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Integrated assessment of the costs and benefits of reactive nitrogen emission and mitigation: a methodological review and framework proposal

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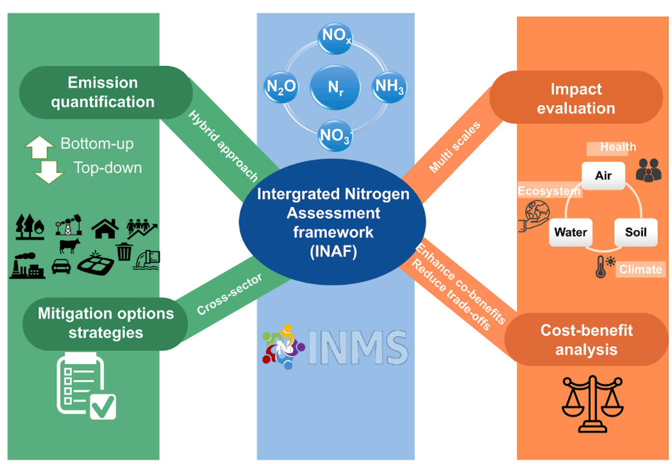
HIGHLIGHTS

- Comprehensive review of nitrogen emission and mitigation assessment methods.
- Identifies key methodological and data gaps across sectors and scales.
- Proposes an integrated assessment framework for Nitrogen.
- Supports evidence-based nitrogen management and policy design.

GRAPHICAL ABSTRACT



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ABSTRACT

Reactive nitrogen (N_r) emissions represent one of the most pressing challenges at the interface of environment, human health, and climate, yet their assessment remains methodologically fragmented and geographically uneven. This review synthesizes 398 studies from environmental science, environmental economics, agricultural systems, epidemiology, and ecosystem ecology published between 2000 and 2025 to evaluate the costs and benefits of nitrogen emissions and mitigation strategies. The methodological approaches discussed include emission inventories, cost-benefit analysis, and integrated assessment models that connect environmental and economic outcomes. We found that despite progress achieved through expanding global and regional studies, significant fragmentation persists in nitrogen assessment approaches, limiting the potential to provide generalizable insights and coherent policy recommendations. Moreover, comprehensive cost-benefit assessments of nitrogen management are often underdeveloped, with significant uncertainties and a lack of integration across

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environmental, economic, and societal dimensions. Building on this analysis, we propose an integrated nitrogen assessment framework (INAF) that systematically connects emission quantification, impact evaluation, mitigation cost and benefit analysis. This framework provides a pathway toward more comprehensive, transparent, and policy-relevant assessments. Our findings emphasize the urgent need for harmonized methodologies, cross-scale integration, and stronger interdisciplinary collaboration. By identifying knowledge gaps and outlining future directions, this review aims to accelerate the development of robust and actionable strategies for sustainable nitrogen management.

1. Introduction

Nitrogen (N) is a key element of the Earth system, indispensable to the formation of proteins and nucleic acids, vital for plant growth, and a cornerstone of agricultural productivity (Battye et al., 2017). The advent of the Haber–Bosch process for synthetic fertilizer production in the early twentieth century represents a pivotal innovation, enabling dramatic increases in global food supply and sustaining unprecedented population growth (Fowler et al., 2013). Yet, this achievement has come at a profound environmental cost (Galloway et al., 2003). Human activity now converts atmospheric dinitrogen (N_2), previously inert and inaccessible to most biota, into a suite of reactive nitrogen (N_r) compounds, including nitrogen oxides (NO_x), ammonia (NH_3), nitrous oxide (N_2O), and nitrate (NO_3^-), at scales that exceed natural biological fixation (Battye et al., 2017). This unprecedented perturbation of the nitrogen cycle has created a chronic surplus of N_r in the environment, generating pervasive externalities for ecosystems, human health, and the climate system (Brink et al., 2011; Erisman et al., 2013).

The consequences of excess N_r manifest across the interconnected spheres of the Earth's Critical Zone, the dynamic, life-sustaining system extending from the vegetation canopy through the soil to the groundwater, where rock, air, water, and living organisms interact (Fig. 1) (Brink et al., 2011; Erisman et al., 2013). In aquatic systems, nitrogen enrichment promotes eutrophication, algal blooms, and hypoxia, resulting in loss of biodiversity, fisheries collapse, and degradation of ecosystem services (Wurtsbaugh et al., 2019). In terrestrial ecosystems, chronic N_r deposition contributes to soil acidification, shifts in microbial processes, and reductions in plant species richness, particularly in nitrogen-sensitive habitats such as heathlands, alpine meadows, and peatlands (Bobbink et al., 2010; Phoenix et al., 2006). In the atmosphere, NO_x and NH_3 are critical precursors of secondary particulate matter ($PM_{2.5}$) and ground-level ozone, pollutants responsible for substantial global burdens of respiratory and cardiovascular disease (Gu et al., 2021a). At the planetary scale, N_2O plays a dual role as both a potent greenhouse gas, approximately 273 times more effective than CO_2 in radiative forcing over a 100-year horizon, and the single most significant ozone-depleting emission of the 21st century (Kanter et al., 2021; Uraguchi et al., 2009). These diverse impact pathways illustrate that nitrogen pollution is an overarching Critical Zone problem: a single emission creates a 'nitrogen cascade' across air, water, soil, and biota, amplifying environmental stress and complicating management responses in a truly systemic manner (Galloway et al., 2003).

This cascade of impacts poses a profound policy dilemma. On the one hand, nitrogen remains indispensable for maintaining food production and global food security (Lassaletta et al., 2016). On the other hand, the increasing environmental, health, and climate damage associated with its overuse represents mounting social and economic costs (Gu et al., 2021b; van Grinsven et al., 2025). Policymakers are confronted with an expanding portfolio of mitigation measures spanning agriculture, energy, waste management, and transport. Yet efforts to prioritize

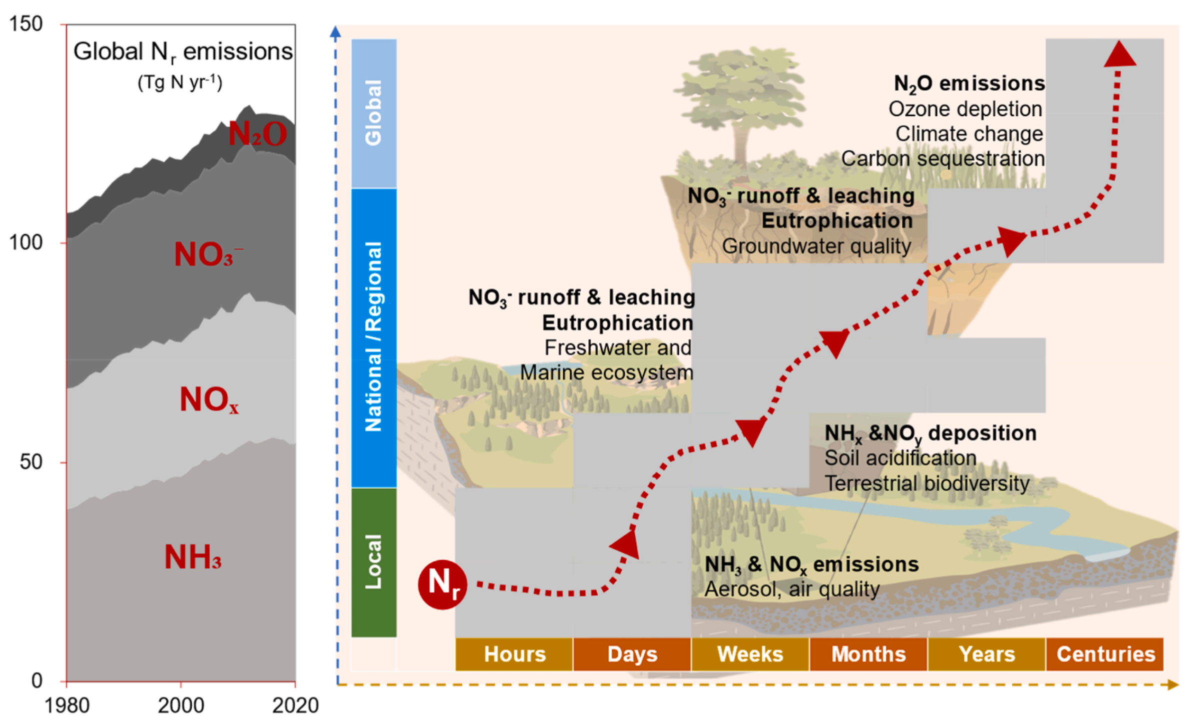

Fig. 1. Global reactive nitrogen (Nr) emissions (1980–2020) and their impacts across the critical zone.
The left panel presents a time series (1980–2020) of global Nr emissions (unit: Tg N yr^{-1}) estimated based on CHANS-Global model (Gu and Zhang, 2025), with stacked bars distinguishing key Nr species (NH_3, NO_x, N_2O, and NO_3^-). The right panel maps N_r impacts to four critical zone compartments: Atmosphere, Hydrosphere, Pedosphere and Climate system.

cost-effective interventions are constrained by a fragmented evidence base (Gu et al., 2021b). This fragmentation manifests in several ways. First, most existing assessments are sector-specific, pollutant-specific, or geographically limited (e.g., European cost-effectiveness studies that cannot be transferred to developing regions due to different economic conditions and practices). Second, methodological inconsistencies pervade the literature-emission factors for the same source vary by factors as much as 2 or 3 between different inventories (Zhang et al., 2017). Health impact valuations differ by orders of magnitude, depending on whether Value of Statistical Life (VSL) or Disability Adjusted Life Years (DALY) are used, and cost assessments may inconsistently include indirect expenses such as transaction costs and behavioral barriers. Third, temporal and spatial mismatches exist between emission sources and impact assessments, for example, agricultural NH_3 emissions may be quantified at farm scale while air quality models operate at regional scale, creating scaling uncertainties that compound through the assessment chain. Moreover, large uncertainties persist in emission inventories (Zhang et al., 2021), exposure–response relationships, and valuation of damages and benefits (van Grinsven et al., 2025), collectively impeding the development of integrated, coherent and robust N policies (Keeler et al., 2016).

This review aims to address these challenges by: (1) evaluating current methodologies for quantifying Nr emissions, impacts, and mitigation costs; (2) identifying key inconsistencies and data limitations across sectors and scales; (3) proposing an integrated nitrogen assessment framework (INAF) to systematically connect emission quantification, impact evaluation, and cost-benefit analysis (CBA) of nitrogen management; and (4) outlining priority areas for future research to advance sustainable nitrogen management.

2. Methods

2.1. Literature search strategy and selection criteria

A systematic and comprehensive literature search was conducted to identify relevant peer-reviewed publications, technical reports, and authoritative book chapters. Primary databases included Web of Science Core Collection and Scopus, supplemented by Google Scholar to ensure coverage of the grey literature and recent pre-prints. The search strategy employed a combination of keywords and Boolean operators tailored to the review's scope. Core terms included: ("reactive nitrogen" OR "nitrogen emission" OR "NH_3" OR "NOx" OR "N_2O" OR "NO_3^-") AND ("Pollution" OR "Impact" OR "cost" OR "benefit" OR "economic assessment" OR "cost-benefit analysis") AND ("mitigation" OR "management" OR "control" OR "abatement" OR "reduction"). The search was focused on literature published between 2000 and 2025 to capture the evolution of studies over the past two decades. The initial search results were screened based on titles and abstracts. Articles were included if they provided original data or critical analysis on the quantification, environmental-economic impact assessment, or cost-effectiveness of nitrogen emission mitigation strategies. Studies were excluded if they were not in English, focused solely on natural nitrogen cycling without an anthropogenic emission link, or addressed only laboratory-scale experiments without policy or assessment implications.

The systematic search initially retrieved 3847 records. After removing duplicates (n = 1205), we screened 2642 unique records by title and abstract. Of these, 2156 records were excluded for not meeting inclusion criteria: 892 focused solely on natural nitrogen cycling without anthropogenic emission links, 634 were laboratory-scale studies without policy implications, 387 were not available in English, 243 addressed only tangential topics (e.g., nitrogen in non-terrestrial systems). The remaining 486 full-text articles were assessed for eligibility, with an additional 178 excluded due to insufficient methodological detail (n = 89), focus on single-compound studies without broader Nr assessment context (n = 54), or lack of quantitative data on costs, benefits, or emissions (n = 35). This process resulted in 308 peer-reviewed articles forming the core of our analysis. This selection process is visually detailed in a PRISMA flowchart available in Supplementary Information (Fig. S1). To supplement the peer-reviewed literature, we included 67 technical reports from authoritative sources (IPCC, EMEP/EEA, EPA, FAO) and 23 book chapters from established nitrogen assessment compilations, bringing the total reviewed literature to 398 sources. The breakdown of included studies by assessment type, geographic distribution and temporal distribution is illustrated in Supplementary Figure S2.

2.2. Analytical framework: sectors, pollutants, and scales

To synthesize the fragmented literature into a coherent critical analysis, this review employs a multi-dimensional analytical framework. The identified literature is systematically categorized and evaluated along four primary axes to identify patterns, inconsistencies, and gaps. First, emissions and mitigation strategies are examined by source sector: agriculture (e.g., fertilizer application, livestock manure), energy and industry (e.g., fossil fuel combustion), transportation, and waste management. Second, the analysis distinguishes between key N_r pollutants, NH_3, NO_x, N_2O, and NO_3^-, recognizing their distinct formation pathways and environmental fates. Third, studies are compared across spatial scales, from local and watershed-level assessments to regional, national, and global analyses, noting the methodologies and challenges specific to each scale. Finally, the assessment dimension of each study is analyzed whether it focuses on environmental effectiveness (e.g., emission reduction potential), economic costs (e.g., marginal abatement cost), integrated social health benefits (e.g., avoided mortality costs), or a full cost-benefit analysis. This structured framework allows for a targeted critique of methodological harmonization and facilitates the identification of cross-cutting research priorities.

3. Current state of knowledge

3.1. Quantifying nitrogen emissions: inventories and models

The accurate quantification of N_r emissions is the foundational step for any subsequent assessment, yet it is burdened with methodological diversity and uncertainty. Our analysis of 127 emission quantification studies reveals that 73 % of reviewed studies highlight significant challenges in emission factor reliability. Emission estimates primarily rely on inventories, which are shaped by international guidelines such as the Intergovernmental Panel on Climate Change (IPCC) methodology for N_2O and the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) Guidebook, and U.S. Environmental Protection Agency (EPA) Emissions Inventory Improvement Program (EIIP) guidance for air pollutants like NO_x and NH_3 (EMEP/EEA, 2023; U.S.EPA, 2023; IPCC, 2019). These guidelines promote a standardized bottom-up approach, calculating emissions as the product of activity data (e.g., amount of fertilizer applied, livestock population, fuel consumption) and an emission factor (EF, the amount of pollutant released per unit of activity). While crucial, this approach is hampered by the significant uncertainty inherent in EFs, particularly for agricultural NH_3, which are highly sensitive to local environmental conditions, management practices, and soil properties (Beusen et al., 2008). In contrast, top-down methods, which combine atmospheric measurements with inverse modeling, provide an independent estimate and can help validate inventories (Luo et al., 2022; Ren et al., 2023). However, these methods face their own set of challenges. Depending on the specific nitrogen compound, appropriate spatial-temporal measurement density may not be available, or concentration signals may remain insignificant compared to high background concentrations (Luo et al., 2022). Ground-based and satellite observation studies have revealed systematic underestimation of urban N_r emissions in current inventories, with summertime urban NH_3 emissions potentially underestimated by factors of 2–3 in major cities like Beijing, highlighting critical gaps in urban emission characterization (Xu et al., 2023). These uncertainties are not uniformly distributed globally but are particularly pronounced in regions with limited monitoring infrastructure, inadequate data collection systems, and insufficient resources for developing locally specific parameters.

3.2. Evaluating the impacts: from environmental fate to socioeconomic costs

Translating emissions to physical impacts, and subsequently into socioeconomic costs, involves complex and often disconnected modeling chains, each introducing its own layers of assumptions and uncertainty. Our literature analysis of 156 impact evaluation studies reveals that atmospheric chemistry transport models are employed in 41 % of air quality impact studies, while hydrological models appear in 29 % of water quality assessments, indicating methodological fragmentation across environmental media.

For environmental endpoints, models are typically structured around the DPSIR (Driving Forces-Pressures-States-Impacts-Responses) framework (Ness et al., 2010), addressing both nitrogen pressures (e.g., emission rates, deposition fluxes) and environmental states (e.g., concentrations, exceedance of critical loads) (Table 1). Atmospheric chemistry transport models like CMAQ (Community Multiscale Air Quality Model), WRF-Chem (Weather Research and Forecasting model coupled with Chemistry), and EMEP MSC-W (European Monitoring and Evaluation Programme Meteorological Synthesizing Centre-West) (Simpson et al., 2012) are used to simulate the dispersion, chemical transformation, and deposition of emitted NO_x and NH_3 (pressures), providing estimates of environmental States such as secondary $PM_{2.5}$ concentrations and O_3 formation (Gao and Zhou, 2024). Critical issues remain inaccurately representing the complex chemistry of N_r species in air quality models, particularly regarding secondary aerosol formation and the interactions between different nitrogen compounds under varying atmospheric conditions (Zhang et al., 2024). For aquatic systems, hydrological and biogeochemical models (e.g., Soil and Water Assessment Tool (SWAT) (Gassman et al., 2007), Integrated Catchments model for Nitrogen (INCA-N) (Wade et al., 2002), Nutrient Export from WaterSheds (NEWS) (Seitzinger et al., 2010)) simulate the leaching of NO_3^- into groundwater and surface waters, predicting eutrophication potential and hypoxia. The quantitative outputs of these models (e.g., concentrations of $PM_{2.5}$, or NO_3^-, exceedance of critical loads for biodiversity) are then used to assess impacts. The valuation of these environmental impacts presents significant challenges. While certain ecosystem services affected by nitrogen, such as carbon sequestration

Table 1
Methods for valuing the societal impacts due to Nitrogen emission and mitigation.

Method	Description	Application	Limitation	Reference
Ecosystem impact				
Replacement Cost Method	Calculate cost of replacing degraded ecosystem services with artificial alternatives	Water treatment facilities replacing wetland filtration; artificial carbon capture replacing forest sequestration	May overestimate costs; doesn't capture all ecosystem functions	(Lu et al., 2018; Agaton and Guila, 2023)
Damage Cost Assessment	Measure direct economic losses from pollution impacts	Fishery losses, tourism decline, healthcare costs, agricultural productivity losses	Limited to measurable economic impacts; excludes intrinsic ecological value	(Del Rossi et al., 2023; Sampat et al., 2021)
Hedonic Pricing	Analyze pollution effects on property values	Property value changes near polluted water bodies or degraded forests	Assumes people have perfect information; limited to areas with property markets	(Ruankham, 2025)
Critical Loads	Threshold nitrogen deposition levels below which harmful effects do not occur	Evaluate risks of eutrophication and acidification: Forest: 10–20 kg N ha^{-1} yr^{-1}; grasslands: 5–15 kg N ha^{-1} yr^{-1}; wetlands: 5–10 kg N ha^{-1} yr^{-1}	Static thresholds; did not account for ecosystem recovery time; regional variation	(Bak, 2014; Hettelingh et al., 2017; Posch et al., 2015)
Willingness to Pay (WTP)	Estimates economic value by directly asking individuals about their willingness to pay for environmental improvements or to avoid damages.	Used to value non-market ecosystem services (e.g., biodiversity conservation, clean water aesthetics) and health outcomes. Often applied via Contingent Valuation Method (CVM) surveys.	Subject to various biases (hypothetical, strategic, information); high survey costs; results can be sensitive to survey design and cultural context; difficult to transfer values across regions.	(Lee et al., 2017; Moreira Da Silva et al., 2020)
Health impact				
Cost of Illness (COI)	Direct medical costs plus productivity losses from nitrogen-related diseases	Healthcare costs for respiratory diseases from NOx and NH_3; treatment costs for methemoglobinemia	Underestimates total burden; excludes pain and suffering	(Pascal et al., 2013)
Exposure (concentration)-Response Functions	Quantitative relationships between nitrogen exposure and health outcomes	Premature deaths from cardiovascular/ respiratory disease due to $PM_{2.5}$ from NOx and NH_3 emissions; methemoglobinemia or cancer mortality from nitrate exposure in drinking water	Difficult to isolate nitrogen effects from other pollutants; population variability in susceptibility	(Giannadaki et al., 2018; Pascal et al., 2013; WHO, 2016)
Value of Statistical Life (VSL)	Monetary value assigned to preventing premature death		Wide variation in VSL estimates across studies and populations	(Chen et al., 2015; Ciarlantini et al., 2025; Masterman and Viscusi, 2018)
Year of Life Loss (YLL)	Measures premature mortality by calculating years lost due to death before expected life expectancy		Assumes uniform value of life years across age groups; doesn't account for quality of life or morbidity	(Gu et al., 2021; Leksell and Rabl, 2001)
Disability-Adjusted Life Years (DALY)	Combines years of life lost (YLL) and years lived with disability (YLD) into single metric		Complex disability weight assignments; cultural and contextual variations in disability perception	(Logue et al., 2012)
Climate impact				
GWP Assessment	Convert N_2O emissions to CO_2 equivalents using warming potentials	100-year GWP of 273 for N_2O; integrated assessment of nitrogen's climate forcing	Fixed time horizon may not reflect actual climate impacts; uncertainty in atmospheric lifetimes	(IPCC et al., 2021; Lee et al., 2023)
Radiative Forcing Calculations	Quantify nitrogen's contribution to climate forcing	Direct N_2O forcing; indirect effects through ozone and aerosols derived from NH_3 and NO_x	Uncertainty in aerosol forcing; regional vs. global estimates	(Etminan et al., 2016; Hauglustaine et al., 2014)
Social Cost of N_2O	Marginal climate damage per unit N_2O emission	Dollar per tonne N_2O using damage cost models	Highly uncertain damage functions; ethical issues with discount rates	(Kanter et al., 2021; Keeler et al., 2016)
Carbon Market Integration	N_2O abatement in carbon trading systems	N_2O destruction projects in CDM; agricultural N_2O offsets	Measurement and verification challenges; additionality concerns; leakage effects	(Lee et al., 2011)

and crop yield enhancement, can be quantified using established economic methods (e.g., the Ecosystem Services Valuation Database, ESVD (Costanza et al., 2014; de Groot et al., 2012)), many other aspects, particularly biodiversity loss and cultural services, resist straightforward monetization. Traditional valuation approaches often fail to fully capture the complex and multifaceted nature of nitrogen's impact on ecosystem structure, function, and the essential services they provide to human societies. These limitations highlight the need for more nuanced and comprehensive methods to assess the true value of nitrogen's environmental effects.

For human health impact assessment, the change in pollutant concentration (e.g., the change in annual average $PM_{2.5}$ exposure for a population) is fed into concentration-response functions. These functions are derived from large-scale epidemiological studies (such as the Global Burden of Disease study) to estimate the attributable burden of disease, typically quantified in terms of premature mortality and morbidity (Cohen et al., 2017; WHO, 2016) (Table 1). However, the health impact assessment of nitrogen-derived air pollution faces the ongoing challenge of incorporating rapidly evolving epidemiological evidence. For instance, recent studies have expanded the range of health endpoints well beyond traditional cardiovascular and respiratory mortality to now include conditions such as diabetes, neurological disorders, cognitive decline, and adverse birth outcomes linked to $PM_{2.5}$ and O_3 exposure (Fu et al., 2019). Furthermore, the monetization of these health impacts is arguably the most consequential and controversial step. It predominantly relies on the Value of a Statistical Life (VSL) or the Value of a Life Year (VLY), whose values vary by orders of magnitude across countries and studies, often based on willingness-to-pay (WTP) studies, particularly from high-income nations (Masterman and Viscusi, 2018; Robinson et al., 2019). Alternative approaches estimate economic costs through forgone labor productivity and direct medical expenses (Holland, 1995). While WTP and human capital approaches typically yield comparable cost estimates for mortality, medical costs generally represent a much smaller proportion of the total economic burden. The transfer of these values across different socioeconomic contexts continues to raise important ethical and methodological questions regarding equity in environmental health valuation (Seleznova et al., 2021).

For the climate endpoint, the impact of N_2O is typically assessed by converting emissions into CO_2-equivalents using Global Warming Potential (GWP) values reported by the IPCC et al. (2021), for example, 273 over a 100-year timeframe in AR6 (Lee et al., 2023), reflecting improved understanding of atmospheric chemistry and radiative forcing mechanisms (Table 1). These CO_2-equivalents are then monetized by multiplying with a social cost of carbon (Ricke et al., 2018; Tol, 2023) or a shadow carbon price (Althammer and Hille, 2016) to estimate climate damages. Both the choice of GWP timeframe (100-year vs. 20-year) and the selected carbon price (which can range from $<$\$10 to $>$\$200 per ton CO_2) are major sources of variability in the final cost estimate.

A key limitation in current assessments is the persistent lack of integration across environmental media. Most studies evaluate impacts in isolation, health studies have used $PM_{2.5}$ concentrations without tracing them to specific nitrogen sources (Cohen et al., 2017), while many water quality analyses have not counted the air pollution co-benefits of fertilizer reduction (Sobota et al., 2013). Such a siloed approach systematically underestimates the mitigation benefits and could lead to inefficient policy decisions. Recent advances in multi-species emission modeling have demonstrated the importance of considering N_r compounds collectively rather than in isolation (Zhang et al., 2025), as emission processes and mitigation strategies often affect multiple species simultaneously. Achieving such integration requires substantial coordination across sectoral experts, rigorous data harmonization, model coupling, and sustained resources, and hence it is highly challenging. Successful implementations have been demonstrated in the European Nitrogen Assessment (ENA), which has quantified that environmental costs of nitrogen pollution in the EU ranged from €70–320 billion annually, substantially exceeding the estimated €20–80 billion in agricultural benefits from nitrogen fertilizer use (Sutton et al., 2011). Subsequent work by Food and Agriculture Organization (FAO, 2025) and through the International Nitrogen Management System (INMS, 2025) has developed more sophisticated frameworks that explicitly track nitrogen flows across environmental compartments while quantifying associated health, ecosystem, and climate impacts. The latest integrated nitrogen cost-benefit analyses (NCBAs) highlight the need for better regional integration and the inclusion of diverse nitrogen impacts, emphasizing the value of considering both short-term and long-term outcomes of nitrogen management strategies (van Grinsven et al., 2025), a contribution to the International Nitrogen Assessment. Despite progress, challenges remain in consistently valuing ecosystem services like biodiversity loss, particularly in data-scarce regions. Spatial and temporal mismatches between nitrogen emissions and their impacts continue to present methodological difficulties, highlighting the need for further refinement of integrated assessment approaches.

3.3. Assessing mitigation options: potential, costs and benefits

Evaluating the mitigation potential and implementation cost of nitrogen pollution mitigation options differs significantly across economic sectors and the type of option (technological, behavioral, or political) (Table 2). These discrepancies present considerable challenges for comparing and prioritizing options across different areas of the economy. The agricultural sector, generally being considered the largest source of nitrogen emissions, employs a wide array of mitigation approaches that are heavily influenced by local conditions (Gu et al., 2021b). These strategies encompass improved nutrient management through advanced fertilizers and precision farming techniques, low emission application, enhanced animal husbandry practices that reduce nitrogen excretion and improve manure handling (Pomar and Remus, 2023), and broader structural changes such as dietary modifications (Lassaletta et al., 2014) and food waste reduction (Chen et al., 2025). The effectiveness and economic viability of these measures show considerable variation, as shown in Table 3. Although many of these approaches can potentially reduce costs for agricultural producers, their widespread implementation faces obstacles including established practices, risk perceptions, and knowledge gaps (Ren et al., 2022).

In contrast, mitigation approaches in the energy and industrial sectors typically involve more technological solutions. The reduction of NO_x emissions in these sectors frequently employs advanced systems such as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) technologies (Palash et al., 2013). While these systems demonstrate high effectiveness in emission control, they require substantial capital investment and ongoing operational expenses (EPA, 2023), making them particularly suitable for large stationary sources like power generation facilities and industrial plants (Krupnick et al., 2000). The transportation sector is undergoing more fundamental changes in its approach to emission reduction, particularly through the adoption of electric vehicles that eliminate direct nitrogen oxide emissions at the point of use (Bradley and Jones, 2002), alongside increasingly stringent emission standards that drive the development and implementation of advanced engine and exhaust treatment technologies (Boulter et al., 2012).

The primary methodology for comparing the economic efficiency of different mitigation options is the Marginal Abatement Cost Curve (MACC) framework (Fig. 2), which organizes various measures according to their cost-effectiveness in reducing nitrogen emissions (Klimont and Winiwarter, 2011; Winiwarter et al., 2010). The Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model has been particularly instrumental in developing these cost curves, providing integrated assessment of emission control potentials and costs across multiple sectors and pollutants, including NH_3, NO_x, and N_2O emissions from agriculture, energy, and industrial sources (Klimont and Winiwarter, 2011). The model has been extensively applied to evaluate

Table 2
Methods for estimating the implementation costs of Nitrogen mitigation.

Specific Method	Description	Application	Limitations	References
Technology cost				
Marginal Abatement Cost Curves (MACCs)	Cost-effectiveness ranking of emission reduction technologies	Agricultural MACCs for NH_3, N_2O reduction; industrial NOx control technologies; wastewater treatment upgrades	Static technology assumptions; doesn't account for learning curves; limited behavioral responses	(Klimont and Winiwarter, 2011; Winiwarter et al., 2017; Zhang et al., 2022)
Engineering Cost Models	Bottom-up technology cost estimation	Selective catalytic reduction (SCR) for power plants; anaerobic digestion for livestock; precision fertilizer application	Technology-specific; doesn't include system interactions; limited scalability analysis	(EPA, 2023; Krupnick et al., 2000)
Learning Curve Analysis	Technology cost reduction over time with deployment	Cost decline of renewable energy reducing NOx; precision agriculture technology adoption	Historical data dependency; uncertain future innovation rates; market structure effects	(Das et al., 2020; Söderholm and Sundqvist, 2007)
Policy cost				
Regulatory Impact Assessment	Comprehensive cost-benefit analysis of nitrogen policies	EU Nitrates Directive costs; US CAFE standards for NOx; fertilizer taxes and subsidies	Baseline scenario dependency; distributional effects; indirect costs	(Kuhn et al., 2019; Van der Straeten et al., 2012)
Carbon Pricing Integration	Joint analysis of carbon and nitrogen pricing	N_2O inclusion in carbon markets; co-benefits of climate policies for N reduction	Price volatility; monitoring challenges; leakage effects	(Niles et al., 2019; Singh et al., 2022)
Behavioral cost				
Adoption Cost Models	Costs including behavioral barriers to technology uptake	Transaction costs; information barriers; risk preferences; social norms in adoption	Quantification challenges; heterogeneous responses; policy design sensitivity	(Brick and Visser, 2015; Tate et al., 2011)
Nudging and Incentives	Behavioral intervention costs for N reduction	Information campaigns; social comparison programs; certification schemes	Effectiveness measurement; long-term persistence; spillover effects	(Mertens et al., 2022; Tor, 2022)

Note: Methods focus on the four core Nr-emitting sectors (agriculture, energy/industry, transport, waste management). Behavioral cost methods address a key gap in existing N_r assessments, emphasizing agricultural sector-specific barriers.

Table 3
Comparative analysis of key agricultural nitrogen mitigation strategies.

Mitigation Strategy	Primary N Pollutant Targeted	Indicative N Loss Reduction efficiency (%) [a]	Indicative Abatement Cost (US$/kg N reduced) [b]	Key Co-benefits or Trade-offs	Key References
Enhanced-Efficiency Fertilizers (EEFs)	N_2O, NH_3, NO_3^-	20–50	−5 to 10	Reduces GHG emissions (N_2O); Improves water quality	(Gu et al., 2021; IPCC, 2019)
Precision Agriculture (VRT) [c]	N_2O, NH_3, NO_3^-	10–30	−10 to 15	Reduces fertilizer costs; Improves farm profitability	(Gu et al., 2021; Ren et al., 2022)
Low-Emission Application (Injection/Band Spreading)	NH_3	60–90	5 to 20	Retains more N value in manure; Potential to increase N_2O emissions	(Klimont and Winiwarter, 2011; Pomar and Remus, 2023)
Manure Storage Covers	NH_3	50–80	10 to 25	Reduces odor; Capital investment cost	(IPCC, 2019; Winiwarter et al., 2010)
Low Protein Feed	NH_3, N_2O	10–30 (from excretion)	−5 to 5	Can reduce feed costs; Improves animal health	(Lassaletta et al., 2014; Pomar and Remus, 2023)
Cover Crops/Legume Integration	NO_3^- (leaching)	30–70	10 to 30	Improves soil health & carbon; Reduces soil erosion	(Gu et al., 2021; Sutton et al., 2011)

Note.
[a] Represents the percentage reduction in losses of the primary targeted N pollutant compared to a conventional baseline practice (e.g., broadcast application of urea).
[b] Represents the net cost to implement the measure per kilogram of N emission reduced. Negative values indicate a net economic benefit (i.e., the savings are greater than the costs). The range reflects variations in technology costs, labor, and potential yield impacts.
[c] VRT: Variable Rate Technology.

policy scenarios and identify cost-effective mitigation portfolios at regional and global scales. Agricultural NH_3 abatement costs typically range from negative costs (cost-saving measures) up to €1000 per tonne N reduced, while industrial NO_x control technologies generally fall within €1000–5000 per tonne N reduced, depending on the specific technology and implementation scale. In this context, the development of reliable and comparable cost curves faces several significant challenges. First, the inconsistencies in how costs are accounted for across different studies, with variations in whether only direct investment costs or additional expenses such as transaction and operational costs are included (Brink et al., 2005; EPA, 2013). The results are also highly sensitive to baseline assumptions regarding energy prices and regulatory frameworks. Furthermore, most assessments fail to incorporate the full range of benefits associated with emission reduction (Van Grinsven et al., 2013; Zhang et al., 2020), particularly those related to improvements in air and water quality, leading to potentially misleading estimates of net costs. These methodological variations and frequent omissions of important co-benefits create challenges in comparing results across studies and sectors (van Grinsven et al., 2025). Adding in differences of local situations between studies, the current state of mitigation cost assessment provides decision-makers with limited and sometimes inconsistent information, limiting its utility for identifying the most economically efficient pathways for comprehensive nitrogen management.

4. Toward an integrated assessment framework for nitrogen

4.1. The pillars of integration: emission, impact, and cost-benefit analysis

The scarcity of truly integrated assessments in our literature review (only 26 studies, 6.5 %) demonstrates the urgent need for the systematic framework. Specifically, our analysis revealed that a landscape of

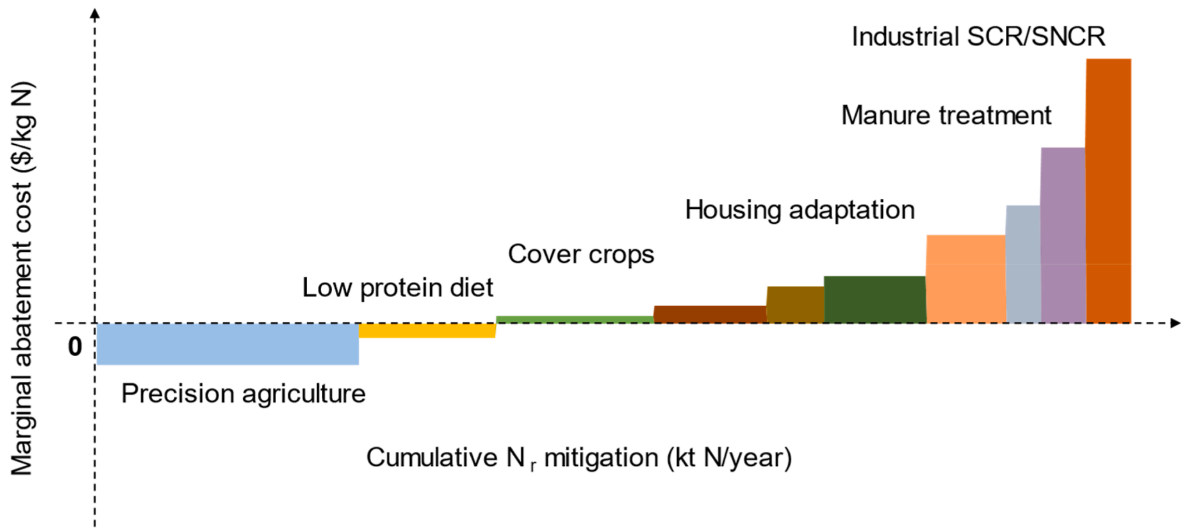

Fig. 2. Conceptual Marginal Abatement Cost Curve (MACC) for Nitrogen mitigation
The y-axis represents the marginal abatement cost, the cost in US dollars to reduce 1 kg of reactive nitrogen emissions. The x-axis represents the cumulative abatement potential in kilotons of N per year achieved by implementing these measures sequentially. Each bar represents a distinct mitigation measure. The height of the bar indicates its cost-effectiveness, while the width indicates its total potential to reduce N emissions annually. Measures are arranged from the most economically favorable (left) to the most expensive (right):Negative cost options (below the x-axis)are "no-regret" or "low-hanging fruit" measures, such as precision agriculture, which can reduce N losses while also generating net economic savings for the user (e.g., through reduced fertilizer costs).Positive cost options (above the x-axis) are measures require a net investment to implement, with costs increasing for more technologically advanced or capital-intensive options like industrial Selective Catalytic Reduction (SCR).

methodological fragmentation impedes coherent policy formulation. To address this, we propose a comprehensive Integrated Nitrogen Assessment Framework (INAF) designed to systematically connect knowledge domains that are often treated in isolation. This framework, illustrated conceptually in Fig. 3, is built upon four interlocking pillars that form a coherent analytical pathway from emission sources to policy-relevant outcomes.

The first pillar, Emission Quantification, serves as the foundational step, generating robust and spatially explicit emission inventories. Moving beyond reliance on any single methodology, it advocates for a

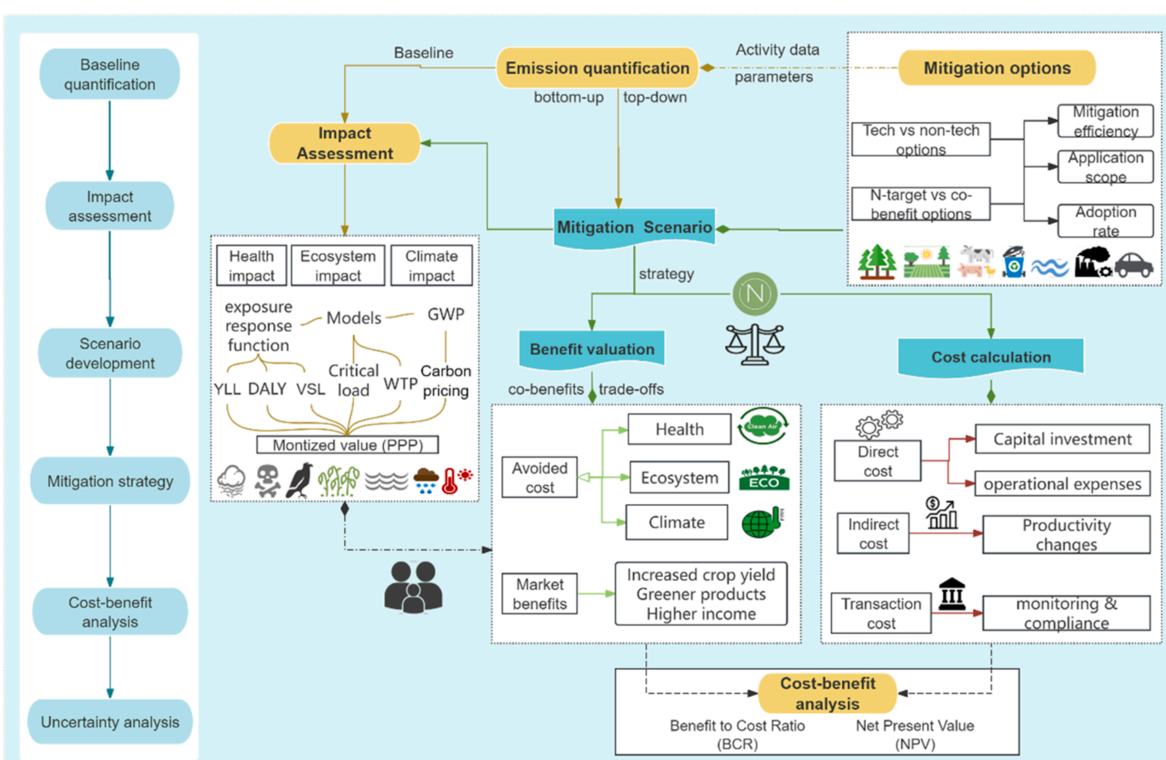

Fig. 3. Integrated Nitrogen Assessment Framework (INAF)
Four interlocking pillars of the proposed INAF include emission quantification, impact assessment, mitigation scenario and cost-benefit analysis. GWP, Global Warming Potential; YLL, Year of Life Loss; DALY, Disability-Adjusted Life Years; WTP, Willingness to pay; VSL, Value of Statistical Life; PPP, Purchasing Power Parity.

hybrid approach. This integrates refined bottom-up inventories with top-down verification through atmospheric measurements (e.g., satellite remote sensing) and inverse modeling (Dammers et al., 2016; Liu et al., 2016). This interaction is crucial for significantly reducing uncertainties, particularly for diffuse agricultural sources like NH_3, and for reconciling discrepancies between reported emissions and observed atmospheric concentrations. The output helps to improve existing inventories and provides a more reliable, spatial-temporally explicit emission field, an essential input for subsequent impact modeling.

The second and most complex pillar, Impact Evaluation, is the core integrative engine of the framework. It is designed to trace the multimedia fate of multi Nr emissions (air, water, land) and their multi-endpoint consequences on the same page. This requires the coupling of complementary models: atmospheric chemistry transport models simulate the dispersion and chemical transformation of NO_x and NH_3 into secondary $PM_{2.5}$ and O_3; hydrological and biogeochemical models track the leaching and runoff of nitrate into water bodies, predicting eutrophication risks; and terrestrial ecosystem models estimate the impacts of nitrogen deposition on biodiversity and soil acidification. The outputs from these models (e.g., changes in $PM_{2.5}$ concentration, nitrate levels in rivers, exceedance of critical loads) are then translated into impacts on human health (e.g., premature mortality, morbidity), ecosystem services (e.g., loss of fisheries, crop damage), and climate forcing (via N_2O). Model coupling is achieved through three primary mechanisms: (1) Sequential coupling, where emission outputs from one model serve as inputs to downstream models (e.g., atmospheric deposition fields from CMAQ feeding into terrestrial ecosystem models); (2) Iterative coupling with feedback loops, where ecosystem responses modify emission patterns in subsequent time steps (e.g., vegetation changes affecting ammonia volatilization rates); and (3) Data harmonization protocols that ensure consistent spatial and temporal resolution across model domains, typically involving regridding to common coordinate systems (e.g., $0.1^\circ \times 0.1^\circ$ grid cells) and synchronizing time steps (hourly to monthly depending on process timescales). A key innovation of this pillar is its design to capture co-benefits and trade-offs across media, ensuring that a mitigation action in one sector (e.g., reducing agricultural NH_3) is evaluated for its potential consequences in another (e.g., changes in N_2O emissions or nitrate leaching).

Our analysis of 89 cost-benefit studies revealed that 67 % fail to account for co-benefits across sectors, directly motivating the comprehensive approach outlined in our third pillar of mitigation option assessment. Established frameworks, e.g., GAINS, have already integrated co-benefits across sectors for atmospheric emissions (notably beyond nitrogen alone) (Amann et al., 2011). Building on this precedent, our mitigation-option assessment has been framed to cover the full spectrum of available measures, ranging from technology-based interventions (e.g., advanced fertilizers, precision application systems, manure treatment technologies) to non-technological approaches (e.g., changes in dietary patterns, food waste reduction, improved farm management practices). This assessment not only distinguishes between options that directly target nitrogen reductions, but also those that deliver nitrogen mitigation as a co-benefit of broader environmental or health objectives (Guo et al., 2024). It involves identifying and characterizing a portfolio of abatement strategies across key sectors (agriculture, industry, energy, transport), then quantifying the associated costs. These include direct capital investment, operational and maintenance expenses, indirect cost from workforce training, regulatory compliance, potential productivity change, monitoring, and transaction costs. Crucially, it also accounts for potential cost savings (e.g., reduced fertilizer expenditure from precision farming). The assessment ensures consistent cost boundaries and baseline assumptions across different measures to enable fair comparison.

The fourth pillar, Integrated Cost-Benefit analysis, combines the monetized benefits (avoided damage costs based on Pillar 2) and the implementation costs (from Pillar 3) into policy-relevant metrics. It employs rigorous probabilistic analysis (e.g., Monte Carlo simulations) to propagate uncertainties throughout the assessment chain, presenting results not as single-point estimates but as probability distributions. The final output is a set of comparable metrics, such as Benefit-to-Cost Ratios (BCR) or Net Present Value (NPV), for specific mitigation measures. This allows policymakers to identify "no-regret" options and rank interventions based on their societal efficiency and net benefit, thereby addressing the fragmentation and inconsistency that currently plagues nitrogen management decisions.

4.2. Key elements for a robust framework

The validity, reliability, and ultimate utility of the proposed INAF depend on strict adherence to several cross-cutting principles that must be embedded throughout the assessment process (Fig. 4). Foremost among these is the principle of consistency, which is essential for enabling meaningful comparison of results across studies and sectors. This principle demands careful harmonization across multiple dimensions of the assessment. System boundaries must be consistently defined, for instance applying a full life-cycle perspective for energy and technology options that consider embedded emissions in manufactured products like fertilizers or electric vehicles, while typically employing a farm-gate perspective for agricultural practices. The temporal and spatial scales of analysis must be appropriately matched to the policy question at hand and consistently applied across all models in the assessment chain, requiring cross-scale reconciliation techniques to ensure that local assessments can be meaningfully aggregated and global models can be downscaled without introducing major errors. Additionally, for future projections, core socio-economic assumptions, including discount rates, baseline trajectories based on Shared Socioeconomic Pathways (SSPs), and energy/agricultural commodity price projections, mitigation implementation timing and mitigation technology development, must be standardized to ensure that results reflect actual differences between mitigation options rather than arbitrary choices in modeling assumptions.

Equally crucial is the principle of transparency, which is non-negotiable for building credibility and enabling reproducibility. This extends far beyond simple data disclosure to encompass comprehensive documentation of the entire analytical chain. It requires full parameterization through explicit listing of all input parameters, emission factors, model configurations, and valuation coefficients along with their sources and justifications. Furthermore, transparency demands careful attention to uncertainty propagation, including clear documentation of the uncertainty distributions assigned to key parameters and demonstration of how these uncertainties are carried through each modeling stage to final cost-benefit results, moving beyond the presentation of single-point estimates to provide a more realistic representation of the assessment's confidence limits. Where possible, embracing an open-source ethos through the use and development of open-source models and public availability of input datasets can significantly enhance transparency by facilitating peer review, validation, and iterative improvement by the broader scientific community.

Finally, the principle of comprehensiveness is what truly distinguishes an integrated assessment from conventional approaches by ensuring that the analysis captures the full spectrum of consequences from any given action. This requires systematic inclusion of co-benefits that might otherwise be overlooked, such as how reducing nitrogen fertilizer overuse not only cuts N_2O and NH_3 emissions but also reduces farmers' input costs, decreases energy consumption from fertilizer manufacturing (thereby reducing CO_2 emissions), and improves water quality with benefits for both aquatic ecosystems and drinking water treatment costs. Omitting these co-benefits significantly undervalues mitigation measures and may lead to suboptimal policy decisions. Perhaps even more critically, the framework must be designed to assess potential trade-offs and avoid problem shifting, such as when mitigation of NH_3 emissions from manure through acidification or anaerobic digestion might inadvertently increase N_2O emissions if not properly

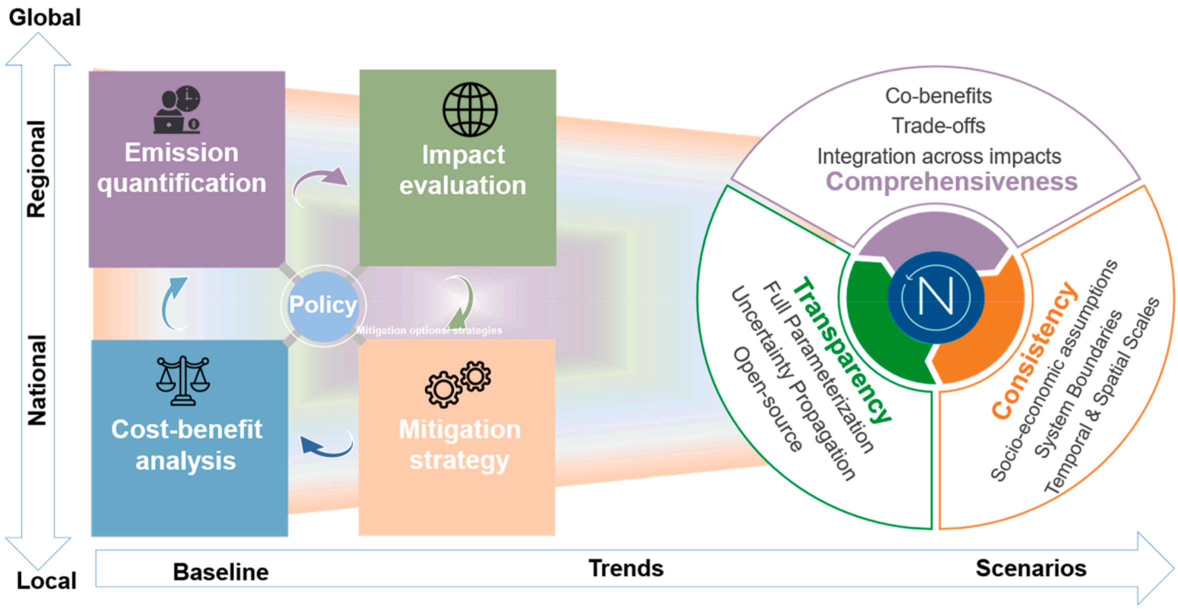

Fig. 4. Key principles for the robust Integrated Assessment Framework (INAF)
Three cross-cutting principles are transparency, comprehensiveness and consistency, with a horizontal axis spanning local, national, regional, and global scales.

managed. A comprehensive INAF must therefore evaluate interventions across all relevant environmental media to prevent recommendations that simply transfer pollution from one sector to another or from one environmental compartment to another, thus ensuring truly sustainable solutions.

4.3. Addressing uncertainty and scalability

A pragmatic integrated framework must explicitly acknowledge and handle inherent uncertainties rather than ignore them, with particular attention to distinguishing between different categories of uncertainty. The framework should address both data uncertainties (e.g., in emission factors, monitoring measurements, and cost parameters) and conceptual uncertainties (e.g., in model structures, dose-response relationships, choice of endpoints and indicators, and valuation methodologies). Quantitative uncertainty analysis, such as Monte Carlo simulation, should be standard practice to propagate data uncertainties from emission factors through impact models to final cost-benefit ratios, presenting results as probability distributions rather than single-point estimates. For addressing conceptual uncertainties and deep uncertainties surrounding future socioeconomic conditions or technological development, scenario analysis and sensitivity testing provide complementary tools. This involves exploring outcomes under different plausible pathways (e.g., Shared Socioeconomic Pathways - SSPs and their implementation for nitrogen scenarios (Kanter et al., 2020)) and explicitly testing how results vary with alternative model structures or indicator choices. Regarding scalability, the conceptual framework is applicable from local to global scales, but its implementation is constrained by data availability. On a national or global scale, the analysis will necessarily rely on broader-average data and models, providing insights into broad policy direction. At the farm or watershed scale, with high-resolution data, the framework can guide precise, targeted interventions. The key is to clearly articulate the scale-dependent limitations of the assessment; a global analysis cannot pinpoint local trade-offs, just as a local study cannot capture global market effects. The framework aims to provide robust assessment possible within the constraints of a given scale, thereby effectively informing level-appropriate decision-making.

4.4. Operationalizing the INAF: lessons from INMS

The proposed INAF addresses nitrogen assessment within Critical Zone systems and could serve as a fundamental concept for broader-scale applications, while comprehensive global assessment would require substantial additional work. As a significant advancement in nitrogen management, the INMS represents the first large-scale implementation of the proposed INAF, providing valuable insights into the framework's operational potential and practical advantages over conventional assessment approaches. Since its deployment in 2019, INMS has been applied across 15 countries spanning diverse economic and agricultural contexts, generating quantitative evidence of the integrated approach's superior performance in informing nitrogen policy decisions (INMS, 2019). The INMS global assessment has demonstrated that integrated analysis reveals higher benefit-cost ratios compared to sector-specific approaches. Comprehensive nitrogen management strategies assessed through INMS showed global benefit-cost ratios of 2.8–4.2, significantly exceeding the 1.5–2.1 ratios identified through traditional fragmented assessments (van Grinsven et al., 2025). This improvement stems primarily from the framework's ability to capture cross-sectoral co-benefits that are systematically overlooked in isolated analyses.

While INMS successfully incorporates all key components of the integrated approach, it also reveals substantial uncertainties and areas requiring improvement. For example, INMS faces significant challenges due to its high data and modeling demands, requiring robust datasets, advanced technical capacity, and substantial computational resources. These requirements pose significant challenges for regions lacking adequate monitoring infrastructure and technical expertise. (De Montis et al., 2016). Building on the experiences of programs such as INMS, the proposed INAF targets to further expand integration in three distinct directions. First, a proposed modular design allows for individual data filling and validation of the respective modules, also allowing for data collection at different quality levels. Next, a focus on cross-sectoral integration for combined evaluation of impacts supports evaluation of co-benefits and trade-offs. Finally, aiming for standardized methodologies and making available default values of parameters facilitates international knowledge transfer and capacity building to enable developing regions to benefit from model structures originally conceived in data-rich contexts. In addition to nitrogen's role, this approach recognizes other stressors (e.g., phosphorus, carbon) contributing to the same environmental endpoints (Kou-Giesbrecht et al., 2023), helping to identify the most cost-effective intervention.

5. Concluding remarks

This review has drawn together a wide but fragmented body of work on the costs and benefits of nitrogen emissions and their mitigation. The complexity of the nitrogen cycle, spanning multiple pollutants, environmental media and scales, makes it difficult for conventional, sector-specific assessments to provide adequate insights. Persistent differences in methodology, data gaps, and inconsistent valuation practices further limit the design of coherent and effective policies. The integrated assessment framework outlined here offers one way forward. By linking emission quantification with impact evaluation and cost-benefit analysis in a transparent and systematic manner, the framework can help decision-makers identify synergies, minimize trade-offs, and prioritize actions that deliver the greatest societal benefits, thereby advancing the transition to sustainable nitrogen management.

CRediT authorship contribution statement

Xiuming Zhang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Wilfried Winiwarter:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Hans J.M. van Grinsven:** Writing – review & editing, Methodology, Conceptualization. **Shaohui Zhang:** Writing – review & editing. **Zbigniew Klimont:** Writing – review & editing, Supervision. **Deli Chen:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecz.2025.100047.

Data availability

No data was used for the research described in the article.

References

Agaton, C.B., Guila, P.M.C., 2023. Ecosystem services valuation of constructed wetland as a nature-based solution to wastewater treatment. Earth 4, 78–92. https://doi.org/10.3390/earth4010006.
Althammer, W., Hille, E., 2016. Measuring climate policy stringency: a shadow price approach. Int. Tax Publ. Finance 23, 607–639. https://doi.org/10.1007/s10797-016-9405-4.
Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., et al., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environ. Modell. Softw. 26, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012.
Bak, J.L., 2014. Critical loads for nitrogen based on criteria for biodiversity conservation. Water, Air, Soil Pollut. 225. https://doi.org/10.1007/s11270-014-2180-x.
Battye, W., Aneja, V.P., Schlesinger, W.H., 2017. Is nitrogen the next carbon? Earths Future 5, 894–904. https://doi.org/10.1002/2017EF000592.
Beusen, A.H.W., Bouwman, A.F., Heuberger, P.S.C., Van Drecht, G., Van Der Hoek, K.W., 2008. Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems. Atmos. Environ. 42, 6067–6077. https://doi.org/10.1016/j.atmosenv.2008.03.044.
Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., et al., 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol. Appl. 20, 30–59. https://doi.org/10.1890/08-1140.1.
Boulter, P.G., Borken-Kleefeld, J., Ntziachristos, L., 2012. The evolution and control of NOx emissions from road transport in Europe. In: Viana, M. (Ed.), Urban Air Quality in Europe. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 31–53. https://doi.org/10.1007/698_2012_162.
Bradley, M.J., Jones, B.M., 2002. Reducing global NOx emissions: developing advanced energy and transportation technologies. AMBIO A J. Hum. Environ. 31, 141–149. https://doi.org/10.1579/0044-7447.
Brick, K., Visser, M., 2015. Risk preferences, technology adoption and insurance uptake: a framed experiment. J. Econ. Behav. Organ. 118, 383–396. https://doi.org/10.1016/j.jebo.2015.02.010.
Brink, C., Grinsven, H.V., Jacobsen, B.H., Velthof, G.L., 2011. In: Sutton, Mark, A., et al. (Eds.), Costs and benefits of nitrogen in the environment in The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, pp. 513–540. https://doi.org/10.1017/9781139151528.
Brink, C., van Ierland, E., Hordijk, L., Kroeze, C., 2005. Cost_effective emission abatement in agriculture in the presence of interrelations: cases for the Netherlands and Europe. Ecol. Econ. 53, 59–74. https://doi.org/10.1016/j.ecolecon.2004.05.008.
Chen, B., Zhang, X., Gu, B., 2025. Managing nitrogen to achieve sustainable food-energy-water nexus in China. Nat. Commun. 16, 4804. https://doi.org/10.1038/s41467-025-60098-5.
Chen, F., Yamashita, K., Kurokawa, J., Klimont, Z., 2015. Cost–benefit analysis of reducing premature mortality caused by exposure to ozone and PM2.5 in East Asia in 2020. Water, Air, Soil Pollut. 226. https://doi.org/10.1007/s11270-015-2316-7.
Ciarlantini, S., Frontuto, V., Pezzoli, A., Gavros, A., Belis, C.A., 2025. Econometric model derived from meta-analysis to estimate VSL and VOLY associated to air pollution at a global level. J. Environ. Manage. 379, 124824. https://doi.org/10.1016/j.jenvman.2025.124824.
Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. Lancet 389, 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6.
Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., et al., 2014. Changes in the global value of ecosystem services. Glob. Environ. Change 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.
Dammers, E., Palm, M., Van Damme, M., Vigouroux, C., Smale, D., Conway, S., et al., 2016. An evaluation of IASI-NH_3 with ground-based fourier transform infrared spectroscopy measurements. Atmos. Chem. Phys. 16, 10351–10368. https://doi.org/10.5194/acp-16-10351-2016.
Das, S., Hittinger, E., Williams, E., 2020. Learning is not enough: diminishing marginal revenues and increasing abatement costs of wind and solar. Renew. Energ. 156, 634–644. https://doi.org/10.1016/j.renene.2020.03.082.
de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., et al., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.
De Montis, A., Ledda, A., Caschili, S., 2016. Overcoming implementation barriers: a method for designing strategic environmental assessment guidelines. Environ. Impact Assess. Rev. 61, 78–87. https://doi.org/10.1016/j.jenvman.2007.03.016.
Del Rossi, G., Hoque, M.M., Ji, Y., Kling, C.L., 2023. The economics of nutrient pollution from agriculture. Annu. Rev. Resour. Econ. 15, 105–130. https://doi.org/10.1146/annurev-resource-111820-021317.
EMEP/EEA, 2023. EMEP/EEA air pollutant emission inventory guidebook 2023. 10.2800/795737.
EPA, 2013. Global Mitigation of Non-CO_2 Greenhouse Gases. U.S. Environmental Protection Agency, Washington, pp. 2010–2030 (EPA-430-R-13-009), Office of Atmospheric Programs. https://www3.epa.gov/climatechange/Downloads/EPAactivities/MAC_Report_2013.pdf.

EPA, 2023. Cost Analysis Models/Tools for Air Pollution Regulations. U.S. Environmental Protection Agency. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution. (Accessed 26 June 2025).

Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B., Petrescu, A.M., et al., 2013. Consequences of human modification of the global nitrogen cycle. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 368. https://doi.org/10.1098/rstb.2013.0116.

Etminan, M., Myhre, G., Highwood, E.J., Shine, K.P., 2016. Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. Geophys. Res. Lett. 43, 12–614. https://doi.org/10.1002/2016GL071930.

FAO, 2025. Food and Agriculture Organization of the United Nations. http://www.fao.org (accessed2025).

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., et al., 2013. The global nitrogen cycle in the twenty-first century. Philos. Trans. R. Soc. Lond. B Biol. Sci. 368, 20130164. https://doi.org/10.1098/rstb.2013.0164.

Fu, P., Guo, X., Cheung, F.M.H., Yung, K.K.L., 2019. The association between $PM_{2.5}$ exposure and neurological disorders: a systematic review and meta-analysis. Sci. Total Environ. 655, 1240–1248. https://doi.org/10.1016/j.scitotenv.2018.11.218.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience 53, 341–356. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

Gao, Z., Zhou, X., 2024. A review of the CAMx, CMAQ, WRF-Chem and NAQPMS models: application, evaluation and uncertainty factors. Environ. Pollut. 343, 123183. https://doi.org/10.1016/j.envpol.2023.123183.

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment tool: historical development, applications, and future research directions. T. ASABE 50, 1211–1250. https://doi.org/10.13031/2013.23637.

Giannadaki, D., Giannakis, E., Pozzer, A., Lelieveld, J., 2018. Estimating health and economic benefits of reductions in air pollution from agriculture. Sci. Total Environ. 622–623, 1304–1316. https://doi.org/10.1016/j.scitotenv.2017.12.064.

Gu, B., Zhang, L., Van Dingenen, R., Vieno, M., Van Grinsven, H.J., Zhang, X., et al., 2021a. Abating ammonia is more cost-effective than nitrogen oxides for global mitigation of particulate matter air pollution. Science 374, 758–762. https://doi.org/10.1126/science.abf8623.

Gu, B., Zhang, X., 2025. The Coupled Human And Natural Systems (CHANS) nitrogen cycling Model- global version. https://person.zju.edu.cn/bjgu#928507 (accessed2025).

Gu, B., Zhang, X., Lam, S.K., Yu, Y., van Grinsven, H., Zhang, S., et al., 2021b. Mitigating nitrogen pollution from global croplands with cost-effective measures. Nature 613, 77–84. https://doi.org/10.1038/s41586-022-05481-8.

Guo, Y., Zhao, H., Winiwarter, W., Chang, J., Wang, X., Zhou, M., et al., 2024. Aspirational nitrogen interventions accelerate air pollution abatement and ecosystem protection. Sci. Adv. 10, eado0112. https://doi.org/10.1126/sciadv.ado0112.

Hauglustaine, D.A., Balkanski, Y., Schulz, M., 2014. A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate. Atmos. Chem. Phys. 14, 11031–11063. https://doi.org/10.5194/acp-14-11031-2014.

Hettelingh, J., Posch, M., Slootweg, J., 2017. European Critical Loads: Database, Biodiversity and Ecosystems at Risk: CCE Final Report 2017. https://doi.org/10.21945/RIVM-2017-0155.

Holland, M.R., 1995. Assessment of the economic costs of damage caused by air-pollution. Water Air Soil Pollut. 85, 2583–2588. https://doi.org/10.1007/BF02418556.

INMS, 2019. International nitrogen management system. Nitrogen: Grasping the Challenge [Summary Report]. https://www.inms.international/ (accessed.

INMS, 2025. International nitrogen management system. https://www.inms.international (accessed2025).

IPCC, 2019. 2019 refinement to the 2006 IPCC guidelines for national GHG inventories. In: Eduardo Calvo Buendia Et Al. IPCC, Switzerland, pp. 45–46, 2019.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Kanter, D.R., Wagner-Riddle, C., Groffman, P.M., Davidson, E.A., Galloway, J.N., Gourevitch, J.D., et al., 2021. Improving the social cost of nitrous oxide. Nat. Clim. Change 1-2. https://doi.org/10.1038/s41558-021-01226-z.

Kanter, D.R., Winiwarter, W., Bodirsky, B.L., Bouwman, L., Boyer, E., Buckle, S., et al., 2020. A framework for nitrogen futures in the shared socioeconomic pathways. Global Environmental Change 61, 102029. https://doi.org/10.1016/j.gloenvcha.2019.102029.

Keeler, B.L., Gourevitch, J.D., Polasky, S., Isbell, F., Tessum, C.W., Hill, J.D., et al., 2016. The social costs of nitrogen. Sci. Adv. 2, e1600219. https://doi.org/10.1126/sciadv.1600219.

Klimont, Z., Winiwarter, W., 2011. Integrated ammonia abatement - modelling of emission control potentials and costs in GAINS. IIASA Interim Report IR-11-027. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Kou-Giesbrecht, S., Arora, V.K., Seiler, C., Arneth, A., Falk, S., Jain, A.K., et al., 2023. Evaluating nitrogen cycling in terrestrial biosphere models: a disconnect between the carbon and nitrogen cycles. Earth Syst. Dynam. 14, 767–795. https://doi.org/10.5194/esd-14-767-2023.

Krupnick, A.J., McConnell, V.D., Cannon, M., Stoessell, T., Batz, M.B., 2000. Cost-Effective Nox Control in the Eastern United States. https://doi.org/10.1080/10473289.2001.10464366.

Kuhn, T., Sch A Fer, D., Holm-M U Ller, K., Britz, W., 2019. On-farm compliance costs with the EU-Nitrates directive: a modelling approach for specialized livestock production in northwest Germany. Agr. Syst. 173, 233–243. https://doi.org/10.1016/j.agsy.2019.03.012.

Lassaletta, L., Billen, G., Garnier, J., Bouwman, L., Velazquez, E., Mueller, N.D., Gerber, J.S., 2016. Nitrogen use in the global food system : past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environ. Res. Lett. 11, 95007. https://doi.org/10.1088/1748-9326/11/9/095007.

Lassaletta, L., Billen, G., Romero, E., Garnier, J., Aguilera, E., 2014. How changes in diet and trade patterns have shaped the N cycle at the national scale: spain (1961–2009). Reg. Environ. Change 14, 785–797. https://doi.org/10.1007/s10113-013-0536-1.

Lee, H., Calvin, K., Dasgupta, D., Krinmer, G., Mukherji, A., Thorne, P., et al., 2023. Synthesis report of the IPCC Sixth Assessment Report (AR6). Longer report. IPCC.

Lee, S., Nguyen, T., Kim, H., Koellner, T., Shin, H., 2017. Do consumers of environmentally friendly farming products in downstream areas have a WTP for water quality protection in upstream areas? Water-Sui 9, 511. https://doi.org/10.3390/w9070511.

Lee, S., Ryu, I., Kim, B., Moon, S., 2011. A review of the current application of N2O emission reduction in CDM projects. Int. J. Greenh. Gas Con. 5, 167–176. https://doi.org/10.1016/j.enpol.2011.05.028.

Leksell, I., Rabl, A., 2001. Air pollution and mortality: quantification and valuation of years of life lost. Risk Anal. 21, 843. https://doi.org/10.1111/0272−4332.215156.

Liu, F., Zhang, Q., van DerA, R.J., Zheng, B., Tong, D., Yan, L., et al., 2016. Recent reduction in NO_x emissions over China: synthesis of satellite observations and emission inventories. Environ. Res. Lett. 2016, 114002. https://doi.org/10.1088/1748-9326/11/11/114002.

Logue, J.M., Price, P.N., Sherman, M.H., Singer, B.C., 2012. A method to estimate the chronic health impact of air pollutants in US residences. Environ. Health Perspect. 120, 216–222. https://doi.org/10.1289/ehp.1104035.

Lu, L., Guest, J.S., Peters, C.A., Zhu, X., Rau, G.H., Ren, Z.J., 2018. Wastewater treatment for carbon capture and utilization. Nat. Sustain. 1, 750–758. https://doi.org/10.1038/s41893-018-0187-9.

Luo, Z., Zhang, Y., Chen, W., Van Damme, M., Coheur, P., Clarisse, L., 2022. Estimating global ammonia (NH_3) emissions based on IASI observations from 2008 to 2018. Atmos. Chem. Phys. 22, 10375–10388. https://doi.org/10.5194/acp-22-10375-2022.

Masterman, C.J., Viscusi, W.K., 2018. The income elasticity of global values of a statistical life: stated preference evidence. J. Benefit-Cost Anal. 9, 407–434. https://doi.org/10.1017/bca.2018.20.

Mertens, S., Herberz, M., Hahnel, U.J., Brosch, T., 2022. The effectiveness of nudging: A meta-analysis of choice architecture interventions across behavioral domains. PNAS 119, e2107346118. https://doi.org/10.1073/pnas.2107346118.

Moreira Da Silva, C.R., Lima, D.S.V.R., Farias, I.F., Oliveira, L.V.C., Fontenele, R.E.S., 2020. Are visitors willing to pay for a green park? : a study in a Brazilian ecological park. Int. J. Soc. Ecol. Sustain. Dev. 11, 1–15. https://doi.org/10.4018/IJSESD.2020070101.

Ness, B., Anderberg, S., Olsson, L., 2010. Structuring problems in sustainability science: the multi-level DPSIR framework. Geoforum 41, 479–488. https://doi.org/10.1016/j.geoforum.2009.12.005.

Niles, M.T., Waterhouse, H., Parkhurst, R., McLellan, E.L., Kroopf, S., 2019. Policy options to streamline the carbon market for agricultural nitrous oxide emissions. Clim. Policy 19, 893–907. https://doi.org/10.1080/14693062.2019.1599802.

Palash, S.M., Masjuki, H.H., Kalam, M.A., Masum, B.M., Sanjid, A., Abedin, M.J., 2013. State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled compression ignition engines. Energ. Convers. Manage. 76, 400–420. https://doi.org/10.1016/j.enconman.2013.08.006.

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., et al., 2013. Assessing the public health impacts of urban air pollution in 25 European cities: results of the Aphekom project. Sci. Total Environ. 449, 390–400. https://doi.org/10.1016/j.scitotenv.2013.01.077.

Phoenix, G.K., Hicks, W.K., Cinderby, S., Kuylenstierna, J.C.I., Stock, W.D., Dentener, F.J., et al., 2006. Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts. Glob. Change Biol. 12, 470–476. https://doi.org/10.1111/j.1365-2486.2006.01104.x.

Pomar, C., Remus, A., 2023. Review: fundamentals, limitations and pitfalls on the development and application of precision nutrition techniques for precision livestock farming. Animal 17, 100763. https://doi.org/10.1016/j.animal.2023.100763.

Posch, M., Duan, L., Reinds, G.J., Zhao, Y., 2015. Critical loads of nitrogen and sulphur to avert acidification and eutrophication in Europe and China. Landsc. Ecol. 30, 487–499. https://doi.org/10.1007/s10980-014-0123-y.

Ren, C., Huang, X., Liu, T., Song, Y., Wen, Z., Liu, X., et al., 2023. A dynamic ammonia emission model and the online coupling with WRF–chem (WRF–SoilN–Chem v1.0): development and regional evaluation in China. Geosci. Model Dev. (GMD) 16, 1641–1659. https://doi.org/10.5194/gmd-16-1641-2023.

Ren, C., Zhang, X., Reis, S., Gu, B., 2022. Socioeconomic barriers of nitrogen management for agricultural and environmental sustainability. Agric. Ecosyst. Environ. 333, 107950. https://doi.org/10.1016/j.agee.2022.107950.

Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nat. Clim. Change 8, 895–900. https://doi.org/10.1038/s41558-018-0282-y.

Robinson, L.A., Hammitt, J.K., O'Keeffe, L., 2019. Valuing mortality risk reductions in global benefit-cost analysis. J. Benefit-Cost Anal. 10, 15–50. https://doi.org/10.1017/bca.2018.26.

Ruankham, W., 2025. Air pollution and housing market valuation: a spatial hedonic pricing approach to welfare loss estimation. Int. J. Hous. Mark. Anal. https://doi.org/10.1108/ijhma-03-2025-0054.

Sampat, A.M., Hicks, A., Ruiz-Mercado, G.J., Zavala, V.M., 2021. Valuing economic impact reductions of nutrient pollution from livestock waste. Resour. Conserv. Recycl. 164, 105199. https://doi.org/10.1016/j.resconrec.2020.105199.

Seitzinger, S.P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., et al., 2010. Global river nutrient export: a scenario analysis of past and future trends. Global Biogeochem. Cy. 24. https://doi.org/10.1029/2009GB003587.

Seleznova, Y., Alayli, A., Stock, S., Müller, D., 2021. Methodological issues in economic evaluations of disease prevention and health promotion: an overview of systematic and scoping reviews. BMC Public Health 21, 2130. https://doi.org/10.1186/s12889-021-12174-w.

Simpson, D., Benedictow, A., Berge, H., Bergstr Om, R., Emberson, L.D., Fagerli, H., et al., 2012. The EMEP MSC-W chemical transport model – technical description. Atmos. Chem. Phys. 12, 7825–7865. https://doi.org/10.5194/acp-12-7825-2012.

Singh, U., Algren, M., Schoeneberger, C., Lavallais, C., O Connell, M.G., Oke, D., et al., 2022. Technological avenues and market mechanisms to accelerate methane and nitrous oxide emissions reductions. iScience 25. https://doi.org/10.1016/j.isci.2022.105661.

Sobota, D.J., Compton, J.E., Harrison, J.A., 2013. Reactive nitrogen inputs to US lands and waterways: how certain are we about sources and fluxes? Front. Ecol. Environ. 11, 82–90. https://doi.org/10.1890/110216.

Söderholm, P., Sundqvist, T., 2007. Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. Renew. Energ. 32, 2559–2578. https://doi.org/10.1016/j.renene.2006.12.007.

Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., et al., 2011. The European nitrogen assessment: sources, effects and policy perspectives. Cambridge university press. https://doi.org/10.1017/CBO9780511976988.

Tate, W.L., Dooley, K.J., Ellram, L.M., 2011. Transaction cost and institutional drivers of supplier adoption of environmental practices. Journal of business logistics 32, 6–16. https://doi.org/10.1111/j.2158-1592.2011.01001.x.

Tol, R.S.J., 2023. Social cost of carbon estimates have increased over time. Nat. Clim. Change 13, 532–536. https://doi.org/10.1038/s41558-023-01680-x.

Tor, A., 2022. The private costs of behavioral interventions. Duke LJ 72, 1673. https://doi.org/10.1017/dlp.2023.2.

Uraguchi, D., Ueki, Y., Ooi, T., 2009. Chiral Organic Ion Pair Catalysts Assembled Through a Hydrogen-Bonding Network. Science 326, 120–123. https://doi.org/10.1126/science.1176758.

Van der Straeten, B., Buysse, J., Nolte, S., Lauwers, L., Claeys, D., Van Huylenbroeck, G., 2012. The effect of EU derogation strategies on the compliance costs of the nitrate directive. Sci. Total Environ. 421, 94–101. https://doi.org/10.1016/j.scitotenv.2012.01.019.

van Grinsven, H.J.M., Gu, B., Rodríguez, A., Jones, L., Brouwer, R., Schulte-Uebbing, L., et al., 2025. Valuing damages and benefits of the altered global nitrogen cycle; lessons for national to global policy support. Environ. Res. Lett. 20, 94014. https://doi.org/10.1088/1748-9326/adf07c.

Van Grinsven, H.J.M., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Jaap Willems, W., 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47, 3571–3579. https://doi.org/10.1021/es303804g.

Wade, A.J., Durand, P., Beaujouan, V., Wessel, W.W., Raat, K.J., Whitehead, P.G., et al., 2002. A nitrogen model for European catchments: INCA, new model structure and equations. Hydrol. Earth Syst. Sci. 6, 559–582. https://doi.org/10.5194/hess-6-559-2002.

WHO, 2016. Ambient air pollution: a global assessment of exposure and burden of disease. World Health Organization. https://doi.org/10.17159/2410-972X/2016/v26n2a4.

Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W., Amann, M., 2017. Technical opportunities to reduce global anthropogenic emissions of nitrous oxide. Environ. Res. Lett. 13, 14011. https://doi.org/10.1088/1748-9326/aa9ec9.

Winiwarter, W., Höglund-Isaksson, L., Schöpp, W., Tohka, A., Wagner, F., Amann, M., 2010. Emission mitigation potentials and costs for non-CO_2 greenhouse gases in Annex-I countries according to the GAINS model. J. Integr. Environ. Sci. 7, 235–243. https://doi.org/10.1080/19438151003774430.

Wurtsbaugh, W.A., Paerl, H.W., Dodds, W.K., 2019. Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. Wiley Interdisciplinary Reviews: Water 6, e1373. https://doi.org/10.1002/wat2.1373.

Xu, J., Lu, M., Guo, Y., Zhang, L., Chen, Y., Liu, Z., et al., 2023. Summertime urban ammonia emissions may be substantially underestimated in Beijing, China. Environ. Sci. Technol. 57, 13124–13135. https://doi.org/10.1021/acs.est.3c05266.

Zhang, H., Zhou, X., Ren, C., Li, M., Liu, T., Huang, X., 2024. A systematic review of reactive nitrogen simulations with chemical transport models in China. Atmos. Res. 309, 107586. https://doi.org/10.1016/j.atmosres.2024.107586.

Zhang, X., Wu, Y., Liu, X., Reis, S., Jin, J., Dragosits, U., et al., 2017. Ammonia Emissions May Be Substantially Underestimated in China. Environ. Sci. Technol. 51, 12089–12096. https://doi.org/10.1021/acs.est.7b02171.

Zhang, M., Zhang, X., Gao, C., Zhao, H., Zhang, S., Xie, S., et al., 2025. Reactive nitrogen emissions from cropland and their dominant driving factors in China. Sci. Total Environ. 968, 178919. https://doi.org/10.1016/j.scitotenv.2025.178919.

Zhang, X., Gu, B., van Grinsven, H., Lam, S.K., Liang, X., Bai, M., Chen, D., 2020. Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. Nat. Commun. 11. https://doi.org/10.1038/s41467-020-18196-z.

Zhang, X., Ren, C., Gu, B., Chen, D., 2021. Uncertainty of nitrogen budget in China. Environ. Pollut. 286, 117216. https://doi.org/10.1016/j.envpol.2021.117216.

Zhang, X., Sun, Y., Liang, X., Lam, S.K., Liu, L., Gu, B., Chen, D., 2022. Costs and benefits of ammonia abatement in Australia. Resour. Conserv. Recycl. 182, 106318. https://doi.org/10.1016/j.resconrec.2022.106318.