ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™ Part of the ENVIRONMENTAL RESEARCH SERIES

ACCEPTED MANUSCRIPT • OPEN ACCESS

Nitrogen budgets in Europe: a methodology to quantify environmentally relevant flows of reactive nitrogen compounds on a national scale

To cite this article before publication: Wilfried Winiwarter *et al* 2025 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ae0da8

Nitrogen budgets in Europe: a methodology to quantify environmentally relevant flows of reactive nitrogen compounds on a national scale

Wilfried Winiwarter[1,2,*], Bettina Schäppi[3], Judith Reutimann[3], Martin Bach[4], Ika Djukic[5], Ulrike Dragosits[6], Inga Grinfelde[7], Maximilian Kanig[8], Filip Moldan[9], Monika Suchowska-Kisielewicz[2], Markus Geupel[10]

1 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

2 Institute of Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland

3 INFRAS AG, Zurich, Switzerland

4 Institute for Landscape Ecology and Resources Management, Justus Liebig University, Giessen, Germany

5 Environment Agency Austria, Vienna, Austria

6 UK Centre for Ecology & Hydrology (UKCEH), Bush Estate, Penicuik, Midlothian, UK

7 Institute of Landscape Architecture and Environmental Engineering, Latvia University of Life Sciences and Technologies, Jelgava, Latvia

8 IfÖL GmbH, Kassel, Germany

9 IVL Swedish Environmental Research Institute, Gothenburg, Sweden

10 Umweltbundesamt, Dessau, Germany

* Corresponding author: winiwart@iiasa.ac.at

Submitted to Environmental Research Letters, April 2025; revised, September 2025

(Focus on Resolving the Global Nitrogen Dilemma - Opportunities and Challenges)

Abstract

Reactive nitrogen compounds are responsible for multiple negative impacts while they remain in the environment, changing their state and chemical form. Here we develop a methodology to trace these compounds throughout the environment using a stringent concept to describe their fate consistently and comprehensively. Using an individual country as the system scale, the individual flows of reactive nitrogen are characterized between and within eight pools reflecting human society, economic sectors and environmental spheres, also accounting for transboundary flows, to create a national nitrogen budget. The methodology has been devised for implementation by national agencies in conjunction with greenhouse gas or air pollution emission inventories, hence it links closely with the structures and data derived in these contexts. The guiding methodological principle is the mass conservation of reactive nitrogen, implemented as a material flow analysis that systematically describes all flows and stock changes. Embedding results obtained from five European countries demonstrates the feasibility of the approach. The major environmental pathways of reactive nitrogen compounds can be traced from industrial processes and agricultural production, including the agri-food chain, indicating levers for policy interventions. Spatial and temporal benchmarking of the results demonstrates comparisons between countries or over time. While further results of practical implementation are needed to assess overall robustness, the budget approach allows for multiple opportunities of data checks and verification to visualize the uncertainty associated to many input data, such as lacking information on nitrogen contents and specific flows, or the relevance of so-far unaccounted-for stocks of reactive nitrogen. Useful applications have been identified that link nitrogen budgets to impacts on human health as well as on ecosystems and the climate, indicating that developing and using national nitrogen budgets may shape improved and information-led policies.

Keywords:

Nitrogen cascade, environmental pollution, cause-effect relationship, biogeochemical cycle, nitrogen use efficiency

1. Introduction

Environmental impacts due to the disruption of the natural biochemical nitrogen flows have been well recognized on the global scale (Rockström et al., 2009; Richardson et al., 2023) as well as regionally (Schulte-Uebbing et al., 2022). Resulting from a largely accelerating global nitrogen cycle (Fowler et al., 2013; Battye et al., 2017), triggered by anthropogenic activities to fix nitrogen (Erisman et al., 2008), specific environmental effects have been recognized for Europe (Sutton et al, 2011a,b) as well as for other world regions (Sutton et al., 2025). A major challenge to devising measures and policies for reducing such impacts is the difficulty to establish a proper link between source and impact. The "nitrogen cascade" (Galloway et al., 2003), describing the cycling of reactive nitrogen compounds (N_r, i.e. all nitrogen species except gaseous N_2) explains their extended fate in the environment, pointing out the considerable potential of simultaneously addressing multiple impacts, but also the difficulty in identifying an individual cause of a given impact related to N_r.

Understanding the nitrogen cascade may contribute to identify simultaneous solutions to environmental problems and to note possible synergies of measures. Elaborating this conceptual idea, nitrogen budgets have been developed as a tool to provide a systematic overview of environmental nitrogen flows between self-defined environmental and anthropogenic pools. Based on the principle of mass conservation, nitrogen budgets allow for a budget closure of the entire system as well as on the level of each pool (see "method" for details). Budget closure helps to validate results and supplements information wherever quantification of a flow becomes impossible. Excluding inert N_2 from the budget, which is present in large excess, allows to focus on the environmentally relevant compounds.

Using nitrogen budgets to trace the fate of nitrogen is not a new idea. Starting from specific compartments, like the atmosphere (Derwent et al., 1978) or agriculture (Oenema et al., 2003), also comprehensive budgets on a national scale have been created (see a more detailed overview provided by Winiwarter et al., 2025, or Djukic et al., 2025). This paper takes advantage of the experience gained from such existing approaches to establish nitrogen budgets by a standardized, comparable methodology established on a national level, reported in full detail by Schäppi et al. (2025). A National Nitrogen Budget (NNB) uses existing information, such as statistical data that are especially well developed on a national level, and environmental information collected nationally to meet the requirements of international agreements. In line with these operational efforts by countries to provide data on their national greenhouse gas emissions (UNFCCC, 2022), national air pollutant inventories (EEA, 2023), or agricultural nutrient budgets in the framework of the statistics on agricultural inputs and outputs (SAIO: EU, 2022), we provide an approach to create NNBs that allow for comparing different years, benchmarking between countries, and devising measures to reduce pollution and impacts, including policy results and useful applications.

2. Method

Nitrogen budgets adopt the method of a material flow analysis (Brunner and Rechberger, 2016), specifically using an elemental balance for nitrogen. The underlying physical principle is mass conservation, and the relevant parameters are stocks and flows. Here stocks represent quantities of N_r in given 'containers', the environmental and anthropogenic pools. Pools are often divided into sub-units (sub-pools). N_r moving between such (sub-)pools is described as a flow. For each of the pools considered, the N_r stock varies according to the sum of all flows into and out of the pool (Eq (1)). The resulting equation of N_r flows can be expressed as

$$\Delta S = \sum F_i \qquad (1)$$

where S represents the stock, ΔS the stock change, and F is any of i flows into (with a positive sign) or out of (with a negative sign) the respective pool in a given time period, which is a year by default. As a conceptual simplification from the real-world conditions, compounds are considered to maintain their chemical form while part of a flow, i.e. any chemical transformation would occur in the pools only.

The equation covers all flows of nitrogen compounds except those of N_2. N_2 flows only become relevant and are included as in- or outflows when converting into N_r, e.g. as occurring during the Haber-Bosch process of industrial N fixation, or when N_r is converted into N_2, as it occurs for example during denitrification, the microbial process of reducing nitrate into molecular N_2. N_2 stocks/stock changes (or flows of N_2 that are not connected to any conversion to or from N_r) are not part of this concept.

Table 1: Pools and sub-pools defined for National Nitrogen Budgets

Pool – Sub-Pool name	*Reference to technical Annex*	*Related IPCC sector*	*Code*
Energy and fuels – Energy conversion	Annex 1	1 Energy	EF.EC
Energy and fuels – Transportation			EF.TR
Energy and fuels – Other energy and fuels			EF.OE
Energy and fuels – Manufacturing industries and construction			EF.IC
Materials and products in industry – Food processing	Annex 2	2 Industrial processes and product use	MP.FP
Materials and products in industry – Other producing industry			MP.OP
Agriculture – Manure management, storage and animal husbandry	Annex 3	3 Agriculture	AG.MM
Agriculture – Soil management			AG.SM
Agriculture – Biofuel production and composting			AG.BC
Forests and semi-natural area – Forests	Annex 4	4 Land use, land-use change and forestry	FS.FO
Forests and semi-natural area – Wetland			FS.WL
Forests and semi-natural area – Other Land			FS.OL
Processing of residues – Solid waste	Annex 5	5 Waste	PR.SO
Processing of residues – Wastewater			PR.WW
Humans and settlements (no sub-pool)	Annex 6	not covered	HS
Atmosphere (no sub-pool)	Annex 7	not covered	AT
Hydrosphere – Groundwater	Annex 8	not covered	HY.GW
Hydrosphere – Surface water			HY.SW

Pool – Sub-Pool name	*Reference to technical Annex*	*Related IPCC sector*	*Code*
Hydrosphere – Coastal water			HY.CW
Hydrosphere – Aquaculture			HY.AC

In order to create NNBs as useful tools for national agencies, the pools were defined so that they are compatible with economic sectors required for other environmental reporting obligations, such as the need to report the emissions of greenhouse gases or of air pollutants. A comprehensive national overview on N_r flows needed to extend beyond these sectors, however, and had to also include pools representing the human society as well as near-nature environments and transporting media (atmosphere, hydrosphere). Table 1 provides the harmonized structure of NNBs as developed by the UN Economic Commission for Europe (UNECE, 2025).

Each pool and sub-pool is characterized by a unique code. Flows between two pools (when existing) are characterized using a combined code linking the two respective pools. Each flow is individually defined in the technical Annexes to the UNECE Guidance Document (Schäppi et al., 2025), and is associated to the pool from which the flow originates, where flow magnitudes are usually better defined as for the pool a flow ends up in. Guidance includes possible data sources, characterization by compounds, and typical nitrogen contents of materials needed to quantify flows.

Schäppi et al. (2025) also describe the overarching method and conventions of NNBs, including a threshold for experts to consider when to report flows explicitly (100 g N/capita and year) – flows smaller than this magnitude may be reported in combination with other, larger flows. Such flows may also be characterized by the specific N_r compounds transported, or by a matrix in which the flow occurs in. Finally, methods to assess and propagate uncertainties have been defined, based on error propagation laws and approaches inherited from emission inventories (EEA, 2023), with guidance also provided on data reconciliation and reporting of uncertainty throughout the NNB.

As NNBs necessarily are limited by spatial boundaries of countries, delineation of flows is also needed with respect to exports and imports. The concept allows for flows from each of the pools and sub-pools to the 'Rest of the World (RW)' or vice versa, to cover N_r mass entering or leaving a country, either by trade, or by natural carriers such as the atmosphere or the hydrosphere. In the latter case, 'Coastal water' is defined as a separate sub-pool, delineated as the area of national territorial waters, which is within 12 nautical miles from any shoreline.

3. Selected results

Here we present a set of standard outputs that can be directly derived using the toolset developed specifically for NNBs. These outputs allow to reveal the potential and the limitations of the approach – to be further elaborated in the discussion section. There are four sets of results to be distinguished, to be developed in more detail or analyzed in a more general level. These are, firstly, a pattern of individual flows (for a given country and year), and secondly an input-output balance at any level (total NNB, any pool, any sub-pool). Thirdly, there are temporal trends of flows and stock changes, and finally approaches for benchmarking, by way of a normalized comparison across sectors or across countries.

Display of individual flows takes advantage of the STAN model (Cencic and Rechberger, 2008). A specific data collection spreadsheet has been developed which can be used as an interface for data input to STAN. The underlying software allows for a full accounting of material balances (including stock changes) and facilitates data display. Moreover, its data reconciliation functionality has been demonstrated to be useful for NNBs to identify data gaps (Djukic et al., 2025). A specific display sheet has been created for NNBs reflecting the eight pools. Further display sheets are available to describe the internal flow structure within a pool. Results shown in Fig. 1 (here for Germany, 2020) identify the major N_r flows – dominated by a few large flows. In this specific case, it is atmospheric fixation in chemical industry (mainly production of mineral fertilizer), with also large flows of imports and exports of chemicals that largely balance. Other large flows comprise mineral fertilizer use or domestically produced compound feed for agriculture, equilibrated by crops and animal products to food and feed industry, leaching to groundwater and different pathways of atmospheric emissions. Another important N_r pathway covers nitrogen contained in fuels and forms molecular N_2 during the combustion stage (with subsequent emission abatement devices supporting this conversion). The display quantifies individual flows (shown in ellipsoids next to each flow) and enables the development an overall concept of a country's N_r flow patterns.

Budgeting across a pool or a whole NNB allows to identify general discrepancies (e.g. due to missing flows, using inappropriate values of N contents). If no such discrepancies can be found, that may be seen as a sign of coherence of data. The NNB data collection sheet enables a direct display of pool budgets (also for sub-pools) and to develop balances that may be interpreted as stock changes (Fig. 2). Stock changes that reappear continuously over years may indicate accumulation or depletion of N_r in any given pool but may possibly also point towards a need to check for potentially missing flows and revise underlying data. In the example of Fig. 2 (taken from the Austrian N budget, Djukic et al., 2025), stock changes are small for most pools, but inputs seem to be generally larger than outputs – either pointing to accumulation in the respective pools or indicating that inputs are better constrained (and covered) than outputs (see discussion). Generally, such discrepancies may demonstrate a need of more thorough investigation (e.g. checking for missing flows, re-evaluating N contents, or assessment of uncertainties in the data). This analysis can be easily extended to assess Nitrogen Use Efficiency (NUE) in any pool (as the ratio of total useful products, including recycling products, divided by N_r inputs) or 'nitrogen waste', the sum of all unused N_r flows leaving a pool. Note that unused N_r flows include the result of denitrification or of NO_x reduction, such that even the intended creation of inert and environmentally neutral molecular N_2, following the definition of Sutton et al. (2021), is considered waste.

Many parameters can be extracted from an NNB in form of their temporal trend. With other parameters held constant, differences between different years may be considered specifically robust. Year-to-year changes for some of the input data are well understood and taken from reliable statistics, while more uncertain data (e.g., nitrogen contents) can be regarded stable over time. Fig. 3 shows, as an example, the quantity of N wasted per source pool. Data are taken from a report by the Scottish Government (2025) for a four-year time series. Results visualize the different respective contributions of sectors, here for Scotland pointing out the importance of agriculture to the overall wastage of N_r. The approach allows also to account for change over time and allow to track temporal variability or even to extrapolate future trends based on the previous developments, with differences remaining small under stable economic conditions on the short time scale used here (see discussion).

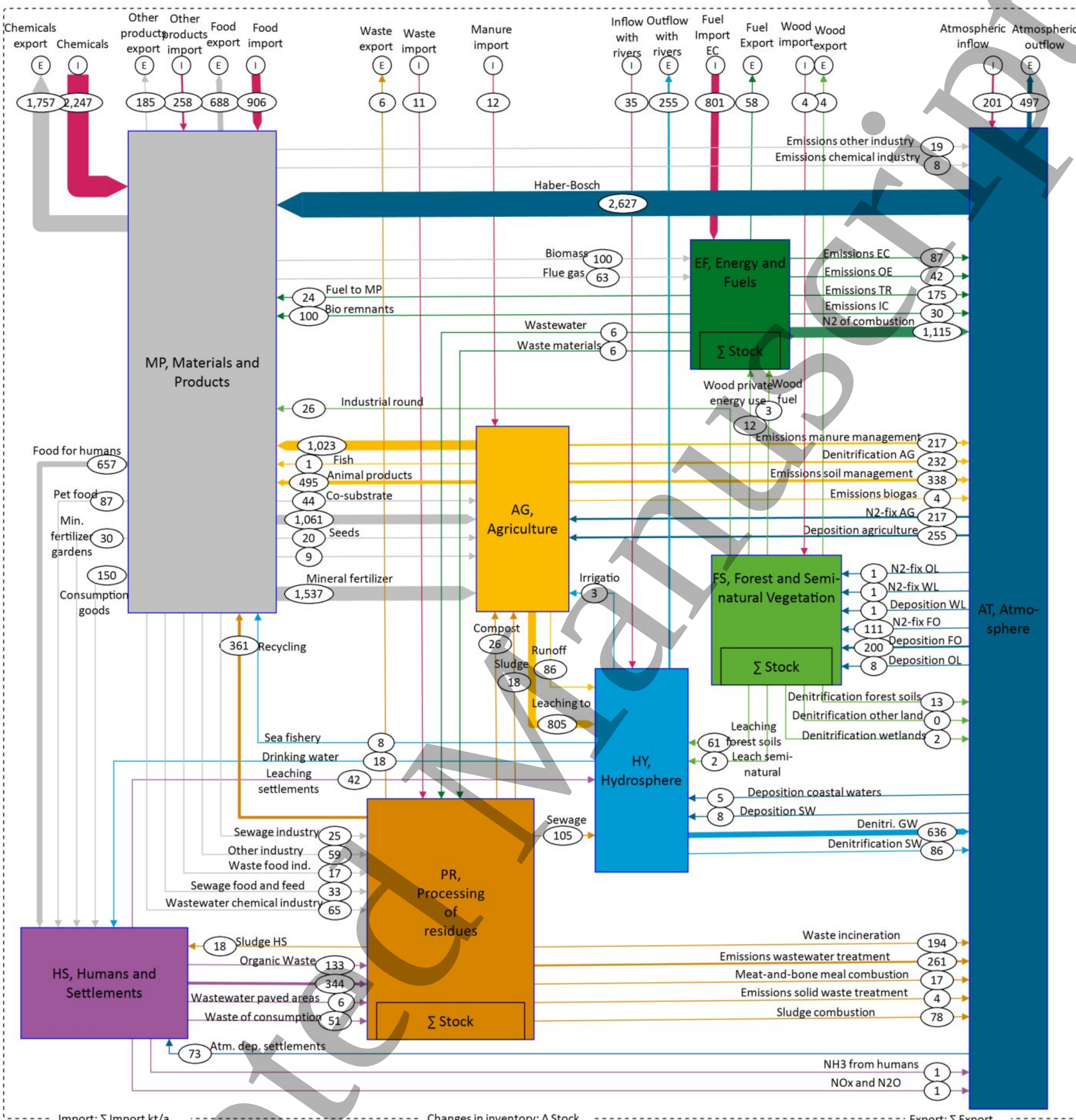

Fig. 1: Mass flows of N_r in kt of N (here for Germany, 2020, depicting individual flows – Bach et al., 2025). The colors of flows refer to the pool they derive from (imports shown in red), the arrow width represents the flow magnitude (stocks or stock changes are not quantified here).

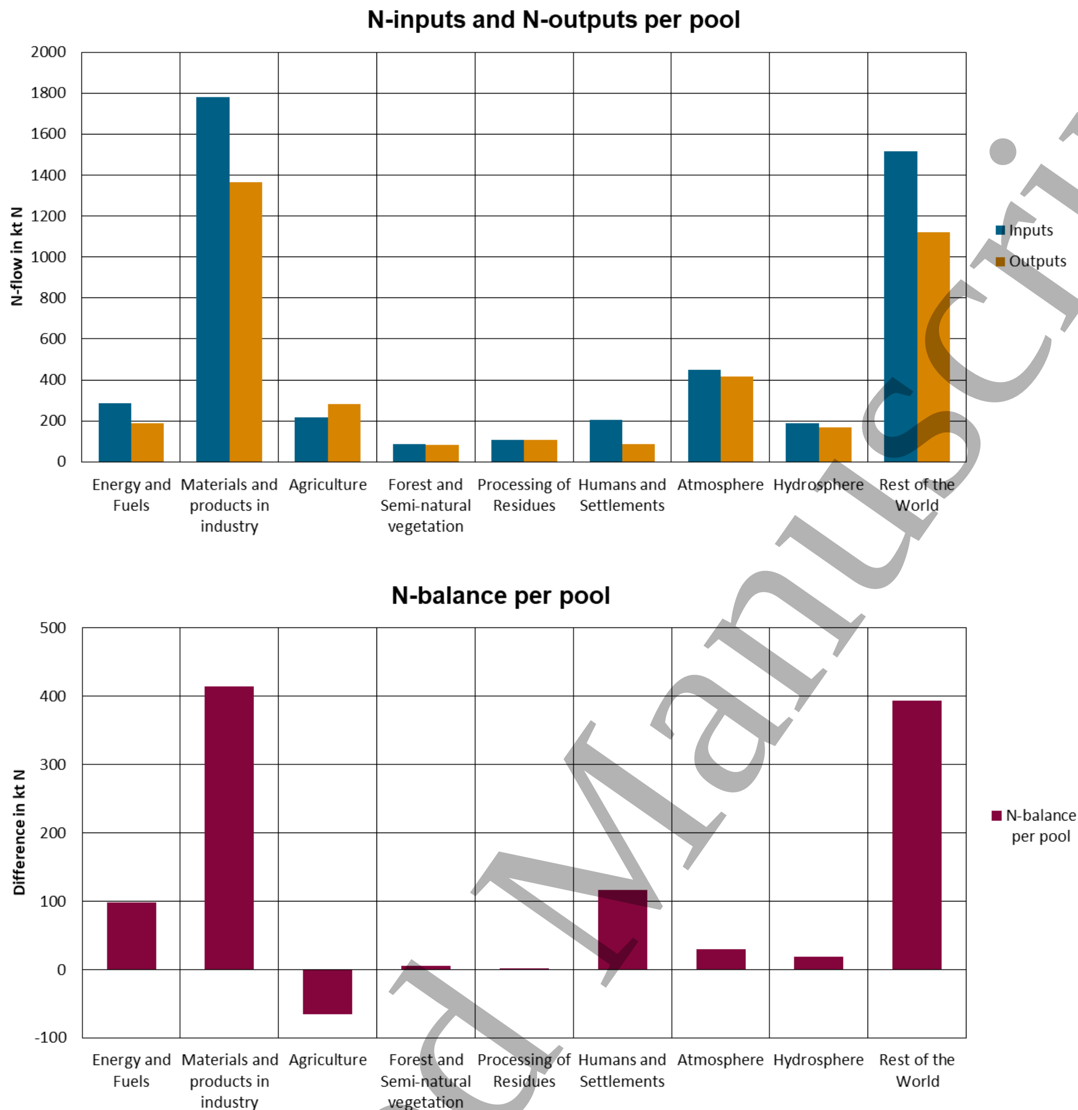

Fig. 2: Summing up N-input and N-output flows for each of the pools (upper panel) and displaying differences (lower panel) to analyze an NNB (data represent Austria, 2015-19 average, Djukic et al., 2025).

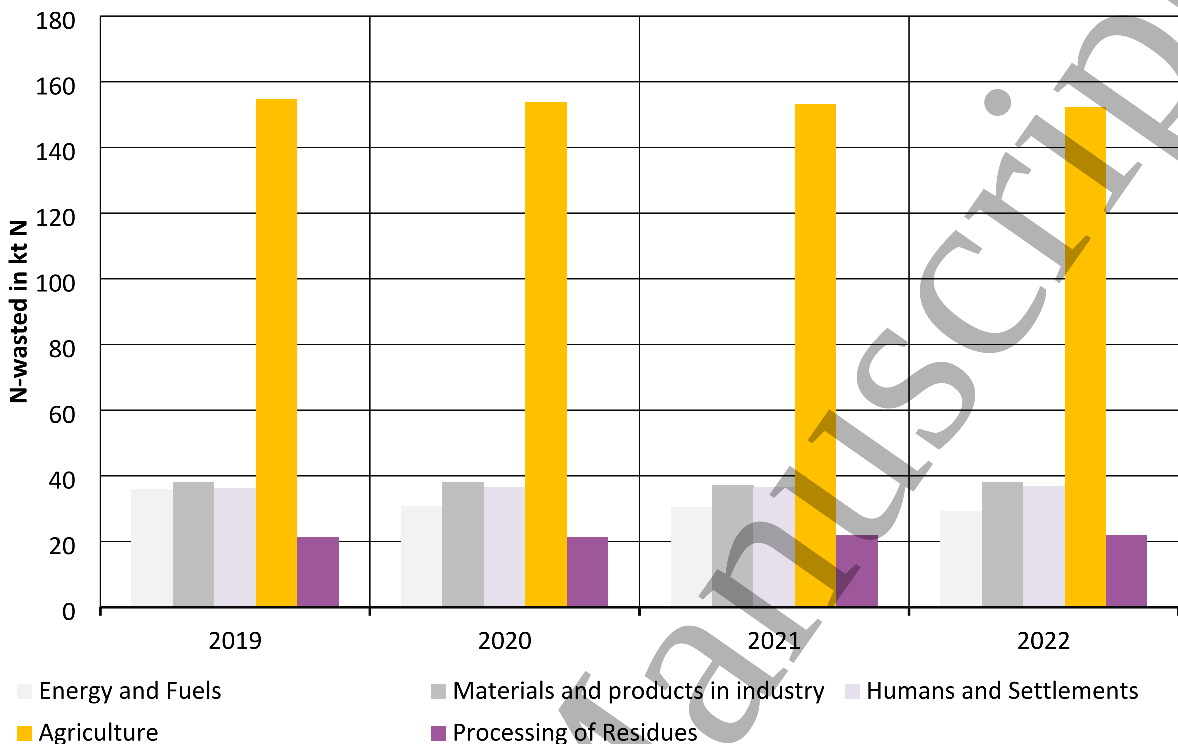

Fig. 3: Temporal development of parameters (here: mass of N wasted by pool) to display trends. Data from Scotland (Scottish Government, 2025) show stable conditions as to be expected over the short time period considered.

In a similar way, comparisons between different spatial units (countries in NNBs) can also be developed, again for a number of different parameters. 'Benchmarking' between countries requires normalization when comparing values in absolute units, in order to account for their different sizes. Options include to divide N flows or stocks by population or by gross domestic product (for a production-based comparison), by area (for an impact-directed comparison) or by a relative parameter such as NUE. Fig. 4 demonstrates the potential of such benchmarking exercise (here: economy-wide NUE as a strongly aggregated indicator). For NNBs, like in all other cases of using aggregated indicators, careful interpretation of results is needed to allow robust conclusions (see discussion).

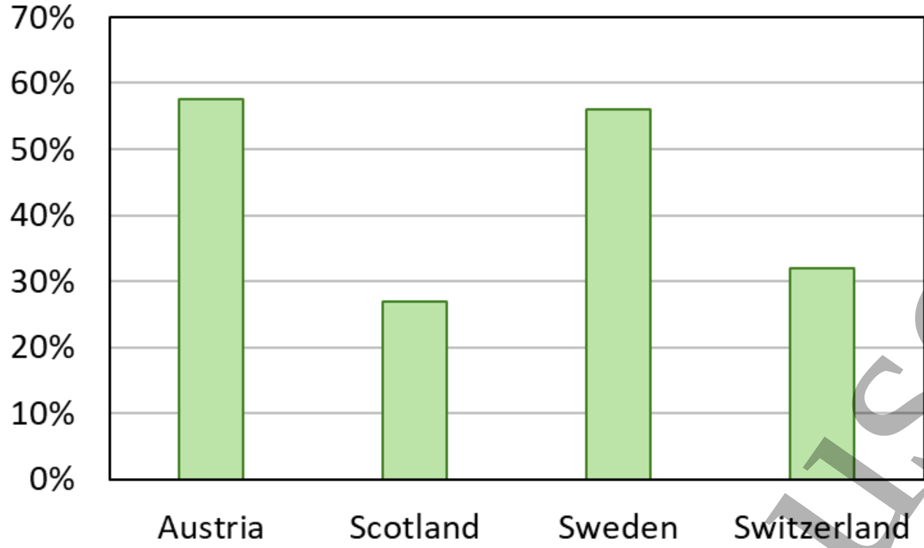

Fig. 4: Spatial benchmarking: normalized comparison of parameters or (as here) comparing parameters in relative units (%), the economy wide NUE (useful N output divided by all N inputs for the whole country), for four European countries that have been providing NNBs using harmonized methodology. Data derived from Djukic et al. (2025); Dragosits et al. (2025); Moldan et al. (2025); Reutimann et al. (2022).

4. Discussion and useful applications

Aiming to provide a comprehensive analysis of environmental N_r and its impacts, nitrogen budgets are not a new concept. The basic idea has been pursued from different perspectives and in part developed independently. An overview of relevant past activities has been provided by Winiwarter et al. (2025). Among the NNBs available, two specific groups can be distinguished, one that is following the CHANS layout (Gu et al., 2015), and the other one that has been performed in the context of the UNECE activities (UNECE, 2013; 2025). The approach discussed here is a further development of the latter, striving for advanced standardization and slightly revising nomenclature.

More generally, nitrogen budgets have been created for different spatial entities. Winiwarter et al. (2020) provide an overview on activities on an urban scale, with Suchowska-Kisielewicz et al. (2024) and Kaltenegger et al. (2023) analyzing the results for specific cities. By contrast, whole-continent budgets have been developed, such as for Europe (Van Egmond et al., 2002) or Asia (Zheng et al., 2002). The larger the unit observed is, the more time is available for N compounds to mix and interact in transport media, and the less important is the import/export term. This is e.g. evident for urban inventories, where two generic flow streams (the agri-food chain and the industry-combustion chain) can be kept strictly separate as the residence time of N_r in the respective pools is too short to allow for complete mixing/transfer between these streams (Winiwarter et al., 2020). Selecting the national scale is useful in practical terms due to data availability, as many high-quality statistical datasets are prepared on that spatial level.

Environmental impacts, however, may often appear on different levels, requiring downscaling to appropriately address scales. This is especially relevant for large countries where scale discrepancies may arguably be largest. In such a case an approach that already covers such downscaling may be advantageous (Sabo et al., 2019).

Scientific approaches using NNBs strive to supplement missing information from models. This has been the case in the European Nitrogen assessment (Leip et al., 2011) as well as for the International Nitrogen Assessment (Bodirsky et al., 2025), where detailed data on a national level have been drawn from a larger scale dataset. Likewise, CHANS (Gu et al., 2015) aggregates available information from different possible sources in a hierarchical manner, making the model usable by countries under very different circumstances. By contrast, the methodology introduced here (with all underlying details presented by Schäppi et al., 2025) mobilizes national data and national expertise to optimize data availability. It may be argued that local knowledge and understanding of local processes benefits data quality and minimizes the risk of errors. Locally performed NNBs, in the context of international agreements and in coordination with similar activities such as national emission inventories (of greenhouse gases or air pollutants) reflect national practices and policies and hence also provide the national perspective on the respective Nr flows. If an inventory agency, entrusted by a national government under an international agreement, produces an NNB (or an inventory), the country accepts responsibility for the flows reported and thus supports finding solutions to resolve environmental impacts. Of course, NNB results need to be as accurate as possible, which can be certified by appropriate quality control mechanisms (see also quality control in GHG inventories, IPCC 2006). The official status of such an NNB, however, provides it with additional legitimization for use in an international policy context.

At this point, it is important to recognize the challenges that are connected with establishing NNBs. Despite efforts of harmonization, and despite the built-in opportunities for checks and validation exercises, there are multiple situations where erroneous quantifications may become determining. Relatively minor discrepancies may shift a pool's N-balance from positive to negative or vice versa. When quantification of flows includes compound material, it may be difficult to correctly assess nitrogen contents (as has been shown for food materials by Kaltenegger and Winiwarter, 2020). High and not well-known N contents of fuels can constitute major elements in NNBs (Hayashi et al., 2021; Clair et al., 2014). Conversion to molecular N_2 during a combustion process is not easy to quantify. More generally, flows out of pools that lack economic interest may be less constrained or even missing entirely. Such missing flows, or accumulation in the pools, are alternative explanations of results as shown in Fig. 2. Pierer et al., (2015) argued for accumulation of material in the 'humans and settlements' pool as the reason of observed discrepancies between input and output, but at this point quantifying stocks and stock changes is not considered or required for NNBs. Possibly this is a methodological shortcoming, also as increasing stocks may have repercussions also on increasing flows, especially when longer-term processes such as storage of N_r in soils or groundwater are considered. Including uncertainty analysis, as integrated in the methodology, and more experience on application of NNBs will be needed to further understand and develop this approach, with more countries participating in such exercises under standardized conditions.

Extending the knowledge base of standardized NNBs will also support interpretation of benchmarking. Temporal trends, as visualized in Fig. 3, may arguably be well represented and robust, reflecting only rather small changes occurring in economic structures over the short time period shown. Still, an NNB (similarly to a national emission inventory) might not capture year-to-year changes of environmental parameters relevant for impacts (weather patterns, water levels). Hence, even the very stagnant conditions visualized in Fig. 3 may be cause for very different impacts. Selecting longer time periods for an analysis, as available for Japan (Hayashi et al., 2021) show greater variability, but that variability would not include the environmental conditions that cause differences in impacts.

Comparing different countries is not straightforward, either. The value of any indicator chosen, such as the economy-wide NUE displayed in Fig. 4, may be characterized strongly by the underlying economic structure rather than representative of the economic performance. Fig. 4 shows much higher NUE for Austria than for Scotland, where the Austrian NUE is strongly characterized by efficiency in the 'materials and processes' pool, which is not important in the Scottish economy (in contrast to Scotland, Austria features important N chemical industry). Also, a high immediate export of materials will increase tendencies towards higher NUE, compared to situations where agriculture plays a major role and national food production is the primary form of useful N_r in end products.

Despite important challenges in the correct interpretation of the detailed results, NNBs are useful for jointly assessing N_r compounds in any medium, such as air, water or soil. They allow the identification of environmentally relevant flows of nitrogen and provide information on mitigation potentials. Specifically, they are clearly useful whenever a balance approach is needed. These are situations that may be regarded as 'useful applications' of NNBs. Such useful applications are to be further developed for standardizing NNBs. Here we merely present the most evident cases. Specific country examples may be taken from existing national exercises, taking account of the considerable uncertainties that are associated with many of the input parameters used to describe NNBs (Häußermann et al., 2022; Moldan et al., 2025; Djukic et al., 2025).

- N_r compounds are relevant in the formation of inorganic aerosols. While different atmospheric regimes allow to discern the importance of NO_x vs. NH_3 as the parameter most strongly contributing to additional particulate matter, full comprehension of the nitrogen cycle is essential to guide policy decisions in the long run, so that they remain valid also for future scenarios (Gu et al., 2021; Liu et al., 2023; Guo et al., 2024). Here budget approaches benefit from combination with appropriate environmental modelling exercises.
- N_r input is a critical parameter for describing the pollution of the Baltic Sea. A Maximum Allowable Input parameter (MAI) has been derived to quantify the remaining operating space for atmospheric deposition, once the riverine inputs are accounted for. Evidently, all inputs to marine waters need to be understood to provide a good understanding of status and possible environmental impacts under different mitigation scenarios (HELCOM 2022).

- N_r contributes to both exceedance of critical loads and critical levels for N-sensitive semi-natural habitats and designated nature conservation sites (Geupel et al., 2022). With multiple transport pathways (surface water, groundwater as well as atmosphere), protection needs of sensitive areas require an understanding of the full nitrogen cycle. NNBs and their scenario possibilities may serve as a decisive tool to better control ecosystem impacts of anthropogenic activities.
- Efforts to regulate N_r in riverine environments also require detailed information on its flows. Further to sectoral balances focusing on soils (Oenema et al., 2003) that aim to address the agricultural impacts on the scale of Nitrate Vulnerable Zones defined under the European Union's Nitrate Directive (see description by Cameira et al., 2019), more comprehensive endeavors have led to the development of an Integrated Nutrient Management Action Plan (Grizzetti et al., 2023), aiming to achieve the European Union's target to reduce nutrient losses by 50% for riversheds and countries.

Further balance approaches, even though not based on this approach, have been used for global nitrous oxide (Tian et al., 2020, 2024), helping to reconcile another set of highly uncertain N_r flows. More useful applications of NNBs can be expected to derive from such efforts, albeit moving the scientific method exploration towards a regulation oriented routine practice.

5. Conclusions

Setting up a highly standardized method to establish NNBs allows national experts to develop comprehensive understanding of the fate of N_r in a country's environment. With a methodology consistent with other obligations such as national emission inventories and national greenhouse gas inventories, NNBs facilitate a view of national N_r flows that is fully in line with the official perspective a country has of its environmental impact, while at the same time allowing for benchmarking and for comparing the results with those of other countries.

Including national information and expertise also aims at harmonizing NNBs with other national planning instruments. A nationally determined NNB, created by an adequate and nationally authorized institution, can be directly linked with scenarios and scopes for future national policies that appropriately consider multiple impacts by N_r. At the same time, the standardized approach allows for comparison with other (neighboring) countries and for trends over time.

Previous NNBs have been established based on strong scientific interest. Enabling stronger policy perspectives is expected to enhance possibilities for useful applications that link potential interventions on the flow pattern of N_r with environmental impacts. More work will be needed to establish robust relationships, but current experience already identifies such applications to determine human and ecosystem health as well as climate impacts of N_r based on budget approaches.

Acknowledgements

This work has been performed in support of the Task Force on Reactive Nitrogen under the UNECE Convention on Long Range Transboundary Air Pollution. Important parts of this work were made possible by a contract of the German Umweltbundesamt (Project FKZ 3722 63 2012). WW and MSK acknowledge support received from NCN via the project SENB (2024/55/B/ST10/01927). At the same time, this work contributes to the International Nitrogen Management System Project (INMS) funded by GEF and implemented by UNEP.

References

Bach M, Kanig M, Beisecker R *et al.* 2025. National Nitrogen Budget: Fortschreibung des nationalen Stickstoff-Inventars für die Jahre 2015 – 2020. Umweltbundesamt TEXTE XX/2025. German Environment Agency, Dessau-Roßlau, Germany (in press).

Battye W, Aneja VP, Schlesinger WH 2017. Is nitrogen the next carbon? Earth's Future 5, 894–904.

Bodirsky BL *et al.* 2025 Assessment of global scale total nitrogen budgets. In: The International Nitrogen Assessment (M.A.Sutton *et al*., Eds.) Chapter 10, Cambridge University Press, Cambridge UK (in press).

Brunner PH, Rechberger H 2016. Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers, Second Edition (2nd ed.). CRC Press.

Cameira MR, Rolim J, Valente F, Faro A, Dragosits U, Cordovil d. S. CM, 2019. Spatial distribution and uncertainties of nitrogen budgets for agriculture in the Tagus river basin in Portugal – Implications for effectiveness of mitigation measures. Land Use Policy 84, 278–293.

Cencic O, Rechberger H 2008. Material Flow Analysis with Software STAN. Journal of Environmental Engineering and Management 18 (1), 5.

Clair TA, Pelletier N, Bittman S, Leip A, Arp P, Moran MD, Dennis I, Niemi D, Sterling S, Drury CF, Yang J, 2014. Interactions between reactive nitrogen and the Canadian landscape: A budget approach: Canadian nitrogen budget. Global Biogeochemical Cycles 28, 1343–1357.

Derwent RG, Dollard GJ, Metcalfe SE, 1988. On the nitrogen budget for the United Kingdom and north-west Europe. Quarterly Journal of the Royal Meteorological Society 114, 1127–1152.

Djukic I *et al.* 2025. Austrian Nitrogen Budget according UNECE guidance. Accepted for publication in Environ Res Lett 20, 094054..

EEA 2023 EMEP/EEA air pollutant emission inventory guidebook 2009 Technical guidance to prepare national emission inventories. EEA Report 06/2023, European Environment Agency, Copenhagen.

Erisman J W, Sutton M A, Galloway J, Klimont Z, Winiwarter W 2008. How a century of ammonia synthesis changed the world. Nature Geosci 1, 636–639.

EU 2022 Regulation (EU) 2022/2379 of the European Parliament and of the Council on Statistics on Agricultural Input and Output. Official Journal of the European Union 7.12.2022, L 315.

Fowler D *et al.* 2013. The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B: Biological Sciences 368, 20130164–20130164.

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, Cosby BJ 2003. The nitrogen cascade. BioScience 53, 341–356.

Geupel M, Loran C, Scheuschner T, Wohlgemuth L, 2022. CCE Status Report 2022. Coordination Centre for Effects TEXTE 135/2022. German Environment Agency, Dessau, Germany

Grizzetti B *et al.* 2023. Knowledge for Integrated Nutrient Management Action Plan (INMAP), EUR 31487 EN, Publications Office of the European Union, Luxembourg.

Gu B, Ju X, Chang J, Ge Y, Vitousek PM, 2015. Integrated reactive nitrogen budgets and future trends in China. Proceedings of the National Academy of Sciences 112, 8792–8797.

Gu B *et al.* 2021. Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM2.5 air pollution. Science 374, 758–762.

Guo Y, Zhao H, Wang X, Zhou M, Chang J, Havlik P, Winiwarter W, Leclere D, Pan D, Kanter D, Zhang L 2024. Aspirational Nitrogen Interventions Accelerate Air Pollution Abatement and Ecosystem Protection. Science Advances 10, eado0112.

Häußermann U *et al.* 2021. National nitrogen budget for Germany. Environ. Res. Commun. 3 095004.

Hayashi K, Shibata H, Oita A, Nishina K, Ito A, Katagiri K, Shindo J, 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. Environmental Pollution 286, 117559.

HELCOM 2022. Pollution load on the Baltic Sea. Summary of the HELCOM Seventh Pollution Load Compilation (PLC-7). Helsinki Commission – HELCOM, Helsinki.

IPCC 2006. 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme, IGES, Tokyo.

Kaltenegger K, Bai Z, Dragosits U, Fan X, Greinert A, Guéret S, Suchowska-Kisielewicz M, Winiwarter W, Zhang L, Zhou F 2023. Urban nitrogen budgets: Evaluating and comparing the path of nitrogen through cities for improved management. Science of The Total Environment 904, 166827.

Kaltenegger K, Winiwarter W, 2020. Global Gridded Nitrogen Indicators: Influence of Crop Maps, Global Biogeochemical Cycles 34, e2020GB006634.

Leip A *et al.* 2011. Integrating nitrogen fluxes at the European scale. Chapter 16. In: The European Nitrogen Assessment. Eds. Sutton M A, Howard C M, Erisman J W, Billen G, Bleeker A, Grennfelt P, van Grinsven H and Grizzetti B. Cambridge University Press, pp. 345-376, Cambridge.

Liu Z, Rieder H, Schmidt C, Mayer M, Guo Y, Winiwarter W, Zhang L 2023. Optimal reactive nitrogen control pathways identified for cost-effective PM2.5 mitigation in Europe. Nature Communications 14, 4246.

Moldan F, Stadmark J, Jutterström S, Ljunggren J 2025. Where Does Sweden's Nitrogen Go? Building a Comprehensive National Nitrogen Budget, submitted to Environ Res Lett, this issue.

Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. European Journal of Agronomy 20, 3–16.

Pierer M, Schröck A, Winiwarter W, 2015. Analysing consumer-related nitrogen flows: A case study on food and material use. Resources, Conservation & Recycling 101, 203–211.

Reutimann J, Ehrler A, Schäppi B 2022. Aktualisierung Stoffflussanalyse Stickstoff für das Jahr 2018. INFRAS AG, Zurich. Available at https://backend.blw.admin.ch/fileservice/sdweb-docs-prod-blwch-files/files/2024/08/27/78602f04-d38d-430e-9ca3-5424302f5128.pdf (accessed April 26, 2025).

Richardson K *et al.* 2023. Earth beyond six of nine planetary boundaries. Science Advances 9, eadh2458

Rockström J *et al.* 2009. A safe operating space for humanity. Nature 461, 472–475.

Sabo R.D., Clark C.M., Bash J., Sobota D., Cooter E., Dobrowolski J.P., et al. 2019. Decadal shift in nitrogen inputs and fluxes across the contiguous United States: 2002–2012. Journal of Geophysical Research: Biogeosciences 124, 3104– 3124.

Schäppi B, Bogler S, Reutimann J, Fehrenbach H 2025. Detailed Annexes to the UNECE "Guidance document on national nitrogen budgets", Umweltbundesamt TEXTE XX/2025. German Environment Agency, Dessau-Roßlau, Germany (in press). https://www.clrtap-tfrn.org/epnb (accessed July 18, 2025)

Schulte-Uebbing L F, Beusen A H W, Bouwman A F, de Vries W 2022. From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610, 507–512.

Scottish Government 2025. Scottish Nitrogen Balance Sheet 2022, May 2025. https:/www.gov.scot/news/scottish-nitrogen-balance-sheet-2022/ (accessed July 18, 2025).

Suchowska-Kisielewicz M, Greinert A, Winiwarter W, Kaltenegger K, Jędrczak A, Myszograj S, Płuciennik-Koropczuk E, Skiba M, Bazan-Krzywoszańska A 2024. The fate of nitrogen in the urban area – The case of Zielona Góra, Poland. Science of The Total Environment 915, 169930.

Sutton M A, Howard C M, Erisman J W, Billen G, Bleeker A, Grennfelt P, van Grinsven H and Grizzetti B (Eds.) 2011a. The European Nitrogen Assessment. Cambridge University Press, pp. 345-376, Cambridge

Sutton M A, Oenema O, Erisman J W, Leip A, van Grinsven H, Winiwarter W, 2011b. Too much of a good thing. Nature 472, 159–161.

Sutton M A, Howard C M, Kanter D R, Lassaletta L, Móring A, Raghuram N, Read N, 2021. The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. One Earth 4, 10–14.

Sutton M A *et al.* (Eds.) 2025. The International Nitrogen Assessment, Cambridge University Press, Cambridge UK (in press).

Tian H *et al.* 2020. A comprehensive global nitrous oxide budget reveals lack of mitigation. Nature 586, 248–256.

Tian, H *et al.* 2024. Global nitrous oxide budget (1980–2020), Earth Syst. Sci. Data, 16, 2543–2604 (2024).

UNECE 2013, UN Economic Commission for Europe: Guidance document on national nitrogen budgets. ECE /EB.AIR/119, Geneva.

UNECE 2025, UN Economic Commission for Europe: Draft revised guidance document on national nitrogen budgets. ECE /EB.AIR/WG.5/2025/3, Geneva.

UNFCCC 2022, UN Framework Convention on Climate Change: Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention. Decision 6/CP.27, FCCC /CP/2022/10/Add.1, Bonn.

Van Egmond K, Bresser T, Bouwman L 2002. The European nitrogen case. Ambio 31, 72–78.

Winiwarter W *et al.* 2020. Urban nitrogen budgets: flows and stock changes of potentially polluting nitrogen compounds in cities and their surroundings – a review. Journal of Integrative Environmental Sciences 17, 57–71.

508 Winiwarter W, Hayashi K, Geupel M, Gu B, Zhang X 2025. INMS Guidance Document on National Nitrogen Budgets. INMS Guidance Document Series (eds. Mark A. Sutton, Martha Schlegel, Jill Baron and Hans J.M. Van Grinsven), INMS Report 2025/02. UK Centre for Ecology & Hydrology, Edinburgh (in press, doi 10.5281/zenodo.15632929).

512 Zheng X, Fu C, Xu X, Yan X, Huang Y, Han S, Hu F, Chen G 2002. The Asian Nitrogen Cycle Case Study. AMBIO: A Journal of the Human Environment 31(2), 79-87.

514