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BIOCHEMICAL CYCLES

Integrated carbon and nitrogen management for cost-effective environmental policies in China

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Carbon and nitrogen are central elements in global biogeochemical cycles. To effectively manage carbon and nitrogen in China, we developed a comprehensive model for quantifying their fluxes, investigating their interplay across 16 human and natural subsystems. Between 1980 and 2020, nitrogen losses in China increased 2.3-fold and carbon emissions surged 6.5-fold. Integrated carbon and nitrogen management holds the potential for a 74% reduction in nitrogen losses to air and water and a 91% decrease in carbon emissions to the atmosphere by 2060. Compared with separate control of carbon or nitrogen, integrated management delivers an additional reduction of 1.8 million tons of nitrogen and 26.5 million tons of carbon by 2060, bringing out a 37% decrease in unit abatement cost and a net societal benefit of 1384 billion USD.

Carbon and nitrogen are fundamental elements in the biogeochemical cycle, playing distinctive roles in shaping both natural and human-dominated ecosystems (*1*, *2*). In natural systems, the carbon and nitrogen cycles are strongly interconnected, collectively influencing vegetation growth and biodiversity while also serving as key indicators of soil health. Within human societies, nitrogen fixation through synthetic fertilizers is indispensable for food production, but it is associated with increased emissions of ammonia (NH_3) and nitrous oxide (N_2O) into air, as well as nitrate (NO_3^-) into water. Additionally, the combustion of fossil fuels exacerbates emissions of nitrogen oxides (NO_x) and carbon dioxide (CO_2). Although carbon and nitrogen are vital for food, feed, and wood production, their excessive losses into the environment pose threats to climate, biodiversity, and air and water quality (*3*–*6*). Since the start of the preindustrial era, anthropogenic emissions of carbon and nitrogen have escalated substantially, surpassing the safe operating boundaries of our planet (*7*).

Human-induced perturbations of global carbon and nitrogen cycles are inherently linked (*8*). For example, elevated CO_2 levels have a fertilizing effect on forest ecosystems (*9*), and nitrogen normally limits vegetation growth and carbon accumulation, whereas carbon sequestration in soils may enhance N_2O emissions (*10*, *11*).

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Regional coordination in carbon and nitrogen management requires a comprehensive insight into the complex interactions within human and natural systems (*12*). However, the integrated management of carbon and nitrogen considering multicompartment (e.g., air, soil, or water bodies) and cross-sector (e.g., industry, agriculture, or forestry) dynamics remains largely unexplored (*13*). In China, the integrated mitigation potential is mainly explored in reducing atmospheric nitrogen pollutants and CO_2 emission across the industrial, energy, and transportation sectors (*14*, *15*). In the agricultural sector, efforts have largely targeted controlling non–point source pollution, particularly nitrate runoff and leaching. However, the interactions and trade-offs between decarbonization strategies and nitrogen reductions remain insufficiently understood. A thorough evaluation of mitigation costs and associated social benefits is crucial to ensure the feasibility of carbon and nitrogen management strategies. Therefore, a generic approach is needed to systematically model regional carbon and nitrogen cycles and to assess the mitigation potential and cost-effectiveness of different strategies, offering effective guidance for policy-making.

To address the knowledge gap, we synthesized carbon and nitrogen flows in China with the Coupled Human and Natural Systems-Carbon and Nitrogen cycles (CHANS-CN) model (fig. S1). First, we investigated carbon and nitrogen sources, fluxes, and fates from 1980 to 2020 across 16 different subsystems (fig. S2). Subsequently, leveraging subsystem-level budgets and mitigation measures, we simulated potential trajectories of carbon and nitrogen fluxes and their coupling from 2020 to 2060 under various management scenarios. Finally, we quantified the cost-effectiveness of integrated carbon and nitrogen management compared with separate strategies. This study provides valuable insights for achieving substantial environmental, climate, and economic benefits through integrated carbon and nitrogen management in China.

Results and discussion

The CHANS-CN model

We first built the CHANS-CN model to integrate carbon and nitrogen flows on a national scale, covering 16 subsystems and >6000 fluxes (see the materials and methods and supplementary text). Carbon and nitrogen inputs predominantly arise from biological fixation, chemical fixation, fossil fuel combustion, industrial processes, and geological activities, along with external imports or exports through trade and other natural sources (e.g., lightning). From 1980 to 2020, China's total carbon inputs increased from 1.5 to 6.5 Pg C year^{-1}, carbon input from fossil fuels increased from 0.6 to 4.6 Pg C year^{-1}, and carbon fixed by plant photosynthesis increased from 0.9 to 1.9 Pg C year^{-1} (fig. S3a). In addition, total nitrogen inputs increased from 23.7 Tg N year^{-1} in 1980 to 77.8 Tg N year^{-1} in 2015, with the proportion of Haber-Bosch nitrogen fixation (*16*) rising from 46 to 77% and biological nitrogen fixation decreasing from 30 to 11%. However, from 2015 to 2020, nitrogen inputs declined slightly but remained 2.7 times higher than in 1980 (fig. S3b). These inputs circulated through subsystems, causing cascading effects, with carbon and nitrogen either stored or lost to the environment. Carbon outputs mainly involve agro-food and feed exports, along with dissolved carbon entering the ocean (*17*) (fig. S4). Nitrogen outputs primarily manifest as N_2 emissions through denitrification (*18*), along with nitrogen entering the atmospheric circulation or the ocean.

To assess the long-term trajectory and impacts of carbon and nitrogen emissions, we introduced the carbon-nitrogen impact equivalent (CNI_{eq}), an index that weighs different compounds based on their monetary value of impacts on climate, ecosystem, and human health (see the materials and methods). From 1980 to 2020, reactive nitrogen (N_r, all nitrogen species except N_2) losses initially increased, peaking around 2012 at 79.0 Tg CNI_{eq} before declining (Fig. 1A). This decline could be attributed to NO_x reductions benefiting from the

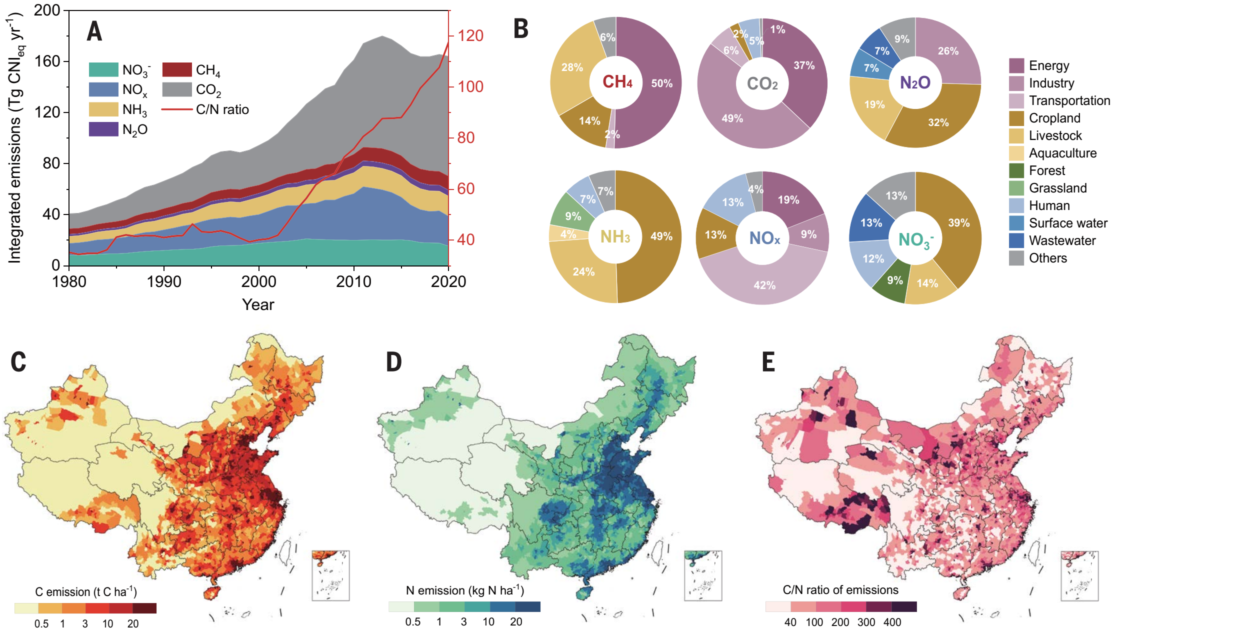

Fig. 1. Spatiotemporal characteristics of carbon and nitrogen emissions and the C/N ratio. (**A**) Carbon and nitrogen emissions, along with C/N (mass/mass) ratio of emissions in China from 1980 to 2020. Note that the carbon emissions consist of CO_2 and CH_4, and nitrogen emissions include NO_3^-, NO_x, N_2O, and NH_3 (see the materials and methods). The red line on the right vertical axis represents the C/N ratio of emissions. (**B**) Relative subsystem contributions (%) to carbon and nitrogen emissions in 2020. (**C** to **E**) Geographical distribution of carbon emission intensity (C), nitrogen emission intensity (D), and the C/N ratio of emissions (E) in 2020. The base map was derived from the Database of Global Administrative Areas (https://gadm.org/).

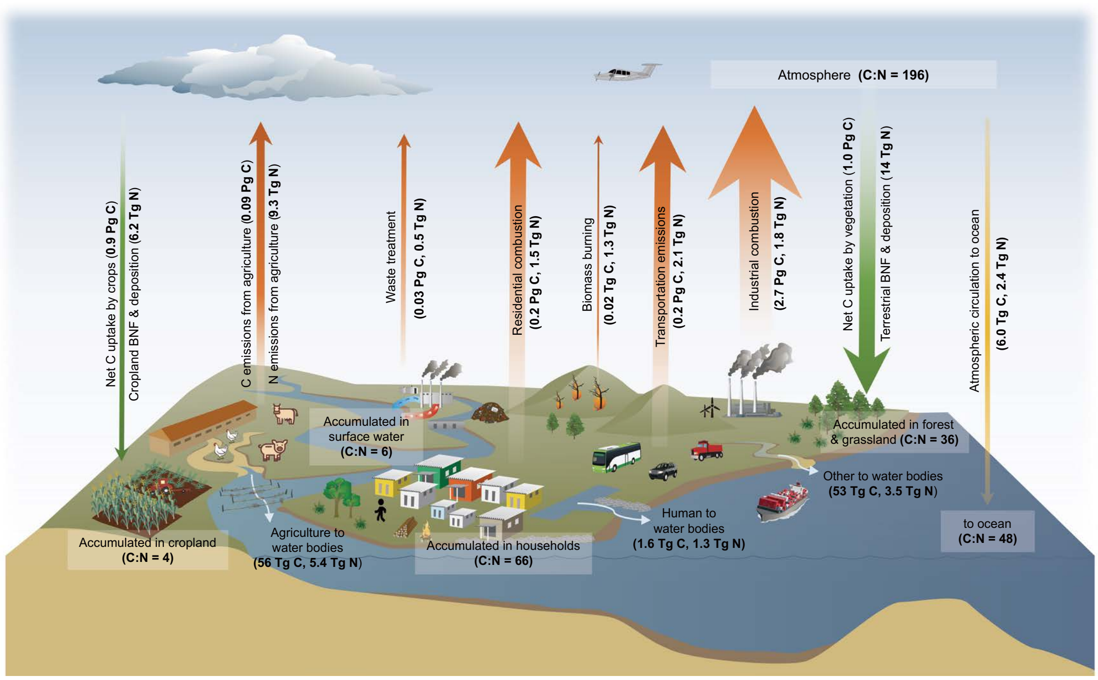

Fig. 2. Terrestrial and atmospheric carbon and nitrogen fluxes and accumulation in 2020. Shown are carbon and nitrogen fluxes and the C/N ratio of accumulation in China for 2020. Orange arrows indicate emissions to the atmosphere, blue arrows indicate emissions to the water bodies (including leaching and runoff), green arrows indicate land deposition, and yellow arrows indicate cycling quantities.

Air Pollution Control Program (*19*) and the decreased NH_3 and NO_3^- emissions due to improved synthetic fertilizer and manure management (*20*, *21*). By contrast, carbon emissions sustained an upward trend, particularly between 2000 and 2013, with an average annual growth rate of 8% (fig. S5). In recent years, the growth has been halted, reaching 105 Tg CNI_{eq} in 2020, signifying a 6.5-fold increase since 1980. Of this, industry and energy contributed >85% of CO_2 emissions and >50% of CH_4 emissions, and agriculture and livestock contributed 42% of CH_4 emissions in 2020 (Fig. 1B). Spatial variations of carbon and nitrogen emissions across China in 2020 are depicted in Fig. 1, C to E, and fig. S6. High carbon emissions were mainly concentrated in areas such as the Yangtze River Delta and the Northeast China Plain, with elevated nitrogen losses occurring in the middle and lower Yangtze Plain and the Northeast China Plain. Regions with a high C/N emissions ratio were predominantly located in densely populated or urbanized regions.

Figure 2 illustrates overall carbon and nitrogen fluxes in China's terrestrial, atmospheric, and aquatic ecosystems in 2020. The grassland and forest subsystems received inputs of 1.0 Pg C and 14 Tg N, primarily from biological fixation and atmospheric deposition. These inputs underwent transformation, recycling, and transfer through processes such as harvesting, runoff, volatilization, and denitrification, ultimately leading to an accumulation with a C/N ratio of 36 in these natural ecosystems (see the materials and methods). Similarly, 0.9 Pg C and 6.2 Tg N entered the cropland subsystem, with a lower C/N ratio of accumulation at 4. The human subsystem, as a core consumer, received 22 Tg N and 0.8 Pg C supplied from subsystems as food, fuel, and commodities (fig. S4), emitting 0.2 Pg C and 1.5 Tg N into the atmosphere, with the C/N ratio of accumulation at 66. In addition, energy and industrial production contributed 85% of carbon and 11% of nitrogen emissions; agricultural practices, including cropland, livestock, and aquaculture, contributed 56% of nitrogen and 3% of carbon emissions. The transportation sector released 2.1 Tg N and 0.2 Pg C through fuel combustion, and waste disposal, including garbage and wastewater, emitted 0.03 Pg C and 0.5 Tg N. The C/N ratio of surface water accumulation was estimated at 6, with agriculture contributing >50%, followed by domestic and industrial wastewater discharge (16%). Assuming a balanced state of emissions and distribution between the atmosphere, ocean, and inland in China, we also estimated carbon and nitrogen fluxes for air-sea circulation, revealing a C/N ratio of ~48.

Coupling between carbon and nitrogen

Based on the CHANS-CN model, we examined the historical and future trends of carbon and nitrogen emissions in China, mainly focusing on their relative magnitudes and coupling processes. Between 1980 and 2000, the C/N ratio of emissions remained stable at ~35 to 44 (Fig. 3A). Agricultural sources contributed ~35% of total emissions, and the share of industry-related sources increased from 42 to 50% (fig. S5). The stable C/N ratio suggests that appropriate carbon fertilization and adequate nitrogen supply may enhance carbon fixation in ecosystems, a trend further supported by satellite observations of the greening in China during this period (*22*, *23*). Over the past two decades, both carbon and nitrogen emissions surged, particularly from industrial sources, contributing 66% in 2020, and the share of agriculture dropped to 20% (figs. S5 and S7). The C/N ratio tripled, reaching 119 by 2020, revealing an asymmetry in carbon and nitrogen emissions. Despite enhanced carbon fertilization effects, the imbalanced

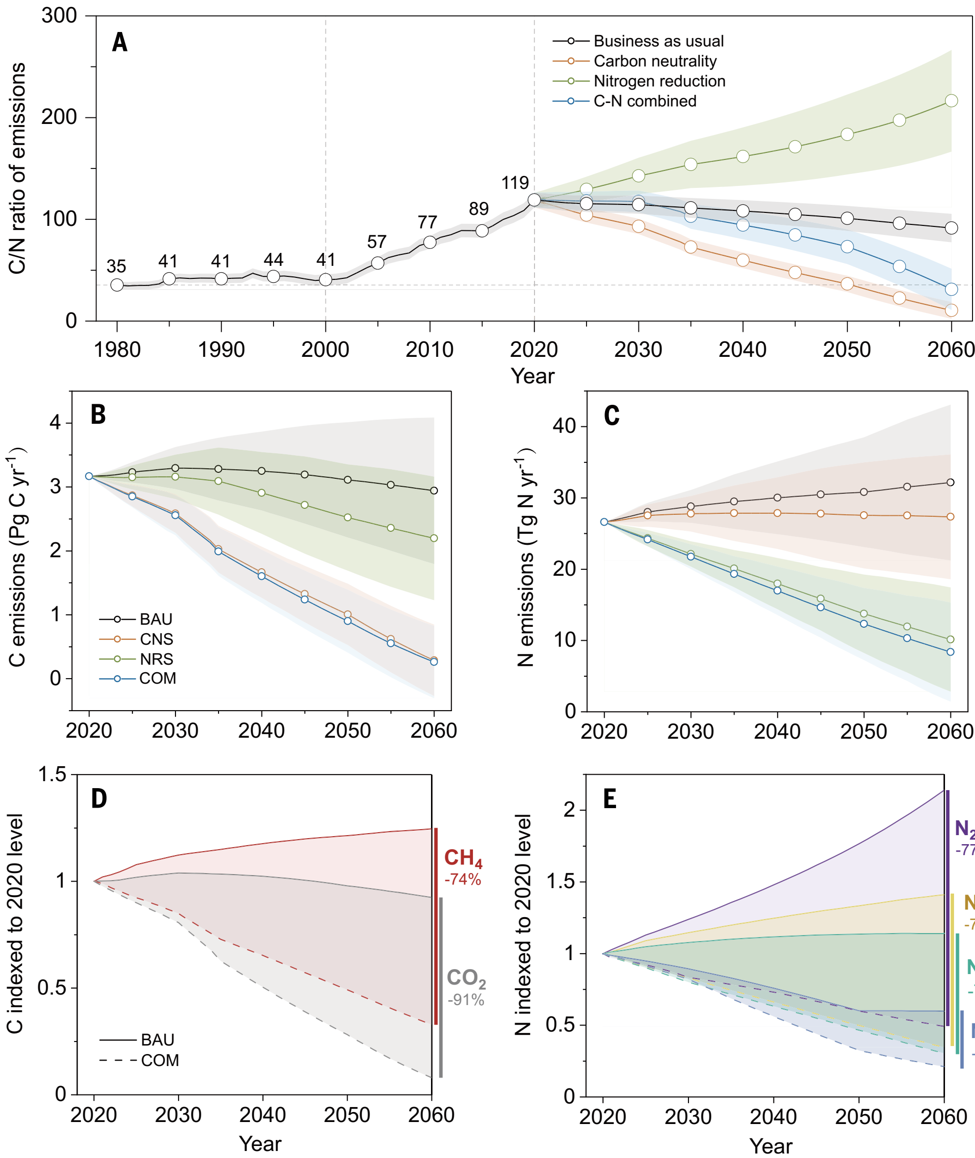

Fig. 3. Future projection of carbon and nitrogen emissions and the C/N ratio under the BAU, CNS, NRS, and COM scenarios. (**A**) C/N ratio of emissions under the BAU, CNS, NRS, and COM scenarios. (**B**) Carbon emissions from 2020 to 2060, including CH_4 and CO_2, standardized in Pg C year^{-1}. (**C**) Nitrogen emissions from 2020 to 2060, including NH_3, NO_3^-, N_2O, and NO_x, standardized in Tg N year^{-1}. (**D** and **E**) Mitigation potential of carbon (D) and nitrogen (E) emissions relative to 2020 levels under the BAU and COM scenarios, respectively.

inputs of carbon and nitrogen have restricted the potential of carbon sinks to offset excessive greenhouse gas emissions (*24*). This underscores the importance of integrated carbon and nitrogen management, which involves coordinating both carbon and nitrogen abatement across subsystems, rather than isolated controls, to safeguard food security and ecosystem carbon sequestration (*25*, *26*).

To evaluate the effects of separate versus integrated management, four management scenarios were simulated based on the CHANS-CN model: nitrogen emission reduction (NRS), carbon emission reduction (CNS), combined carbon and nitrogen emission reduction (COM), and a business-as-usual (BAU) scenario (see the materials and methods and tables S1 and S2). The NRS focuses exclusively on nitrogen management, mainly through agricultural practices and dietary transitions, and the CNS centers on carbon management, targeting fossil fuel production and consumption. By contrast, the COM emphasizes integrated management across all subsystems, aiming to mitigate the trade-offs of isolated measures. From 2020 to 2060, the C/N ratio of emissions under the BAU scenario is projected to decline slightly, with an average value of 107 (Fig. 3A). Under the NRS scenario, the C/N ratio will increase to 217 by 2060 due to inadequate control over carbon emissions. Conversely, the C/N ratio for CNS will continue to decrease, returning to historically low levels by 2050, but nitrogen losses will remain high, at ~26 Tg N year^{-1} (Fig. 3C). The COM scenario demonstrates the greatest mitigation potential, reducing carbon emissions by 91% and nitrogen emissions by 74% by 2060. Specifically, emissions of CH_4 and CO_2 could decrease by 74 and 91% (Fig. 3D), and emissions of N_2O, NH_3, NO_3^-, and NO_x would decrease by 77, 75, 73, and 65%, respectively (Fig. 3E). The C/N ratio under the COM scenario in 2060 will fall between that of NRS and CNS scenarios, around the historical range of 35 to 44 observed between 1980 and 2000, when China experienced relatively good environmental quality, a stable food supply, and effective carbon sequestration (*22*, *27*, *28*).

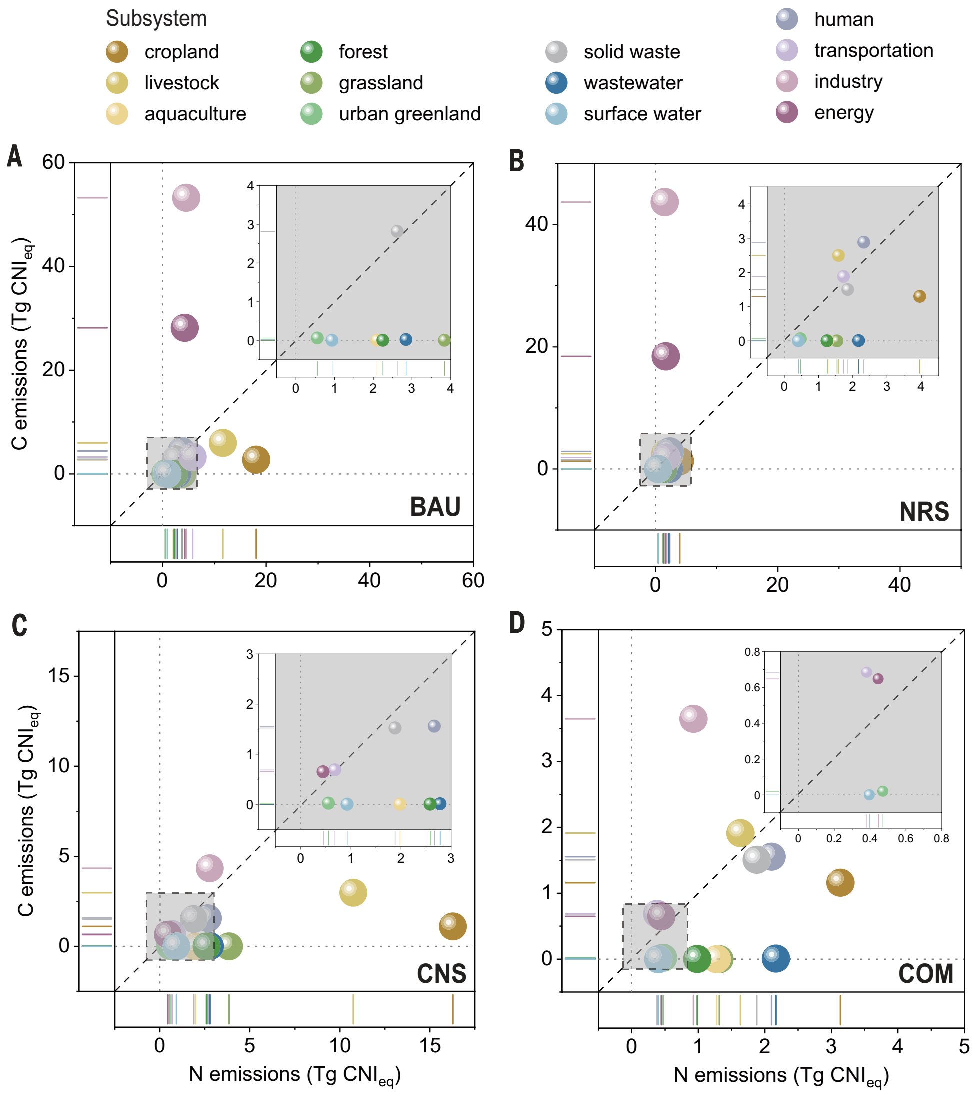

Fig. 4. Coupling degrees of carbon and nitrogen emissions for various subsystems in 2060. (**A** to **D**) Coupling degrees of carbon and nitrogen emissions under the BAU (A), NRS (B), CNS (C), and COM (D) scenarios in 2060. The horizontal coordinate represents nitrogen emissions, and the vertical coordinate represents carbon emissions, both normalized to Tg CNI$_{eq}$ (see the materials and methods). The gray portion is an enlarged view within the small box. Note that the proximity to the dashed line indicates the degree of coupling between carbon and nitrogen emissions.

To prioritize integrated mitigation strategies at the subsystem level, we further analyzed the coupling processes in which certain carbon and nitrogen emissions share common sources or a single mitigation measure can reduce both emissions to some extent. To quantify the degree of coupling, we introduced two parameters, SE_1 and SE_2, representing the coupling degrees of emission and mitigation, respectively, within a range of 0 to 1 (see the materials and methods). A coupling degree of 1 indicates that a biogeochemical process results in equivalent carbon and nitrogen emissions (SE_1) or that a mitigation measure can reduce both emissions equally (SE_2), as defined by CNI$_{eq}$. A smaller coupling degree signifies weaker connections between carbon and nitrogen emissions and their mitigations. Most subsystems, especially transportation, human, and garbage subsystems, exhibited robust carbon-nitrogen coupling (fig. S8). However, this coupling pattern weakened from 2000 to 2020. Taking the industry and energy subsystems as examples, before 2000, the average coupling degree SE_1 for these subsystems was ~0.98, whereas by 2020, these coefficients had dropped to 0.52 and 0.59, respectively, as carbon emissions became dominant. Without further intervention, these coefficients are projected to be 0.54 and 0.68 by 2060, indicating persistent imbalances in carbon and nitrogen emissions along historical trajectories (Fig. 4A and fig. S9).

Nitrogen management alone will enhance the coupling of carbon and nitrogen emissions in the cropland and livestock subsystems, with coupling degree SE_1 increasing by 13% (to 0.86) and 5% (to 0.98), respectively, by 2060 (Fig. 4B). Similarly, carbon management alone will improve coupling degree SE_1 in the industry and energy subsystems by 87 and 66%, respectively (Fig. 4C). However, relying solely on carbon or nitrogen mitigation strategies reduces the overall coupling degree SE_1 by 12 and 15% across all sectors, respectively, highlighting the inherent trade-offs of singular mitigation solutions. By contrast, integrated management will elevate China's overall carbon-nitrogen coupling degree SE_1 to 0.98 by 2060. Substantial improvements will occur in the energy, industry, livestock, and cropland subsystems, with their SE_1 increasing by 66, 54, 39, and 17%, respectively (Fig. 4D).

The coupling degree SE_2 values of carbon and nitrogen reductions under each scenario are illustrated in fig. S10. From 2020 to 2060, integrated management ensures that the coupling degree SE_2 of carbon and nitrogen reductions exceeds 0.92 across the entire system. Subsystems with higher SE_2, such as human (0.98), garbage (0.95), transportation (0.94), and livestock (0.93), suggest that their embedded abatement measures are crucial entry points for integrated management. Nevertheless, in certain subsystems where carbon or nitrogen processes dominate the overall biogeochemical dynamics, the COM strategy does not always outperform separate management. For example, in forest and grassland ecosystems, substantial nitrogen reductions may decrease nitrogen bioavailability, consequently weakening their carbon sequestration potential (*25*). Conversely, for wastewater and surface water subsystems, which are dominated by nitrogen emissions with low coupling degrees, integrated management may fail to demonstrate coupling advantages.

Co-benefits of carbon and nitrogen management

Integrated carbon and nitrogen management offers considerable economic opportunities at relatively low intervention costs, with net social benefits expected to rise continuously as mitigation measures permeate various sectors. Here, we quantified total abatement costs based on metric unit costs, baseline activity levels, and implementation rates; social benefits reflect the avoided damage costs attributed to the carbon and nitrogen emission reduction (see the materials and methods and table S3). Under the CNS scenario, the implementation cost in 2060 is estimated at 371 billion USD, yielding a net benefit of 1036 billion USD, with the highest mitigation costs in the energy (accounting for 77%) and industry (15%) subsystems (Fig. 5A). Conversely, the NRS scenario presents a lower implementation cost of 101 billion USD, with a net social benefit of 932 billion USD by 2060 (Fig. 5C), primarily benefiting the livestock (22%) and cropland (21%) subsystems. The total abatement cost across all subsystems under the COM scenario will be 424 billion USD, and the resulting social benefits will reach 1809 billion USD, surpassing the costs fourfold (Fig. 5E). In addition, the cost-benefit ratio under carbon-focused management will increase and then decrease from 2020 to 2060, peaking at 4.9 by around 2035. By contrast, the cost-benefit ratio for nitrogen-focused management will continue to increase, reaching 10.2 in 2060, driven by benefits from the transportation, livestock, and cropland subsystems (fig. S11). Thus, we suggest prioritizing carbon mitigation measures with supplementary nitrogen reduction before carbon peak to unleash the abatement potential of high-carbon-emitting industries under a progressively stricter carbon pricing market. In the long term, nitrogen mitigation options will be more cost-effective and can actively stimulate carbon co-reduction in China.

By integrating the carbon and nitrogen mitigation potential, we further analyzed the marginal abatement costs of various subsystems in 2060. Under the CNS scenario, the subsystems with the highest marginal abatement costs are wastewater treatment, energy, and forest, at 10.40, 9.00, and 6.20 USD per kg CNI_{eq}, respectively (Fig. 5B). By contrast, subsystems including transportation and cropland, despite having lower abatement potential, exhibit negative costs (i.e., cost savings), alleviating economic pressures. In the NRS scenario, the subsystems with the highest marginal costs are garbage, wastewater

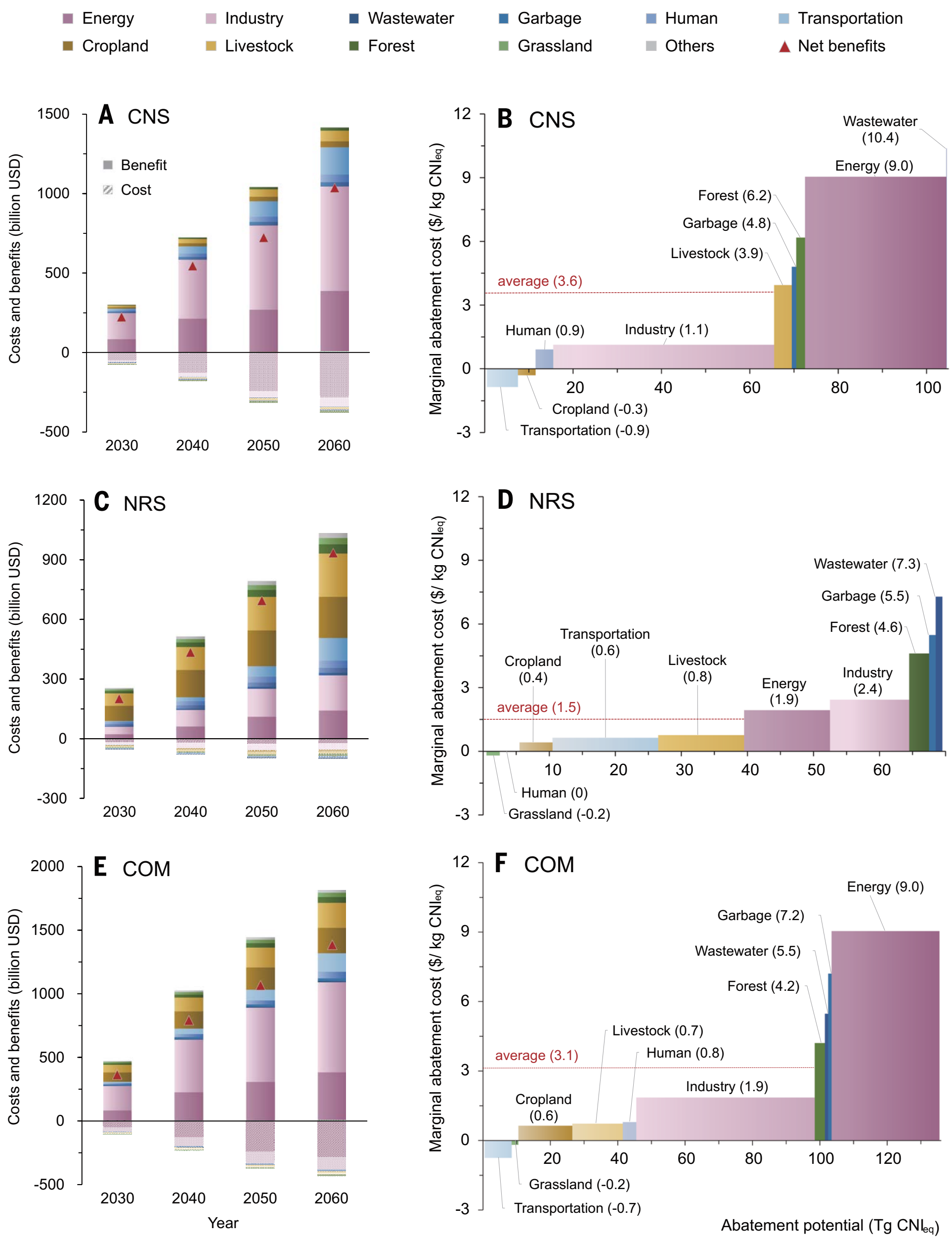

Fig. 5. Cost-benefit analysis of the subsystem abatement under the CNS, NRS, and COM scenarios. (**A** to **F**) Total implementation costs, social benefits, and net social benefits (in billions of USD) are shown for subsystem abatement in 2030, 2040, 2050, and 2060 under the CNS (A), NRS (C), and COM (E) scenarios. Marginal abatement costs (USD per kg CNI_{eq}) are shown for 10 subsystems under the CNS (B), NRS (D), and COM (F) scenarios in 2060. Note that six subsystems (aquaculture, pets, urban green land, surface water, groundwater, and atmosphere) are classified as "others" and include no specific abatement measures, so their implementation costs are not considered.

treatment, and forest, at 7.30, 5.50, and 4.60 USD per kg of CNI_{eq}, respectively (Fig. 5D). The human subsystem incurs minimal additional abatement costs but contributes 2.9 Tg CNI_{eq} of the total emission reduction by 2060. Further, our findings indicate that if carbon and nitrogen emissions are managed separately, then the average unit abatement cost in 2060 would be 5.00 USD per kg of CNI_{eq}. However, under integrated carbon and nitrogen management, the average abatement cost will be 3.10 USD per kg of CNI_{eq} (Fig. 5F), representing a 37% reduction in unit costs and demonstrating a promising dual-benefit advantage for China.

Feasibility and policy implications

This study traces the spatiotemporal dynamics of China's carbon and nitrogen budgets at the human-nature interface, revealing an imbalance in carbon and nitrogen emissions. Moreover, we delve into the potential of integrated management in terms of cost-effectiveness that harmonize production processes with China's broader natural and socioeconomic conditions, facilitating an orderly reduction of carbon emission and nitrogen pollution. Recent policy developments, such as the Implementation Plan for Synergistic Pollution and Carbon Reduction, underscore the feasibility of integrated carbon and nitrogen management within China's socioeconomic and ecological development trajectory (*29*). These efforts reflect not only the theoretical viability but also the practical applicability of integrated strategies to address the dual challenges of pollution and climate change.

To fully harness the advantages of integrated management, it is crucial to prioritize measures with high cost-benefit ratios. Specifically, for the energy sector, optimizing power transmission and energy storage infrastructure to accelerate the adoption of clean energy sources such as wind and solar power should be prioritized (*30*, *31*). In transportation, a focal point could be improving fuel efficiency to reduce energy consumption (*32*). In livestock management, proper feed additives can effectively reduce feeding costs by minimizing intake (*33*). The combined strategy is not always the optimal solution considering short-term urgent needs. For example, if a region is experiencing severe eutrophication and requires nitrogen-intensive actions that may increase carbon emissions, it may still be worthwhile, because local citizens might prioritize water quality during that short period. Thus, given the heterogeneity of natural resources and economic constraints, customized combinations of measures and their priorities should be tailored to different times and regions (*34*, *35*). Further, the complexity of interactions between subsystems necessitates a holistic approach to ensure that integrated actions span the entire industrial chain (*12*). For instance, manure management between the feeding and storage stages in the livestock subsystem could affect manure recycling and its application to cropland, and human consumption patterns could affect the efficiency and costs of downstream waste treatment. As a populous and pollution-intensive nation, China's adaptive and effective pathway for integrated carbon and nitrogen management can provide valuable insights for other developing countries to facilitate informed environmental policies.

Beyond technical measures, integrated carbon and nitrogen management provides a strong theoretical foundation for nature-based solutions. It is estimated that, driven by China's carbon neutrality target, by 2060, ~20% of carbon emissions will be sequestered by terrestrial ecosystems (*36*). To maximize the potential of nature-based climate solutions and to enhance the co-benefits of multiple ecosystem services (*37*), it is crucial to incorporate external factors such as climate change into the model, supporting the formulation of multilevel and resilient governance strategies (*38*). Moreover, our innovative modeling framework, applicable to carbon and nitrogen, can also be extended to other elements such as phosphorus and sulfur in the future (*39*, *40*). The multidimensional expansion will deepen our understanding of the coupling dynamics within biogeochemical cycles and clarify the diverse constraints and co-benefits engendered by human intervention. Additionally, the coupling evaluation system will evolve from a binary-element configuration to a multielement one (*41*) to facilitate the identification of optimal solutions for managing various mitigation targets, ultimately fostering holistic and cost-effective environmental policies.

REFERENCES AND NOTES

1. P. Falkowski *et al.*, *Science* **290**, 291–296 (2000).
2. X. Zhang, B. B. Ward, D. M. Sigman, *Chem. Rev.* **120**, 5308–5351 (2020).
3. J. N. Galloway *et al.*, *Science* **320**, 889–892 (2008).
4. C. Bellard, C. Bertelsmeier, P. Leadley, W. Thuiller, F. Courchamp, *Ecol. Lett.* **15**, 365–377 (2012).
5. H. D. Matthews, N. P. Gillett, P. A. Stott, K. Zickfeld, *Nature* **459**, 829–832 (2009).
6. F. Wang *et al.*, *The Innovation Geoscience* **1**, 100015 (2023).
7. K. Richardson *et al.*, *Sci. Adv.* **9**, eadh2458 (2023).
8. N. Gruber, J. N. Galloway, *Nature* **451**, 293–296 (2008).
9. J. Cui *et al.*, *Nat. Clim. Chang.* **14**, 511–517 (2024).
10. E. Du, W. de Vries, *Environ. Pollut.* **242**, 1476–1487 (2018).
11. L. F. Schulte-Uebbing, G. H. Ros, W. de Vries, *Glob. Chang. Biol.* **28**, 899–917 (2022).
12. Y. Li, S. Sang, S. Mote, J. Rivas, E. Kalnay, *Natl. Sci. Rev.* **10**, nwad054 (2023).
13. S. Niu, L. Song, J. Wang, Y. Luo, G. Yu, *Sci. China Life Sci.* **66**, 771–782 (2023).
14. H. Qian *et al.*, *Nat. Sustain.* **4**, 417–425 (2021).
15. H. Yang *et al.*, *J. Clean. Prod.* **185**, 331–341 (2018).
16. V. Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (MIT Press, 2004).
17. P. Regnier, L. Resplandy, R. G. Najjar, P. Ciais, *Nature* **603**, 401–410 (2022).
18. D. Fowler *et al.*, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **368**, 20130164 (2013).
19. State Council of China, "The action plan on the prevention and control of air pollution" [in Chinese] (State Council of China, 2013); https://www.gov.cn/zwgk/2013-09/12/content_2486773.htm.
20. Ministry of Agricultural and Rural Affairs, "The zero increase of fertilizer and pesticides action" [in Chinese] (MOA, 2015); http://www.moa.gov.cn/govpublic/ZZYGLS/201505/t20150525_4614695.htm.
21. Ministry of Agricultural and Rural Affairs, "National plan of sustainable agricultural development 2015-2030" [in Chinese] (MOA, 2015); http://www.moa.gov.cn/nybgb/2015/liu/201712/t20171219_6103855.htm.
22. S. Piao *et al.*, *Glob. Chang. Biol.* **21**, 1601–1609 (2015).
23. H. Tian *et al.*, *Global Biogeochem. Cycles* **25**, GB1007 (2011).
24. C. Terrer *et al.*, *Nat. Clim. Chang.* **9**, 684–689 (2019).
25. F. Shang *et al.*, *Nat. Commun.* **15**, 7738 (2024).
26. X. Zhang *et al.*, *Nat. Rev. Earth Environ.* **5**, 717–731 (2024).
27. R. Yousefi *et al.*, *J. Environ. Manage.* **326**, 116847 (2023).
28. L. Xu, G. Yu, N. He, *J. Geogr. Sci.* **29**, 49–66 (2019).
29. Q. Zhang *et al.*, *Environ. Sci. Ecotechnol.* **16**, 100280 (2023).
30. F. Wang *et al.*, *Innovation* **2**, 100180 (2021).
31. Y. Wang *et al.*, *Nature* **619**, 761–767 (2023).
32. Y. Liu *et al.*, *J. Clean. Prod.* **207**, 1023–1032 (2019).
33. T. A. Woyengo, E. Beltranena, R. T. Zijlstra, *J. Anim. Sci.* **92**, 1293–1305 (2014).
34. B. Yu *et al.*, *Nat. Commun.* **14**, 8342 (2023).
35. A. Zeng *et al.*, *J. Clean. Prod.* **140**, 1226–1235 (2017).
36. Y. Huang *et al.*, *Natl. Sci. Rev.* **9**, nwac057 (2022).
37. N. Lu *et al.*, *Nat. Clim. Chang.* **12**, 847–853 (2022).
38. N. Seddon *et al.*, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **375**, 20190120 (2020).
39. Z. Luo *et al.*, *Nat. Food* **5**, 48–58 (2024).
40. M. Fakhraee *et al.*, *Nat. Rev. Earth Environ.* **6**, 106–125 (2025).
41. J. Luo *et al.*, *Ecol. Indic.* **170**, 112977 (2025).

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Supplementary Text; Figs. S1 to S11; Tables S1 to S9; References (*42*–*291*)

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