Guidance Document on National Nitrogen Budgets

International Nitrogen Management System

INMS Guidance Document Series

Published by the UK Centre for Ecology & Hydrology (UKCEH), Edinburgh UK, on behalf of the GEF/UNEP funded International Nitrogen Management System (INMS).

DOI:10.5281/zenodo.15632929 ISBN: 978-1-906698-87-4

This publication is available online at www.inms.international/reports

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Recommended citation Winiwarter, W., Hayashi, K., Geupel, M., Gu, B. and Zhang, X. (2025) *Guidance document on national nitrogen budgets.* INMS Guidance Document Series (Series Editors: M.A. Sutton, M. Schlegel, J. Baron and H.J.M. Van Grinsven). UK Centre for Ecology & Hydrology, Edinburgh, UK.

INMS Report 2025/01

About the International Nitrogen Management System (INMS) INMS is a global science-support system for international nitrogen policy development established as a joint activity of the United Nations Environment Programme (UNEP) and the International Nitrogen Initiative (INI). It is supported with funding through the Global Environment Facility (GEF) and over 80 project partners through the 'Towards INMS' project (2017-2025). INMS provides a cross-cutting contribution to multiple programmes and intergovernmental conventions relevant for the nitrogen challenge. These include the Global Partnership on Nutrient Management (GPNM) and the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), the UN Convention on Biological Diversity (CBD) and the UNECE Convention on Long-Range Transboundary Air Pollution (Air Convention), through its Task Force on Reactive Nitrogen (TFRN). INMS receives major additional funding through the work of the GCRF (Global Challenge Research Fund) South Asian Nitrogen Hub supported by the UK Research & Innovation (UKRI).

Cover photo Sunset over the lotus section of Shinobazu Pond, Ueno Park, Taito City, Tokyo, Japan by DLKR on Unsplash

Acknowledgements We gratefully acknowledge the work of the authors and the support provided by the reviewers Ulli Dragosits and Filip Moldan. Meetings, preparation and publication of the Guidance Document were kindly supported by contributions from the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP) project "Towards the International Nitrogen Management System" (INMS) which is executed by the UK Centre for Ecology & Hydrology. Visit www.inms.international for more details. We also gratefully acknowledge the editorial and design expertise provided by Shel Evergreen. This document forms a contribution to the work of GPNM, INI, the UNECE TFRN and other international processes in implementing UNEA Resolution 4/14 and 5/2.

INMS Guidance Document on National Nitrogen Budgets

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Foreword

One of the grand challenges of the International Nitrogen Management System (INMS) is to bring different parts of the nitrogen cycle together. Much work has been done in different countries and globally on specific aspects of nitrogen flows and impacts. This has been reflected in a past fragmentation between scientific communities and policies relevant for nitrogen. In this way, there are plenty of publications and policies concerning nitrogen and air pollution (such as from nitrogen oxides and ammonia), or nitrogen and water pollution (especially for nitrate pollution, but also relevant for organic nitrogen). Other publications and policies tend to deal with greenhouse gas emissions including nitrous oxide, and still others address impacts on human health and ecosystems.

This kind of fragmentation has often led to pollution mitigation being seen as a cost to stakeholders, which has encouraged some stakeholders to resist action, especially if accompanied by proposals for regulations. By contrast, we increasingly see reactive nitrogen as a valuable resource, which means that reducing wasteful losses to the environment can rather contribute to improving economic performance. According to the *Our Nutrient World* report, around 200 million tonnes of reactive nitrogen compounds is lost to the environment every year, including by emissions of reactive nitrogen and by denitrification to atmospheric di-nitrogen. If we multiply this global waste of nitrogen resources ('nitrogen waste') by a nitrogen price of 1.5 to 3 USD per kg N (representative for 2022-2023 and relatively high due to effects of the Russian invasion on the global N fertilizer market), we get a global nitrogen waste worth 300-600 billion USD annually.

The numbers point to the strong case for action to manage nitrogen better with higher efficiency and less wasted resources across all sectors of the economy. In fact, the case for action is even stronger, given the social costs of nitrogen pollution, as air and water pollution and climate change contribute to shortening human lives and damaging ecosystems and which costs tend to be even higher than that of nitrogen waste. The implication is that society needs to link these issues up.

This is where National Nitrogen Budgets can help, since these bring together all nitrogen flows, and can help inform countries on the most important opportunities where they can reduce wasted nitrogen resources. The present INMS Guidance Document is therefore an important step to helping countries develop such budgets. It complements the existing UNECE Guidance Document on National Nitrogen Budgets, providing wider guidance and comparison with the CHANS modelling approach. The document is relevant globally and should be seen as an important contribution to supporting the UNEP Working Group on Nitrogen as it looks to follow up the UNEA 4/14 and 5/2 resolutions on Sustainable Nitrogen Management, the Colombo Declaration and the nutrient targets of the Kunming-Montreal Global Biodiversity Framework.

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Preface

Environmental impacts from human activities are caused by a multitude of different compounds released to the atmosphere, water bodies or to the soil. Typically, many of these compounds contain nitrogen, and nitrogen compounds contribute to a great number of such impacts. Attribution of specific impacts to individual compounds remains difficult, as chemical transformation and transport between environmental compartments masks any direct causal relationship. Covering the aggregation of nitrogen compounds, as a nitrogen budget, is a useful way to address environmental impacts related to nitrogen more generally. In this INMS Guidance Document on National Nitrogen Budgets (NNB), we introduce and compile existing information on nitrogen budgets as a comprehensive tool to report and analyse nitrogen flows and stocks at a national level. As a substance flow analysis, the NNB approach considers the physical principle of mass conservation. It relies on the fact that any amount of nitrogen inside a given system remains there, even though it can change its chemical form and move across different pools in that system.

The purpose of this guidance document is to provide relatively simple methods to establish NNBs for a comprehensive coverage of nitrogen in the environment, thereby efficiently considering many environmental issues simultaneously, including co-benefits and trade-offs across different forms, sources and effects of nitrogen and across policy areas. Such low-effort methods are suitable especially for governments, agencies and others who intend to tackle certain aspects within the complexity of the "nitrogen cascade", as the suite of transformations and transport of nitrogen compounds in the environment is often called. For N budgets to be a useful tool for the INMS Demonstration Regions, and other countries and regions more widely, the methods need to be adequate for use across a wide range of environmental, economic or policy conditions. At the same time, it is important to flag limitations in setting of system boundaries and data acquisition, as well as the need for harmonisation of approaches. This will help results to be as useful as possible, including for comparisons / benchmarking and monitoring the trends in the effects of environmental regulations over time. This NNB guidance document strives to cover all those issues.

As the authors of this document, we are keen to see NNBs widely used, with users taking advantage of the tools described here. With the instruments provided, we wish to facilitate a joint-up treatment of all nitrogen compounds, whether affecting to human health, ecosystem health, soil health and the global climate (the pollution endpoints), and we expect that such a joint-up approach will also be beneficial for policy processes internationally.

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Executive summary

"National Nitrogen Budgets" have been recognised as simple tools to quantify and validate data on nitrogen flows across all parts of the economy and environment on a country level. About a dozen countries globally have established such budgets at the time of writing of this INMS Guidance Document. The document lays out the theoretical concepts and foundations of nitrogen budgets based on mass conservation principles, also pointing out the importance of system boundaries.

Two well-established approaches are presented and discussed in more detail: the CHANS (Coupled Human and Natural Systems) model originally developed in China and the EPNB (UNECE Expert Panel on Nitrogen Budgets) approach, which was designed for operating under the data-rich conditions of the harmonised statistical database of the European Union countries. Both benefit from data collections on environmental topics already in place, which includes quantitative assessments of climate (greenhouse gas inventories for submission to the United Nations Framework Convention on Climate Change: UNFCCC) and air quality (air pollutant emissions as established under the UNECE Convention on Long-Range Transboundary Air Pollution: Air Convention) or water quality (monitoring water contamination under the Nitrates Directive of the European Union). The comprehensive descriptions of the two approaches (together with the references to more detailed material in the annexes or related guidance documents) not only enable identification of the communalities and differences between the approaches, but also provide guidance for selecting the most suitable budgeting method, depending on data availability and the specific interests of a country. In summary, the more rigid and data intensive EPNB approach is considered more appropriate for regulatory use, also because it allows no discrepancy to other national reporting obligations. By contrast, CHANS may be more appropriate for exploratory studies and in situations where robust statistical data may be difficult to obtain.

Some country examples of National Nitrogen Budgets are presented to demonstrate the value, as well as the limitations, of the respective approaches. Nitrogen Budgets are shown to monitor change/trends over time and to distinguish differences between countries and regions for compatible system boundaries and methodologies. Furthermore, budget approaches prove to support validation of nitrogen flow data used in inventories or other routine monitoring systems.

Nitrogen budgets provide valuable input for calculating indicators such as the nitrogen use efficiency (NUE), the recycling rate or pollution levels/loss rates caused by practices operating with nitrogen compounds. Typical challenges relate to the differentiation between denitrification (release as N_2) and accumulation in certain pools, or the valuation of nitrogen in fuels that contribute significantly to a national budget, but upon combustion are again largely released as molecular N_2. Identifying appropriate N content values for the respective materials flowing between pools may often be critical for being able to properly close budgets. Establishing wide-spread use of "National Nitrogen Budgets" will further improve comparability and help increase insights for holistic policy development and develop even more applications.

Chapter 1: Introduction

1.1 The relevance of nitrogen

Nitrogen, a chemical element (N), is the main component of the atmosphere (78%), present almost exclusively in its molecular form, dinitrogen (N_2). Molecular nitrogen is very stable, so to form a chemical bond with another element, it needs particular conditions and considerable amounts of energy. But N is also versatile in its chemical bonding once activated from its molecular form. It can form compounds with many different elements, often multiple compounds with the same set of elements. Chemical transformation between such compounds is typically fast and easy, and depending on the property of a specific compound, N may be transported with the atmosphere or with water bodies. We define such N compounds as "reactive nitrogen" (N_r), which cover all compounds except the unreactive N_2.

Under natural conditions, N_r is a scarce resource, despite of the abundance of N_2. Yet it plays an essential part in the metabolism of life. Among many other compounds, amino acids contain N, which can polymerize into proteins via the peptide bond, effectively binding via the N atom. Proteins are central in all metabolic processes of plants, animals and life in general. Thus, they are also responsible for plant growth. Since the advent of agriculture, material containing N_r has been identified as an effective plant nutrient. Plants grow better and yields are higher when soils are adequately treated with fertilizers. While originally organic fertilizers were used (animal manure, plant material such as crop residues, or human excreta) or biological processes able to fix nitrogen from the air (legumes in symbiosis with bacteria facilitate Biological Nitrogen Fixation, BNF), in the early 20th century industrial-level fixation was invented. The Haber-Bosch process yields ammonia, a compound rich in N, to allow for processing into further compounds used as mineral fertilizers. This allows fertilization with N_r in ample quantities (Smil, 2001; Erisman et al., 2008). Together with other human interference, most notably the formation of nitrogen oxides during combustion of fossil fuels, the global nitrogen cycle has doubled since pre-industrial times (Fowler et al., 2013).

The beneficial aspects of N_r availability to biological activity of nitrogen compounds, however, also have side-effects. When present in abundance, ecological systems will likewise absorb it, but response may be different. Some compounds may be harmful (e.g., nitrogen oxides, ammonia or particulate matter in air, nitrate in water), while others can affect the soil quality by acidification or excess nutrient availability (eutrophication). Plant species that manage to thrive under conditions of low nitrogen availability are outcompeted, reducing biodiversity. Reactive N may also convert to nitrous oxide, a greenhouse gas. Water and air pollution, greenhouse gases, ecosystem effects and soil health are subsumed in the WAGES acronym developed under the European Nitrogen Assessment (Sutton et al., 2011) and are all effects of too much nitrogen (see also Tomich et al., 2016; Abrol et al., 2017).

1.2 Developing N budgets for N management

The term "nitrogen cascade" refers to the ability of N_r to contribute to varied environmental issues through transformation. Just one N_r molecule can undergo transformations and exchange between environmental media (air, water, soil), and then contribute to various environmental problems (Galloway et al., 2003, 2004, 2008). This notion covers the difficulty of specifically and individually tackling any of the individual environmental issues that are triggered by excess nitrogen. But this also provides an opportunity to address multiple issues at the same time and to take advantage of co-benefits when one measure, reducing nitrogen pollution, proves beneficial for several environmental parameters simultaneously (Sutton et al., 2019).

Nitrogen budgets stem from this concept. They imitate the nitrogen cascade as a model approach. A full economic and environmental system of a country (for a national budget) is split into homogeneous compartments (pools). Flows of N_r in and out of the compartment, as well as stock changes in this compartment, are being recorded. For each compartment, N_r flows into the pool and flows out of the pool need to balance for reasons of mass consistency. Any remaining imbalance leads to stock changes. Given all these elements are quantified, available data can be validated (for each individual compartment and for the total system). In case one of the elements is missing, it can be deduced as the difference from other available data.

Using N_r instead of nitrogen deviates from a complete elemental flow analysis (Brunner and Rechberger, 2003). Reactive N is not fully mass conservative, as it can also be fixed from atmospheric N_2 in certain situations (biological fixation, industrial production or combustion), and it may be converted back to N_2 (e.g., in a microbial process called denitrification). These processes can be described as sources and sinks, respectively, of N_r and need specific consideration. While this needs extra attention, separating N_r from molecular N_2 is essential for the approach, as N_2 is available in orders of magnitude higher quantity and that species would by far dominate any budget consideration. Hence, molecular N_2 is treated as fully outside of the system boundaries.

1.3 Spatial resolution and arguments for a national approach

To create and implement nitrogen budgets, it is essential to identify adequate spatial and temporal boundaries and to choose compartments for which data would be compiled. Such a selection ideally attempts to optimize on the available data, to minimize on known errors, and it extends on the achievable impact of the resulting budgets.

Lateral transport is one critical element that is typically difficult to adequately capture. Using a global approach (the whole world as one simple "box") allows to fully avoid dealing with transport. The "planetary boundaries" (Rockström et al., 2009, Steffen et al., 2015) do just that: threshold values for total anthropogenic nitrogen fluxes are presented (in combination with other thresholds) as a global total.

Breaking down such targets to specific pollution aspects (de Vries et al., 2013) creates its own challenges as then lateral transport will again become relevant.

Similarly, spatial system boundaries can be chosen to minimize any transport effects just by considering large areas. For example, continental nitrogen budgets have been established for Europe Asia and in a comparable manner for the whole of the United States (van Egmond et al., 2002; Zheng et al., 2002; Howarth et al., 2002). Both transport in environmental media and due to trade, while relevant (Lassaletta et al., 2014a), remain relatively small when summarised across large areas. In a related way, transport may be ignored when the transporting medium is part of the system. Specifically, this is possible with runoff in rivers and overall nutrients collected for the whole of a catchment (e.g., Rabalais et al., 1996). In this way, flows crossing the system boundaries can be minimised to a single exit point, the river's estuary.

For many applications, further improving the spatial resolution of a nitrogen budget may be essential. That will require a change in strategy, as nitrogen flows across system boundaries (lateral transport) cannot be ignored any longer. Nitrogen budgets will also have to consider imports and exports (for each of the compartments or as a common import/export pool), in addition to the overall flow balance, the stock change, and the sources and sinks that had already been discussed.

The national level is a particularly relevant unit for any environmental analysis. While most countries are too small to allow ignoring import and export (and hence extra effort is needed), a considerable advantage is the widespread availability of data. As part of the data infrastructure provided to policy makers, citizens, planners and businesses, countries collect and make accessible a wealth of information. This includes statistics on economically relevant activities and environmental monitoring of nitrogen compounds, such as agricultural livestock and crop data or emission inventories. Employing such data sources to quantify flows of reactive nitrogen in and out of each defined compartment (budget approach) allows for the recreation of flows that cannot be established directly. Moreover, employing a national scale allows to provide direct input to environmental policies and decision making, which often are particularly strong and hence effective on a national level. In the following sections, we describe successful applications and provide guidance on how national nitrogen budgets can be established.

1.4 Previous examples of national N budgets

While specific national data is a crucial asset for national nitrogen budgets, compiling the data and developing a consistent methodology is a tedious job. Hence, it is not surprising that early attempts to develop national nitrogen budgets started based on limited datasets. The homogeneous data environment made available in the European Union via its central statistical office, EUROSTAT, allowed for the development of sets of nitrogen budgets on a comparable level for all of Europe (Leip et al. 2011). However, further country-specific data was not employed in this exercise — data that would be helpful to address national practices of agriculture and animal husbandry, waste and wastewater processing, or more specifically, the fate of industrial N_r compounds.

In order to benefit from further datasets that may be available at national scale, national projects on N budget were started independently from within individual countries (Table 1). Several of these reports have been developed in the framework of the UNECE Expert Panel on Nitrogen Budgets (EPNB) or have been using the CHANS (Coupled Human and Nature Systems) model. These two approaches will be further represented in the guidance provided in this document.

Table 1.1. Available national nitrogen budgets. The list attempts to be exhaustive in terms of countries, informing about the respective latest dataset.

Country described	Source	Comment
European Union	Leip et al. (2011)	Based on Eurostat statistics, international data have been used to create national N budgets (for the total of the European Union as well as selected countries plus Switzerland)
Switzerland	Reutimann et al. (2022)	The latest of several national reports produced for the Swiss BAFU and BAL is available at the web site of the contractor INFRAS, Zurich, Switzerland. It is informed by the EPNB approach but includes deviations.
Germany	Bach et al. (2020) Häußermann et al. (2021)	While a series of national reports has been published, the latest one has been developed closely reflecting the European EPNB approach
Canada	Clair et al. (2014)	In part using the approach developed for Europe, N flows in Canada have been compiled to a national budget
Denmark	Hutchings et al. (2014)	Contributing to the work of the EPNB, a Danish N budget was established
U.S.A.	Sabo et al. (2019)	Not only the national total, but also regional differences were developed in a national N budget for the U.S.A.
New Zealand	Parfitt et al. (2012).	Different scales and timelines have been established in a largely independent approach
Estonia and Latvia	Iital et al. (2023)	As part of an Interreg-project, national nitrogen budgets have been quantified for both countries
China	Gu et al. (2015)	An available national N budget derived from the application of the CHANS model
Japan	Hayashi et al. (2021)	A national N budget derived using the concept of the CHANS model with modifications considering key features of nitrogen flows in Japan

Country described	Source	Comment
Scotland	Scottish Government (2021)	The Scottish nitrogen budget (considered an own country under UK terms) uses EPNB guidance. The resulting output is called the Scottish Nitrogen Balance Sheet
Sweden	Stadmark et al. (2019) For updates use search term "nitrogen budget" at IVL's publication page (see reference)	Based on the EPNB approach, Sweden provides sectoral reports to eventually cover all sectors.
Austria	Djukic et al. (2024)	Implementing guidance provided by EPNB, this report covers its application to Austria.

Chapter 2: Estimating nitrogen budgets for a nation

2.1 What we need to estimate

The following three elements need to be defined for estimating a nitrogen budget for a nation (Figure 2.1).

- Boundaries: Two types of boundaries are needed, one is the spatial boundary (e.g., a nation) and the other is the system boundary of target activities (e.g., crop production, animal production, industry, etc.) within an entity, i.e. the national boundary in this case (Zhang et al, 2020).
- Pools: An economic or environmental sector considered as a subsystem within the system boundary (Figure 2.1). A pool may have sub-pools as necessary.
- Nitrogen flows: A mass flow of nitrogen connecting two pool(s) and/or sub-pool(s). Flows can be nitrogen chemical species (e.g., ammonia (NH_3) emission from land to the atmosphere) and commodities containing nitrogen (e.g., food supply to humans).

The nitrogen balance of a pool is calculated as the difference between total inflow to the pool and total outflow from the pool. Imports and exports constitute special flows across the system boundaries. In addition, sources (places of N fixation) and sinks (places of N_r release in form of molecular N_2) and stock changes in any of the pools need to be considered. A national nitrogen budget (NNB) consists of all these elements within a nation.

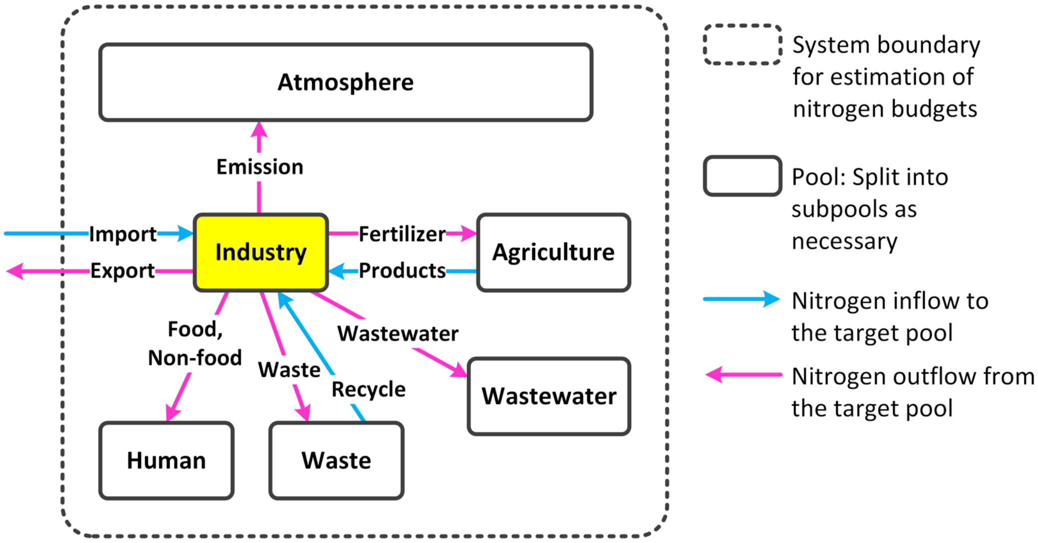

Figure 2.1. Conceptual example of boundary, pools, and nitrogen flows. The example displays all flows connected to the industry pool (referred to as "target pool"). Original graphic produced for this document © UKCEH 2025.

Table 2.1. Example of pools for national nitrogen budget estimation.

Pool (example)	
Economic sectors	Energy and fuels
	Industry
	Agriculture (Crop production/Livestock production)
	Fisheries
	Forestry
	Human settlements
	Processing of residues, Waste (Solid waste/Wastewater)
Environmental sectors	Atmosphere
	Forest and semi-natural vegetation
	Surface water/groundwater
	Coastal zone (if included)

2.2 Selection of candidate approach

In the following sections, this guidance document covers three different candidate approaches to quantify NNBs. The approaches differ by the amount and the comparability of input data required, by the rigor of guidance, and by the effort required to obtain adequate results.

Figure 2.2 provides quick and transparent guidance to support selecting any of these approaches as soon as a decision is taken to develop an NNB. Briefly, the first decision depends on whether information on nitrogen fluxes will be required at high detail. If this is not the case, the generic modelling approach will suffice (Chapter 5, this volume). Users who wish to learn in detail about nitrogen flows between sectors need to choose a more specific approach. If, for any given country, it will be good enough to understand the internal situation of that country, the CHANS approach may be appropriate (Chapter 4, this volume). In case users also wish to compare or benchmark with other countries, it may be best to strive for using the more rigid EPNB approach (Chapter 3, this volume).

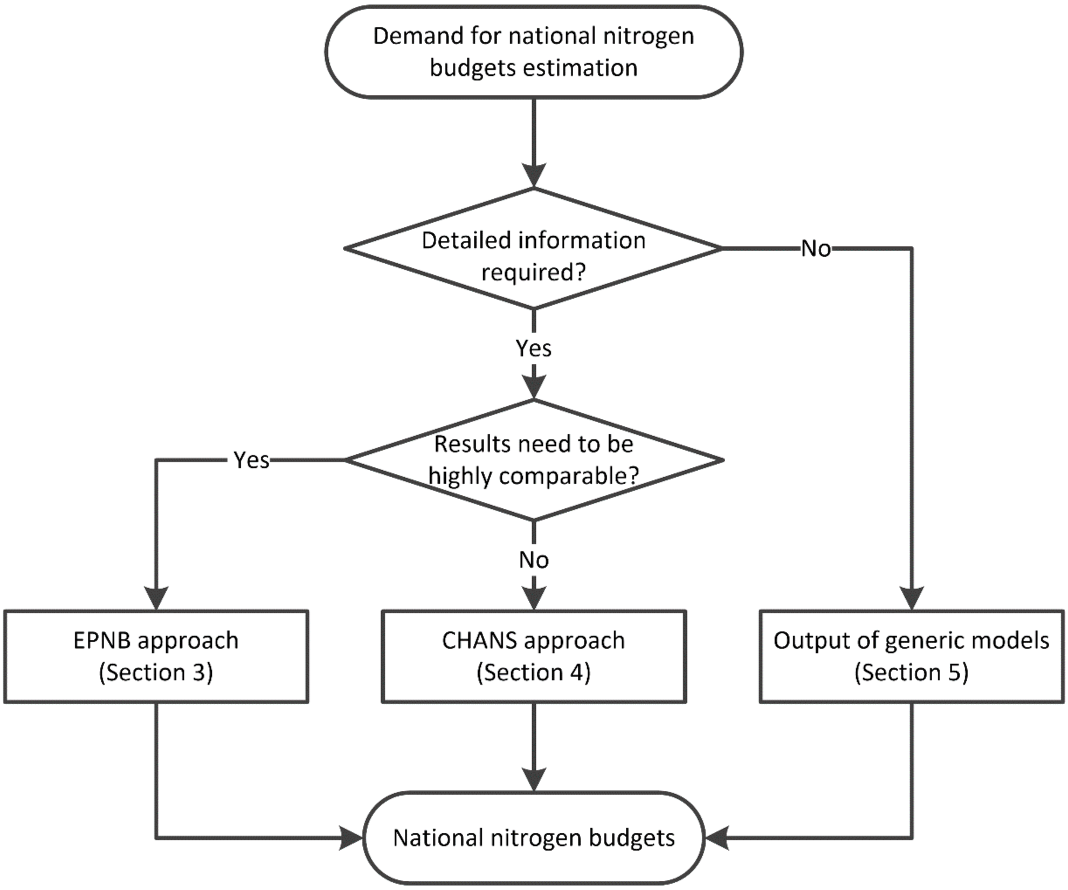

Figure 2.2. Flow chart to select an approach to estimate national nitrogen budgets. Original graphic produced for this document © UKCEH 2025.

Chapter 3: Expert Panel on Nitrogen Budgets (EPNB)

3.1 General overview on the UNECE guidance document

The initial purpose of the work of the Expert Panel on Nitrogen Budget (EPNB) is to support country experts in their efforts to limit atmospheric emissions, primarily of NO_x and NH_3. The EPNB is a part of the Task Force on Reactive Nitrogen (TFRN), which operates under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP, i.e., the 'Air Convention') and specifically addresses the needs of the revised Gothenburg Protocol. The protocol, a piece of international legislation ratified by the European Union and many individual European countries plus the U.S.A. and Canada, aims to improve air quality for citizens concerned by limiting the emissions of a range of classical air pollutants. National emission ceilings have been defined (for European countries only), and national N budgets are seen as a tool to address the underlying causes of substance release to the atmosphere. Hence, the atmosphere is the primary target of the effort, and national inventory agencies, which typically address both air pollutants and greenhouse gas emissions, are the main addressees of the guidance provided. However, national N budgets also have a wider, holistic remit, including all environmental compartments (such as the hydrosphere, soils, vegetation) and the economy.

The UNECE guidance document (UNECE GD) on national nitrogen budgets was officially adopted in 2013 and is available in all UNECE languages (English, French and Russian; UNECE, 2013). The UNECE GD concisely defines the purpose and the structure of the nitrogen budgets to be developed. In consideration of the targeted users, the concept takes advantage of existing compilations these users, mainly national inventory agencies, are providing anyway. Such compilations include the greenhouse gas emission inventories for submissions to the UNFCCC, typically in the Common Reporting Format (CRF). Under the air convention, parties also are obliged to provide air pollutant emission inventories. These two sets of inventories have been harmonised for a decade already, and guidance for both is available and regularly updated (IPCC, 2019; EEA, 2019). Hence, the EPNB approach directly builds on environmental pools related to the sectors used for Greenhouse Gas (GHG) inventories. The private sector (often missing in economic statistics), and water as well as atmosphere as major environmental media were added to cover the full scope of environmental N flows.

The detailed description of the individual pools and their division into sub-pools, the recommended data sources and sets of default parameters to be used are not part of the high-level UNECE GD itself but have been shifted to "Annexes" which can be updated according to the experts' best knowledge (upon endorsement of the Task Force on Reactive Nitrogen). Annexes have been created for each individual pool and are available at the EPNB's web site (www.clrtap-tfrn.org/epnb). A current (2025) update providing major consistency improvements also uses a slightly revised nomenclature in the pool structure. Figure 3.1 uses this new nomenclature already, referring to "5. Processing of residues" as the only change on that level. In contrast, Appendix 1 of this document describes the currently valid version according to UNECE (2013).

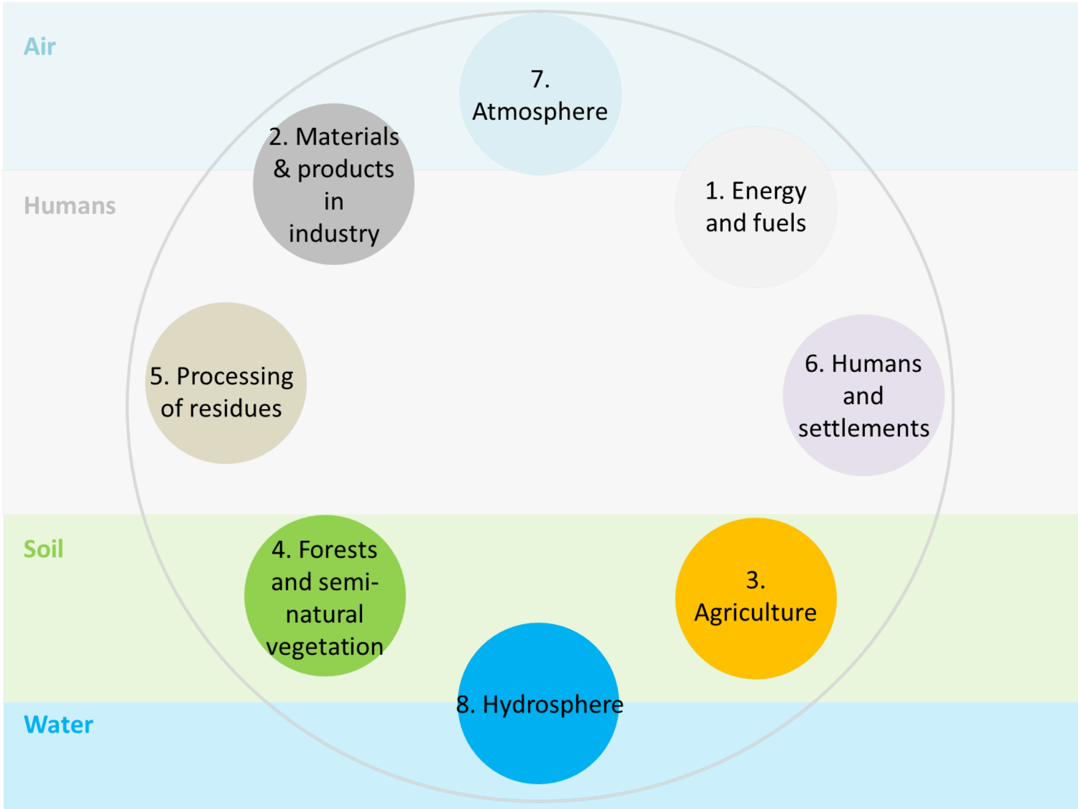

Figure 3.1. Visualisation of the EPNB pool concept of the UNECE Expert Panel on Nitrogen Budgets. Individual pools refer to economic sectors as described in IPCC 2019, expanded by the environmental sectors. Nomenclature used refers to the anticipated changes of an update to be introduced by the end of 2025, slightly deviating from the detailed description provided in Appendix 1. © EPNB, Creative Commons (CC BY-SA 4.0).

In addition to the individual Annexes for each pool, an "Annex 0" provides an overview and guidance on the use of the whole set, focusing on definitions and principles valid for all pools. This includes guidance on how the system boundaries are organized, using the territorial principle, i.e. where flows occur, rather than considering the citizenship of persons responsible for a flow. Flows to be quantified are those of reactive nitrogen compounds, basically all forms of N, including conversion to and from molecular N_2 (e.g., through N fixation or denitrification). The overall budget, available for each pool, sub-pool, and, if applicable, also the sub-sub-pool, adheres to Equation (3.1), where import and export across the territorial boundaries are included as inflow or outflow:

$$\sum N_{inflow} + \sum N_{source} = \sum N_{outflow} + \sum N_{sink} + \sum N_{stockchange} \qquad (3.1)$$

Hence, flows are balanced separately for each pool. As necessarily there needs to be an inflow (into a pool) matched by an outflow (from a different pool), the Equation (3.1) allows to over-determine the overall system, enabling checks of the validity and plausibility of results.

Each flow is described in a specific nomenclature, defining its pool of origin and destination. Also "sources" and "sinks" can be defined, which are mostly fixation of atmospheric N_2, or denitrification which converts reactive N (N_r) to di-nitrogen (N_2) or vice versa. Flows are characterised by size – if smaller than 100 g N capita^{-1} yr^{-1}, a flow can be merged with other (similar) flows without loss of too much detail.

Information on nitrogen forms (e.g., oxidized vs. reduced forms), matrices (e.g., N contained in food) or transport media (e.g., N in river water) is considered important. Certain N forms are considered "inactive". This is, for example, the case for N contained in mineral oils, which should be balanced but not considered environmentally relevant. Even in combustion processes, the major part will be converted to N_2, and the part released as NO_x is typically best captured by emission factors that are available.

3.2 Tiered scheme and recommendations

For each of the flows contained in the EPNB approach, two different schemes are provided for quantification. A simpler "Tier 1" scheme uses simplified default data and international factors, while the more complex "Tier 2" takes advantage of more detailed national information where available. To apply the EPNB approach to a country outside Europe, it is important that the applicability of the default EPNB pool concept (Figure 3.1) to the country is reviewed, i.e., whether there are any pools or sub-pools not represented in the default concept. If such a pool exists, the NNB compilers need to identify and estimate the nitrogen flows connected with such pools independently. Next, applicability of the Tier 1 scheme of the EPNB approach needs to be examined, where the statistical data available in the target country need to be reviewed as to whether they are fit for purpose. If this is the case, the parameters of the EPNB approach may be used directly. Otherwise, the parameters should be replaced with those reflecting the situation of the target country, via the Tier 2 scheme.

Chapter 4: The Coupled Human and Natural Systems (CHANS) model

4.1 Overview on the Coupled Human and Natural Systems (CHANS) model

The Coupled Human and Natural Systems (CHANS) model framework was originally developed and implemented for China (Gu et al., 2015). This general overview focuses on a Chinese application, specificities of its use in other countries are considered in the next section (Section 4.2, this volume). The structure of the model is shown in Figure 4.1. In the horizontal direction, it covers the whole territory of a country. Within these horizontal boundaries, cropland, grassland, forest, urban, surface water and other subsystems are included. In the vertical direction, the upper boundary is defined as ~1 km above the ground. For the lower boundary, everything above the bedrock is considered part of the system, including soils and groundwater, but mineral resources are not included because they can contribute to N cycling only after mining and burning (comparable to the "inactive" N in the EPNB approach). Nitrogen cycling starts from the entry of reactive N (N_r) that is activated from N_2 into the system or from direct N_r input to the system from outside of the target boundary (import). Nitrogen cycling terminates when N_r is transformed to N_2 or lost to outside the system (export).

A nitrogen mass balance is used to calculate and quantify N inputs and outputs, and then to determine if the system is an N source (input < output) or N sink (output < input). The N balance calculations of the whole system and for each subsystem follow the basic principle of Equation (4.1):

$$\sum_{h=1}^{m} \mathrm{IN_h} = \sum_{g=1}^{n} \mathrm{OUT_g} + \sum_{k=1}^{p} \mathrm{Acc_k} \qquad (4.1)$$

where $\mathrm{IN_h}$ and $\mathrm{OUT_g}$ represent N inputs and outputs, respectively, and $\mathrm{Acc_k}$ represents the different N accumulation terms. N input to the whole system includes Haber-Bosch N fixation (HBNF), biological N fixation (BNF), fossil fuel combustion, and imports of N-containing products (for China, mostly animal feed). Most N input cycles into different subsystems, for example NO_x emission from fossil fuel combustion further deposits onto three major landscapes, natural land (i.e., forest, grassland), water bodies and cropland. N output from the whole of China mainly includes riverine N transport to coastal waters, atmospheric circulation that transports N_r away from China, denitrification, and exports of N-containing products. N accumulation is calculated as the difference of inputs and outputs.

See Appendix 2 of this volume for details of each subsystem of the CHANS model.

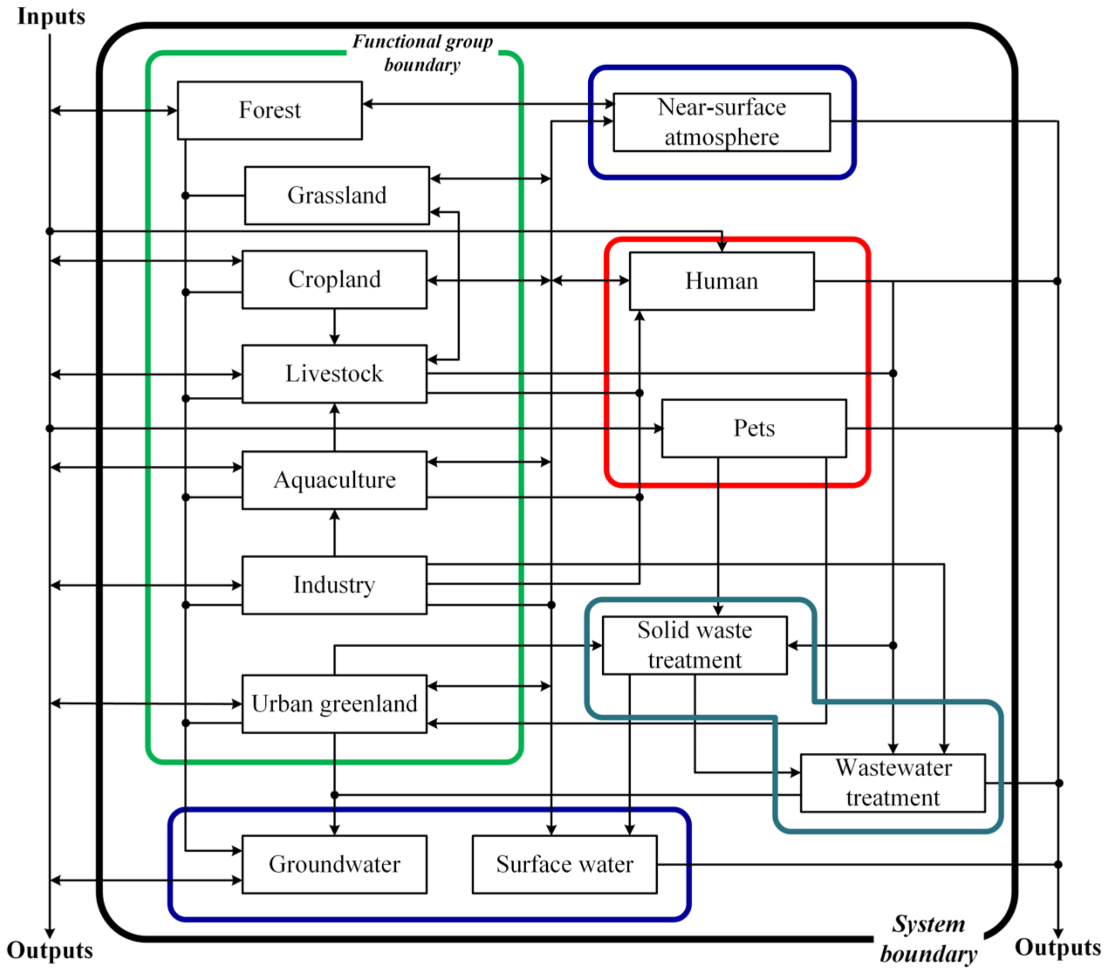

Figure 4.1. The Coupled Human And Natural Systems (CHANS) model structure. Arrows represent N fluxes; solid rectangular boxes in black represent systems and subsystems; solid rectangular boxes in colours represent boundaries of functional groups, with green lines representing the processor, red the consumer, cyan the remover, and blue the life-supporter. Within the boundary, the system is divided into 14 subsystems: cropland, grassland, forest, livestock, aquaculture, industry, humans, pets, urban green land, wastewater treatment, solid waste treatment, atmosphere, surface wate and groundwater. Source: Gu et al., 2015 © Baojing Gu, Creative Commons (CC BY-SA 4.0).

4.2 Guidance to use the CHANS model to other countries

While originally developed for China, the comprehensive scheme of the CHANS model can be applied to other countries with necessary considerations and modifications. There are three levels of detail, described as Tier 1, Tier 2 and Tier 3 approaches.

The Tier 1 approach uses the original CHANS model without changing the model scheme and parameters. It can be used when the original CHANS model covers the key nitrogen flow structure of the target country. Certain activity data are required for the target country, and international and national statistics can be used as data sources to obtain the activity data necessary.

The **Tier 2** approach is similar to Tier 1, but the parameters of the default CHANS model (Table 4.1) are modified to better reflect the processes in the target country (e.g., emission factors, treatment efficiency, and per capita food consumption), where adequate information is available.

The **Tier 3** approach is more challenging, but it should be considered for implementation if the key nitrogen flow structure of the target country is different from that of the original CHANS model (Figure 4.1). Here, it may be necessary to redefine nitrogen flows, sub-pools, and/or pools, together with developing methods to calculate each of the redefined nitrogen flows. This needs to be supported with the relevant activity data and parameters necessary for the calculations. If data are not available for some aspects, the parameters of the original CHANS model can be applied. To apply the Tier 3 approach, clear understanding is necessary of which economic sectors have large N flows in the target country. The following possible pools need specific attention:

- Energy consumption: Fossil fuels (coal and oil) and fuelwood
- Industrial nitrogen fixation: Haber-Bosch process
- Agriculture: Crop production, livestock production, taking into account relevant practices
- Fisheries: Aquaculture and wild-caught fisheries
- Forestry: Production of timber, fuel wood, pulp and other minor forestry products
- Industry: Chemicals other than fertilizer, manufacturing
- Waste management: Municipal waste, industrial waste, treatment styles
- International trade: Crops, animals, fish, forestry and industrial products
- Stock changes caused by specific activities. Especially, N surplus or N removal (as in soil mining) may occur in specific activities affecting soil, forest and aquatic resources.

Table 4.1. Key activity data (D) and parameters (P) used in the original CHANS model.

D/P	Description	Unit
Pool: Cropland		
D1	Fertilizer applied	Tg N yr^{-1}
D2	Crop yield	Tg yr^{-1}
D3	Irrigation	10^9 m^3 yr^{-1}
P1	Symbiotic N fixation rate	kg N ha^{-1} yr^{-1}
P2	Non-symbiotic N fixation rate	kg N ha^{-1} yr^{-1}
P3	Livestock excretion recycled ratio	%
P4	Human excretion recycled ratio	%
P5	N deposition	kg N ha^{-1} yr^{-1}
P5	N concentration of irrigation	mg N L^{-1}
P6	Grain N content	%
P7	Straw N content	%
P8	Harvest index	–
P9	Fate of straw	%
P10	N loss ratio	%
Pool: Grassland		
P11	Fertilization rate on artificial grassland	kg N ha^{-1} yr^{-1}
P12	Non-symbiotic N fixation rate	kg N ha^{-1} yr^{-1}
P13	Grass N content	%
P14	Volatilization rate of manure input	%
P15	Burning rate of dry manure	%
P16	N leaching rate of N input	%
P17	Denitrification rate of N input	%
P18	N_2O emission rate of N input	%
Pool: Forest		
P19	Wood N content	%
P20	Symbiotic N fixation rate	kg N ha^{-1} yr^{-1}
P21	Non-symbiotic N fixation rate	kg N ha^{-1} yr^{-1}
P22	Denitrification rate	kg N ha^{-1} yr^{-1}

D/P	Description	Unit
P23	Runoff rate	kg N ha^{-1} yr^{-1}
P24	N_2O emission rate	kg N ha^{-1} yr^{-1}
Pool: Livestock		
D4	Livestock production	Tg yr^{-1}
P25	N content of livestock products	%
P26	N excreta rate for animal	kg N $capita^{-1}$ yr^{-1}
P27	NH_3 emission factor for animal	kg N $capita^{-1}$ yr^{-1}
P28	N_r leaching rate of excreta	%
P29	N_r runoff rate of excreta	%
Pool: Aquaculture		
D5	Aquaculture production	Tg yr^{-1}
P30	Ratio of feed to products	kg N (kg $N)^{-1}$
P31	Ratio of fertilizer to feed	%
P32	N content of aquaculture products	%
P33	Volatilization rate	%
P34	Runoff rate	%
P35	Denitrification rate	%
P36	N_2O emission rate	%
Pool: Industry		
D6	Haber-Bosch N fixation	Tg N yr^{-1}
D7	Industrial products	Tg yr^{-1}
D8	Fossil fuel consumption	Tg yr^{-1}
D9	Wastewater discharge	Gg N yr^{-1}
P37	Industrial product N content	%
P38	N_r leaching rate of wastewater	%
P39	NO_x emission factors	g N kg^{-1}
Pool: Urban green-land		
P40	Fertilization rate to urban lawn	kg N ha^{-1} yr^{-1}
P41	Ratio of pet excreta back to lawn	%
P42	Biological N fixation	kg N ha^{-1} yr^{-1}

D/P	Description	Unit
P43	N loss ratio	%
Pool: Human		
D10	Population	billion
D11	Urbanization	%
P44	Food consumption	kg N $capita^{-1}$ yr^{-1}
P45	Excretion discharge	kg N $capita^{-1}$ yr^{-1}
P46	NH_3 emission factor	kg N $capita^{-1}$ yr^{-1}
P47	Excretion leaching ratio	%
P48	Fate of human excretion	%
P49	Food waste ratio	%
Pool: Pet		
P50	Food consumption	kg N $capita^{-1}$ yr^{-1}
P51	Ratio of excretion to lawn	%
P52	Ratio of excretion to landfill	%
Pool: Wastewater treatment		
P53	Wastewater leaching ratio	%
P54	Wastewater denitrification ratio	%
P55	N_2O emission ratio	%
Pool: Surface water		
P56	Denitrification ratio of N input	%
P57	N_2O emission ratio	%

Chapter 5: Generic nitrogen budget estimation at national scale

5.1 Overview of general nitrogen budget estimation

While meticulous accounting of N budgets across multiple systems is important to acquire a comprehensive view of N management gaps across sectors, it requires intensive data collection and validation. This may not be feasible in many countries, particularly in the least developed ones. Therefore, it becomes imperative to establish methods and databases that provide initial assessment of key N budget terms for major N management systems for countries worldwide.

Several global models or databases have been developed to grasp the fate of N in and the release of N from an anthropogenic system. Most focus on agricultural systems, which accounts for more about 90% of reactive N inputs to anthropogenic systems (Zhang et al., 2020). That also means that non-agricultural systems (combustion, industry, wastewater) often remain unaccounted for with this approach. Table 5.1 provides a summary of available datasets and analysis of global and national N budgets for agricultural production (Zhang et al., 2021).

Table 5.1. Spatial and temporal characteristics of available databases for crop production on a global scale.

N management system	**Source**	**Spatial characteristics**		**Temporal characteristics**	
		Coverage	Resolution	Coverage	Resolution
Cropland	Zhang et al. (2015)	Global	Country	1961–2015	Annual
Cropland	Lu and Tian (2017)	Global	0.5° × 0.5°	1961–2015	Annual
Cropland	Nishina et al. (2017)	Global	0.5° × 0.5° (country)	1961–2010	Annual
Cropland **Livestock** **Agro-food system**	Lassaletta et al. (2014b; 2016)	Global	Country	1961–2013	Annual
Cropland	Conant et al. (2013)	Global	Country	2000	One year
Cropland	Mueller et al. (2012; 2014)	Global	5 min × 5 min	1965–2010	5-year
Cropland **Livestock** **Agro-food system**	Bodirsky et al. (2012; 2014)	Global	Country	1970–2005	Annual

N management system	Source	Spatial characteristics		Temporal characteristics	
		Coverage	Resolution	Coverage	Resolution
Industry					
Cropland **Livestock** **Agro-food system**	Bouwman et al. (2013)	Global	Country and some sub-country	2000	One year
Cropland **Livestock** **Industry**	GLOBIOM Skalský et al. (2008), Herrero et al. (2013), Valin et al. (2013), Havlík et al. (2014), Chang et al. (2021)	Global	Country	1961–2017	Annual
Cropland **Livestock**	FAOSTAT FAO (2023)	Global	Country	1961–current	Annual

5.2 Methods and performance of global models for nitrogen budget estimation

Among the existing global models or databases, there is a consensus on the key N budget terms to be quantified for crop production systems and the fundamental methodology for their quantification. Table 5.2 summarises the typical methods used to quantify key N budget terms for crop production systems in a national scale, including major N inputs (synthetic fertilizer input, manure input, biological N fixation and N deposition) and productive N output (harvested N).

Moving beyond crop production systems, quantifying the N budget for livestock and wider food systems can be more complex, often hindered by the scarcity of reliable data. For instance, livestock raised on pastures exhibit a very different N use intensity compared to those raised in Concentrated Animal Feeding Operations (CAFOs). Unfortunately, comprehensive data on manure collection, treatment and recycling in these diverse production systems is still lacking in many countries. The Global Livestock Environmental Assessment Model (GLEAM) provides necessary data for accounting N flows and emissions throughout the livestock supply chain (Uwizeye et al., 2020). However, given the dynamic nature of the rapidly expanding livestock sector, extensive efforts are still needed to ensure data and parameters are accurate and up to date. To circumvent data limitation, Li et al. (2022) proposed to define a system boundary for agricultural production systems (referred to as the "Animal-plant-soil system" in the paper) and consider manure recycling as an internal component, thereby negating part of the data requirement. This approach simplified the assessment of N Use Efficiency (NUE) within the agricultural production systems, as it only requires the quantification of several N budget terms beyond those for crop production. The additional N budget terms include N inputs to pasture, imported or recycled by-products as feed, N in non-feed crop and animal products. However, it is worth acknowledging that such simplification may limit our capacity to pinpoint opportunities for improving livestock and manure management.

Among existing N budget estimates, large uncertainties persist, even in extensively researched domains such as national scale crop N budgets. For instance, an intercomparison project for existing crop N budget estimates compared 13 nitrogen budget datasets covering 115 countries and regions over 1961–2015 (Zhang et al., 2021) and revealed large discrepancies among datasets. Taking data for the year 2000 as an example, the range for synthetic fertilizer input was largest in China, varying by 8 Tg N yr^{-1}, corresponding to 36% of the median value of all estimates, 23 Tg N yr^{-1}. The largest range in estimates for manure inputs was seen for India, 5 Tg N yr^{-1}, corresponding to a normalised range of 262% at a median value of 2 Tg N yr^{-1}. Hence, this intercomparison study has allowed for the development of a benchmark nitrogen budget dataset, derived from central tendencies of the original datasets. This dataset can be used in model comparisons and inform sustainable nitrogen management in food systems (Zhang et al., 2021).

In light of the large uncertainties, there is a pressing need for initiatives to enhance both the availability and quality of N budget data. Building on the first intercomparison project on N budget databases (Zhang et al., 2021), a consortium of researchers and stakeholders have embarked on further enhancing nutrient budget quantification for crop systems and beyond. A notable stride in this direction has been the joint release of a national scale crop nutrient budget database in November 2022, facilitated by the United Nations Food and Agriculture Organization (FAO), International Fertilizer Association (IFA), and several academic institutions (FAO, 2022). This database, covering the major crop nutrient budget terms for 1961-2020, will be annually updated henceforth. In the coming years, continuous enhancements will be implemented, and its scope is anticipated to broaden beyond cropland.

Table 5.2. Key parameters for cropland N budget calculation on a national scale (Zhang et al., 2021). See term descriptions below.

Process	Dominating method to quantify the process	Key parameters
N Harvested *N output as harvested crops*	$QN_{harvested,j} = \sum_{cr} QP\_crop_{cr,j} \cdot NC_{cr}$	$QP\_crop_{cr,j}$ NC_{cr}
N Fertilizer *N input as fertilizer*	$QN_{fer,j} = QNfer_j \cdot frac\_Nfer_{crop,j}$	$QNfer_j$ $frac\_Nfer_{crop,j}$
N Manure *N input as manure*	$QN_{man,j} = \sum_{lv} Liv_{lv,j} \cdot Ex_{lv,j} \cdot Collect_{lv,j} \cdot frac\_crop_{lv,j}$	$Liv_{lv,j}$ $Ex_{lv,j}$ $Collect_{lv,j}$ $frac\_crop_{lv,j}$
N Fixation *N input as biological N fixation*	$QN_{fix,j} =$ $\sum_{cr} \begin{cases} NFR_{cr,j} \cdot QP\_crop_{cr,j} \\ N_{fix,cr,j} \cdot A_{cr,j} (when\ NFR_{cr,j}\ is\ not\ available) \end{cases}$ $NFR_{cr,j} = \%\text{Ndfa}_{cr,j} \cdot NC_{cr} \cdot BGN_{cr,j}/NHI_{cr,j}$ or $NFR_{cr,j} = NC_{cr}$	$N_{fix,cr,j}$ $NFR_{cr,j}$
N Deposition *N input as atmospheric deposition*	$QN_{dep,j} = N_{dep,j} \cdot A_j$	$NFR_{cr,j}$ A_j

Term descriptions of Table 5.2

$QN_{harvested,j}$	**Quantity of harvested N for a region j**
$QN_{fer,j}$	Quantity of fertilizer input for a region j
$QN_{man,j}$	Quantity of manure input for a region j
$QN_{fix,j}$	Quantity of biological N fixation for a region j
$QN_{dep,j}$	Quantity of atmospheric deposition for a region j
$QP\_crop_{cr,j}$	Quantity of crop production for crop type cr
NC_{cr}	N content per unit weight for crop type cr
$QNfer_j$	Total N fertilizer consumption
$frac\_Nfer_{crop,j}$	Fraction of N fertilizer used for crop production in region j
$Liv_{lv,j}$	Number of livestock for livestock type lv and region j
$Ex_{lv,j}$	Excretion rate of livestock for livestock type lv and region j
$Collect_{lv,j}$	Collection rate of manure for livestock type lv and region j

$\boldsymbol{frac\_crop_{lv,j}}$	Fraction of collected manure applied to cropland for livestock type lv and region j
$\boldsymbol{A_{cr,j}}$	Land area for crop type cr and region j (e.g., harvested area or cropland area)
$\boldsymbol{NFR_{cr,j}}$	Scaling factor for N fixation rate based on crop yield, estimated as the function of the percentage of N uptake from fixation ($\%\mathrm{Ndfa}_{cr,j}$), below ground biomass ($\mathrm{BGN}_{cr,j}$), and harvested index ($\mathrm{NHI}_{cr,j}$) in some studies, and is equivalent to NC_{cr} in other studies
$\boldsymbol{N_{dep,j}}$	Atmospheric deposition rate for a region j

Chapter 6: Country case studies based on guidance

Advantages and benefits of performing an NNB can be best appreciated based on previous experiences. From among the examples listed in Table 1.1, here we provide descriptions of case studies from countries representing the respective approaches. This is, specifically, Germany (for EPNB), China and Japan (both based on CHANS).

6.1 Germany nitrogen budget using EPNB approach

In Germany, integrated data compilation to display the N cycle and the contribution of different sectors to the reactive N problem have been used to guide policy since the mid-1990s. This facilitated several subsequent projects to quantify N flows. The most important N flows in the German N cycle now have been calculated for four budgeting periods. The most recent German Budget (Bach et al., 2020) and its fluxes representing the average of the 2010-2014 period were calculated following the EPNB-approach for eight pools: atmosphere, energy and fuels, material and products in industry, humans and settlements, agriculture, forest and semi-natural vegetation, waste, and hydrosphere, as well as for the transboundary N-flows. In Germany, in total 6,275 Gg N yr^{-1} were estimated to be introduced into the nitrogen cycle annually. In contrast, only 4,648 Gg N yr^{-1} is removed from the German N-cycle in a managed way.

The most important input flows are ammonia synthesis (Haber-Bosch process, 43 %), domestic extraction, import and processing of nitrogenous fossil fuels such as lignite, coal, crude oil (37 %), net import of food, feed and materials (12 %) and biological N fixation (5 %).

In terms of quantified sinks, combustion of fuels in combination with NO_x abatement devices (catalytic or non-catalytic reduction of NO_x) and refining of crude oil account for 58 % of the removal of N_r. Denitrification in waters, soils, and wastewater treatment contributes to 24% of removal. In both cases, N_2 is formed as the output compound. Finally, 16 % of removals are exported via the atmosphere and hydrosphere to neighbouring countries and into coastal waters.

The difference between introduced and removed N_r amounts to 1,627 Gg N yr^{-1}. This difference can be interpreted in two ways: either the difference corresponds to the surplus in Germany's National N budget, i.e., the amount of reactive N in the environment is increased annually by this amount, or the difference can be attributed to the uncertainties in determining N-flows.

The repeated data compilation over time enables the illustration of key trends and developments of the N cycle, as well as the identification of the most important fields for action. Figure 6.1 shows the condensed results of the four budgeting periods on the overall development of N emissions in Germany and the contributions of four main sectors. Total N emissions declined by roughly 40% from 2,572 Gg N yr^{-1} in 1995 to an average of 1,574 Gg N yr^{-1} in the budgeting period 2010–2014. However, the decline has slowed since the budgeting period 2005–2010. While the share of traffic and wastewater emissions to overall N discharges has clearly been decreasing since 1995, the contribution of agricultural activities has been increasing from about 45% in 1995 to an average of 67% during the budgeting period 2010–2014.

The budgeting data are used to inform the German public about the nitrogen problem and to give advice to policy makers. The results have been published in different reports and web portals in German (e.g., Geupel et al., 2021).

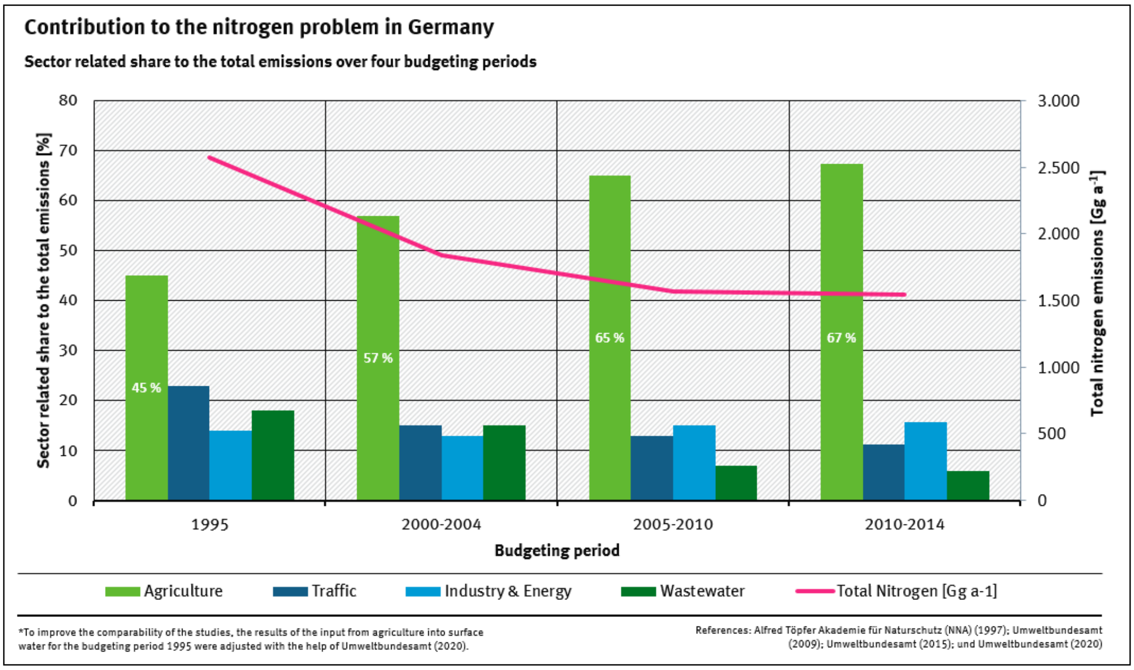

Figure 6.1. The bar chart shows condensed results of four budgeting periods on the overall development of N emissions in Germany and the contribution of four economic sectors. Sources: Bach et al., 2020, Häußermann et al. 2021). © German Environment Agency (Umweltbundesamt), Creative Commons (CC BY-SA 4.0).

6.2 China nitrogen budget using CHANS approach

To feed an increasingly affluent population, China uses about one third of global N_r to produce food. Nevertheless, it still imports over 100 million tons of grain to meet the national food demand. A large amount of the N_r input is lost to the environment during the production and consumption of food at the country scale, resulting in serious environmental pollution in China. At the same time, substantial socioeconomic developments have taken place since the late 1970s. To solve the double challenge of producing more food with less pollution, we applied our N assessment framework to China for the period of 1980 to 2015.

Simulation with CHANS showed that total N_r input to China increased from 25 to 71 Tg N yr^{-1} between 1980 and 2015, of which 74% and 89%, respectively, were derived from anthropogenic sources. After input within the boundary of China, N_r cascaded through the 14 subsystems and produced about 20 Tg N yr^{-1} in food and feed in 2015, while losses to the environment amounted to around 50 Tg N yr^{-1}. Agricultural sources were responsible for approximately 91% of total NH_3 emissions; fossil fuel combustion accounted for 90% of total NO_x emissions; agricultural and natural sources (forest and surface water) together dominated N_2O emissions in China. Agricultural sources and human sewage contributed most of the N_r discharge to surface water, while agricultural sources and landfill leaching were responsible for the bulk of N_r discharges to groundwater (Gu et al., 2015). The modelled N_r fluxes to the environment were validated using data from ground based national monitoring networks of air and water quality and remote sensing data providing column concentrations of NH_3 and NO_2. N fluxes to air (NH_3 and NO_x emissions) were well validated using remote sensing data with a regression (R^2) of more than 0.7, while N fluxes to water showed a less strong regression (R^2 ~0.5). This is due to the complex N cycling processes which occur in water bodies (e.g., denitrification). Increasing the number of monitoring sites for water N concentrations could help to reduce the uncertainty by providing more data for a robust validation of N fluxes to water bodies.

6.3 Japan nitrogen budget using modified CHANS approach

Nitrogen budgets for Japan from 2000 to 2015 were estimated using available statistics, datasets and literature using the CHANS model concept with the Tier 3 approach (see Section 4.3), given the large differences in N flows between Japan and China. The pools and sub-pools used in the estimation of the Japanese N budget are shown in Table 6.1. The concrete method to calculate each of the N flows is shown in the Supplementary Information of Hayashi et al. (2021).

Table 6.1. Pools and sub-pools used in the Japanese nitrogen budgets estimation.

<table>
<tr><th colspan="2">Pools</th><th>Sub-pools</th><th>Characteristics</th></tr>
<tr><td rowspan="15">Economic sectors</td><td rowspan="2">Energy and fuels</td><td>Combustion</td><td>Fuels used for energy conversion</td></tr>
<tr><td>Transportation</td><td>Fuels used for transport machinery</td></tr>
<tr><td rowspan="6">Industry (including international trade)</td><td>Fuels</td><td>Fossil fuels, fuelwood, recycled materials</td></tr>
<tr><td>Artificial fixation</td><td>Haber-Bosch and Frank-Caro processes</td></tr>
<tr><td>N fertilizer</td><td>Chemical and organic fertilizers</td></tr>
<tr><td>Food industry</td><td>All food sources for human</td></tr>
<tr><td>Feed industry</td><td>All feed sources (animals, fish, pet)</td></tr>
<tr><td>Manufacture</td><td>All other non-food goods</td></tr>
<tr><td rowspan="3">Cropland</td><td>Field</td><td>Land received agricultural input</td></tr>
<tr><td>Crops</td><td>All crops (food, feed, non-food use)</td></tr>
<tr><td>Straw and residues</td><td>Removed from cropland to use</td></tr>
<tr><td rowspan="2">Livestock</td><td>Animals</td><td>Mostly cattle, pig and poultry</td></tr>
<tr><td>Manure</td><td>Recycled, treated or loss</td></tr>
<tr><td>Grassland</td><td>Field</td><td>Pasture and meadow</td></tr>
</table>

Pools		Sub-pools	Characteristics
		Forage	Harvested grass for feed industry
	Fisheries	Fish farming area	Inland waters and seawaters
		Fish	Cultivated and wild-caught fish
	Human settlements	Human	Food consumer
		Food	Supplied food
		Non-food products	Supplied goods and manufacture
		Pet	Dogs and cats
	Solid waste	Industrial waste	From all types of industry
		Domestic waste	From human settlements
		Reuse and recycle	As fuel, fertilizer, feed and materials
		Incineration	Burned as intermediate treatment
		Landfill	Direct disposal and final landfill
	Wastewater	Sewage	Industrial and domestic wastewater
		Sludge	Sludge generated in treatment
	Urban green	–	Urban parks and golf links
Environmental sectors	**Atmosphere**	–	
	Forest	–	Natural and semi-natural vegetation
	Terrestrial water	Water body	Surface water and groundwater
		Wetland	
	Coastal zone	Water body	Within 12 nautical miles from the baseline
		Tideland	

In Japan, reactive N lost to the environment has decreased in both atmospheric emissions and losses to terrestrial water (such as rivers, lakes) from 2000 to 2015 (Figure 6.2). The distinct reduction in the atmospheric emissions of nitrogen oxides from transportation, at –4.3% yr^{-1}, was attributed to both emission controls and a decrease in energy consumption. Reductions in runoff and leaching from land as well as the discharge of treated water were also found at –1.0% yr^{-1} for both. The potential N load (N waste) in Japan in 2010 was 5,760 Gg N yr^{-1}, of which 1,960 Gg N yr^{-1} was lost to the environment as N_r (64% to air and 36% to waters), and the remainder assumed as molecular N_2 (Figure 6.3) (Hayashi et al., 2021).

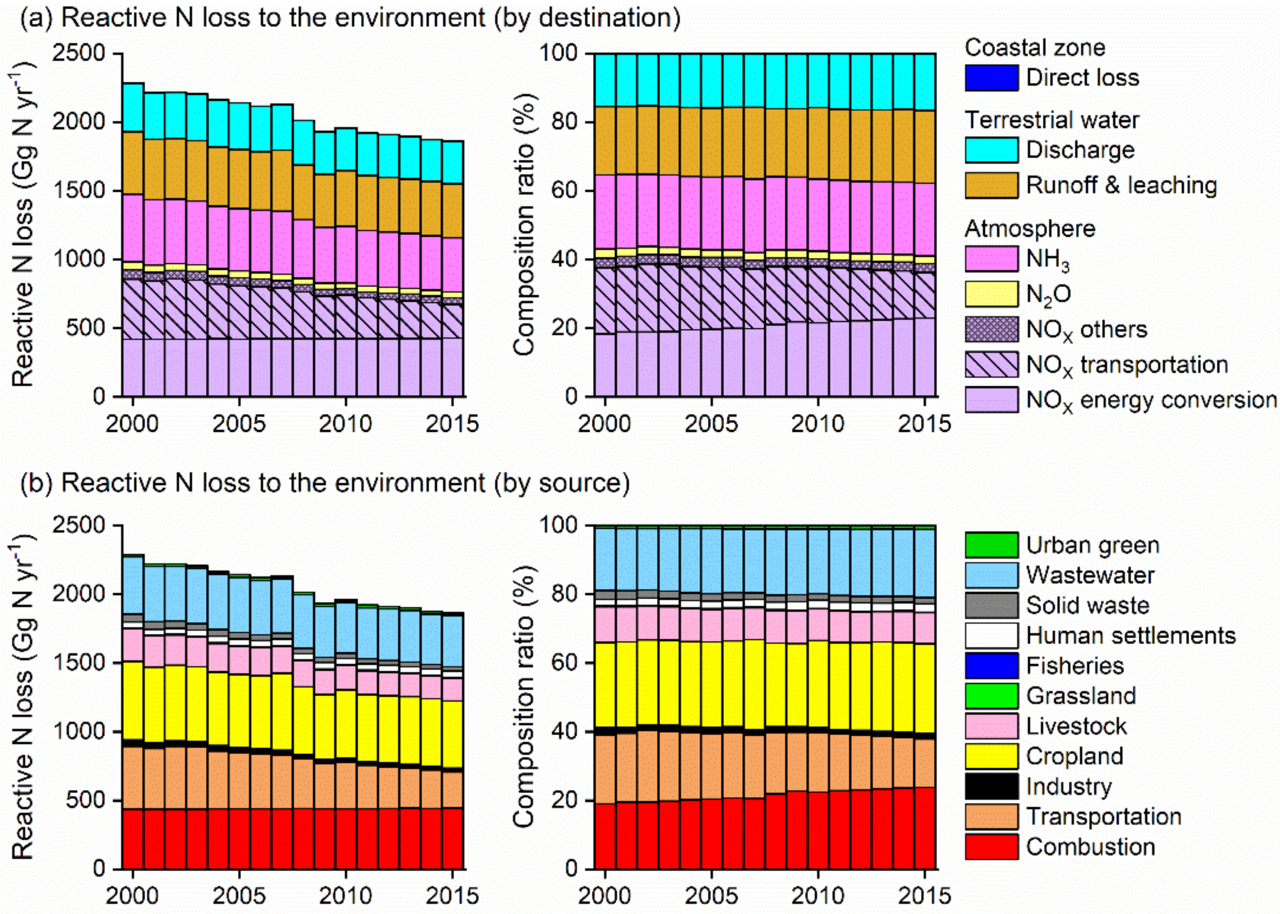

Figure 6.2. Environmental N_r loss in Japan from 2000 to 2015 Source: Hayashi et al., 2021

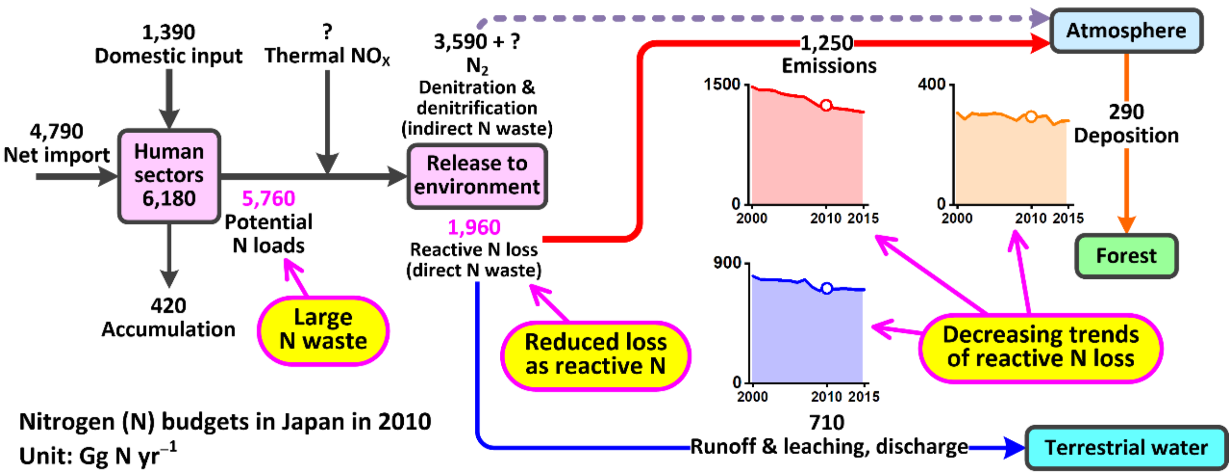

Figure 6.3. N waste and environmental N_r loss in Japan in 2010 Source: Hayashi et al., 2021; © 2021 The Authors (CC-BY 4.0).

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Appendix 1: The EPNB approach for national nitrogen budgets

A1.1 Background

Reactive nitrogen in the environment is responsible for a wide range of different adverse impacts. The versatility of the element to occur in chemical compounds with quite different properties and the ability to convert easily between compounds make it also mobile between environmental compartments (air, water, soils, vegetation). This, in turn, creates the need for integrative treatment of nitrogen-related problems – measures aimed to resolve just one issue related to N inevitably create new problems elsewhere in the N cycle (often referred to as "pollution swapping").

A multitude of data is available on ambient concentrations of N pollutants and N related mass flows in the environment. This is the case also for flows into the environment from human activities, in particular economic activities. Adopting a mass balance approach that includes mainly the "reactive nitrogen" (all nitrogen chemically fixed) allows to separate the environmentally relevant compounds from the by far predominant form, molecular N_2, the main component of the atmosphere. "National nitrogen budgets" (NNBs) have been established to bring together available information on reactive nitrogen across all sectors of the environment and the economy of a country and to provide the information needed to develop holistic instead of sectoral solutions (UN-ECE, 2013).

The "Expert Panel on Nitrogen Budgets" (EPNB) was established in 2008 under the Task Force on Reactive Nitrogen, a body under the air convention. While organised under an air pollution convention, the Task Force (and hence the Expert Panel) strives for holistic approaches, covering all aspects of environmental and economic N flows, not just those to and from the atmosphere.

A1.2 Rationale and Definition of Pools

The EPNB has been working to create the basis for operational nitrogen budgets to be established by national authorities. Guidelines have been developed aiming to allow national experts to create harmonised and comparable representations of nitrogen flows across all relevant pools. Given the framework EPNB operates in, the prime target group of countries is that of the UNECE area – covering the European Union and other Western European countries, but also extending into Eastern Europe, Caucasus and Central Asia (EECCA countries). This requires some flexibility regarding differences in sets of input data that can be derived from national statistics.

The task is somewhat similar to the establishment of national greenhouse gas or air pollutant emission inventories. The latter especially are within the mandate of the Convention on Long Range Transboundary Air Pollution, and they provide a blueprint for the work of EPNB:

- Guidelines established within the Convention enable the production of annual emission inventories by the parties

- Render them comparable between countries to be used for the core purpose of the Convention
- Identify ways to effectively reduce long range transboundary air pollution

At the same time, inventory preparations consider other existing frameworks and make use of efforts that already have been spent elsewhere.

A main motivation and a guiding principle for NNBs under the EPNB guidance is to integrate, as much as available, existing efforts from compiling national information. E.g., above mentioned emission inventories already carry a lot of relevant information, as several air pollutants or greenhouse gases are N_r compounds at the same time. Rich guidance and extensive datasets exist for GHG and air quality emission inventories that can be provided by countries with very different availability in national statistics. Data sources also include fundamental energy and production statistics, which are core elements of any economic planning and policy development, and this data can be applied also to derive flows of N_r compounds.

The "pools" used by EPNB to describe the reservoirs of reactive nitrogen in the anthroposphere reflect the source sectors defined for GHG inventories and also used in air quality emission inventories (IPCC, 2006). The numerical sequence of the pools is aligned with the sector allocation of the reporting guidelines for emission-related activities (Figure 1). Anthropogenic activities hence are described in the pools "Energy and fuels (1)", "Materials and products in industry (2)", "Agriculture (3)", "Forest and semi-natural vegetation (4)" and "Waste (5)". Further pools are needed to cover flows of N compounds outside the directly economically relevant sectors. These flows are mainly contained in the "Humans and Settlements (6)" pool and include the activities of private households, which are often not or only poorly reflected in statistical data. Moreover, there are pools for the environmental compartments of the nitrogen cycle representing air and water, "Atmosphere (7)" and "Hydrosphere (8)". Conceptually, soils (another environmental compartment) are covered in relation to their respective economic use – in the pools Agriculture, Forests and Waste (the latter with regard to landfill activities). In the absence of any relevant transport processes between pools, nitrogen remains in these respective pools, where it may accumulate or undergo conversion.

According to the EPNB guidance, closer consideration of the fate of N within each pool is carried out by introducing specific structures within pools. Such structures may consist of sub-pools within a pool, as well as flows between sub-pools that would not be visible when visualizing at pool-level resolution only. In order to allow consistent representation, these structures within pools are specifically addressed, identified and quantified (see an example in Figure A1.1). Like the pools themselves, this sub-structure is guided by the principle of including as much information as possible from existing datasets such as national emission inventories, hence also mimicking the sub-structures from emission inventories (IPCC, 2006).

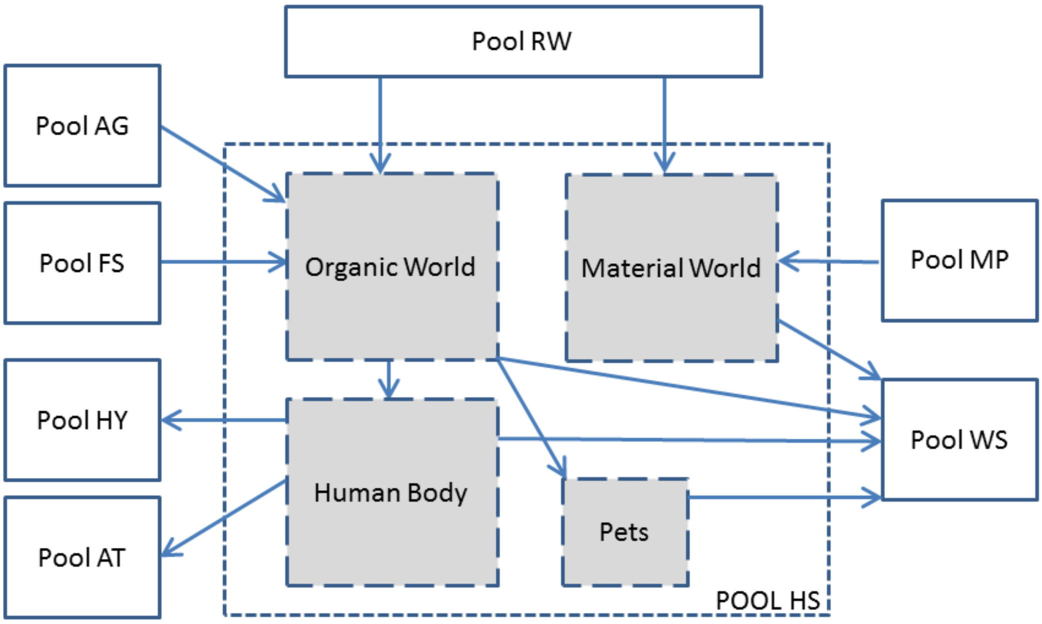

Figure A1.1. Example of a sub-pool structure and flows within sub-pools as well as to and from external pools (here for the Pool HS, Humans and Settlements. See Table A1.1 below for explanation of 2-letter codes of other Pools. Source: EPNB, 2021 © EPNB, Creative Commons (CC BY-SA 4.0).

Table A1.1 lists all the sub-pools contained in the EPNB guidance. The ID consists of a numeral (for the pool) and a single letter designating the respective sub-pool. A two-letter code has been developed describing pool and sub-pool, respectively, combined by a period sign (as in "FE.EC"). The system also allows for a third level of pools (sub-sub-pool, in the ID designated with a number), and even a fourth level is possible if needed, using lower case letters (such as 1A2f as overall ID). In addition, detailed categories are expected to follow the IPCC guidance, where available.

Table A1.1. List of all sub-pools defined. The ID consists of the numerical sequence of pools plus a letter identifying the respective sub-pool. Likewise, the Code consists of two letters identifying the respective pool, followed by a period sign and two letters for the sub-pool.

ID	Code	Description (pool and sub-pool)
1A	EF.EC	Energy and Fuels - Energy conversion
1B	EF.IC	Energy and Fuels - Manufacturing industries and construction
1C	EF.TR	Energy and Fuels - Transport
1D	EF.OE	Energy and Fuels - Other energy and fuels
2A	MP.FP	Industrial processes - Food processing
2B	MP.NC	Industrial processes - Nitrogen chemistry
2C	MP.OP	Industrial processes - Other producing industry
3A	AG.AH	Agriculture - Animal husbandry

ID	Code	Description (pool and sub-pool)
3B	AG.MM	Agriculture - Manure management and manure storage
3C	AG.SM	Agriculture - Soil management
4A	FS.FO	Forests and semi-natural area - Forest
4B	FS.OL	Forests and semi-natural area - Other Land
4C	FS.WL	Forests and semi-natural area - Wetland
5A	WS.SW	Waste - Solid waste
5B	WS.WW	Waste - Wastewater
6A	HS.OW	Humans and settlements - Organic world
6B	HS.HB	Humans and settlements - Human Body
6C	HS.MW	Humans and settlements - Material World
6D	HS.PE	Humans and settlements - Non-agricultural animals (pets)
7	AT	Atmosphere (no sub-pool)
8A	HY.GW	Hydrosphere - Groundwater
8B	HY.SW	Hydrosphere - Surface water
8C	HY.CW	Hydrosphere - Coastal water
*	RW	"Rest of the World", trans-boundary nitrogen flows

The concepts developed here, in contrast to the reality of national budgets, do not consider spatial boundaries that limit the extent covered. For a complete treatment, flows across such boundaries obviously also change the stocks of the respective (national) pools. Hence, imports and exports associated with any pool also need to be considered. In the overall concept of pools, they may be regarded as flows to an extra pool, labelled "Rest of the World", code RW.

A1.3 Quantification – stocks and flows

As a material balance model, NNBs describe the fate of N_r as a sequence of stocks (within a pool or sub-pool) and flows (between two pools or sub-pools, respectively). In each pool, the stock change then materializes as the sum of all flows (in and out of the pool). Further, the above-mentioned imports and exports of each pool also have to be considered. Finally, we need to remember that the mass balance is not fully closed, as molecular nitrogen – present in much higher quantities than N_r – also plays a role. Fixation of N_2, as an energy intensive process, is rather limited, but nevertheless must not be neglected. Also, at the other end, decay of N_r into molecular N_2 (e.g., denitrification) also needs to be covered. Thus, the overall equation governing the stocks contained in each pool is:

$$\Delta S_i = \sum F_{i,j} + Imp_i - Ex_i + Fix_i - Dec_i \quad \text{(A1)}$$

where *ΔS* is the stock change, *F* a specific flow, *Imp* and *Ex* stand for Import and Export across country border and *Fix* and *Dec* represent fixation and decay of N_r in pool *i* (and connecting to pool *j* for the flows, with positive values for influx and negative for outflux).

Most interesting in any stock-flow model are the flows, especially where flows reflect the release of compounds to the environment, with possibly detrimental consequences. Flows connect pools and deliver material from one stock to another stock. Physical unit used is mass of N per time (for flows, source, sink, as well as stock change). EPNB specifically defines each possible flow between specific pools or sub-pools (or even lower-level pools). They may occur within a pool (between sub-pools of this pool) or between primary pools. In all cases, we differentiate flows out of a pool (with negative signs) and flows into a pool (with positive signs). For full identification of a single flow, its matrix also needs to be identified (the substance in which a flow is embedded). Providing matrix information allows to specify different flows between the same pools. Often, flow quantities of a matrix (water, air, …) will be rather easy to obtain, then the concentration of N_r in the matrix is a key parameter underlying quantitative N_r flows.

Occasionally, it may be useful to provide species information as the matrix – as often specific flows of N are intrinsically connected with certain chemical species. This can be products of chemical industry (e.g., nitric acid or urea) or pollutant emissions (such as nitric oxide). For a given chemical species, its N content can be established precisely based on its stoichiometry. On the species level, however, estimating balances is meaningless as chemical and biological processes within pools lead to rapid and unforeseeable transformations between chemical compounds (such as urea that quickly converts to ammonia and carbon dioxide when applied as fertilizer). Species information may help to validate model results with information derived from measurements, and it will improve the knowledge on possible impacts of N compounds.

Flows can then be characterised unambiguously by the pool they start from, the pool they end up in, and by the matrix. EPNB use the codes of the starting pool, that of the destination pool and the matrix, separated by dashes (see examples in Table A1.2). A full list of flows can be found in the EPNB guidelines (EPNB, 2021).

Table A1.2. Examples of flows in National Nitrogen Budgets (NNB's), from the EPNB Guidance Document (EPNB, 2021).

POOL (START)	POOL (END)	MATRIX	TOTAL CODE	DESCRIPTION
MP	AG.AH.NDAI	SOYC	MP-AG.AH. NDAI-SOYC	Soya cake in compound feed fed to non-dairy cattle from industrial processing
AG.SM	AT	NH3	AG.SM-AT-NH3	Ammonia emission to the atmosphere from agricultural soil management
AG.SM	HY	NO3	AG.SM-HY-NO3-SURFW	surface water runoff NO_3-N losses to the hydrosphere from agricultural soil management

Flows in the sense of an NNB refer to the N_r contained in the matrix, like also the stocks are represented as amount (mass) of N_r. Typically, flow levels may be available for the matrix instead of the N_r amount, e.g. amounts of wheat sent from farms to food processing, or effluent flows of a wastewater treatment plant. Hence, the N_r content in a matrix needs to be determined or assessed from appropriate references to retrieve appropriate values. This can be fairly straightforward when the N content is fixed or well known – e.g. when the matrix is a chemical species (e.g., NH_3, NO_x, N_2O, proteins), its elemental composition is fully determined and hence its N-content given by stoichiometry. For other matrices (N content in food, in fibers, in compound materials) N contents may be more difficult to obtain, and they may also be variable. The EPNB guidelines (EPNB, 2021) provide lists of typical N contents for relevant flows.

As many flows (such as emissions) are characterised by operations in the pool releasing these flows (and typically are not influenced by activities in the receiving pool), EPNB has made it a principle to report flows (and typically also to quantify flows) with the pools they originate from. Hence the starting pool (and also the first letters of the code, see Table A1.2) identify where a flow is described in the guidelines (EPNB, 2021). These guidelines provide information how the respective flows should be calculated and recommend, depending on the ambition level of the agency performing the budget calculation, a simpler (Tier 1) approach based on international data only, or a more detailed (Tier 2) approach that would require specific national information to be considered, if available.

Due to structural differences between countries' economies and environments, the importance of specific sectors, activities, and, hence, also N_r flows may vary strongly. While, for comparison purposes, standardization and full coverage of all flows is essential, it may be a waste of effort to analyse in detail all flows if they are not important in a specific situation. A threshold of 100 g N_r per person and year (100 tons per million inhabitants and year) has been established to determine whether a flow is relevant or not. Flows lower than this threshold may be assessed and reported in combination, as they are not considered of primary relevance. On the other hand, for any flows that exceed the threshold by a factor of 10, the possibility to split such a flow of 1 kg N_r per person and year should be considered, if such a split is meaningful.

A1.4 Data treatment, limitations and uncertainty

In essence, NNBs trace the flows of N_r through anthropogenic and environmental pools. Within each pool or sub-pool, flows can be balanced against stock changes, sinks and sources. This allows to validate information collected, identify redundancies and errors, but also to complement missing information. Flows are derived using methodologies and data provided by national inventories, and from other relevant statistics taking into account N_r contents of the respective matrix.

While differentiation of individual N_r species is normally not performed on a budget level, a distinction between "inactive" components and N_r may be meaningful. There is no conclusion or guidance available yet, but it is clear that certain forms of N in compounds (in addition to N_2 itself) will be rather inactive and not readily contributing to environmental degradation. Such compounds first need to be "activated" (in a similar way as N_2 needs to be fixed) before being relevant as N_r. An example for this would be Chile saltpeter that would have no environmental impact before being mined from the Atacama Desert. Also, the N contained in fossil fuels and their products only becomes relevant at the combustion of such fuels, which appear in the NNB as NO_x emission factors. Current guidance is to report such flows for completeness, if possible, even if their environmental relevance may be limited. Fossil fuel N contributes significantly to the N budgets in many countries without providing adequate impacts.

Any tools performing such mass balances can be used to help illustrate the NNB system. Some applications have taken advantage of the STAN (subSTance flow Analysis) model (Cencic and Rechberger, 2008), an open-source tool available from Vienna University of Technology. This tool, in addition to covering stock-flow analysis and enabling data exchange with standard spreadsheets (Excel), also allows for data reconciliation and uncertainty treatment.

EPNB (2021) includes guidance on how to describe uncertainty in the data, which, given the often-limited quality of information available, remains at semi-quantitative levels. Uncertainty margins may range from 10% to a factor of four discrepancy around a central value. Such semi-quantitative analysis, however, is only rarely able to provide input for a full uncertainty assessment and may only serve to recommend specific methodological improvements.

A1.5 Preferred input information

With most countries in the UNECE domain having to provide obligatory emission information on greenhouse gases to the United Nations Framework Convention on Climate Change (UNFCCC) as well as on air pollutants to UNECE, the use of high-quality statistics is a prerequisite. Statistical information on activities that determine atmospheric release and on technologies that potentially limit such release are also central to NNBs. International databases such as EUROSTAT, International Energy Agency (IEA), Food and Agriculture Organization of the United Nations (FAO), and from industry organisations such as the International Fertilizer Association (IFA) are available, often based on high quality and coordinated efforts of national statistical offices and inventory agencies. Especially countries of the European Union (EU) are requested by EUROSTAT to provide harmonised statistics on energy consumption, industrial activity, agriculture, and land use and waste. Results are thus on a comparable level. In addition, environmental data (concentrations of air pollutants such as NO_x, or of water contaminants like nitrate in groundwater or surface water) are being recorded in these countries and made available on central databases, such as that of the European Economic Area (EEA). EU candidate countries have been provided with instruments and expertise to update and adjust their national data collections, in an effort to converge with EU standards. Countries outside that range (this mostly concerns the EECCA countries) may be limited to using international statistics and default "Tier 1" factors.

For many matrices, data on default N_r contents have been recorded and made available by EPNB (2021). However, N content values, especially those of agricultural products, can vary significantly. Also, the level of data aggregation may become relevant – e.g., FAO data may provide results on oilseeds, often having high N content in oilseed cakes, while olives would fall into the same category but almost without N (Kaltenegger and Winiwarter, 2020). Depending which products, the product group really consists of, results can differ remarkably, and discrepancies may occur in a balancing effort. Such discrepancies observed may be valuable to identify problems and to suggest improvements, e.g. to summarize products as much as possible along similar N contents.

A1.6 Storage and handling of results

While the data structure has been well defined, an agreed format of data transfer and storage is still missing in the EPNB guidance. Preliminary discussions with the Centre for Emission Inventory and Projections (CEIP) confirm their willingness to handle and implement storage of NNBs. CEIP is responsible to collect and make available national inventories for air pollutants under the LRTAP convention, so it appears most logical to extend their data handling also to NNBs under the same convention.

Starting from STAN material flow analysis and structured data export of NNBs, a Nitrogen Budget visualization tool is being developed as part of INMS activities and directly contributing to EPNB. This visualization tool (and the data structure/template needed to populate the visualization) will help define the template required to eventually transfer data to the CEIP as the collecting agency, such that the same template can be used to store NNB data and make them available for calculating useful indicators (another area of work of the EPNB) and/or visualization. Information on the further developments of the data structure, on the visualization tool and the methodology will continue to be available on the web site of the Expert Panel on Nitrogen Budgets (https://www.clrtap-tfrn.org/epnb).

Appendix 1 References

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Appendix 2: Subsystems of the CHANS model

A2.1 Introduction

The original framework of the CHANS (Coupled Human and Natural Systems) model (Gu et al., 2015) is explained here in detail. The input N cascading through and between the 14 subsystems including complex interactions are indicated by the N output from one subsystem as N input to another subsystem. Figure A2.1 illustrates the overall model structure of N cycling in the 14 subsystems. The total N input to each subsystem varies substantially. The six most important subsystems in the China case study are: industry, cropland, livestock, human, atmosphere and hydrosphere. Here, we show a detailed breakdown of the N fluxes linking these and also all other subsystems.

The N budget of the whole system includes only four N inputs (Haber-Bosch N fixation [HBNF], biological N fixation [BNF], NO_x emitted during fossil fuel combustion [NOx-FF], and import of N containing products), four N outputs (N_2 emissions, N_r transported to other countries or the ocean via air or water pathways, and export of N containing products), and N_r accumulation (Figure A2.1).

In practice, these items can be all calculated at the subsystem level. For instance, the total biological N fixation (BNF) input can be calculated as a sum of BNF input to cropland, grassland, forest, aquaculture and urban green-land. Therefore, the N budgets of the 14 subsystems can be calculated first, then the N input to, output from and accumulation within a country can be extracted to build the overall N balance. The following sections describe the N budgets of the 14 subsystems, with definitions of subsystem boundaries and calculation of each N flux. The calculations all consistently follow mass balance principles (i.e., inputs equal the sum of outputs and accumulation), and if there is interaction between two subsystems — output of one subsystem as input of another subsystem — these two N fluxes should be equal. N inputs to the human subsystem can be extracted to estimate the benefits of N use to a country's population, as well as N flows lost to the environment (such as NH_3, NO_x, N_2O to the atmosphere and N_r leaching or runoff to groundwater) to assess their environmental costs.

Basically, the input data to the CHANS model could be divided into two groups: socioeconomic data and N cycling parameters. The socioeconomic data include population, food production and consumption, proportion of straw been used, wood production, land use, irrigation amount, national water N concentration, etc. Socioeconomic data are normally obtained from national statistics, FAO database, national monitoring network, remote sensing, etc. N cycling parameters include information such as NH_3, NO_x, N_2O emission rate or ratio from different subsystems and sources, N_r runoff or leaching to water bodies, N concentration of different products (grain, straw, wood, etc.). These parameters are from global field experiments, which cover all the global regions and have been integrated into the CHANS model. All users can see these parameters in the CHANS Excel sheet, and modifications are available if they have more specific national data.

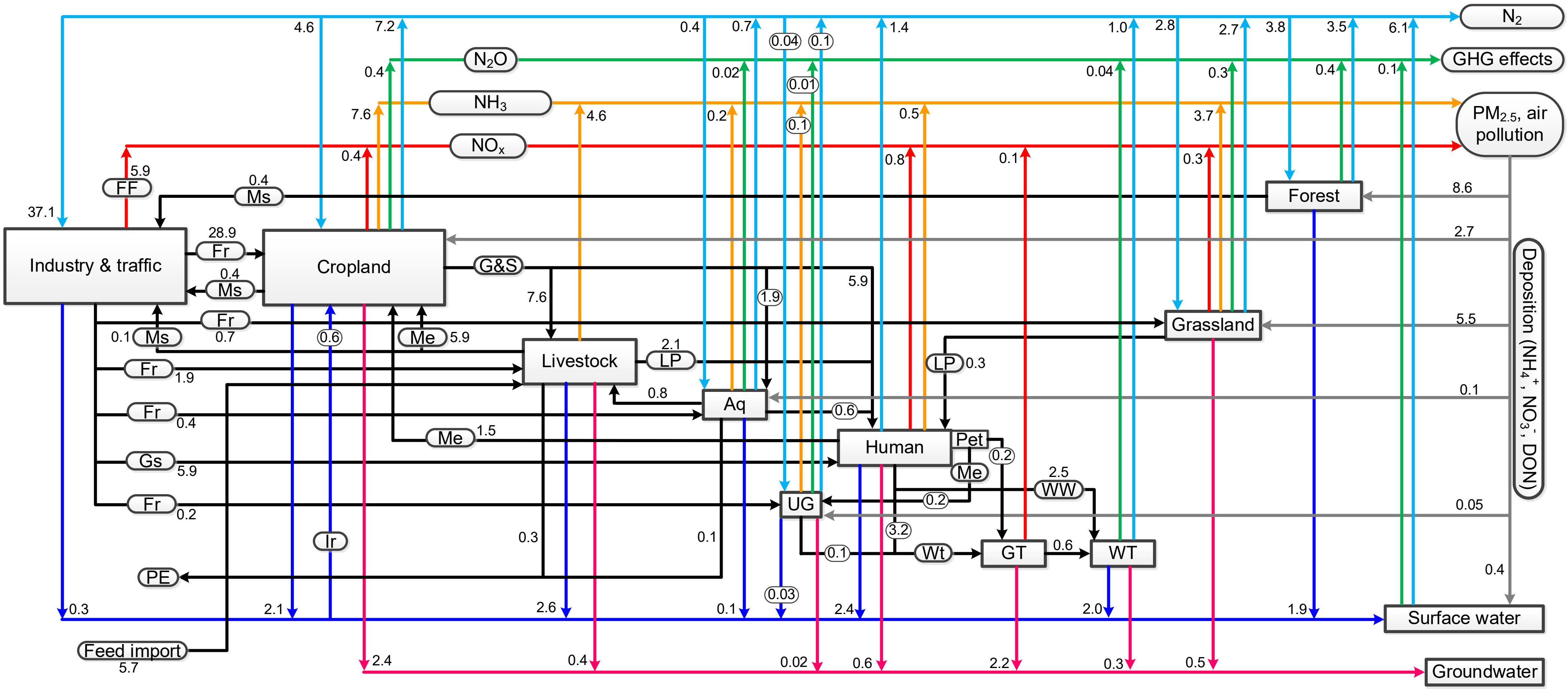

Figure A2.1. N cycling among the 14 subsystems in China in 2010. ***FF***, fossil fuel combustion; ***Ms***, materials; ***Fr***, fertilizer; ***Gs***, goods; ***PE***, products export; ***Me***, manure; ***G&S***, grain and straw; ***LP***, livestock products; ***Aq***, aquaculture; ***UG***, urban greenland; ***WT***, waste treated; ***GT***, garbage treatment subsystem; ***WW***, wastewater; ***WT***, wastewater treatment subsystem. Unit, Tg N yr^{-1}. Fluxes with a value < 0.01 Tg N yr^{-1} are not listed. Source: Gu et al., 2015 © Baojing Gu, Creative Commons (CC BY-SA 4.0)

In the following section, we have more detailed examples on how to calculate the N fluxes using cropland as an example. Other subsystems also follow the similar roles, and model details can be found in the CHANS Excel sheet © Baojing Gu available in the online supplement to this Guidance Document: https://www.inms.international/file/1572

A2.2 Cropland subsystem (CL)

All of the N input to, output from, and accumulation within cropland soils are considered in the CHANS model. Inputs include fertilizer N, BNF, manures, recycled straw, N deposition and irrigation; outputs include grain and straw harvested and removed from the croplands, N losses to air (NH_3, NO, N_2O, N_2) and water (both surface waters and groundwater); N accumulation refers to changes in both the soil organic and inorganic N content. The calculation equations for total cropland N inputs (A2.1) and total cropland N outputs (A2.2) are as follows:

$$\mathrm{CL_{IN}} = \mathrm{CLIN_{Fer}} + \mathrm{CLIN_{BNF}} + \sum_{i=1}^{2} \mathrm{CLIN_{Exc,i}} + \mathrm{CLIN_{Dep}} + \mathrm{CLIN_{Irr}} + \mathrm{CLIN_{Str}} \quad \text{(A2.1)}$$

$$\mathrm{CL_{OUT}} = \sum_{i=1}^{4} \mathrm{CLOUT_{Crop,i}} + \sum_{i=1}^{5} \mathrm{CLOUT_{Str,i}} + \sum_{i=1}^{6} \mathrm{CLOUT_{Loss,i}} \quad \text{(A2.2)}$$

where $\mathrm{CL_{IN}}$ and $\mathrm{CL_{OUT}}$ are the total N input to and output from cropland; $\mathrm{CLIN_{Fer}}$ is synthetic fertilizer application; $\mathrm{CLIN_{BNF}}$ is the BNF, including symbiotic and non-symbiotic N fixation; $\mathrm{CLIN_{Exc,i}}$ is excretion recycled to cropland from both livestock and humans; $\mathrm{CLIN_{Dep}}$ is N deposition, including both dry and wet deposition; $\mathrm{CLIN_{Irr}}$ is N_r input to cropland from irrigation; $\mathrm{CLIN_{Str}}$ is the straw recycled to cropland; $\mathrm{CLOUT_{Crop,i}}$ is crop production, including crops used as human food, livestock feed, aquaculture feed and industrial materials; $\mathrm{CLOUT_{Str,i}}$ is straw production, including straw used as feed, fuel in rural areas and industrial materials, recycled to cropland, and burned in the field; $\mathrm{CLOUT_{Loss,i}}$ is N_r loss during crop production, including NH_3, N_2, N_2O and NO_x emissions, riverine runoff , and leaching to groundwater.

Fertilizer N applied to cropland can be directly obtained from national statistical data or FAO data. Total BNF is estimated by the symbiotic N_2 fixation rate of leguminous plants multiplied with the sown area and the non-symbiotic N fixation rate for rice, sugarcane and other crops with their respective sown areas. N deposition is estimated based on the per hectare deposition rate from a synthesis of existing measurements obtained from literature, from a national monitoring network, or from atmospheric modelled data if there are no measurements or monitored data. Irrigation can input considerable amounts of N_r to croplands given the eutrophic surface water and groundwater, and this source is estimated by the total irrigated water volume from national statistics and average N concentration in the water used, which is usually obtained from a monitoring network. Manure inputs to cropland are estimated from the livestock subsystem.

Grain N harvested is estimated by using total production figures and N concentrations for each crop type. The total production of cropland includes five cereals (wheat, rice, corn, millet, barley), beans, potatoes, cotton, oil crops, hemps, sugarcane, sugar beet, tobacco, tea, fruits and vegetables. Other crops that are not included above can be added in a more summarised format, such as “other cereals”, “other fruit”, etc. Then, using harvesting indices (default value, could be changed if have national specific measured data) and N concentrations (default value, could be changed if have national specific measured data) of straw of different crops, the total harvested N in straw can be estimated. The fate of grains can be assumed as first supplied to humans as food (based on human demand), the remainder supplied to aquaculture and livestock as feed, and if the supply is smaller than human demand, then imported grains are required. The grain supplied to humans and aquaculture can be estimated based on FAO statistics and national data. The fate of straw produced can be estimated as straw used as feed, fuel in rural areas and industrial materials, recycled to croplands, and burned in the field; the proportions of these utilisation patterns can be estimated by the synthesis of national statistics and literature data. N losses to air and water are affected by the N input type, land use and climatic zone, all these influencing factors are in the model and related parameters could be chosen when applying the model on specific country. N accumulation is calculated as the difference between N inputs and outputs, which is considered as an increase or decrease of soil N content based on the relative relationships between input and output.

A2.3 Grassland subsystem (GL)

The boundary of the grassland subsystem includes both the grasslands and the grazing animals that utilize it, given their tight coupling both in space and function. N inputs to grasslands include BNF, N deposition and fertilizer N application to intensively managed grasslands. Outputs include animal products and N losses to air and water. The in-situ excretion and forage grazed by animals are both considered as within-system N cycling. Nevertheless, both the N fluxes for grazing animals and grassland still can be calculated to supply more information on the integrated grassland subsystem. N accumulation refers to changes in both soil organic and inorganic N contents in grasslands and the difference in livestock biomass N stock between two consecutive years. The calculations are as follows:

$$\mathrm{GL_{IN}} = \mathrm{GLIN_{Fer}} + \mathrm{GLIN_{BNF}} + \mathrm{GLIN_{Dep}} \tag{A2.3}$$

$$\mathrm{GL_{OUT}} = \mathrm{GLOUT_{Product,i}} + \sum_{i=1}^{6} \mathrm{GLOUT_{Loss,i}} \tag{A2.4}$$

where $\mathrm{GL_{IN}}$ and $\mathrm{GL_{OUT}}$ are the total N input to and output from the grassland subsystem; $\mathrm{GLIN_{Fer}}$ is N fertilizer applied to managed grasslands; $\mathrm{GLIN_{BNF}}$ is BNF, symbiotic and non-symbiotic N fixation; $\mathrm{GLIN_{Dep}}$ is N deposition, including both dry and wet deposition; $\mathrm{GLOUT_{Product}}$ is the animal products from grazing livestock; $\mathrm{GLOUT_{Loss}}$ is N_r loss from grasslands, including burning of livestock excreta, NH_3, N_2, N_2O and NO_x emissions, and leaching.

Fertilizer N use on grasslands occurred mainly on artificial grasslands, obtained from national statistics or FAO database. The BNF and N deposition input to grasslands can be estimated both based on the grassland area and their rates of N input following the similar way as in croplands. Degradation of grasslands may reduce the BNF rate and changes in the net primary productivity (NPP) of leguminous plants in grasslands can be used to estimate symbiotic BNF, which is normally estimated from NDVI. For non-symbiotic BNF, a constant rate can be estimated. Forage production can be calculated based on the NPP estimates grasslands, which is normally estimated from NDVI. We provided default values for all the afore mentioned parameters, and modification could be done once more specific national data is available.

Animal products and the excretion generated on grasslands can be estimated by the same strategy as in the livestock subsystem. The fate of excretion may be recycled to grasslands or burned by herdsmen for cooking and heating in some regions or countries, which need survey to obtain the proportions. Similar to croplands, recycled manures can also be lost to the air via NH_3, NO, N_2O and N_2, to surface water via runoff and to groundwater via leaching, and their emission factors could be found in the CHANS model.

A2.4 Forest subsystem (FR)

Forest includes many types, e.g., evergreen broadleaf, deciduous broad-leaved, mixed conifer and broadleaf, coniferous forest, shrub and bamboo. N inputs to forest subsystem included BNF and N deposition, while the N outputs referred to timber harvested N_r loss to the environment. The calculations are as follows:

$$\mathrm{FR_{IN}} = \mathrm{FRIN_{BNF}} + \mathrm{FRIN_{Dep}} \quad \text{(A2.5)}$$

$$\mathrm{FR_{OUT}} = \mathrm{FROUT_{Timber}} + \sum_{i=1}^{5} \mathrm{FROUT_{Loss,i}} \quad \text{(A2.6)}$$

BNF can be estimated based on the area of each forest type and their N fixation rate. Similar estimation can also be applied to the N input from deposition by using the N deposition rate. Total timber N harvested can be estimated with a general N concentration of the woods, and the amount of the timber is from national statistics or FAO database. About half of the N input to forest subsystem is accumulated in the forest. With elevated N deposition input, a proportion of these inputs can leach to the surface water and groundwater. NH_3, N_2O and N_2 emission from different types of forest can be estimated based on the emission rates in field experiments, which could be obtained from the CHANS model.

A2.5 Livestock subsystem (LS)

To reflect the contribution of grasslands to livestock production, the total livestock production can be split into two categories: 1) grazing animals and 2) non-grazing animals. To simplify the calculation, grazing animals can be assumed to only feed by forage and the other animals are fed grain, straw and food residues. The non-grazing animal feeding operations (NAFO) can be considered as the livestock subsystem, while grazing animals are included in the grassland subsystem. The inputs to NAFO include grain (both domestic and imported), straw, fish feed and food residues, and outputs are animal products and excretion. For the NAFO, animal excretion is partly recycled to cropland as manure except for that lost to air or water. The equations for total N inputs (A2.7) and total N outputs (A2.8) used for the calculation are as follows:

$$\mathrm{LS_{IN}} = \sum_{i=1}^{2} \mathrm{LSIN_{Crop}} + \mathrm{LSIN_{Fer}} + \mathrm{LSIN_{Str}} + \mathrm{LSIN_{Aqu}} + \mathrm{LSIN_{Res}} \quad \text{(A2.7)}$$

$$\mathrm{LS_{OUT}} = \sum_{i=1}^{2} \mathrm{LSOUT_{Meat,i}} + \mathrm{LSOUT_{Indu}} + \sum_{i=1}^{6} \mathrm{LSOUT_{Exc,i}} \quad \text{(A2.8)}$$

where $\mathrm{LS_{IN}}$ and $\mathrm{LS_{OUT}}$ are the total N inputs to and outputs from the livestock subsystem; $\mathrm{LSIN_{Crop}}$ is crops used as livestock feed both from domestic production and imports; $\mathrm{LSIN_{Fer}}$ is the urea input for straw ammoniation to produce feed; $\mathrm{LSIN_{Str}}$ is the straw used as feed; $\mathrm{LSIN_{Aqu}}$ is the fishmeal used as livestock feed; $\mathrm{LSIN_{Res}}$ is the food residue used for feed, mainly in rural households and from restaurants; $\mathrm{LSOUT_{Meat,i}}$ is livestock products, including meat, milk and eggs, which are transferred to the human subsystem or exported; $\mathrm{LSOUT_{Indu}}$ is the livestock product that is not used as food, including cocoons, leather, wool, etc.; $\mathrm{LSOUT_{Exc,i}}$ is livestock excretion, which is recycled to cropland, lost through riverine runoff, leached to groundwater, NH_3 volatilization, and N_2 and N_2O emission. N accumulation in the livestock subsystem is considered as the difference in livestock biomass N stock between two consecutive years.

Livestock N production can be estimated based on the total production and the N concentration of each livestock product, which could be obtained from national statistics or FAO. Based on the livestock raised each year and the excretion generated per animal, the total excretion of N by livestock can be estimated, which is provided within the CHANS model and modification could be done if national parameters are available. Considering the livestock N stock between two consecutive years combined with livestock production and excretion, the total demand of feed N in one year can be estimated. The feed demand is first satisfied by grain transferred from croplands, followed by straw and the fertilizer used for straw treatment (to increase the palatability and protein content), fishmeal supplied from aquaculture, and food residues; if there is still a gap between demand and supply, feed imports can be assumed to fill this gap; in contrast, if the demand is smaller than the supply, feed (counted as grain) export occurred. International trade data from national data providers can be used to crosscheck and validate the estimates of feed imports.

A large proportion of the livestock N excretion is emitted as NH_3 before the manure is applied to cropland. The remainder of the excretion go to cropland, runoff to surface waters, or leaching to groundwater.

A2.6 Aquaculture subsystem (AQ)

Aquaculture refers to both natural and cultivated fish production. The production from natural fishery is considered as an input to the subsystem. For the cultivated fishery, feed, N fertilizer and N deposition are considered as inputs. Besides the aquaculture products harvested, the input N lost to the environment via runoff, denitrification and volatilization.

$$\mathrm{AQ_{IN}} = \mathrm{AQIN_{Crop}} + \mathrm{AQIN_{Fer}} + \mathrm{AQIN_{Fishery}} + \mathrm{AQIN_{Dep}} \qquad \text{(A2.9)}$$

$$\mathrm{AQ_{OUT}} = \sum_{i=1}^{3} \mathrm{AQOUT_{Meat,i}} + \sum_{i=1}^{5} \mathrm{AQOUT_{Loss,i}} \qquad \text{(A2.10)}$$

where $\mathrm{LS_{IN}}$ and $\mathrm{LS_{OUT}}$ are the total N input and output to aquaculture subsystem; $\mathrm{AQIN_{Crop}}$ is crop that used as aquaculture feed; $\mathrm{AQIN_{Fer}}$ is fertilizer input to aquaculture subsystem; $\mathrm{AQIN_{Fishery}}$ is natural fishery; $\mathrm{AQIN_{Dep}}$ is N deposition, including both dry and wet deposition; $\mathrm{AQOUT_{Meat}}$ is aquaculture production, including fish, shrimp, crab, shellfish, algae and other aquatic products that can be transferred to human or livestock subsystems, or exported to external systems; $AQOUT_{Loss}$ is N_r loss during aquaculture production, including emissions of N_2, N_2O and NH_3, riverine runoff and sedimentation. N accumulation is calculated as the difference of AQ_{IN} and AQ_{OUT}.

Aquaculture production can be estimated based on the total production and the N concentration of each aquaculture species. Aquaculture feed use can be estimated based on the average feed conversion ratio (FCR), and the N fertilizer use can be estimated as a proportion of the total feed use. Total N deposition can be estimated based on the total aquaculture area and the N deposition rate per hectare. The aquaculture production can be assumed to satisfy domestic human need first, and the rest is used as livestock feed, except the amount used for export. The N surplus can be calculated as the total N input minus the N harvested in aquaculture production. Then, the emissions of NH_3, N_2 and N_2O and runoff can be estimated as a proportion of total N surplus, respectively.

A2.7 Industry subsystem (ID)

The industrial subsystem is an N processor system, which does not accumulate N in the system. The main N inputs are N_2 for the HBNF, fossil fuel for energy supply and agricultural nonfood goods for processing. The N outputs are N fertilizer, non-food goods, and N losses during the industrial production processes.

$$ID_{IN} = IDIN_{N2} + \sum_{i=1}^{3} IDIN_{Crop,i} + IDIN_{Str} + \sum_{i=1}^{4} IDIN_{LS,i} + IDIN_{Timber} + IDIN_{Fuel} \quad (A2.11)$$

$$ID_{OUT} = IDOUT_{Fer} + \sum_{i=1}^{m} IDOUT_{NA,i} + \sum_{i=1}^{n} IDOUT_{NB,i} + \sum_{i=1}^{4} IDOUT_{Loss,i} \quad (A2.12)$$

where LS_{IN} and LS_{OUT} are the total N input and output to aquaculture subsystem; $IDIN_{N2}$ is HBNF in factories; $IDIN_{Crop,i}$ is agricultural product transferred to industry, including cotton, hemp, tobacco, etc.; $IDIN_{Str}$ is straw transferred to industry for material production; $IDIN_{LS,i}$ is the livestock product transferred to industry, including cocoon, leather, wool, etc.; $IDIN_{Timber}$ is timber from the forest subsystem used for production of furniture and other wood products; $IDIN_{Fuel}$ fossil fuel combustion during industrial production, calculated as:

$$IDIN_{Fuel} = \sum_{i=1,j=1}^{n} (Fuel_{i,j} \times NOxN_{i,j}) \quad (A2.13)$$

where $Fuel_{i,j}$ is the consumption of fuel j in sector i; $NOxN_{i,j}$ is the emission of NOx in sector i when consumed per unit fuel j; the sector i includes electrical, construction, gas production, smelting, commercial, transportation and other industries; fuel j includes coal, oil, natural gas, coke, gasoline, kerosene, diesel and fuel oil.

$IDOUT_{Fer}$ is N_r fertilizer production, which is used on croplands, artificial grasslands, urban lawns, aquaculture, and livestock feed production; $IDOUT_{NA,i}$ comprises industrial products made from synthetic NH_3 (N_A), including synthetic fibers, drugs, nitrile rubber, synthetic detergents, plastics, nitric acid, explosives and other products, not including fertilizer; $IDOUT_{NB,i}$ covers industrial products made from the materials transferred from agriculture and forestry (N_B), including cotton, hemp, tobacco, silk, leather, sheepskin, wool, wood furniture, etc.; $\mathrm{IDOUT_{Loss,i}}$ is the N_r loss during industrial production, including wastewater discharge, NOx emissions, denitrification (both N_2 and N_2O) in industrial wastewater treatment plants. The industrial subsystem is only considered as a processing center, thus, we assume that there is no N accumulation in industrial subsystem.

A2.8 Urban green land subsystem (UG)

The urban green-land subsystem is composed of two parts: urban lawn and forests including shrubs. Urban lawn has similar N cycling as upland, and urban forest areas are assumed to have similar conditions as natural forests. For urban lawn, N fertilizer is an important input during lawn maintenance. Part of pet N excretion is also returned to urban lawn. Other N inputs including N deposition and BNF are applied both to urban lawn and forest areas. The N inputs to the urban green land are important to the growth of grass and trees. Lawn mowing and tree pruning remove N uptake and output its N_r as green waste. Other N outputs mainly refer to the N loss after N is applied to green land.

$$\mathrm{UG_{IN}} = \mathrm{UGIN_{Fer}} + \mathrm{UGIN_{PetExc}} + \mathrm{UGIN_{BNF}} + \mathrm{UGIN_{Liter}} + \mathrm{UGIN_{Dep}} \quad \text{(A2.14)}$$

$$\mathrm{UG_{OUT}} = \sum_{i=1}^{3} \mathrm{UGOUT_{Clip,i}} + \sum_{i=1}^{5} \mathrm{UGOUT_{Loss,i}} \quad \text{(A2.15)}$$

where $\mathrm{UG_{IN}}$ and $\mathrm{UG_{OUT}}$ are the total N input and output to urban green land; $\mathrm{UGIN_{Fer}}$ is fertilizer applied to urban lawn; $\mathrm{UGIN_{PetExc}}$ is pet excretion recycled to urban lawn; $\mathrm{UGIN_{BNF}}$ is BNF in urban green land; $\mathrm{UGIN_{Liter}}$ is the liter recycled back during lawn and tree clipping; $\mathrm{UGIN_{Dep}}$ is N deposition, including both dry and wet deposition; $\mathrm{UGOUT_{Clip,i}}$ the N removal through lawn and tree clipping, which is recycled to green land, or sent to landfill or garbage burning; $\mathrm{UGOUT_{Loss,i}}$ is N_r loss from green land, including NH_3 volatilization, riverine runoff, N_2 and N_2O emission, and leaking to groundwater. N accumulation is calculated as the difference of $\mathrm{UG_{IN}}$ and $\mathrm{UG_{OUT}}$.

A2.9 Human subsystem (HM)

The human subsystem mainly refers to the consumption of food, non-food goods and energy. Therefore, the N inputs to human subsystem include all the food items such as grain, livestock and aquaculture products, agricultural, forestry and industrial goods such as cotton and nylon, biomass and fossil fuel for energy use. Part of the input food is calculated as a loss through food waste, and the rest is assumed to be discharged as excretion. For the non-food goods, structural ones usually accumulate in human settlements or are sent to landfill as solid waste, and non-structural ones are released to the environment once used. For energy use, emissions of NO_x, NH_3, N_2O and N_2 can be released to the air during the energy generation process.

$$\mathrm{HM_{IN}} = \sum_{i=1}^{3} \mathrm{HMIN_{Food,i}} + \sum_{i=1}^{2} \mathrm{HMIN_{Indu,i}} + \mathrm{HMIN_{Fuel}} + \mathrm{HMIN_{Str}} \quad \text{(A2.16)}$$

$$\mathrm{HM_{OUT}} = \sum_{i=1}^{4} \mathrm{HMOUT_{WW,i}} + \sum_{i=1}^{2} \mathrm{HMOUT_{WG,i}} + \sum_{i=1}^{2} \mathrm{HMOUT_{NOx,i}} \quad \text{(A2.17)}$$

where $\mathrm{HM_{IN}}$ and $\mathrm{HM_{OUT}}$ are the total N input and output to human subsystem; $\mathrm{HMIN_{Food,i}}$ is human food consumption, including crop, livestock product (meat and milk) and aquaculture product (fish and others); $\mathrm{HMIN_{Indu,i}}$ is human industrial product consumption, including N_A and N_B; $\mathrm{HMIN_{Fuel}}$ is the NOX emission from domestic fossil fuel consumption; $\mathrm{HMIN_{Str}}$ is straw used as biofuel for cooking; $\mathrm{HMOUT_{WW,i}}$ is human excretion, which can be recycled to cropland, sent to wastewater treatment plants, discharged to surface water or leaching to groundwater; $\mathrm{HMOUT_{WG,i}}$ is the garbage, including food waste and industrial product abandoned; $\mathrm{HMOUT_{NOx,i}}$ is the NO_x emission from fuel consumption, including $\mathrm{HMIN_{Fuel}}$ and $\mathrm{HMIN_{Str}}$. N accumulation in human subsystem is relates to the increase of N-contained in human bodies, as well as industrial products accumulated in human settlements.

The per capita human food consumption can be obtained from FAO data, human goods and fossil fuel consumption can be retrieved from national statistics. Straw burning refers to straw used for energy in rural area. The proportion of the four destinations of human excretion can be compiled from investigations or literatures. About 10-30% of the food supply is lost as food waste, and, for rural areas, can be assumed to be reused as livestock feed, whereas in urban areas is sent to garbage treatment including composting. All non-structural, non-food goods are lost to the environment, whereas half of the structural non-food goods are considered to be sent to the garbage treatment at the end of their economic life.

$$\mathrm{HMIN_{Fuel}} = \sum_{i=1,j=1}^{n}(\mathrm{Fuel_{i,j}} \times \mathrm{NOxN_{i,j}}) \quad \text{(A2.18)}$$

where $\mathrm{Fuel_{i,j}}$ is the consumption of fuel j in sector i; $\mathrm{NOxN_{i,j}}$ is the emission of NO_x in sector i when consumed per unit fuel j; the sector i includes electrical, heating, cooking and other household activities, fuel j includes coal, oil, natural gas, coke, gasoline, kerosene, diesel and fuel oil. NO_x emission from biomass burning can be estimated based on the NO_x emission factors per straw burning.

A2.10 Pet subsystem (PT)

The pet subsystem is an affiliated subsystem of the human system. It does not produce any food, goods or energy for human consumption, but consumes these products in the same way as humans. Only dogs and cats are considered here; others, such as reptiles or gerbils are exclude owing to small numbers.

$$\mathrm{PT_{IN}} = \sum_{i=1}^{2}\mathrm{PTIN_{Feed,i}} \quad \text{(A2.19)}$$

$$\mathrm{PT_{OUT}} = \sum_{i=1}^{2}\mathrm{PTOUT_{Waste,i}} \quad \text{(A2.20)}$$

where $\mathrm{PT_{IN}}$ and $\mathrm{PT_{OUT}}$ are the total N input and output to pet subsystem; $\mathrm{PTIN_{Feed,i}}$ is pet feed input, including dog and cat feed; $\mathrm{PTOUT_{Waste,i}}$ is pet excretion, which is sent to landfill or recycled to urban green land (6). The numbers of dogs and cats can be estimated based on the numbers of households and pet ownership rates in both rural and urban area. No N accumulation is assumed in this subsystem.

A2.11 Wastewater treatment subsystem (WT)

WT subsystem is an N removing system that treats liquid waste to reduce its environmental impacts. The inputs refer to all the wastewater collected and sent to treatment facilities, and the outputs refer to the N loss from this subsystem such as N_2 emission. No N_r accumulation was considered in this subsystem, only N removal.

$$\mathrm{WT_{IN}} = \mathrm{WTIN_{HM}} + \mathrm{WTIN_{LS}} + \mathrm{WTIN_{GT}} + \mathrm{WTIN_{Rain}} \qquad \text{(A2.21)}$$

$$\mathrm{WT_{OUT}} = \mathrm{WTOUT_{Den}} + \mathrm{WTOUT_{NH3}} + \mathrm{WTOUT_{Lea,runoff}} + \mathrm{WTOUT_{Slu}} \qquad \text{(A2.22)}$$

where $\mathrm{WT_{IN}}$ and $\mathrm{WT_{OUT}}$ are the total N input and output to wastewater treatment subsystem; $\mathrm{WTIN_{HM}}$, $\mathrm{WTIN_{LS}}$, $\mathrm{WTIN_{GT}}$ and $\mathrm{WTIN_{Rain}}$ are the domestic wastewater, livestock excretion, landfill leachate treated in wastewater treatment plant and rain in urban area that leaches to the wastewater collecting system, respectively; $\mathrm{WTOUT_{Den}}$ is the denitrification in the wastewater treatment plant, including both N_2 and N_2O emissions; $\mathrm{WTOUT_{Lea,runoff}}$ is the N_r leaching during the wastewater transferred to the wastewater treatment plant and discharge to rivers after treatment; $\mathrm{WTOUT_{Slu}}$ is the N_r contained in the sludge after treatment.

A2.12 Garbage treatment subsystem (GT)

The GT subsystem is an N removing system that treats solid waste to reduce its environmental impacts. The inputs refer to all the waste sent to the treatment facilities, and the outputs refer to the N losses from this subsystem such as leachate or atmospheric emissions. N_r accumulation was considered in this subsystem owing to landfill.

$$\mathrm{GT_{IN}} = \mathrm{GTIN_{UG}} + \mathrm{GTIN_{HM}} + \mathrm{GTIN_{PT}} \qquad \text{(A2.23)}$$

$$\mathrm{GT_{OUT}} = \mathrm{GTOUT_{Lea}} \qquad \text{(A2.24)}$$

where $\mathrm{GT_{IN}}$ and $\mathrm{GT_{OUT}}$ are the total N input and output to garbage treatment subsystem; $\mathrm{GTIN_{UG}}$ is the green waste sent to landfill from urban green land subsystem; $\mathrm{GTIN_{HM}}$ is garbage from human subsystem; $\mathrm{GTIN_{PT}}$ is pet excretion sent to landfill; $\mathrm{GTOUT_{Lea}}$ is the N_r contained in garbage released to groundwater.

A2.13 Surface water subsystem (SW)

The SW system receives N_r inputs from other subsystems and can also transfer N_r to other countries/oceans through drainage. All the rivers, lakes and wetlands that can receive water flowing into can be considered. No N_r accumulating in this subsystem is assumed.

$$\mathrm{SW_{IN}} = \sum_{i=1}^{9} \mathrm{SWIN_{Sub,i}} \qquad \text{(A2.25)}$$

$$\mathrm{SW_{OUT}} = \mathrm{SWOUT_{Irr}} + \mathrm{SWOUT_{Den}} + \mathrm{SWOUT_{Exp}} \qquad \text{(A2.26)}$$

where SW_{IN} and SW_{OUT} are the total N input and output to surface water subsystem; $SWIN_{Sub,i}$ is the N_r transferred from other 9 subsystems; including cropland, livestock, aquaculture, forest, industry, urban green land, human, wastewater treatment and atmospheric deposition. $SWOUT_{Irr}$ is the irrigation losses to cropland; $SWOUT_{Den}$ is denitrification in surface water, including both N_2 and N_2O emission; $SWOUT_{Exp}$ is the N_r transferred to ocean via rivers.

A2.14 Atmosphere subsystem (AT)

AT solely receives N_r input from other subsystems and can also transfer N_r to other countries/oceans through atmospheric circulation and deposition; no N_r accumulation is assumed for this subsystem. Thus, the input N is either transferred to different countries or deposited to the land area.

$$AT_{IN} = \sum_{i=1}^{13} ATIN_{Item,i} \quad (A2.27)$$

$$AT_{OUT} = ATOUT_{Dep} + ATOUT_{Exp} \quad (A2.28)$$

where AT_{IN} and AT_{OUT} are the total N input and output to near-surface atmosphere subsystem; $ATIN_{Item,i}$ is the N_r emission from other subsystems to near-surface atmosphere, mainly NH_3 and NOX, including emissions from industrial fossil fuel combustion, domestic fossil fuel combustion, NH_3 volatilization from cropland, livestock, aquaculture, grassland and urban green land, straw burning as biofuel, straw burning in field, garbage burning, and N_2O emissions; $ATOUT_{Dep}$ is N deposition, including both dry and wet deposition; $ATOUT_{Exp}$ is the N_r transferred to surrounding areas through atmospheric circulation.

A2.15 Groundwater subsystem (GW)

GW receives N_r inputs from other subsystems. All the groundwater that can receive water influx is considered. Owing to the few linkages between the groundwater subsystem and other parts of global water cycles, all the input N_r is assumed to accumulate in this subsystem, except losses for irrigation through pumping of groundwater.

$$GW_{IN} = \sum_{i=1}^{6} GWIN_{Item,i} \tag{A2.29}$$

$$GW_{OUT} = GWOUT_{Irr} \tag{A2.30}$$

where GW_{IN} and GW_{OUT} are the total N input and output to groundwater subsystem; $GWIN_{Item,i}$ is N_r input to groundwater from other subsystems; including N_r leaching from cropland, grassland, livestock, urban lawn, wastewater, landfill, etc.; $GWOUT_{Irr}$ is irrigation N pumping from groundwater.

Appendix 2 Reference

Gu, B., Ju, X., Chang, J., Ge, Y., Vitousek, P.M., 2015. Integrated reactive nitrogen budgets and future trends in China. Proceedings of the National Academy of Sciences of the United States of America 112, 8792–8797. https://doi.org/10.1073/pnas.1510211112

National nitrogen budgets are tools to compile and evaluate data on the use of nitrogen compounds, their environmental fate and potential impacts. Such budgets provide input necessary to derive valuable indicators such as nitrogen use efficiency, nitrogen surplus/deficit or nitrogen recycling rate. They help identify key flows and intervention points and allow decision-making by governments and agencies to tackle the nitrogen cascade.

This INMS Guidance Document discusses, with country examples, the concepts and foundations of nitrogen budgets using the CHANS (Coupled Human and Natural Systems) model originally developed for China and the EPNB (UNECE Expert Panel on Nitrogen Budgets) approach created on the basis of statistics available within the European Union.

The Guidance Document is aimed at governments, agencies and researchers who can all benefit from the concepts and approaches as they look to establish nitrogen budgets for other parts of the world. With environmental losses representing a waste of nitrogen resources currently worth hundreds of billion USD annually, nitrogen budgets provide a key tool to inform mitigation strategies that benefit the economy and protect the environment at the same time.