# Nitrogen budget: a tool to validate information on nitrogen fluxes

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**Abstract**

Reactive nitrogen compounds, released by anthropogenic activities, may take different pathways in the environment, not all of which are easily traceable. Nitrogen budgets allow using surrogate information for fluxes that otherwise cannot easily be measured or validation of flux quantities for which an independent second set of data can be made available. In order to reliably assess nitrogen budgets and to make them comparable, the harmonization of approaches is required. Such a harmonizing effort has been performed under the European "air quality" convention, the Convention on Long-Range Transboundary Air Pollution. Based on existing efforts to collect data on fluxes of nitrogen compounds, specifically in the framework of the convention, from national greenhouse gas inventories mandatory under UNFCCC, or in connection with European activities of EUROSTAT or OECD, a guidance document has been developed to allow assessing national nitrogen budgets. Eight individual "pools" have been identified that are considered the start- and endpoints of environmental fluxes. The guidance document allows fluxes between pools to be properly assigned and quantified and provides a framework for consistent nomenclature. This paper shows complete and partial applications of the concept, and demonstrates the advantages of harmonizing approaches. It takes available published budgets for several European and non-European countries, analyzes them for compatibility, and evaluates nitrogen budgets for their potential contribution to a sustainable development of agriculture and beyond agriculture. From the few available examples is can be shown that nitrogen budgets allow to identify missing information as well as to define areas of intervention into the nitrogen regime. Comparing over time shows trends, e.g. as a result of environmental legislation, comparing between countries displays national characteristics useful for benchmarking. Linking towards specific abatement, nitrogen budgets may help in attaining "planetary boundaries" for nitrogen.

**Key Words**

Europe, transboundary air pollution, integration, agro-environmental indicator

## Introduction

The concept of mass conservation is central in science. Just slight modifications are needed to render it useful for describing the "nitrogen cascade" (Galloway et al., 2003), the sequence of environmental impacts due to nitrogen compounds. We just need to remember some key boundary facts: (i) almost all environmental N (more than 99%) exists in molecular form ($N_2$) and constitutes the major part of the atmosphere. In this form it is almost unreactive and exerts no effects on the biosphere. (ii) Considerable energy is needed to force molecular nitrogen into chemical bonding. While "fixed" nitrogen (also called "reactive nitrogen", Nr) also can be very stable, its content of chemical energy clearly distinguishes it from molecular nitrogen. (iii) Conversion between different forms of Nr is possible rather easily, can be stimulated by microbial action, and determines the extent to which Nr is exposed to transport processes (with different Nr forms to be more or less affected by transport).

Considering mass conservation of Nr thus allows to track environmentally active nitrogen forms across the cascade, which constitute merely a small fraction of all available N yet account for all of the relevant effects of the nitrogen cycle. Only the steps of N fixation (as a microbial mechanism, in the atmosphere via lightning, a combustion product or, of increasing relevance, industrial fixation via the Haber-Bosch process) and dissipation (e.g., in soils or in wastewater treatment plants by recombination into molecular $N_2$) need extra consideration as sources or sinks, while any efforts to distinguish individual Nr species are minimized.

Numerous approaches to quantify Nr in the environment exist, which allow to better understand the formation and the fate of environmentally relevant Nr compounds. Using gross N-balances as agro-environmental indicators (OECD, 2008) facilitated to work out trends and to estimate nitrogen use efficiencies in different countries, including the changes over time. On a continental scale, N budgets have been assessed for Europe (van Egmond et al., 2002), Asia (Zheng et al., 2002) and North America (Howarth et al., 2002); also global approaches (Fowler et al., 2013) have been made available. Not all of the existing studies are fully comparable, and some are even prone to misinterpretation (e.g. as identified by Winiwarter et al., 2011).

In parallel to work done for the European Nitrogen Assessment (Leip et al., 2012), activities to create national nitrogen budgets in Europe were linked and attempts to harmonize this work commenced. Studies performed for Switzerland (Heldstab et al., 2010) and for Germany (Umweltbundesamt, 2009) provided the blueprints to the work of the Expert Panel on Nitrogen Budgets (EPNB), an informal working group contributing to the activities of the Convention on Long Range Transboundary Air Pollution (LRTAP) of the UN-ECE. The EPNB developed a Guidance Document on National Nitrogen Budgets (UNECE, 2013; in the following termed GD) in order to organize a consistent and comparable data collection and representation. This paper reports on the development of this document and of the detailed "annexes" guiding towards harmonized reporting of nitrogen flows. The specific challenges that appeared during its production allow detailed insights in the underlying mechanisms and provide important quality information. With just a few quantitative results available to-date, first conclusions on the practical applicability can be presented and the benefits created by nitrogen budgets are explained beyond the original expectations.

## Methods

*Structuring Nitrogen Budgets*

In essence, an N budget takes the form of a material flow analysis. Stocks and flows of material (in this case: Nr) within and between pools or sub-pools are being registered and noted. The challenge is to convert such approaches into comparable results (between two approaches, or between countries). That can was made possible by observing the following principles:

- focus on flows (which are easier to determine/measure), ignore stocks
- choose pools and pool boundaries for which appropriate information (statistics) is available
- take advantage of existing national data collection activities relevant for Nr flows.

As a consequence of these principles, assessment of flows follows, where available, existing guidelines, Specifically those developed for reporting of greenhouse gas emissions to UNFCCC, and of the emissions of air pollutants according to UN-ECE. The latter reports are mandatory for the entire UN-ECE region, thus are in principle available to the whole target region. Hence, also the pools selected reflect the source sectors defined under UNFCCC, and the approach taken by EPNB even attempts to mimic the codes used to define these sectors. As N budgets are more comprehensive, additional pools had to be introduced. Moreover, the concept of trade, which is not needed for national emission inventories, had to be introduced (see e.g. Lassalletta et al., 2014, for an assessment of trade on national Nr budgets).

The resulting set of pools is presented in Figure 1. Subpools have been described in detail by UNECE (2013) and its annexes. Pools 1-5 ("energy" to "waste") clearly reflect the UNFCCC source sectors, while terminology has been adjusted to the specific topic. The additional pools 6-8 reflect those areas beyond the society's economic realm, for which statistics are often not readily available, but which also are indispensable in describing a full N budget. Despite some differences, the overall system has been conceptualized to be harmonized across all pools, each of which is represented in an own "Annex" to the GD.

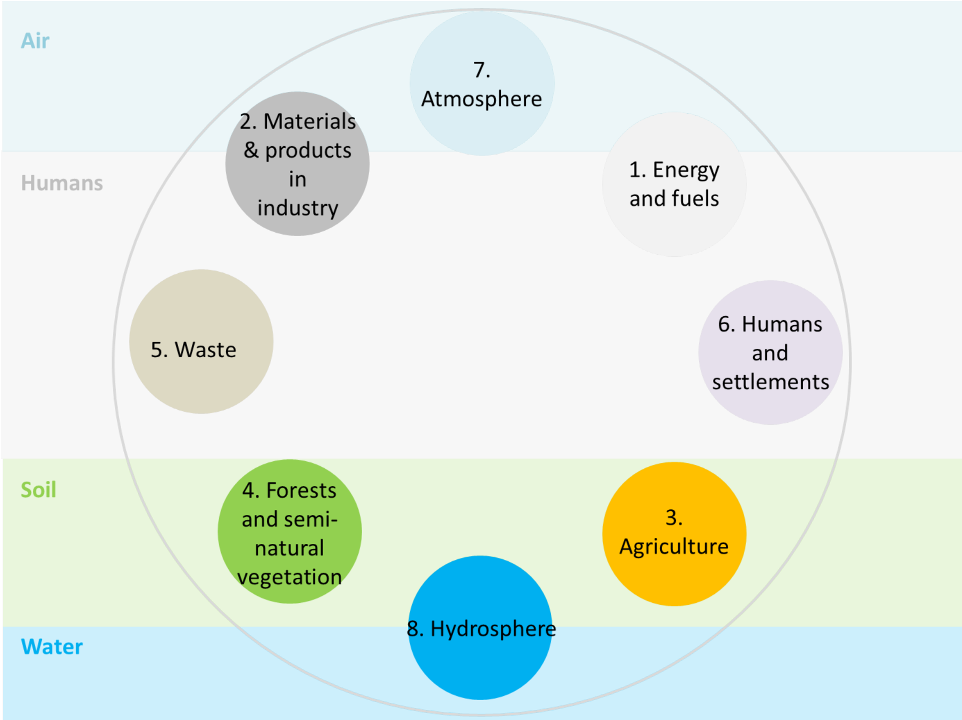


**Figure 1. Specific pools identified for national N budgets under UN-ECE (UNECE, 2013). Background indicates the respective "spheres" concerned. Arrows between two respective pools may be used to indicate relevant flows determining Nr exchange for each specific pool.**

*Challenges identified*
Developing documents for each of the pools individually (annexes to the GD) posed considerable challenges, partly resulting from the novelty of the approach, partly just reflecting the specifically different conditions between pools. The following paragraphs address these issues, which have been covered in detail in the respective annexes.

Characterizing the flows between pools is the central element of an N budget. In the GD, these flows need to be characterized only once, associated with one of the pools. In a concept to optimize guidance, description on quantifying the respective flow should be provided wherever the quality of information is considered higher. In most cases, flows are the consequence of processes occurring in the pool the flow originates from. Hence, the decision was, in general, to describe flows together with the respective pool they start from rather than with the recipient. This procedure points to a better quality of the underlying statistical data, moreover it takes advantage of additional knowledge of actual underlying processes that cause the respective N flow.

The flow concept will result in also describing sources, sinks and stock changes. Sources refer to points where molecular N is converted into reactive N (as in Haber Bosch synthesis), sinks describe conversion processes that release molecular $N_2$ (such as denitrification occurring in wastewater treatment plants).While it seems questionable to which extent also other non-reactive forms may exist ("locked" N, e.g. contained in synthetic materials or in mineral oil), which would have to be "activated" before becoming environmentally relevant (e.g. during a combustion process), such an "activation" in some cases may be difficult to detect. Thus the guidance document recommends that such "locked" N should not be ignored, but treated just like any other Nr. Specific impact assessment (as typically performed in life cycle assessments) would be needed in order quantify the potential damage of different Nr forms, but that is beyond the scope of an N budget.

The GD has been prepared with a claim to be useful in all of the Convention area, including most of Europe and extending into the Caucasus region and into parts of central Asia. Thus guidance is required for a considerable range of conditions regarding data availability and data quality. In order to support establishing N budgets in such diverse background conditions, the GD allows for different Tier levels. Countries in which information is not so easily available may opt for an N budget to be developed at a lower Tier (Tier 1), which requires less national information and hence can be obtained with a smaller overall effort. Countries having well-developed reporting systems, however, need to be encouraged to consider applying a higher Tier (Tier 2 or 3) for their budgets in order to optimize output quality.

Much of this statistical information used by country experts provides information on flows of certain material, but not of N itself. Here reliable data on N-content is needed. Such information can be derived from publicly available databases like Fooddata (DTU, 2015) or Feedipedia (INRA, 2016), which provide the N contents of a wide range of products. In order to provide consistent N budgets, it turns out to be useful to take advantage of internationally tested and approved datasets, as long as no specific national measurement data can be used.

For some of the pools (most evidently for agriculture) key information is available already, as a result of country obligations for data submission to international bodies under international agreements. The GD strives to render information consistent across different reporting guidelines. Considerable attention has been given to liaise with these relevant activities, like those of Eurostat and OECD, and to take advantage of data collected and procedures developed for other reporting activities. Both aspects have been considered in the development of the respective annexes.

Specific attention is needed for cross-boundary transport of Nr. The GD foresees, for each pool, the accounting of imports and exports. While this concept easily allows assessment of economically relevant material, additional difficulties arise when transport media are rivers or air (as is the case for the hydrosphere or atmosphere pools), or when transport activities are not registered (humans and settlements pool). In these cases, transport modelling or estimation from secondary sources were identified as being adequate methods.

**Results**

Little practical experience is available to-date in applying the guidelines described above. The underlying documentation only became publicly available in 2016. Experts were previously restricted to work on preliminary versions, to which only EPNB members (authors and reviewers of the GD as well as other signed-up experts) had access. This co-development of guidance and application meant to contribute to the practicability of the suggested approaches. The following examples demonstrate that results turn out to be useful.

*A partial N budget for Austria*

Created originally from considerations of an individual pool (humans and settlements) in the N budget, Pierer et al. (2015) trace the nitrogen flows within the consumer sphere. The specific challenge in assessing flows of this pool consists of the lack of statistics (mostly concerning "private" activities for which statistical information is rare or not collected). Nevertheless, the authors have been able to quantify flows into and out of this pool, and they also assessed the uncertainties in the estimates. A discrepancy of higher inflows than outflows became evident, exceeding the uncertainty bounds. Looking into details of the specific compounds that make up the flow, the authors have been able to associate the problem with synthetic material containing N – which either accumulates in the pool associated with private activities (humans and settlements) or for which data on flows to the waste pool are inadequate. Here the N budget allows to identify specific flows for which further improvement is desirable.

*Budget derived indicators*

The above-mentioned N budgets of Switzerland and Germany (as well as the later studies conducted in connection with EPNB work) demonstrate how quantitative information on nitrogen flows provides environmentally relevant statements. In their study on Canada, Clair et al. (2014) identified the agriculture pool as the most relevant, with mineral fertilizer and biological nitrogen fixation adding about the same amounts of N to soils. One result is that a considerable amount of N accumulates in soil, another result refers to the sizeable exports of Nr (mostly to the U.S.) in the form of commodities like mineral fertilizer and food products, but also as mineral oil products containing N, which at least in this form will not be easily released to the environment but needs to be accounted for nevertheless. Different in magnitude, but conceptually similarly interesting are the major nitrogen flows for Denmark (Hutchings et al., 2015). Here soil receives Nr mostly from mineral fertilizer and from animal manure, with a considerable amount leaching to groundwater and impacting the hydrosphere. Trade brings net imports, based on mineral fertilizer and animal feed which is about twice as high as Nr in food exports. Compared to Canada, the possible intervention points to tackle excess nitrogen flows are placed very differently. Factors presented allow a simple assessment of key efficiency parameters, such as output/input relationships of N, or relevant transfer factors between specific pools.

*Temporal trends of indicators*
While assessing a unique situation for a specific country already provides a reasonable overview that can be used for environmental planning, the comparison between two (or more) time intervals is even more interesting. Here specific country conditions like special economic situations – which possibly are difficult to resolve – remain to show up. More strikingly differences in Nr related parameters over time can be identified as a result of a change in underlying activities, thus proving that a certain intervention influences Nr flows. If an observed change is the result of some abatement measure, the temporal trend can be taken to evaluate and review this measure.

The OECD (2008) compared nitrogen use efficiencies in its member countries as reported 1990-92 vs. 2002-04 and identified a distinct increase in most cases, pointing towards considerable environmental improvements. Also, the above mentioned Danish study (Hutchings et al., 2015) provided two data sets, 1990 and 2010. Results demonstrate that the national efforts to reduce nitrate losses to groundwater indeed were successful, which allowed for halving of both mineral fertilizer input and nitrogen losses to groundwater. This also reduced all other flows related to the hydrosphere, while many other flows remained in a similar magnitude. Both cases prove the potential of repeating N budgets to better understand the performance of certain industries as well as the performance of environmental action.

*Multi-country comparison*
Structural differences between countries – but also possible inconsistencies in available data or approaches – can be identified by comparing detailed results. A first intercomparison has been made available by Leip et al. (2011). These authors performed a centralized exercise covering 6 European countries (UK, France, Netherlands, Germany, Switzerland, Czech Republic), which may be analysed for national differences. Some incidents are a clear result of the geographic circumstances, especially with regard to the hydrosphere: UK and France report exports of Nr to coastal waters, while Switzerland or Czech Republic release Nr to rivers only. In contrast, the Netherlands receive considerable amounts of Nr via rivers, which again is exported to coastal waters, supplemented with national effluents. Based on this data, Nr delivered by feed imports makes up a considerable share (80%) of total food production in the Netherland. The equivalent estimates were about half for Switzerland, 35% for Germany and UK, and only 5% for France. The Czech Republic provides no data for feed import. Netherlands also leads other countries in the amount of N fixed in industry (about 80% of which are exported), topped in absolute numbers only by France. Germany's N fixation is much smaller, and UK's industry fixes only half that of the Dutch amount despite having 3-5 times the population. Population ratios are roughly reflected when comparing $NO_x$ emissions to the atmosphere from transport. A more thorough analysis seems worthwhile and very relevant to understand the levers to tackle environmental nitrogen, but will require further harmonization and completeness on some elements of the budgets, e.g. the agriculture pool.

*Outlook: Link to regional and farm budgets*
Impacts of Nr affect receptors and recipients differently, depending on proximity to sources and release rates. This fact calls for improved spatial information in order to devise measures. Especially for large countries, the spatial resolution of national budgets is poor, thus a call for regional budgets seems a logical next step. However, N budgets are based on statistical information – information which typically is available on a national scale. Regional N budgets thus should not be expected as being developed independently, but rather as a downscaling exercise from national budgets once the methodological developments described here become operative, increasing their reliability.

Some information, relevant also for regional budgets, may be taken from other collected data: Several countries (at least Germany, Netherlands, Denmark) either required, or now require farm operators to provide detailed information on nitrogen flows. Farm budgets typically are created as farmgate budgets, i.e. internal transactions within a farm are ignored (feed produced on-site or manure applied), only Nr contained in products sold and resources purchased is considered. Information on farm budgets may, ultimately, also provide important information to national budgets, once these are thoroughly developed.

## Conclusion

Nitrogen budgets on different scale are starting to become a useful tool for environmental planning. Harmonization of methods, especially under the UN-ECE LRTAP convention and for budgets on the national scale, is expected to pave the way for making results comparable. Interesting results can already be derived from the few N budgets available to-date.

The planetary boundary discussion (see Steffen et al., 2015) demonstrates that the global N cycle has been considerably affected by anthropogenic activities, in a way that safe boundaries are being exceeded. Detailed indicators are needed that allow to analyse trends and points of intervention. One approach is to develop regional boundaries, to at least obtain a better spatial understanding of problems (de Vries et al., 2013). Moreover, nitrogen budgets offer the opportunity to provide the detailed indicators for further action, and need to be further developed.

A comprehensive overview on existing approaches using N indicators has been compiled by Galloway et al. (2015). These authors emphasize the importance of indicators to assess and compare seemingly similar situations. Based on benchmarking of indicators, the potential for improvements can be estimated for installations / communities / institutions that do not apply "best available technology". Here N budgets clearly are able to provide the parameters needed, in a form to make them comparable across different countries and applications. Thus N budgets can perform as an important link between "planetary boundaries" expressing the needs to limit exceedance of Nr, and the tools required to implement measures to abate Nr release.

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