

Context-adaptive organic alternatives to conventional chemical fertilizers deliver synergistic outcomes across China

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Abstract: Synthetic nitrogen (N) fertilizer sustains crop production but causes large reactive N losses and greenhouse gas emissions. Organic replacements (ORR) are promoted to improve sustainability, yet evidence remains fragmented and lacks spatially explicit, region-adaptive recommendations. We synthesized 216 field studies across China using a mixed-effects meta-analysis, and quantified how climate, soil, and farming practices modulate ORR effect sizes. We then coupled our estimated responses with net ecosystem economic benefit accounting, scenario cost–benefit analysis, and benefit–area prioritization. On average, ORR increased yield by 10% and soil organic carbon by 21%, while reducing CH_4 and N_2O emissions by 41% and 23%. Our results also highlight differences between ORRs. Straw replacement delivered consistently positive economic returns and consistent performance across soil–climate regions, whereas biochar and other organic inputs showed stronger regional trade-offs, with benefits contingent on local soil–climate conditions and cost structures. National annual benefits from ORR (3,414–7,786 million CNY) exceeded their costs (215–533 million CNY). Spatial prioritization further indicated that targeting the highest-return 16–18% of cropland could capture 68–80% of total ORR benefits, equivalent to approximately 3.3–6.2 billion CNY yr⁻¹ in monetized production, ecosystem, health and climate gains. This integrated framework translates heterogeneous field evidence into actionable, spatially targeted ORR strategies.

Introduction

The massive expansion of synthetic nitrogen (N) fertilizer use was a cornerstone of the Green Revolution, fundamentally decoupling global food production from natural soil N constraints and sustaining billions of lives¹. However, these agricultural gains have come at substantial environmental costs. The rapid expansion of synthetic N inputs has profoundly transformed the global nitrogen cycle, amplified the nitrogen cascade across atmospheric, terrestrial and aquatic systems, and contributed to the transgression of the planetary boundary for biogeochemical flows²⁻⁴. Currently, more than half of the synthetic N applied to croplands, equivalent to nearly 120 Tg N annually, is lost to the atmosphere and aquatic systems. Such losses drive a cascade of ecological degradation, including accelerated soil acidification, aquatic eutrophication, and groundwater nitrate contamination, while simultaneously intensifying the emissions of greenhouse gases (GHG) and air pollutants, notably nitrous oxide (N₂O) and ammonia (NH₃)⁵⁻⁷. Consequently, reconciling food security with these environmental and climate burdens has become a central challenge for sustainable agriculture⁸.

To address this challenge, organic replacements (ORR), defined as the partial or complete replacement of synthetic N with organic amendments such as livestock manure, crop residues and compost, have emerged as a promising strategy for circular nutrient management^{9,10}. Global syntheses and long-term field experiments indicate that ORR can improve crop performance while enhancing soil organic carbon (SOC) stocks and microbial activity^{11,12}. Evidence from China shows that optimized manure use can reduce synthetic N inputs by 39% and reactive N losses by 22%, while increasing crop yields by 2–20%¹³. Long-term experiments across major agricultural regions, including the North China Plain, the Yangtze River Basin and Northeast China, report improvements in soil structure and microbial diversity, alongside reductions in nitrate leaching and GHG emissions¹⁴⁻¹⁶. In water-limited regions such as the Loess Plateau and Xinjiang, studies suggest that commercial organic fertilizers and pelleted manure can enhance soil water retention and crop productivity^{17,18}. Collectively, these findings

underscore the substantial agronomic and environmental potential of ORR as a component of sustainable intensification.

Despite these promising outcomes, the evidence base for ORR remains largely fragmented, characterized by a proliferation of site-specific studies and broad syntheses that overlook critical regional heterogeneities. The performance of ORR is not universal; rather, it is governed by a set of complex variables, including pedoclimatic conditions, soil texture, cropping system architectures, and localized availability of organic feedstocks^{19,20}. Without accounting for this spatial variability, blanket implementation risks unintended biogeochemical and economic trade-offs. For instance, inappropriate organic amendments can exacerbate ammonia volatilization, nutrient imbalances, and emissions of N₂O and CH₄, particularly in flooded paddy systems^{21,22}. Importantly, management strategies optimized for one objective may not necessarily maximize co-benefits across other dimensions. Practices that prioritize crop productivity may differ substantially from those designed to maximize soil carbon sequestration or minimize greenhouse gas emissions, highlighting the need to explicitly evaluate trade-offs and synergies among multiple sustainability targets. These uncertainties underscore the pressing need for spatially explicit and integrative assessments capable of identifying region-specific optimization pathways that balance agronomic productivity, climate mitigation, and long-term soil sustainability across diverse agroecosystems.

China, as the world's largest consumer of synthetic N²⁴, serves as a perfect testbed for the large-scale transition toward ORR. National initiatives such as the “zero growth in chemical fertilizer use” policy launched in 2015 have promoted livestock manure recycling, straw return, and compost application^{25,26}. While these efforts have generated valuable local insights, most studies frequently focus on individual sites and isolate agronomic and environmental metrics, rarely synthesizing them into a cross-regional framework capable of guiding systematic optimization. In addition, many evaluations overlook economic dimensions that ultimately influence adoption feasibility. Addressing these gaps is essential to ensure that ORR strategies are not only biophysically sound, but also economically viable and socially acceptable.

To bridge these critical knowledge gaps, a systematic and multi-dimensional evaluation of ORR performance across China's diverse agro-ecological landscapes is urgently needed. Our study addresses three key questions: (1) What are the comparative effects of different organic material types used for ORR (e.g., straw, biochar, and commercial organic fertilizers) on soil fertility, crop yield, and GHG emissions? (2) How can spatial heterogeneity in climate, soil, and cropping systems be incorporated to optimize ORR strategies that sustain crop yields, improve soil health, and mitigate environmental risks? (3) What economic trade-offs and co-benefits arise under alternative ORR scenarios, and how can these insights inform regionally tailored policy design and nutrient-circularity programs?

Here, we synthesize evidence from 216 field studies conducted between 1973 and 2023 to quantify the effects of ORR on crop yield, soil organic carbon, and CH₄ and N₂O emissions using a meta-analysis, and to examine how these effect sizes are moderated by organic material type, climate, soil properties, and management practices. We then link these effect-size estimates to net ecosystem economic benefit (NEEB) accounting and scenario-based cost-benefit analysis. By doing so, we translate heterogeneous field evidence into spatially explicit estimates of crop yield, SOC, GHG mitigation and monetary benefits, and identify high-return areas for ORR implementation. Based on these analyses, we develop a regionally adaptive recommendation framework that integrates agronomic, environmental, and economic indicators to enable precision nutrient management in Chinese agriculture. Our analysis reveals that optimized ORR implementation can potentially catalyze a systemic shift in agricultural sustainability. By providing a scalable framework to reconcile intensive productivity with environmental stewardship, our findings offer a scientific basis for policymakers, extension services and farmers to accelerate the transition towards resilient, low-carbon and circular agricultural systems in China and across the global South under mounting climate and food security pressures.

Results

Effects of organic replacements

Across all 216 studies, ORR generated consistent, statistically significant co-benefits for production and climate-related outcomes. On average, SOC increased by 21%, crop yields rose by 10%, and CH₄ and N₂O emissions were reduced by 41% and 23%, respectively (Fig. 1a). These national-scale averages indicate that ORR can deliver “win–win” outcomes, but the spread of individual effect sizes shown in Fig. 1a also suggests substantial between-site variability that is not adequately reflected when only considering the mean effect size.

To identify the drivers of this heterogeneity, we examined climate, soil, and management moderators. Supporting analyses show that the responses of SOC, GHG emissions, and crop yields to the application of ORR materials also depended on factors such as mean annual temperature (MAT), mean annual precipitation (MAP), soil texture, soil pH, initial SOC, total nitrogen (TN), and irrigation methods (Supplementary Fig. 1). Climatic gradients consistently moderated ORR responses: increasing MAT and MAP were associated with smaller gains in yield and SOC, and with weaker reductions in N₂O emission intensity under warmer and wetter conditions. However, MAT/MAP alone accounted for only a limited share of the between-study variability ($R^2 \approx 0.01$ – 0.11 ; Fig. 1c), indicating that additional soil and management factors contribute substantially to the observed heterogeneity. Collectively, these results justify the subsequent region-adaptive analyses, because a uniform ORR strategy is unlikely to deliver comparable co-benefits across China’s diverse agro-climatic zones.

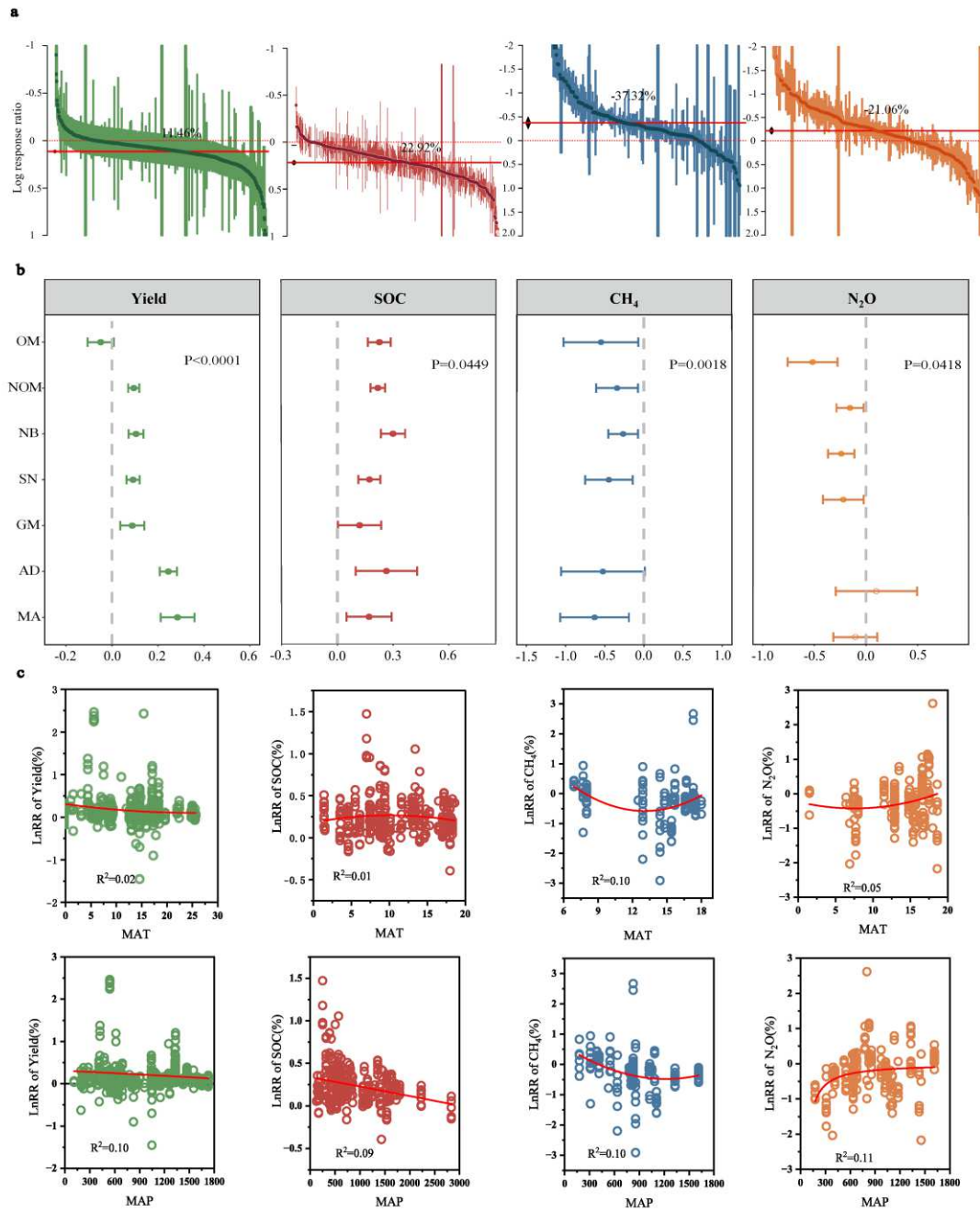


Fig.1 | Effects of Organic replacements (ORR) on carbon sequestration, crop yield, and greenhouse gas (GHG) emissions in agricultural soils. (a) Effects sizes of ORR on soil carbon sequestration, crop yield, and GHG emissions by study. (b) Effects of different ORR material types on soil carbon sequestration, crop yield and GHG emissions: chemical fertilizer (OM), partial organic fertilizer replacement (NOM), partial biochar replacement (NB), partial straw replacement (SN), green manure replacement (GM), other nutrient replacement materials (AD) and mixed replacement of the above materials (MA). (c) Effects of mean annual temperature (MAT) and mean annual precipitation (MAP) on soil carbon sequestration, crop yield, and GHG emissions to climatic factors.

Suitability of different organic replacement material types

Across most agricultural regions, straw replacement delivered the highest NEEB (1.47×10^4 – 3.75×10^4 CNY ha⁻¹), substantially outperforming organic fertilizer replacement (-6.73×10^4 – 2.94×10^4 CNY ha⁻¹) and biochar replacement (-16.27×10^4 – 2.12×10^4 CNY ha⁻¹). Consistent with this pattern, straw replacement also exhibited the broadest and most flexible application window across crops and regions (3–37 t ha⁻¹), suggesting a comparatively robust option under diverse agro-climatic contexts (Fig. 2). This pattern likely reflects differences in input costs and operational flexibility among replacement strategies.

Suitable application rates varied markedly by region and cropping system (Fig. 2a). Southwest China and South China required higher soil amendment inputs (15–37 t ha⁻¹). In rice systems, Northeast China showed the lowest organic fertilizer replacement rates (0.3–0.75 t ha⁻¹), whereas North China displayed the widest suitable range for biochar replacement in wheat systems (3–6.22 t ha⁻¹). Beyond these overall patterns, organic fertilizer and biochar strategies exhibited pronounced regional heterogeneity in net benefits (Fig. 2b). For example, biochar application in rice systems drove NEEB down to -13.73×10^4 CNY ha⁻¹, coinciding with intensified GHG emissions, whereas in North China biochar increased maize NEEB to 2.12×10^4 CNY ha⁻¹ (Fig. 2b). Together, these results highlight that while straw replacement is broadly applicable, the suitability of organic fertilizer and biochar replacements is strongly region- and crop-dependent, underscoring the need for region-adaptive ORR deployment.

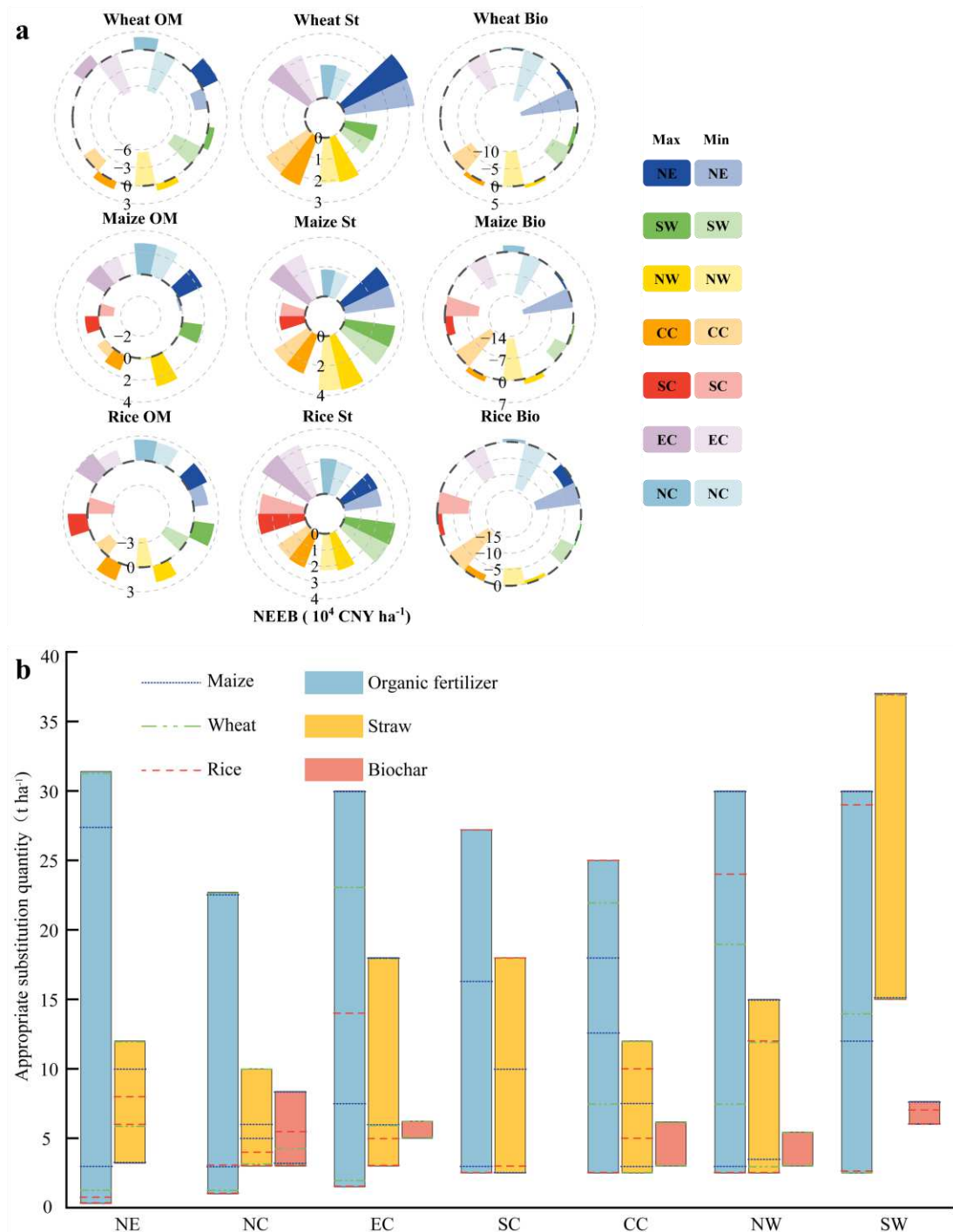


Fig.2 | Replacement rates and by net ecosystem economic benefit (NEEB) of Organic replacement (ORR) strategies across China's agricultural regions. China was divided into seven agricultural regions: NE, Northeast China; NC North China; EC, East China; SC, South China; CC, Central China; NW, Northwest China; SW, Southwest China. a, Application amount of ORR strategies in each region. b, NEEB of ORR strategies by region; Max and Min indicate the maximum and minimum NEEB values, respectively. OM, organic fertilizer replacement; St, straw replacement; Bio, biochar replacement.

Regional benefits of organic replacements

The performance of ORR strategies varied markedly across regions (Fig. 3). Positive NEEB values indicate that ORR strategies can increase yields and carbon sequestration while reducing GHG emissions across agricultural regions. Wheat yields in Central China increased by up to 0.72 t ha^{-1} , and the largest yield gain was observed for rice in Northwest China at 1.17 t ha^{-1} (Fig. 3). The largest reduction in GHG emissions was observed in rice systems in North China, reaching up to $11 \text{ t eq CO}_2 \text{ ha}^{-1}$. Carbon sequestration was greatest in Southwest China, ranging from 1.93 to 2.19 Mg ha^{-1} .

For organic fertilizer replacements, yield gains were highest in Central China (13–18%), carbon sequestration increases were highest in North China (26–28%), and GHG reduction peaked in Northwest China (73%). For straw replacement, the largest yield gains occurred in Southwest China (7–19%), whereas the strongest carbon sequestration (20–98%) and GHG reduction (64%) were observed in Northwest China. For biochar replacement, yield gains were greatest in Southwest China (up to 17%), while carbon sequestration (34–39%) and GHG reduction (up to 43%) peaked in North China.

By contrast, even under positive NEEB conditions, biochar replacement delivered only modest gains in yield, carbon sequestration, and GHG reduction in Northeast China and South China. Notably, ORR in maize systems in Southwest China increased GHG emissions by 97%, highlighting a pronounced trade-off in specific crop–region contexts (Fig. 3).

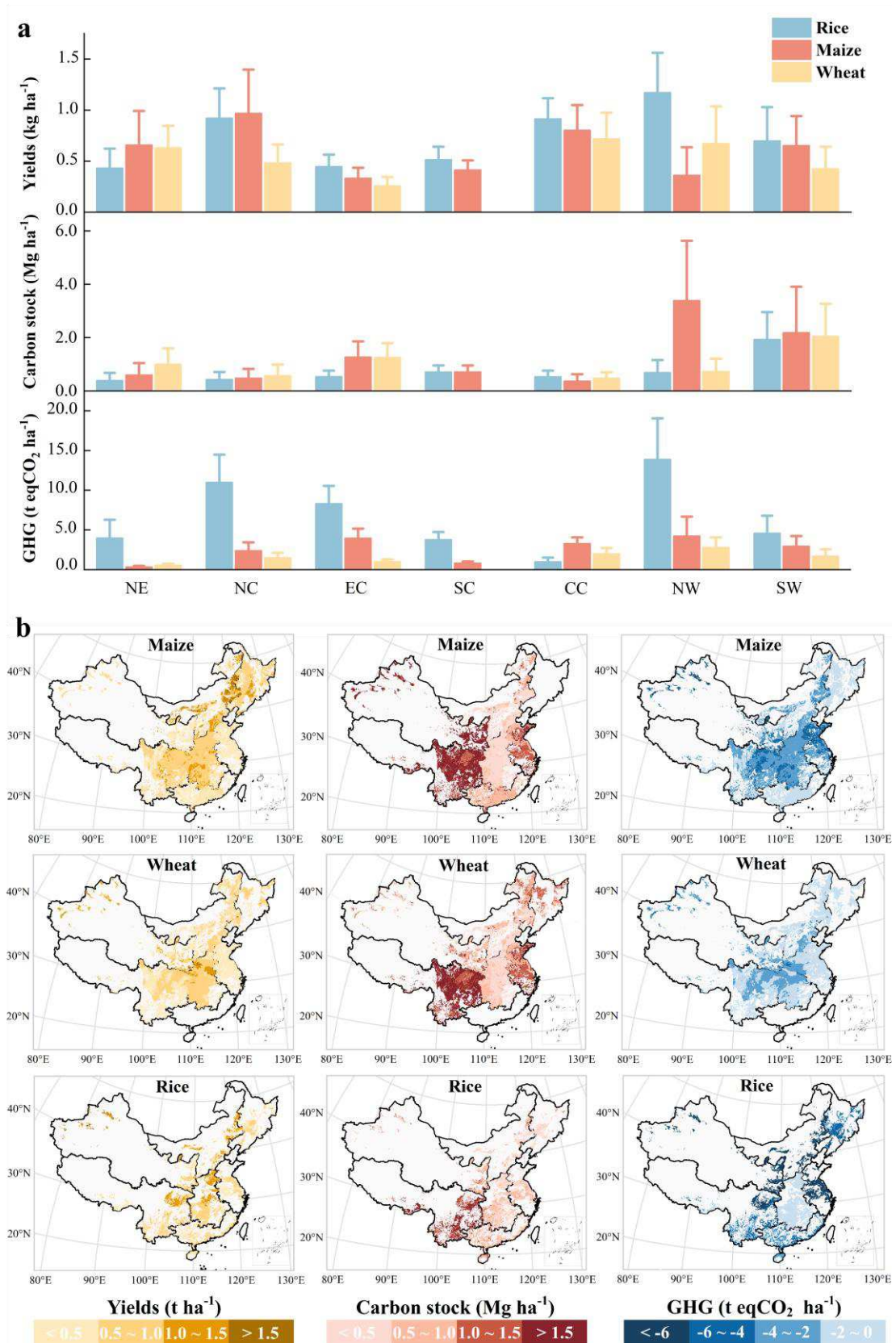


Fig. 3 | Regional benefits of Organic replacements across China's agricultural regions. Yield, carbon sequestration and greenhouse gas emissions outcomes are expressed in t ha⁻¹, Mg ha⁻¹ and t CO₂-eq ha⁻¹, respectively. a, Benefits for the three major staple-crop systems across

China's agricultural regions; values are presented as mean $\pm$ s.d. **b**, Spatial distribution of benefits for the three major staple-crop systems across China's agricultural regions. Blank regions on the map indicate that the strategy does not generate positive benefits for the cropping systems in those regions.

National cost-benefit analysis of organic replacements

ORR implementation generated both costs and benefits for cropland ecosystems and human health. Across combinations of agricultural regions and staple-crop systems, the selected strategies required ORR inputs spanning 0.53–46.0 t ha⁻¹. The required application amounts of these materials were generally higher under the carbon-sequestration priority (SOCS) and GHG reduction priority (GHGS) scenarios than under the yield-increase priority (PROS) scenario, reflecting the greater reliance on straw and biochar in mitigation-oriented portfolios. We conducted a national cost–benefit assessment across three priority-target scenarios—PROS, SOCS, and GHGS. While developing these scenarios, for each region–crop system, we selected the ORR strategies that maximized the corresponding priority benefit (yield increase, carbon sequestration, or GHG mitigation) based on the regional benefit profiles (Supplementary Fig. 2), forming a region-adaptive portfolio of strategies (Supplementary Table 2).

Across the scenarios, additional organic material inputs resulted in annual implementation costs of 215–533 million CNY yr⁻¹, while total benefits ranged from 4,861 to 7,787 million CNY yr⁻¹. Under the PROS scenario, costs were lowest at 215 million CNY yr⁻¹ and the portfolio delivered the largest product gains, reaching 1,535 million CNY yr⁻¹; ecosystem, health, and climate benefits contributed 2,182, 423, and 809 million CNY yr⁻¹, respectively, resulting in a net benefit of 4,734 million CNY yr⁻¹. Under the SOCS scenario, costs rose to 457 million CNY yr⁻¹ and product benefits declined to 1,169 million CNY yr⁻¹, while ecosystem and climate benefits increased modestly to 2,384 and 884 million CNY yr⁻¹, yielding a net benefit of 4,403 million CNY yr⁻¹. By contrast, the GHGS scenario incurred the highest costs at 533 million CNY yr⁻¹ but delivered the largest ecosystem and climate benefits, reaching 4,687 and 1,738 million CNY yr⁻¹; despite the smallest product gains of 912 million CNY yr⁻¹,

this scenario achieved the highest net benefit of 7,254 million CNY yr⁻¹ (Fig. 4).

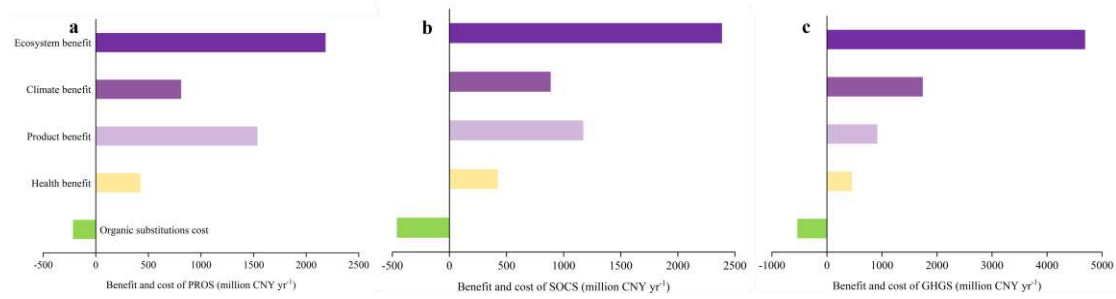


Fig.4 | Costs and benefits of Organic replacements under alternative priority scenarios. a–c, (a) Yield-increase priority (PROS), (b) carbon-sequestration priority (SOCS), and (c) greenhouse gas reduction priority (GHGS) (c).

Spatial prioritization of organic replacements strategies at the national scale

Under different ORR scenarios, cumulative benefits increased logarithmically with cumulative cropland area (Fig. 5), indicating a strong spatial concentration of returns: a relatively small fraction of cropland delivers disproportionately large benefits, while marginal gains diminish as progressively lower-return areas are included. Consistent with this pattern, the slope of the cumulative benefit curve (k) delineated clear spatial priority tiers. Priority zones ($k > 2$) represent high-leverage locations where additional deployed area yields large incremental benefits, sub-priority zones ($1 < k \leq 2$) provide moderate incremental returns; and non-priority zones ($k \leq 1$) contribute limited additional benefits per unit area.

For organic fertilizer replacement, priority zones accounted for ~18% of cropland area while delivering ~76% of total benefits, concentrated in Central China, East China, and Northeast China (Fig. 5a). For straw replacement, priority zones clustered in East China, Central China, and Southwest China, where 18% of cropland area generated 68% of total benefits (Fig. 5b). For biochar replacement, priority zones were mainly located in Southwest China, Central China, and North China with 16% of cropland area contributing ~80% of total benefits (Fig. 5c). Collectively, priority zones consistently accounted for approximately 15–18% of the entire cropland area while contributing the majority of total benefits, underscoring the feasibility of achieving large national-scale gains through spatially targeted deployment rather than uniform expansion²⁷.

Sub-priority zones delivered moderate additional gains, covering 7–11% of cropland area and contributing 9.65–16.26% of total benefits across ORR strategies. These zones broadly coincided with the priority belts, with higher shares in Central China and East China for organic fertilizer and straw replacement, and in Central China and Southwest China for biochar replacement. In contrast, non-priority zones encompassed most cropland (71–78%) but contributed only 11–16% of total benefits, with concentrations in Southwest China, Northwest China, and North China for organic fertilizer replacement; North China and Northeast China for straw replacement; and East China and Central China for biochar replacement.

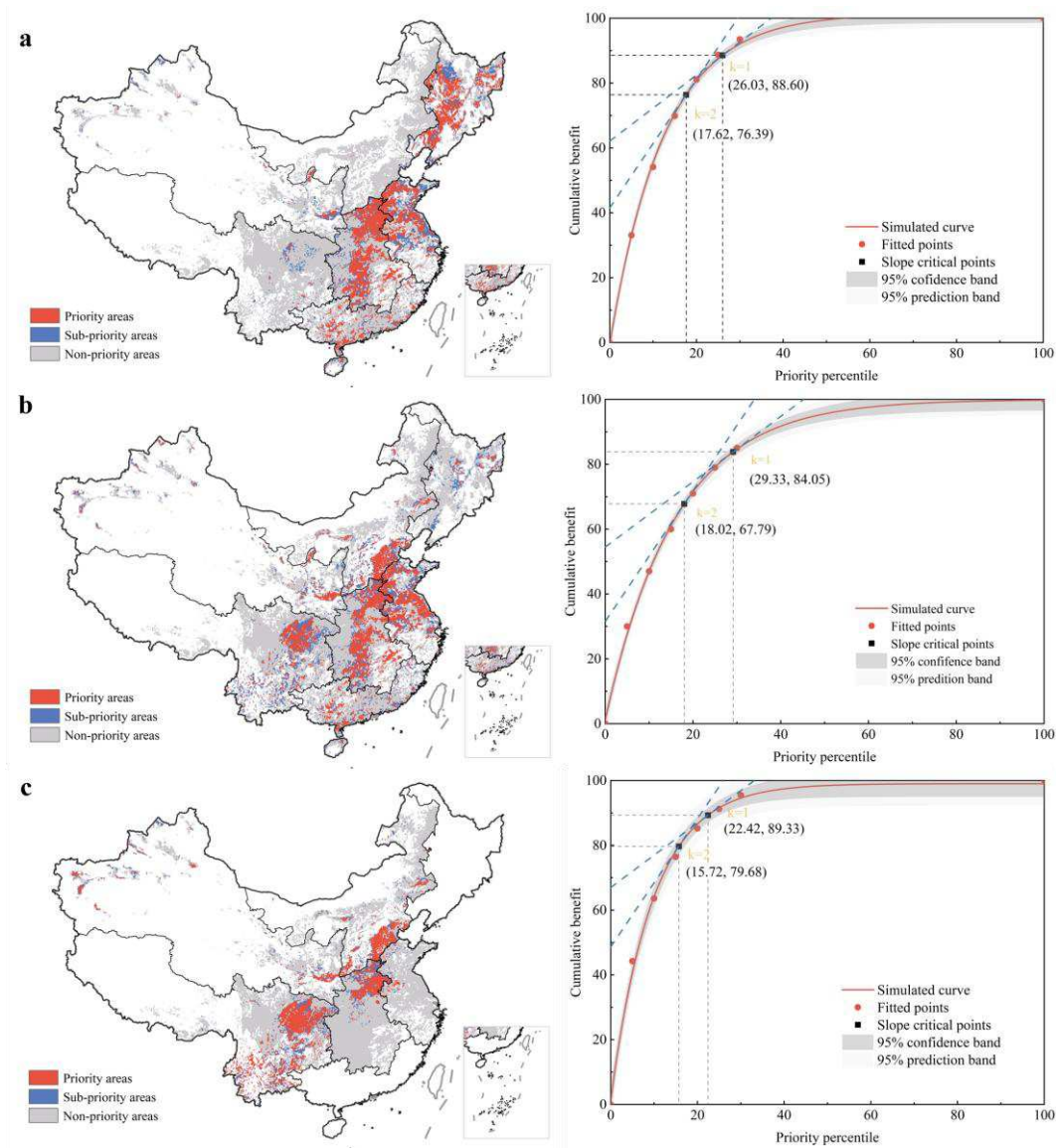


Fig.5 | National priority regions for ORR and cumulative benefit–area curves under alternative replacement strategies. (a) organic fertilizer replacement. (b) straw replacement. (c) biochar replacement.

Discussion

ORR is increasingly recognized as a promising solution for sustaining crop yields while reducing reliance on synthetic N and alleviating environmental externalities^{28,29}. Despite growing interest, existing evaluations, from global meta-analyses to national case studies, often rely on single-site observations, generalized assumptions or yield-centred metrics. Consequently, regional heterogeneity in soil–climate conditions, management practices, and socioeconomic constraints has not been fully incorporated into ORR assessments³⁰. This limitation hampers the development of adaptive strategies for efficient, large-scale implementation. By integrating a meta-analysis with NEEB accounting, our study moves beyond existing literature to provide a multi-dimensional evaluation of ORR strategies across China's diverse agricultural zones.

Our findings confirm that while ORR can, on average, enhance soil organic carbon, sustain or increase crop productivity, and reduce GHG emissions, its environmental and economic efficacy shows profound regional variation. Importantly, our identification of spatial priority zones suggests that implementing ORR on a relatively small proportion of cropland could capture a disproportionately large share of national-level agronomic, environmental, and economic benefits. This "hotspot" effect suggests that the pathway to sustainable nutrient management is not uniform nationwide adoption, but a spatially optimized, precision-targeted deployment. Our findings align with experimental studies and meta-analyses showing that partially substituting chemical fertilizers with organic inputs can increase SOC and reduce nitrogen-related losses while maintaining crop yields^{5,31}. Previous studies also suggest that straw return and organic fertilizer application can improve soil structure, nutrient availability and microbial activity, thereby supporting both agronomic performance and environmental outcomes^{32,33}. In contrast to many existing evaluations that rely on single-site experiments or national-average assumptions, our approach reveals substantial differences in the suitability and performance of specific replacement strategies across agricultural regions. Notably, although biochar is often presented as a broadly effective mitigation option, our results indicate that its benefits are strongly context-dependent and may be confined to specific

soil–climate settings^{34,35}. This context dependency likely arises from interactions between biochar properties and local soil–climate conditions, which regulate carbon stabilization processes, nutrient dynamics, and emission pathways, thereby leading to divergent agronomic and environmental outcomes across regions.

The regional patterns identified in this study further highlight the importance of tailoring ORR strategies to local soil–climate conditions and nutrient cycling processes. For example, the relatively low demand for organic inputs in Northeast China is consistent with the inherently high fertility of black soils³⁶. By contrast, the strong performance of straw replacement in southern regions aligns with evidence that straw return can help mitigate nutrient leaching under high-rainfall conditions³⁷. The limited feasibility of biochar in some regions may therefore be associated with altered greenhouse gas dynamics under specific environmental conditions, where biochar-induced changes in aeration, nitrogen transformation, or microbial processes can offset potential climate benefits. For instance, a recent meta-analysis showed that biochar significantly increased crop yield and reduced soil acidity in acidic soils, but had neutral or inconsistent effects in neutral to alkaline soils, suggesting that its mitigation potential is strongly constrained by baseline soil properties and climate interactions⁴⁸. Compared with biochar, straw and organic fertilizers appear to be more broadly ecologically adaptable, potentially because they more consistently shape carbon–nitrogen interactions and microbial processes across diverse environments³⁸. These region-specific mechanisms may help explain the differentiated performance of ORR strategies across China’s agricultural zones.

Although the comprehensive benefits of ORR are evident, effective implementation remains a major challenge. By identifying optimal application rates and spatial priority zones for different replacement strategies, this study provides a basis for improving the efficiency of large-scale deployment. However, farmers ultimately determine whether such strategies are adopted, and relatively high upfront costs may reduce short-term economic returns, thereby limiting adoption willingness. These findings suggest that region-specific incentive mechanisms may be necessary to align farmer decision-

making with broader environmental and climate objectives^{39,40}. In the context of China's predominantly smallholder-based agricultural system, short-term approaches that accommodate limited mechanization and fragmented land management may be particularly relevant. Carefully designed incentive schemes that reward actual replacement practices could help lower adoption barriers while supporting longer-term transitions toward sustainable nutrient management.

While this study identifies substantial spatial heterogeneity in the agronomic, environmental and economic performance of ORR, translating these potentials into realized large-scale outcomes remains challenging. Our meta-analytical and accounting framework does not fully capture long-term behavioral responses, evolving market conditions or region-specific institutional constraints that shape adoption decisions, particularly within smallholder-dominated systems. Upfront investment costs and uncertain short-term returns may further limit farmer uptake, even in regions with high biophysical potential. These considerations suggest that uniform nationwide promotion is unlikely to deliver optimal outcomes. Instead, spatially differentiated implementation—prioritizing high-return regions and aligning replacement pathways with local soil–climate contexts—may provide a more efficient route to reconcile food production with climate mitigation and environmental protection. Policy mechanisms that reduce initial adoption barriers and link incentives to measurable environmental gains could facilitate more effective scaling of ORR under increasing climate and resource pressures.

Methodology

Systematic search strategy and data compilation

This study evaluated the benefits of ORR strategies for agricultural ecosystems in China. We conducted a comprehensive search of peer-reviewed literature indexed in Web of Science through December 2023 to quantify the effects of organic replacement practices on multiple ecosystem outcomes. The analysis focused on three core functions

relevant to agricultural ecosystems: food supply, carbon storage, and climate regulation. Accordingly, yield, soil organic carbon stock (SOC stock), and emissions of nitrous oxide (N₂O) and methane (CH₄) were identified as target variables.

We used the following search terms for titles and topics: ("Organic replacement" or "organic fertilizer" or "biochar" or "straw") and ("organic carbon" or "SOC" or "CH₄" or "N₂O" or "yield"). Studies were included if they met the following criteria: (1) the study reported a field experiment conducted in mainland China with sufficient site information (latitude/longitude or a clear site description); macro-scale assessments, reviews, laboratory incubations, and modelling studies were excluded. (2) The experiment covered at least one complete growing season (planting to harvest) and focused on rice, maize, or wheat. (3) The organic amendment application method was clearly described, and other management practices such as tillage, planting pattern, and irrigation were kept identical across treatments. (4) Treatment and control plots were comparable in site conditions, baseline soil properties, sampling time and protocol, and experimental duration. (5) Measurement methods for the reported indicators were clearly described and consistent across treatments. (6) Soil sampling was conducted at harvest, with sampling depth and replication explicitly reported. Data and standard deviations must be extractable from figures/tables/text or calculable.

Ultimately, the study incorporated 2,122 valid data pairs from 216 publications. This screening process followed the PRISMA methodology (<http://www.prisma-statement.org/index.htm>) (Supplementary Fig. 3). Data were extracted from tables and figures using Web Plot Digitizer (v3.8) to obtain means, sample sizes, and standard deviations (SD). When studies reported standard errors (SE), SD was calculated as $SD = SE\sqrt{N}$. For studies lacking variability measures, SD was estimated by multiplying means by the average coefficient of variation across all studies. The primary data sources are shown in Supplementary Fig. 4. The spatial distribution of data sources spans China's major grain production regions (rice, wheat, and maize), supporting the geographic representativeness of the meta-analysis.

Meta-analysis

This study employed weighted natural log response ratios ($\ln(RR)$) and variances to quantify the effects of organic amendments on soil organic carbon content, greenhouse gas (CH_4 , N_2O) emissions, and crop yields in agricultural soils, with organic amendment application as the treatment and conventional fertilization as the control. The calculation was performed as equation (1):

$$\ln(RR) = \ln \frac{X_o}{X_c} = \ln X_o - \ln X_c \quad (1)$$

where X_o represents the mean values of soil organic carbon content, yield-scaled $\text{CH}_4/\text{N}_2\text{O}$ emissions, crop yield, or other relevant indicators under organic amendment application, and X_c denotes the corresponding mean values under conventional fertilization.

Using the `escalc` function in the R package *metafor*, we calculated the effect size and its variance for each paired comparison⁴¹. Subsequently, the `rma.mv` function's mixed-effects model was applied to determine the overall effects of organic fertilizers compared to conventional fertilization on SOC content, GHG emissions, and crop yields, along with their 95% confidence intervals (CIs). These mixed-effects models were weighted by the inverse of the variance and used study ID as the random effect. Publication bias was assessed using funnel plots (Supplementary Fig. 5). Funnel plots indicated no clear publication bias for any target variable, supporting the robustness of subsequent inferences. To better characterize the magnitude of treatment effects on specific indicators, the percentage change was calculated as $E = (\exp(\ln R_{++}) - 1) \times 100\%$. When the 95% CI of the effect size overlapped with zero, it indicated no significant difference between organic fertilizers and conventional fertilization. Conversely, non-overlapping 95% CIs indicated statistically significant meta-analysis results ($p < 0.05$), demonstrating that the treatment either significantly increased or decreased the target variable.

Due to differences in the experimental sites where the data were collected from, the data in the database were classified by nutrient replacement material type, climatic

factors, soil properties, and field management measures. The replacement types were classified as: full organic fertilizer replacement for chemical fertilizer (OM), partial organic fertilizer replacement (NOM), partial biochar replacement (NB), partial straw replacement (SN), green manure replacement (GM), other nutrient replacement materials (AD), and mixed replacement of the above nutrient materials (MA). The climate types were classified into three temperature zones in China: temperate, subtropical, and tropical. Soil texture was simplified into four types based on the United States Department of Agriculture classification: clay, clay loam, loam, and sand. Soil pH was classified as acidic ($\text{pH} < 6.5$), neutral ($6.5-7.5$), and alkaline (> 7.5). The initial SOC content of the soil was classified into low ($\leq 10 \text{ g kg}^{-1}$), medium ($10-20 \text{ g kg}^{-1}$), and high ($\geq 20 \text{ g kg}^{-1}$) concentration levels. Total nitrogen concentration was classified into low ($\leq 1.0 \text{ mg kg}^{-1}$), medium ($1.0-2.0 \text{ mg kg}^{-1}$), and high ($\geq 2.0 \text{ mg kg}^{-1}$) levels. Available phosphorus and available potassium concentrations were classified as $\leq 15 \text{ mg kg}^{-1}$, $15-100 \text{ mg kg}^{-1}$, $100-150 \text{ mg kg}^{-1}$, and $\geq 150 \text{ mg kg}^{-1}$. Land use types were classified as paddy fields and drylands. Cropping systems were classified into one, two, or three cropping systems. Rotation patterns were classified as "YES" and "NO". Irrigation methods were classified as rain-fed irrigation, intermittent irrigation, and continuous irrigation.

Suitability assessment

To evaluate organic replacement across China, we grouped major grain-producing areas into seven agricultural regions based on climatic, geographic and hydrological characteristics: Northeast (Heilongjiang, Liaoning and Jilin), North (Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia), East (Anhui, Shandong, Jiangsu, Zhejiang and Shanghai), Central (Hubei, Hunan, Henan and Jiangxi), South (Guangdong, Guangxi, Fujian and Hainan), Northwest (Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang) and Southwest (Chongqing, Sichuan, Guizhou and Yunnan) (Supplementary Fig. 5)⁴².

NEEB refers to the comprehensive assessment of a management practice or technology's impact on both ecosystems and economies, considering ecosystem

services and economic benefits⁴³. In this study, we employed NEEB to evaluate the regional suitability of ORR strategies. A positive NEEB ($NEEB > 0$) indicates that the ecological benefits of ORR exceed its costs, whereas a negative NEEB ($NEEB < 0$) indicates that costs outweigh benefits. We calculated NEEB for organic fertilizer application across the seven agricultural regions as follows:

$$Economic\ benefit = Yield \times Price_r - N_{OS} \times Price_{OS} \quad (2)$$

$$Environment\ benefit = N \times Price_n + \Delta N_r \times Price_{N_r} \quad (3)$$

$$NEEB = Economic\ benefit - Environment\ benefit \quad (4)$$

where *Yield* represents crop yield per unit area ($kg\ ha^{-1}$), *Price_r* denotes crop market price ($CNY\ kg^{-1}$), *N_{OS}* indicates the application rate of organic substitutes ($kg\ ha^{-1}$), and *Price_{OS}* stands for the unit price of organic substitutes ($CNY\ kg^{-1}$). *N* refers to nitrogen fertilizer application rate ($kg\ ha^{-1}$), *Price_n* is nitrogen fertilizer unit price ($CNY\ kg^{-1}$), and *ΔN_r* represents reactive nitrogen losses ($kg\ N\ ha^{-1}$) or corresponding changes in direct/indirect greenhouse gas emissions from N_2O-N , leaching, runoff, and NH_3-N volatilization ($Mg\ eqCO_2\ ha^{-1}$), converted according to the Intergovernmental Panel on Climate Change (IPCC) guidelines⁴⁴. *Price_{N_r}* indicates the trade price of direct/indirect greenhouse gases ($CNY\ Mg\ eqCO_2^{-1}\ ha^{-1}$). Additional information on emission factors and market prices/costs can be found (Supplementary Table 1).

The cost-benefit analysis excluded other operational costs because management expenses were assumed to be standardized across sub-regions and largely insensitive to organic substitute application rates.

Potential estimation

This study calculated the changes in soil carbon storage⁴⁵, GHG emissions⁴⁶, and crop yield following ORR using the following equations.

$$\Delta SOC_{Stock} = \sum_i SOC_j \times ESOC_{ij} \times BD_j \times H \times 10 \quad (5)$$

$$EGHG_{S_{ij}} = (ECH_{4,ij} \times \frac{16}{12} \times 28 + EN_2O_{ij} \times \frac{44}{28} \times 265) / (\frac{16}{12} \times 28 + \frac{44}{28} \times 265) \quad (6)$$

$$\Delta GHGs = \sum_i EGHGs_{ij} \times Yield_{ij} \times EF_{ij} \quad (7)$$

$$\Delta Yield = \sum_i Y_j \times Ey_{ij} \quad (8)$$

where the increment subscript baseline, ΔSOC_{Stock} is the change in carbon sequestration ($Mg\ ha^{-1}$), SOC_j is the SOC ($g\ kg^{-1}$) in region j ; $ESOC_{ij}$ is the percentage change in SOC under application of the ith ORR in region j ; BD_j is the soil bulk density ($Mg\ m^{-3}$) in region j ; H is the soil layer thickness (m); 10 is the unit conversion coefficient; and this study mainly considers the soil carbon storage in the 0-20 cm soil layer. The $\Delta GHGs$ is the change in GHG emissions ($kg\ eqCO_2\ ha^{-1}$); $ECH_{4,ij}$ and EN_2O_{ij} are the percentage change in CH_4 and N_2O emissions from cropland in region j under application of the ORR, derived from the meta-analysis; $Yield_{ij}$ is the total yield (kg) of the ith crop in region j , EF_{ij} is the GHG emissions per unit yield ($kg\ CO_2\ kg^{-1}$) of the ith crop in region j (data from the World Resources Institute). $\Delta Yield$ is the change in per-area yield of rice, wheat, and maize in region j ($kg\ ha^{-1}$), Y_j is the average per-area yield of rice, wheat and maize in region j ($kg\ ha^{-1}$), and Ey_{ij} is the percentage change in crop yield in region j under application of the ORR, derived from the meta-analysis.

To estimate aggregate changes in crop yield, GHG emissions and carbon sequestration across agricultural regions under ORR scenarios, we used the following equations:

$$SOC_{Stock} = \Delta SOC_{Stock} \times A_j \quad (9)$$

$$GHGs = \Delta GHGs \times A_j \quad (10)$$

$$Yield = \Delta Yield \times A_j \quad (11)$$

where A_j is the harvested area (ha) of rice, maize, and wheat in the region j .

Cost and benefits

The implementation costs under different ORR scenarios and the benefits in terms of production, ecology, health, and climate were evaluated.

Implementation costs

The implementation cost of the ORR strategy scenario comes from the purchase of organic replacement substances. Among the three organic replacement substances, straw was treated as locally available and therefore incurred no purchase cost. To calculate the national implementation cost of ORR, we obtained biochar and organic

fertilizer prices from market research (Supplementary Table 1) and combined them with statistical data on nationwide harvest areas for rice, wheat, and maize. Costs were calculated as equation (12):

$$Cost_{OS} = \sum_i A_i \times N_{OS} \times Price_{OS} \quad (12)$$

where $Cost_{OS}$ represents the additional cost (in CNY) resulting from the implementation of ORR. A_i represents the harvest area (ha) of the crop, and i represents the crop type (rice, wheat, maize).

Net production benefits

Net production benefits from national ORR implementation were calculated as equation (13):

$$Benefit_{pro} = \sum_i \Delta Yield_i \times \beta_i \quad (13)$$

where the $Benefit_{pro}$ denotes the net production benefit (CNY) attributable to yield gains under the ORR strategy. β_i is the unit net production benefit of crop (CNY per 50 kg). The data on the unit net production benefit are sourced from the National Cost and Benefit Compilation of Agricultural Products⁴⁷.

Ecosystem benefit

Ecosystem benefits are the benefits nitrogen reduction provides to the ecosystem, which are equivalent to the reduction in the cost of avoiding relevant damages.

$$Benefit_{eco} = \sum_m \Delta NL_m \times ECost_m \quad (14)$$

Here, m denotes the nitrogen-loss pathway, including N_2O , NH_3 , and NO_3^- . ΔNL_m is the quantity of nitrogen loss via the pathway m (kg) under the optimized scenario, and $ECost_m$ represents the monetary ecosystem benefits per unit reduction in the pathway m (CNY kg N^{-1}).

Human health benefits

Based on a cause-specific integrated exposure–response function, we obtained unit health damage costs for nitrogen emissions in China from a previous study⁴⁸. The function was established based on epidemiological data estimating the relative risk of death from exposure to air pollution (specifically fine particulate matter, PM_{2.5}) and water pollution across different regions of the world. A detailed description of the health

impacts of nitrogen pollution can be found in the World Bank report and on the Global Burden of Disease website (<http://ghdx.healthdata.org/>). The health benefits generated by the implementation of ORR are calculated according to the following formula:

$$Benefit_{hea} = \sum_m \Delta NL_m \times HCost_m \quad (15)$$

where $HCost_m$ is the monetary health benefit of the m th nitrogen loss mitigation (CNY kg N⁻¹).

Climate benefit

The climate-related benefits across scenarios are calculated as the sum of the benefits from GHG reduction and the climate impacts of NH₃ reduction.

$$Benefit_{cli} = \nabla GHG \times CCost_{GHG} - (\nabla E_{NH_3} \times CCost_{NH_3}) \quad (16)$$

Where ∇GHG is the GHG emission reduction in a specific scenario (kg eqCO₂). $CCost_{GHG}$ represents the monetary climate benefit due to GHG emission mitigation, which is assumed to be the carbon price, of CNY 64.6 t eqCO₂⁻¹ ⁴⁹. $CCost_{NH_3}$ represents the monetary impact on the climate due to changes in NH₃ emission mitigation, which is associated with the cooling effect of NH₃ and NO_x on the global climate, based on previous studies⁵⁰.

Priority areas based on benefit-area curve fitting

This study used global benefit–area curves to identify priority areas for different ORR strategies⁵¹. We first calculated the composite benefit for each grid cell as follows:

$$Benefit_{net} = Benefit_{cli} + Benefit_{hea} + Benefit_{eco} + Benefit_{pro} - Cost_{OS} \quad (17)$$

In the formula, $Benefit_{net}$ denotes the net benefit of implementing an ORR strategy, calculated as the sum of production, ecosystem, health and climate benefits minus the implementation cost. First, we ranked the $Benefit_{net}$ values across all grid cells in descending order to form the sequence $(b_1, \dots, b_i, \dots, b_m)$, where b_1 and b_m are the maximum and minimum values, respectively. Under the j th grade, the cumulative percentage of $Benefit_{net}$ (Pb_j) and the corresponding cumulative percentage of grids (Pa_j) were calculated according to the following equations:

$$Pb_j = \sum_{i=1}^j b_i / NB_{total} \times 100\% \quad (18)$$

$$Pa_j = \sum_{i=1}^j a_i / A_{total} \times 100\% \quad (19)$$

where b_i is the $Benefit_{net}$ of grid cell (a_i); and a_i denotes the grid cell corresponding to b_i ; NB_{total} is the total $Benefit_{net}$ across all grid cells, and A_{total} is the total number of grid cells. Further, we constructed the ordered set $[(P_{a1}, P_{b1}) \dots (P_{ai}, P_{bi}) \dots (P_{am}, P_{bm})]$. The cumulative benefit-area curve (Pb_j) and its curve slope (k) were calculated as follows:

$$Pb_j = f(Pa_j) \quad (20)$$

$$k = f'(Pa_j) \quad (21)$$

The priority regions for ORR were classified into three areas based on the k of benefit-area curve: priority areas ($k > 2$), sub-priority areas ($1 < k \leq 2$), and non-priority areas ($k \leq 1$).

Uncertainty and robustness analyses

To quantify uncertainty and assess robustness, we performed diagnostics at both the meta-analysis and decision-output levels. We quantified heterogeneity using τ^2 and I^2 , evaluated small-study effects using Egger-type regression alongside funnel-plot inspection, and tested sensitivity via leave-one-out analyses across comparisons (Supplementary Table 4; Supplementary Figs. 7–10). To propagate meta-analysis uncertainty into scenario outputs, we implemented a study-level cluster bootstrap to generate empirical distributions of the pooled yield response and a combined GHG-reduction factor from yield-scaled CH_4 and N_2O , and recalculated NEEB for each region–crop–strategy combination by scaling yield-dependent economic and GHG-related environmental terms accordingly (Supplementary Table 5; Supplementary Table 6). We further evaluated the robustness of spatial prioritization by perturbing grid-level NEEB surfaces with multiplicative lognormal noise ($\sigma = \sqrt{\tau^2_yield}$) and repeating the benefit–area ranking and k -based zoning, summarizing the resulting variability in the area and benefit shares of priority tiers (Supplementary Figs. 11–12). Collectively, these analyses indicate that our main conclusions are qualitatively robust to heterogeneity, influential comparisons, and uncertainty propagation (Supplementary Table 4; Supplementary Tables 5–6; Supplementary Figs. 7–12).

Data availability

The gridded data on crop harvested areas and yields were sourced from Spatial Production Allocation Model⁵². The gridded data on cropland soil SOC content and bulk density were obtained from the Harmonized World Soil Database version 2.0 (<https://doi.org/10.4060/cc3823en>). Source data are provided in the Source Data file. All source data are available with this paper.

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