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Austrian nitrogen budget following UNECE guidance

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Abstract

Human activity over the past century has greatly disrupted the natural nitrogen (N) balance, harming health and the environment. Sustainable nitrogen management requires cross-sectoral governance, but studies tracking nitrogen flows across sectors are limited. This study assesses cross-sectoral sources, flows, and sinks of reactive nitrogen (Nr) in Austria, identifying direct N_r inputs and emitting sectors. Using the 'UNECE-Guidance Document on National Nitrogen Budgets' and material flow analysis, we quantified Austria's national nitrogen budget for 2015–2019. Results show the main nitrogen inflows and outflows from imports and exports in the consumer goods and chemical industries. Energy imports also contribute significantly. Some nitrogen is temporarily stored (e.g. in products) or transferred between sectors. However, not all of this N-loss is of direct environmental concern. Annually, 389 kt N_r are lost directly to the environment and causing significant environmental and economic consequences. Direct N_r inputs primarily originate from agriculture (39.3%) and energy/transport (20.7%), with around 30% from cross-border fluxes via water (13.9%) and air (16.6%). The remaining 10% stem from settlements, waste management, and industry. This study highlights the complexity of nitrogen sources and sinks in Austria and underscores the need for improvements towards reduced uncertainties in future research, including higher-resolution spatial data to account for regional variability.

1. Introduction

Reactive nitrogen (N_r) is vital for life but naturally limited. Over the past century, human activities—especially fossil fuel combustion and the Haber–Bosch process—have increased anthropogenic N_r production over tenfold, turning nitrogen from a scarce resource into a surplus (Galloway *et al* 2008). This dramatic increase has pushed N_r beyond its planetary boundaries (Richardson *et al* 2023), with wide-ranging impacts on climate, ecosystems, biodiversity, and human health (Häußermann *et al* 2021).

While nitrogen fertilization has been vital for agricultural productivity, the associated environmental damage now outweighs its economic benefits in many regions (Leip *et al* 2011). The sustainable management of N_r is thus a critical cross-sectoral challenge and of great importance for achieving multiple United Nations Sustainable Development Goals (United Nations 2015). The reduction of N_r emissions is therefore a central task of various environmental policies. However, studies that monitor all-encompassing cross-sectoral N-flows remain rare.

International frameworks such as the UNECE Convention on Long-Range Transboundary Air Pollution (UNECE 1999) and the EU National Emission Ceilings Directive (Directive 2016/2284/EU 2020) recommend member states to develop national nitrogen budgets (NNB). NNBs serve as comprehensive tools for quantifying N_r sources, sinks, and fluxes within defined spatial and temporal boundaries. They provide critical insights into emission hotspots, pollution swapping, and opportunities for synergistic mitigation strategies (Galloway *et al* 2003). Several countries have compiled NNBs of varying detail and scope, including the Netherlands (Kroeze 2003), Germany (Umweltbundesamt Deutschland 2009a, 2009b, Geupel and Frommer 2015), Switzerland (BAFU 2010, Heldstab 2013), the USA (Doering III 2011, Sabo *et al* 2019), Denmark (Hutchings *et al* 2014), Canada (Clair *et al* 2014), Great Britain (Worrall *et al* 2016), Scotland (Carnell *et al* 2019), China (Gu *et al* 2015, Zhang *et al* 2021), Japan (Hayashi *et al* 2021), New Zealand (Parfitt *et al* 2012), and Norway (Hohmann-Marriott 2025). Continental budgets have been developed for Europe (van Egmond *et al* 2002, Leip *et al* 2011) and Asia (Zheng *et al* 2002).

To guide policy decisions, various studies on nitrogen flows in Austria have addressed different aspects of nitrogen cascades. These include the nitrogen budget for national food and material consumption (Pierer *et al* 2015), the gross nutrient balance (considering both nitrogen and phosphorus) in the agricultural sector according to the EUROSTAT manual (Schwarzl 2024), coupled national phosphorus and nitrogen turnover (Tanzer *et al* 2018), urban nitrogen budgets (Kaltenegger *et al* 2023), national and regional nitrogen balances related to agricultural production and consumption (Strenge *et al* 2023), potential environmental impacts at the agricultural catchment scale (Mehdi-Schulz *et al* 2024), and forest ecosystems (Jandl *et al* 2012, Dirnböck *et al* 2017). These studies have all provided important information on specific nitrogen flows, but a comprehensive, overarching picture remained missing and a comparison of the obtained data with those of other countries remained challenging due to the use of different system boundaries and hence different levels of detail. To address these challenges, the task force on reactive nitrogen developed a standardized guideline for calculating NNBs (UNECE 2013). Yet, few studies have fully adopted this framework to date. These concern Germany (Häußermann *et al* 2021) and Scotland (Scottish Government 2021). A comprehensive NNB is also being developed for Sweden (IVL 2019–2022). Building on this, we present the first comprehensive NNB for Austria following the UNECE guidance. The main objectives of this study are to estimate the current cross-sectoral sources, flows, and sinks of N_r in Austria, and to identify major N_r flows to the environment and their sectoral origins.

2. Materials and methods

We followed the national N-budgets guidance document (UNECE 2013) to calculate the national N-budget for Austria. In brief, we assessed the flows of N across and within eight sectors (*Atmosphere (AT), Energy and Transport (EF), Industrial Production (MP), Humans and Settlements (HS), Agriculture (AG), Forest and Semi-natural Vegetation (FS), Waste Management and Wastewater Disposal (WS), Hydrosphere (HY)*), as well as the transboundary N-flows with the rest of the world (RW). A sector may have multiple sub-sectors. A nitrogen budget covers reactive nitrogen compounds as well as the flows of unreactive nitrogen (N_2) and other N_r forms such as organic nitrogen (N_{org}), which includes nitrogen bound in organic molecules like proteins and amino acids, and total nitrogen (N_{tot}) which encompasses all forms of nitrogen, both organic and inorganic, when they are serving as the source of N_r. Only flows greater than one kiloton annually (k N a^{-1}) were considered for this analysis. Additionally, the N-sinks (such as N storage in trees or soils) and emissions as a consequence of land-use changes (e.g. the conversion of grasslands into arable land) were included in the N-budget calculation. The N budget quantifies all nitrogen inputs, outputs, internal sources, sinks, and stock changes within a defined system, like a sector or nation. Here, “Balance” refers to a methodological check for completeness, ensuring that all flows are included. Surpluses or deficits (balance gaps) are unexplained discrepancies between inputs and outputs, while stock changes reflect measurable variations from known processes.

The UNECE guidelines are currently being revised. The updated version, detailed by Winiwarter *et al* (this issue) with extensive annexes (Schäppi *et al* 2025), maintains the original concepts while improving transparency and consistency. In the present work, however, we use the nomenclature and toolset of the UNECE (2013) guidance version. That includes a slightly different set of sub-pools, and the use of a ‘waste’ pool that will now be renamed to ‘processing of residues’.

Data on N_r flows were primarily sourced from official national statistics, governmental reports, and scientific literature. For certain N-flows, values were derived based on expert judgments and back-calculation from other N-flows or models. The uncertainty of N flows is assigned to four different classes for each flow, ranging from 1 (low uncertainty; 10%) to 4 (high uncertainty; 75%), according to the guidance provided by Schäppi et al (2025). If different uncertainty levels were identified, the higher one was used as total uncertainty. Where available, the 2015–2019 average was provided. In some cases, individual years were used.

In order to calculate mass balances, perform a plausibility check, carry out error propagation of initial data uncertainties, reconcile data, conduct error screening, and visually display the nitrogen flows, we used the freely available material flow analysis software STAN version 2.6.801 (Material Flow Analysis, TU Vienna, www.stan2web.net). In the output graphs, flows are shown as arrows and sectors/sub-sectors as boxes. Arrow color matches the source pool, and width reflects flow size. Imports and exports are included. Stock changes appear as values inside the relevant box, with a positive sign indicating a sink (when stocks increase). The nonlinear data reconciliation is based on the conventional weighted least-squares minimization approach, and error propagation is performed following procedure as described by Cencic (2016).

The statistics, databases, and calculation for individual N-flows have been detailed by Häußermann *et al* (2021), Umweltbundesamt (2024), and methodological detail as well as sector-specific results are presented in the supplement (figures S1–S8).

3. Results

3.1. Austrian nitrogen budget

For the calculation of the Austrian NNB, 128N-flows and six stock changes across eight sectors have been considered (figure 1). The largest nitrogen inflows and outflows in Austria are driven by imports and exports associated with consumer goods (727 kt N a^{-1} in imports and 612 kt N a^{-1} in exports) and the chemical industry (368 kt N a^{-1} in imports and 237 kt N a^{-1} in exports). Additional significant inflows come from the import of energy carriers (200 kt N a^{-1}) and ammonia synthesis (417 kt N a^{-1}; figure 1). In contrast, biological nitrogen fixation contributes 33 kt N per year. On the outflow side, the reduction to N2 (either during combustion or via microbial denitrification) is estimated to be 92 and 98 kt N a^{-1}, respectively, while a significant amount of nitrogen is exported to neighboring countries via rivers (126 kt N a^{-1}). Sinks were identified with estimated stock changes in the sectors of forest and semi-natural vegetation (39.3 kt N a^{-1}), Human and Settlements (31 kt N a^{-1}), Hydrosphere (7.5 kt N a^{-1}), Waste (2.4 kt N a^{-1}). In contrast, stock changes in the energy and fuel (−6.2 kt N a^{-1}), and agriculture (−153 kt N a^{-1}) sectors reduce the size of the pool.

The total annual nitrogen imports to Austria (1515 kt N) exceed exports (1121 kt N), yielding a surplus of 394 kt N per year. Some nitrogen is temporarily stored (e.g. in products) or transferred between sectors.

A detailed analysis of the nitrogen budgets in individual pools (figures S1–S8) shows a major surplus in the MP pool (415 kt N a^{-1}), though with high uncertainties. Of the 49 inflows and outflows of the pool, data uncertainty has been estimated with 75% for 9 flows and with 50% for 14 flows. The HS pool had a moderate surplus of 136 kt N a^{-1}, retaining 57.1% of inflows annually. EF and FS pools also showed moderate surpluses of 104 kt N a^{-1} and 60 kt N a^{-1}, respectively. In contrast, HY and WS pools were nearly balanced (19.1 kt N a^{-1} and −1.4 kt N a^{-1}). The AG pool showed a deficit of −64 kt N a^{-1}, matching the nitrogen input from biological N-fixation on Austria's arable and grassland areas, which is not fully captured in the current approach (only preceding crop effects were considered (Umweltbundesamt 2019, Schwarzl 2021)). The AT pool had the highest deficit at −197 kt N a^{-1}.

3.2. N_r loss to the environment in Austria

Annually, around 389 kt of reactive nitrogen are released into the environment in Austria, spreading through the atmosphere and water bodies to forests and semi-natural vegetation. The primary sources of direct N_r inflows (excluding N_2 flows) into the environment are the agriculture sector (153 kt N a^{-1}) and the energy and transport sectors (80 kt N a^{-1}). Approximately 30% of nitrogen inputs come from transboundary flows via water (108 kt N a^{-1}) and air (163 kt N a^{-1}). The remaining nearly 10% is attributed to the sectors of humans and settlements (20 kt N a^{-1}), waste and wastewater management (17 kt N a^{-1}), and industrial production (0.4 kt N a^{-1}, figure 2).

Of the environmentally relevant direct nitrogen emissions (excluding transfers between environmental compartments and imports from abroad), at least 80.4 kt N a^{-1} are attributed to NO_x, 54.9 kt N a^{-1} to NH_3, 6.3 kt N a^{-1} to N_2O, and 76.1 kt N a^{-1} to NO_3 (table 1). While 90% of NO_x emissions originate from the energy sector, agriculture is the largest source of NH_3 and NO_3 emissions (50.0 and 75.9 kt N a^{-1}, respectively) and contributes to nearly 80% of all N_2O emissions (5.1 kt N a^{-1}).

4. Discussion

This study presents the current status of cross-sectoral nitrogen flows and sinks in Austria for the period 2015–2019, in accordance with (UNECE 2013) standardized guidance. A closed balance is a key objective of any material flow analysis. The Austrian NNB is not closed, showing an overall balance difference of 394 kt N a^{-1} between all inflows (3469 kt N a^{-1}) and outflows (3075 kt N a^{-1}) of the eight sectors, which constitutes about 11% of the total nitrogen inflows. This finding aligns with those in Germany, which report a surplus of 9% (Häußermann *et al* 2021), and in the Netherlands, where the surplus is 8% (Olsthoorn and Fong 1998). Similarly, nitrogen budgets for each individual pool show surpluses

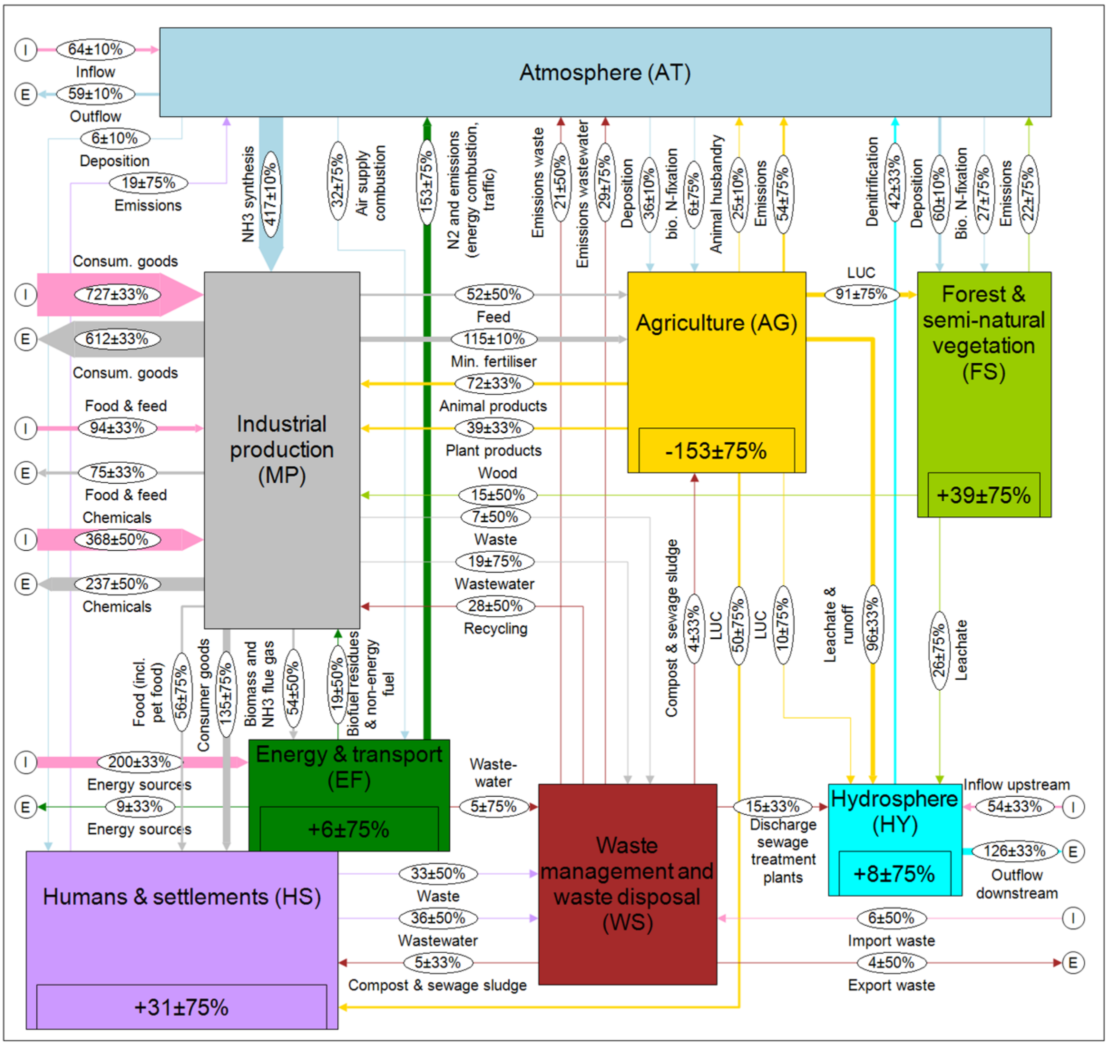

Figure 1. Nitrogen pools, stocks, and N-flows (>3 kt N a^{-1} ± uncertainty) of the National Nitrogen Budget for Austria (mean 2015–2019). Sectors are shown as boxes, flows as arrows, and stock changes as numbers within the corresponding sector boxes. LUC = land use change. Trans-boundary N flows are shown as import (I) and export (E). Some N flows are partly aggregated to maintain visibility.

Table 1. Direct anthropogenic emissions of reactive nitrogen species into the environment in Austria (mean 2015–2019), categorized by respective sectors. N_{tot} refers to total nitrogen (organic + inorganic).

Source	NO_x-N	NH_3-N	N_2O-N	NO_3-N	N_{tot}
	(kt N a^{-1})				
Agriculture	3.4	50.0	5.1	75.9	18.2
Energy and fuels	76.9	2.8	0.7	0.0	0.0
Humans and settlements	0.0	0.6	0.1	0.2	18.9
Waste	0.0	1.3	0.3	0.0	15.3
Material and products	0.1	0.1	0.2	0.0	0.0
Total	80.4	54.9	6.3	76.1	52.4

of varying magnitudes, except for the agriculture pool, which shows a slight deficit. These findings highlight the need for continued efforts to enhance the accuracy and availability of underlying data to ensure more reliable assessments. When considering the full biological nitrogen fixation potential of both arable and grassland areas, the agricultural nitrogen balance would be nearly neutral, aligning with the findings in Germany (Häußermann *et al* 2021), indicating that the real figures may be better expressed by the potentials than the current estimate. Even if a system appears balanced overall, uncertainties in flows and stocks can cause imbalances. For instance, the Swedish agricultural N budget shows a 15%

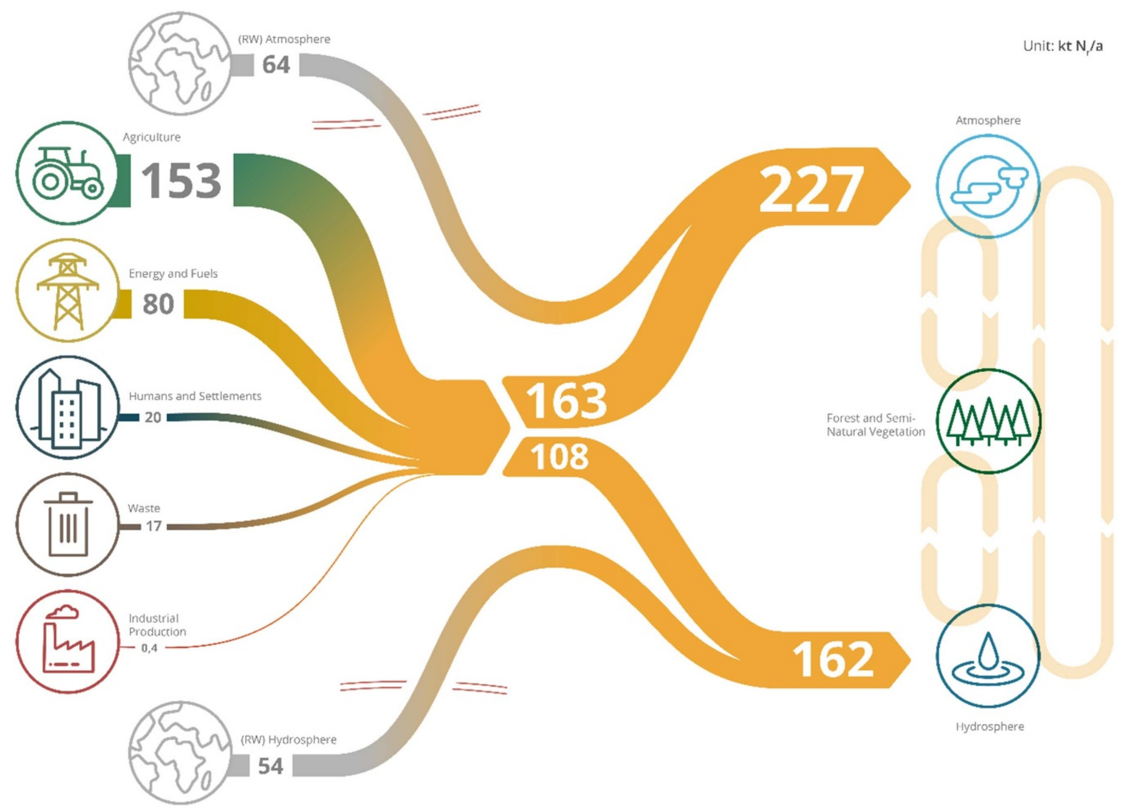

Figure 2. Total inputs (kt N a^{-1}) of reactive nitrogen into the environment in Austria, including transboundary (RW) nitrogen flows, and the contributing sectors.

imbalance (IVL 2019–2022), aligning with the 20% average surplus observed in six European countries (Leip *et al*). Discrepancies with the Austrian agricultural N budget may result from data uncertainties (e.g. nitrogen estimates in feed and soil denitrification rates) or unaccounted flows (e.g. soil stock changes, especially in peat soils used for arable farming). Each year, 57% of all nitrogen inflows stay in the human and settlements sector (figure S4). This is two times higher than the 27% reported for Austria in 2010 (Pierer *et al* 2015) and also exceeds the 40% recorded for Germany between 2010 and 2014 (Häußermann *et al* 2021). This suggests some nitrogen accumulation in the form of durable consumer goods, which can re-enter the cascade as N_r emissions from the processing of discarded items, potentially affecting the environment (Kaltenegger *et al* 2023). It may also indicate missing flows, such that real stock accumulation would be smaller than expressed here. Further data collection on flows and accumulation of N_r will be needed for effectively guiding the implementation of measures, also in comparison to the experience gained in other countries.

STAN's data reconciliation reveals six flows exceeding uncertainty thresholds (table 2), highlighting key data gaps. In 'Energy and Transport', missing data likely relate to fuel N content. In forests, discrepancies like negative N_2 fixation values and uncertainties in N_2 denitrification point to inaccuracies in input data and poor differentiation between reactive and non-reactive nitrogen. Estimating 'Ammonia Synthesis' from literature may have further contributed to model discrepancies, as precise data for the single Austrian plant were unavailable due to confidentiality reasons.

Calculating inter-sectoral nitrogen flows requires a comprehensive understanding, highlighting the need to involve different stakeholders to fill existing data gaps. Regular updates, as prescribed by the Scottish Climate Act 2019 (Scottish Government 2019), could also improve data accuracy significantly.

4.1. Environmental N_r state in Austria

To avoid harmful effects on ecosystem health, the critical nitrogen load for terrestrial ecosystems should not exceed an input of 5–30 kg of nitrogen per hectare per year (Bobbink and Hettelingh 2022). In Austria, 389 kt of reactive nitrogen are released into the environment annually, with two-thirds entering the atmosphere and one-third the hydrosphere (figure 2). The estimated atmospheric nitrogen input of 227 kt N a^{-1} would correspond to a potential deposition of 14.93 kg N ha^{-1} a^{-1}, which is close to or exceeds the critical loads established for Austrian ecosystems—commonly ranging from 5 to 10 kg N ha^{-1} a^{-1} for sensitive habitats and 10–15 kg N kg N ha^{-1} a^{-1} for semi-natural forests

Table 2. N-flows (± uncertainty) where data reconciliation in STAN exceeds the input data uncertainty range. $Z > 1$ means that the value changed more than would be expected based on data uncertainty.

Flow	Input (kt N a^{-1})	Output	Z
Energy sources industry	28.6 ± 9.4	8.7 ± 0.8	2.1
Biological N fixation in the forest	23.8 ± 17.9	−11.8 ± 12.4	2.0
Energy sources household, trade, and commerce	15.5 ± 5.1	6.9 ± 0.6	1.6
N_2 emissions from energy generation	72.4 ± 54.3	154.1 ± 37.7	1.5
Energy sources traffic	22.2 ± 7.3	11.4 ± 3.2	1.5
Ammonia synthesis	417.3 ± 41.7	369.1 ± 34.7	1.2

and grasslands (Umweltbundesamt 2008). This indicates a risk of eutrophication and biodiversity loss in vulnerable ecosystems. To better trace atmospheric nitrogen sources and pathways, sector-specific deposition data are needed. This requires detailed atmospheric transport and source–receptor modeling, beyond the scope of this study and recommended for future work. For comparison, we identified four countries with similar timeframes and methodologies to Austria: Scotland, Germany, Austria (following UNECE guidance), Switzerland, and Japan (using comparable data sources UNECE reporting, OECD etc). On a per-capita basis, out of these countries Switzerland and Japan had the lowest N_r losses to the environment (15 kg N per capita and year), while Scotland, Austria, and Germany report much higher losses (25–33 kg N per capita and year; table 3). This subset-based comparison does not represent a global ranking but highlights the need for standardized guidance to ensure comparability and continuous improvement of nitrogen budget data.

N losses have a significant impact not only on ecosystems and human health but also lead to considerable economic consequences. A loss of 389 kt of nitrogen corresponds to fertilizer costs of approximately 389 million euros, calculated using an average 2024 price of around 1€ kg^{-1} N for nitrogen-based fertilizers such as calcium-ammonium-nitrate and urea (Agrar Markt Austria 2025).

The largest sources of N_r emissions into the environment in Austria come from the agriculture and energy sectors, with 152 kt N and 80 kt N per year, respectively (figure 2). Austria is making significant efforts to improve nitrogen use efficiency in agriculture (e.g. by promoting low-emission technologies for the application of farm manure in the Austrian agri-environmental Program) and reduce nitrogen pollution (e.g. by increasing the share of renewable energy (BMNT 2019). However, in a broader context, these measures have shown only modest or partly positive results. Beyond national efforts, regional improvements are crucial, especially given the substantial transboundary N_r inputs into Austria's environment (118 kt N per year). This further emphasizes the importance of considering long-range transboundary pollution for national budgets and highlights the need for cross-border standardization of measures and monitoring, as seen in the International Danube River Protection Convention. Quantifying pollution supports international cooperation by clarifying shared responsibilities and cross-border impacts. In parallel, national nitrogen footprints offer a consumption-based perspective, capturing trade-related nitrogen pollution and complementing territorial N budgets.

Our study demonstrates that the highest emissions of nitrate (NO_3), ammonia (NH_3), and nitrous oxide (N_2O) are linked to the agricultural sector and nitrogen oxides (NO_x) to the energy and fuel sector. National air emission inventories, reported annually, are the main source for emission estimates. However, yearly data and evolving methods complicate comparisons with the five-year averages used in nitrogen budgets. Still, N budgets complement inventories by offering a more comprehensive view of N flows across sectors and environmental compartments, helping reveal hidden losses and improve nitrogen management (Sutton *et al* 2013).

5. Conclusions

This study applied material flow and mass balance concepts and standardized guidance to analyze nitrogen cascades at the national scale, highlighting sources, sinks, and cross-sectoral interactions. Key challenges continue to be the lack of harmonized methodologies, which complicates cross-sectoral and international comparisons as well as the availability and accuracy of data. However, through UNECE guidance and the estimation of NNB, important progress is being made in addressing aspects of standardization, data availability, and accuracy. The effects of N_r on the environment are heterogeneous both temporally and spatially (Strenge *et al* 2023), highlighting the need to incorporate higher-resolution spatial data to account for regional variability. Moreover, addressing data gaps (particularly in quantifying denitrification in soils and water, biological N fixation, N-flows in the MP sector, and those linked to land-use change) requires further research and monitoring. Achieving this will be more feasible through stronger collaboration with stakeholders, including policymakers, academia, NGOs, industry, and other key actors.

Table 3. Comparison of national nitrogen budgets for N_r loss (kt N a^{-1}) from anthropogenic sources to the environment.

			Reactive nitrogen loss from anthropogenic sources (kt N a^{-1})			Reactive nitrogen loss from anthropogenic sources per capita (kg N cap^{-1} a^{-1})			
Country	Year	Population (million)	Air	Water	Total	Air	Water	Total	References
Scotland	Closest to year 2015	5.4	55	123	178	10	23	33	(Dragosits *et al* 2025)
Austria	Mean 2015-2019	8.6	157	117	274	18	14	32	(Umweltbundesamt 2024)
Germany	Closest to year 2015	81.7	1015	1029	2044	12	13	25	(Häußermann *et al* 2021)
Japan	Closest to year 2015	127.1	1149	697	1846	9	5	15	(Hayashi *et al* 2021)
Switzerland	2020	8.6	72	59	131	8	7	15	(Heldstab 2013)

Integrated, cross-sectoral governance is essential to effectively tackle nitrogen challenges, as isolated efforts may shift rather than reduce environmental burdens. Creating a national nitrogen dialogue committee could be key to developing a comprehensive action plan and management strategy, in alignment with the UNEA Resolution 4/14 2019 and the UNEA Resolution 5/2 2022. Repeated evaluation of the nitrogen budget will build time series data, helping to identify trends and assess the effectiveness of the actions taken (Zoboli *et al* 2016). The 'Call for data' initiatives, as considered within the UNECE Expert Panel on Nitrogen Budgets, or legally binding reporting obligations, would provide a valuable opportunity for data verification and updates, with further uncertainty assessments planned within the scope of ongoing data preparation efforts.

'Living well, within the limits of our planet,' is one of the goals of several environmental action programs. Austria has surpassed its sustainable resource consumption limits, with potential risks to the environment, climate, and human health. Establishing a planetary boundary indicator, such as a national integrated nitrogen target (Umweltbundesamt 2020), addressing five planetary boundaries and their associated SDGs (SDG 6 Water, SDG 13 Climate, SDG 15 Biodiversity, SDGs 13 + 15 Nitrogen flows, SDG 3 Health), would enhance nitrogen management communication nationally and internationally and help mitigate impacts. Since national values and targets for Austria do not reflect pressures on individual ecosystems, a regionalized assessment using an integrated nitrogen indicator is needed. This is the subject of ongoing research.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

ID designed the study with extensive input from HLW. CB, TD, OG, HLW, SM, BS, PW, ID, JT accomplished data preparation and analyses for different sectors. JT conducted material flow analyses and PS prepared the tables. ID wrote the manuscript with contribution from all authors. The authors declare no conflict of interest.

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References

Agrar Markt Austria 2025 Düngemittel_Endverbraucherpr_2003-2024_quartalsweise (available at: www.ama.at/marktinformationen/getreide-und-olsaaten/dungemittel) Accessed 28 April 2025)
BAFU 2010 *Stoffflussanalyse für das Jahr 2005* (BAFU)
BMNT 2019 *Evaluierung verschiedener ÖPUL Maßnahmen in Hinblick auf die Reduktion von Treibhausgasemissionen, insbesondere Lachgas: endbericht* (BMNT)
Bobbink R and Hettelingh J P (eds) 2022 *Review and revision of empirical critical loads and dose-response relationships: Proceedings of an expert workshop, (Noordwijkerhout, 23–25 June 2010)* (RIVM)
Carnell E J, Thomas I N, Tomlinson S J, Bell V A M L, Skiba U, Dore A J, Eory V and Dragosits U 2019 *A Nitrogen Budget for Scotland* (SEPA)
Cencic O 2016 Nonlinear data reconciliation in material flow analysis with software STAN *Sustain. Environ. Res.* **26** 291–8
Clair T A *et al* 2014 Interactions between reactive nitrogen and the Canadian landscape: a budget approach *Glob. Biogeochem. Cycles* **28** 1343–57
Directive 2016/2284/EU 2020 Analysis of ecosystem monitoring data under article 9—final report (Ecologic Institute and Ramboll Management Consulting)
Dirnböck T, Foldal C, Djukic I, Kobler J, Haas E, Kiese R and Kitzler B 2017 Historic nitrogen deposition determines future climate change effects on nitrogen retention in temperate forests *Clim. Change* **144** 221–35
Doering III E A 2011 *Reactive nitrogen in the United States: an analysis of inputs, flows, consequences, and management options: a report of the EPA Science Advisory Board* (United States Environmental Protection Agency)
Dragosits U *et al* 2025 *Establishing a Scottish Nitrogen Balance Sheet 2021* (Scottish Government)
Galloway J N, Aber J D, Erisman J W, Seitzinger S P, Howarth R W, Cowling E B and Cosby B J 2003 The nitrogen cascade *BioScience* **53** 341
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 2008 Transformation of the nitrogen cycle: recent trends, questions, and potential solutions *Science* **320** 889–92
Geupel M and Frommer J 2015 *Reaktiver Stickstoff in Deutschland: ursachen, Wirkungen, Maßnahmen* (Umweltbundesamt GmbH)
Gu B, Ju X, Chang J, Ge Y and Vitousek P M 2015 Integrated reactive nitrogen budgets and future trends in China *Proc. Natl Acad. Sci. USA* **112** 8792–7
Häußermann U *et al* 2021 National nitrogen budget for Germany *Environ. Res. Commun.* **3** 95004
Hayashi K, Shibata H, Oita A, Nishina K, Ito A, Katagiri K, Shindo J and Winiwarter W 2021 Nitrogen budgets in Japan

from 2000 to 2015: decreasing trend of nitrogen loss to the environment and the challenge to further reduce nitrogen waste *Environ. Pollut.* **286** 117559
Heldstab J 2013 Stickstoffflüsse in der Schweiz 2020 *Stoffflussanalyse und Entwicklungen (Umwelt -Wissen 1309)* (Bundesamt für Umwelt) p 107
Hohmann-Marriott M F 2025 A nitrogen budget for Norway analysis of nitrogen flows from societal and natural sources (1961–2020 *PLoS One* **20** e0313598
Hutchings N J, Nielsen O-K, Dalgaard T, Mikkelsen M H, Børgesen C D, Thomsen M, Ellermann T, Højberg A L, Mogensen L and Winther M 2014 A nitrogen budget for Denmark; developments between 1990 and 2010, and prospects for the future *Environ. Res. Lett.* **9** 115012
IVL 2019–2022 *Nitrogen budget—Agriculture Sweden (2019), Swedish National Nitrogen Budget—Forest and semi-natural vegetation (2020), Swedish National Nitrogen Budget–Hydrosphere (2020), Swedish National Nitrogen Budget–Atmosphere (2022)* (Swedish Environmental Research Institute: IVL 2019–2022)
Jandl R, Smidt S, Mutsch F, Fürst A, Zechmeister H, Bauer H and Dirnböck T 2012 Acidification and nitrogen eutrophication of Austrian forest soils *Appl. Environ. Soil Sci.* **2012** 1–9
Kaltenegger K, Bai Z, Dragosits U, Fan X, Greinert A, Guéret S, Suchowska-Kisielewicz M, Winiwarter W, Zhang L and Zhou F 2023 Urban nitrogen budgets: evaluating and comparing the path of nitrogen through cities for improved management *Sci. Total Environ.* **904** 166827
Kroeze C *et al* 2003 Uncertainties in the fate of nitrogen I: an overview of sources of uncertainty illustrated with a Dutch case study *Nutr. Cycl. Agroecosyst.* **66** 43–69
Leip A *et al* 2011 Integrating nitrogen fluxes at the European scale *The European Nitrogen Assessment* ed M A Sutton, C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfelt, H van Grinsven and B Grizzetti (Cambridge University Press) pp 345–76
Mehdi-Schulz B, Zoboli O, Schürz C, Strenge E, Lima E M, Parajka J, Wang C, Zessner M and Schönhart M 2024 The impacts of climate change on nitrogen losses to the environment in Austria: a dual model analysis across spatial and temporal scales to support policy decisions *Sci. Total Environ.* **918** 170730
Olsthoorn C S M and Fong N P K 1998 The anthropogenic nitrogen cycle in the Netherlands *Nutr. Cycl. Agroecosyst.* **52** 269–76
Parfitt R L, Stevenson B A, Dymond J R, Schipper L, Baisden W T and Ballantine D J 2012 Nitrogen inputs and outputs for New Zealand from 1990 to 2010 at national and regional scales *N.Z. J. Agric. Res.* **55** 241–62
Pierer M, Schröck A and Winiwarter W 2015 Analyzing consumer-related nitrogen flows: a case study on food and material use in Austria *Resour. Conserv. Recycl.* **101** 203–11
Richardson K *et al* 2023 Earth beyond six of nine planetary boundaries *Sci. Adv.* **9** eadh2458
Sabo R D *et al* 2019 Decadal shift in nitrogen inputs and fluxes across the contiguous United States: 2002–2012 *JGR Biogeosci.* **124** 3104–24
Schäppi B, Bogler S, Reutimann J and Fehrenbach H 2025 Detailed Annexes to the UNECE "Guidance document on national nitrogen budgets", version no. 4/2025 *Umweltbundesamt TEXTE 05/2025* (German Environment Agency, Dessau-Roßlau, Germany) (available at: www.clrtap-tfrn.org/epnb) (Accessed 26 June 2025)
Schwarzl B 2021 *Österreichische Stickstoff- und Phosphorbilanz der Landwirtschaft: aktualisierung 2021* (Umweltbundesamt GmbH)
Schwarzl B 2024 *Österreichische Stickstoff- und Phosphorbilanz der Landwirtschaft nach EUROSTAT-Vorgaben: aktualisierung 2024* (Umweltbundesamt GmbH)
Scottish Government 2019 *Establishing a Scottish Nitrogen Balance Sheet: Scotland Act 2019* vol 2019
Scottish Government 2021 *The Scottish Nitrogen Balance Sheet*
Strenge E, Zoboli O, Mehdi-Schulz B, Parajka J, Schönhart M, Krampe J and Zessner M 2023 Regional nitrogen budgets of agricultural production systems in Austria constrained by natural boundary conditions *J. Environ. Manage.* **347** 119023
Sutton M A *et al* 2013 *Our nutrient world: the challenge to produce more food and energy with less pollution; [global overview on nutrient management]* (Centre for Ecology & Hydrology)
Tanzer J, Zoboli O, Zessner M and Rechberger H 2018 Filling two needs with one deed: potentials to simultaneously improve phosphorus and nitrogen management in Austria as an example for coupled resource management systems *Sci. Total Environ.* **640–641** 894–907
Umweltbundesamt Deutschland 2009a *Hintergrundpapier zu einer multimedialen Stickstoffminderungsstrategie* (Umweltbundesamt Deutschland)
Umweltbundesamt Deutschland 2009b *Integrierte Strategie zur Minderung von Stickstoffemissionen* (Umweltbundesamt Deutschland)
Umweltbundesamt 2008 Critical loads für Schwefel-und Stickstoffeinträge in Ökosysteme (Report / Umweltbundesamt REP-0178) (Wien: Umweltbundesamt)
Umweltbundesamt 2019 *Stickstoff- und Phosphorbilanz in der Landwirtschaft: umstellung der Österreichischen Stickstoff- und Phosphor-Bilanz der Landwirtschaft auf EUROSTAT-Vorgaben* (Umweltbundesamt GmbH)
Umweltbundesamt 2020 Integrated nitrogen indicator, national nitrogen target and the current situation in Germany (DESTINO Report 1) UBA-Texte 97/2020 (Umweltbundesamt, Dessau-Roßlau) (available at: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_97-2020_integrated_nitrogen_indicator_national_nitrogen_target_and_the_current_situation_in_germany_destino_report_1.pdf) (Accessed15 August 2025)
Umweltbundesamt 2024 *Nationales Stickstoffbudget (2015–2019) gemäß EPNB-Leitfaden: reaktive Stickstoffflüsse (Report/Umweltbundesamt REP-0897)* (Umweltbundesamt)
UNEA Resolution 4/14 2019 *Promoting Sustainable Practices and Innovative Solutions for Curbing Food Loss and Waste: UNEA Resolution 4/14*
UNEA Resolution 5/2 2022 *Sustainable Nitrogen Management: UNEA Resolution 5/2*
UNECE 1999 *Convention on Long-Range Transboundary Air Pollution. (1999). Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone (Gothenburg Protocol), Article 7, paragraph 3: Gothenburg Protocol*
UNECE 2013 Economic commission for Europe. Executive body for the convention on long-range transboundary air pollution: guidance document on national nitrogen budgets (available at: www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNB_new/ECE_EB.AIR_119_ENG.pdf)
United Nations 2015 *Transforming Our World: The 2030 Agenda for Sustainable Development: A/RES/70/1* (United Nations)
van Egmond K, Bresser T and Bouwman L 2002 The European nitrogen case *Ambio* **31** 72–78
Winiwarter W *et al* 2025 Nitrogen budgets: quantifying environmentally relevant flows of reactive nitrogen compounds on a national scale *Environ. Res. Lett.* (in preparation)
Worrall F, Burt T P, Howden N J K and Whelan M J 2016 The UK's total nitrogen budget from 1990 to 2020: a transition from source to sink? *Biogeochemistry* **129** 325–40
Zhang X, Ren C, Gu B and Chen D 2021 Uncertainty of nitrogen budget in China *Environ. Pollut.* **286** 117216
Zheng X, Fu C, Xu X, Yan X, Huang Y, Han S, Hu F and Chen G 2002 The Asian nitrogen cycle case study *Ambio* **31** 79–87
Zoboli O, Laner D, Zessner M and Rechberger H 2016 Added values of time series in material flow analysis: the Austrian phosphorus budget from 1990 to 2011 *J. Ind. Ecol.* **20** 1334–48