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Managing nitrogen to achieve sustainable food-energy-water nexus in China

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Nitrogen holds a crucial place in sustaining the food-energy-water (FEW) nexus, which underpins human society. Its importance spans food production, energy generation, and water quality preservation. Here we show that comprehensive nitrogen management strategies offer the dual benefits of satisfying China's food requirements and boosting nitrogen energy production from straw by 1 million tonnes (26%) compared to 2020. Simultaneously, these strategies could lead to a reduction of 8 million tonnes (−31%) in nitrogen fertilizer usage, a decrease of 3.8 million tonnes (−46%) in nitrogen-induced water pollution, and a halving of water consumption in agriculture, all relative to 2020 levels. These transformative changes within the FEW nexus could result in national societal gains of around US$140 billion, against a net investment of just US$8 billion. This highlights the cost-effectiveness of such strategies and their potential to support China's sustainable development goals, especially in hunger relief, clean energy, and aquatic ecosystem protection.

Food, energy, and water represent critical lifelines that underpin human well-being, societal progress, and economic resilience[1]. These sectors form the cornerstone of the United Nations sustainable development goals (SDGs), emphasizing the necessity of adequate, nutritious food for public health and food security, reliable energy for economic endeavors, and clean water for consumption, agriculture, and natural ecosystems[2,3]. The interconnectedness of these sectors is mediated through essential biogeochemical cycles, such as the nitrogen (N) cycle. Notably, N fertilizer usage is instrumental for roughly half of the global grain production[4], which fuels the supply of food and biofuels, whereas N losses from agricultural activities impact water quality[5]. Consequently, effectively managing N within the food, energy, and water nexus (FEW nexus) is pivotal for advancing global sustainability. This is particularly critical in densely populated regions like China, where substantial challenges loom over the FEW nexus, exacerbated by limited resources to sustain rapid socio-economic growth[6].

China, accounting for about 30% of the world's N fertilizer use, strives to bolster food production[7]. Between 1980 and 2020, China's grain production soared by 120%, alongside a 494% increase in chemical fertilizer use[8]. Despite these efforts, the annual grain output of 669 million tons still falls short of domestic needs by roughly 140 million tons[9]. However, the consequences of over-fertilization have precipitated significant environmental degradation. The inefficient application of N fertilizer, coupled with a low rate of straw and manure recycling, contributes to China's lagging N use efficiency (NUE) compared to other nations, leading to considerable N dispersion into the air, soil, and water[10–12]. Given China's status as one of the countries with the least per capita water resources globally[13], its water quality faces challenges, with agricultural runoff significantly exacerbating nitrate levels[14]. Addressing the challenges of food security, energy efficiency, and environmental protection necessitates a shift towards more effective N management, propelling China towards a sustainable trajectory for the FEW nexus. While existing research has mapped China's N dynamics, integrating these insights within the FEW-N framework remains less explored. Recent advancements in N management technologies, such as precision agriculture, enhanced-efficiency fertilizers, and improved manure management practices, offer possible solutions. Key obstacles include the misalignment between governance scales and biophysical realities. Overcoming these challenges necessitates a

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systematic understanding of the complex interactions within the FEW nexus and N cycles.

In this work, the Coupled Human and Natural Systems (CHANS) N budget model[15] was selected for this study due to its comprehensive ability to integrate diverse subsystems—such as cropland, livestock, industry and surface water—into a unified N budget framework, which is crucial for understanding the complex interactions within the FEW nexus. This research delves into the evolution of China's FEW nexus from 1980 to 2020, exploring and quantifying the influence of N management practices on its sustainability. We selected metrics such as the extent of cultivated land, livestock units, agricultural NUE, N fertilizer intensity, and N loss per unit of grain and meat production, alongside agricultural water use, N leaching, and runoff concentrations, as indicators of sustainability across the food, energy, and water dimensions. Furthermore, we build alternative scenarios for the FEW nexus's sustainable advancement under three Shared Socioeconomic Pathways (SSPs) from 2021 to 2060. Lastly, we project the implementation costs and societal benefits of N management at the provincial level to assess the feasibility of these measures in a context-specific manner, aiming to inform policy decisions not only within China but also in pursuit of a sustainable global future.

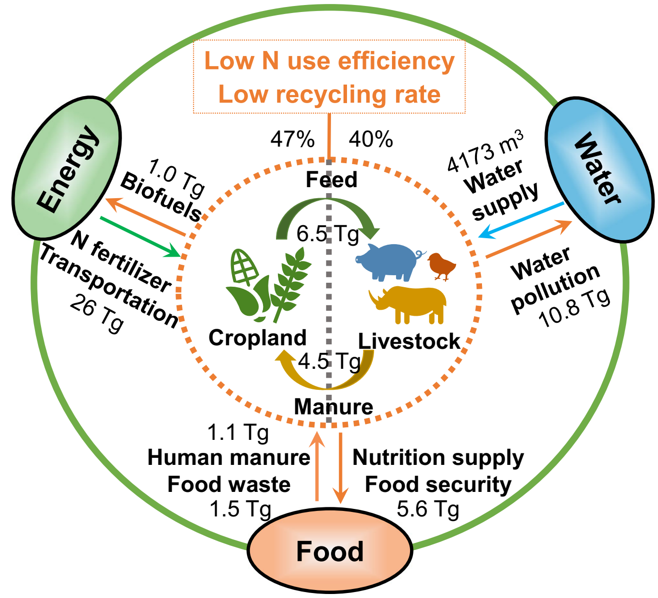

Fig. 1 | The relationships between food, energy, and water (FEW) nexus and the crop-livestock system. The figures provided reflect the actual conditions within China as of 2020, with values expressed in teragrams (Tg) denoting the nitrogen (N) fluxes. The system boundary for the FEW nexus in this study encompasses all N fluxes directly associated with the production, utilization, and management of food, energy, and water resources in China. Indirect N emissions, such as those from fossil fuel combustion in industry and transportation, are outside the primary quantified scope. Icons sourced from Microsoft Office's built-in icon library.

Results and discussion

Variation of the food-energy-water nexus

A significant challenge in modeling the FEW nexus is capturing the multifaceted interactions between human activities and natural processes. The CHANS model addresses this by explicitly incorporating feedback loops between human actions (e.g., fertilizer application, wastewater treatment) and natural responses (e.g., N emissions, leaching, and runoff). Our approach goes beyond descriptive analysis, contributes to the current knowledge frontier by providing a nuanced, systems-level understanding of N management within the FEW nexus. By integrating food security, energy use, and water pollution, which allows us to identify synergies and trade-offs that are not apparent when analyzing these sectors in isolation.

The intricate relationships among food, energy, and water can be reflected through the crop-livestock system (Fig. 1), where N cycling plays a central role in shaping these interdependencies. Nitrogen fertilizer is critical in enhancing crop yields, with energy systems supporting their production. However, the application of N fertilizer, while boosting agricultural productivity[16], often leads to significant losses due to improper use and inadequate management. These losses contribute to serious water pollution and resource waste, which disrupt the balance with the FEW nexus. Agricultural by-products such as straw are often abandoned instead of being utilized as renewable energy, further exacerbating resource wastage. The crop-livestock system's dependence on water resources is also considerable, however, N losses and the inefficient recycling of manure to cropland pollute water bodies, degrade water quality[17], and in turn, affect both energy and food production. Water inefficiencies in agricultural irrigation practices compound this issue, contributing to further wastage and increasing the pressure on already limited water supplies. In recent years, shifts in China's dietary structure—particularly the growing demand for animal-based food—have further stressed the demand for N fertilizer and water in feed production. Meanwhile, underutilized organic resources, such as human excrement and food waste, exacerbate inefficiencies in energy use. The continued reliance of fossil fuels in agriculture remains problematic, as their combustion not only releases nitrogen oxides (NO_x), polluting the air and through forming fine particulates ($PM_{2.5}$) and ground-level ozone[18], which harms crop yields, but also deposits N compounds into soil and water through atmospheric deposition, leading to nutrient imbalances and water eutrophication and biodiversity loss. The unbalanced N fluxes between the FEW systems and the crop-livestock system, and between cropland and livestock in the crop-livestock system itself, highlight the issues of low NUE and manure recycling ratio. Therefore, synergies between how to optimize N inputs to achieve high agricultural yields, minimize energy consumption associated with N production and application, and reduce N induced water pollution are key to achieving FEW sustainability.

In our analysis, we evaluated the performance of the FEW nexus at the provincial level in China for 2020 (Fig. 2a; Supplementary Fig. 1; "Method"). Our findings indicated that southern provinces like Sichuan, Chongqing, Hubei, Hunan, and Jiangxi outperform their northern counterparts in terms of sustainable development, with sustainability scores above 70. These regional differences can be attributed to a combination of factors, including variations in agricultural practices, policy implementation, and socio-economic conditions. Southern regions typically have more diversified agricultural systems, incorporating a mix of crops, aquaculture, and livestock, which promotes the full use of available resources. Moreover, southern provinces have benefited from more proactive policy implementation, including stricter environmental regulations and larger investments in sustainable technologies, supported by local governments that prioritize ecological conservation. For example, provinces like Guangdong and Jiangsu have implemented more advanced water-saving irrigation technologies and integrated nutrient management strategies than their northern counterparts. Socio-economic factors also play a significant role, southern regions generally enjoy higher levels of economic development, with a GDP (gross domestic product) per capita of at least US$10,000 (based on China's 2020 provincial-level GDP data), along with better infrastructure and greater access to markets and technology, all of which facilitate the adoption of sustainable practices. Additionally, higher educational levels, reflected in tertiary education enrollment rates exceeding 55%, and stronger environmental awareness among farmers—evidenced by investment in environmental protection of at least 0.6% of GDP—further contribute to the broader acceptance and implementation of sustainable agricultural methods. In contrast, Shanxi, which is heavily reliant on coal

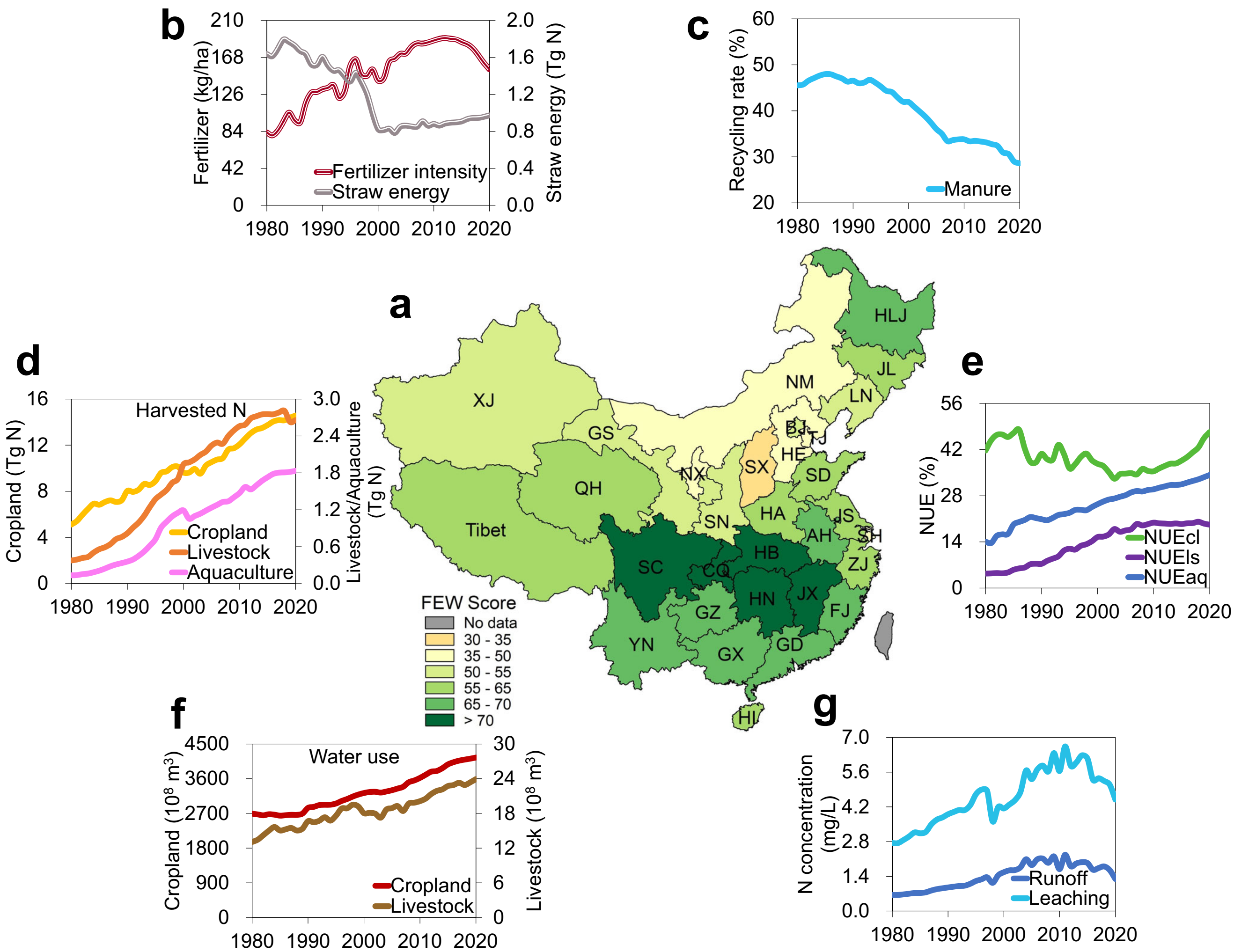

Fig. 2 | Trends in the food, energy, and water (FEW) nexus in China, 1980–2020. **a** FEW nexus scores by province in 2020, a higher nexus score indicates better performance in achieving sustainability across the food, energy, and water systems; **b** Intensity of nitrogen (N) fertilizer application on cropland and the utilization of straw for bioenergy; **c** Rate of manure recycling, encompassing both livestock manure and human excreta; **d** Nitrogen harvested from cropland, livestock, and aquaculture; **e** Nitrogen Use Efficiency (NUE) for cropland (NUE_{cl}), livestock (NUE_{ls}), and aquaculture (NUE_{aq}); **f** Use of water in agriculture, including irrigation on croplands and in livestock farming; **g** Nitrogen concentration, covering both runoff and leaching. Abbreviations for the 31 provinces, autonomous regions, and municipalities directly under the Central Government are provided in Supplementary Table 14. Basemap is from GADM.

and thermal power, lags in scores[19] due to the significant amounts of NO_x released during combustion process, contributing to air and water pollution.

From 1980 to 2020, an increase in N fertilizer application per unit of cropland was observed in China[20], paralleled by a decrease in the conversion of crop residues into energy (Fig. 2b). The growing demand for food, fiber, and feed, spurred by a rising population and changing agricultural practices[21], including an increased cultivation of vegetables and fruits[22], necessitated more N fertilizer use. The decline in converting crop residues to energy, coupled with the dropping recycling rate of manure (Fig. 2c), is largely attributed to rapid industrialization, urbanization[23], and the decoupling of crop and livestock farming[24,25], making manure recycling to cropland challenging. Additionally, the convenience of synthetic fertilizers over manure in terms of storage, transport, and application has led to a preference for synthetic options to boost crop yield and productivity[26].

The use of N fertilizer, combined with advancements in agricultural technology and supportive polices, has played a key role in the dramatic surge in China's grain production, which increased from 320 million tonnes in 1980 to 669 million tonnes in 2020, representing a 109% growth[9] (Fig. 2d). Despite recent improvements, China's cropland NUE has historically hovered around 30%, notably lower than the global average of 55%[12] (Fig. 2e). Several factors contribute to this low efficiency, including the limited capacity of crops to absorb N, long-term excessive application of N fertilizers leading to soil acidification, and improper fertilization methods, such as uneven application or missing critical growth stages. In contrast, improvements in both the production and NUE of livestock and aquaculture have been noted, due to advancements in industrial animal farming and an increase in monogastric livestock[25,27]. Additionally, the shift in dietary preferences from primarily starchy staples to a more diversified diet—incorporating more meat, dairy, fish, and poultry—has spurred the growth of animal husbandry[28]. The expansion in agricultural production in recent decades has also significantly increased the demand for water resources[29]. However, outdated irrigation technologies have resulted in persistently low water-use efficiency, causing agricultural water consumption to rise continuously (Fig. 2f). At the same time, this agricultural expansion has incurred substantial environmental costs, including coastal water eutrophication and water quality deterioration due to the escalated N fertilizer usage and intensified livestock production[22,30–32], with N concentrations in surface and groundwater increasing continuously (Fig. 2g).

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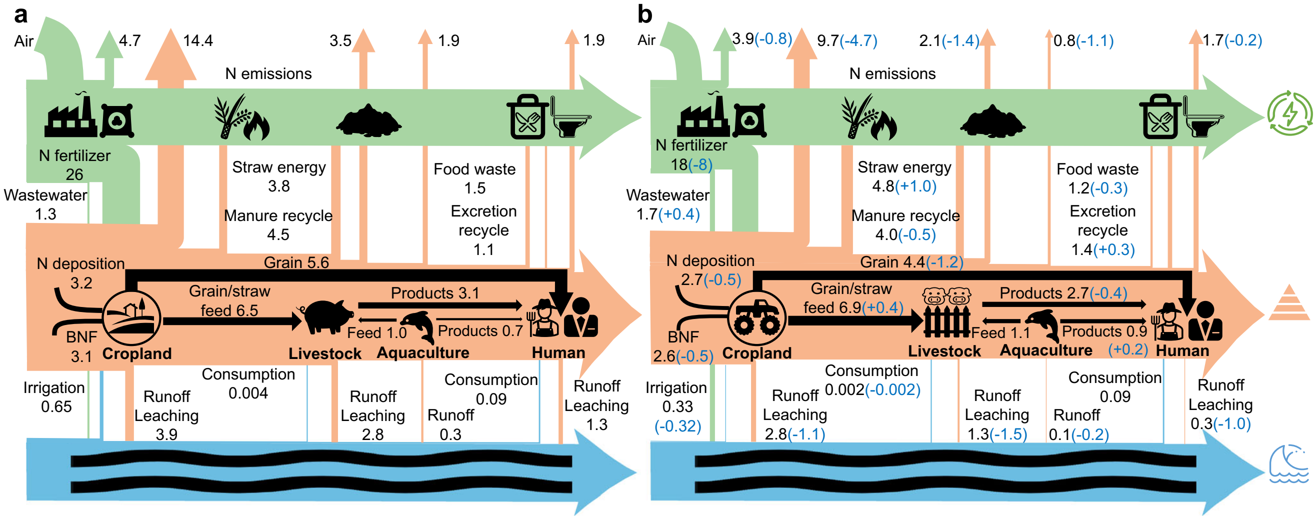

Fig. 3 | Nitrogen budget and its impact on the FEW nexus in China for 2020 and with improved N management. **a** N budget (Tg) in 2020; **b** N budget (Tg) under N management in 2020, with enhanced nitrogen management practices. The FEW (food, energy, and water) nexus is detailed through the Coupled Human and Natural Systems (CHANS) framework, incorporating subsystems as follows: the food system encompasses cropland, livestock, aquaculture, and human subsystems; the energy system is made up of industry, wastewater treatment plants (WWTPs), cropland, livestock, and human subsystems; while the water system comprises surface and groundwater subsystems. The diagram uses colored lines to illustrate nitrogen flows out of these systems: green for energy, orange for food, and blue for water. Internal nitrogen cycling within the food system is marked by black arrows. Red numbers with plus or minus signs depict the variation in N fluxes within the FEW nexus between 2020 and following the implementation of nitrogen management strategies. Icons sourced from Microsoft Office's built-in icon library.

Nitrogen management for food-energy-water nexus

In response to shifting dietary preferences, China is poised to enhance aquaculture while scaling back on crop and livestock production. This shift could lead to a 21% reduction in China's grain output (Fig. 3), primarily due to the decrease in projected cultivated areas. On the one hand, adjusting dietary structures could reduce human demand for grain, which in turn leads to a decrease in cultivated land. On the other hand, China is a typical example of excessive fertilization, where the overuse of fertilizers has not resulted in the expected yield increase[33], and in some cases, it has even stabilized or declined. Thus, grain yields could be increased by adopting better cropland management practices—such as the 4R nutrient stewardship (right source, right rate, right time and right place), along with optimal irrigation and tillage—with reduced fertilizer application per unit area, further decreasing the cultivated area. This reduction in cultivated land could also directly result in a 16% decrease in both N deposition and biological nitrogen fixation (BNF) inputs to croplands. Furthermore, a reduction in livestock farming, alongside improved manure management practices, would lead to a diminished total volume of manure recycled, despite an uptick in the overall manure recycling rate. Expanding wastewater treatment capabilities is pivotal in mitigating the direct release of rural wastewater into surface water. Additionally, curtailing food wastage would not only conserve economic resources but also bolster food security and alleviates the strain on waste management systems from food waste[34].

Incorporating these N management strategies into the CHANS N budget model (Supplementary Method 1 and Supplementary Table 1), we projected alterations in China's FEW nexus N budget for 2020. These strategies are forecasted to slash N losses to both air (NH_3, NO_x, N_2O, and N_2) and water (surface runoff and groundwater leaching) by 8.2 Tg (31%) and 3.8 Tg (46%), respectively (Fig. 3). Such interventions are expected to diminish N fertilizer application to Chinese croplands by 8 Tg (31%), while still satisfying the population's dietary requirements, and elevate agricultural NUE across cropland, livestock, and aquaculture from 28% to 36%. Moreover, these measures are anticipated to augment straw-based energy production by 1 Tg (26%) and halve irrigation water consumption, thereby harmonizing N fluxes between the energy and food systems under N management.

To evaluate the impact of N management on the sustainable development of the FEW nexus, we developed sustainability indicators for food, energy, and water, with detailed provincial performance for 2020 available in Supplementary Fig. 2. Notable reductions were observed in provinces like Sichuan and Hainan, which have high per capita grain and meat consumption[8], at 45% and 53%, respectively (Fig. 4a, b). In economically affluent provinces such as Guangdong and Beijing, where food consumption heavily relies on imports with minimal local production, shifting agricultural production due to dietary changes necessitates an expansion in local grain cultivation and a reduction in livestock product imports.

The reductions in N fertilizer application intensity, which range from 2% to 52% across various provinces (average 15%) (Fig. 4d), are the result of several key factors, including advancements in precision agriculture, targeted policy interventions, and shifts in farmer behavior. For example, significant investments have been made in precision agriculture technologies in Jiangsu and Zhejiang. These include soil testing, variable rate application of fertilizers, and the use of drones and sensors to monitor crop health and nutrient needs. These technologies allow farmers to apply fertilizers more efficiently, reducing the overall quantity needed without compromising crop yields. Provinces like Sichuan and Hunan have benefited from strong government support for sustainable farming practices. Policies such as subsidies for environmentally friendly fertilizers, training programs on sustainable farming, and strict regulations on fertilizer use have played a crucial role in encouraging farmers to reduce their reliance on chemical fertilizers. For example, the "Zero Growth Action Plan for Fertilizer Use" policy has been particularly effective in driving down fertilizer application rates in these regions. Farmers in provinces like Shandong and Anhui have voluntarily integrated manure and compost into their farming systems, which not only improves soil health but also reduces the need for synthetic fertilizers. Additionally, peer-to-peer learning and community-led initiatives have helped spread best practices across farming communities. This decrease in N fertilizer usage, coupled with other mitigation efforts, has the potential to decrease energy losses in crop and livestock production by 8–42% (average 27%) and 8–48% (average 30%), respectively (Fig. 4e, f), while boosting agricultural NUE by 9% to 64% (average 32%) (Fig. 4c).

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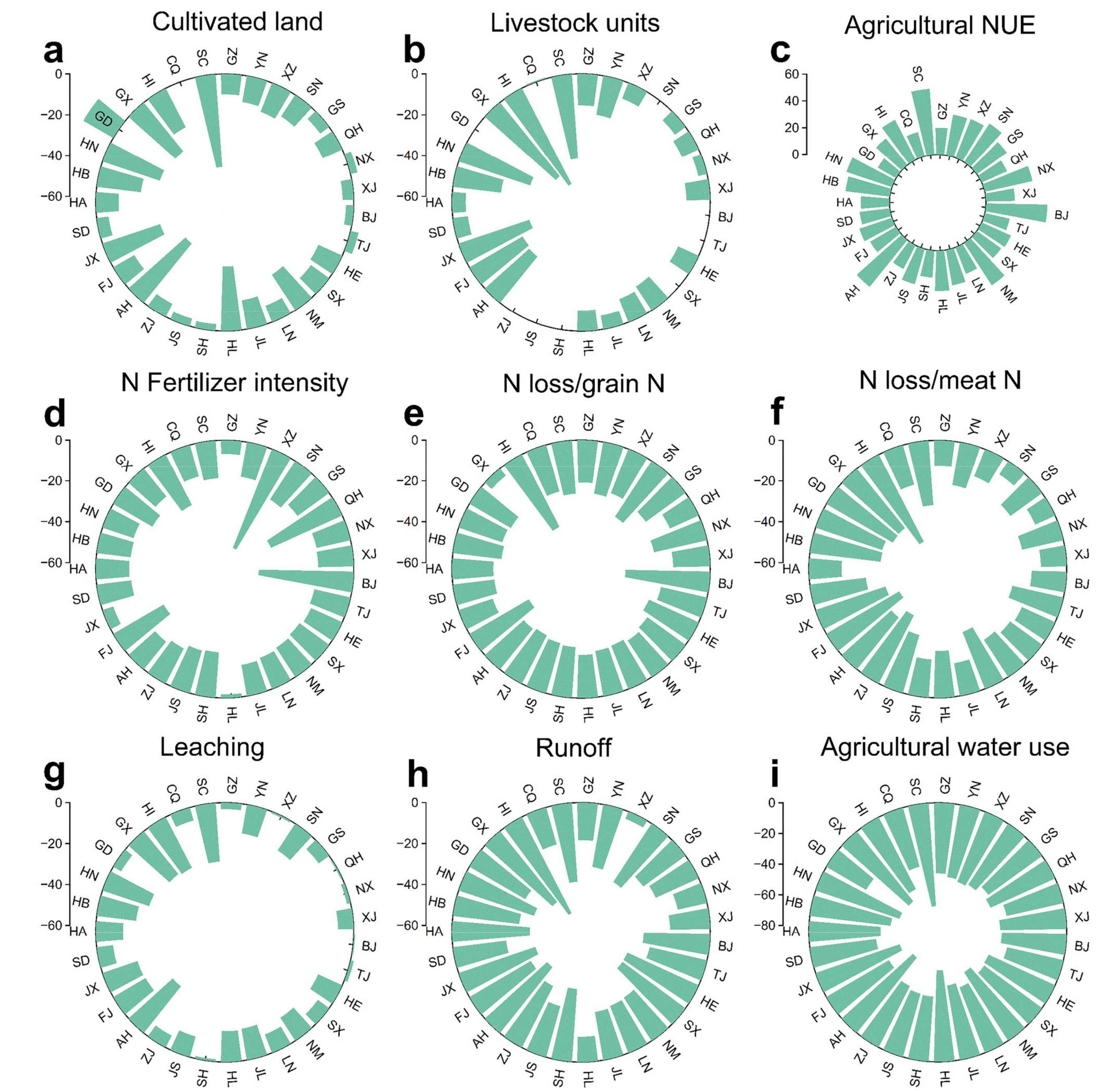

Fig. 4 | Impact of nitrogen management on sustainability of the food, energy, and water nexus across China's provinces in 2020. a Total cultivated area; **b** Livestock units, specifically swine; **c** Agricultural Nitrogen Use Efficiency (NUE); **d** Intensity of nitrogen fertilizer application on croplands; **e** Nitrogen loss per unit of grain produced; **f** Nitrogen loss per unit of meat produced; **g** Nitrogen concentration in groundwater; **h** Nitrogen concentration in surface water; **i** Agricultural water use. The impacts are determined by calculating the percentage difference between the actual values in 2020 and those observed under nitrogen management scenarios at the provincial level. The uncertainty ranges about the impacts of N management on the sustainability of the FEW nexus can be found in Supplementary Table 16.

Consequently, water quality in China could benefit significantly, with N concentrations in groundwater and surface water decreasing by 1–34% (average 16%) and 5–55% (average 36%), respectively (Fig. 4g, h). Furthermore, agricultural water consumption may decrease by 30–67% (average 50%) (Fig. 4i).

Implementation of measures towards 2060

To conduct a quantitative analysis of the future dynamics within China's FEW nexus, this study incorporates projected shifts in population and urbanization levels based on the SSPs, detailed in Supplementary Table 8. The year 2060 is chosen as the analysis endpoint, aligning with China's commitment to carbon neutrality[35], a milestone expected to influence the FEW nexus significantly. The scenarios explored include SSP1 (opting for a sustainable path), SSP2 (maintaining the status quo), and SSP5 (prioritizing rapid economic growth), with incorporation of a spectrum of according N optimization strategies from comprehensive to minimal (Supplementary Table 9). SSP1, marked by an advanced urbanization rate and the smallest population forecast for China by 2060, shifts emphasis from mere economic expansion to a broader focus on enhancing human well-being, thereby profoundly benefiting the FEW nexus through rigorous N management. Conversely, SSP5 embodies a high-consumption, energy-intensive model reliant on

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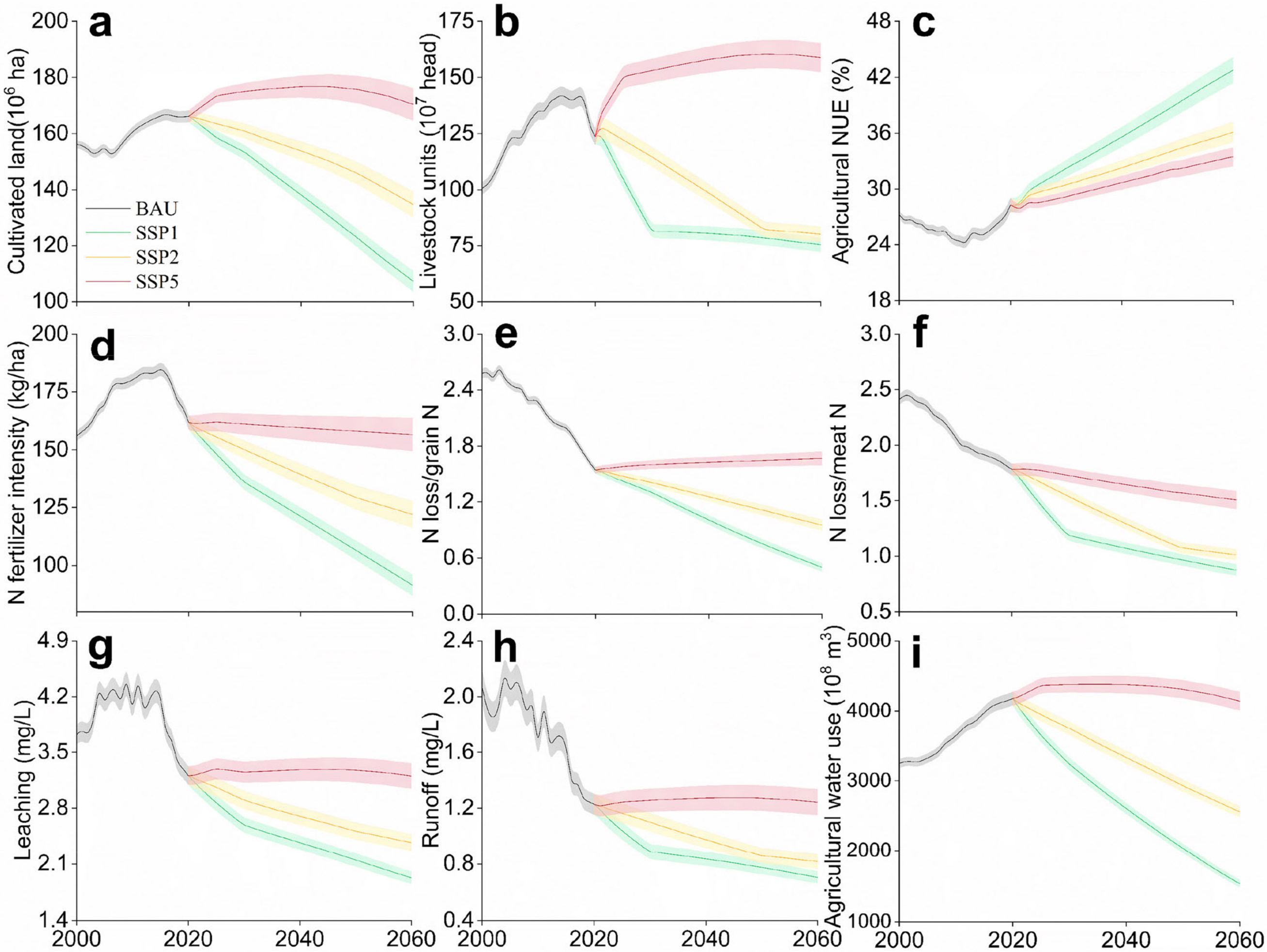

Fig. 5 | Trends of the FEW Nexus in response to N management under SSP scenarios by 2060. **a** Changes in total area cultivated; **b** Variations in pig population density; **c** Improvements in Agricultural Nitrogen Use Efficiency (NUE); **d** Adjustments in nitrogen fertilizer application intensity; **e** Reductions in nitrogen loss per unit of grain produced; **f** Decreases in nitrogen loss per unit of meat produced; **g** Alterations in nitrogen concentration in groundwater; **h** Modifications in nitrogen concentration in surface water; **i** Shifts in agricultural water consumption. The shaded areas behind each line represent the range of uncertainty. Values are generated through simulations using the CHANS model, with BAU denoting the "business as usual" scenario.

extensive fossil fuel use, achieving notable economic gains at the expense of severe environmental degradation with little N management. SSP2 serves as a middle ground, where economic, social, and technological developments proceed along historical trends, with moderate adjustments in population and environmental management practices on N and FEW nexus. More details on N management settings for FEW nexus under different SSPs following China's future sustainable strategies could be found in Supplementary Table 9.

The projections for 2060 under these diverse SSP scenarios highlight varying impacts on agricultural land use and livestock management, with changes ranging from a 35% decrease to a 3% increase in cultivated areas and a 39% reduction to a 28% increase in livestock units (Fig. 5a, b). Notably, SSP1 and SSP2 are anticipated to achieve significant declines in N loss per unit of grain and meat, alongside improvements in irrigation efficiency, leading to reduced agricultural water consumption (Fig. 5d, f, i). These adjustments could contribute to notable improvements in water quality, evidenced by a decrease in N leaching by 26% and 40% for SSP1 and SSP2, respectively, and a reduction in N runoff by 33% and 43%, respectively (Fig. 5g, h). In contrast, SSP5 suggests a stable or mildly decreasing trend in performance indicators related to energy and water management. Despite the variations in assumed development trajectories, all SSP scenarios predict an improvement in agricultural NUE, with increases ranging from 18% to 51% (Fig. 5c), underscoring the potential for enhanced sustainability across different future paths. Also, the details of uncertainty analysis can be found in Supplementary Tables 10 and 11.

Costs and benefits

To enhance N management for FEW nexus across China in 2020, the net expenditure for considering adjustments in labor, materials, and services amounted to 8 billion United States Dollar (USD) (Fig. 6). It is critical to underscore the considerable net gains derived from reductions in fertilizer consumption, agricultural water use, and food imports, which are estimated at 14 billion USD. These savings primarily emerge from diminished food imports, attributable to dietary modifications and a decrease in food wastage.

The comprehensive economic advantage to the nation from improved N management—encompassing savings on fertilizers, the generation of straw energy, benefits to human health, ecosystem preservation, and climate change mitigation, alongside the reduced expenditures on water use and food imports—approximates to a sum 18 times greater than the implementation costs, reaching 140 billion USD. Notably, the dividends of enhanced N management disproportionately favor the central and coastal provinces of China (Fig. 6), with the former enjoying considerable environmental and health benefits, and the latter seeing reductions in costs linked to

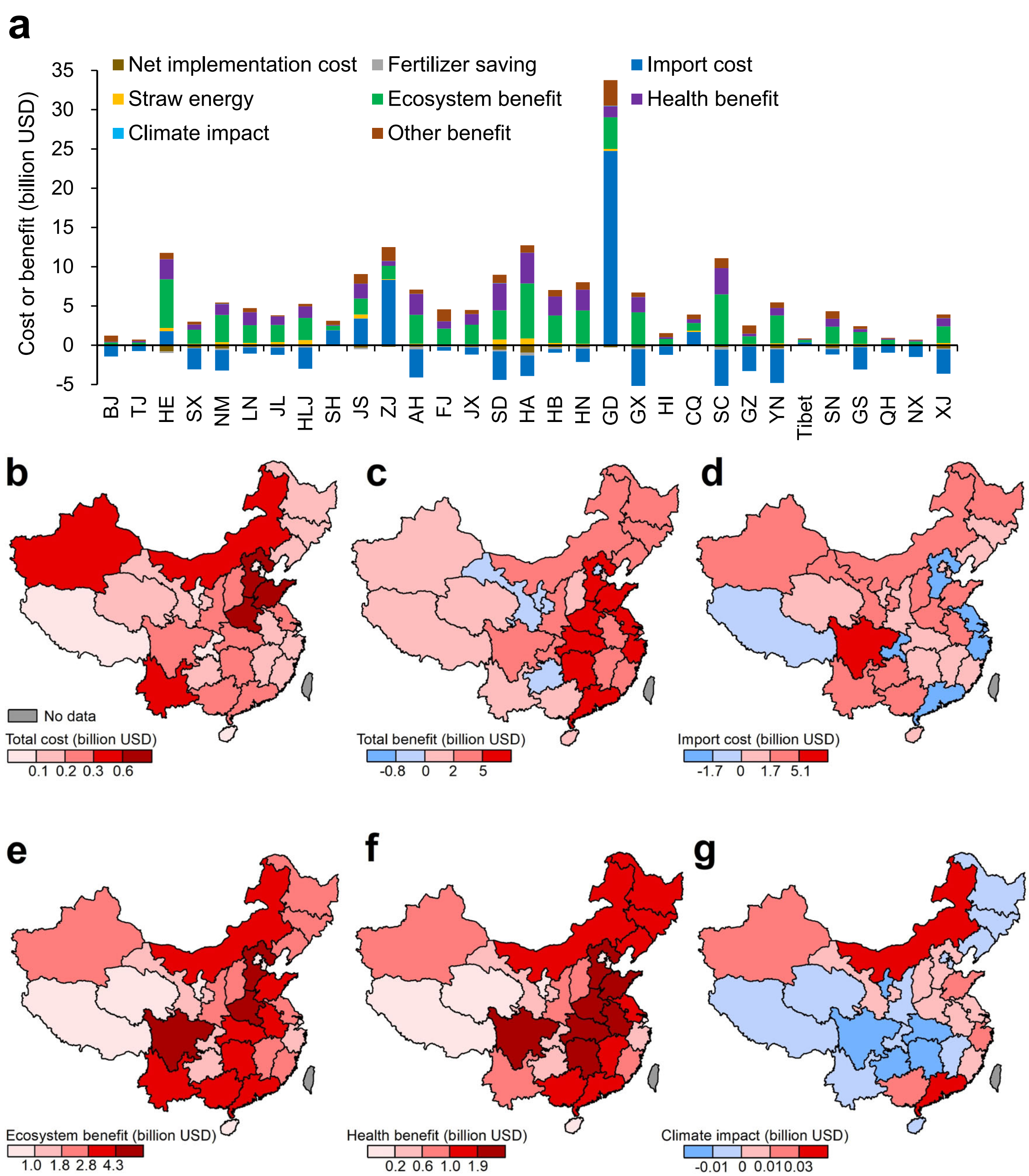

Fig. 6 | Costs and benefits of implementing N management measures in 2020. **a** Distribution of total costs and benefits across provinces under nitrogen management, where negative values indicate costs and positive values denote benefits; **b** Aggregate cost of implementing nitrogen management measures; **c** Total accrued benefits from nitrogen management; **d** Savings on import costs attributable to dietary shifts and reduced food waste; **e** Benefits to ecosystems resulting from improved nitrogen management; **f** Health benefits derived from reduced pollution and improved environmental quality; **g** Impact on climate through changes in greenhouse gas emissions. Fertilizer savings reflect the cost reduction from enhanced agricultural Nitrogen Use Efficiency (NUE) and increased rates of manure recycling. Import cost savings emerge from changes in food consumption patterns and minimized food wastage. The uncertainty of the costs and benefits can be found in Supplementary Figs. 6–7. Basemaps are from GADM.

excess food consumption and waste, thereby curtailing food import costs. Moreover, the valorization of straw for energy, contributing an additional 7 billion USD, predominantly benefits the northeastern provinces, known for their extensive soybean cultivation. Furthermore, a decrease in agricultural land and livestock production, along with advancements in irrigation efficiency, have led to savings in water usage costs.

Beyond the savings from fertilizer, food, and water consumption, and the amplified use of straw as an energy source, about 40 billion USD of the benefits are attributed to a decline in premature mortality rates, especially from respiratory conditions exacerbated by $PM_{2.5}$ pollution. An additional 78 billion USD in benefits is derived from diminished impacts on ecosystem services, such as the loss of recreational areas and property devaluation due to eutrophication. However, the financial impact related to climate change is relatively minor in comparison, pegged at merely 0.1 billion USD. Our findings also suggest that cutting N emissions in certain regions might inadvertently amplify global warming, as reduced NH_3 emissions from cropland diminish atmospheric N deposition, which in turn lowers carbon sequestration in natural ecosystems[36]. Despite this, the overwhelmingly positive benefit-cost ratio strongly advocates for the adoption of these N management strategies.

Perspectives and policy implications

To enhance the sustainability of China's FEW nexus through improved N management, it is imperative to develop a policy framework grounded in the insights derived from previous analyses. This framework must encompass strategic N management, leverage cost-benefit analysis to guide investments, and ensure synergy within the FEW nexus for optimized outcomes. Reflecting on the key findings from the refined content, the following policy recommendations offer a tailored approach:

Implementation of N management. These N management measures were ranked based on criteria such as effectiveness, cost-efficiency (Supplementary Figs. 3 and 4). Based on this ranking, policy should prioritize the following actions: first, promote dietary shifts and reduce food waste through nationwide campaigns that encourage healthier diets and minimize food waste at all levels, which have the highest benefit among all N management measures. Here, we assume that promoting dietary shifts and reducing food waste have no direct technical costs, although this option may entail substantial implementation costs related to public awareness campaigns, behavioral change efforts, and monitoring. Second, optimize N fertilizer application, increase manure recycling, and improve sewage treatment by providing training programs for farmers on precision agriculture, supporting advanced manure treatment technologies, and upgrading sewage infrastructure with financial incentives and public-private partnerships. While these measures require more investment, they are essential for reducing N pollution and have the most significant effect in achieving the sustainability of FEW nexus, which needs to be implemented immediately. Third, improve irrigation efficiency and enforce zero straw burning by incentivizing water-saving technologies and alternative straw disposal methods through subsidies and training programs. Although their N-related benefits are modest and their contribution to the FEW sustainability is relatively small, these measures entail considerable co-benefits in terms of public health, such as reducing air pollution, which are essential to implement and can be effectively carried out by farmers with proper government support and guidance. Finally, policies should be tailored to regional conditions by developing localized strategies that reflect the unique agricultural practices and environmental challenges, ensuring the most effective outcomes for FEW nexus sustainability.

Promoting FEW nexus synergies with N management. The seven N management measures proposed in this study are closely aligned with several policies released by China in recent years, such as the "Zero Growth Action Plan for Fertilizer Use," the "Regulations on the Prevention and Control of Pollution from Animal Husbandry," the "Rural Living Environment Improvement Action Plan," and the "Water-Saving Society Construction Plan." These policies emphasize the scientific validity and feasibility of the measures to promote FEW nexus synergies with N management. Specifically, optimizing N fertilizer application, increasing manure recycling, and adjusting dietary structure demonstrate significant sustainable development benefits across the FEW nexus. Optimizing N fertilizer application ensures food security while reducing energy consumption in fertilizer production and mitigating water pollution caused by N loss. Increasing manure recycling promotes the efficient use of manure resources, enhances soil fertility and crop quality, and reduces energy waste and environmental burden. Adjusting dietary structure helps alleviate agricultural resource pressure by reducing demand for resource-intensive agricultural products, thereby lowering energy consumption and pollution emissions in production. Additionally, reducing food waste, achieving zero straw burning, and improving irrigation efficiency focus on the effective utilization of existing resources, which helps address energy shortages. Enhancing wastewater treatment rates can significantly improve water quality. Of course, the role of digital innovations in improving the sustainability and resilience of agricultural systems in China cannot be ignored[37], particularly in economically developed regions. Technologies such as remote sensing, which enable efficient crop monitoring and pest prediction, and precision agriculture, which optimizes fertilization and irrigation to significantly reduce resource waste, are gradually being adopted. However, these advancements face challenges due to the unique characteristics of agricultural production in China and the limited economic capacity of farmers, especially in central and western regions where infrastructure, financial support, and technical training are lacking. To further promote these technologies, government policy support and financial subsidies will be necessary[38].

Economic justification for N Management. Draw upon detailed cost-benefit analysis to substantiate the economic viability and environmental necessity of transitioning towards sustainable N management. The analysis has highlighted an 18-fold return on investment, emphasizing substantial national benefits, including savings from reduced fertilizer use, lower agricultural water consumption, and diminished food imports. This underscores the economic efficiency of improved N management, justifying government and private sector investment in such initiatives. Policies should facilitate access to funding for research into sustainable N practices and technologies, and establish economic incentives for stakeholders across the FEW nexus to adopt N-efficient solutions. Moreover, the government could explore public-private partnerships to fund large-scale infrastructure projects that support sustainable N and waste management.

Potential barriers of N management. China's N management faces complex interconnected challenges across technical, economic, and social dimensions. At the farm level, the implementation of precision fertilization and manure recycling is hampered by limited access to advanced technology and high initial investment costs, particularly affecting small-scale farmers. The agricultural sector's fragmented nature and underdeveloped industrial support systems further complicate the adoption of sustainable practices. Regional disparities compound these difficulties, as inconsistent policy enforcement and varying levels of infrastructure development—especially in wastewater treatment and irrigation—lead to uneven implementation outcomes across different areas. Societal barriers present another significant challenge. Farmers often lack awareness of and training in new management techniques, while public understanding of sustainable dietary choices remains limited. Traditional practices persist despite environmental concerns, and efforts to reduce food waste face cultural resistance. The market for organic fertilizers remains underdeveloped, reflecting broader structural challenges in transforming agricultural practices. To address these challenges effectively, China requires a comprehensive approach that includes: strengthening technological research and knowledge transfer, developing targeted economic incentives, enhancing farmer education programs, and creating region-specific implementation strategies. Success will depend on coordinating the interests of various stakeholders while acknowledging local conditions and constraints.

By adhering to these strategic recommendations, China can effectively navigate the complexities of sustainable N management within the FEW nexus, leveraging both the environmental and economic benefits identified through rigorous analysis. Many global regions experience issues related to N pollution and inefficient resource use. The integration of the N cycle within the FEW nexus, as demonstrated in this study, highlights the interconnected nature of these challenges and the need for holistic, cross-sectoral approaches. This perspective encourages countries to adopt integrated management practices that consider the full spectrum of environmental, economic, and social impacts.

Methods

Data sources

The data involved in the study can be divided into two categories: (i) socioeconomic information such as crop/livestock production,

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population and sewage discharge were obtained from the following authoritative sources: the National Bureau of Statistics of China, the China Statistical Yearbook[8], the China Statistical Yearbook on Environment[39], the China City Statistical Yearbook[40], the China Rural Statistical Yearbook[41], the China Industry Statistical Yearbook[42], the China Population & Employment Statistics Yearbook[43], the China Fishery Statistical Yearbook[44] and the China Forestry and Grassland Yearbook[45]. In addition, the future population and urbanization rate towards 2060 of SSPs were obtained from Huang et al.[46]; (ii) coefficients and parameters used for the calculation of N fluxes such as N concentrations in grain and straw or the rate of BNF were mainly taken from the synthesis of peer-reviewed literature and field measurements. The most important coefficients and parameters can be found in Gu et al.[15] and Zhang et al.[47]

Shared socioeconomic pathways (SSPs)

SSPs describe pathways for global socioeconomic development, encompassing factors such as population growth, economic development, energy demand, technological progress, and land use change. SSPs provide a framework for the socioeconomic context of climate change without directly addressing greenhouse gas concentrations or radiative forcing. They outline potential human development trajectories under varying social, economic, and environmental policy scenarios, divided into five distinct pathways: SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-Fueled Development), representing a range from sustainable development (SSP1) to high-carbon growth (SSP5). This study uses population and urbanization data from three scenarios—SSP1, SSP2, and SSP5—integrated with N management measures of varying intensity (Supplementary Table 9). For example, by 2060, NUE is projected to increase by 40%, 20%, and 0% under SSP1, SSP2, and SSP5, respectively, compared to 2020. Additionally, dietary structure in SSP1 and SSP2 is expected to align with the Chinese Dietary Guidelines by 2030 and 2050, respectively, while SSP5 assumes no dietary change, remaining above dietary guideline standards. More details on these assumptions are provided in Supplementary Table 9. Through these analyses, the study explores the impact of N management on the sustainable development of FEW nexus.

Nitrogen budget

The CHANS model was used in this study to estimate the national N budget. CHANS is a mass balance model with a N focus, consisting of 14 subsystems (Cropland, Forestland, Grassland, Industry, Livestock, Aquaculture, Urban Greenland, Human, Pets, Wastewater treatment plants, Solid waste treatment, Surface water, Groundwater and Atmosphere), which combines N input and output fluxes across the 14 subsystems to provide a comprehensive understanding of the overall N budget in this paper. By firmly restricting interactions between subsystems, the CHANS model can estimate the N fluxes of 14 subsystems and lower the calculation's uncertainty. The CHANS model was calibrated using data from various authoritative sources such as the National Bureau of Statistics of China and validated by comparing model outputs with observed N fluxes reported in peer-reviewed literature and field measurements from 1980 to 2020. The model parameters were adjusted iteratively to minimize discrepancies between simulated and observed data, ensuring the model accurately reflects N dynamics across the 14 subsystems involved. The principle of the CHANS model is the mass balance of the whole system and each subsystem, shown as Eq. (1):

$$\sum_{h=1}^{m} IN_h = \sum_{g=1}^{n} OUT_g + \sum_{k=1}^{p} ACC_k \tag{1}$$

where IN (Tg) and OUT (Tg) represent the total N input (e.g., fertilizer, feed, wastewater) and N output (e.g., grain yields, runoff, NH_3 and N_2O) respectively, and ACC (Tg) represents N accumulation that is calculated as the difference of inputs and outputs. If there is N flow from one subsystem to another, the flux in the two related subsystems should be equal. This was used to constrain the estimation of N fluxes. A simplified version of the CHANS can be downloaded for free at https://person.zju.edu.cn/en/bjgu. More details can be found in Supplementary Method 2–8.

However, a key limitation of the CHANS model is its reliance on available data, which may not fully capture the spatial and temporal variability of N flows and their regional impacts. Additionally, the model may oversimplify certain feedback loops and nonlinear interactions within the FEW nexus, leading to uncertainties in its predictions. Assumptions, such as fixed technical efficiency or a static policy environment, also limit the model's ability to accurately project future scenarios under changing conditions. Moreover, while the CHANS model integrates multiple sectors, it may not sufficiently account for socioeconomic factors such as market dynamics, behavioral changes, or governance structures that play a crucial role in N management decisions. Acknowledging these limitations is crucial for interpreting the results and for guiding future research that aims to refine and expand the model to better capture the complexities of N management within the FEW nexus.

The baseline of N budget in 2020 was built first, then the SSP scenarios with corresponding parameters adjusting were integrated into CHANS model to forecast the N budget from 2021 to 2060. Total population, urbanization rate and dietary structure are the key parameters influencing the N budgets of SSP scenarios. Details about the data and parameters can be found in Supplementary Tables 8 and 9.

Spatial distribution of food-energy-water performances in 2020

We first constructed potential link between SDGs and the FEW nexus by performing a keyword search in the existing literature. The keywords for each SDG were compared to different keywords related to "food security", "clean energy" or "water pollution" to cover potentially relevant academic literature. In addition, keywords such as "China" or "Chinese FEW" were added to the query, so the literature review is made specific to the national or regional context. In the case where no specific information is found, information is then extrapolated from global studies. Ultimately, we identified 7 of the 17 SDGs as being directly related to FEW nexus. These SDGs encompass Zero Hunger (SDG 2), Good Health and Well-being (SDG 3), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG 7), Industry, Innovation and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), and Life Below Water (SDG 14), the details can be found in Supplementary Table 12.

The arithmetic mean of the SDG scores within each system was used to represent the performance of the sustainability of the FEW nexus at the provincial scale in China. It is important to note that the SDG scores discussed in our paper are distinct from generally published scores by the difference in indicator system and the number of SDGs considered. For the score of each SDG, we estimated it at the national and provincial levels by using the arithmetic mean of the normalized values of N indicators (Supplementary Table 13) we established for that SDG based on the methodology of the 2018 SDG Index and Dashboards[48]. While for the N indicators of each SDG, we first reviewed indicators from a combination of the published articles, the United Nations' official list of global SDG indicators[49], the 2018 SDG Index and Dashboards Report[48], the report of the United Nations titled "Indicators and a Monitoring Framework for the SDGs"[50] to extract some referenceable indicators that can be adjusted, such as replacing indicators like CO_2 emission per unit of value added with amount of fuel NO_x emissions per gross industrial product per year. For SDGs without referenceable indicators, we selected N indicators based on specific targets of SDGs in conjunction with the N fluxes of the 14 subsystems in the CHANS that align with the theme. This led to situations where some specific indicators of SDGs could correspond to multiple N indicators (such as 6.3.2, Proportion of bodies of water with good ambient water quality), while some specific indicators have few. Additionally, there were N indicators that simultaneously corresponded to specific indicators in different SDGs (such as the amount of discharged N admitted per unit water flow). For each SDG, we generalized as many indicators as possible based on data availability and relevance, either as single N fluxes (e.g., N deposition) or by corresponding calculations between several N fluxes (e.g., NUE). The calculation of several scores is shown from Eq. (2) to Eq. (4).

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \times 100 \tag{2}$$

where x is the original data value of each N indicator, max/min represents the upper/lower bounds for the best/worst performance (Supplementary Table 13), and x' is the normalized indicator value (also referred to as normalized indicator score) for a given indicator. All normalized values that exceeded the upper bound scored 100, and all normalized values that that below the lower bound scored 0. The range of values from the worst performance (score 0) to the best performance (score 100) was distributed between the upper and lower boundaries.

$$Score_{SDG,j} = \overline{\sum_{i=1}^{m} x'_i} \tag{3}$$

where x'_i is the ith normalized indicator score of the jth SDG, m represents the number of indicators for that SDG, $Score_{SDG,j}$ refers to the score of jth SDG.

$$Score_{FEW} = \overline{\sum_{j=1}^{7} Score_{SDG,j}} \tag{4}$$

where $Score_{FEW}$ refers to the score of FEW nexus, seven SDGs have been identified as directly relevant to FEW nexus.

Choice of upper and lower bounds: the upper and lower bounds for each indicator were determined based on a combination of historical data, literature benchmarks, and expert judgment. Specifically, upper bound (max(x)) represents the best possible performance observed in the dataset or the maximum target level defined by international or national standards. For example, the upper bound of the dietary structure was set at 40% of the recommended value of the Chinese Dietary Guidelines. While lower bound (min(x)) represents the worst possible performance or the minimum acceptable level of performance, often based on baseline data from the least efficient or most polluting systems. For instance, the lower bound for N runoff was set at levels observed in highly polluted watersheds with poor N management practices.

Implications for SDG scores: the choice of these bounds directly influences the resulting SDG scores, as they determine the range within which the performance of each province or region is assessed. A province with a score close to the upper bound indicates that it is performing at or near the optimal level for that indicator, whereas a score near the lower bound suggests significant room for improvement. By carefully selecting these bounds based on a combination of empirical data and sustainability targets, the normalization process ensures that the SDG scores accurately reflect the relative performance of different provinces in the context of N management and its impact on the FEW nexus.

Effectiveness of N indicator systems: to verify the effectiveness of this system, we conducted a regression analysis comparing the FEW index scores for China, calculated using our N indicator system, with scores based on the UN's indicator system (both representing the average scores of 7 FEW-related SDGs). The results showed a high correlation between the two, indicating that despite using different indicator systems, the results calculated in this study are consistent with the official scores. This demonstrates the effectiveness and reliability of the indicator system used in this study for assessing FEW's performance. The results can be found in Supplementary Fig. 5.

The potential of nitrogen management on food-energy-water sustainability

We explored several measures to achieve the sustainable development of FEW nexus by improving N management based on CHANS model in 2020. Those measures are developed to reduce water pollution while safeguarding food security and human health. These measures include diet shifts, increased rate of manure recycling and wastewater treatment, optimized N fertilizer application and irrigation efficiency, zero straw burning, and reduced food waste.

Diet shifts. In China, animal-based food consumption per capita has increased ~12-fold since 1961[51], while the increasing proportion of animal protein in the diet has already exceeded the level recommended in the Chinese dietary guidelines, the preference for red meat consumption (pork, beef and sheep) at the expense of vital food like vegetables, fruits, fish and dairy has left nearly one-third of China's provinces facing a substandard diet. Based on the 2020 baseline, we assume that all provinces in China achieve a moderate level of compliance with the recommended values of the Chinese dietary guidelines. As for the SSPs, we assume that SSP1 and SSP2 reach the recommended values in 2030 and 2050, respectively, while SSP5 maintains the current development trend without alteration.

Increased manure recycling rate. In the early nineties, China exceeded the United States and Europe as the world's biggest livestock producer[52]. However, compared to the United States and European Union, China has lower livestock productivity, while experiencing relatively higher nutrient losses and greenhouse gas emissions per unit of animal protein produced. Particularly concerning is that only 1/3 of livestock manure is recycled back to cropland in China, significantly lower than the rates of 81% in the European Union and 74% in the United States[53]. At the same time, the rate of human excreta being returned to cropland is declining rapidly with the widespread use of chemical fertilizers. Building on the 2020 baseline, we assume that the recycling rate of livestock manure and rural human excreta to cropland reaches 60% in all provinces of China. However, for urban human excreta, which has a processing rate of 90%, the recycling rate remains unchanged at 5%. As for the SSPs, we project that SSP1 and SSP2 will achieve the assumed values in 2030 and 2050, respectively, while SSP5 maintains the current development trend without alteration.

Increased wastewater treatment rate. The urban wastewater treatment rate in China is 97.5% in 2020, with almost all wastewater being treated. However, owing to a lack of specific rural wastewater data, we extrapolated from established town data, resulting in a rural wastewater treatment rate of 61% in China in 2020. For our analysis, we assume that by 2020, 100% of urban wastewater and 60% of rural wastewater across 31 provinces in China will be integrated into wastewater systems, with nutrient N removal during treatment at the current level. As for the SSPs, we assume that SSP1 and SSP2 will attain the assumed values by 2030 and 2050, respectively, while SSP5 will maintain its existing development trajectory without alteration.

Optimized N fertilizer application. Based on the 2020 baseline, we hypothesize that China optimizes crop fertilization by integrating N fertilizer management measures with increased rates of manure recycling (both human and livestock) to croplands, which safeguards grain output while reducing environmental pollution. As for the SSPs, we assume that the N fertilizer use efficiency of SSP1 and SSP2 will increase by 40% and 20%, respectively, by 2060, while SSP5 will maintain the current development trend without alteration.

Optimized irrigation efficiency. Based on the 2020 baseline, we assume that China improves the efficiency of irrigation water use by adopting advanced irrigation technologies and methods, and enhanced irrigation management practices. As for the SSPs, we assume

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that the irrigation use efficiency of SSP1 and SSP2 will increase by 40% and 20%, respectively, by 2060. Conversely, SSP5 is assumed to maintain the current development trend without alteration.

Zero straw burning. China is a country with abundant straw resources[54]. However, straw, as a bioenergy source, has long been removed from the cropland or openly burned in our country, causing environmental pollution and wasting resources. Here, based on the 2020 baseline, we assume that China adopt a zero straw burning policy, facilitating the conversion of more straw into energy and industrial raw materials, thereby achieving energy recycling. As for the SSPs, we assume that SSP1 and SSP2 will achieve zero straw burning by 2030 and 2050, respectively, while SSP5 will maintain the current development trend without alteration.

Reduced food waste. Surveys conducted in China show that 27% of the food produced annually for human consumption (~349 Mt) is lost or wasted[55]. Here, based on the 2020 baseline, we assume that under dietary restructuring, China will reduce food waste by 20% through the implementation of mitigation strategies such as improving technology, increasing awareness, and altering cooking styles. As for the SSPs, we assume that SSP1 and SSP2 will achieve a 20% reduction in food waste by 2030 and 2050, respectively, while SSP5 will maintain the current development trend without alteration.

Nine indicators of food-energy-water nexus

Based on the N fluxes of cropland, livestock, aquaculture, groundwater, and surface water subsystems in the CHANS model for 2020, benchmarked against key contemporary issues in China's food, energy, and water sectors, such as food security, energy-efficient utilization, and water pollution, and combining with the availability and relevance of the data, we have summarized the indicators as accurately as possible for each aspect. These indicators include both single values (e.g., agricultural water use) and corresponding calculations derived from multiple N fluxes (e.g., agricultural NUE). Finally, we constructed a systematic framework of three indicators for each system, resulting in a total of nine indicators to characterize FEW nexus.

Food system. Indicators included in the food system are cultivated land, livestock units (LU), and agricultural NUE (NUE_{ag}). Of those, cultivated land includes all areas including cereals, beans, tubers, oil crops, sugar crops, vegetables, fruits, and other crops. The calculation of the other two indicators for province *i* is formulated as Eq. (5):

$$\mathrm{LU}_i = \sum_{h=1}^{m} Stock_h + \sum_{g=1}^{n} Output_g \tag{5}$$

Where *Stock* (10^4 head) and *Output* (10^4 head) represent the total stock of milk-producing and egg-producing livestock (*h*) (e.g., dairy cattle and layer chicken) and total output of meat-producing livestock (*g*) (e.g., swine, beef cattle, goat/sheep, and poultry). All numbers are converted to pig units when comparing animal numbers: 1 dairy cattle = 10 pigs; 1 beef cattle = 5 pigs; 3 sheep/goats = 1 pig; 15 layer chickens = 1 pig; 60 broiler chickens = 1 pig.

Agricultural NUE, including cropland, livestock, and aquaculture subsystems, is defined as the ratio of harvested N to total N input[56], as shown in Eq. (6):

$$\begin{aligned}\mathrm{NUE}_{ag,i}(\%) &= \frac{HarvestedN_{ag,i}}{TotalNinput_{ag,i}} \times 100 \\ &= \frac{HarvestedN_{crop,i} + HarvestedN_{ls,i} + HarvestedN_{aq,i}}{TotalNinput_{crop,i} + TotalNinput_{ls,i} + TotalNinput_{aq,i}} \times 100\end{aligned} \tag{6}$$

Where *Harvested* N_{crop} (Tg), *Harvested* N_{ls} (Tg), and *Harvested* N_{aq} (Tg) denote N harvested from cropland (grain N, feed N), livestock (edible N and industrial materials), and aquaculture subsystems (aquatic product N), respectively. Of course, feed N offered to livestock by the cropland and aquaculture subsystems, and straw recycled from the cropland are subtracted from the harvested N. While the *Total N* $input_{crop}$ (Tg), *Total N* $input_{ls}$ (Tg), and *Total N* $input_{aq}$ (Tg) represent the total N input to cropland (e.g., N fertilizer, BNF, and irrigation), livestock (e.g., grain/straw feed, fish power, and food waste), and aquaculture subsystems (e.g., N fertilizer, fish feed, and N deposition), respectively.

Energy system. Indicators included in the energy system are N fertilizer intensity (FER), N loss/grain N (LG), and N loss/meat N (LM). The calculations of the indicators for country/province *i* in this system are shown from Eq. (7) to Eq. (9):

$$\mathrm{FER}_i = \frac{N\ Fertilizer_{crop,i}}{Cultivated\ land_i} \tag{7}$$

Where FER (kg/ha) indicates fertilizer intensity (the amount of N fertilizer applied per unit cropland). *N Fertilzier*$_{crop}$ (Tg) refers to the input of N fertilizer to the cropland.

$$\mathrm{LG}_i = \frac{N\ Loss_{crop,i}}{Grain\ harvestedN_i} \tag{8}$$

Where *N loss*$_{crop}$ (Tg) denotes the total N lost in different forms during crop production, including NH_3, N_2O, NO_x, leaching and runoff. *Grain harvested N* (Tg) is the sum of the yield of each crop multiplied by their N content.

$$\mathrm{LM}_i = \frac{N\ Loss_{ls+aq,i}}{Meat\ harvested\ N_{ls+aq,i}} \tag{9}$$

Where *N loss*$_{ls+aq}$ (Tg) represents the total N lost in different forms during meat production (both livestock and aquaculture), including NH_3, N_2O, NO_x, leaching, and runoff. *Meat harvested N* (Tg) is the sum of the product of each meat multiplied by their N content.

Water system. Indicators included in the water system are N leaching concentration (Leaching), N runoff concentration (Runoff), and agricultural water use ($Water_{ag}$). The calculations of the indicators for country/province *i in this system* are shown from Eq. (10) to Eq. (12):

$$\mathrm{Leaching}_i = \frac{N\ Accumulation_i}{Groundwater\ volume_i} \tag{10}$$

Where *N Accumulation* (Tg) indicates the amount of N that accumulates in groundwater (calculated as total leaching minus the amount used for irrigation of cropland). While the *Groundwater volume* (10^8 m^3) refers to the amount of water in the ground.

$$\mathrm{Runoff}_i = \frac{N\ to\ riverine_i}{Surface\ water\ volume_i} \tag{11}$$

Where *N to riverine* (Tg) indicates the amount of N lost to surface water (calculated as total runoff minus the amount used for irrigation of cropland and volatilization). While the *Surface water volume* (10^8 m^3) refers to the amount of water on the surface.

$$\mathrm{Water}_{ag,i} = Water_{crop,i} + Water_{ls,i} \tag{12}$$

$Water_{crop}$ (10^8 m^3) and $Water_{ls}$ represent the amount of water used for crop production and livestock farming, respectively, where the amount of water used for livestock farming is calculated according to the ratio of feed to water.

Cost-benefit analysis

On the basis of the changes in N input and output fluxes for the 14 subsystems of CHANS under different management measures, the provincial N budget data are used for the cost and benefit calculation.

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Here, we define the cost of improving N management to achieve the sustainability of FEW nexus as the direct expenditure (the sum of investment costs and operation costs). In the western regions, the cost of N management measures is relatively low due to several factors. Firstly, the lower economic level and more traditional agricultural practices in these areas result in less use of fertilizers and irrigation, leading to a lower starting point for N management. Therefore, the initial costs for implementing N management measures, such as fertilizer optimization and wastewater treatment are relatively low. Additionally, lower labor costs in the western regions further reduce the overall implementation costs. However, as economic development progresses and agriculture shifts towards modernization and intensification, the complexity of N management will increase, which may lead to higher costs. The calculation of implementation cost ($IC_{i,j}$) in province i and N term j is shown as Eq. (13):

$$\mathrm{IC}_{i,j} = \Delta E_{i,j} \times UC_{i,j} \tag{13}$$

$$\Delta \mathrm{E}_{i,j} = |E_{i,j,2020} - E_{i,j,measure}| \tag{14}$$

in which $UC_{i,j,}$ represents the integrated unit implementation cost of the improvement of N management to achieve sustainable development of the FEW nexus in province i, which is derived from the online GAINS model database and statistical yearbook and adjusted for differences between provinces. Further details can be found in Supplementary Table 14. This study has not explicitly considered the crop-specific impacts of reduced straw burning in China due to data limitations. Instead, we have used the average labor cost at the provincial level to calculate the total implementation cost across different regions. $\Delta E_{i,j}$ is the change in wastewater/straw treatment and N emission/loss in different forms, such as NH_3, N_2O, leaching and runoff (the difference between the actual situation in 2020 and under the measure intervention) which has been expressed in Eq. (14).

The benefits of improving N management to achieve sustainable development of the FEW nexus in this study can be divided into direct economic benefits ($DIR_{benefit,i}$) and indirect societal benefits ($SOC_{benefit,i,j}$), economic benefits ($DIR_{benefit,i}$) refer to the total cost saving ($\Delta COS_{benefit,i}$) due to changes in food/feed import through diet shift and food waste down, or the reduced fertilizer and agricultural water use through optimized fertilization and improved irrigation techniques, as well as the increased straw energy and urban population, as shown in Eq. (15). It is worth noting that as a natural resource, water is priced uniformly across all provinces, mainly due to government regulation and centralized management, ensuring fair distribution and efficient use. For the N fertilizer and straw energy, we used national market prices without considering regional or crop-specific variations due to data limitations, to evaluate the total benefit across different regions. In contrast, the prices of grain vary significantly between provinces due to factors such as production costs, climate conditions, and transportation expenses. Additionally, there are clear disparities in urban and rural incomes across different regions. Societal benefits ($SOC_{benefit,i,j}$) are defined as the sum of avoided damage costs of premature mortality by air pollution ($HH_{benefit,i,j}$), ecosystem health ($EH_{benefit,i,j}$), and GHG mitigation benefit ($GHG_{benefit,i,j}$), as shown in Eq. (16):

$$\mathrm{DIR}_{\mathrm{benefit},i} = \sum \Delta COS_{benefit,i} = \sum_k (COS_{i,2020,k} - COS_{i,measure,k}) \tag{15}$$

$$\mathrm{SOC}_{\mathrm{benefit},i,j} = EH_{benefit,i,j} + HH_{benefit,i,j} + GHG_{benefit,i,j} \tag{16}$$

in which $COS_{i,2020}$ represents the current cost in 2020, while the $COS_{i,measure}$ refers to the cost under different N management measures.

Several USA and EU have examined the damage cost of N effect on ecosystems[57–62]. We do not yet have costs and benefits data available for other countries/regions of the world. In order to evaluate the benefits and trade-offs associated with N-related management actions for various areas, we assume that the unit N damage to the ecosystems in the EU and the USA applies to other regions after correcting for variations in the willingness to pay (WTP) for ecosystem services, as shown in Eq. (17):

$$\mathrm{EH}_{\mathrm{benefit},i,j} = \sum_k \Delta E_{i,j,k} \times \partial_{US,k} \times \frac{WTP_i}{WTP_{US}} \times \frac{PGDP_i}{PGDP_{US}} \tag{17}$$

in which ∂_{US} is the estimated unit ecosystem damage cost of N emission/loss in the USA in the 2000s[59]; WTP_i and WTP_{US} are the values of the WTP for ecosystem service in country/province i and the USA, respectively; $PGDP_i$ and $PGDP_{US}$ stand for the per capita gross domestic product (in constant 2020 USD) of province i and the USA, respectively. The welfare implications of transforming damages are based on WTP; the data source of WTP can be found in Supplementary Table 15.

The health benefit ($HH_{benefit,i,j}$) refers to the benefit of prevented mortality derived from $PM_{2.5}$ mitigation caused by improving N management. We derived the provincial-specific unit health damage costs of N emission from the methodology of Gu et al.[63], which connected the economic cost of mortality per unit of Nr emission with the population density, gross domestic product per capita, urbanization, and N-share. The calculation of health benefits from N management is shown in Eq. (18):

$$\mathrm{HH}_{\mathrm{benefit},i,j} = \sum_k \Delta E_{i,j,k} \times HCost_{i,k} \tag{18}$$

in which $\Delta E_{i,j}$ is the estimated reduction of N emission/loss in cropland, livestock, aquaculture, human, and WWTP (wastewater treatment plant) subsystem, $HCost_{i,k}$ represents the unit health damage cost of N emission/loss (Supplementary Table 14). NH_3 and NO_x emissions primarily affect local and regional air quality and thus have direct health impacts that vary significantly depending on local environmental conditions and population density. Consequently, the benefits of reducing NH_3 emissions are spatially heterogeneous and must be assessed within the specific context of each province's unique characteristics, such as agricultural practices, meteorological conditions, and ecological sensitivities. While N_2O is a potent greenhouse gas with a long atmospheric lifetime, it contributes to global climate change rather than causing localized impacts. Therefore, the benefits of reducing N_2O emissions are considered globally uniform and are mainly related to mitigating climate change impacts. Also, the health benefits of reducing runoff and leaching are consistent in all provinces of China.

For monetary evaluation of the climate impact, we used the regional-weighted N damage cost to multiply with the reduction of N emission, as shown in Eq. (19):

$$\mathrm{GHG}_{\mathrm{benefit},i,j} = \sum_k \Delta E_{i,j,k} \times CCost_{i,k} \tag{19}$$

In which $CCost_{i,k}$ represents the unit damage cost to the climate in USD per kg N (Supplementary Table 14). This evaluation accounts for the dual effects of N compounds on global climate: N_2O contributes to global warming, whereas NO_x and NH_3 emissions are considered to have a cooling effect on the global climate.

It is worth noting that a key limitation of the cost-benefit analysis in this study is based on an idealized scenario where N management measures are assumed to be implemented uniformly and effectively across China. While this approach provides a useful upper bound for evaluating the potential benefits, it does not explicitly account for real-world inefficiencies and transaction costs associated with policy implementation. These include variability in farmer responses to agri-environmental policies, differences in regional adoption rates, and the costs of monitoring, enforcement, and education required to ensure compliance. Additionally, transaction costs such as administrative expenses, subsidy allocation, and infrastructure development for policy enforcement are not considered. As a result, the estimates presented here likely overstate the achievable benefit-to-cost ratio, offering an optimistic perspective under ideal conditions. We emphasize that the actual outcomes may differ due to these limitations, and further research incorporating these factors would provide a more comprehensive assessment of the feasibility and impact of nitrogen management strategies.

Data availability

Data supporting the findings of this study are available within the article and its supplementary information files. Source data are provided with this paper.

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Author contributions

B.G. and B.C. designed the study. B.C. performed the research. X.Z. assisted with the CHANS model, scenario setting, and cost-benefit analysis. B.C. wrote the paper, B.G., and X.Z. revised the paper. B.G., B.C, and X.Z. all contributed to the discussion of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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