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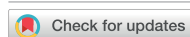


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Nitrogen budgets in Europe: a methodology to quantify
environmentally relevant flows of reactive nitrogen compounds on
a national scale

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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 compounds 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.

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 (Erismann *et al* 2008), specific environmental effects have been recognized for Europe (Sutton *et al* 2011a, 2011b) 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 , which is present in large excess, from the budget 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* 1988) 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 (equation (1)). The resulting equation of N_r flows can be expressed as

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

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.

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).

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	EE.EC
Energy and fuels—transportation			EE.TR
Energy and fuels—other energy and fuels			EE.OE
Energy and fuels—manufacturing industries and construction			EE.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
Hydrosphere—coastal water			HY.CW
Hydrosphere—aquaculture			HY.AC

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.

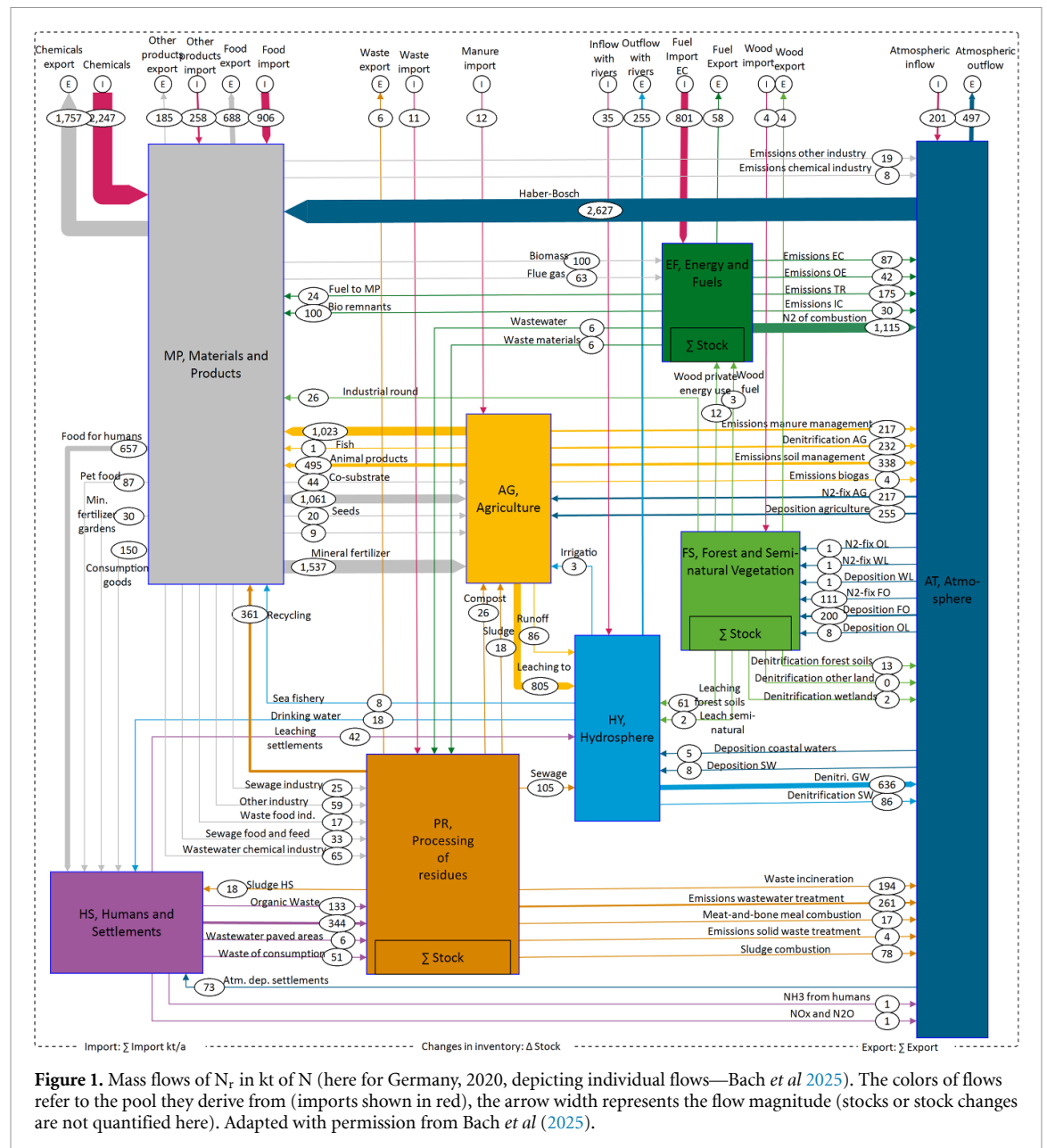
As NNBs necessarily are limited by spatial boundaries of countries, delineation of flows is also needed with respect to exports and imports. The concept

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.

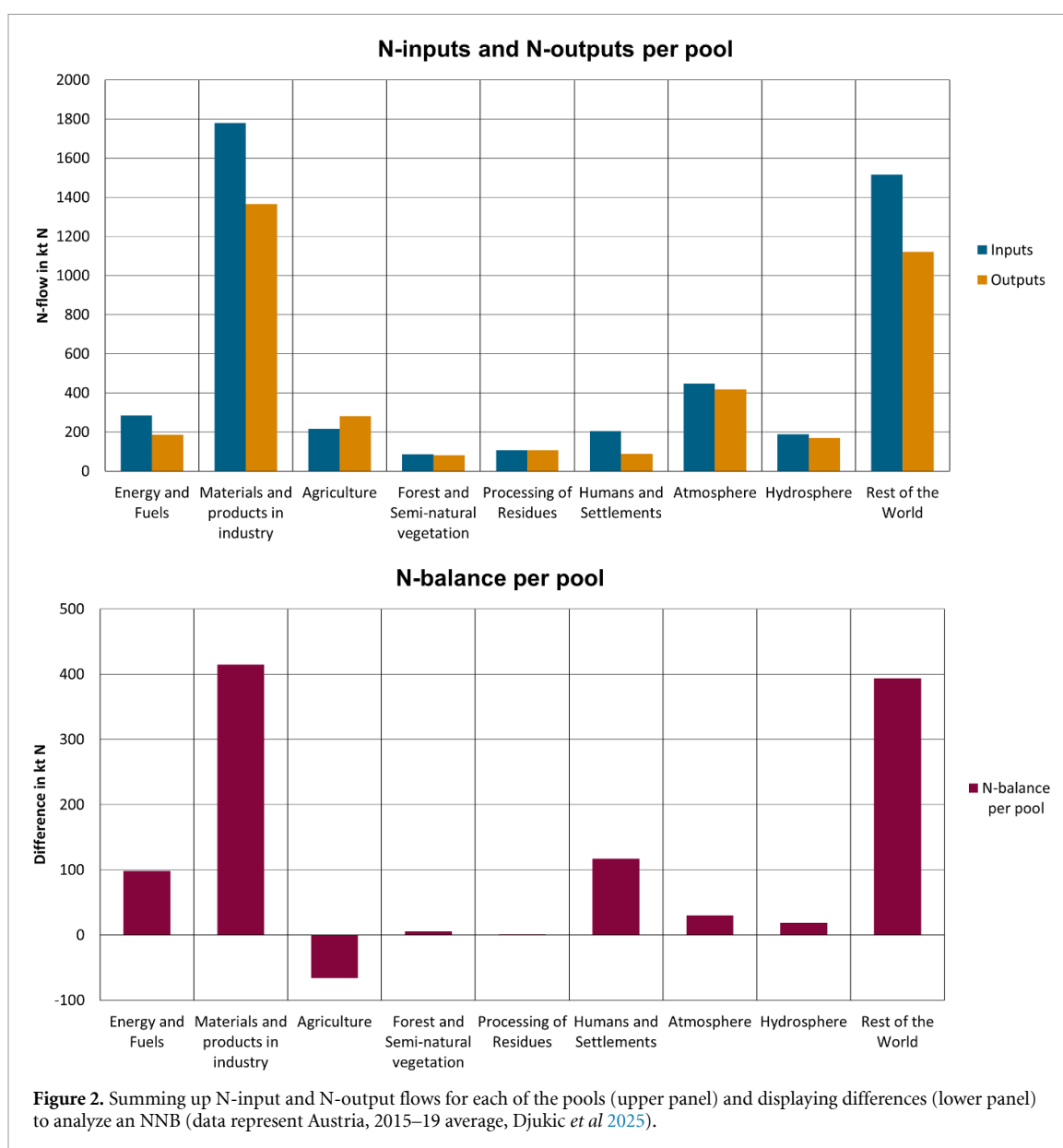
The display of individual flows takes advantage of the STAN model (Cencic and Rechberger 2008). A specific data collection spreadsheet has been developed which can be used as an interface for data



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 figure 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.

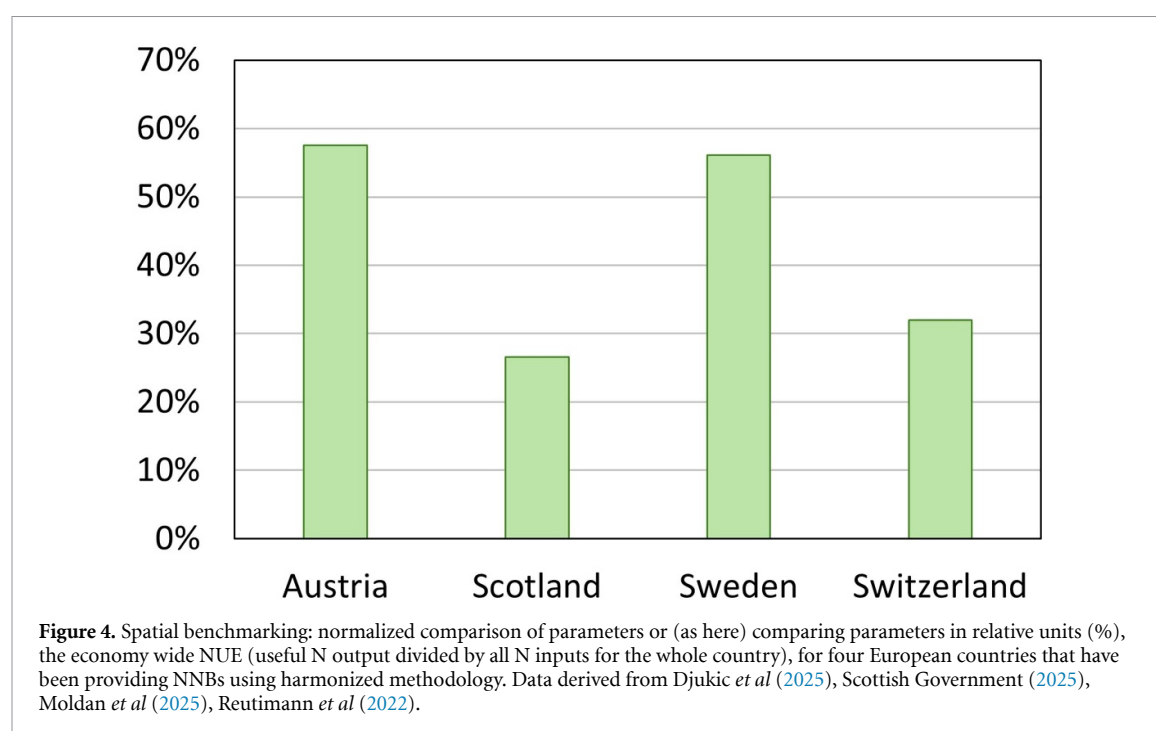
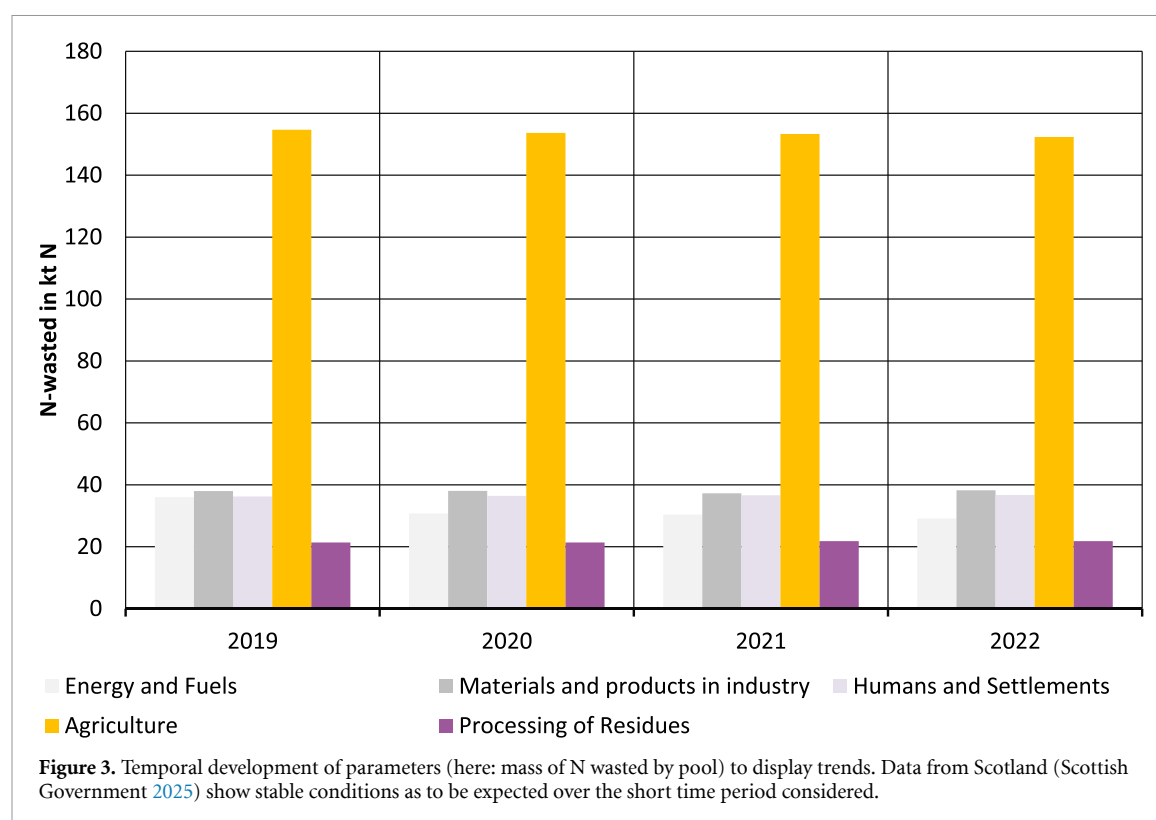
Budgeting across a pool or a whole NNB allows to identify general discrepancies (e.g. due to missing flows, using inappropriate values of N contents). If no such discrepancies can be found, that may be seen as a sign of coherence of data. The NNB data collection sheet enables a direct display of pool budgets (also for sub-pools) and to develop balances that may be interpreted as stock changes (figure 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 figure 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. Figure 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 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).

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. Figure 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).

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 Schächli *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 N_r 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 (Clair *et al* 2014, Hayashi *et al* 2021). 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 figure 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 figure 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 figure 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 figure 4, may be characterized strongly by the underlying economic structure rather than representative of the economic performance. Figure 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* 2021, Djukic *et al* 2025, Moldan *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 modeling exercises.
- N_r input is a critical parameter for describing the pollution of the Baltic Sea. Maximum Allowable Input (MAI) has been determined as a parameter 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 method from scientific exploration towards the practice of a regulation oriented routine.

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.

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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