

# Optimal nitrogen rate strategy for sustainable rice production in China

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Siyuan Cai<sup>1,2,6</sup>, Xu Zhao<sup>1,6</sup>✉, Cameron M. Pittelkow<sup>3</sup>, Mingsheng Fan<sup>4</sup>, Xin Zhang<sup>5</sup> & Xiaoyuan Yan<sup>1</sup>✉

Avoiding excessive agricultural nitrogen (N) use without compromising yields has long been a priority for both research and government policy in China<sup>1,2</sup>. Although numerous rice-related strategies have been proposed<sup>3–5</sup>, few studies have assessed their impacts on national food self-sufficiency and environmental sustainability and fewer still have considered economic risks faced by millions of smallholders. Here we established an optimal N rate strategy based on maximizing either economic (ON) or ecological (EON) performance using new subregion-specific models. Using an extensive on-farm dataset, we then assessed the risk of yield losses among smallholder farmers and the challenges of implementing the optimal N rate strategy. We find that meeting national rice production targets in 2030 is possible while concurrently reducing nationwide N consumption by 10% (6–16%) and 27% (22–32%), mitigating reactive N (Nr) losses by 7% (3–13%) and 24% (19–28%) and increasing N-use efficiency by 30% (3–57%) and 36% (8–64%) for ON and EON, respectively. This study identifies and targets subregions with disproportionate environmental impacts and proposes N rate strategies to limit national Nr pollution below proposed environmental thresholds, without compromising soil N stocks or economic benefits for smallholders. Thereafter, the preferable N strategy is allocated to each region based on the trade-off between economic risk and environmental benefit. To facilitate the adoption of the annually revised subregional N rate strategy, several recommendations were provided, including a monitoring network, fertilization quotas and smallholder subsidies.

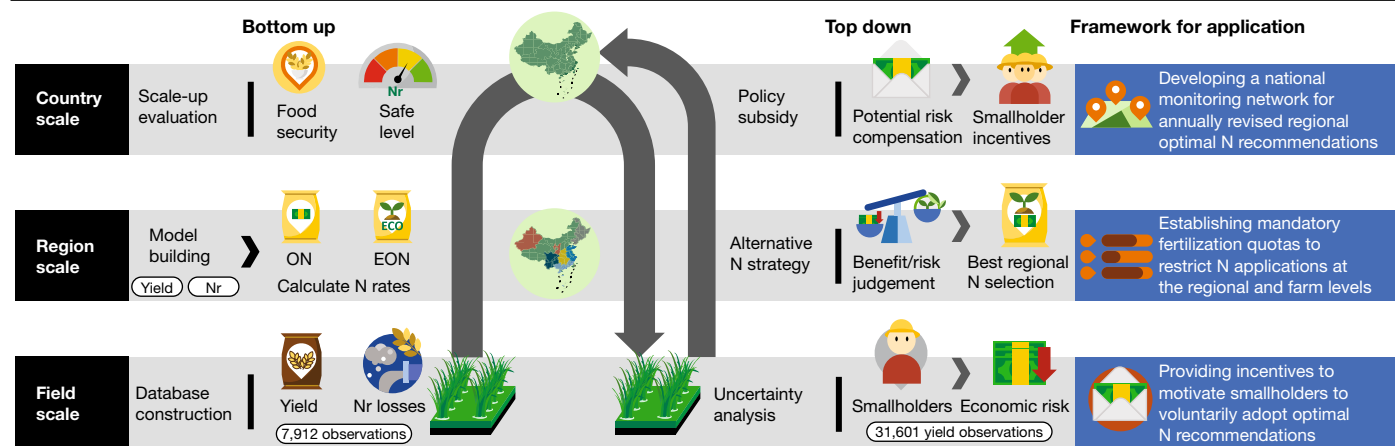
Cereal production has been the main focus of both scientists and policy-makers to ensure food security by 2050 (refs. <sup>6,7</sup>). However, agricultural intensification, especially that driven by increased chemical N use, has resulted in a series of environmental burdens<sup>8,9</sup>. Early work estimated that the global damages of Nr pollution, representing 0.3–3% of global gross domestic product<sup>10</sup>, may negate the economic gains associated with higher crop yields. Further evidence from other studies and efforts suggest a need to rethink sustainable N management for food security<sup>11–13</sup>. To address these challenges, a new model of N management that not only quantifies the benefits of fertilizer N use for crop productivity but also explicitly accounts for environmental and human health damage costs associated with Nr pollution is necessary<sup>11–14</sup>.

Rice-based cropping systems in China are a global hotspot for Nr losses, including airborne Nr losses such as NH<sub>3</sub> and N<sub>2</sub>O and waterborne Nr losses owing to leaching and runoff, contributing an estimated 2 megatonnes (Mt) year<sup>–1</sup> Nr to the environment<sup>15</sup>. Despite these challenges, a national rice production goal of 218 Mt year<sup>–1</sup> by 2030 is required for rice self-sufficiency in China<sup>16</sup>, signifying that prudent management of N inputs is needed to narrow the yield gap and boost rice production. Owing to current high rates of N fertilizer input, it is thus critical to close the N use efficiency (NUE) gaps between China (25–35%) and other leading regions of the world

(52–67%)<sup>17–19</sup>, particularly by focusing on existing gaps among different cropping regions in China (22–70%)<sup>20</sup>. To support this transformation, policies are urgently needed to guide region-specific N management practices, helping farmers to balance the benefits of N use for crop productivity with Nr losses and associated social costs to humanity<sup>2,21</sup>.

Avoiding excessive N use while maintaining yields has been a top research and government priority in China<sup>2,4,15,22</sup>. Yet, the feasibility of policies targeting N rate reductions will depend on the economic risk facing individual farmers. Uniform recommendations based on compiled data tend to exaggerate or underestimate crop N demand at the field level at which N management decisions are made, thereby impairing crop productivity or profitability<sup>23</sup>. Mobilizing millions of smallholders to reduce N rates is therefore challenging, partly because of their risk-averse nature. Thus, quantifying the probability of yield risk owing to management changes is vital to understanding the likelihood of farm-scale adoption of optimal N rate<sup>24</sup>. Meanwhile, the degree to which environmental policies interfere with national efforts to meet future rice production targets must be determined. Evaluating such trade-offs for food security is fundamental for implementing N management practices with well-documented long-term advantages for soil fertility and environmental quality<sup>25</sup>.

<sup>1</sup>State Key Laboratory of Soil and Sustainable Agriculture, Changshu National Agro-Ecosystem Observation and Research Station, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, People's Republic of China. <sup>2</sup>University of Chinese Academy of Sciences, Beijing, People's Republic of China. <sup>3</sup>Department of Plant Sciences, University of California, Davis, Davis, CA, USA. <sup>4</sup>College of Resources and Environmental Sciences, China Agricultural University, Beijing, People's Republic of China. <sup>5</sup>Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, USA. <sup>6</sup>These authors contributed equally: Siyuan Cai, Xu Zhao. ✉e-mail: zhaoxu@issas.ac.cn; yanxy@issas.ac.cn



**Fig. 1 | Schematic illustration of the research workflow.** The bottom-up processes comprise three steps. First, field trials for rice yield and Nr losses were constructed from 462 peer-reviewed articles (7,912 observations). Second, subregional models were developed and used to determine ON and EON based on economic benefit and NEEB. Third, nationwide rice production, N consumption and Nr losses under ON and EON were estimated and compared

with the corresponding safe level. Three steps were included in the top-down method for analysing the uncertainty of subregional ON and EON. First, the potential risk for smallholders was quantified by the site-year models from 31,601 yield observations. Second, the subregional net benefit was assessed to optimize the subregional N strategy. Third, the potential subsidy to incentivize smallholders to apply optimal N was quantified.

Although two of the optimal N application strategies attempting to maximize economic and environmental performance (the economically optimal N rate (ON) and the ecologically optimal N rate (EON)) for rice systems have been assessed<sup>15,22</sup>, their viability in fulfilling food security and environmental sustainability, as well as their potential yield risk for smallholders and the preferable strategies for diverse subregions in China remain unexplored. Herein, using a combination of bottom-up and top-down strategies, we evaluate these two optimal N application strategies for rice systems at the subregional scale to cover these knowledge gaps (Fig. 1). Yield and Nr losses in response to N inputs were first quantified on the basis of 7,912 monitoring observations from 462 peer-reviewed publications covering the six different rice cultivation subregions of China (Supplementary Fig. 1 and Supplementary Note 1). Next, the economic benefits of N fertilizer and environmental and human health damage costs under two N optimal strategies were calculated, with the difference reflecting the net ecosystem economic benefit (NEEB)<sup>26</sup> (Supplementary Table 1). The impacts of these N strategies on rice productivity, environmental sustainability (Nr losses) and long-term soil fertility (N balance) were then compared with farmer practices (FN) for each subregion. The advantages and limitations of our comprehensive synthesis of the literature are discussed further in Supplementary Note 2 (Supplementary Figs. 2 and 3).

### Food security within the Nr threshold

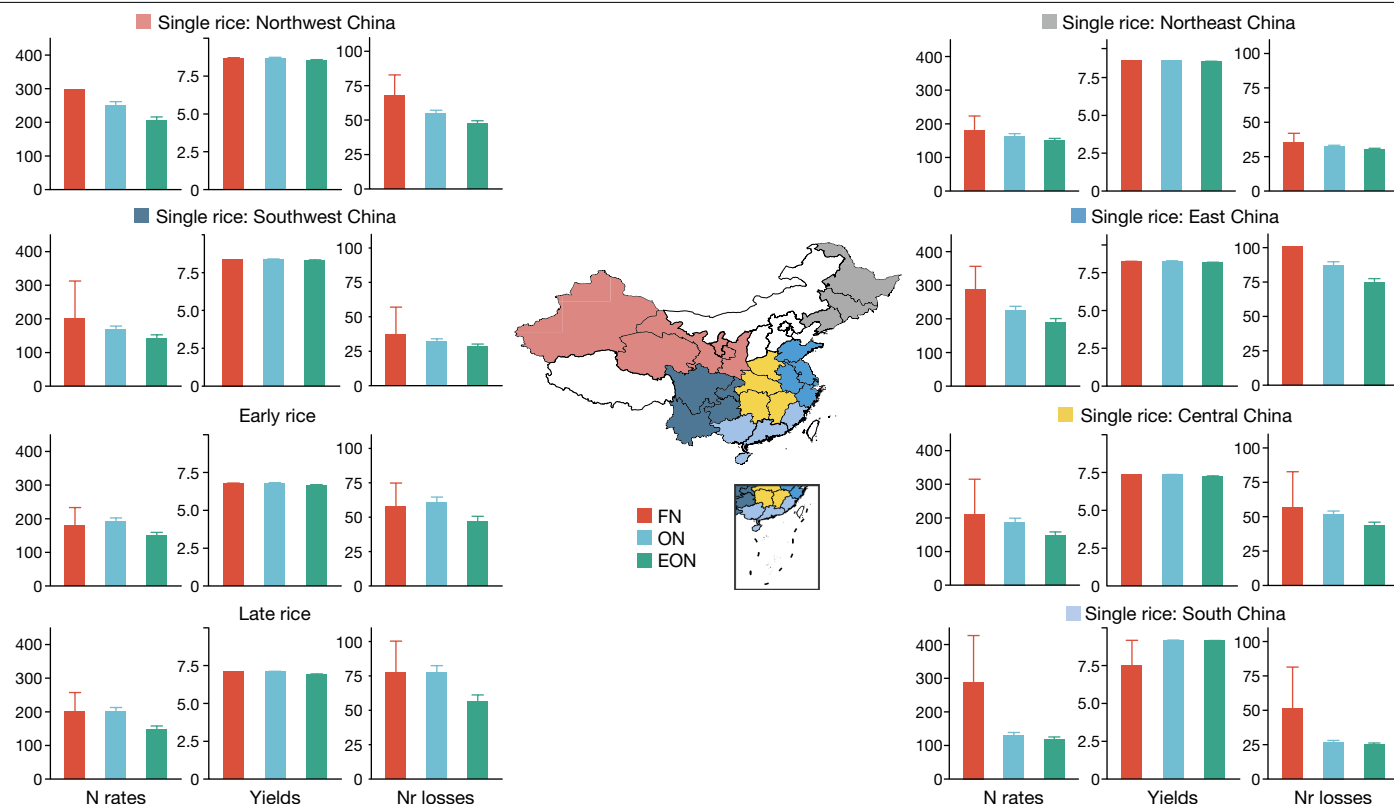
Both optimized N strategies contributed to substantial reductions in area-based N inputs (18–32%, with a national average of 231 kg N ha<sup>-1</sup> for FN compared with 189 and 155 kg N ha<sup>-1</sup> for ON and EON, respectively) and Nr losses (12–27%, with a national average of 60 kg N ha<sup>-1</sup> for FN compared with 53 and 44 kg N ha<sup>-1</sup> for ON and EON, respectively) without impairing yields, making it possible to exceed the demand for rice in China in 2030 (218 Mt) while reducing nationwide N consumption by 10–27% (0.64–1.75 Mt), and mitigating Nr losses by 7–24% (0.11–0.40 Mt) for ON and EON, respectively (Figs. 2 and 3).

From a regional perspective, current fertilizer N consumption levels (FN) for rice are disproportionately high (0.80–1.46 Mt) in East, Central and Southwest China (Fig. 3a), which together contribute to more than half of the Chinese national fertilizer N consumption for rice (6.36 Mt). Accordingly, these N fertilization hotspots are critical for reducing nationwide N fertilizer consumption when comparing the two optimal N rate strategies (ON or EON) to FN, accounting for around 20–30%

of the total N fertilizer consumption cutback (Fig. 3a). By applying the proper rate of N fertilizer according to the relationship between Nr losses and crop productivity of each rice cultivated subregion (Extended Data Fig. 1), the total N fertilizer consumption would decrease by 0.68–1.75 Mt across China, which accounts for 10–27% of the current national anthropogenic N input for rice cultivation. A governmental document released in 2020 by Chinese policymakers, based on soil testing and fertilizer recommendations, targeted fertilizer N consumption for rice in China to be 3.9–5.1 Mt (ref. <sup>27</sup>), a threshold that is comparable with N input by adopting EON in our study (Fig. 3a). The comparison of results for the two optimal N rates with preceding studies (Extended Data Table 1) is further discussed in Supplementary Note 3.

The application of optimal N strategies had a minor influence on the area-based and region-scaled rice production (Figs. 2 and 3a and Supplementary Note 4), amounting to a <2% decline nationwide under EON and a roughly 0.4% increase under ON. Rice yield performance under ON exhibited incremental improvements in most subregions of China, of which East and South China contributed 0.22–0.66 Mt year<sup>-1</sup> to the yield growth. By contrast, yield performance under EON differed between the subregions, with Central China and late rice cultivar subregions showing a yield decrease of 0.81–1.13 Mt year<sup>-1</sup>, whereas South China exhibited a 0.64 Mt year<sup>-1</sup> yield growth. Food demand in China is estimated to peak in 2030 when the population reaches 1.47 billion (ref. <sup>28</sup>). On the basis of a bottom-up estimation combining yield changes and rice planting area in 2018 for each subregion, total national rice production through ON and EON was estimated to be 232 and 228 Mt, respectively (Fig. 3a), which is sufficient to meet the predicted rice demand of China in 2030 (218 Mt).

More than 25% of fertilizer N applied to rice fields was lost to the environment as Nr (N leaching, N<sub>2</sub>O emissions, NH<sub>3</sub> volatilization and N runoff) under FN (1.69 Mt year<sup>-1</sup>; Fig. 3a). The trends of total Nr loss as a function of increasing N rate varied across subregions owing to large variations in climate, soil and management conditions (Extended Data Fig. 1), resulting in different levels of optimized N input and associated Nr losses (Extended Data Fig. 2, Supplementary Note 4 and Supplementary Figs. 4–8). The largest mitigation potential of area-based total Nr losses (7–42%) under ON and EON suggest a pronounced need for optimizing N inputs for East, Central and Southwest China and double-rice cultivation systems (Fig. 2). Indeed, these subregions represented a Nr discharge hotspot owing to high area-scaled Nr losses under FN and a large rice cropping area, leading to prominent mitigation benefits from



**Fig. 2 | Key area-based performance responses to different N application strategies in different subregions of China.** Values of N rates, rice yields and Nr losses are in  $\text{kg N ha}^{-1}$ ,  $\text{Mg ha}^{-1}$  and  $\text{kg Nr ha}^{-1}$ , respectively. Early rice and late rice are part of the double-rice cropping system located mostly in Central and

South China. Error bars represent the values under the upper and lower bounds of the N rates (mean value  $\pm$  s.d. for FN and the profitable N rate range within  $\$2.47 \text{ ha}^{-1}$  for ON and EON).

ON and EON implemented in East China (79–105 kt reduction), Central China (25–64 kt reduction) and double-rice cropping systems (0–159 kt reduction) (Fig. 3a and Extended Data Fig. 3). Together, optimizing N inputs in these subregions contributed to 60% and 81% of the national Nr loss reduction potential under ON and EON, respectively.

The safe level of Nr pollution for rice production in China is estimated to be 0.73–1.35 Mt by the risk indicator method (Fig. 3a), which reflects how much present Nr losses must be reduced to reach the environmentally critical threshold by multiplying risk indicators with estimated Nr losses<sup>29</sup> (Supplementary Table 2). Under FN and ON, the level of Nr losses for national rice production exceeded the upper Nr threshold by 24% and 16%, respectively, whereas total Nr losses for EON remained below this upper threshold (Fig. 3a). In terms of the primary contributor to Nr pollution, the results differed for the four main Nr loss pathways (Fig. 3b). The optimized strategies were generally capable of reducing leaching/runoff losses and  $\text{N}_2\text{O}$  emissions below environmental thresholds in different subregions (but not all), whereas—regardless of N strategy— $\text{NH}_3$  volatilization led to the biggest Nr losses in Chinese paddy fields, surpassing the environmental threshold by 4–260% (Fig. 3b).

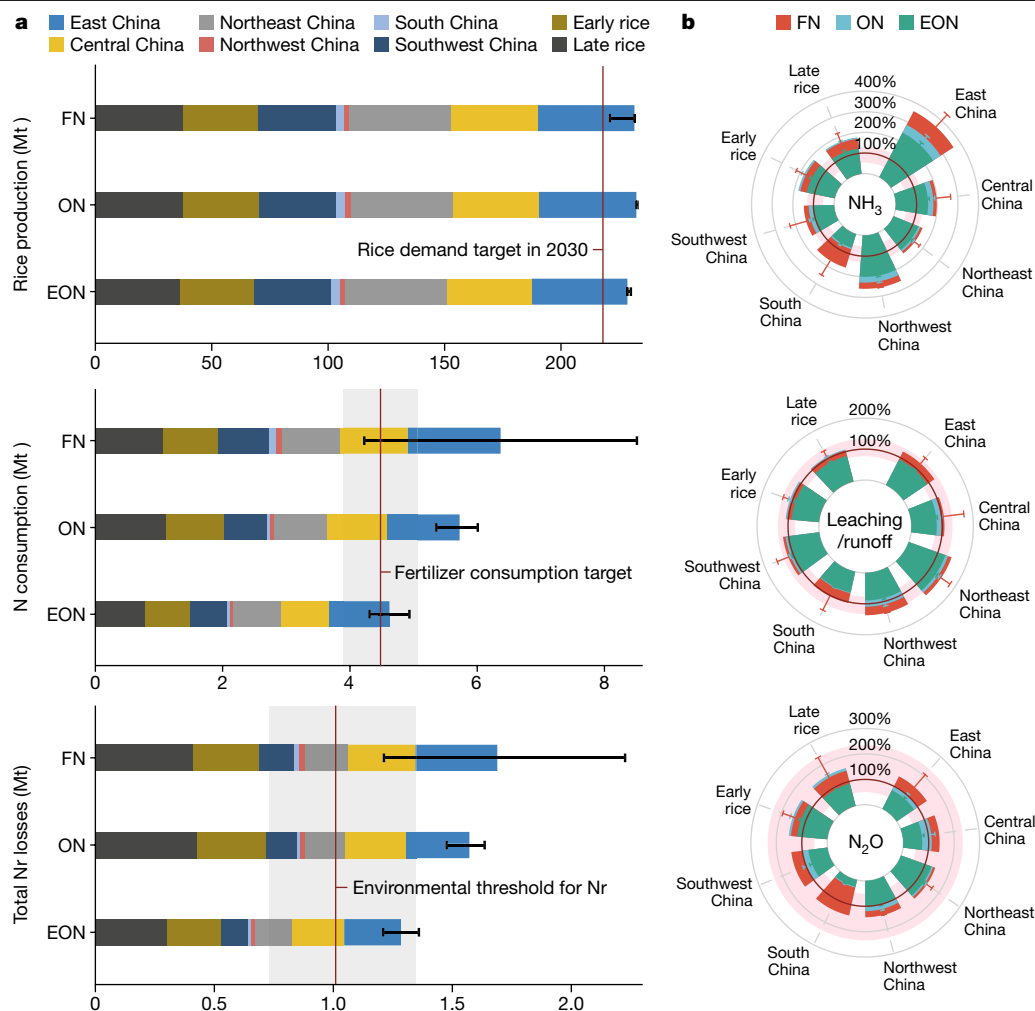
## Uncertainty facing smallholders

Using another extensive database of separate on-farm N rate experiments (31,601 site-years), the economic risk of implementing these strategies at the farmer level was assessed to inform the feasibility of meeting national rice production targets and designing a preferable N strategy (ON or EON) for each subregion to achieve balance between the environmental benefits and smallholder profits (Fig. 1, Supplementary Figs. 9–11 and Supplementary Note 5). The results indicate that the more environmentally robust N application rate (EON) does not risk severely decreasing rice production at the farm level, with yields

decreasing by more than 5% in 8–37% of site-years across subregions (Fig. 4). By contrast, more than 15–44% of farmers across subregions could improve their rice yield by more than 5% when adopting optimal N strategies. Nationally, there was a low risk of yield reductions and, in many cases, a potential yield benefit for optimal N fertilizer strategies at the field level (10% and 15% of site-years had >5% yield reductions, whereas 22% and 24% of site-years had >5% yield gains within 31,601 site-years for ON and EON, respectively).

When including the economic costs of N fertilizer and environmental damages associated with Nr losses to assess both economic benefits and NEEB, less than 10% of site-years decreased economic benefits or NEEB by more than 5% for ON compared with FN throughout subregions of China, whereas the probability for high benefits (>5%) was considerably greater (Fig. 4, Supplementary Fig. 11 and Extended Data Fig. 4). Adopting ON across subregions showed a 1–17% and 1–16% possibility of a low reduction risk ( $\leq 5\%$ ) for economic benefit and NEEB, respectively, yet a 16–56% and 24–86% possibility of enhancing the economic benefit and NEEB by more than 5%. The potential for high reduction risk (>5%) for economic benefit and NEEB was 1–13% for the EON across subregions, but the total economic risk (reduction in economic benefit) in Northeast China remained high (more than 40% of farm sites; Fig. 4). Caution of the underlying risk for yield penalties is necessary when applying optimal N strategies to subregions with high yield variations, such as single-rice regions South and Northeast China and double-rice cropping systems. It indicates that economic barriers cannot be ignored for at least a proportion of farmers.

Among all indicators of N use evaluated here, N balance serves as a sustainability reference to the soil fertility and the Nr emission potential<sup>30</sup>. Despite the economic incentives for returning straw to agricultural fields adopted by the Chinese government since 2000, there are disparities in how various subregions handle straw<sup>31</sup>. Therefore, we estimated soil N



**Fig. 3 | Performance of different N application strategies for different subregions under planting areas in 2018.** Planting areas are from ref. <sup>49</sup>. **a**, Rice production, N fertilizer consumption and total Nr losses. **b**, Airborne ( $\text{NH}_3$  volatilization and  $\text{N}_2\text{O}$  emissions) and waterborne (leaching and runoff) Nr losses and thresholds under different N application strategies in each subregion. In **a**, error bars represent production and fertilizer consumption for the upper and lower bounds of the N rates (mean value  $\pm$  s.d. for FN and the profitable N rate range within \$2.47  $\text{ha}^{-1}$  for ON and EON) and the crimson

vertical lines denote rice production demand for China in 2030 (218 Mt; Chen et al.<sup>16</sup>), the fertilizer N consumption threshold for rice released by the Ministry of Agriculture and Rural Affairs of the People's Republic of China<sup>27</sup> (3.9–5.1 Mt, with ranges shown in grey colour) and the environmental threshold for Nr losses (1.01 Mt, with upper and lower limits (shown in grey colour) between 0.72 and 1.35 Mt based on the ranges of FN). In **b**, all Nr losses are normalized against the environmental threshold for Nr (the crimson circle with its ranges shown in light pink).

balance in different rice subregions of China and found that both straw management scenarios (returned versus removed from fields) could maintain soil fertility under two optimal N strategies (Extended Data Fig. 5). Yet, a low-level N balance under straw removal should be vigilantly dealt with in double-rice cropping to prevent mining of soil nutrients over time, as large uncertainty exists in the estimation of denitrification  $\text{N}_2$  loss (Supplementary Table 3). A higher N balance was obtained with straw returned, ranging from 87 to 138  $\text{kg N ha}^{-1}$  for the single-rice cropping systems and 77 to 103  $\text{kg N ha}^{-1}$  for the double-rice cropping systems under optimal fertilizer N strategies (Extended Data Fig. 5). Although straw retention has substantial advantages for maintaining soil quality, improving nutrient cycling and increasing rice productivity<sup>32,33</sup>, it exhibits a higher Nr discharge potential and enhanced  $\text{CH}_4$  emissions<sup>34</sup>, which may offset the environmental benefit gained when considering the high social costs of enhanced  $\text{CH}_4$  and Nr losses.

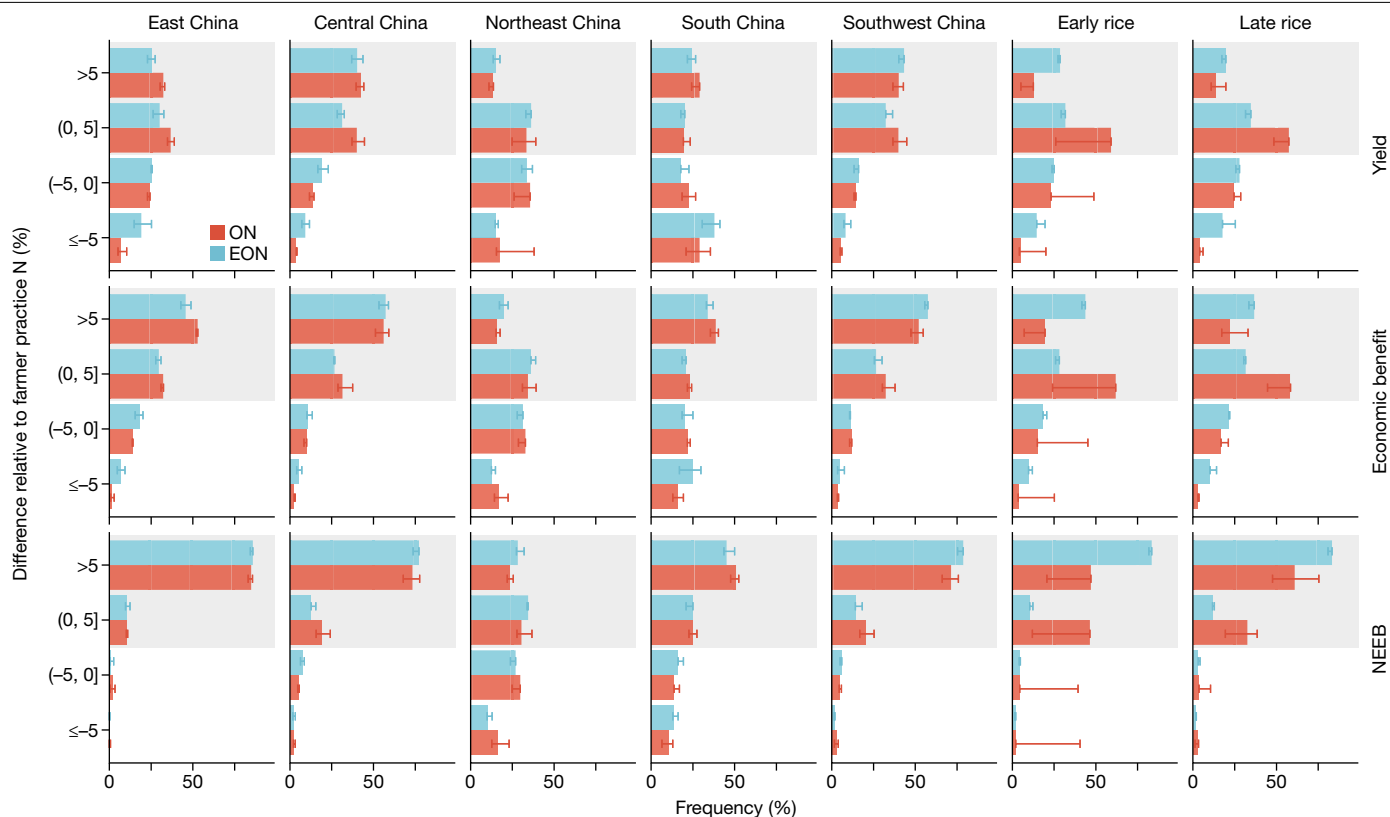
Yield-scaled Nr loss is another sustainability metric that can help to reconcile the dual goals of improving food production and environmental sustainability<sup>35</sup>. By applying ON, the single-rice cultivation showed 4–35% lower yield-scaled Nr losses compared with FN (Fig. 5). For the double-rice cropping system under ON, it exhibited a

15% mitigation potential compared with FN. Ambitious reduction of FN to EON resulted in a greater reduction in yield-scaled Nr losses, amounting to 13–43% reductions under the single-rice cropping system and 36–39% reductions under the double-rice cultivation system (Fig. 5).

The results demonstrated that NUE was notably enhanced by optimizing N inputs, surpassing the NUE target of 40% in China<sup>18</sup> (Extended Data Fig. 6). By adopting optimal N strategies, NUE could be increased on a relative basis by 16–102% across subregions (Fig. 5). A greater increase in NUE was observed in subregions in which overfertilization was prevalent (such as East, Central, South and Southwest China). By contrast, in Northeast China and double-rice cropping systems that had lower FN, NUE improvements were restricted. Overall, the application of optimal N practices can increase NUE by 30% and 36% for ON and EON, respectively, in China (Extended Data Fig. 6).

To identify the more preferable N strategy (ON or EON) for diverse subregions in China, we constructed a conceptual framework based on the environmental benefits outweighing the potential economic risks (Extended Data Fig. 7). Under this comparison with select N rates, single-rice cropping subregions, such as East, Central and Southwest China, as well as early and late rice cropping systems were suitable for





**Fig. 4 | Distribution of changes in economic indicators when reducing N rates to optimal levels.** Results are based on 31,601 site-years of on-farm N fertilizer response trials. The farmer practice N rate (150% MN) was set as the control N level. Grey shading indicates positive impact categories (increase

relative to farmer practice) and white shading indicates negative impact categories (decrease relative to farmer practice). Error bars represent the results for the upper and lower bounds of the optimal N rates (the profitable N rate range within \$2.47 ha<sup>-1</sup> for ON and EON).

the implementation of EON. Single-rice subregions such as South and Northeast China were not eligible for a more environmentally resilient N application rate owing to their high economic risks or poor environmental benefits; hence, ON was chosen as the optimal N strategy for these two subregions.

## Recommendations for N optimization

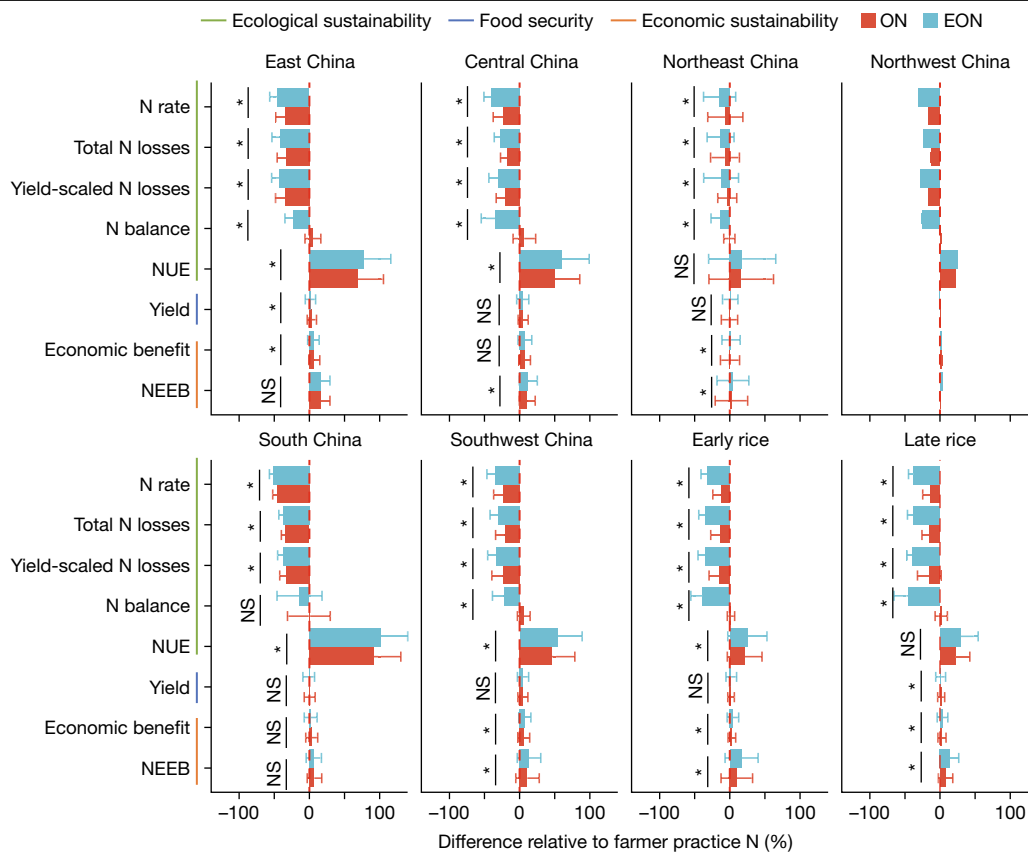
In countries such as China where smallholder farms dominate agricultural production<sup>36</sup>, the high heterogeneity of soil fertility in small farms increases the differences in fertilizer dependencies. Meanwhile, farmer willingness to adopt N reduction strategies depends on the economic condition and farm size, among other factors, thereby increasing the difficulty of widespread strategy adoption (Supplementary Fig. 9 and Supplementary Note 6). Furthermore, fluctuation in climate and soil conditions would necessitate an adjustment of the N optimal strategy over time given changes in yield and N<sub>r</sub> losses, which would further complicate the development and implementation of optimized N rates. Consequently, we propose a combination of approaches to address these challenges (Fig. 1).

In terms of technological support, establishing a large regional research trial network to obtain more precise optimal N rate recommendations that are revised annually for different subregions, similar to the 'Maximum Return to Nitrogen' across the Corn Belt states in the USA<sup>37</sup>, is essential for increasing the feasibility of optimal N rates. Future climatic and soil quality changes will have an effect on rice production<sup>38</sup>, as well as N<sub>r</sub> losses, necessitating a research infrastructure that can also rapidly react to changing environmental conditions and policies. Considering the thousands of existing on-farm trials in China<sup>22</sup>, building such a network focused on N management would not

necessarily require extra costs but a cooperative campaign to assemble and interpret data.

To achieve the ambitious environmental targets for N pollution in China, policymakers may consider implementing an obligatory fertilization quota to restrict N applications at the farm or regional levels based on the preferable N optimal strategy for different subregions in this study. For instance, the revised European Union Nitrates Directive in Germany imposed fertilizing planning functioning as a fertilization quota at the farm level, resulting in a 10% reduction in state-level N input with little compliance cost<sup>39</sup>. Moreover, smallholders tend to be hesitant to adopt knowledge-based management technology, whereas large-scale farms are more likely to be influenced by policy knowledge<sup>2,40,41</sup>. Scaling up farm size and closing the yield gaps of smallholder farms is another potential option, which would rearrange the cropping area to eliminate low-productivity and high-risk farmland. The feasibility of scaling up farm size, however, depends on the process of urbanization, which could increase the average farm size by 170% in 2050 when the urbanization level increased by 40% (ref. <sup>42</sup>). Owing to numerous challenges facing farmers and the low adoption of improved N management practices, new policy efforts are also being focused on targeting other actors in the food supply chain, such as input suppliers, food traders and processors, retailers and consumers, to reduce N pollution<sup>43</sup>.

In terms of smallholders, governmental subsidies are one of the policy tools to incentivize improved N management. However, it is hard to predict beforehand the potential economic risks for the portion of farmers who would face yield losses. To explore the magnitude of incentives that could be offered to promote adoption in a conservative manner, we estimated the government subsidy needed to compensate all farmers following adoption of the optimum N strategies by



**Fig. 5 | Effects of reducing N rates to optimal levels on indices of ecological sustainability, food security and economic sustainability.** The results are based on 31,601 site-years of on-farm N fertilizer response trials. The farmer practice N rate (150% MN) was set as the control N level. Its performance can be

found in Supplementary Table 4. N balance was in the straw returned scenario. Values are presented as the mean  $\pm$  s.d. \* and NS denote  $P < 0.05$  and  $P > 0.05$ , respectively (Tukey's honestly significant difference test).

multiplying the possible economic risk within the lower inner fence in the box plot (10.3% for ON and 13.6% for EON; Extended Data Fig. 7) by the provincial cropping area (Extended Data Fig. 8). Under these assumptions, government handouts would be around US \$3 billion (Supplementary Fig. 12 and Supplementary Note 7). This represents about 3% of gross economic benefit, 11% of net economic benefit of fertilizer N addition when subtracting the unfertilized control and 65% of the environmental benefit gains under the optimum N strategies. Although the subsidy is intended to protect farmers from the potential revenue risks when applying optimal N rates, most of the smallholders (more than 70% site-years across subregions) can boost rice yields when applying optimal N rates (Fig. 4). The trend of providing a direct governmental subsidy for rice is increasing continuously in China, from \$3.3 ha<sup>-1</sup> in 2003 to \$127.9 ha<sup>-1</sup> in 2008 (ref. 44), and—based on this trend—a rough estimate of China's rice subsidy is around \$357 ha<sup>-1</sup> in 2020 (Supplementary Fig. 12), which is considerably higher than our evaluated subsidy (\$106 ha<sup>-1</sup>). Those funds can be used to implement knowledge-based N management practices such as the use of high-efficiency N fertilizers, fertilizer deep placement technique and site-specific techniques to improve yield performance<sup>45–48</sup>. The combination of other knowledge-based N managements incentivized by subsidy would further boost the benefits of adopting optimal N rates, creating a benign circle of food security and environmental sustainability.

Global agriculture confronts two formidable challenges: meeting substantial increases in food demand and keeping the food production system within environmental boundaries. Further refinement of N management to incorporate site-specific techniques such as soil and plant testing, satellite remote-sensing-based diagnostics and portable optical

sensors could indeed boost fertilizer NUE<sup>45–47</sup>. However, the adoption of these technologies is limited in both the USA and China<sup>3,21</sup>, probably attributed to their complexity, costliness and political obstacles. Considering its simplicity, low cost and adaptability, an annually revised regional N rate guideline that balances the environmental benefits and smallholder profits is therefore a more practical strategy to deploy as a foundation, while moving towards site-specific N management in the long run.

## Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-022-05678-x>.

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## Methods

### Description of subregions

In China, rice production systems were divided into six agro-ecological subregions for a single rice cultivar based on distinctive climatic, topographic, geographic and hydrologic properties: East China, Central China, Northeast China, Northwest China, South China and Southwest China. Early and late rice were mostly cultivated in Central and South China subregions, and the subregional data were integrated to represent different rice species. The total cropping area occupied by the six agro-ecological subregions that encompassed single-rice and double-rice cultivations was 30.03 Mha, which represented 99% of the rice cultivation land in China<sup>50</sup>. Details about the climate and cropping management in the subregions are provided in Supplementary Note 1.

### Construction of databases

A database was constructed on the basis of published peer-reviewed articles and master's/PhD theses retrieved from the Web of Science (Thomson Reuters) and the China National Knowledge Infrastructure (CNKI) published between January 1991 and January 2021 to understand the effects of fertilizer N input on rice yield and Nr losses (leaching, runoff, NH<sub>3</sub> volatilization and N<sub>2</sub>O emissions). The following search terms were used as keywords: 'rice' and 'China', 'leaching' or 'runoff' or 'N<sub>2</sub>O' or 'NO<sub>3</sub><sup>-</sup>' or 'nitrous oxide' or 'ammonia' or 'NH<sub>3</sub>' or 'reactive N', and 'yield' and 'China'. Duplicates in the database were removed. Studies were selected for inclusion using the following criteria: (1) field-based or undisturbed lysimeter experiments with rice cultivation in China in the selected six subregions; (2) the N form input was urea or ammonium or nitrate without straw or organic manure incorporation or slow-release/controlled-release fertilizer application; (3) at least one of the following indices was monitored throughout the cropping season and reported: yield, N<sub>2</sub>O emissions, Nr leaching, Nr runoff and NH<sub>3</sub> volatilization; (4) measurement was conducted for an entire rice-growing season; (5) measurement for NH<sub>3</sub> was within at least a week after N application; (6) N<sub>2</sub>O was conducted at least once per month using the static chamber method; and (7) the geographic coordinates (latitude and longitude) were provided.

In the database, 462 studies encompassing 7,912 observations were compiled, of which the number of articles comprising data for yield, NH<sub>3</sub> runoff, N<sub>2</sub>O runoff, Nr runoff and Nr leaching was 301, 115, 187, 77 and 86, respectively, with several parameters reported in some studies (Supplementary Fig. 1a). Units of value were extracted from the articles and standardized for each variable (for example, kg N ha<sup>-1</sup> for inorganic N input or Nr losses and Mg ha<sup>-1</sup> for yield production). Figure digitization was performed using OriginPro (version 2019b, OriginLab) when the data were presented in plots. Subregion databases were subsequently grouped for: (1) crop species (single rice, early rice or late rice), (2) observation type (yield, NH<sub>3</sub>, N<sub>2</sub>O, Nr runoff or Nr leaching); and (3) subregions for single rice (East China, Central China, Northeast China, Northwest China, South China and Southwest China).

For uncertainty analysis of the economic risk of optimal N strategies at the farmer level, a database of paddy field trials was constructed between 2005 and 2012 using 31,601 site-year yield observations in 195 counties, 17 provinces and covering five subregions (East China, Central China, Northeast China, South China and Southwest China). The geographical distribution map is presented in Supplementary Fig. 1b. The same treatments were adapted for each on-farm trial: no N fertilizer, medium N application rates (MN), 50% MN and 150% MN. The MN rates were established by local experts in consonance with the target yield (10% higher than the average yields of the past 5 years), ranging from 45 to 360 kg N ha<sup>-1</sup>. 150% MN was used as the N rate to ensure maximum grain yield<sup>3</sup> and set as farmer practice N rate for uncertainty analysis. Fertilizer N was applied three times by broadcasting during the sowing, tillering and panicle stages at a ratio of 8:5:7. The area for each plot was

50 m<sup>2</sup> (5 × 10 m). On-farm management techniques such as sowing, transplanting, disease control and pest control were performed by local farmers. The yield of each trial was measured by subsampling a 2.5 × 4-m section at harvest.

### Estimation of ON and EON

To obtain ON and EON, subregion-specific yield and Nr loss (leaching, runoff, NH<sub>3</sub> volatilization and N<sub>2</sub>O emissions), response models were established on the basis of the peer-reviewed article database for each single-rice subregion or early/late rice species by the following equations:

$$\text{Yield} = \alpha_i + \beta_i N + \gamma_i N^2 \quad (1)$$

$$\text{Nr} - \text{NH}_3 = \delta_i + \varepsilon_i N \quad (2)$$

$$\text{Nr} - \text{N}_2\text{O}/\text{Leaching}/\text{Runoff} = \zeta_i \times e^{\eta_i N} \quad (3)$$

in which Yield is rice grain yield (in Mg ha<sup>-1</sup>);  $N$  is the N fertilizer application rate (in kg N ha<sup>-1</sup>);  $\alpha_i$ ,  $\beta_i$ ,  $\gamma_i$ ,  $\delta_i$ ,  $\varepsilon_i$ ,  $\zeta_i$  and  $\eta_i$  are the corresponding parameters for each subregion or early/late rice species; and  $\text{Nr} - \text{NH}_3$  is the NH<sub>3</sub> volatilization Nr loss (in kg N ha<sup>-1</sup>). Linear and nonlinear mixed-effect models were fitted to data with site as a random effect to account for between-study variability using the maximum likelihood method in the nlme package of R software version 4.0.1 (refs.<sup>51,52</sup>). Assumptions of normality and homogeneity of variance were evaluated using diagnostic plots. Marginal and conditional  $r^2$  were calculated to obtain the variance explained by the fixed and random effects of each model<sup>53</sup>. The population prediction interval procedure was used to calculate the confidence limits in R software by the MASS package based on Bolker<sup>54</sup>.

The economic benefit and NEEB were determined for the six different subregions by the following equations:

$$\text{Economic benefit} = \text{Yield} \times \text{Price}_r - N \times \text{Price}_n \quad (4)$$

$$\text{NEEB} = \text{Yield} \times \text{Price}_r - N \times \text{Price}_n - \text{Nr} \times \text{Price}_{\text{Nr}} \quad (5)$$

in which  $\text{Price}_r$  is the price of rice (in \$ Mg<sup>-1</sup>);  $\text{Price}_n$  is the price of N fertilizer input (in \$ kg<sup>-1</sup> N);  $\text{Nr}$  is the reactive N losses (in kg N ha<sup>-1</sup>) or its corresponding direct/indirect greenhouse gas (GHG) emissions (in Mg CO<sub>2</sub>-eq ha<sup>-1</sup>) from N<sub>2</sub>O, leaching, runoff and NH<sub>3</sub> volatilization transformed in reference to IPCC guidelines<sup>55</sup>;  $\text{Price}_{\text{Nr}}$  is the price of Nr costs of acidification, eutrophication, health or GHG trade (in \$ kg<sup>-1</sup> N or \$ Mg<sup>-1</sup> CO<sub>2</sub>-eq); and  $\text{Nr} \times \text{Price}_{\text{Nr}}$  is the environmental costs of Nr. More information on the emission factors and market prices/costs is provided in Supplementary Table 1. Other operational costs were not included in the cost-benefit analysis, as it was assumed that the agricultural management costs were standardized across subregions and the optimized N application rate would have negligible effects on the operational costs.

ON and EON of each subregion were then estimated using equations (4) and (5) by the Brent method for general-purpose optimization in the stats package of R software version 4.0.1 (ref.<sup>52</sup>). The maximum number of iterations was set to 999. The FN for different subregions was set as the current N application levels obtained from the farmer surveys listed in Extended Data Table 1. The upper and lower bounds of the N rates were mean value ± standard deviation (s.d.) for the FN (survey) and the profitable N rate range within \$2.47 ha<sup>-1</sup> for ON and EON<sup>37</sup>.

### Assessment of N sustainable indices

For evaluating the environmental performance of different N rates, the following N environmental indices were calculated:



$$\text{Total Nr losses} = (\text{Nr} - \text{NH}_3) + (\text{Nr} - \text{N}_2\text{O}) + (\text{Nr} - \text{leaching}) + (\text{Nr} - \text{runoff}) \quad (6)$$

$$\text{Yield-scaled total Nr losses} = \text{Total Nr losses} / \text{Yield} \quad (7)$$

$$\text{N balance} = N_{\text{fer}} + N_{\text{fix}} + N_{\text{dep}} + N_{\text{irr}} + N_{\text{seed}} - N_{\text{har}} - \text{Total Nr losses} - N_{\text{den}} \quad (8)$$

$$\text{N use efficiency} = (N_T - N_C) / N_{\text{fer}} \quad (9)$$

in which  $N_{\text{fer}}$  is the N fertilizer application rate (in kg N ha<sup>-1</sup>);  $N_{\text{fix}}$  is the non-symbiotic N fixation obtained from Zhu<sup>56</sup> (45 kg N ha<sup>-1</sup>);  $N_{\text{dep}}$  is the seasonal atmospheric N deposition<sup>57</sup> (East China: 23.16 kg N ha<sup>-1</sup>; Central China: 23.05 kg N ha<sup>-1</sup>; Northeast China: 19.89 kg N ha<sup>-1</sup>; Northwest China: 9.852 kg N ha<sup>-1</sup>; South China: 16.49 kg N ha<sup>-1</sup>; and Southwest China: 18.20 kg N ha<sup>-1</sup>);  $N_{\text{irr}}$  is the seasonal irrigation N input, calculated as the irrigation N concentration obtained from the China National Environmental Monitoring Centre<sup>58</sup> (East China: 2.42 mg N l<sup>-1</sup>; Central China: 2.14 mg N l<sup>-1</sup>; Northeast China: 2.95 mg N l<sup>-1</sup>; Northwest China: 2.75 mg N l<sup>-1</sup>; South China: 2.07 mg N l<sup>-1</sup>; and Southwest China: 2.37 mg N l<sup>-1</sup>) multiplied by the irrigation water inflow rate<sup>59</sup> (Northern China: 1,026 mm and Southern China: 736 mm);  $N_{\text{seed}}$  is the N input from rice seed with a seeding rate of 70 kg ha<sup>-1</sup> (ref. <sup>60</sup>); and  $N_{\text{har}}$  is the harvested plant N output calculated as the grain N content  $\times$  grain yield + straw N content  $\times$  grain yield  $\times$  ratio of grain to straw (0.97 (ref. <sup>61</sup>)). The grain N contents (East China: 0.014 ( $n = 133$ ); Central China: 0.012 ( $n = 46$ ); Northeast China: 0.010 ( $n = 143$ ); South China: 0.012 ( $n = 19$ ); and Southwest China: 0.011 kg N kg<sup>-1</sup> grain ( $n = 79$ )) and straw N contents (East China: 0.0092 ( $n = 122$ ); Central China: 0.0070 ( $n = 46$ ); Northeast China: 0.0057 ( $n = 129$ ); South China: 0.0085 ( $n = 25$ ); and Southwest China: 0.0074 kg N kg<sup>-1</sup> ( $n = 82$ )) were obtained from the peer-reviewed publication database.  $N_{\text{den}}$  is denitrification N<sub>2</sub> losses, which was quantified by the difference between the total N losses and Nr losses. Total N losses, as stated by Zhu et al.<sup>62</sup>, were estimated as the difference between 100% and NUE when the latter was derived from N in the whole plant. The ratio of NUE for the whole plant to NUE for the aboveground plant was estimated to be 1.4, according to Zhu et al.<sup>62</sup>.

The N balance was classified into two scenarios based on  $N_{\text{har}}$ , in which scenario 1 included N harvested grain and scenario 2 included both N harvested grain and straw. NUE was calculated by the N difference approach defined as aboveground harvested N in the fertilized scenario ( $N_T$ ) minus the aboveground harvested N in the non-fertilized scenario ( $N_C$ ) divided by the N fertilizer input.

### Feasibility and uncertainty analysis

To evaluate the risk of applying optimal N rates, quadratic yield response functions were fitted to the on-farm field database composed of 31,601 site-year yield observations at each site-year by using the NLIN procedure in SAS statistical software version 9.4 (SAS Institute). Different subregional N application strategies (FN (150% MN), ON and EON) were then input in the site-specified yield response models (910, 526, 2,241, 124, 686, 1,048 and 1,145 site-year quadratic yield response functions for East China, Central China, Northeast China, South China, Southwest China, early rice and late rice, respectively; Supplementary Figs. 1 and 9). Each interrelated economic benefit, NEEB, yield-scaled Nr loss or N balance was calculated using equations (4), (5), (7) and (8), respectively. On the basis of the farmer-level yield in response to N application strategies (FN, ON and EON), the probability distribution could inform the economic risk (compared with FN) of site-year variation under regional optimal N rates. In Supplemental Note 5, a comprehensive regional description of the uncertainty analysis is presented.

To quantify the safe level of rice cropping systems' Nr losses to the environment, the environmental thresholds were obtained for air (NH<sub>3</sub> volatilization), water (leaching/runoff Nr losses) and atmospheric pollution (N<sub>2</sub>O emission) determined by the risk indicator<sup>29</sup> (ratio of present pollution and critical level; Supplementary Table 3). This approach presupposes that present Nr losses, either as air emissions or as water discharge, should be reduced in land for which the N indicators are already exceeded. The quantification of the rice-specific Nr threshold is predicated on the assumption that each agricultural cropping system should at least contribute equally to meeting the environmental mitigation goal. The critical Nr losses are calculated as the present average Nr output level estimated by Nr models (Extended Data Fig. 2) multiplied by the risk indicator. The upper and lower Nr thresholds were estimated by the upper and lower levels of current Nr losses based on the scale of FN (Extended Data Table 1).

To obtain information on food security concerning Chinese rice food demand in 2030 (ref. <sup>16</sup>), total rice production (in Mt) was estimated on the basis of the rice cropping area in 2018 (ref. <sup>49</sup>) and the average subregional rice yield under a questionnaire-based household survey of FN (Extended Data Table 1) obtained from the subregion-specific yield response models:

$$\text{Total rice production} = \sum \text{Yield}_{\text{sub}} \times \text{Area}_{\text{sub}} \quad (10)$$

Subsequently, we used a similar bottom-up method to quantify the total N fertilizer consumption (in Mt) and total Nr losses (in Mt) under rice cultivation in China by N fertilizer application rates and Nr losses (in kg N ha<sup>-1</sup>) for different N fertilizer strategies and rice cropping areas (in ha) in 2018.

We performed a sensitivity analysis to estimate the effects of variations in Nr loss price, fertilizer price and rice price on EON with a  $\pm 50\%$  range. Each price in the range was fitted to equation (5) and EON was estimated using the maximum likelihood method, as mentioned previously. The results of the sensitivity analysis are available in Supplementary Note 2 (Supplementary Figs. 2 and 3).

### Subregional preferable N strategy determination and subsidy estimation

To evaluate whether EON or ON is appropriate for subregional N optimization, we calculated the subregional net benefit by subtracting subregional economic risk from its environmental benefit. To eliminate the influence of outliers on our analysis, the economic risk for smallholders with economic risk beyond the inner fence (lower inner fence:  $Q1 - 1.5 \times (Q3 - Q1)$ ; higher inner fence:  $Q3 + 1.5 \times (Q3 - Q1)$ ), in which Q1 is the 25th percentile and Q3 is the 75th percentile) are excluded from the calculation of subregional economic risk (Extended Data Fig. 7a). The subregional economic risk was then determined to be the mean value within the lower fence ( $-10.3\%$  for ON and  $-13.6\%$  for EON). When the subregional net benefit is negative, the subregion is deemed undesirable under EON and ON is adopted as an alternative (Extended Data Fig. 7b). The environmental benefit (in \$ ha<sup>-1</sup>) is calculated using equation (11):

$$\text{Environmental benefit} = \Delta \text{Nr} \times \text{Price}_{\text{Nr}} \quad (11)$$

in which  $\Delta \text{Nr}$  is the change in reactive N losses (in kg N ha<sup>-1</sup>) or the associated direct/indirect GHG emissions (in Mg CO<sub>2</sub>-eq ha<sup>-1</sup>) under EON compared with FN.

To estimate the potential governmental subsidy for the compensation of a proportion of vulnerable farmers (economic risk within 10.3% and 13.6% for ON and EON, respectively) when adopting subregional optimal N rates, the mean provincial subsidy was quantified on the basis of the subregional economic risk (in \$ ha<sup>-1</sup>) and multiplied by the corresponding provincial area (in ha). The potential

subregional government subsidy is elaborated in Supplementary Note 7 (Supplementary Fig. 12).

## Data availability

The core data for the study were obtained from the selected studies (see supplementary references), including their supplementary information and data files. All model input datasets and the extensive on-farm data are available at <https://doi.org/10.5281/zenodo.7307739>.

## Code availability

The code to replicate the key findings and figures of the paper are available at [https://github.com/CarolejaneCosmos/Optimal\\_N\\_rice\\_China](https://github.com/CarolejaneCosmos/Optimal_N_rice_China). Further code is available from the corresponding author on reasonable request. Maps in the study were generated in R version 4.0.1 using map data from the Resource and Environment Science and Data Center (<https://www.resdc.cn/data.aspx?DATAID=202>).

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**Competing interests** The authors declare no competing interests.

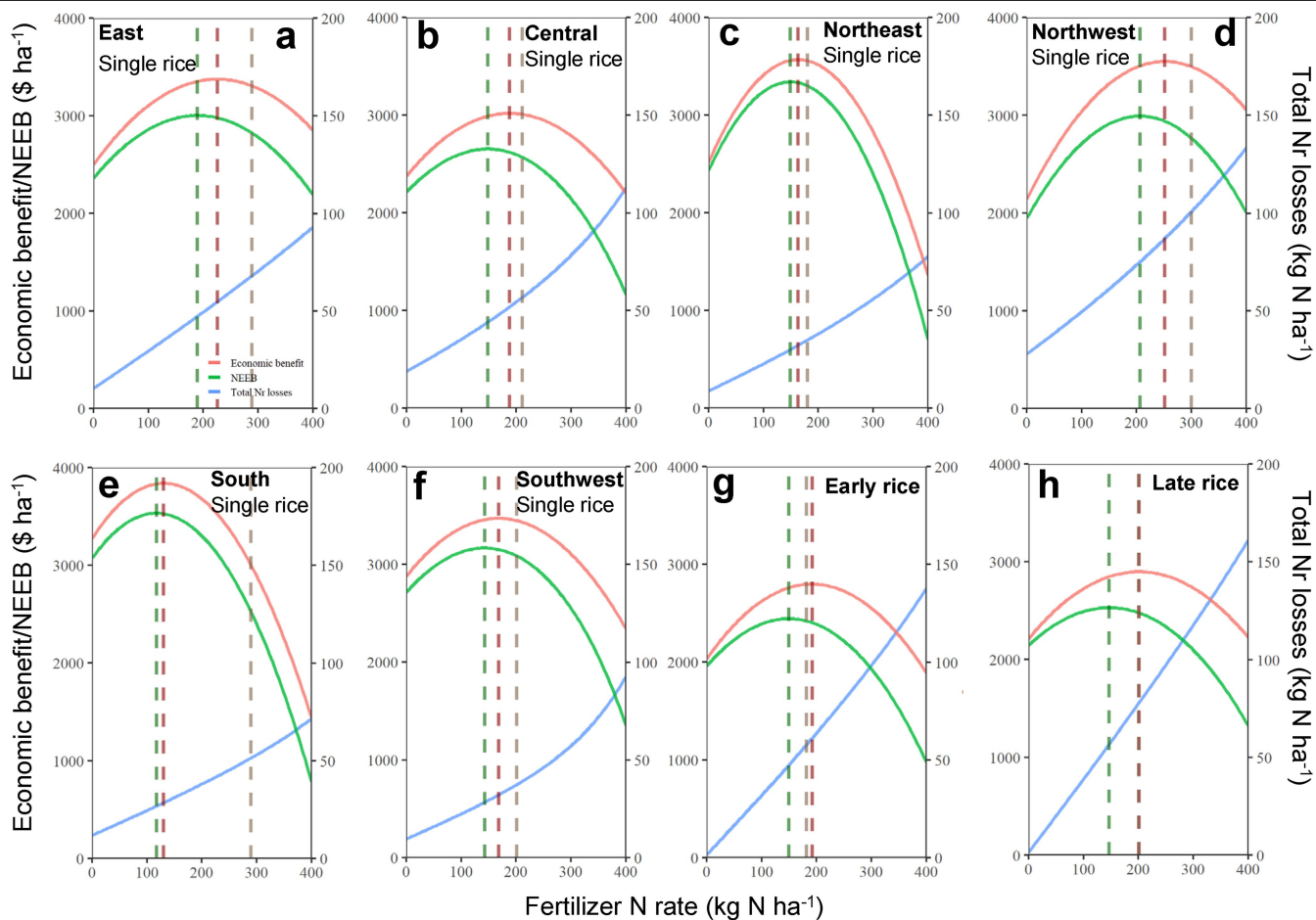
## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41586-022-05678-x>.

**Correspondence and requests for materials** should be addressed to Xu Zhao or Xiaoyuan Yan.

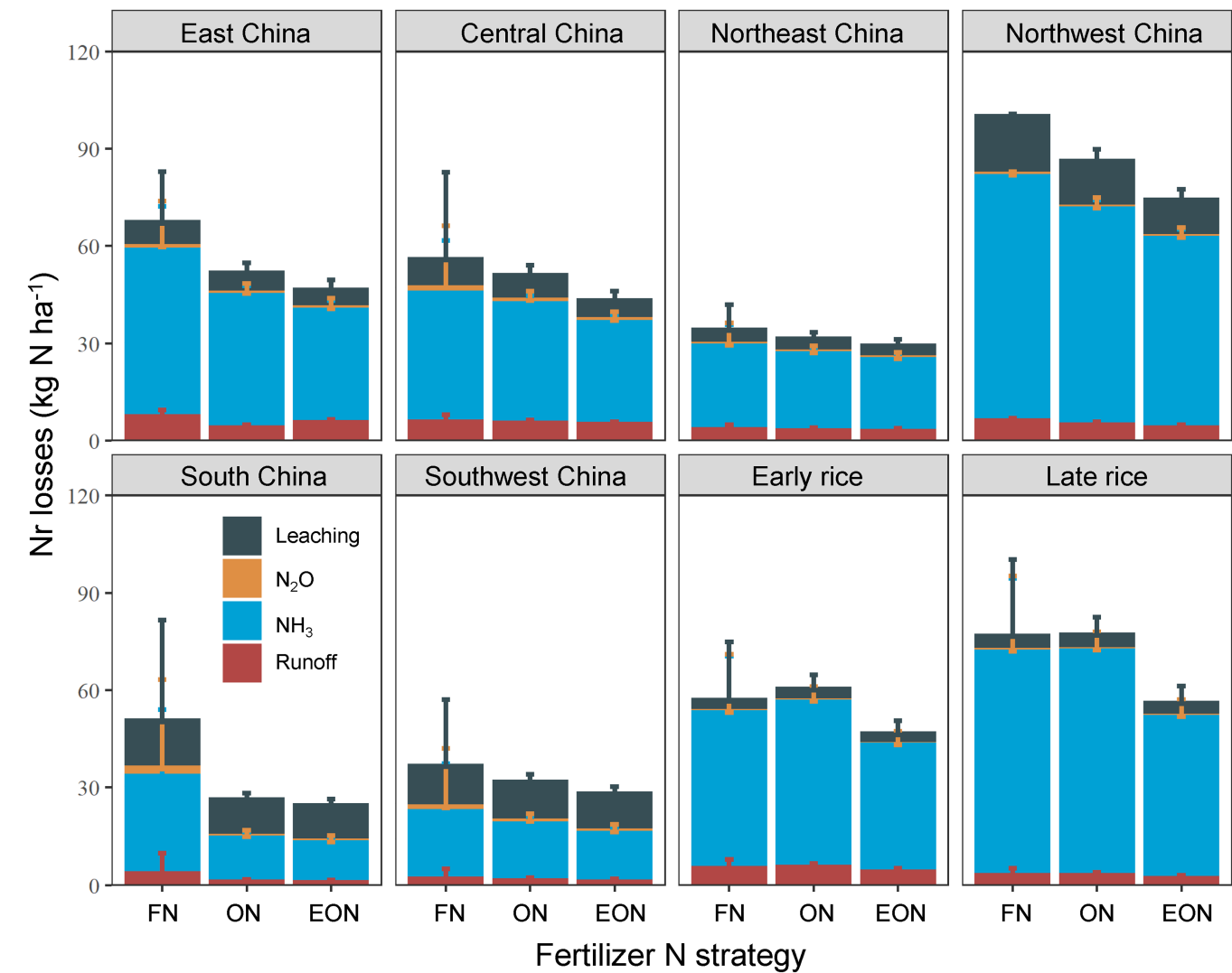
**Peer review information** Nature thanks Baojing Gu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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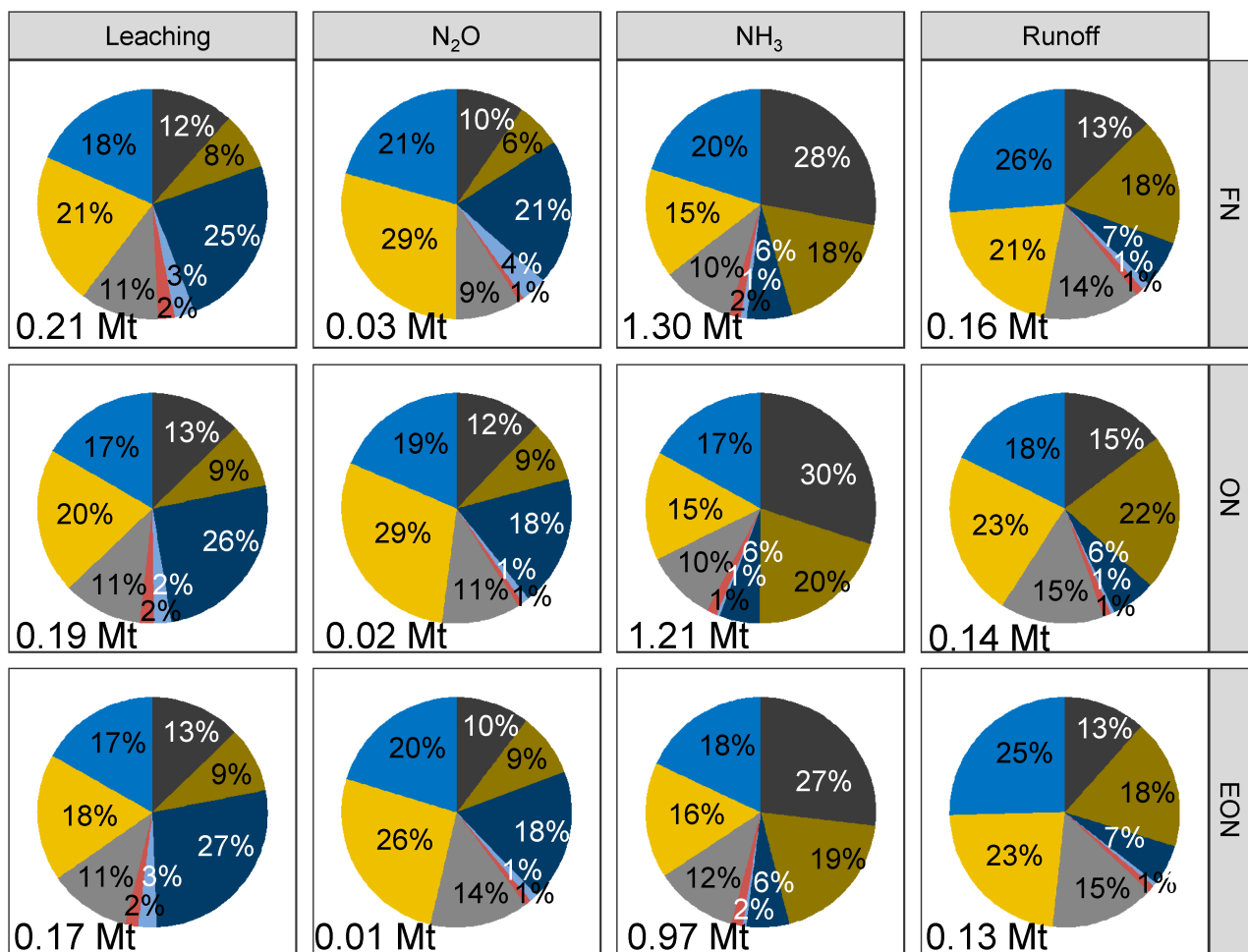
**Extended Data Fig. 1 | Total N losses, economic benefit and NEEB response to the N rate.** Single-rice (a–f) and double-rice (g,h) (early rice/late rice) cropping systems in different subregions based on the peer-reviewed

publication database. Intersections of the dashed lines are farmer practice N rate (FN, survey), optimal N rates (ON) or ecologically optimal N rates (EON).



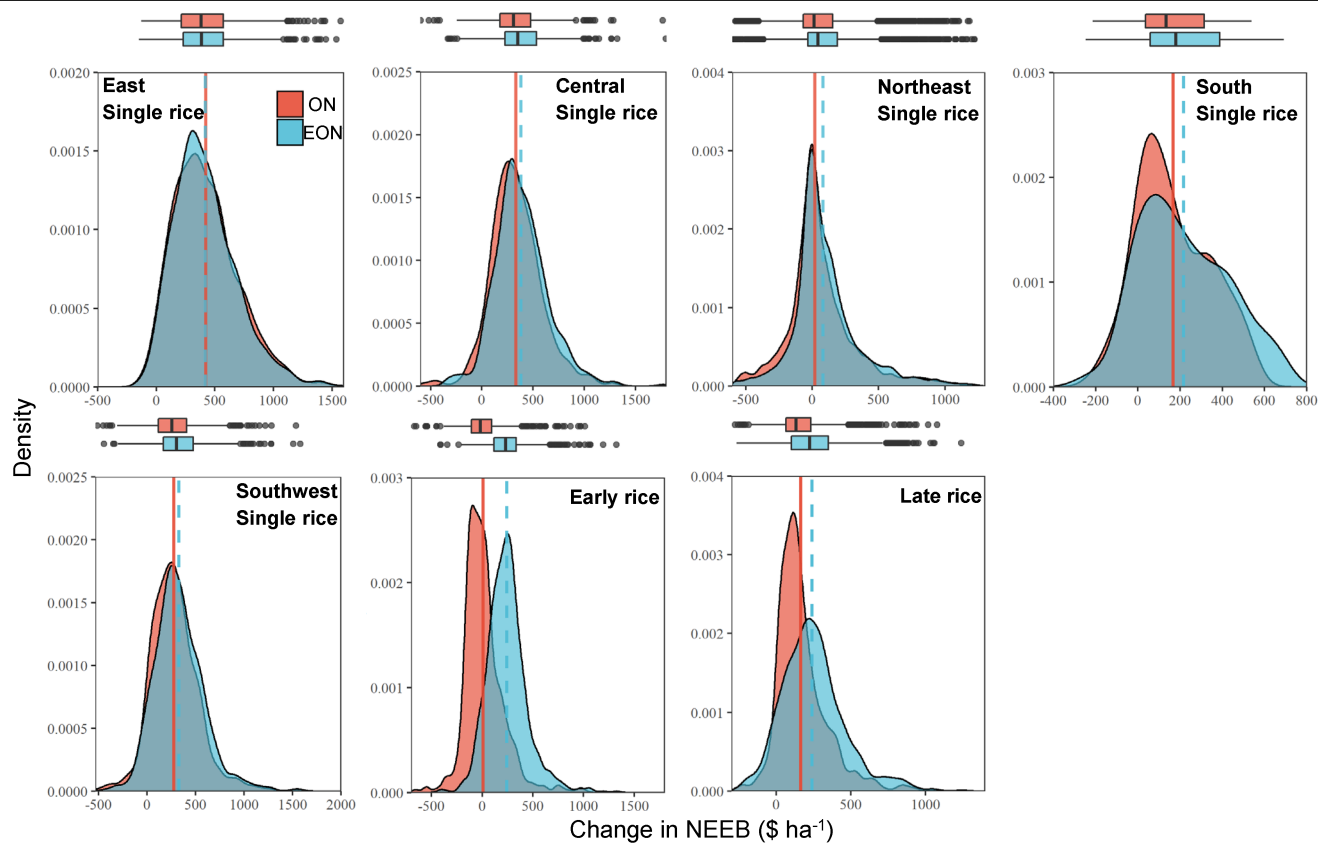
**Extended Data Fig. 2 | Subregional-area-based Nr losses encompassing N leaching, N<sub>2</sub>O emissions, NH<sub>3</sub> volatilization and N runoff under three N management strategies across China.** Error bars represent the values under

the upper and lower bounds of the N rates (mean value ± SD for FN and the profitable N rate range within \$2.47 ha<sup>-1</sup> for ON and EON).



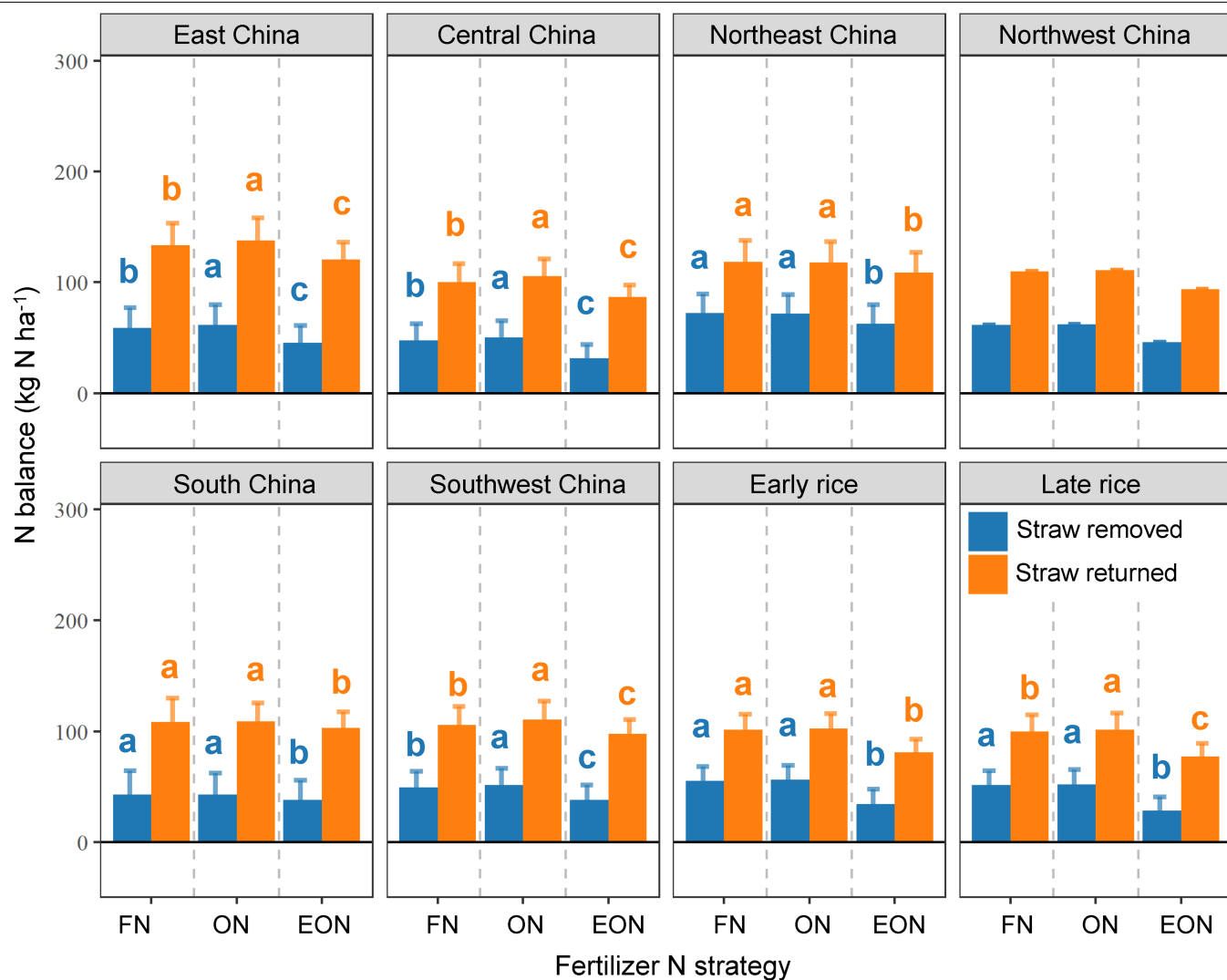
**Extended Data Fig. 3 | Regional-based annual Nr losses encompassing N leaching, N<sub>2</sub>O emissions, NH<sub>3</sub> volatilization and N runoff under three N management strategies across China.** Values under the pie charts are the regional-based Nr losses in the four pathways.





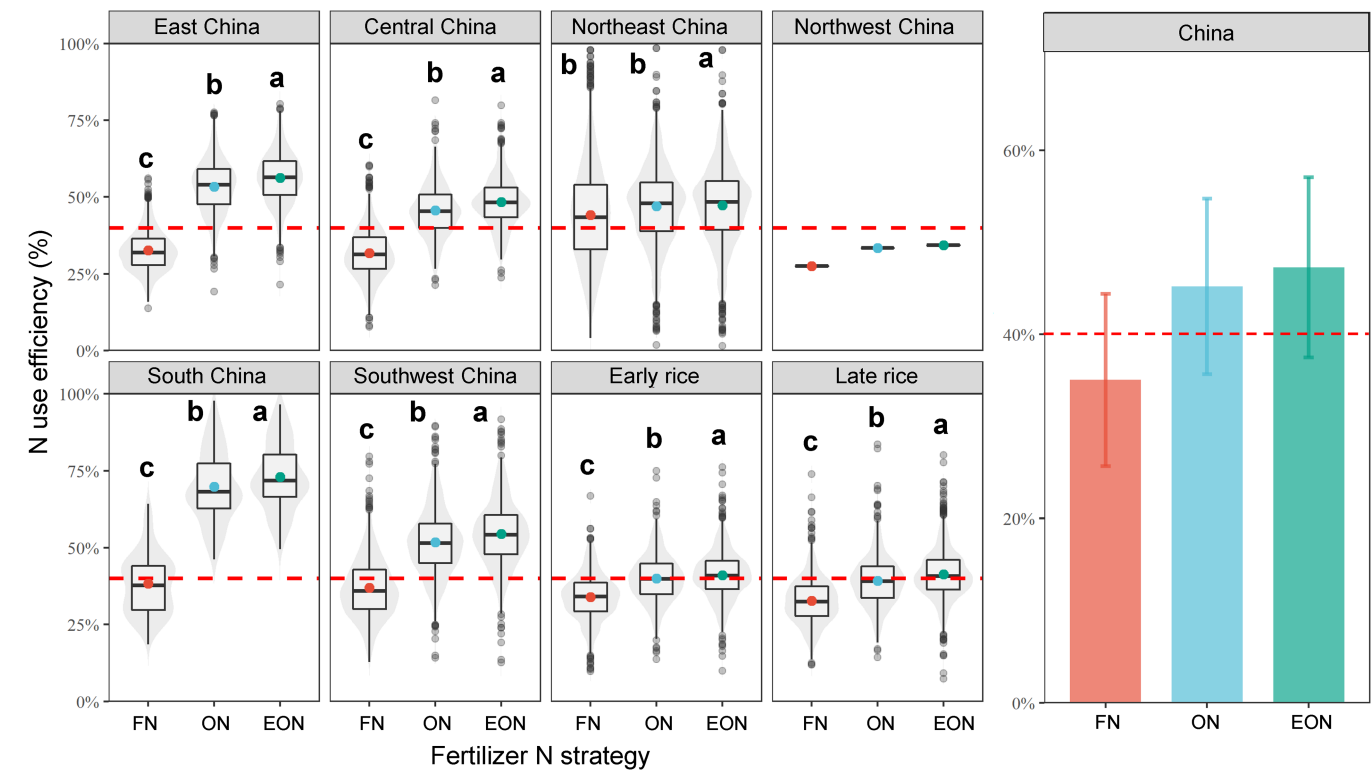
**Extended Data Fig. 4 | Effects of reducing N rates from the FN rate (150% MN) to the ON or EON rate for single-rice and double-rice (early rice/late rice) cropping systems on the probability distribution of the change in NEEB in**

**each site-year on-farm field experiment. The coloured vertical lines represent the mean values.**



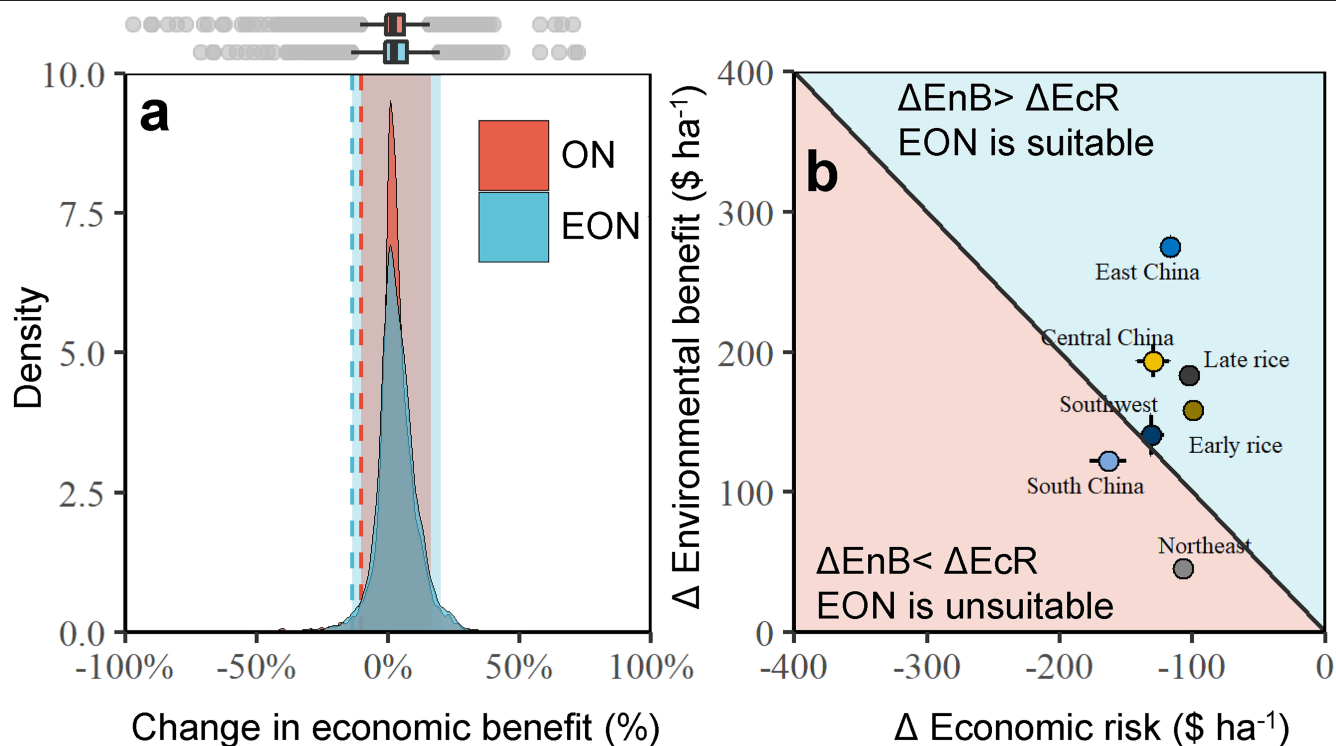
**Extended Data Fig. 5 | Effect of FN (150% MN), ON or EON on the N balance in two straw management scenarios (straw removed and straw returned) for single-rice and double-rice (early rice/late rice) cropping systems. Values**

are presented as means  $\pm$  SD. Different letters indicate significant differences ( $P < 0.05$ , Tukey's honestly significant difference test).



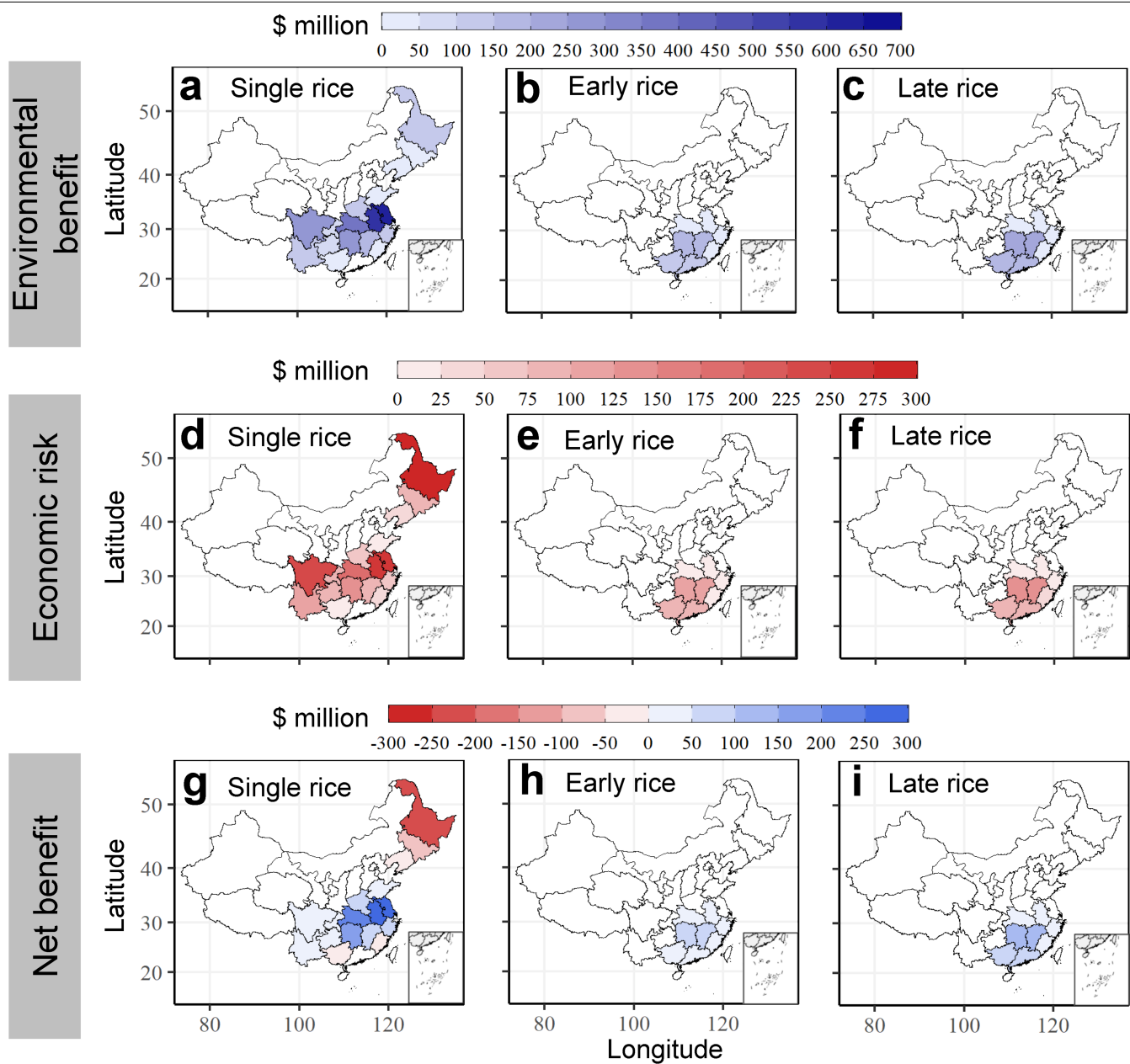
**Extended Data Fig. 6 | NUE response to FN, ON and EON for single-rice and double-rice (early rice/late rice) cropping systems in different rice subregions of China and the national mean value.** Length of the vertical lines: minimum and maximum values; boxes: upper and lower quartiles; horizontal lines in the box: median; dot in boxes: mean. The dashed red lines

denote NUE targets (40%) declared by the 'Action Plan for Targeting Zero Growth of Synthetic Fertilizer Use of China'<sup>18</sup>. National values are presented as means  $\pm$  SD. Different letters indicate significant deviations ( $P < 0.05$ , Tukey's honestly significant difference test).



**Extended Data Fig. 7 | Conceptual framework for the decision of the optimized strategy for each subregion. a,** Relative change in economic benefit when reducing N rates from the farmer practice N rate (150% MN) to ON or EON. The box plot is used to identify the lower fence for ON (-10.3%) or EON (-13.6%). **b,** Comparison between environmental benefit change and economic

risk within the lower fence when reducing N rates from the farmer practice N rate (150% MN) to EON for single-rice and double-rice (early rice/late rice) cropping systems. When the environmental benefit is higher than economic risk, EON is deemed suitable.  $\Delta \text{EnB}$ , environmental benefit change;  $\Delta \text{EcR}$ , economic risk within the lower fence.



**Extended Data Fig. 8 | Environmental benefit gain, economic risk and net benefit across China. a, d, g, Single rice. b, e, h, Early rice. c, f, i, Late rice. Net benefit was estimated by subtracting economic risk in 10.3–13.6% yield risk**

when reducing N rates (from the farmer practice N rate (150% MN) to the optimized strategy) from environmental benefit.

Extended Data Table 1 | Nitrogen fertilizer application strategies for different rice cultivation subregions in China

| N fertilizer strategy        | East China               | Central China | Northeast | Northwest | South China | Southwest | Central/South China |           |
|------------------------------|--------------------------|---------------|-----------|-----------|-------------|-----------|---------------------|-----------|
|                              | Single rice              |               |           |           |             |           | Early rice          | Late rice |
|                              | (kg N ha <sup>-1</sup> ) |               |           |           |             |           |                     |           |
| FN (Survey) <sup>a</sup>     | 289                      | 211           | 181       | 300       | 289         | 201       | 181                 | 200       |
|                              | (67)                     | (104)         | (43)      |           | (138)       | (111)     | (52)                | (57)      |
| FN (150% MN) <sup>b</sup>    | 359                      | 253           | 189       | -         | 243         | 225       | 227                 | 238       |
|                              | (65)                     | (37)          | (57)      |           | (27)        | (39)      | (38)                | (33)      |
| ON <sup>c</sup>              | 242                      | 171           | 197       | -         | 184         | 162       | 255                 | 232       |
|                              |                          | (10)          |           |           | (39)        | (9)       |                     |           |
| ON (this study) <sup>d</sup> | 226                      | 188           | 163       | 251       | 130         | 168       | 192                 | 201       |
|                              | (12)                     | (12)          | (8)       | (11)      | (9)         | (11)      | (11)                | (12)      |
| EON (this study)             | 189                      | 148           | 149       | 206       | 117         | 142       | 149                 | 147       |
|                              | (12)                     | (11)          | (8)       | (10)      | (9)         | (10)      | (11)                | (12)      |

<sup>a</sup> FN from the survey results, of which values in East, Northeast and South China and double rice in Central and South China are obtained from Zhang et al.<sup>15</sup>. Values in parentheses of FN represent the SD. Values in Central and Southwest China are from Wu et al.<sup>22</sup>. Values in parentheses of FN represent the SD, whereas values in parentheses of ON are based on the profitable N rate range within \$2.47 ha<sup>-1</sup>. The value in Northwest China is from Zhang et al.<sup>63</sup>.

<sup>b</sup> FN under 150% MN is from the on-farm field database, of which MN represents medium N application rates opted by local experts (further details provided in Methods).

<sup>c</sup> ON: optimal N rate from previous studies. Values in East and Northeast China and double rice in Central and South China are obtained from Zhang et al.<sup>15</sup>. Values in Central, South and Southwest China are from Cui et al.<sup>4</sup>, defining optimal N as the ISSM framework, which consists of a crop module from which cropping strategies can be determined on the basis of crop model simulations for optimal use of solar and thermal resources in a specific region.

<sup>d</sup> ON: economic optimal N rate in this study. EON: ecological optimal N rate in this study.