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Reviews and syntheses: Constraining the Nitrous Oxide (N_2O) Budget Across Scales: A Critical Review of Sources, Sinks, Estimation Methods, and Knowledge Gaps

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Abstract

Nitrous oxide (N_2O) budget assessments integrate evidence from microbial processes, surface flux measurements, emission inventories, and atmospheric observations, but these approaches do not necessarily constrain the same quantities. We systematically reviewed 80 peer-reviewed studies published between 2002 and 2024, using a PRISMA-based screening procedure to examine research themes, environmental systems, and estimation approaches. We additionally audited the evidence endpoints and accounting boundaries of 23 selected studies. Of the 80 studies, 53 were classified as source-focused, 22 as budget-imbalance-focused, and five as sink-focused. Although 12 studies were originally classified as top-down, six provided observation-constrained spatial emission inversions; two inferred sources through other atmospheric approaches, and four primarily examined atmospheric lifetime, transport variability, or observing-system capability. The audit also showed that microbial N_2O reduction, locally negative surface exchange, and atmospheric chemical removal are distinct quantities: evidence for one cannot, by itself, establish the magnitude of another. Some integrated assessments incorporate shared model inputs or source products, warranting caution when interpreting agreement as independent confirmation. These findings distinguish the distribution of research methods from the comparability and independence of the budget constraints they provide. Greater transparency in accounting boundaries, evidence provenance, and observational evaluation is needed to improve N_2O budget interpretation.

Keywords

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Nitrous oxide; Global N_2O budget; Source–sink accounting; Atmospheric inversion; Net surface exchange; Evidence comparability

1. Introduction

Nitrous oxide (N_2O) has been identified as one of the most important trace gases in the Earth system, given that it is both a long-lived greenhouse gas and the primary ozone depleting emission of the 21st century (Davidson and Kanter, 2014; Ravishankara et al., 2009; Thompson et al., 2019; Tian et al., 2024). N_2O levels in the atmosphere have been steadily rising since preindustrial times and the latest NOAA measurement (Fig. 1) indicates that globally averaged N_2O concentrations have exceeded 339 ppb by the end of 2025, consistent with a persistent positive imbalance between atmospheric N_2O sources and removal (Lan et al., 2026; Thompson et al., 2019; Tian et al., 2024; Tian et al., 2020). The continued increase in atmospheric N_2O indicates a persistent imbalance between global sources and sinks, while uncertainties remain in the magnitude, attribution, and temporal variability of individual source and sink components. Recent observational and modeling results also imply that stratospheric effects may play a significant role in tropospheric N_2O variability, which also makes the interpretation of surface emission signals and budget closure more complicated (Nevison et al., 2024). N_2O has a long lifetime and high radiative efficiency, so current emissions will lead to long-lasting impacts on climate forcing and stratospheric chemistry, underscoring the need to assess the global budget with urgency (Davidson and Kanter, 2014; Feng and Li, 2023; Ravishankara et al., 2009; Tian et al., 2024).

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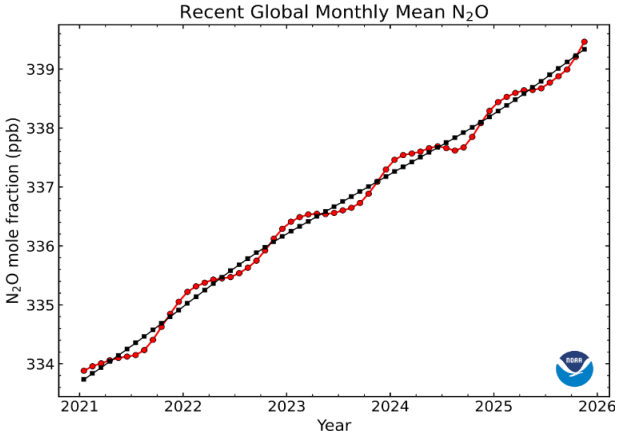


Fig. 1. Recent global monthly mean nitrous oxide (N_2O) concentrations (from NOAA Global Monitoring Laboratory, accessed on 05 March 2026).

The persistent increase in atmospheric N_2O is symbolic of the extensive human modification of the nitrogen cycle, including fertilizers, manure, fossil fuels, biomass burning, water quality, and exchanges across land, water, and atmosphere boundaries (Davidson and Kanter, 2014; Erisman et al., 2011; Galloway et al., 2008; Oenema et al., 2005). Agriculture continues to be the largest anthropogenic source, as synthetic nitrogen additions and livestock emissions greatly increase nitrification and denitrification losses from soils and managed systems (Cui et al., 2024; Del Grosso et al., 2008; Oenema et al., 2005; Smith, 2017). However, the N_2O response to increase nitrogen inputs is nonlinear and strongly influenced by soil moisture, temperature, pH, substrate availability, and management, which explains the wide variation in emission factors across crops, regions, and climates (Butterbach-Bahl et al., 2013; Cui et al., 2021; Li et al., 2022; Liu et al., 2022; Shcherbak et al., 2014; Wrage et al., 2001). Further, reactive nitrogen is redistributed by atmospheric deposition, leaching, runoff, and land to water transfer, complicating attribution beyond direct soil emissions.

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Whereas agricultural soils dominate the anthropogenic budget, the global N_2O cycle also includes significant contributions from natural soils, inland waters, estuaries, oceans, wastewater, and high latitude or permafrost environments, many of which are poorly understood (Dong et al., 2023; Hugelius et al., 2024; Wang et al., 2024; Yang et al., 2020; Yao et al., 2020). These sectors are not currently well represented in global assessments, making indirect pathways, episodic emissions and potential sink mechanisms difficult to appropriately account for to close the budget. Indeed, recent research has also demonstrated that some inland waters can be net sinks in certain circumstances, while traditional emission factor estimates may overestimate emissions from freshwater and estuarine environments, suggesting that key controls such as hydrology, residence time and biogeochemical stoichiometry remain poorly represented (Aho et al., 2023; Maavara et al., 2019; Song et al., 2024; Wang et al., 2024).

Thus, constructing the global N_2O budget is challenging not only because emissions come from multiple sectors, but also because key estimation approaches vary in assumptions, scales, and uncertainties (Deng et al., 2022b; Saikawa et al., 2014; Stell et al., 2022; Thompson et al., 2014). Bottom-up inventories and process-based models can provide spatial detail, but are sensitive to activity data, emission factors and model setup, while atmospheric inversions provide observation-constrained estimates of surface emissions, with regional and sectoral attribution influenced by observational coverage, transport representation, and prior assumptions (Del Grosso et al., 2008; Tian et al., 2018).

Existing assessments have substantially improved estimates of global N_2O sources and sinks, yet the evidence used to evaluate the N_2O budget constrains different components of the nitrogen cycle. Process-level observations of N_2O production and reduction,

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measurements of net surface–atmosphere exchange, bottom-up inventories, and atmospheric inversions do not necessarily provide equivalent or independent information. This review systematically examines 80 peer-reviewed studies published during 2002–2024 to assess research patterns, source–sink representation, estimation approaches, and methodological uncertainties. A focused assessment of 23 selected studies Table S1 further evaluates the budget quantities constrained by different evidence types, their accounting boundaries, and identifiable relationships among published estimates. By distinguishing mechanistic understanding from quantitative constraints on net exchange and atmospheric removal, the review identifies limitations in the comparability of existing evidence and discusses their implications for N_2O budget assessment.

2 Materials and Methods

2.1 Definition of the global N_2O budget

The global N_2O budget was considered in terms of exchanges between terrestrial and aquatic systems and the atmosphere, together with chemical removal from the atmospheric reservoir. Net surface exchange reflects the combined effects of N_2O production, consumption, and transport within environmental systems, whereas atmospheric N_2O removal occurs predominantly through photochemical processes in the stratosphere (Prather et al., 2015; Tian et al., 2024). This distinction is important because microbial reduction of N_2O to N_2 within soils or aquatic environments does not necessarily represent an additional atmospheric sink; its effect on the atmospheric budget depends on the resulting net exchange across the surface–atmosphere boundary. Accordingly, this review evaluates N_2O sources, consumption processes, net surface exchange, atmospheric

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constraints, and estimation uncertainties while distinguishing the budget quantities represented by different forms of evidence (Aho et al., 2023; Tian et al., 2024).

2.2 Search strategy and study classification

A systematic literature search was conducted following the principles of the PRISMA 2020 framework (Page et al., 2021). Peer-reviewed studies were retrieved from the Web of Science Core Collection (WoSCC), which was selected as the primary bibliographic database to ensure a consistent and reproducible literature search framework. The search targeted studies addressing the N_2O budget at global and large spatial scales, including assessments of emission sources, sink processes, estimation approaches, and uncertainties associated with terrestrial, aquatic, and other environmentally relevant systems.

The search strategy combined five groups of keywords using Boolean operators: (1) N_2O-related terms ("nitrous oxide" OR "N_2O"); (2) budget-related terms ("budget" OR "source–sink" OR "emission inventory"); (3) estimation-related terms ("inversion" OR "model" OR "inventory" OR "emission factor"); (4) uncertainty-related terms ("uncertainty" OR "assessment" OR "reconciliation"); and (5) ecosystem-related terms ("agriculture" OR "soil" OR "forest" OR "wetland" OR "aquatic"). The keyword groups were designed to capture the major dimensions of N_2O budget research, including emission sources, sink processes, budget assessment, estimation methodologies, and associated uncertainties across different environmental systems. The initial search strategy was intentionally broad to maximize retrieval of potentially relevant studies. Subsequent relevance screening and refinement procedures were applied to remove records unrelated to environmental N_2O cycling, atmospheric budget assessment, or quantitative evaluation of N_2O sources and

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sinks. The initial search identified 33,800 records. After removing duplicates and records that did not meet the initial document-type, category, or relevance criteria, 3,379 records remained for title and abstract screening. This was reduced to 1,118 records for relevance prioritization, of which 814 were assessed in full text. After final eligibility screening, 80 studies were retained for quantitative synthesis.

The retrieved records were screened through a multistage process based on predefined eligibility criteria. Studies were retained when they provided quantitative evidence or methodological insights related to N_2O sources, sinks, budget estimation, uncertainty assessment, or comparisons among estimation approaches at global or regional scales, or when smaller-scale studies provided process-level evidence directly relevant to interpreting the broader N_2O budget. Studies were excluded when they focused on non-environmental applications of N_2O, were unrelated to atmospheric N_2O budgets or ecosystem nitrogen cycling, or did not provide information relevant to N_2O source-sink assessment, budget quantification, or methodological evaluation.

Following the literature screening, relevance prioritization, and full-text eligibility assessment, 80 peer-reviewed studies were retained for quantitative synthesis and detailed evaluation (Fig. 2). The complete list of included studies and their classification characteristics is provided in Supplementary Table S2, which enhances transparency, reproducibility, and traceability of the review database.

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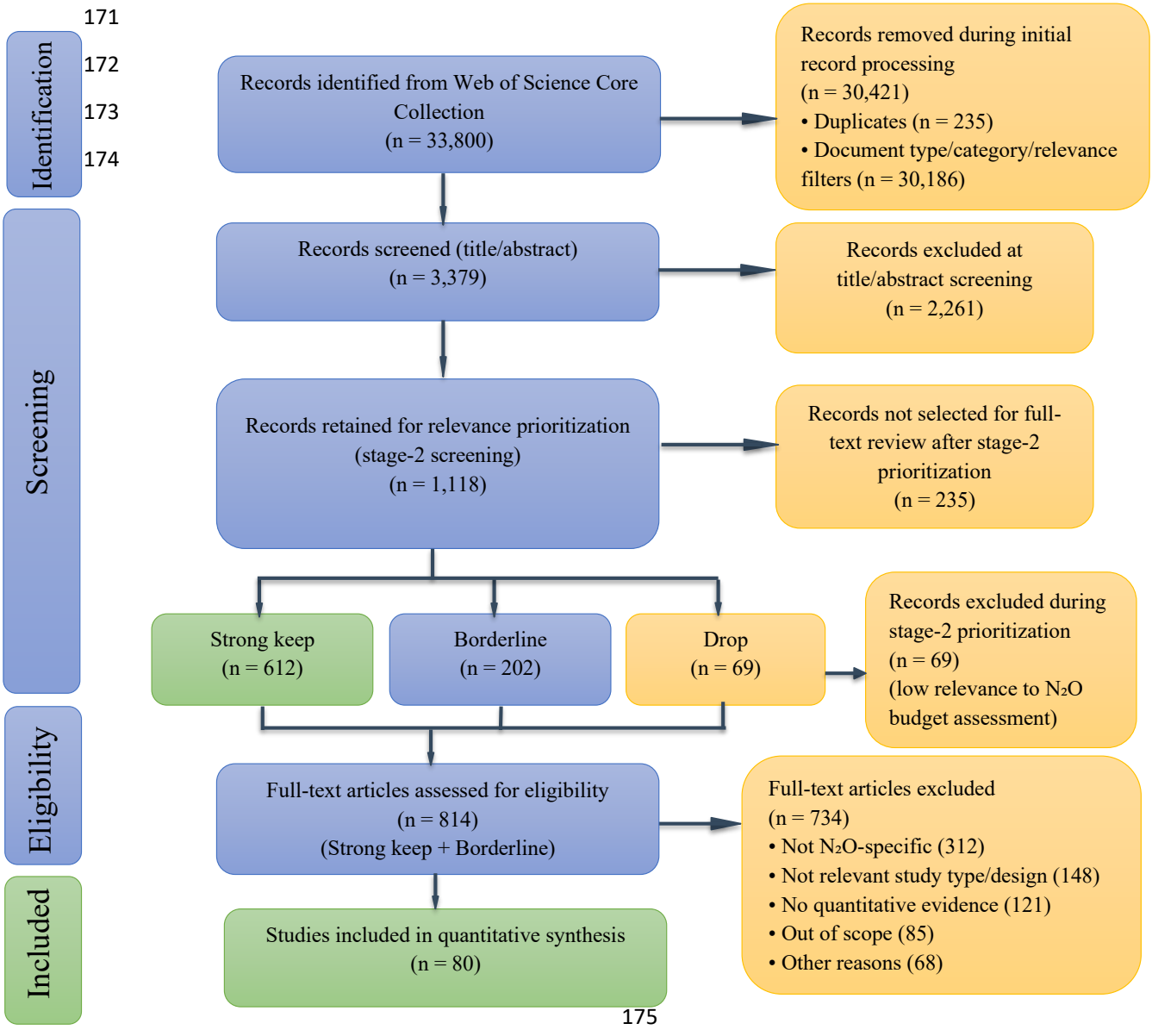


Fig. 2. PRISMA 2020-based flow diagram illustrating the identification, initial screening, relevance prioritization, eligibility assessment, and final selection of studies included in the systematic review.

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For thematic synthesis, the selected studies were classified into three major research themes: source-focused studies, sink-focused studies, and budget imbalance studies. Each study was further categorized according to its dominant system focus, including agriculture, aquatic systems, methods/budget, natural systems, waste/industry, and general/mixed categories. Studies evaluating estimation approaches were classified into five methodological groups: bottom-up, top-down, process-based approaches, combined/comparative approaches, and hybrid/integrated approaches. These classification frameworks were used to quantitatively evaluate research trends, methodological development, ecosystem representation, and remaining uncertainties in N_2O budget assessment.

To assess the comparability of evidence used in N_2O budget research, a focused methodological audit was conducted using 23 studies from the original 80-publication database. These comprised all 12 studies originally classified as top-down, all five studies classified as sink-focused, and six additional studies selected to examine integrated budget assessments, aquatic and wetland emissions, and comparisons among estimation approaches. Each study was examined according to the primary budget quantity constrained, the type of observational or modeling evidence, relevant accounting boundaries, and identifiable relationships with other published estimates. Additional evidence endpoints were recorded where supported by the study methods, while the original dominant classifications were retained. This targeted assessment was intended to identify methodological and accounting limitations rather than estimate their prevalence across the entire literature.

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3 Results and Discussion

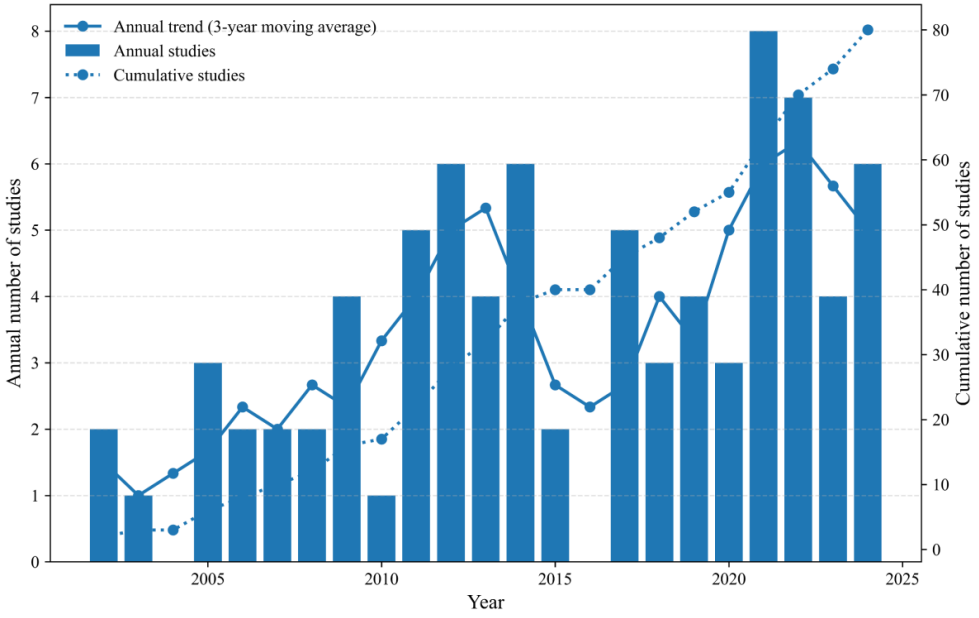
3.1 Continued growth in publications

Following the screening and eligibility assessment, 80 peer-reviewed studies were retained for quantitative synthesis. As shown in Fig. 3, publication activity remained relatively limited during the early years covered by the dataset but increased progressively after 2010. The dataset includes 16 studies published during 2002–2009, followed by 36 studies during 2010–2019 and 28 studies during 2020–2024, demonstrating a substantial expansion of research activity over the last two decades. The cumulative publication curve increased continuously, indicating sustained growth in scientific attention toward N_2O budget assessment across different spatial scales and environmental systems. This increasing research activity occurred alongside advances in atmospheric observations, nitrogen-cycle assessments, and improved modelling capabilities, which have supported more comprehensive evaluations of N_2O sources, sinks, and uncertainties across spatial scales.

The quantitative classification of the selected studies shows the overall distribution of research emphasis within the N_2O budget literature. Among the 80 reviewed studies, source-focused studies remained dominant, accounting for 53 studies (66.25%), while budget imbalance studies represented 22 studies (27.50%) and sink-focused studies accounted for 5 studies (6.25%). The temporal distributions of these themes further indicate that source-focused research remained prominent throughout the study period, whereas budget-imbalance studies became more visible in the later literature, reflecting increasing attention to atmospheric constraints, source attribution, and reconciliation among different estimation approaches. Across the same periods, source-focused studies numbered 15, 21, and 17, respectively, whereas budget-imbalance studies increased from 0 studies in 2002-

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2009 to 12 in 2010-2019 and 10 in 2020-2024. Earlier studies in the review included work on historical atmospheric reconstruction and baseline budget estimation, whereas later studies increasingly incorporated atmospheric observations, inversion-based constraints, and regional assessments (Macfarling Meure et al., 2006; Prather et al., 2015; Prokopiou et al., 2017; Scheehle and Kruger, 2006; Schilt et al., 2010). The increased research activity after 2010 coincided with broader advances in nitrogen-cycle assessments, coordinated international research efforts, and model intercomparison activities that improved understanding of N_2O sources, uncertainties, and budget variability (Fowler et al., 2013; Sutton et al., 2011; Tian et al., 2018). This development also occurred alongside the continued increase in atmospheric N_2O concentrations, which has strengthened the need for improved source attribution, historical reconstruction, and evaluation of remaining budget uncertainties (Liang et al., 2022; Lickley et al., 2021).



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Fig.3. Annual and cumulative number of studies included in the review. Bars show the number of studies published per year, the solid line shows the 3-year moving average of annual publications, and the dotted line shows the cumulative number of included studies.

A further notable aspect is that recent studies have expanded the methodological scope of N_2O budget research beyond traditional source inventory approaches toward more comprehensive assessments of atmospheric constraints, methodological uncertainty, and regional-scale processes. Although source-focused studies remained dominant in the final database, recent works increasingly incorporated atmospheric inversions, transport model optimization, bottom-up and top-down reconciliation, and cross-scale uncertainty analysis to better constrain N_2O emissions and budget variability (Nevison et al., 2018; Petrescu et al., 2021; Wells et al., 2015; Wells et al., 2018; Xu et al., 2021). Meanwhile, research coverage has expanded to include aquatic systems, inland water bodies, and other previously less represented sectors, contributing to a broader understanding of N_2O sources and uncertainties across environmental systems (Pan et al., 2023). Generally, the publication trend demonstrates that N_2O budget research has developed into a more interdisciplinary field, while increasing atmospheric concentrations and remaining uncertainties in emission quantification continue to motivate further investigations.

3.2 Geographic distribution and publication outlets

3.2.1 Geographic distribution of study domains

The geographic classification of the 80 reviewed studies revealed a strong predominance of research conducted at broad spatial scales. As shown in Fig. 4, 53 studies (66.25%) had a global geographic scope, whereas 18 studies (22.50%) focused on individual countries or subnational regions, 5 studies (6.25%) addressed regional or supra-national domains, and 4 studies (5.00%) examined oceanic or marine domains. Among the country-specific

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studies, China was represented by seven studies and the United States by six, while India, the United Kingdom, France, New Zealand, and Sweden were each represented by one study. The regional category included studies covering North America, Europe, the European Union together with the United Kingdom, and the northern permafrost region, whereas the marine category comprised global-ocean and Eastern Tropical Pacific investigations. Overall, the distribution demonstrates that the reviewed N_2O literature is dominated by studies with global coverage, while geographically explicit country- and region-specific investigations constitute a smaller proportion of the evidence base.

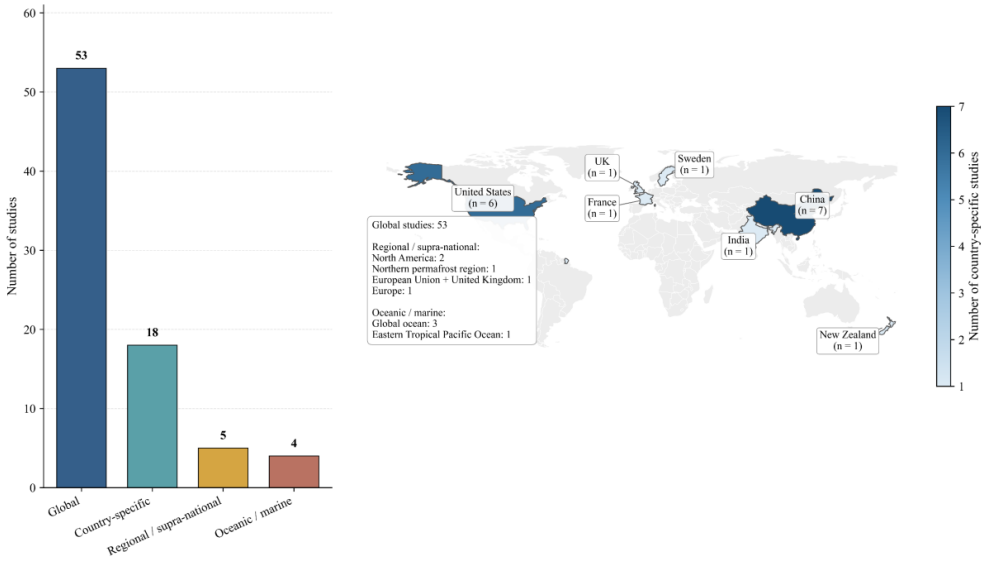


Fig. 4. Geographic distribution of study domains represented in the reviewed N_2O budget literature. (a) Distribution of studies according to geographic extent, including global, country-specific, regional/supra-national, and oceanic/marine categories. (b) Country-level distribution of geographically specific studies after assigning subnational studies to their respective countries; global, regional/supra-national, and oceanic studies are summarized separately.

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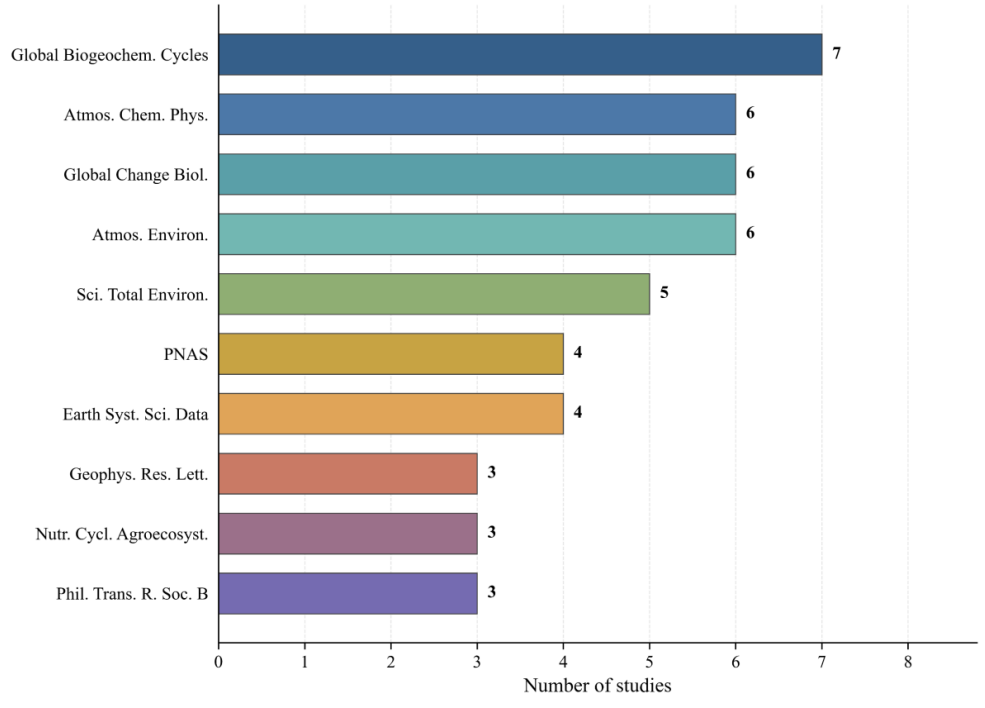
Within the country-specific subset, China and the United States accounted for the largest numbers of studies, with seven and six studies, respectively. Studies focused on the United States covered a range of topics, including regional source reconciliation, agricultural systems, and N_2O production from stream networks, illustrating the diversity of processes investigated within a single national domain (Beaulieu et al., 2011; Deng et al., 2022a; Griffis et al., 2013). China-focused studies similarly addressed several important anthropogenic source processes, particularly fertilizer-related emissions, rice cultivation, and cropland nitrogen management (Jiang et al., 2017; Li et al., 2005; Qu et al., 2014; Zou et al., 2009). Beyond these two countries, the broader database also included studies addressing national and regional emission accounting, European-scale assessments, atmospheric processes, and groundwater- and soil-related N_2O dynamics, demonstrating the range of environmental settings represented within the review (Butterbach-Bahl et al., 2009; Freing et al., 2012; Skiba et al., 2012; Solazzo et al., 2021; Vilain et al., 2012). Research on grazed pastoral systems, measurement approaches, and emission-factor development further illustrates the contribution of livestock-based production systems to the geographically explicit evidence base (Barton et al., 2015; Cowan et al., 2021; Klein et al., 2003). Normally, the geographic distribution indicates that although the reviewed literature contains studies from multiple environmental regions, country-specific evidence is concentrated in a limited number of locations, while most studies in the database were conducted at global or broader regional scales.

3.2.2 Distribution of publication outlets

The reviewed studies were distributed across a diverse range of publication outlets, although a substantial proportion appeared in a relatively small group of journals. As shown

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in Fig. 5, Global Biogeochemical Cycles contained the largest number of included studies (7), followed by Atmospheric Chemistry and Physics, Global Change Biology, and Atmospheric Environment, with 6 studies each. Science of the Total Environment contributed 5 studies, while Proceedings of the National Academy of Sciences and Earth System Science Data each accounted for 4 studies. Geophysical Research Letters, Nutrient Cycling in Agroecosystems, and Philosophical Transactions of the Royal Society B, each contained 3 studies. Together, these ten journals accounted for 47 of the 80 studies (58.75%), indicating a moderate concentration of the reviewed literature within a core group of outlets. The disciplinary scope of these journals further shows that N_2O budget research spans atmospheric chemistry, global biogeochemistry, ecosystem science, environmental assessment, and agricultural nitrogen cycling, reflecting the multidisciplinary nature of efforts to quantify N_2O sources, sinks, and budget uncertainties.



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Fig. 5. Distribution of the ten most represented journals among the 80 studies included in the N_2O budget review. Bars indicate the number of reviewed studies published in each journal.

The studies represented in these journals span a broad range of research topics, including agricultural nitrogen responses, regional emission reconciliation, marine N_2O production, groundwater-related losses, grassland budgets, and assessments of inventory uncertainty (Beaulieu et al., 2011; Cowan et al., 2021; Freing et al., 2012; Griffis et al., 2013; Qu et al., 2014; Saggar et al., 2013; Solazzo et al., 2021; Xu et al., 2021). The strong representation of Global Biogeochemical Cycles and Earth System Science Data among the most frequently represented journals highlights the importance of large-scale biogeochemical assessment, data synthesis, and integrated budget evaluation within the reviewed literature. Taken together, the journal distribution illustrates the multidisciplinary character of N_2O budget research, in which process-level studies coexist with broader efforts to integrate observations, inventories, models, and uncertainty assessments across environmental systems and spatial scales.

3.3 Sources, sinks, and budget imbalance in the global N_2O literature

3.3.1 Dominance of source focused studies

Source-focused research constituted the largest thematic component of the reviewed literature, comprising 53 of the 80 studies (66.25%), compared with 22 budget-imbalance studies (27.50%) and 5 sink-focused studies (6.25%), as summarized in Fig. 6a. The quantitative subtheme analysis in Fig. 6b further shows that agricultural-soil sources accounted for 27 studies, aquatic sources for 15, other source categories for 6, natural terrestrial sources for 4, and waste/industrial sources for 1. The dominance of source-focused studies likely reflects the wide range of N_2O-emitting systems and the importance

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of emission quantification for inventories and mitigation. The breadth of these categories indicates that source-oriented research encompasses a wide range of anthropogenic and natural processes rather than being confined to a single sector. Fig. 7 provides the corresponding conceptual framework of N_2O emission pathways, distinguishing anthropogenic direct and indirect sources from natural sources and linking them to processes such as fertilizer and organic-N inputs, atmospheric deposition, nitrogen leaching and runoff, oceanic production, and soil nitrification and denitrification. At the broader system level, Fig. 6f shows that methods/budget studies were the most represented category (24 studies), followed by agriculture (22), aquatic systems (15), natural systems (8), general/mixed studies (7), and waste/industry (4). These frequencies describe the distribution of research attention within the reviewed literature and should not be interpreted as direct estimates of the relative magnitude of N_2O emissions from each system. Smaller anthropogenic categories, including transport-related emissions, nevertheless remain part of comprehensive source inventories and contribute to the overall diversity of source accounting (Wallington and Wiesen, 2014).

The emphasis on source quantification is also reflected in repeated efforts to constrain global N_2O emission totals using different estimation frameworks, as summarized in Table 1. Syakila and Kroeze (2011) estimated global N_2O emissions at approximately 19 Tg N yr^{-1} for the mid-2000s, while Thompson et al. (2014) reported inversion-based global totals ranging from 17.5 to 20.1 Tg N yr^{-1} during 1999–2009. More recent assessments yielded 17.0 Tg N yr^{-1} from bottom-up approaches and 16.9 Tg N yr^{-1} from top-down approaches for 2007–2016, followed by estimates of 18.2 versus 17.4 Tg N yr^{-1} for 2010–2019 and 18.5 versus 17.0 Tg N yr^{-1} for 2020. Taken together, these assessments indicate broadly

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385 comparable central estimates of the global N_2O source magnitude across periods and
386 methodological frameworks, while also revealing substantial differences in uncertainty
387 ranges and source attribution (Stell et al., 2022; Syakila and Kroeze, 2011; Thompson et
388 al., 2014; Tian et al., 2024; Tian et al., 2020). Table 1 therefore illustrates the continuing
389 methodological effort to constrain and reconcile N_2O source estimates, rather than
390 providing a direct explanation for the numerical dominance of source-focused studies in
391 the reviewed literature.

392 Table 1. Representative global N_2O budget estimates reported in major synthesis studies

393

Reference	Period	Scope	Method class	Bottom-up estimate (Tg N yr^{-1})	Top-down estimate (Tg N yr^{-1})	Global total estimate (Tg N yr^{-1})
(Syakila and Kroeze, 2011)	2006	Global	Budget synthesis			19.0
(Thompson et al., 2014)	1999-2009	Global	Top-down inversion		17.5-20.1	17.5-20.1
(Tian et al., 2020)	2007-2016	Global	Bottom-up	17.0 (12.2-23.5)		17.0 (12.2-23.5)
(Tian et al., 2020)	2007-2016	Global	Top-down		16.9 (15.9-17.7)	16.9 (15.9-17.7)
(Stell et al., 2022)	2011-2020	Global	Top-down inversion		17.2 (16.7-17.7)	17.2 (16.7-17.7)
(Tian et al., 2024)	2010-2019	Global	Bottom-up	18.2 (10.6-25.9)		18.2 (10.6-25.9)
(Tian et al., 2024)	2010-2019	Global	Top-down		17.4 (15.8-19.2)	17.4 (15.8-19.2)
(Tian et al., 2024)	2020	Global	Bottom-up	18.5 (10.6-27.0)		18.5 (10.6-27.0)
(Tian et al., 2024)	2020	Global	Top-down		17.0 (16.6-17.4)	17.0 (16.6-17.4)

394 Within the source-focused literature, agricultural soils represented the largest source
395 subtheme, accounting for 27 of the 53 source studies, while agriculture was identified as

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the system focus in 22 of the 80 reviewed studies (Fig. 6b and Fig. 6f). These publication frequencies indicate the prominence of agricultural systems within the reviewed evidence base, but they should not be interpreted as a direct measure of agriculture's proportional contribution to the atmospheric N_2O budget. Independently of publication frequency, agriculture is widely recognized as a major anthropogenic source of N_2O because fertilizer use, manure management, and other reactive-nitrogen inputs enhance the availability of substrates for microbial N_2O production in managed soils (Alexandratos and Bruinsma, 2012; Crippa et al., 2021; Davidson, 2009). Global compilations have likewise identified fertilized soils as an important component of anthropogenic N_2O emissions while demonstrating substantial variation in emission rates according to nitrogen input, climate, soil properties, and management practices (Bouwman et al., 2002a; Bouwman et al., 2002b). Accordingly, the agricultural studies included in this review encompass fertilizer application, manure management, crop production, and livestock-related nitrogen cycling, reflecting the diversity of processes considered within agricultural source assessments rather than simply the magnitude of the sector's emissions (Chadwick et al., 2011; Herridge et al., 2008; Peoples et al., 2009; Venterea et al., 2012). Intensive vegetable systems provide one example of this variability, with both fertilizer-induced and background emissions responding strongly to high nitrogen inputs and local management conditions (Wang et al., 2011). Other studies have examined specific modifiers of agricultural N_2O production, including legume-derived nitrogen inputs, tillage practices, soil aeration, and associated changes in N_2O yield (Rochette, 2008; Rochette and Janzen, 2005). Emission variability has also been documented in perennial cropping systems such

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as fruit orchards, further illustrating the need to represent diverse agricultural management systems when evaluating N_2O sources (Gu et al., 2019).

Aquatic systems formed the second-largest source subtheme after agricultural soils, accounting for 15 of the 53 source-focused studies, compared with 27 studies on agricultural soils. Fig. 6b therefore indicates that aquatic N_2O research represents a substantial component of the source-focused literature, while Fig. 6c shows that aquatic-source studies recur across multiple publication years rather than being confined to a single period. At the broader system level, aquatic systems also accounted for 15 of the 80 reviewed studies, following methods/budget and agriculture in the system-focus classification shown in Fig. 6f. These publication counts describe the representation of aquatic research within the review and should be distinguished from the magnitude of aquatic N_2O emissions themselves. Table 2 provides representative sectoral estimates showing that direct agricultural emissions remain a major anthropogenic component, while natural land and ocean sources contribute substantially to the overall N_2O budget and inland-water and marine systems constitute identifiable source categories. Because the estimates in Table 2 are derived from different studies, time periods, and partially overlapping source definitions, they should be interpreted as representative sectoral evidence rather than summed directly to reconstruct a single global budget.

Table 2. Representative estimates of major N_2O source sectors reported in the reviewed literature.

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Category	Value	Uncertainty / range	Unit	Time basis	System class	Reference
Direct agricultural emissions	3.9	best estimate	Tg N yr^{-1}	2020	Anthropogenic	(Tian et al., 2024)
Indirect anthropogenic emissions	1.3	best estimate	Tg N yr^{-1}	2020	Anthropogenic	(Tian et al., 2024)
Other direct anthropogenic sources	2.1	best estimate	Tg N yr^{-1}	2020	Anthropogenic	(Tian et al., 2024)
Natural land + ocean sources	11.8	7.3-15.9	Tg N yr^{-1}	2010-2019	Natural	(Tian et al., 2024)
Ocean emissions	4.2	±1.0	Tg N yr^{-1}	Climatological annual mean	Aquatic/marine	(Yang et al., 2020)
River emissions	0.2913	±0.0586	Tg N yr^{-1}	2016	Aquatic/inland waters	(Yao et al., 2020)
Lakes and reservoirs	0.0646	±0.0121	Tg N yr^{-1}	2010s	Aquatic/inland waters	(Li et al., 2024)
Inland waters (rivers + lakes/reservoirs)	0.3196	±0.0582	Tg N yr^{-1}	2010s	Aquatic/inland waters	(Li et al., 2024)

Representative aquatic-source estimates further illustrate the contribution of marine and inland-water systems to the N_2O budget. Oceanic emissions have been estimated at 4.2 ± 1.0 Tg N yr^{-1}, while riverine emissions were estimated at 0.2913 ± 0.0586 Tg N yr^{-1} for 2016 and emissions from lakes and reservoirs at 0.0646 ± 0.0121 Tg N yr^{-1} for the 2010s; a combined estimate for inland waters reached approximately 0.3196 ± 0.0582 Tg N yr^{-1} (Li et al., 2024; Yang et al., 2020; Yao et al., 2020). Although these estimates are smaller than the major agricultural source components summarized in Table 2, they demonstrate that aquatic systems constitute quantifiable components of the N_2O budget across both marine and inland-water environments. Their representation in 15 source-focused studies,

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together with the temporal distribution shown in Fig. 6c, indicates sustained attention to aquatic sources within the reviewed literature rather than a recent or isolated research emphasis.

Beyond their contribution to sectoral emission totals, aquatic systems exhibit substantial spatial variability in N_2O production and release. River networks are particularly heterogeneous, with network-scale analyses showing that small streams can contribute disproportionately to riverine N_2O emissions because of differences in hydrological connectivity, nitrogen availability, and biogeochemical processing (Marzadri et al., 2021). More broadly, streams, rivers, estuaries, and coastal waters participate actively in N_2O cycling, particularly where denitrification, nitrate transport, and excess reactive-nitrogen loading interact across terrestrial–aquatic interfaces (Codispoti, 2010; Seitzinger et al., 2006; Weitzman and Kaye, 2018). Groundwater-mediated indirect emissions represent an additional pathway because subsurface nitrogen transport and transformation can alter both the location and timing of N_2O production and subsequent release to the atmosphere (Jurado et al., 2017).

Waste- and industry-related pathways were comparatively less represented in the reviewed literature. In the source-subtheme classification, only 1 of the 53 source-focused studies was assigned to the waste/industrial category, while 4 of the 80 studies were classified under waste/industry at the broader system level in Fig. 6f. This limited representation should not be interpreted as evidence that such emissions are negligible, because wastewater treatment and selected industrial processes can generate N_2O through biologically and chemically mediated nitrogen transformations (Bogner et al., 2008; Kampschreur et al., 2009). Within wastewater treatment systems, N_2O production can vary

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considerably with treatment configuration, nitrogen-removal pathways, operational conditions, and the methods used to quantify emissions, making these sources relevant to sector-specific assessments despite their small representation in the present database (Massara et al., 2017). Interactions between wastewater reuse and agricultural management further illustrate that waste-related pathways can overlap with terrestrial nitrogen cycling, because irrigation with treated wastewater may modify soil nitrogen availability and associated N_2O emissions (Xu et al., 2017). Taken together, the source-focused literature reviewed here spans agricultural, aquatic, natural terrestrial, and waste/industrial pathways, demonstrating broad process diversity while also revealing substantial differences in the level of research attention among source categories.

3.3.2. Limited sink representation and persistent budget imbalance

Sink-focused research remains comparatively sparse within the reviewed literature, and its temporal distribution is intermittent rather than continuous across the study period, as shown in Fig. 6d. This limited representation should not be interpreted as evidence that N_2O sink processes are inherently more difficult to measure or constrain; rather, it indicates that sink processes have received substantially less attention within the literature captured by this review. Nevertheless, the underlying mechanisms are environmentally complex. Soils and aquatic systems can consume N_2O when microbial reduction to N_2 is favored, and the magnitude and occurrence of this sink behavior are influenced by interacting controls including microbial community composition, oxygen availability, nitrate supply, redox conditions, and hydrological connectivity (Chapuis-Lardy et al., 2007; Jones et al., 2013; Sanford et al., 2012; Tangen and Bansal, 2022). Accordingly, the present evidence

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supports describing N_2O sinks as underrepresented in the reviewed budget literature, rather than attributing their limited publication frequency to measurement difficulty alone.

Methodological constraints may nevertheless contribute to the limited characterization of N_2O sinks. In contrast to clearly positive emission fluxes, net N_2O uptake can be small, intermittent, and strongly dependent on local environmental conditions, making it more difficult to detect consistently across space and time. Demonstrating net consumption therefore often requires high-precision measurements together with careful consideration of atmospheric undersaturation, hydrological transport, gas exchange, and microbial reduction pathways. These requirements can complicate the detection and upscaling of sink behavior, particularly in heterogeneous soils and inland-water systems (Aho et al., 2023; Chapuis-Lardy et al., 2007).

A further consideration is that N_2O accounting and mitigation frameworks have historically placed greater emphasis on quantifying emission-producing activities than on explicitly representing consumption pathways. Inventory and reporting systems are primarily structured around identifying anthropogenic emissions from sectors such as agriculture, wastewater treatment, and other managed sources, whereas sink processes are generally less explicitly represented even though they can influence estimates of net N_2O exchange and overall budget closure (Baasansuren et al., 2019; Ipcc, 2006; Tian et al., 2024). This asymmetry in accounting and assessment frameworks is consistent with the stronger representation of emission-producing systems in the reviewed literature, while N_2O consumption pathways remain comparatively less developed as a distinct research focus (Aho et al., 2023; Chapuis-Lardy et al., 2007).

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Evidence from freshwater and wetland systems demonstrates that N_2O exchange can shift between emission and uptake under different environmental conditions. Aho et al. (2023) reported N_2O undersaturation in 14–30% of freshwater observations and 38% of modeled cases, indicating that negative air–water exchange may partially offset positive emissions. However, the frequency of undersaturation cannot be directly interpreted as the magnitude of annual atmospheric uptake at regional or global scales. Similarly, Tangen and Bansal (2022) identified locally negative or near-zero N_2O fluxes in prairie wetlands, although the regional wetland system remained a net emitter. These findings emphasize the distinction between microbial N_2O consumption, measured net surface exchange, and the upscaling of positive and negative fluxes. As summarized in Table 3, the contribution of terrestrial and aquatic consumption processes to N_2O budget assessments therefore depend on their measurable effects on net surface exchange, rather than on the occurrence of microbial reduction or local uptake alone.

Alongside the limited representation of sink-focused research, budget-imbalance studies formed the second-largest thematic component of the reviewed literature. Their internal distribution shows that methodological discrepancies were the dominant concern (12 studies), followed by trend and growth assessments (5), budget-closure studies (4), and explicit source–sink imbalance analyses (1). The temporal pattern in Fig. 6e further shows that budget-imbalance research became more prominent after 2010, reflecting increasing attention to differences among inventories, atmospheric inversions, process-based models, and scaling approaches. Rather than identifying entirely new source categories, much of this work therefore addresses the reconciliation of estimates derived from different observational and modelling frameworks. Such discrepancies can arise from limited or

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intermittent flux observations, differences in chamber design and sampling frequency, incompletely characterized indirect pathways, and uncertainties introduced when scaling measurements from individual sites to regional or broader budgets (Philibert et al., 2013; Rochette, 2011). These methodological and scaling uncertainties help explain why achieving consistent budget closure remains a central challenge in N_2O assessment, without implying that they are responsible for the comparatively small number of sink-focused studies.

A complementary pattern emerges from the system-level classification in Fig. 6f. Methods/budget studies were the most frequently represented category (24 studies), followed by agriculture (22), aquatic systems (15), natural systems (8), general/mixed studies (7), and waste/industry (4). Although natural systems were less frequently represented in the final review database than methodological/budget, agricultural, and aquatic studies, this should not be interpreted as limited importance of natural ecosystems in the broader N_2O literature. Natural terrestrial ecosystems have been investigated through global inventories, process-based models, and data-driven assessments, including estimates of N_2O emissions from natural soils, forests, and grasslands and analyses of their spatial and temporal variability (Liao et al., 2023; Saikawa et al., 2013; Zhang et al., 2019; Zhuang et al., 2012). These studies demonstrate that natural-soil N_2O emissions are substantial, spatially heterogeneous, and sensitive to climatic and biogeochemical controls. The pattern observed in Fig. 6f therefore reflects the composition of the present review database rather than the overall importance or maturity of natural-ecosystem research**.** Together with the limited representation of sink-focused studies and the prominence of

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methodological-discrepancy analyses, this finding highlights the need to integrate natural, managed, aquatic, source, and sink processes more consistently in N_2O budget assessments.

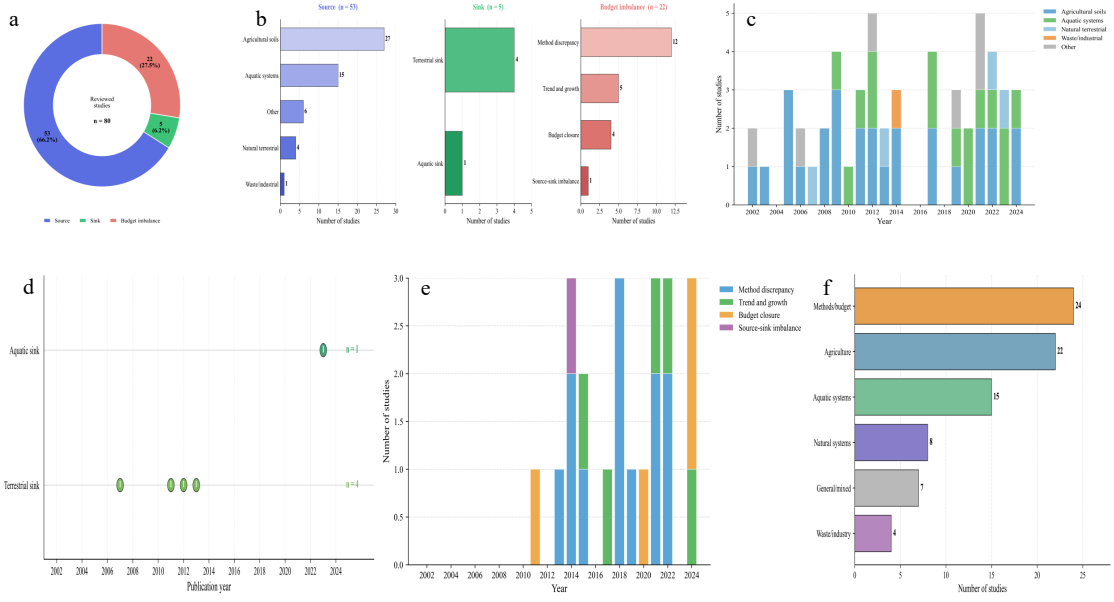


Fig. 6. Quantitative distribution and temporal evolution of research themes in the reviewed N_2O budget literature. (a) Overall distribution of source, sink, and budget-imbalance studies; (b) subtheme counts within each major theme; (c) temporal distribution of source-focused studies; (d) temporal distribution of sink-focused studies; (e) temporal distribution of budget-imbalance studies; and (f) system-focus distribution of the reviewed studies.

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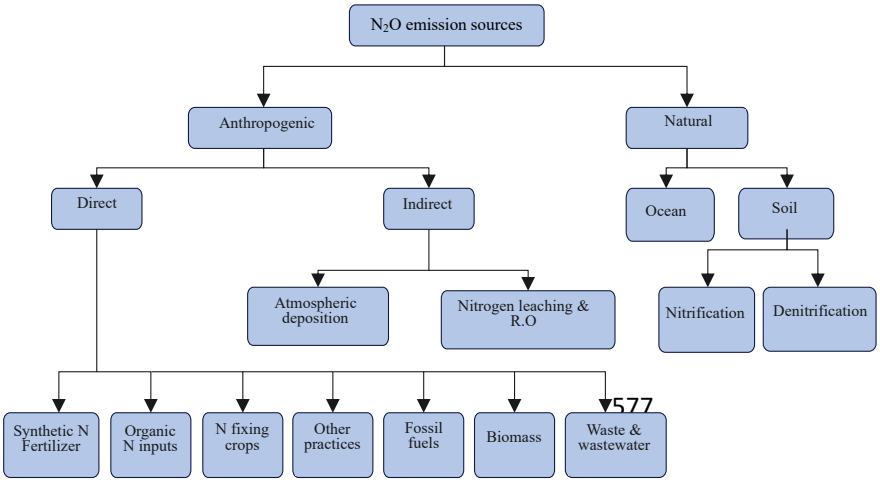


Fig. 7. Schematic classification of global N_2O emission sources

3.4 Estimation approaches and methodological uncertainty

3.4.1 Bottom-up and process-based approaches predominate

The methodological composition of the reviewed literature is more diverse than suggested by the earlier classification. Bottom-up approaches constituted the largest single methodological class, accounting for 29 of the 80 studies (36.25%), followed closely by process-based approaches with 24 studies (30.00%). Top-down approaches represented 12 studies (15.00%), while combined/comparative and hybrid/integrated approaches accounted for 8 (10.00%) and 7 studies (8.75%), respectively, as summarized in Fig. 8a. Together, bottom-up and process-based approaches therefore comprised approximately two-thirds of the reviewed literature, indicating that direct source estimation and mechanistic representation remain central components of N_2O budget assessment. Fig. 8b summarizes the representative methodological frameworks within these five classes: bottom-up studies commonly relied on emission factors, inventories, field measurements, and empirical or statistical upscaling; studies classified as process-based investigated

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biogeochemical mechanisms through modeling, experimental research, and process-oriented syntheses; and top-down studies primarily applied atmospheric inversions and transport-model constraints. Combined/comparative studies explicitly reconciled or compared estimates across methodological frameworks, whereas hybrid/integrated studies incorporated observation–model integration, multi-method synthesis, and other data–model combinations.

The substantial representation of bottom-up approaches is consistent with their established role in national and sectoral greenhouse-gas accounting, where emissions can be estimated from activity data, emission factors, land-management information, and standardized reporting frameworks (Baasansuren et al., 2019; Ipcc, 2006). Earlier syntheses of field-based N_2O measurements also provided an important empirical foundation for subsequent inventory development through the compilation of emission factors and large-scale statistical extrapolation (Bouwman et al., 2002a; Bouwman et al., 2002b). Fig. 8c shows that bottom-up approaches occur throughout the review period, while process-based, top-down, combined/comparative, and hybrid/integrated approaches become increasingly represented in the later literature, indicating a gradual diversification of methodological frameworks rather than replacement of bottom-up estimation. Despite their operational value, bottom-up estimates remain sensitive to the selection of emission factors, spatial and temporal representativeness of observations, scaling assumptions, and the treatment of uncertainty, all of which can influence regional and broader emission estimates (Del Grosso et al., 2008; Solazzo et al., 2021). Large-scale inventory compilations further demonstrate the importance of consistent dataset harmonization, sectoral coverage, and source

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classification when comparing N_2O estimates across regions and reporting frameworks (Minx et al., 2021).

Table 3 evaluates the budget quantities constrained by different forms of N_2O evidence and the limitations involved in comparing them. The distinction is particularly important for source–sink accounting, where microbial N_2O reduction, measured net surface exchange, and atmospheric chemical removal describe different processes and accounting boundaries. Evidence of microbial reduction capacity does not establish net atmospheric uptake, while observations of negative fluxes at individual sites cannot alone determine regional or global annual sink magnitudes (Aho et al., 2023; Jones et al., 2013; Tangen and Bansal, 2022). Similarly, atmospheric inversions provide observation-constrained estimates of aggregate surface emissions but do not uniquely resolve the individual biogeochemical processes responsible for those emissions (Stell et al., 2022; Thompson et al., 2014; Wells et al., 2018). Integrated assessments combine several estimation approaches, making the identification of shared model inputs and underlying data relationships important when interpreting agreement between published estimates (Tian et al., 2024). These distinctions indicate that methodological diversity does not necessarily correspond to an equivalent diversity of independent constraints on the N_2O budget.

Table 3. Evidence constraints, accounting boundaries, and implications for evaluating the global N_2O budget.

Evidence and representative studies	Budget quantity constrained	Limitation for budget interpretation	Implication for synthesis
Microbial N_2O reduction (Sanford et al., 2012)	Biological mechanisms and capacity for N_2O reduction	Does not establish annual net atmospheric uptake	Distinguish microbial consumption from

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			net surface exchange
Freshwater undersaturation (Aho et al., 2023)	Observed undersaturation and modeled implications for aquatic emissions	Undersaturation frequency alone cannot quantify global annual atmospheric uptake	Require gas-transfer, spatial and temporal integration
Wetland flux measurements (Tangen and Bansal, 2022)	Local chamber-measured N_2O exchange and regional upscaling	Locally negative fluxes do not establish a net-negative regional budget	Preserve positive and negative fluxes during upscaling
Atmospheric emission inversions (Stell et al., 2022; Thompson et al., 2014; Wells et al., 2018)	Observation-constrained regional or global surface emissions	Sectoral attribution depends partly on priors, transport representation and observational coverage	Compare estimates over matched periods, regions and accounting boundaries
Observing-system simulation (Wells et al., 2015)	Potential emission constraints from observational networks	Simulation-based information potential is not a realized observation-derived posterior emission estimate	Distinguish observing-system capability from measured emission constraints
Atmospheric chemical loss (Prather et al., 2015)	Atmospheric lifetime and chemical removal	Does not directly measure soil or aquatic N_2O uptake	Separate atmospheric chemical removal from terrestrial and aquatic exchange
Integrated budget assessment (Tian et al., 2024)	Global and regional budgets combining multiple estimation approaches	Some estimates share model frameworks, source products or methodological inputs	Trace source-product relationships before interpreting agreement as independent confirmation

The sources of uncertainty summarized in Table 4 are heterogeneous and vary across both environmental systems and estimation frameworks. For bottom-up assessments, uncertainty arises from spatial variability in emission controls, incomplete activity data, limited representation of indirect and aquatic pathways, and the transfer of locally derived

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emission factors to broader spatial scales. Measurement design can introduce an additional source of uncertainty because chamber configuration, sampling frequency, and flux-integration procedures can materially influence annual N_2O estimates (Barton et al., 2015). Top-down estimates are subject to a different set of constraints, including atmospheric transport representation, observational-network coverage, prior assumptions, and source-partitioning limitations. Consequently, the larger representation of bottom-up studies in the reviewed literature should be interpreted as evidence of methodological prevalence rather than methodological certainty.

Table 4. Major sources of uncertainty across N_2O source sectors and estimation frameworks.

Category / system	Main uncertainty sources	Regions where uncertainty is especially important	Representative references
Agricultural soils (direct emissions)	Spatial variation in fertilizer rate, crop type, soil texture, pH, moisture, and climate; nonlinear N response; limited representativeness of default emission factors	China, India, North America, Europe, intensive croplands globally	(Bouwman et al., 2002a; Bouwman et al., 2002b; Shcherbak et al., 2014; Tian et al., 2019; Venterea et al., 2012)
Livestock and manure systems	Variability in manure storage, grazing intensity, urine patches, feed composition, and climate controls on nitrification–denitrification	New Zealand, Australia, Europe, livestock-dense mixed systems	(Chadwick et al., 2011; Klein et al., 2003; Oenema et al., 2005)
Indirect emissions (deposition, leaching, runoff, groundwater)	Poorly constrained transfer pathways, delayed downstream emissions, weak linkage between land N surplus and emission location, limited field validation	Europe, North America, agricultural catchments, river-connected landscapes	(Seitzinger et al., 2006; Tian et al., 2024; Vilain et al., 2012; Weitzman and Kaye, 2018)
Inland waters (streams,	Sparse measurements, strong temporal	North America, Europe, tropical	(Beaulieu et al., 2011; Maavara et al., 2019; Pan

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Category / system	Main uncertainty sources	Regions where uncertainty is especially important	Representative references
rivers, lakes, reservoirs)	variability, uncertain gas-transfer velocities, hydrological residence time effects, poor global scaling	reservoirs, river networks, under-sampled regions	et al., 2023; Yao et al., 2020)
Estuaries and coastal waters	Strong gradients in salinity, nutrient loading, wastewater influence, tidal exchange, and seasonal hypoxia; few globally comparable observations	Asia, Europe, wastewater-influenced estuaries, coastal hotspots	(Codispoti, 2010; Dong et al., 2023; Feng and Li, 2023)
Natural soils and unmanaged ecosystems	Low measurement density, episodic fluxes, freeze–thaw and moisture pulses, uncertainty in sink behavior and N_2O reduction to N_2	Forests, grasslands, wetlands, high-latitude and semi-natural systems	(Butterbach-Bahl et al., 2013; Chapuis‐Lardy et al., 2007; Tangen and Bansal, 2022)
Wastewater and industrial sources	Limited direct monitoring, technology-specific emission variability, incomplete reporting, simplification in default coefficients	Urban wastewater systems, industrial point sources, developed and emerging economies	(Bogner et al., 2008; Kampschreur et al., 2009)
Bottom-up inventory estimates	Dependence on activity data quality, emission factors, scaling assumptions, incomplete coverage of indirect and aquatic pathways	Global inventories, national reporting systems, data-poor regions	(Baasansuren et al., 2019; Ipcc, 2006; Solazzo et al., 2021; Tian et al., 2024)
Top-down inversion estimates	Dependence on transport models, sparse observational networks, prior assumptions, spatial resolution, source partitioning difficulty	North America, Europe, global inversions, poorly monitored regions	(Nevison et al., 2018; Stell et al., 2022; Thompson et al., 2014; Wells et al., 2015; Wells et al., 2018)
Bottom-up–top-down reconciliation	Different system boundaries, inconsistent sector attribution, atmospheric transport	North America, Europe, global synthesis studies	(Deng et al., 2022b; Griffis et al., 2013; Petrescu et al., 2021; Xu et al., 2021)

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Category / system	Main uncertainty sources	Regions where uncertainty is especially important	Representative references
/ regional comparison	uncertainty, mismatch between inventory categories and atmospheric signals		

3.4.2 Increasing methodological diversification beyond bottom-up approaches

Although bottom-up approaches remain the largest single methodological class, the temporal pattern in Fig. 8c shows increasing diversification of N_2O budget research through greater use of process-based, top-down, combined/comparative, and hybrid/integrated approaches in the later literature. These methods address different components of methodological uncertainty rather than serving as direct substitutes for one another. Fig. 8d shows a particularly clear thematic differentiation: process-based approaches are concentrated mainly in source-focused and sink-focused studies, whereas top-down approaches are concentrated within budget-imbalance research, where atmospheric observations are used to constrain or reconcile large-scale emission estimates. Combined/comparative and hybrid/integrated approaches occur less frequently but provide an explicit link between observational, modelling, and inventory approaches. At the system level, Fig. 8e further indicates that process-based methods are widely represented in aquatic, agricultural, and natural systems, while top-down approaches are concentrated in methods/budget studies. Together, these patterns show that methodological development in the reviewed literature has progressed from reliance on individual estimation frameworks toward a broader combination of mechanistic, atmospheric, comparative, and integrated approaches.

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Process-based approaches complement inventory-based estimation by explicitly representing the environmental and biogeochemical controls governing N_2O production and consumption. In aquatic systems, network-based modelling has shown that hydro-morphological characteristics can improve representation of riverine N_2O emissions beyond approaches based primarily on dissolved inorganic nitrogen scaling (Marzadri et al., 2022). In terrestrial systems, dynamic representations of nitrification and denitrification, including DNDC-family and related process-based frameworks, allow N_2O responses to soil moisture, temperature, substrate availability, and management to vary through time rather than being represented by fixed emission coefficients (Butterbach-Bahl et al., 2009). Process-based modelling has also been extended to natural forest and grassland ecosystems, providing a mechanistic basis for evaluating N_2O emissions from systems that are less represented than agricultural systems in the present review (Ma et al., 2022). Consistent with this breadth of application, Fig. 8e shows that process-based approaches are represented across aquatic, agricultural, natural, and waste/industry systems. Their value therefore lies in resolving environmental controls and nonlinear responses that are difficult to capture with static factors alone, while their performance remains dependent on model structure, parameterization, input data, and observational evaluation.

Atmospheric approaches provide several complementary constraints on the N_2O budget, although these constraints are not equivalent. Of the 12 studies originally classified as top-down in the present database, six performed observation-constrained spatial emission inversions, two addressed atmospheric source inference through other approaches, and four primarily examined atmospheric lifetime, transport-related variability, or observing-system capability. This distinction is important because atmospheric emission inversions

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estimate surface fluxes, whereas atmospheric-lifetime studies constrain chemical removal and observing-system simulations evaluate potential observational information (Prather et al., 2015; Stell et al., 2022; Wells et al., 2015; Wells et al., 2018). Consequently, the original top-down category represents a broader range of atmospheric evidence than emission inversion alone. Comparisons with bottom-up estimates should therefore consider the constrained quantity, spatial and temporal coverage, prior assumptions, and relationships among underlying data products. As illustrated in Table 3, these characteristics determine whether different estimates provide directly comparable information or complementary constraints on the N_2O budget.

Taken together, Fig. 8a–e and Tables 3–4 indicate that the diversity of approaches represented in N_2O budget research should be distinguished from the diversity of budget quantities independently constrained. Differences in accounting boundaries, observational support, model assumptions, and data dependence limit the direct comparability of some estimates. Improved budget reconciliation therefore requires not only integrating additional methods but also identifying which components of net surface exchange and atmospheric loss are constrained by each approach.

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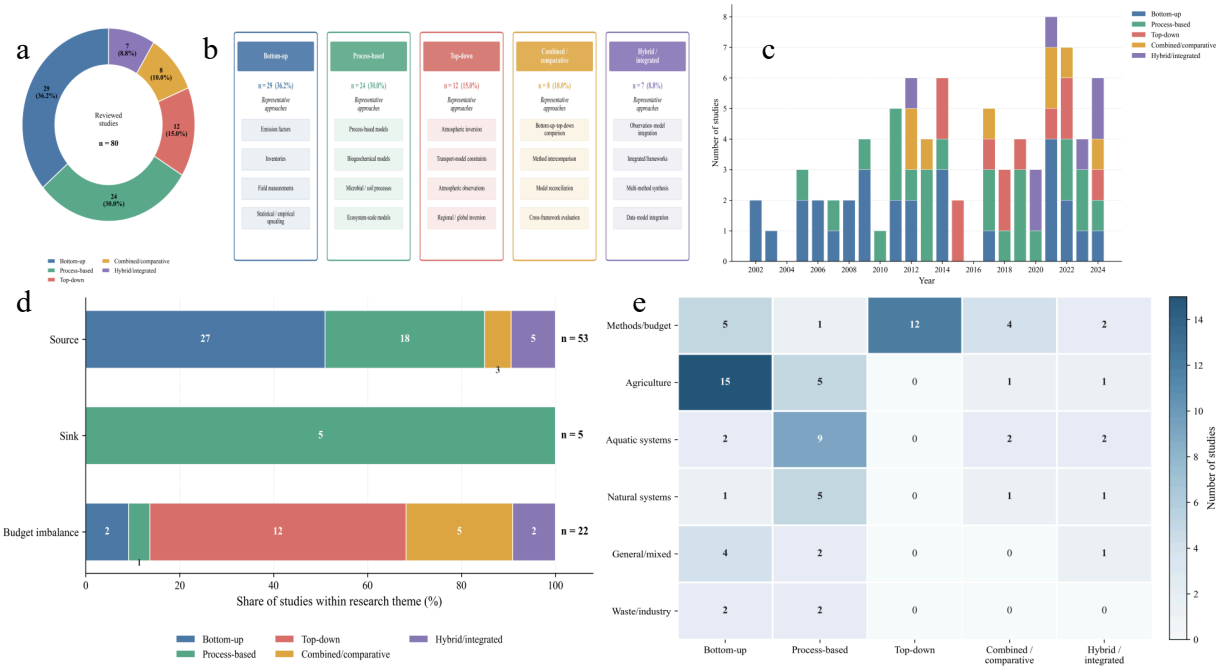


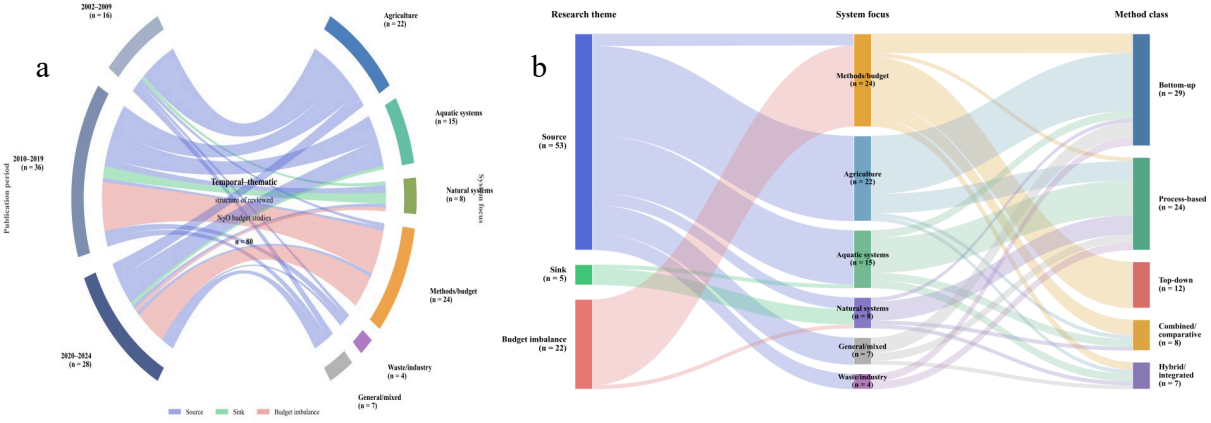
Fig. 8. Distribution and methodological structure of estimation approaches in the reviewed N_2O budget literature. (a) Overall distribution of method classes; (b) representative methodological frameworks within each class; (c) temporal evolution of method classes; (d) distribution of method classes across research themes; and (e) distribution of method classes across system-focus categories.

3.5 Research structure and comparability of N_2O budget evidence

Figure 9 summarizes the relationships among publication periods, research themes, environmental systems, and methodological approaches across the 80 reviewed studies. Agricultural and aquatic systems remain prominent within source-focused research, whereas methods/budget studies are more closely associated with top-down, combined/comparative, and hybrid approaches (Fig. 9a–b). These relationships illustrate how research priorities and methodological applications are distributed across the literature.

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721 However, the widths of the connections represent numbers of publications rather than the
722 magnitude of N_2O fluxes, the strength of observational constraints, or the independence of
723 published estimates. Consequently, the integrated classification provides information about
724 research coverage but cannot independently establish how effectively different
725 components of the global N_2O budget are constrained.



726

727 Fig. 9. Integrated structure and evolution of N_2O budget research. (a) Temporal–thematic
728 relationships among publication periods, research themes, and system-focus categories,
729 where ribbon widths represent the number of studies connecting each period with each
730 system and ribbon colors indicate research theme. (b) Integrated relationships among
731 research themes, system-focus categories, and methodological classes, with flow widths
732 proportional to the number of studies in each pathway.

733 A more detailed assessment of the evidence underlying these methodological categories
734 reveals an important limitation in interpreting their contribution to budget reconciliation.
735 Among the 12 studies originally classified as top-down, six performed observation-
736 constrained spatial emission inversions, two provided other forms of atmospheric source
737 inference, and four primarily investigated atmospheric chemical lifetime, transport-related
738 variability, or observing-system capability (Liang et al., 2022; Nevison et al., 2024; Prather

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et al., 2015; Prokopiou et al., 2017; Stell et al., 2022). Although these studies provide complementary atmospheric information, they do not constrain identical budget quantities. Similar distinctions arise in the evidence for N_2O consumption. Microbial reduction capacity, observed negative surface exchange, and atmospheric chemical removal represent different processes and cannot be treated as interchangeable measures of an atmospheric sink (Aho et al., 2023; Jones et al., 2013; Tangen and Bansal, 2022).

These differences have implications for the interpretation of agreement among published budget estimates. Integrated assessments may incorporate inversion frameworks, emission inventories, and ecosystem models that share methodological assumptions or underlying source products (Tian et al., 2024). Agreement among such estimates does not necessarily constitute independent confirmation of their accuracy. Comparability also depends on consistent spatial and temporal coverage, system boundaries, and uncertainty treatment. The evidence assessment summarized in Table 3 therefore identifies a limitation that is not captured by the thematic relationships in Fig. 9: the diversity of methods represented in the literature does not necessarily correspond to an equivalent diversity of independently comparable budget constraints. Because the detailed endpoint assessment covered 23 selected studies, this conclusion concerns the documented limitations of those studies rather than their prevalence across the entire 80-study database.

4 Future Research Directions

Three research priorities emerge from the distinction between process-level evidence, net surface exchange, and atmospheric budget constraints. First, greater emphasis is needed on quantifying the magnitude, persistence, and spatial extent of N_2O uptake across terrestrial

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and aquatic environments. Although microbial reduction and locally negative fluxes have been documented, their contribution to regional and annual net exchange remains difficult to establish. Future studies should combine direct flux measurements with investigations of microbial processes, redox conditions, soil moisture, and hydrological variability. Measurements covering both emission and uptake periods would help determine whether locally observed N_2O consumption measurably offsets positive emissions at larger scales (Aho et al., 2023; Tangen and Bansal, 2022).

Second, improved reconciliation between bottom-up and top-down estimates requires greater consistency in the quantities and boundaries being compared. Future assessments should explicitly harmonize spatial domains, reporting periods, emission sectors, and the treatment of indirect aquatic pathways. They should also document shared prior inventories, model assumptions, observational inputs, and source products to distinguish complementary estimates from genuinely independent constraints. Where feasible, comparisons should incorporate independent observations and evaluate the sensitivity of inferred emissions to transport representation, prior assumptions, and uncertainty treatment. Such evaluations would help establish whether agreement between estimation approaches reflects stronger observational constraints or partly shared methodological information (Stell et al., 2022; Tian et al., 2024).

Third, more geographically representative observations are needed to test the applicability of existing emission estimates across different environmental and management conditions. The limited country- and region-specific representation in the reviewed database, particularly for parts of Africa, South Asia, and Latin America, indicates priorities for

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further literature assessment and targeted observational research, although publication frequency alone cannot establish the absence of measurements. Long-term monitoring and coordinated measurements across agricultural, natural, and aquatic systems would improve the evaluation of spatial extrapolation and seasonal variability. Future N_2O budget assessments should therefore prioritize transparent evidence provenance, comparable accounting boundaries, and independent observational evaluation alongside improvements in model complexity and geographic coverage.

5 Limitations

Several limitations should be considered when interpreting this review. The literature search was restricted to the Web of Science Core Collection and predefined search, screening, language, document-type, and publication-period criteria; therefore, relevant studies indexed elsewhere or reported in grey literature may have been missed. Although the final 80 studies were classified using standardized thematic, system, and methodological categories, some interpretive judgment was unavoidable for multidisciplinary studies spanning multiple topics. In addition, direct comparison among published estimates remains constrained by differences in spatial and temporal coverage, system boundaries, reporting units, and methodological assumptions. These factors may influence the representation of research themes, geographic patterns, and methodological trends identified in the review.

The detailed evidence-endpoint assessment covered 23 selected studies within the original 80-publication database, comprising 12 originally classified as top-down, five as sink-focused, and six additional studies representing complementary estimation approaches and

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environmental systems. As this was a targeted assessment rather than a representative sample, the findings cannot establish the prevalence of individual evidence types across the complete database. Furthermore, identifying shared methodological inputs or source-product relationships does not establish statistical dependence among estimates or quantify its effects on budget uncertainty. The review therefore does not provide an independent recalculation of global N_2O emissions or a numerical assessment of how these relationships affect published budget estimates.

6 Conclusions

This systematic review examined 80 peer-reviewed studies published between 2002 and 2024 to evaluate research patterns, source–sink representation, estimation approaches, and the evidence supporting N_2O budget assessments. The original classification revealed a strong emphasis on emission sources, with 53 source-focused studies compared with five primarily addressing sinks. Although methodological approaches have diversified, the findings indicate that research coverage and methodological frequency should not be interpreted as direct measures of the strength or independence of quantitative budget constraints. A focused assessment of 23 selected studies further identified differences in the budget quantities addressed by commonly grouped evidence types. Of the 12 studies originally classified as top-down, six provided observation-constrained spatial emission inversions, while the others addressed different forms of atmospheric source inference, chemical loss, transport variability, or observing-system capability. Similarly, evidence of microbial N_2O reduction and locally negative surface fluxes does not necessarily establish sustained atmospheric uptake at regional or global scales. These distinctions demonstrate

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the importance of separating process-level evidence, net surface exchange, and atmospheric removal when evaluating N_2O source–sink relationships. The synthesis also highlights limitations in interpreting agreement among published bottom-up and top-down estimates when their spatial and temporal boundaries, underlying model inputs, or data sources differ. Improved budget assessment therefore requires transparent identification of the quantities constrained by each approach, consistent accounting boundaries, and careful evaluation of uncertainty and source-product relationships. Together, these considerations provide a basis for interpreting the complementary roles of existing estimation methods and identifying where additional independent observations are needed to improve N_2O budget constraints.

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independently reviewed and verified by the authors, who take full responsibility for the manuscript.

Data Availability Statement

The study-level classification data supporting this systematic review are provided in Supplementary Tables S1 and S2. The underlying dataset and analysis scripts used for the quantitative synthesis and figures are publicly available through Zenodo (Iqbal et al., 2026). The original publications used to compile the database are cited in the reference list.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

Aho, K., Maavara, T., Cawley, K., and Raymond, P.: Inland waters can act as nitrous oxide sinks: observation and modeling reveal that nitrous oxide undersaturation may partially offset emissions, Geophysical Research Letters, 50, e2023GL104987,https://doi.org/10.1029/2023GL104987, 2023.

Alexandratos, N. and Bruinsma, J.: World agriculture towards 2030/2050: the 2012 revision, ESA Working Paper No. 12-03, https://www.fao.org/4/ap106e/ap106e.pdf, 2012.

Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., and Federici, S.: 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/, 2019.

Barton, L., Wolf, B., Rowlings, D., Scheer, C., Kiese, R., Grace, P., Stefanova, K., and Butterbach-Bahl, K.: Sampling frequency affects estimates of annual nitrous oxide fluxes, Scientific Reports, 5, 15912,https://doi.org/10.1038/srep15912, 2015.

Beaulieu, J. J., Tank, J. L., Hamilton, S. K., Wollheim, W. M., Hall Jr, R. O., Mulholland, P. J., Peterson, B. J., Ashkenas, L. R., Cooper, L. W., and Dahm, C. N.: Nitrous oxide emission from denitrification in stream and river networks, Proceedings of the National Academy of Sciences, 108, 214-219,https://doi.org/10.1073/pnas.1011464108, 2011.

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., and Gao, Q.: Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation), Waste Management & Research, 26, 11-32,https://doi.org/10.1177/0734242X07088433, 2008.

Bouwman, A., Boumans, L., and Batjes, N.: Emissions of N2O and NO from fertilized fields: Summary of available measurement data, Global Biogeochemical Cycles, 16, 6-1-6-13,https://doi.org/10.1029/2001GB001811, 2002a.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Bouwman, A. F., Boumans, L., and Batjes, N. H.: Modeling global annual N2O and NO emissions from fertilized fields, Global Biogeochemical Cycles, 16, 28-21-28-29,https://doi.org/10.1029/2001GB001812, 2002b.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philosophical Transactions of the Royal Society B: Biological Sciences, 368,https://doi.org/10.1098/rstb.2013.0122, 2013.

Butterbach-Bahl, K., Kahl, M., Mykhayliv, L., Werner, C., Kiese, R., and Li, C.: A European-wide inventory of soil NO emissions using the biogeochemical models DNDC/Forest-DNDC, Atmospheric Environment, 43, 1392-1402,https://doi.org/10.1016/j.atmosenv.2008.02.008, 2009.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., and Misselbrook, T.: Manure management: Implications for greenhouse gas emissions, Animal Feed Science and Technology, 166, 514-531,https://doi.org/10.1016/j.anifeedsci.2011.04.036, 2011.

Chapuis-Lardy, L., Wrage, N., Metay, A., CHOTTE, J. L., and Bernoux, M.: Soils, a sink for N2O? A review, Global Change Biology, 13, 1-17,https://doi.org/10.1111/j.1365-2486.2006.01280.x, 2007.

Codispoti, L. A.: Interesting times for marine N2O, Science, 327, 1339-1340,https://doi.org/10.1126/science.1184945, 2010.

Cowan, N., Bhatia, A., Drewer, J., Jain, N., Singh, R., Tomer, R., Kumar, V., Kumar, O., Prasanna, R., and Ramakrishnan, B.: Experimental comparison of continuous and intermittent flooding of rice in relation to methane, nitrous oxide and ammonia emissions and the implications for nitrogen use efficiency and yield, Agriculture, Ecosystems & Environment, 319, 107571,https://doi.org/10.1016/j.agee.2021.107571, 2021.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A.: Food systems are responsible for a third of global anthropogenic GHG emissions, Nature Food, 2, 198-209,https://doi.org/10.1038/s43016-021-00225-9, 2021.

Cui, X., Bo, Y., Adalibieke, W., Winiwarter, W., Zhang, X., Davidson, E. A., Sun, Z., Tian, H., Smith, P., and Zhou, F.: The global potential for mitigating nitrous oxide emissions from croplands, One Earth, 7, 401-420,https://doi.org/10.1016/j.oneear.2024.01.005, 2024.

Cui, X., Zhou, F., Ciais, P., Davidson, E. A., Tubiello, F. N., Niu, X., Ju, X., Canadell, J. G., Bouwman, A. F., and Jackson, R. B.: Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation, Nature Food, 2, 886-893,https://doi.org/10.1038/s43016-021-00384-9, 2021.

Davidson, E. A.: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860, Nature Geoscience, 2, 659-662,https://doi.org/10.1038/ngeo608, 2009.

Davidson, E. A. and Kanter, D.: Inventories and scenarios of nitrous oxide emissions, Environmental Research Letters, 9, 105012,https://doi.org/10.1088/1748-9326/9/10/105012, 2014.

Del Grosso, S. J., Wirth, T., Ogle, S. M., and Parton, W. J.: Estimating agricultural nitrous oxide emissions, EOS, Transactions American Geophysical Union, 89, 529-529,https://doi.org/10.1029/2008EO510001, 2008.

Deng, J., Guo, L., Salas, W., Ingraham, P., Charrier-Klobas, J. G., Frolking, S., and Li, C.: A decreasing trend of nitrous oxide emissions from California cropland from 2000 to 2015, Earth's Future, 10, e2021EF002526,https://doi.org/10.1029/2021EF002526, 2022a.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Deng, Z., Ciais, P., Tzompa-Sosa, Z. A., Saunois, M., Qiu, C., Tan, C., Sun, T., Ke, P., Cui, Y., and Tanaka, K.: Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions, Earth System Science Data, 14, 1639-1675,https://doi.org/10.5194/essd-14-1639-2022, 2022b.

Dong, Y., Liu, J., Cheng, X., Fan, F., Lin, W., Zhou, C., Wang, S., Xiao, S., Wang, C., and Li, Y.: Wastewater-influenced estuaries are characterized by disproportionately high nitrous oxide emissions but overestimated IPCC emission factor, Communications Earth & Environment, 4, 395,https://doi.org/10.1038/s43247-023-01051-6, 2023.

Erisman, J. W., van Grinsven, H., Grizzetti, B., Bouraoui, F., Powlson, D., Sutton, M. A., Bleeker, A., and Reis, S.: The European nitrogen problem in a global perspective, The European nitrogen assessment: Sources, effects and policy perspectives, 9-31,https://doi.org/10.1017/CBO9780511976988.005, 2011.

Feng, R. and Li, Z.: Current investigations on global N2O emissions and reductions: Prospect and outlook, Environmental Pollution, 338, 122664,https://doi.org/10.1016/j.envpol.2023.122664, 2023.

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., and Galloway, J. N.: The global nitrogen cycle in the twenty-first century, Philosophical Transactions of the Royal Society B: Biological Sciences, 368,https://doi.org/10.1098/rstb.2013.0164, 2013.

Freing, A., Wallace, D. W., and Bange, H. W.: Global oceanic production of nitrous oxide, Philosophical Transactions of the Royal Society B: Biological Sciences, 367, 1245-1255,https://doi.org/10.1098/rstb.2011.0360, 2012.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., Martinelli, L. A., Seitzinger, S. P., and Sutton, M. A.: Transformation of the nitrogen cycle: recent trends, questions, and potential solutions, Science, 320, 889-892,https://doi.org/10.1126/science.1136674, 2008.

Griffis, T., Lee, X., Baker, J., Russelle, M., Zhang, X., Venterea, R., and Millet, D.: Reconciling the differences between top-down and bottom-up estimates of nitrous oxide emissions for the US Corn Belt, Global Biogeochemical Cycles, 27, 746-754,https://doi.org/10.1002/gbc.20066, 2013.

Gu, J., Nie, H., Guo, H., Xu, H., and Gunnathorn, T.: Nitrous oxide emissions from fruit orchards: A review, Atmospheric Environment, 201, 166-172,https://doi.org/10.1016/j.atmosenv.2018.12.046, 2019.

Herridge, D. F., Peoples, M. B., and Boddey, R. M.: Global inputs of biological nitrogen fixation in agricultural systems, Plant and Soil, 311, 1-18,https://doi.org/10.1007/s11104-008-9668-3, 2008.

Hugelius, G., Ramage, J., Burke, E., Chatterjee, A., Smallman, T. L., Aalto, T., Bastos, A., Biasi, C., Canadell, J. G., and Chandra, N.: Permafrost region greenhouse gas budgets suggest a weak CO2 sink and CH4 and N2O sources, but magnitudes differ between top-down and bottom-up methods, Global Biogeochemical Cycles, 38, e2023GB007969,https://doi.org/10.1029/2023GB007969, 2024.

IPCC: 2006 IPCC guidelines for national greenhouse gas inventories, Institute for Global Environmental Strategies, Hayama, Japan, https://www.ipcc-nggip.iges.or.jp/public/2006gl/, 2006.

Iqbal, U., Xiao, Q., Alem, B. B., Talal, M., Zhang, H., and Chen, B.: Reviews and syntheses: Constraining the Nitrous Oxide (N_2O) Budget Across Scales: A Critical Review of Sources,

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Sinks, Estimation Methods, and Knowledge Gaps (1.0), Zenodo [dataset],https://doi.org/10.5281/zenodo.23034942, 2026.
Jiang, Y., van Groenigen, K. J., Huang, S., Hungate, B. A., van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., and Wang, L.: Higher yields and lower methane emissions with new rice cultivars, Global Change Biology, 23, 4728-4738,https://doi.org/10.1111/gcb.13737, 2017.
Jones, C. M., Graf, D. R., Bru, D., Philippot, L., and Hallin, S.: The unaccounted yet abundant nitrous oxide-reducing microbial community: a potential nitrous oxide sink, The ISME Journal, 7, 417-426,https://doi.org/10.1038/ismej.2012.125, 2013.
Jurado, A., Borges, A. V., and Brouyère, S.: Dynamics and emissions of N2O in groundwater: A review, Science of the Total Environment, 584, 207-218,https://doi.org/10.1016/j.scitotenv.2017.01.127, 2017.
Kampschreur, M. J., Temmink, H., Kleerebezem, R., Jetten, M. S., and Van Loosdrecht, M. C.: Nitrous oxide emission during wastewater treatment, Water Research, 43, 4093-4103,https://doi.org/10.1016/j.watres.2009.03.001, 2009.
Klein, C. A. d., Barton, L., Sherlock, R. R., Li, Z., and Littlejohn, R. P.: Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils, Australian Journal of Soil Research, 41, 381-399,https://doi.org/10.1071/SR02128, 2003.
Lan, X., Thoning, K. W., and Dlugokencky, E. J.: Trends in globally-averaged CH4, N2O, and SF6 determined from NOAA Global Monitoring Laboratory measurements, NOAA Global Monitoring LaboratoryVersion 2026-03, https://doi.org/10.15138/P8XG-AA10, 2026.
Li, C., Frolking, S., Xiao, X., Moore III, B., Boles, S., Qiu, J., Huang, Y., Salas, W., and Sass, R.: Modeling impacts of farming management alternatives on CO2, CH4, and N2O emissions: A case study for water management of rice agriculture of China, Global Biogeochemical Cycles, 19,https://doi.org/10.1029/2004GB002341, 2005.
Li, Y., Tian, H., Yao, Y., Shi, H., Bian, Z., Shi, Y., Wang, S., Maavara, T., Lauerwald, R., and Pan, S.: Increased nitrous oxide emissions from global lakes and reservoirs since the pre-industrial era, Nature Communications, 15, 942,https://doi.org/10.1038/s41467-024-45061-0, 2024.
Li, Z., Zeng, Z., Song, Z., Tian, D., Huang, X., Nie, S., Wang, J., Jiang, L., Luo, Y., and Cui, J.: Variance and main drivers of field nitrous oxide emissions: a global synthesis, Journal of Cleaner Production, 353, 131686,https://doi.org/10.1016/j.jclepro.2022.131686, 2022.
Liang, Q., Nevison, C., Dlugokencky, E., Hall, B. D., and Dutton, G.: 3-D atmospheric modeling of the global budget of N2O and its isotopologues for 1980–2019: The impact of anthropogenic emissions, Global Biogeochemical Cycles, 36, e2021GB007202,https://doi.org/10.1029/2021GB007202, 2022.
Liao, J., Huang, Y., Li, Z., and Niu, S.: Data-driven modeling on the global annual soil nitrous oxide emissions: Spatial pattern and attributes, Science of the Total Environment, 903, 166472,https://doi.org/10.1016/j.scitotenv.2023.166472, 2023.
Lickley, M., Solomon, S., Kinnison, D., Krummel, P., Mühle, J., O'Doherty, S., Prinn, R., Rigby, M., Stone, K. A., and Wang, P.: Quantifying the Imprints of Stratospheric Contributions to Interhemispheric Differences in Tropospheric CFC-11, CFC-12, and N2O Abundances, Geophysical Research Letters, 48, e2021GL093700,https://doi.org/10.1029/2021GL093700, 2021.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Liu, H., Zheng, X., Li, Y., Yu, J., Ding, H., Sveen, T. R., and Zhang, Y.: Soil moisture determines nitrous oxide emission and uptake, Science of the Total Environment, 822, 153566,https://doi.org/10.1016/j.scitotenv.2022.153566, 2022.

Ma, M., Song, C., Fang, H., Zhang, J., Wei, J., Liu, S., Chen, X., Zhang, K., Yuan, W., and Lu, H.: Development of a process-based N2O emission model for natural forest and grassland ecosystems, Journal of Advances in Modeling Earth Systems, 14, e2021MS002460,https://doi.org/10.1029/2021MS002460, 2022.

Maavara, T., Lauerwald, R., Laruelle, G. G., Akbarzadeh, Z., Bouskill, N. J., Van Cappellen, P., and Regnier, P.: Nitrous oxide emissions from inland waters: Are IPCC estimates too high?, Global Change Biology, 25, 473-488,https://doi.org/10.1111/gcb.14504, 2019.

Macfarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP, Geophysical Research Letters, 33,https://doi.org/10.1029/2006GL026152, 2006.

Marzadri, A., Bellin, A., Tank, J., and Tonina, D.: Predicting nitrous oxide emissions through riverine networks, Science of The Total Environment, 843, 156844,https://doi.org/10.1016/j.scitotenv.2022.156844, 2022.

Marzadri, A., Amatulli, G., Tonina, D., Bellin, A., Shen, L. Q., Allen, G. H., and Raymond, P. A.: Global riverine nitrous oxide emissions: The role of small streams and large rivers, Science of The Total Environment, 776, 145148,https://doi.org/10.1016/j.scitotenv.2021.145148, 2021.

Massara, T. M., Malamis, S., Guisasola, A., Baeza, J. A., Noutsopoulos, C., and Katsou, E.: A review on nitrous oxide (N2O) emissions during biological nutrient removal from municipal wastewater and sludge reject water, Science of the Total Environment, 596, 106-123,https://doi.org/10.1016/j.scitotenv.2017.03.191, 2017.

Minx, J. C., Lamb, W. F., Andrew, R. M., Canadell, J. G., Crippa, M., Döbbeling, N., Forster, P. M., Guizzardi, D., Olivier, J., and Peters, G. P.: A comprehensive and synthetic dataset for global, regional, and national greenhouse gas emissions by sector 1970–2018 with an extension to 2019, Earth System Science Data, 13, 5213-5252,https://doi.org/10.5194/essd-13-5213-2021, 2021.

Nevison, C., Andrews, A., Thoning, K., Dlugokencky, E., Sweeney, C., Miller, S., Saikawa, E., Benmergui, J., Fischer, M., and Mountain, M.: Nitrous oxide emissions estimated with the CarbonTracker-Lagrange North American regional inversion framework, Global Biogeochemical Cycles, 32, 463-485,https://doi.org/10.1002/2017GB005759, 2018.

Nevison, C. D., Liang, Q., Newman, P. A., Stephens, B. B., Dutton, G., Lan, X., Commane, R., Gonzalez, Y., and Kort, E.: Observational and model evidence for a prominent stratospheric influence on variability in tropospheric nitrous oxide, Atmospheric Chemistry and Physics, 24, 10513-10529,https://doi.org/10.5194/acp-24-10513-2024, 2024.

Oenema, O., Wrage, N., Velthof, G. L., van Groenigen, J. W., Dolfing, J., and Kuikman, P. J.: Trends in global nitrous oxide emissions from animal production systems, Nutrient Cycling in Agroecosystems, 72, 51-65,https://doi.org/10.1007/s10705-004-7354-2, 2005.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., and Brennan, S. E.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, bmj, 372,https://doi.org/10.1136/bmj.n71, 2021.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Pan, H., Zhou, Z., Zhang, S., Wang, F., and Wei, J.: N2O emissions from aquatic ecosystems: A review, Atmosphere, 14, 1291,https://doi.org/10.3390/atmos14081291, 2023.
Peoples, M. á., Brockwell, J., Herridge, D., Rochester, I., Alves, B., Urquiaga, S., Boddey, R., Dakora, F., Bhattarai, S., and Maskey, S.: The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems, Symbiosis, 48, 1-17,https://doi.org/10.1007/BF03179980, 2009.
Petrescu, A. M. R., Qiu, C., Ciais, P., Thompson, R. L., Peylin, P., McGrath, M. J., Solazzo, E., Janssens-Maenhout, G., Tubiello, F. N., and Bergamaschi, P.: The consolidated European synthesis of CH 4 and N 2 O emissions for the European Union and United Kingdom: 1990–2017, Earth System Science Data, 13, 2307-2362,https://doi.org/10.5194/essd-13-2307-2021, 2021.
Philibert, A., Loyce, C., and Makowski, D.: Prediction of N2O emission from local information with Random Forest, Environmental Pollution, 177, 156-163,https://doi.org/10.1016/j.envpol.2013.02.019, 2013.
Prather, M. J., Hsu, J., DeLuca, N. M., Jackman, C. H., Oman, L. D., Douglass, A. R., Fleming, E. L., Strahan, S. E., Steenrod, S. D., and Søvde, O. A.: Measuring and modeling the lifetime of nitrous oxide including its variability, Journal of Geophysical Research: Atmospheres, 120, 5693-5705,https://doi.org/10.1002/2015JD023267, 2015.
Prokopiou, M., Martinerie, P., Sapart, C. J., Witrant, E., Monteil, G., Ishijima, K., Bernard, S., Kaiser, J., Levin, I., and Blunier, T.: Constraining N 2 O emissions since 1940 using firn air isotope measurements in both hemispheres, Atmospheric Chemistry and Physics, 17, 4539-4564,https://doi.org/10.5194/acp-17-4539-2017, 2017.
Qu, Z., Wang, J., Almøy, T., and Bakken, L. R.: Excessive use of nitrogen in Chinese agriculture results in high N2O/(N2O+ N2) product ratio of denitrification, primarily due to acidification of the soils, Global Change Biology, 20, 1685-1698,https://doi.org/10.1111/gcb.12461, 2014.
Ravishankara, A., Daniel, J. S., and Portmann, R. W.: Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century, Science, 326, 123-125,https://doi.org/10.1126/science.1176985, 2009.
Rochette, P.: No-till only increases N2O emissions in poorly-aerated soils, Soil and Tillage Research, 101, 97-100,https://doi.org/10.1016/j.still.2008.07.011, 2008.
Rochette, P.: Towards a standard non-steady-state chamber methodology for measuring soil N2O emissions, Animal Feed Science and Technology, 166, 141-146,https://doi.org/10.1016/j.anifeedsci.2011.04.063, 2011.
Rochette, P. and Janzen, H. H.: Towards a revised coefficient for estimating N2O emissions from legumes, Nutrient Cycling in Agroecosystems, 73, 171-179,https://doi.org/10.1007/s10705-005-0357-9, 2005.
Saggar, S., Jha, N., Deslippe, J., Bolan, N., Luo, J., Giltrap, D., Kim, D.-G., Zaman, M., and Tillman, R.: Denitrification and N2O: N2 production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts, Science of the Total Environment, 465, 173-195,https://doi.org/10.1016/j.scitotenv.2012.11.050, 2013.
Saikawa, E., Schlosser, C., and Prinn, R.: Global modeling of soil nitrous oxide emissions from natural processes, Global Biogeochemical Cycles, 27, 972-989,https://doi.org/10.1002/gbc.20087, 2013.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Saikawa, E., Prinn, R., Dlugokencky, E., Ishijima, K., Dutton, G., Hall, B., Langenfelds, R., Tohjima, Y., Machida, T., and Manizza, M.: Global and regional emissions estimates for N 2 O, Atmospheric Chemistry and Physics, 14, 4617-4641,https://doi.org/10.5194/acp-14-4617-2014, 2014.

Sanford, R. A., Wagner, D. D., Wu, Q., Chee-Sanford, J. C., Thomas, S. H., Cruz-García, C., Rodríguez, G., Massol-Deyá, A., Krishnani, K. K., and Ritalahti, K. M.: Unexpected nondenitrifier nitrous oxide reductase gene diversity and abundance in soils, Proceedings of the National Academy of Sciences, 109, 19709-19714,https://doi.org/10.1073/pnas.1211238109, 2012.

Scheehle, E. A. and Kruger, D.: Global anthropogenic methane and nitrous oxide emissions, The Energy Journal, 27, 33-44,https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-2, 2006.

Schilt, A., Baumgartner, M., Schwander, J., Buiron, D., Capron, E., Chappellaz, J., Loulergue, L., Schüpbach, S., Spahni, R., and Fischer, H.: Atmospheric nitrous oxide during the last 140,000 years, Earth and Planetary Science Letters, 300, 33-43,https://doi.org/10.1016/j.epsl.2010.09.027, 2010.

Seitzinger, S., Harrison, J. A., Böhlke, J., Bouwman, A., Lowrance, R., Peterson, B., Tobias, C., and Drecht, G. V.: Denitrification across landscapes and waterscapes: a synthesis, Ecological applications, 16, 2064-2090,https://doi.org/10.1890/1051-0761(2006)016[2064:DALAWA]2.0.CO;2, 2006.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen, Proceedings of the National Academy of Sciences, 111, 9199-9204,https://doi.org/10.1073/pnas.1322434111, 2014.

Skiba, U., Jones, S., Dragosits, U., Drewer, J., Fowler, D., Rees, R., Pappa, V., Cardenas, L., Chadwick, D., and Yamulki, S.: UK emissions of the greenhouse gas nitrous oxide, Philosophical Transactions of the Royal Society B: Biological Sciences, 367, 1175-1185,https://doi.org/10.1098/rstb.2011.0356, 2012.

Smith, K. A.: Changing views of nitrous oxide emissions from agricultural soil: key controlling processes and assessment at different spatial scales, European Journal of Soil Science, 68, 137-155,https://doi.org/10.1111/ejss.12409, 2017.

Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M., and Janssens-Maenhout, G.: Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, Atmospheric Chemistry and Physics, 21, 5655-5683,https://doi.org/10.5194/acp-21-5655-2021, 2021.

Song, C., Zhu, J.-J., Willis, J. L., Moore, D. P., Zondlo, M. A., and Ren, Z. J.: Oversimplification and misestimation of nitrous oxide emissions from wastewater treatment plants, Nature Sustainability, 7, 1348-1358,https://doi.org/10.1038/s41893-024-01420-9, 2024.

Stell, A. C., Bertolacci, M., Zammit-Mangion, A., Rigby, M., Fraser, P. J., Harth, C. M., Krummel, P. B., Lan, X., Manizza, M., and Mühle, J.: Modelling the growth of atmospheric nitrous oxide using a global hierarchical inversion, Atmospheric Chemistry and Physics, 22, 12945-12960,https://doi.org/10.5194/acp-22-12945-2022, 2022.

Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B.: Assessing our nitrogen inheritance,https://doi.org/10.1017/CBO9780511976988.004, 2011.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Syakila, A. and Kroeze, C.: The global nitrous oxide budget revisited, Greenhouse Gas Measurement and Management, 1, 17-26,https://doi.org/10.3763/ghgmm.2010.0007, 2011.
Tangen, B. A. and Bansal, S.: Prairie wetlands as sources or sinks of nitrous oxide: Effects of land use and hydrology, Agricultural and Forest Meteorology, 320, 108968,https://doi.org/10.1016/j.agrformet.2022.108968, 2022.
Thompson, R. L., Chevallier, F., Crotwell, A. M., Dutton, G., Langenfelds, R. L., Prinn, R. G., Weiss, R. F., Tohjima, Y., Nakazawa, T., and Krummel, P. B.: Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion, Atmospheric Chemistry and Physics, 14, 1801-1817,https://doi.org/10.5194/acp-14-1801-2014, 2014.
Thompson, R. L., Lassaletta, L., Patra, P. K., Wilson, C., Wells, K. C., Gressent, A., Koffi, E. N., Chipperfield, M. P., Winiwarter, W., and Davidson, E. A.: Acceleration of global N2O emissions seen from two decades of atmospheric inversion, Nature Climate Change, 9, 993-998,https://doi.org/10.1038/s41558-019-0613-7, 2019.
Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., Davidson, E. A., Prather, M., Ciais, P., and Muntean, M.: Global nitrous oxide budget (1980–2020), Earth System Science Data, 16, 2543-2604,https://doi.org/10.5194/essd-16-2543-2024, 2024.
Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., and Janssens-Maenhout, G.: A comprehensive quantification of global nitrous oxide sources and sinks, Nature, 586, 248-256,https://doi.org/10.1038/s41586-020-2780-0, 2020.
Tian, H., Yang, J., Lu, C., Xu, R., Canadell, J. G., Jackson, R. B., Arneth, A., Chang, J., Chen, G., and Ciais, P.: The global N 2 O model intercomparison project, Bulletin of the American Meteorological Society, 99, 1231-1251,https://doi.org/10.1175/BAMS-D-17-0212.1, 2018.
Tian, H., Yang, J., Xu, R., Lu, C., Canadell, J. G., Davidson, E. A., Jackson, R. B., Arneth, A., Chang, J., and Ciais, P.: Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty, Global Change Biology, 25, 640-659,https://doi.org/10.1111/gcb.14514, 2019.
Venterea, R. T., Halvorson, A. D., Kitchen, N., Liebig, M. A., Cavigelli, M. A., Grosso, S. J. D., Motavalli, P. P., Nelson, K. A., Spokas, K. A., and Singh, B. P.: Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems, Frontiers in Ecology and the Environment, 10, 562-570,https://doi.org/10.1890/120062, 2012.
Vilain, G., Garnier, J., Tallec, G., and Tournebize, J.: Indirect N2O emissions from shallow groundwater in an agricultural catchment (Seine Basin, France), Biogeochemistry, 111, 253-271,https://doi.org/10.1007/s10533-011-9642-7, 2012.
Wallington, T. and Wiesen, P.: N2O emissions from global transportation, Atmospheric Environment, 94, 258-263,https://doi.org/10.1016/j.atmosenv.2014.05.018, 2014.
Wang, J., Xiong, Z., and Yan, X.: Fertilizer-induced emission factors and background emissions of N2O from vegetable fields in China, Atmospheric Environment, 45, 6923-6929,https://doi.org/10.1016/j.atmosenv.2011.09.045, 2011.
Wang, J., Bouwman, A. F., Vilmin, L., Beusen, A. H., van Hoek, W. J., Liu, X., and Middelburg, J. J.: Global inland-water nitrogen cycling has accelerated in the Anthropocene, Nature Water, 2, 729-740,https://doi.org/10.1038/s44221-024-00282-x, 2024.

https://doi.org/10.5194/egusphere-2026-6468
Preprint. Discussion started: 5 November 2026
© Author(s) 2026. CC BY 4.0 License.

Weitzman, J. N. and Kaye, J. P.: Nitrogen budget and topographic controls on nitrous oxide in a shale-based watershed, Journal of Geophysical Research: Biogeosciences, 123, 1888-1908,https://doi.org/10.1029/2017JG004344, 2018.

Wells, K. C., Millet, D. B., Bousserez, N., Henze, D., Chaliyakunnel, S., Griffis, T. J., Luan, Y., Dlugokencky, E., Prinn, R. G., and O'Doherty, S.: Simulation of atmospheric N 2 O with GEOS-Chem and its adjoint: evaluation of observational constraints, Geoscientific Model Development, 8, 3179-3198,https://doi.org/10.5194/gmd-8-3179-2015, 2015.

Wells, K. C., Millet, D. B., Bousserez, N., Henze, D. K., Griffis, T. J., Chaliyakunnel, S., Dlugokencky, E. J., Saikawa, E., Xiang, G., and Prinn, R. G.: Top-down constraints on global N 2 O emissions at optimal resolution: application of a new dimension reduction technique, Atmospheric Chemistry and Physics, 18, 735-756,https://doi.org/10.5194/acp-18-735-2018, 2018.

Wrage, N., Velthof, G. L., Van Beusichem, M. L., and Oenema, O.: Role of nitrifier denitrification in the production of nitrous oxide, Soil Biology and Biochemistry, 33, 1723-1732,https://doi.org/10.1016/S0038-0717(01)00096-7, 2001.

Xu, R., Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Davidson, E. A., Nevison, C., Winiwarter, W., Shi, H., and Pan, S.: Magnitude and uncertainty of nitrous oxide emissions from North America based on bottom-up and top-down approaches: Informing future research and national inventories, Geophysical Research Letters, 48, e2021GL095264,https://doi.org/10.1029/2021GL095264, 2021.

Xu, S., Hou, P., Xue, L., Wang, S., and Yang, L.: Treated domestic sewage irrigation significantly decreased the CH4, N2O and NH3 emissions from paddy fields with straw incorporation, Atmospheric Environment, 169, 1-10,https://doi.org/10.1016/j.atmosenv.2017.09.009, 2017.

Yang, S., Chang, B. X., Warner, M. J., Weber, T. S., Bourbonnais, A. M., Santoro, A. E., Kock, A., Sonnerup, R. E., Bullister, J. L., and Wilson, S. T.: Global reconstruction reduces the uncertainty of oceanic nitrous oxide emissions and reveals a vigorous seasonal cycle, Proceedings of the National Academy of Sciences, 117, 11954-11960,https://doi.org/10.1073/pnas.1921914117, 2020.

Yao, Y., Tian, H., Shi, H., Pan, S., Xu, R., Pan, N., and Canadell, J. G.: Increased global nitrous oxide emissions from streams and rivers in the Anthropocene, Nature Climate Change, 10, 138-142,https://doi.org/10.1038/s41558-019-0665-8, 2020.

Zhang, K., Zhu, Q., Liu, J., Wang, M., Zhou, X., Li, M., Wang, K., Ding, J., and Peng, C.: Spatial and temporal variations of N2O emissions from global forest and grassland ecosystems, Agricultural and Forest Meteorology, 266, 129-139,https://doi.org/10.1016/j.agrformet.2018.12.011, 2019.

Zhuang, Q., Lu, Y., and Chen, M.: An inventory of global N2O emissions from the soils of natural terrestrial ecosystems, Atmospheric Environment, 47, 66-75,https://doi.org/10.1016/j.atmosenv.2011.11.036, 2012.

Zou, J., Huang, Y., Qin, Y., Liu, S., Shen, Q., Pan, G., Lu, Y., and Liu, Q.: Changes in fertilizer-induced direct N2O emissions from paddy fields during rice-growing season in China between 1950s and 1990s, Global Change Biology, 15, 229-242,https://doi.org/10.1111/j.1365-2486.2008.01775.x, 2009.