application of organic and inorganic fertilizer; RF reducing fertilization.

Postponing N application, S/CRFs, and formula fertilization had wide applicability nationwide, and the other six optimized fertilization practices had various degrees of regional restrictions. A total of 98.8% of all paddy fields in China were suitable for straw incorporation, followed by deep fertilization (81.4%), green manuring (67.0%), reducing fertilization (44.0%), biochar addition (33.7%), and combined application

of organic and inorganic fertilizers (23.4%). Optimized fertilization has great potential in China, particularly under the coupling scenarios of multiple fertilization practices.

Straw incorporation and green manuring are mainly distributed in central and southern China, which have rich water and heat resources (Hong et al. 2019; Zhou et al. 2020). Reducing fertilization is mainly distributed in areas

Table 3 Overall effects of optimized fertilization practices for rice production at the country level under recommended scenarios. RF, Reducing fertilization; GM, Green manuring; SI, Straw incorporation; PNA, Postponing N application; S/CRFs, Slow/controlled-release fertilizers; YIR, yield increasing rate (%); NLRR, N loss-reducing rate (%).

Practice combination		Application areas of fertilization practices (%)	YIR (%)	NLRR (%)
Scenario 1	RF + GM	81.4	3	15
Scenario 2	RF + SI	99.2	4	20
Scenario 3	RF + PNA	100	4	25
Scenario 4	RF + S/CRFs	100	5	30
Scenario 5	RF + SI + GM	100	7	24
Scenario 6	RF + PNA + GM	100	7	28
Scenario 7	RF + PNA + SI	100	8	32
Scenario 8	RF + S/CRFs + GM	100	8	31
Scenario 9	RF + S/CRFs + SI	100	9	35

with excessive amounts of fertilizer, such as the Yangtze River Basin. As a new optimized fertilization practice, biochar addition is mainly used in Jiangsu and Zhejiang Provinces and scatters in the Northeast Plain. The combined application of organic and inorganic fertilizers is applied to regions with large-scale breeding industries, such as Hunan, Sichuan, Yunnan, and Henan provinces, and can realize the recycling of breeding waste.

With the development of technologies, the distribution of fertilization practices may change. For example, hydrothermal conditions and time affect the decomposition of rice straw (Luyima et al. 2019); microbial inoculants can be used to promote crop straw decomposition to solve these problems (Kumar et al. 2019; Wang et al. 2020); and machine-transplanted rice with side-deep fertilization (MRSF) is a recommended strategy to reduce labor costs and TN loss in sustainable production in China (Zhong et al. 2021a), which will promote the application of straw incorporation and deep fertilization.

3.4 Overall effect of optimized fertilization practices for rice production at the country level

Figure 5h and Fig. S1 show the spatial distribution of N fertilizer amount and rice yield at the country level. The high-yield regions were mainly distributed in Jilin and Liaoning Provinces in Northern China and Jiangsu, Hubei, Henan, and Shandong Provinces in central and eastern China, which also featured high N fertilization rates. China is still at the stage of raising rice yields with high fertilization and irrigation levels, which is the main reason why NPS pollution from paddy fields is severe in China (Zhuang et al. 2019).

By comparing the key factors for practice selection, formula fertilization, biochar addition, and deep fertilization have good yield-increasing and N loss-reducing effects, but their relatively high inputs of labor, mechanical power, or technology limit the promotion and application of practices to some degree at present; reducing fertilization, postponing N application, S/CRFs, green manuring, and straw incorporation are five eco-friendly and easy-to-operate fertilization practices with wide distribution, low inputs, and good effects in China.

The combination of multiple practices can significantly reduce TN loss and effectively improve rice yield (Shi et al. 2020; Zhou et al. 2020). Reducing fertilization is a necessary practice for cost savings and TN loss reduction in regions with excessive use of N fertilizer; moreover, with a greater number of adopted optimized fertilization practices, the YIR and NLRR are higher, but accordingly, the labor inputs are greater. Therefore, the recommended combination scenario would better have no more than three practices in the same region. On the basis of the above findings, nine recommended

combination scenarios (Scenarios 1–9) of optimized fertilization practices at the country level were determined, as shown in Table 3. For an example of Scenario 3 (reducing fertilization and postponing N application), two practices were combined and applied at the country level, and the spatial distribution of the practice combination under Scenario 3 was identified, as shown in Fig. S2. Furthermore, the comprehensive effects of recommended combination scenarios were estimated at the country level (Table 3).

By fully implementing the nine given combination scenarios based on the above five practices at the country level, the YIR_{total} and $NLRR_{total}$ reached 3–9% and 15–35% under suitable application areas of 81.4–100% of all paddy fields, respectively. Among the two-practice combination scenarios, Scenario 3 (reducing fertilization and postponing N application) and Scenario 4 (reducing fertilization and S/CRFs) had relatively good effects; among the three-practice combination scenarios, Scenario 7 (reducing fertilization, postponing N application, and straw incorporation) and Scenario 9 (reducing fertilization, S/CRFs, and straw incorporation) had relatively good effects. For Scenario 3, the YIR_{total} and $NLRR_{total}$ were 4% and 25% suitable for 100% of all paddies, respectively, which were better than single reducing fertilization (–2% and 20% suitable for 44.0% of all paddies) and single postponing N application (5% and 18% under 100% of all paddies). Overall, the effects under combination scenarios were significantly better than those under single practice.

4 Conclusions

Optimized fertilization is a promising management practice for sustainable rice production. Green manuring, straw incorporation, postponing N application, formula fertilization, reducing fertilization, deep fertilization, S/CRFs, combined application of organic and inorganic fertilizers, and biochar addition are nine frequently used optimized fertilization practices. Environmental protection has become an important driver to promote the implementation of optimized fertilization practices, after yield-increasing demand. Biochar addition had the highest YIR (15%) and NLRR (40%). Overall, most practices generally increased yield by more than 5% and reduced TN losses by more than 15%.

Under the current rice yields at the country level, 76.5% of all paddies in China were overfertilized regions. Widespread overfertilization is the primary cause of TN loss and underutilization of N fertilizer. The application of optimized fertilization practices is largely affected by regional environmental factors (including soil conditions, hydrothermal conditions, and terrain), fertilization conditions, poultry and livestock breeding scales, inputs, effects, and planting habits. Postponing N application,

S/CRFs, and formula fertilization were categorized under general applications without region restrictions, followed by straw incorporation (98.8% of total paddy areas), deep fertilization (81.4%), green manuring (67.0%), reducing fertilization (44.0%), biochar addition (33.7%), and combined application of organic and inorganic fertilizers (23.4%). Reducing fertilization, postponing N application, S/CRFs, green manuring, and straw incorporation are five eco-friendly and easy-to-operate fertilization practices with wide distribution, low inputs, and good effects in China. By fully implementing the recommended combination scenarios based on five practices at the country level, the total YIR and NLRR reached 3~9% and 15~35%, respectively.

The application of optimized fertilization in China has noticeable potential to improve fertilizer use efficiency and further alleviate non-point source pollution while ensuring a high yield. Future fertilization measures, tailored to local conditions, need to scientifically combine multiple fertilization practices. The integrated effects of optimized fertilization practices with other management practices, such as irrigation and tillage, will be a significant research direction in paddy systems. In addition, optimized fertilization practices have huge potential to mitigate greenhouse gas emissions. The positive versatility of optimized fertilization practices will be another research focus area in the future.

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Data availability The datasets analyzed during the current study are available in the file 'Supplementary Material 1'.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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