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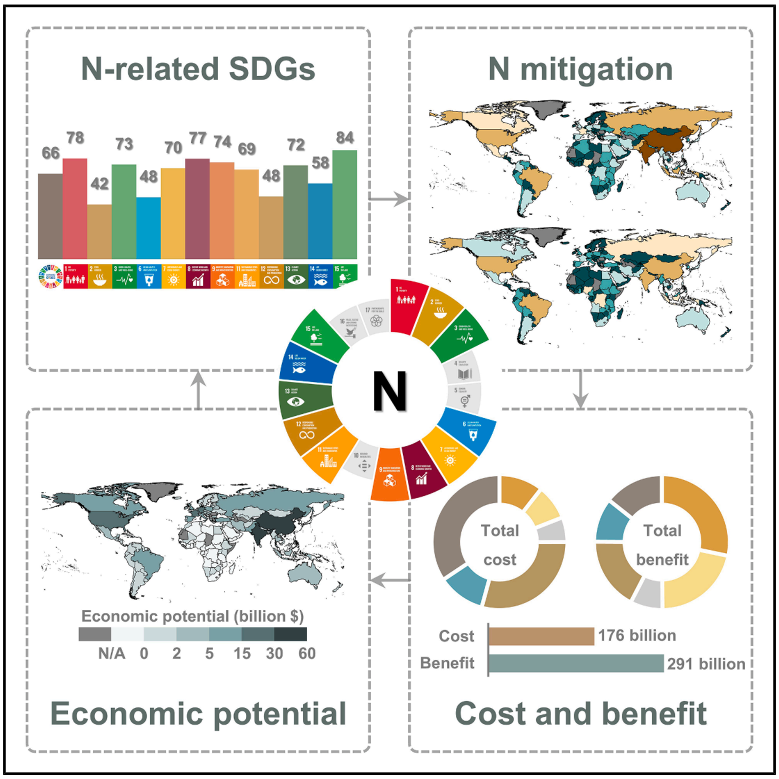
Cutting global nitrogen emissions by one-third for balanced and achievable SDGs by 2030

Graphical abstract



Highlights

- Reducing nitrogen emissions by 32% is essential for meeting achievable SDGs
- Current mitigation efforts address only 57% and 33% of air and water targets
- An investment of $176 billion could generate an economic benefit of $291 billion
- Socioeconomic changes could complement technical solutions for sustainable progress

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In brief

Achieving the SDGs by 2030 is increasingly difficult. Using an SDG-driven framework, we show that meeting balanced and achievable nitrogen-related targets by 2030 requires a one-third reduction in global nitrogen emissions, including 30 million tonnes from the atmosphere and 20 million tonnes from aquatic systems. Current strategies can achieve only half of this goal, despite $176 billion in mitigation investments that generate $291 billion in benefits. This demonstrates that technologies should be combined with socioeconomic transitions to advance the SDGs.

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Cutting global nitrogen emissions by one-third for balanced and achievable SDGs by 2030

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SCIENCE FOR SOCIETY The world is confronting escalating nitrogen pollution, a major driver of environmental degradation and public health risks. Excessive emissions impair air and water quality, damage biodiversity, and intensify climate change, thereby slowing progress toward the SDGs. Despite ongoing mitigation efforts, current measures remain insufficient. Meeting balanced and achievable objectives by 2030 will require reducing global nitrogen emissions by one-third. Such reductions could generate up to $291 billion in combined economic and environmental benefits. This study highlights the need for more effective nitrogen management that couples technological advances with broader systemic transformations. Cross-sector investments and targeted policies will be essential for achieving a sustainable and nitrogen-balanced future.

SUMMARY

Achieving the Sustainable Development Goals (SDGs) by 2030 is becoming difficult as global progress lags. Nitrogen is key to food security and environmental sustainability, making its management crucial for advancing multiple goals within the timeline. Here, we introduce an SDG-driven framework to evaluate nitrogen management under sustainable shared socioeconomic pathways. We show that meeting balanced and achievable targets, defined as an average nitrogen-related SDG index score above 75 with individual target scores exceeding 60, requires reducing global nitrogen emissions by 50 million tonnes (Tg) by 2030, 32% of 2020 levels, entailing decreases of 30 Tg in the atmosphere and 20 Tg in aquatic ecosystems. Existing technological strategies can deliver only half of the required mitigation, even with investments of $176 billion that yield economic benefits of $291 billion. This highlights that technologies alone are insufficient, and meaningful progress toward the SDGs depends on integrating mitigation techniques with broader socioeconomic transitions.

INTRODUCTION

The growing severity of global environmental challenges demands integrated and effective management strategies.[1,2] Adopted by the United Nations (UN) in 2015, the Sustainable Development Goals (SDGs) provide a comprehensive framework to address poverty, environmental degradation, and climate change by 2030.[3] Comprising 17 goals and 169 targets across social, economic, and environmental dimensions, they constitute an urgent and universally relevant agenda and serve as a benchmark for guiding sustainable development strategies. However, given the complexity and scale of the goals, achieving a perfect score on all SDGs by 2030 now seems increasingly unattainable. Recognizing the interconnections among SDGs and their underlying drivers is essential for accelerating progress. Increasing attention has been given to the interactions between specific elements, such as carbon,[4,5] nitrogen,[6,7] and phosphorus,[8] and their relationships with the SDGs. Literature reviews and expert evaluations have qualitatively assessed these linkages,[9,10] and modeling approaches have been used to quantify connections between environmental goals.[11,12]

Among these goals, nitrogen is of particular importance.[13] Nitrogen acts as both an enabler and a constraint in achieving the SDGs, with its impacts spanning environmental, social, and economic dimensions. When used efficiently, nitrogen can catalyze progress across multiple goals: it enhances food security and poverty alleviation (SDGs 1 and 2) by improving agricultural productivity,[14,15] reduces pollution and disease burden to improve health outcomes (SDG 3),[16] and supports clean water access (SDG 6) through improved wastewater management.[17] Optimized nitrogen use also facilitates cleaner energy systems (SDG 7),[18] promotes green economic growth (SDG 8),[19] and supports sustainable production and consumption (SDGs 9 and 12).[20,21] By reducing air pollution and improving urban water systems, it contributes to more sustainable cities and communities (SDG 11).[22] Furthermore, effective nitrogen management can mitigate climate change (SDG 13),[23] protect aquatic ecosystems (SDG 14),[24] and conserve terrestrial biodiversity (SDG 15).[25] However, excessive or inefficient use exacerbates pollution, ecosystem degradation, and health risks, undermining progress toward these goals. Realizing nitrogen's potential in sustainable development requires explicitly recognizing and balancing these contrasting effects. Despite its central role, limited research has examined how global nitrogen cycles may change under SDG implementation or assessed the broader implications of such changes. Quantifying these dynamics is essential for ensuring environmental protection and long-term sustainability. Integrated cross-sectoral management is critical to maximize nitrogen's positive contributions to SDGs while minimizing trade-offs.[6,26,27] Considering economic, social, and environmental dimensions highlights the need to balance nitrogen's impacts across these domains to sustain overall progress.[28–30]

Here, we address these gaps by evaluating potential changes in the global nitrogen releases in the context of meeting achievable SDGs by 2030. We first develop a nitrogen-related SDG indicator system to assess how achieving key targets directly or indirectly affects nitrogen inputs and outputs. Using the coupled human and natural systems (CHANS) nitrogen model, we quantify global nitrogen releases in 2020. We then conduct the nitrogen-related SDG achievement (NSA) scenario to assess changes in nitrogen emissions by 2030, assuming the realization of achievable nitrogen-related SDG targets under sustainable shared socioeconomic pathways (SSPs). This scenario is characterized by an average nitrogen-related SDG index score exceeding 75, with all individual target scores above 60. In parallel, maximum feasible reductions under the best technically feasible reduction (BFR) scenario in 2030 are estimated, representing optimal implementation of current mitigation technologies. A cost-benefit analysis further quantifies the economic costs and co-benefits of achieving maximum reductions, including benefits for ecosystem services, human health, and climate mitigation. We introduce an innovative SDG-target-driven framework to predict nitrogen emissions in 2030, offering a forward-looking view of how nitrogen management can align with global sustainability goals. By exploring potential changes in the global nitrogen cycle under viable SDG implementation, this study provides scientific insights to inform integrated nitrogen management strategies for a sustainable future.

RESULTS AND DISCUSSION

Nitrogen-related SDG challenges

To systematically assess the interplay between nitrogen and SDG progress, we developed an integrated scoring framework that links key nitrogen cycle components, including atmospheric emissions, leaching and runoff, and nitrogen use efficiency (NUE), with 12 nitrogen-related SDGs and 31 associated targets (Table S3). Incorporating socioeconomic dimensions, the framework provides a transparent, quantitative basis for evaluating global and regional progress on nitrogen-related SDGs. In this system, the average index score reflects overall national or regional performance in nitrogen emissions and management, with higher values indicating stronger progress toward relevant targets. A score of 0 indicates a complete failure to meet nitrogen-related sustainability targets, whereas a score of 100 represents full achievement of all targets. Given the urgency of the 2030 timeline, we define scores above 60 as reflecting balanced progress across nitrogen-related goals and scores above 75 as falling within the achievable range for meeting these targets by the deadline.

We found that the global average score was 66 (range: 45–90) in 2020 (Figures 1A and S1), with marked disparities across SDGs. SDG 2 scored the lowest, highlighting persistent challenges in achieving global food security. Indicators such as crop yield and NUE reveal a substantial gap between current agricultural practices and the zero-hunger target. In contrast, environmental SDGs (e.g., SDGs 13 and 15) generally scored higher than economic-focused goals (e.g., SDGs 7–12, excluding SDG 10), suggesting that the most critical nitrogen challenges occur in human-dominated systems, such as agriculture, industry, and waste management, while natural ecosystems experience comparatively lower nitrogen pressures. These findings underscore the need to prioritize nitrogen reductions in high-emission sectors to accelerate progress across multiple goals.

Regional differences further illustrate uneven challenges and opportunities (Figure 1B; Tables S4 and S5). High-income countries tend to perform better in several nitrogen-related SDGs, particularly SDGs 2, 6, 9, and 12. For example, OECD (Organization for Economic Co-operation and Development) countries averaged scores of 63 for SDG 2 and 88 for SDG 9, reflecting higher agricultural NUE, advances in clean industry, and sustainable infrastructure. Their mature industrial systems and nitrogen pollution control measures also support sustainable production and consumption.[31] In contrast, Sub-Saharan Africa and Small Island Developing States recorded nitrogen-related SDG 2 scores of only 25 and 20, respectively, reflecting extremely low agricultural productivity and associated food insecurity. Targeted interventions to improve nitrogen management and enhance sustainable agricultural practices are urgently needed in these vulnerable regions. Developing economies in East and South Asia also face severe challenges,[32] with the lowest regional score for SDG 13 driven by high nitrous oxide (N_2O) emissions, underscoring the importance of nitrogen mitigation for climate action.

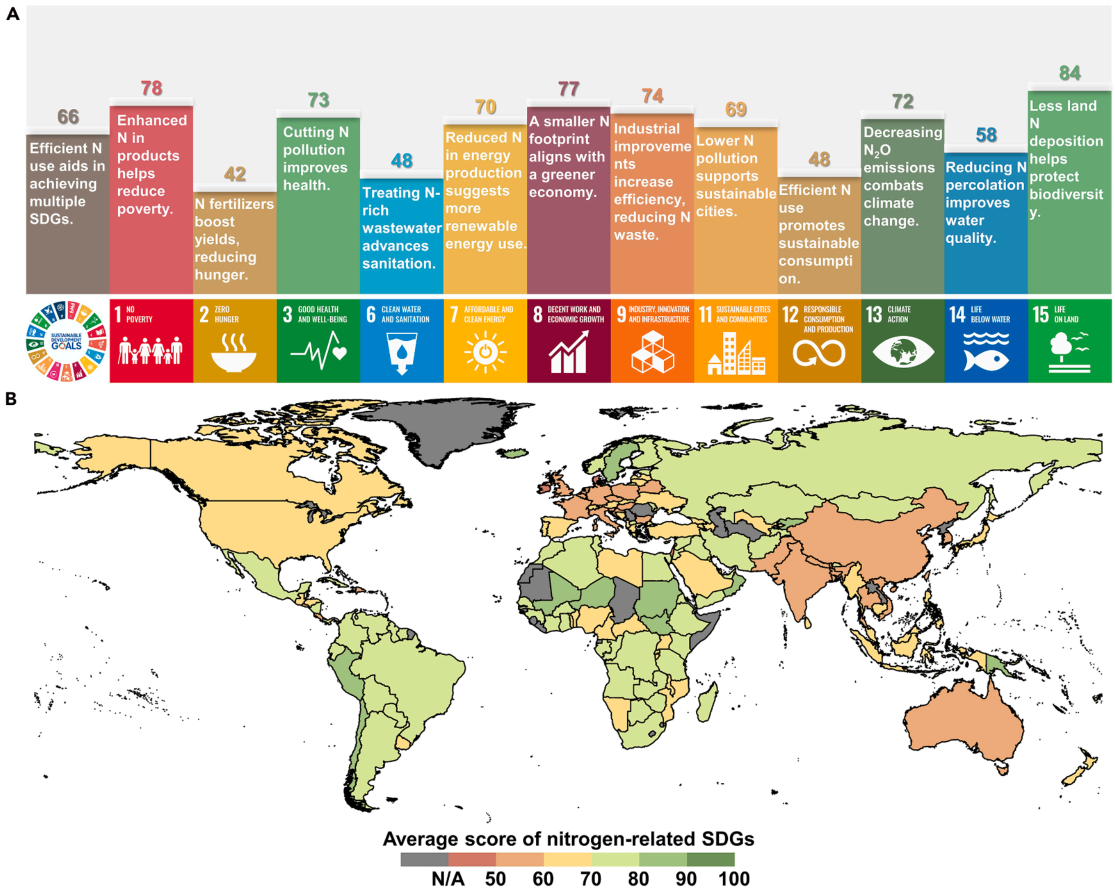

Figure 1. Global and regional average scores for nitrogen-related SDGs

(A) Global average scores for 12 nitrogen-related Sustainable Development Goals (SDGs) based on 2020 data. Average scores refer to the mean performance of each country or region across nitrogen-related indicators, reflecting their overall advancement toward relevant SDG targets.

(B) Spatial distribution of national average scores for 12 nitrogen-related SDGs.

The base map in (B) is applied from the Database of Global Administrative Areas (https://gadm.org/).

The nitrogen-related SDG scores presented here focus specifically on environmental and agricultural dimensions of nitrogen use rather than overall SDG performance. Lower-income countries tend to score poorly on SDGs 2 and 12 due to agricultural inefficiency and related socioeconomic challenges yet often score higher on environmental SDGs such as 3, 13, and 15, reflecting lower nitrogen-related pollution from less-intensive agriculture and limited industrial activity. Conversely, some high-emission regions, notably in East and South Asia, exhibit a complex balance, where industrial nitrogen use drives economic growth while intensifying environmental pressures. By explicitly linking SDG progress to nitrogen performance, this analysis provides a more nuanced perspective on sustainability, highlighting the need for regionally tailored strategies that integrate nitrogen management with broader development priorities.

Reshaping nitrogen for SDG achievement

Using the CHANS model, we estimated the global nitrogen budget in 2020 (Figure S3). We found that total nitrogen releases reached approximately 156 Tg (range: 122–186 Tg, 1 Tg = 10^9 kg), comprising ammonia (NH_3), nitrogen oxides (NO_x), N_2O, and nitrate (NO_3^-). NH_3 and NO_3^- accounted for the largest shares (Figure 2C), contributing 40% (63 Tg) and 36% (56 Tg) of total losses, respectively. Agriculture was the dominant source of NH_3 emissions, with croplands releasing 22 Tg (35% of the global total) and livestock farming contributing a further 34% through manure management. Croplands were also the largest source of NO_3^- contamination, with 16 Tg entering aquatic ecosystems in 2020. Household activities and waste management, including sewage and waste disposal, generated 34% of global NO_3^- emissions, highlighting the urgent need for improved wastewater treatment. Industrial activities were responsible for more than 70% of NO_x emissions, making industrial emission control a key mitigation priority. Although annual N_2O emissions were smaller at 7 Tg, their potency as a greenhouse gas makes them a major contributor to climate change.

Given the urgent 2030 timeline, we developed the NSA scenario to quantify the nitrogen reductions required to meet achievable nitrogen-related SDGs. This scenario assumes achievement of the nitrogen-related SDG targets under sustainable SSP1, maximizing the achievable potential for sustainable development. Under this scenario, total nitrogen releases would need to fall by 32% to 106 Tg (range: 86–126 Tg) by 2030. Specifically, NH_3, NO_x, N_2O, and NO_3^- emissions would decline to 42 (33%),

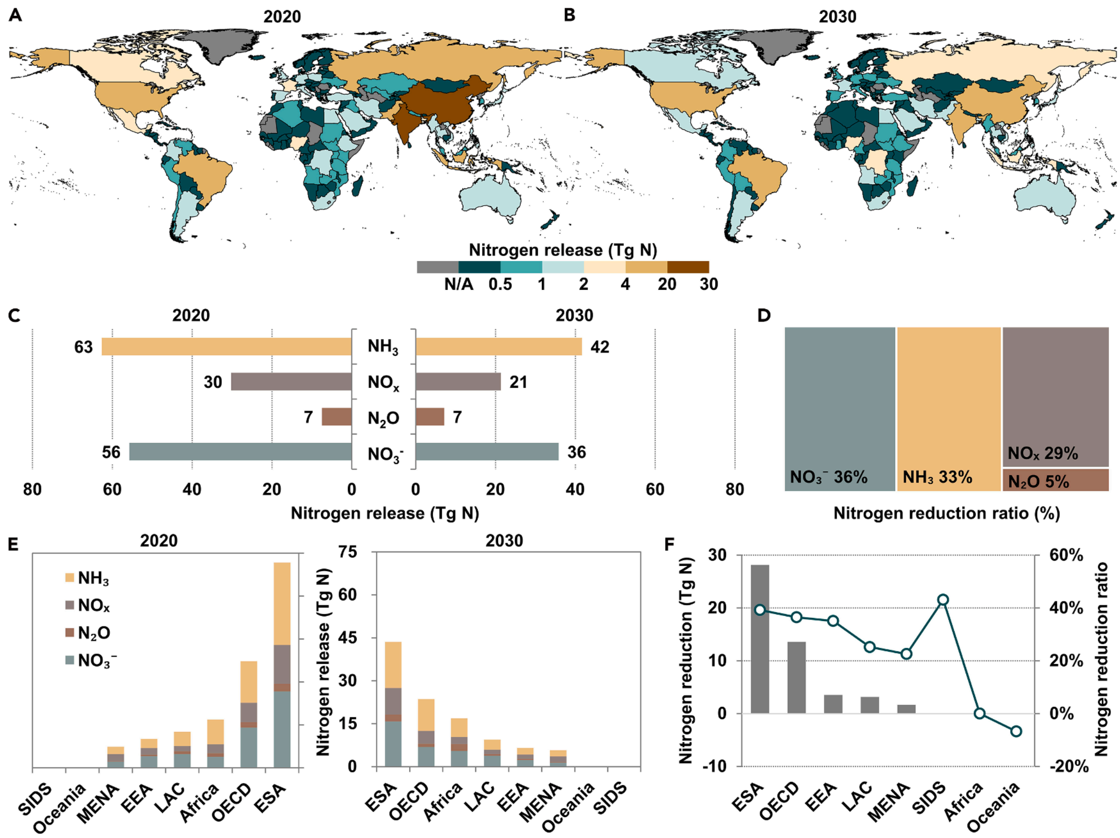

Figure 2. Global nitrogen releases in 2020 and under the NSA scenario

(A) Spatial distribution of global nitrogen releases in 2020.

(B) Spatial distribution of global nitrogen releases projected for the nitrogen-related SDG achievement (NSA) scenario.

(C) Comparison of total releases for ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), and nitrate (NO_3^-) between 2020 and the NSA scenario.

(D) The reduction ratio of NH_3, NO_x, N_2O, and NO_3^- in the NSA scenario compared to 2020.

(E) Comparison of NH_3, NO_x, N_2O, and NO_3^- losses across 8 regions (Organization for Economic Co-operation and Development members [OECD], Eastern Europe and Central Asia [EEA], Middle East and North Africa [MENA], Latin America and the Caribbean [LAC], East and South Asia [ESA], Sub-Saharan Africa [Africa], Oceania, and Small Island Developing States [SIDS]) in 2020 and under the NSA scenario. The specific country divisions can be found in Table S1 and Figure S8.

(F) Absolute (left *y* axis) and relative (right *y* axis) reductions in nitrogen releases across 8 regions in 2020 and under the NSA scenario.

The base map in (A) and (B) is applied from the Database of Global Administrative Areas (https://gadm.org/).

21 (29%), 7 (5%), and 36 (36%) Tg, respectively (Figures 2C and 2D). This reduction would raise the average nitrogen-related SDG to 79 (range: 63–100) (Figure S2). This indicates that even under a low-emission scenario (i.e., SSP1) in the future, global nitrogen emissions will still need to be reduced by approximately one-third to meet the achievable nitrogen-related targets within the set time frame.

Regional patterns reveal stark differences in reduction potential (Figure 2B). East and South Asia, responsible for 46% of global emissions in 2020, could cut emissions by 39% (28 Tg) under the NSA scenario, reflecting the scale of transition required. In Africa, the potential reduction is the smallest at 3%, constrained by population growth and the need to expand fertilizer use to boost food production. In such contexts, improving NUE is essential to minimize additional releases. Oceania, contributing less than 1% of global emissions, faces challenges similar to those of the least developed countries. Population growth and economic expansion could increase emissions by 7% by 2030, underscoring the need for proactive nitrogen management even in low-emission regions.

Although the NSA scenario outlines an ambitious pathway for nitrogen reduction, implementation will be challenging. While nitrogen control is not a prerequisite for all SDGs, it is critical for those directly linked to nitrogen, and its absence would undermine progress on multiple environmental and resource-related goals. Regions with high emissions, particularly East and South Asia, face the most demanding transitions across agriculture, industry, and wastewater management. Differentiated responsibilities and capacities must therefore be reflected in global strategies, supported by technology transfer, financial assistance, and governance reforms to translate ambitious targets into feasible action.

Technical mitigation potential

To assess the feasibility of achieving nitrogen mitigation targets under the NSA scenario by 2030, we developed the BFR scenario, which represents the highest plausible implementation

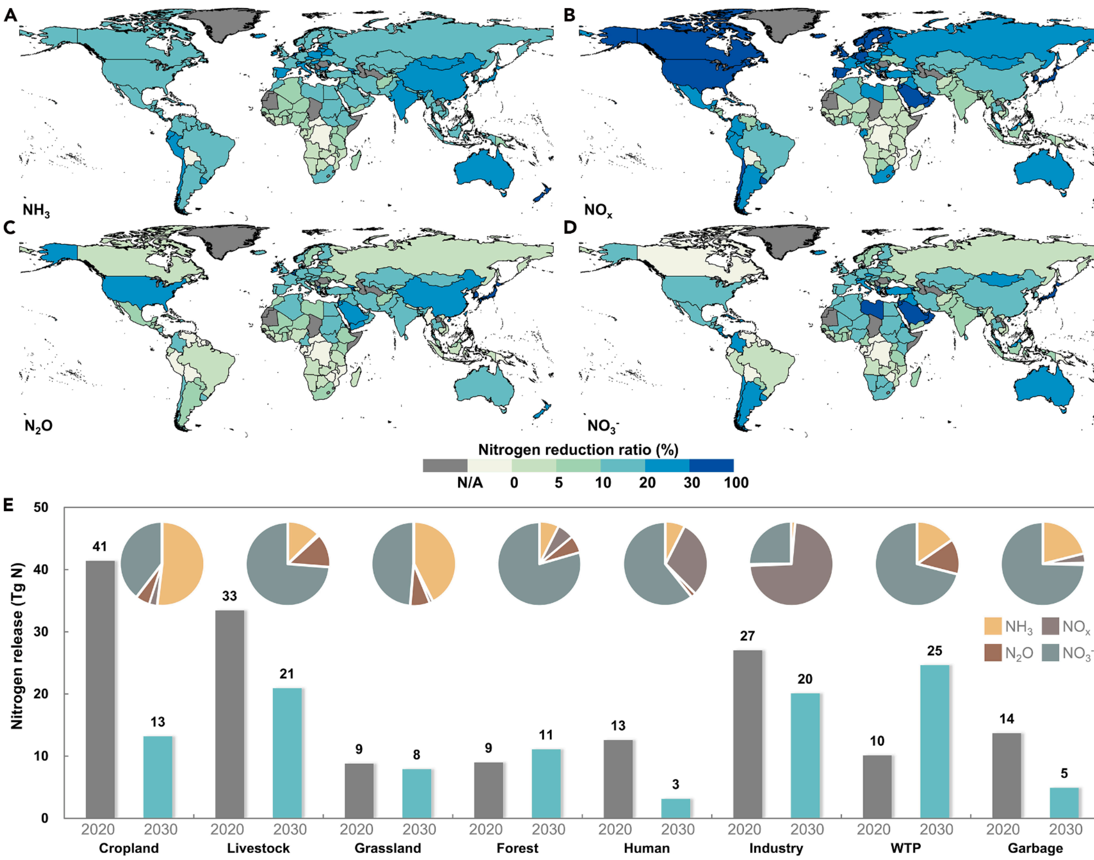

Figure 3. Nitrogen reductions under the BFR scenario

(A–D) Spatial reduction ratios of (A) ammonia (NH_3), (B) nitrogen oxides (NO_x), (C) nitrous oxide (N_2O), and (D) nitrate (NO_3^-) under the best technically feasible reduction (BFR) scenario. The reduction ratios refer to the percentage decrease in nitrogen releases in the BFR scenario compared to the 2020 baseline.

(E) Global reduction volumes of NH_3, NO_x, N_2O, and NO_3^- by 8 subsystems (WTP, wastewater treatment plants) under the BFR scenario. The reduction volumes indicate the absolute amount of nitrogen reduction under the BFR scenario relative to 2020. The 8 pie charts represent the proportion of increase or decrease in four nitrogen forms (NH_3, NO_x, N_2O, and NO_3^-) across 8 subsystems.

The base map in (A)–(D) is applied from the Database of Global Administrative Areas (https://gadm.org/).

rate of currently available mitigation technologies. The BFR scenario integrates 18 nitrogen management and mitigation combinations across six subsystems (Table S6) and assesses the reduction potential for four major nitrogen forms, aiming to balance nitrogen-related targets from a practical and attainable perspective.

Globally, the BFR scenario projects a 15% decline in nitrogen releases, reducing total losses to 132 Tg (range: 105–160 Tg). Reduction potential varies substantially among nitrogen forms. NO_x shows the largest relative decrease at 19% (6 Tg) (Figures 3B and 3E), driven primarily by industrial and household sectors, with reduction efficiencies of 24% and 7%, respectively (Figure S4B). These gains are enabled by technical measures such as household energy combustion control, exhaust gas treatment, and process improvements, indicating that these sectors should be prioritized for future technology deployment. NH_3 emissions could be reduced by 17% (11 Tg) (Figures 3A and 3E), with croplands contributing the largest share (6 Tg). However, on a sectoral basis, the industrial subsystem offers the highest overall mitigation potential, with reductions of up to 22%, underscoring opportunities beyond agricultural sources.

For N_2O, the BFR scenario achieves a 12% reduction (1 Tg) (Figures 3C and 3E). Notably, the main contributors to this reduction are industry and waste management, with efficiencies of 50% and 23%, respectively, rather than cropland and livestock systems, which account for most emissions. This highlights the importance of targeting complex, often overlooked emission sources through systemic interventions. NO_3^- losses to water remain dominated by agriculture, but mitigation is constrained by the diffuse nature of these sources, relying on less centralized measures, such as crop variety shifts and riparian buffer zones. In contrast, wastewater treatment plants and waste management systems can achieve reductions of 43% and 23%, respectively, through centralized treatment, making them critical to controlling nitrogen pollution in aquatic environments.

Regionally, the highest mitigation potential is found in high-emission, densely populated countries such as China and India (Figures 3A–3D). East and South Asia and OECD countries also demonstrate significant potential due to high baseline emissions and stronger economic capacity to invest in mitigation measures aligned with SDG targets.[33,34] By contrast, Latin America, the

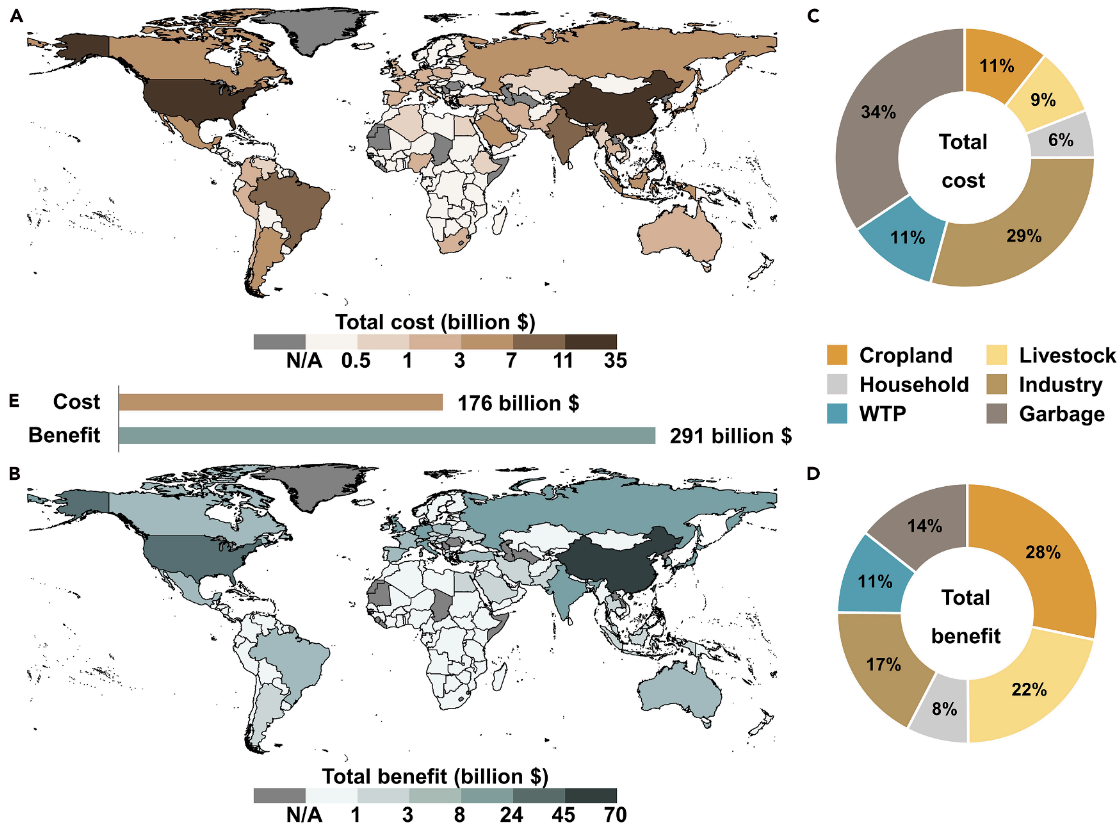

Figure 4. Cost and benefit analysis of nitrogen reductions under the BFR scenario
(A) Spatial distribution of nitrogen reduction costs under the best technically feasible reduction (BFR) scenario.
(B) Spatial distribution of nitrogen reduction benefits under the BFR scenario.
(C) Proportion of reduction costs across different subsystems (WTP, wastewater treatment plants).
(D) Proportion of reduction benefits across different subsystems.
(E) Comparison of total costs and benefits of nitrogen reduction under the BFR scenario.
The base map in (A) and (B) is applied from the Database of Global Administrative Areas (https://gadm.org/).

Caribbean, and Sub-Saharan Africa generally show reduction potentials below 10%, reflecting economic limitations that restrict large-scale implementation of available technologies. These disparities highlight the importance of international cooperation, particularly in technology transfer and financial assistance, to enable broader adoption of effective nitrogen management strategies.[35,36]

Comparing the BFR scenario with NSA targets reveals that, even under optimal technical deployment, current measures fall short of meeting nitrogen-related SDGs by 2030. The shortfalls for NH_3, NO_x, and NO_3^- are 10 (20%), 3 (13%), and 13 (27%) Tg, respectively (Figure S5). For N_2O, available technologies could exceed the NSA target by an additional 8% (Figure S5I), suggesting that this goal is technically attainable. These results indicate that while existing technologies can deliver substantial reductions, bridging the gap to NSA compliance will require institutional innovations, behavioral change, and policy-driven interventions. Overall, the BFR scenario underscores the challenge of achieving nitrogen-related SDG targets within the current decade. Closing the remaining gaps will require more efficient and innovative mitigation measures, supported by strengthened international collaboration to address technological and resource disparities and to accelerate progress toward sustainable nitrogen management.

Cost and benefit analysis

Based on global nitrogen release estimates under the NSA and BFR scenarios, we evaluated the implementation costs (ICs) of the BFR pathway and the associated economic and environmental co-benefits. Under the BFR scenario, the total global cost of implementing all nitrogen mitigation measures is estimated at \$176 billion (range: \$139–\$213 billion) (Figure 4E), with substantial variation across systems and regions. Solid waste management and industrial sectors require the highest investments, \$60 billion (34% of the total) and \$52 billion (29%), respectively (Figure 4C), reflecting both their mitigation potential and the capital-intensive nature of technology upgrades. The industrial sector's central role in reducing NO_x emissions, coupled with its potential for greenhouse gas abatement, underscores the need for targeted investment and policy support. Regionally, OECD members bear the highest costs (\$65 billion), driven by industry (\$22 billion) and waste management (\$25 billion), which together account for 73% of the regional total. East and South Asia, along with Latin America and the Caribbean, also face

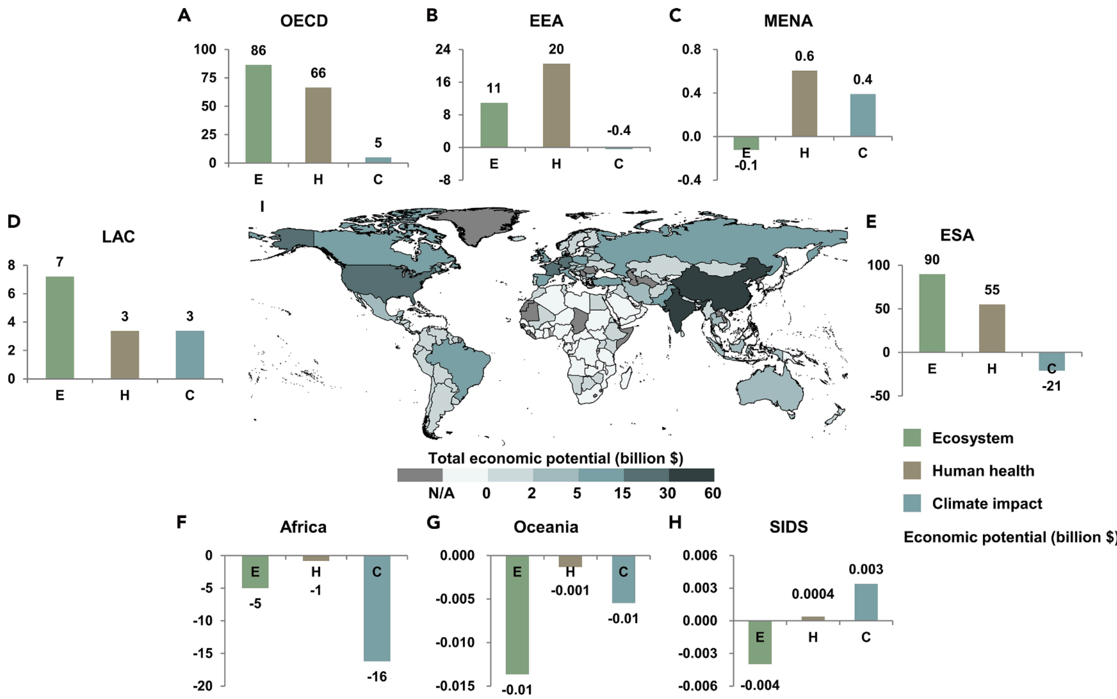

Figure 5. Potential economic benefits from achieving nitrogen-related SDGs

(A–H) The economic potential (E, ecosystem benefits; H, human health benefits; C, climate impact benefits) of nitrogen-related Sustainable Development Goals (SDGs) achievement across 8 sustainable development regions (SDRs): (A) Organization for Economic Co-operation and Development members (OECD); (B) Eastern Europe and Central Asia (EEA); (C) Middle East and North Africa (MENA); (D) Latin America and the Caribbean (LAC); (E) East and South Asia (ESA); (F) Sub-Saharan Africa (Africa); (G) Oceania; and (H) Small Island Developing States (SIDS).

(I) Spatial distribution of total economic potential. The negative economic potential values indicate that nitrogen reductions under the best technically feasible reduction (BFR) scenario already meet or exceed the nitrogen-related SDG achievement (NSA) scenario targets in these regions, resulting in no additional cost-effective potential.

The base map in (I) is applied from the Database of Global Administrative Areas (https://gadm.org/).

substantial investment requirements, with a combined $7.9 billion, approximately one-third of which is attributable to solid waste management. This highlights opportunities for advancing waste recycling, energy recovery, and circular economy models to enhance cost efficiency.

The total global economic benefits of nitrogen mitigation under the BFR scenario are estimated at $291 billion (range: $272–$311 billion) (Figure 4E), about 1.7 times the cost. These include $166 billion in ecosystem service gains and $151 billion in health improvements, partially offset by $25 billion in negative climate impacts (Figure S6). Among systems, cropland achieves the highest benefit-cost ratio, with benefits 4.4 times greater than costs (Figure S7B), reflecting low ICs for measures such as optimized fertilizer use and soil management, combined with large environmental and socioeconomic returns. Livestock and household systems also exceed a ratio of two, indicating strong cost-effectiveness. By contrast, industry and solid waste management have ratios below one, driven by high technological and infrastructure costs. These estimates do not include co-benefits from industrial controls, such as reductions in greenhouse gases and other air pollutants, which would likely improve their economic performance.

To explore the additional gains from achieving NSA scenario targets, we estimated the economic potential, the untapped socioeconomic value that could be realized by advancing from BFR-level mitigation to SDG-aligned reductions (Figure 5). Global economic potential is projected at $305 billion (range: $285–$326 billion), which could be unlocked through innovations in mitigation technology, policy incentives, and cross-sectoral investment strategies that lower costs and expand technical feasibility. High-emission countries such as China, India, and the United States hold the largest potential (Figure 5I). In contrast, Oceania and Sub-Saharan Africa exhibit negative economic potential (Figures 5F and 5G) because their BFR-level reductions already meet or exceed NSA targets, leaving little scope for additional cost-effective gains. Other regions retain significant untapped potential due to unmet nitrogen reduction targets under the BFR scenario.

Assessing economic potential is critical for identifying both challenges and opportunities in meeting the 2030 nitrogen-related SDGs. While barriers remain, mobilizing this potential can stimulate innovation, attract investment in sustainable industries, and reinforce the case for long-term economic and environmental returns. These future gains are often discounted in policy decisions due to short-term political and fiscal pressures. Instruments such as nitrogen pricing, targeted subsidies, and results-based financing could help internalize long-term societal benefits and offset immediate costs, enabling more ambitious and sustained action toward sustainable nitrogen management.

Policy implications and perspective

Achieving global nitrogen reduction within the SDG framework presents both significant opportunities and formidable challenges. The BFR scenario demonstrates considerable potential for lowering emissions across nitrogen forms and subsystems, yet even under optimal technical deployment, global efforts fall short of meeting the ambitious NSA targets. This underscores the need for phased, pragmatic approaches that balance economic, social, and technological realities. Socioeconomic transformation must be recognized as a structural enabler of sustained nitrogen mitigation rather than merely a supplementary measure. Institutional strategies can play a crucial role in complementing technical mitigation, helping to bridge the gap where current nitrogen mitigation technologies fall short of achieving nitrogen-related SDGs. Addressing nitrogen overuse will require fundamental shifts in production and consumption. Without confronting these underlying drivers, even the most advanced technologies cannot deliver durable outcomes. Integrating nitrogen strategies into broader efforts on sustainable development, poverty alleviation, and inclusive growth is therefore essential for advancing the SDG agenda.

Despite the mitigation potential identified in our scenarios, systemic barriers threaten real-world implementation. These include inadequate infrastructure for nitrogen recovery, limited financial and institutional capacity in low-income countries, low public awareness of nitrogen issues, and fragmented governance across sectors and jurisdictions. Removing these foundational obstacles is critical to sustaining progress. Investments in systems with high benefit-cost ratios, such as cropland, livestock, household, and wastewater treatment, can deliver substantial reductions and economic gains. Sectors with lower cost-effectiveness, such as industry, warrant a comprehensive evaluation that incorporates co-benefits from greenhouse gas abatement and air quality improvements. Aligning nitrogen reduction policies with broader environmental and climate objectives can amplify societal returns. Regionally, East and South Asia represent critical hotspots due to their high emissions and reduction costs, requiring targeted measures to improve resource use efficiency, facilitate technology transfer, and build institutional capacity. OECD countries offer opportunities to advance circular economy pathways by exploiting untapped potential in waste valorization and energy recovery. Such regional contrasts highlight the need for tailored mitigation strategies and strengthened international cooperation to address technological and financial disparities.

To align nitrogen management with the SDGs, governments should prioritize cost-effective, high-efficiency technologies, particularly for addressing diffuse non-point sources from agriculture. Integrating nitrogen strategies into broader policy agendas, such as climate action (SDG 13), clean water and sanitation (SDG 6), and sustainable agriculture (SDG 2), can improve policy coherence, strengthen synergies, and enhance resource efficiency. The economic potential quantified in the NSA scenario reinforces the long-term value of nitrogen mitigation, not only through environmental gains but also via avoided health costs and improved agricultural productivity. Although achieving the 2030 targets remains highly challenging, the substantial untapped potential provides a compelling incentive for more ambitious and coordinated action. Policies must extend beyond short-term reduction goals to establish robust technological, institutional, and governance frameworks that support adaptive and sustained nitrogen management well beyond 2030.

METHODS

Systematic literature analysis

Nitrogen plays a pivotal role in achieving the SDGs by 2030. This study systematically evaluates the diverse impacts of nitrogen on the SDGs, identifying both opportunities and challenges. A comprehensive literature review, supplemented by expert judgment, was conducted to analyze the bidirectional relationships between nitrogen and 12 SDGs. SDGs 4 (quality education), 5 (gender equality), 10 (reduced inequalities), 16 (peace, justice, and strong institutions), and 17 (partnerships for the goals) were excluded, as they focus primarily on social dimensions with limited direct linkage to nitrogen. The analysis considered four major nitrogen forms, NH_3, NO_x, N_2O, and NO_3^-, with other compounds such as nitrite (NO_2^-) and ammonium (NH_4^+) consolidated into their most stable end form, NO_3^-.

The assessment examined both positive and negative nitrogen-SDG interactions (Figure S1; Table S2) and quantified how progress toward individual goals could influence the global nitrogen cycle. Certain SDGs promote nitrogen efficiency through technological innovation and mitigation strategies, whereas others may unintentionally intensify nitrogen pollution through industrial expansion or agricultural intensification. Confidence levels for each finding were determined based on the strength of the literature and expert consensus. This integrated evaluation provides critical insight into the complex linkages between nitrogen management and sustainable development, informing targeted strategies to maximize synergies and minimize trade-offs.

Nitrogen-related SDG score

To evaluate interactions between nitrogen and progress toward the SDGs, we developed an integrated assessment framework comprising indicator selection, data normalization, and score computation. Indicator identification drew on multiple information sources and was guided by three criteria: (1) alignment with official UN SDG frameworks, including the UN's official SDG indicator list[37] and the 2023 Sustainable Development Report[38]; (2) direct relevance to nitrogen flows and processes represented in the CHANS nitrogen model[39]; and (3) data availability and cross-national consistency to ensure comparability. In addition to official UN indicators, nitrogen-specific metrics were derived to capture key nitrogen cycle components, including inputs, outputs, losses, and efficiencies. These indicators were integrated with socioeconomic datasets to construct a correlation matrix linking nitrogen dynamics to SDG performance (Table S3). Grounding the indicator set in policy frameworks, nitrogen modeling, and harmonized global datasets ensures a scientifically robust basis for comparing nitrogen management performance across countries.

To enable standardized cross-country and cross-SDG comparisons, all indicator values were normalized to a 0–100 scale, where 0 represents the worst observed performance and

100 the best. A perfect score indicates performance equivalent to leading global examples under a specific nitrogen-related SDG target, reflecting an optimal state of nitrogen governance. Improvements in pollution control, agricultural efficiency, and environmental governance are expected to increase scores, with nitrogen-related SDG performance advancing in parallel with overall SDG progress.

For pre-existing indicators from the 2023 SDR Index, published bounds were adopted.[38] New indicators were assigned upper and lower limits through a systematic framework combining distributional analysis and expert judgment.[11] To avoid confusion where lower values represent better outcomes, performance categories were expressed as "best performing" and "worst performing." National datasets were normalized using standard equations (Equation 1), and normalized values were aggregated into nitrogen-related SDG Index scores using the arithmetic mean.[11,38] Equal weighting was applied to all SDGs, consistent with global SDG assessment methodologies, which emphasize balanced advancement across all goals under the "leave-no-one-behind" principle. This approach reflects the normative commitment that all 12 nitrogen-related SDGs are interdependent and should be pursued simultaneously to prevent unintended trade-offs:

$$x' = \frac{x - x_{worst}}{x_{best} - x_{worst}} \times 100, \quad \text{(Equation 1)}$$

where x represents the original data value, x_{best} and x_{worst} denote the respective upper and lower boundaries for optimal and minimal performance, respectively, and x' is the resulting value after applying the normalization process.

CHANS model

The CHANS model represents the complete nitrogen balance across an integrated system of 14 interconnected subsystems: cropland, livestock, aquaculture, industry, urban greenland, humans, pets, wastewater treatment plants, garbage, forest, grassland, surface water, groundwater, and the atmosphere.[39] By accounting for nitrogen inputs and outputs in each subsystem, the model enables a comprehensive quantification of the system-wide nitrogen budget and the influence of both anthropogenic and natural drivers. In this study, the upgraded CHANS-global model consolidates these into eight subsystems by merging aquaculture, urban greenland, humans, and pets into a "household" category and grouping surface water, groundwater, and the atmosphere into environmental receptors. Environmental receptors are excluded from the analysis of systemic interactions.

The model operates on the principle of nitrogen mass balance at both the overall system and individual subsystem levels.[39,40] Nitrogen cycling begins with the activation of atmospheric N_2, either through biological or industrial processes or through direct import of reactive nitrogen from external sources, and ends when reactive nitrogen is either converted back to N_2 or exported from the system. Nitrogen accumulation is calculated as the difference between total inputs (e.g., fertilizers, feed, and biological nitrogen fixation) and total outputs (e.g., harvested products, runoff, leaching, and NH_3 and NO_x emissions) (Equation 2):

$$\sum_{a=1}^{d} IN_a = \sum_{b=1}^{e} OUT_b + \sum_{c=1}^{f} ACC_c, \quad \text{(Equation 2)}$$

where $\sum IN$ represents nitrogen inputs, $\sum OUT$ represents nitrogen outputs, and $\sum ACC$ represents nitrogen accumulation, denoting the net nitrogen change within the system.

For flows between subsystems, the flux in the donor subsystem equals that in the recipient subsystem, ensuring strict flux balance. This constraint provides consistency in flow estimates, reduces uncertainty, and enables robust quantification of nitrogen transfers across all components. Detailed nitrogen budgets for the eight subsystems, along with corresponding data sources, are provided in Notes S1 and S2.

Scenario analysis

To assess global nitrogen emission dynamics in line with nitrogen-related SDGs for 2030 and to evaluate the feasibility of achieving these goals, we designed two scenarios using the updated CHANS-global model.

NSA scenario

This scenario assumes the attainment of all 12 nitrogen-related SDGs by 2030, with socioeconomic conditions following the SSP1.[41] All nitrogen-related targets embedded within the SDG framework are considered balanced met, including global food security and nutrition, a 50% reduction in food waste, a green transition in energy systems, and full recovery and treatment of anthropogenic wastewater. Based on our nitrogen indicator framework (Table S3), countries that had already achieved or exceeded the best-performing emission levels in 2020 are assumed to maintain them, while underperforming countries are expected to reach the 2020 levels of the best-performing nations by 2030. The resulting global nitrogen emission budget represents the upper limit of sustainable nitrogen releases consistent with SDG realization, incorporating the socioeconomic trajectory projected under SSP1.

BFR scenario

This scenario reflects the maximum possible reduction achievable by 2030 through the deployment of currently available mitigation measures, assuming a sustainable development pathway consistent with SSP1. The analysis focuses on human-dominated systems, cropland, livestock, household, industry, wastewater treatment plants, and solid waste management, while natural systems such as grassland and forest, where human intervention is minimal, are excluded. National nitrogen budgets are estimated by applying optimal implementation rates of effective nitrogen mitigation measures compiled from extensive literature (Tables S7 and S8). Global nitrogen mitigation (ΔE_k) for each emission type k under the BFR scenario is calculated using reduction efficiencies and Equation 3:

$$\Delta E_k = \sum_s \sum_m EF_{k,s} \times AD_s \times M_{k,s,m} \times \mu_{k,s,m}, \quad \text{(Equation 3)}$$

where $EF_{k,s}$ represents the baseline nitrogen emission factor for a specific source s and nitrogen species k (i.e., NH_3, NO_x, N_2O, and NO_3^-); AD_s denotes the activity data of the source s, quantifying the scale of nitrogen-emitting activities; $M_{k,s,m}$ reflects the adoption level of mitigation measures for the specified source, measure, and species; and $\mu_{k,s,m}$ indicates the efficiency of the applied mitigation measure in reducing emissions for the specified source, measure, and species. Under conditions where no abatement strategies are deployed, $M_{k,s,m}$ defaults to 1, and $\mu_{k,s,m}$ is set to 0, implying unmitigated emissions. This dynamic formula facilitates nuanced modeling of emission reductions by incorporating diverse mitigation strategies across subsystems and regions.

To account for potential interaction effects among mitigation measures, we applied a sector-specific approach based on technological characteristics and data availability. In the industry and household subsystems, where measures often target the same emission processes (e.g., low-NO_x burners and staged combustion), technologies were treated as functionally overlapping. In these cases, the most representative or cost-effective option for each country was selected rather than aggregating effects, thereby avoiding overestimation of mitigation potential and reflecting practical implementation constraints. In contrast, for cropland and livestock systems, we drew on extensive experimental evidence regarding the independent and combined effects of multiple practices (e.g., split nitrogen application, nitrification inhibitors, anaerobic digestion, and low crude protein feeding). For measures identified as non-interacting, combined abatement rates were calculated using a multiplicative approach (Equations 4 and 5):

$$\eta_{A+B} = \eta_A + (1 - \eta_A) \times \eta_B \quad \text{and (Equation 4)}$$

$$\eta_{A+B+C} = \eta_A + (1 - \eta_A) \times \eta_B + [1 - (\eta_A + (1 - \eta_A) \times \eta_B)] \times \eta_C , \quad \text{(Equation 5)}$$

where A, B, and C are the different mitigation measures included in the combination and η_{A+B+C} denotes their respective abatement rates.

For interacting or overlapping measures, we applied empirically derived abatement efficiencies from studies evaluating their joint implementation rather than using the multiplicative formula. This approach explicitly accounts for both synergistic effects and diminishing returns, yielding more realistic estimates of nitrogen mitigation potential.

Cost and benefit analysis

The cost-benefit analysis in this study quantifies changes in atmospheric and aquatic nitrogen losses resulting from the adoption of mitigation measures across multiple subsystems. The cost of nitrogen reduction is defined as the direct expenditure, including initial investment and operational costs, required to implement these measures. Total costs are calculated by summing expenditures across six human-influenced subsystems: cropland, livestock, household, industry, wastewater treatment plants, and solid waste management. Cost estimates primarily draw on the greenhouse gas and air pollution interactions and synergies (GAINS) model (https://gains.iiasa.ac.at/models/index.html), which incorporates regional economic conditions, technological capacities, and operational requirements, including maintenance and social management. This ensures accurate and region-specific cost assessments. Additional cost data for specific measures were obtained from supplementary literature sources (Table S6). Detailed descriptions of the GAINS model methodology are available in its primary documentation.[42] The IC and total mitigation cost (TC) for country i by 2030 were calculated using Equations 6 and 7:

$$IC_{i,k} = \sum_m \Delta E_{i,k,m} \times UC_{i,k,m} \quad \text{and (Equation 6)}$$

$$TC_i = \sum_n \sum_k IC_{i,k,n} , \quad \text{(Equation 7)}$$

where k denotes a specific type of nitrogen losses; m refers to individual or combined mitigation measures; n represents the subsystems targeted for reductions; ΔE quantifies the reduction in nitrogen emissions, as calculated from Equation 3; and UC is the unit abatement cost associated with the most effective mitigation strategies.

For each country or region, the most representative or cost-effective mitigation measure was selected to avoid overestimating total ICs. When multiple measures were applied to the same subsystem or process, costs were calculated as the sum of individual unit abatement costs. This additive approach does not capture potential cost interactions, such as infrastructure sharing, scale efficiencies, or resource competition, due to the scarcity of detailed joint cost data in the literature. The assumption is consistent with methodologies adopted in previous large-scale studies.[43,44] In industry, household, and waste treatment subsystems, where measures often overlap in scope or target the same emission pathway, only the most representative or cost-effective measure was implemented in each region to avoid double counting. In contrast, agriculture-related subsystems often allow for compatible combinations of measures (e.g., controlled-release fertilizers with precision irrigation). In such cases, the total cost was calculated as the direct sum of unit costs for each measure. While this method may not capture potential additive or synergistic effects on costs, it provides a conservative and transparent estimate across sectors and regions, reducing the risk of underestimating total expenditures.

The social benefits ($SOC_{benefit}$) of reducing nitrogen emissions in a given country i are quantified as the sum of three components: ecosystem health benefits ($EH_{benefit}$), human health benefits ($HH_{benefit}$), and climate impact benefits ($CC_{benefit}$). The total social benefit for a specific nitrogen form k is represented as Equation 8.

$$SOC_{benefit,i,k} = EH_{benefit,i,k} + HH_{benefit,i,k} + CC_{benefit,i,k} \quad \text{(Equation 8)}$$

The environmental impacts of nitrogen are dominated by water pollution, including eutrophication and biodiversity loss in aquatic ecosystems from NO_3^- discharges. In terrestrial systems, the emission and deposition of reactive nitrogen contribute to soil acidification and declines in biodiversity. Unit ecosystem health benefits represent the avoided damage costs to ecosystems resulting from reduced nitrogen releases. These costs are derived from studies conducted in the United States and EU, which quantify the economic impacts of nitrogen-related ecosystem damage.[43,45–48] To enable global applicability, values are adjusted for differences in willingness to pay (WTP) for ecosystem services and for purchasing power parity. Specifically, unit nitrogen damage costs from the United States and EU are applied as proxies for other countries after accounting for regional economic conditions. The ecosystem health costs for a specific nitrogen emission form k in country i are calculated using Equations 9 and 10:

$$EH_{benefit,i,k} = \sum_{n} \Delta E_{i,k,n} \times UEH_{cost,i,k} \quad \text{and (Equation 9)}$$

$$UEH_{cost,i,k} = Ecost_{i,k,2020} \times \sqrt[\alpha]{\frac{PGDP_{i,k,y}}{PGDP_{i,k,2020}}} * \frac{Density_{i,k,y}}{Density_{i,k,2020}}, \quad \text{(Equation 10)}$$

where ΔE denotes the reduction in nitrogen emissions, calculated for various subsystems n; UEH_{cost} represents the unit cost of nitrogen damage to ecosystems, adjusted for WTP and purchasing power parity differences; $Ecost_{i,k,2020}$ denotes the baseline regional-specific unit nitrogen damage costs to the ecosystem; $PGDP_{i,k,y}$ and $PGDP_{i,k,2020}$ refer to the national GDP per capita in the year y and in 2020, respectively; $Density_{i,k,y}$ and $Density_{i,k,2020}$ refer to nitrogen emission density in kg N ha^{-1} in the year y and in 2020, respectively; and α is the coefficient for ecosystem damage cost adjustment and is derived by correlation analysis between past nitrogen damage costs and PGDP and emission intensity. This approach supports the evaluation of benefits and trade-offs associated with nitrogen management strategies across regions.

The human health benefits of nitrogen mitigation are primarily derived from reductions in atmospheric nitrogen pollution and associated particulate matter, particularly $PM_{2.5}$ (particulate matter with a diameter less than 2.5 μm), which poses substantial risks to human health.[44,49] Benefits include reductions in premature mortality and related healthcare expenditures, encompassing both direct costs (medical treatment and hospitalization) and indirect costs (productivity losses from illness or absenteeism). Unit human health benefits are estimated using the value of a statistical life (VSL) methodology, which assigns an economic value to avoided premature deaths. This calculation integrates local air pollution levels, the health impacts of nitrogen-related pollutants, and country-specific healthcare cost data. Adjustments are made for regional differences in income, purchasing power, and healthcare systems to ensure accurate representation across countries. National unit health damage costs of nitrogen emissions are derived from Gu et al.,[44] which link the economic cost of mortality per unit of nitrogen emission to population density, GDP per capita, urbanization rate, and nitrogen emission share. This approach captures regional economic and demographic disparities. The human health costs for nitrogen emission form k in country i are calculated using Equations 11 and 12:

$$HH_{benefit,i,k} = \sum_{n} \Delta E_{i,k,n} \times UHH_{cost,i,k} \quad \text{and (Equation 11)}$$

$$UHH_{cost,i,k} = Hcost_{i,k,2020} \times \sqrt[\beta]{\frac{PGDP_{i,k,y}}{PGDP_{i,k,2020}}} * \frac{Density_{i,k,y}}{Density_{i,k,2020}}, \quad \text{(Equation 12)}$$

where ΔE is the reduction in nitrogen emissions for subsystem n; UHH_{cost} represents the unit human health damage cost of nitrogen emissions; $Hcost_{i,k,2020}$ denotes the baseline national-specific unit health damage costs; and β is the coefficient for health damage cost and is derived by correlation analysis between past nitrogen damage costs and PGDP and emission intensity. This integrated approach ensures a robust and regionally nuanced evaluation of the human health benefits resulting from nitrogen emission mitigation strategies.

The benefits of climate change mitigation through nitrogen emission reductions are primarily derived from the reduction of nitrogen compounds such as NO_x and NH_3, which have direct and complex effects on climate systems. NO_x and NH_3 contribute to cooling, while N_2O is a potent greenhouse gas that significantly contributes to global warming.[50] The monetary evaluation of unit climate impact benefits involves calculating the reduction in nitrogen emissions and the associated climate impacts, which are regionally weighted to account for the varying climate sensitivities and emission profiles of different regions.[43,51] The climate change impact benefits for country i and nitrogen form k are calculated according to Equations 13 and 14:

$$CC_{benefit,i,k} = \sum_{n} \Delta E_{i,k,n} \times UCC_{impact,i,k} \quad \text{and (Equation 13)}$$

$$UCC_{impact,i,k} = Cimpact_{i,k,2020} \times \sqrt[\gamma]{\frac{PGDP_{i,k,y}}{PGDP_{i,k,2020}}} * \frac{Density_{i,k,y}}{Density_{i,k,2020}}, \quad \text{(Equation 14)}$$

where ΔE is the reduction in nitrogen emissions; UCC_{impact} represents the monetized climate impact per kg of nitrogen reduced, expressed in USD; $Cimpact_{i,k,2020}$ refers to the regional monetized climate impact in 2020; and γ is the coefficient for climate impact adjustment and was obtained by analyzing the relationship between historical damage costs and PGDP and emission intensity. This framework accounts for the dual effects of nitrogen compounds, balancing their cooling and warming impacts to evaluate the net climate benefits.

Uncertainty analysis

We employed 10,000 Monte Carlo simulations to quantify the uncertainty of nitrogen losses (NH_3, NO_x, N_2O, and NO_3^-) for 166 countries under the 2020 baseline, the BFR scenario, and the NSA scenario. The simulations incorporated multiple data sources and parameters, with uncertainty characterized by the coefficient of variation (CV) (Table S9). Activity data derived from official statistics or direct measurements exhibited relatively low CVs (5%–10%), whereas parameters drawn from literature or multi-source integration typically showed higher CVs (20%–50%). Emission factors and mitigation implementation rates had the highest CVs (often exceeding 50%–100%), reflecting substantial heterogeneity from both natural conditions and human factors.

Uncertainty in nitrogen loss estimates arises from both data limitations and simplifications in model assumptions. The CHANS model integrates data from sources such as FAOSTAT and the World Bank, using national-level nitrogen budgets to estimate emissions and environmental impacts. While this approach streamlines complex nitrogen cycling processes, it cannot fully capture spatial and temporal heterogeneity in biogeochemical dynamics, introducing potential biases. To address regional variation in technical capacity, socioeconomic conditions, and management practices, we sourced key parameters and CVs from region-specific literature wherever possible. This improved contextual accuracy in estimates of nitrogen fluxes, mitigation potential, and ICs. Incorporating spatially explicit data helped reflect localized variability in baseline conditions and mitigation feasibility, enhancing the policy relevance of results.

Nonetheless, the lack of high-resolution spatial and temporal data, together with model simplifications of spatial heterogeneity in biogeochemical and hydrological processes, may bias results. Mitigation efficiency and unit cost parameters exhibit high uncertainty, with many statistical distributions and CVs originating from earlier studies, notably Zhang et al.,[52,53] where differences in assumptions, resolution, and methods further contribute to variability. Nitrogen-related SDG scores, derived from emission-based indicators, are also influenced by the subjectivity of indicator selection, potentially omitting some dimensions of SDG performance. In the cost-benefit analysis, the assumption of constant unit costs at increasing implementation rates adds uncertainty, as costs can be affected by economies of scale, technological innovation, and local conditions.

Monte Carlo simulations generated data distributions for all variables and estimated ranges for global nitrogen releases, cost-benefit outcomes (Table S10), nitrogen-related SDG scores in 2020 (Table S11), and projected scores for 2030 (Table S12). All uncertainty ranges reported here are model-based plausible bounds rather than statistical confidence intervals, reflecting uncertainties in inputs, assumptions, and methodologies. Cropland and livestock emerged as the largest contributors to overall uncertainty, owing to the high sensitivity of emission factors and mitigation efficiencies to local conditions. Furthermore, our analysis of reactive nitrogen flows does not fully account for all environmental pathways or transformation processes. Although these uncertainties are systematic rather than random, they do not compromise the validity of spatial and temporal comparisons. Continued improvements in spatial-temporal resolution and nitrogen cycle modeling are expected to substantially enhance the accuracy of global nitrogen emission assessments.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to the lead contact, Baojing Gu (bjgu@zju.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

Data supporting the findings of this study are available within the article and its supplemental information. The source data are archived in Zenodo (https://doi.org/10.5281/zenodo.17666880). Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

B.G. conceived the idea. Y. Zhou conducted the research and data analysis. X.Z. provided support for the cost-benefit analysis. X.Z. and L.C. contributed to the development of mitigation measures. Y.Z. contributed to the mitigation measures and uncertainty analysis. X.X., Y.Z., Y.C., J.Z., H.T., and J.X. contributed to the construction of the CHANS-Global model. Y. Zhou and B.G. wrote the paper. O.D., M.P., J.G.-O., and C.M. contributed to the polishing of the paper. All authors contributed to the discussion and revision of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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