ECONOMY-WIDE NITROGEN BALANCES AND INDICATORS: CONCEPT AND METHODOLOGY

By Albert Bleeker[(1)], Mark Sutton[(2)], Wilfried Winiwarter[(3)] & Adrian Leip[(4)]

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1. Role of nitrogen and global environmental change

1. Nitrogen is an abundant element on earth, making up nearly 80% of the earth's atmosphere. However, as atmospheric di-nitrogen (N_2), it is ***unreactive***[1] and cannot be assimilated by most organisms. By contrast there are many ***reactive*** nitrogen (N_r) forms that are essential for life, but are naturally in very short supply. These include ammonia (NH_3), nitrates, amino acids, proteins and many other forms.

2. Until the 19th century, limited availability of these N_r compounds severely constrained both agricultural and industrial productivity. At the start of the twentieth century, several industrial processes were developed to fix N_2 into N_r. The most important process turned out to be the ***Haber–Bosch process***, with N_r creation greatly increasing from the 1950s. In addition, combustion processes have substantially increased the creation and release of N_r as nitrogen oxides (NO_x).

3. Human ***emissions*** of NO_x and NH_3 to the atmosphere have now increased about fivefold since pre-industrial times. Atmospheric N deposition in large regions of the world exceeds natural rates by an order of magnitude. Much is deposited in N-limited ecosystems, leading to unintentional fertilization and loss of biodiversity.

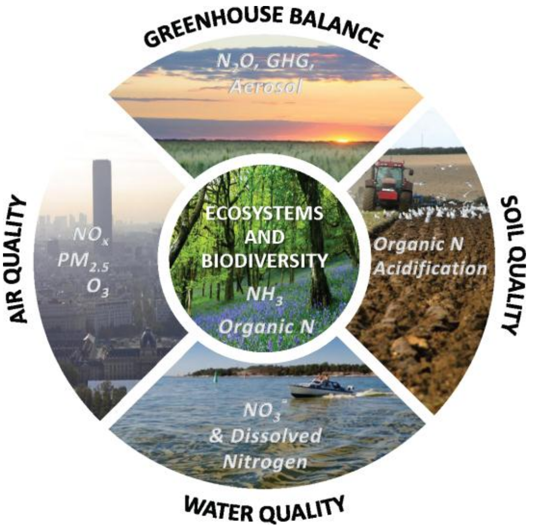
4. Similarly, the transfer of N_r from terrestrial to coastal systems has doubled since pre-industrial times. As with terrestrial ecosystems, many of the coastal ecosystems are N_r-limited, such that abundance in N_r leads to algal blooms and a decline in the quality of surface and ground waters. In addition, reactive nitrogen alters the balance of greenhouse gases, enhances tropospheric ozone formation, depletes stratospheric ozone, increases soil acidification and stimulates the formation of secondary particulate matter in the atmosphere, all of which have negative effects on people and the environment.

5. In natural systems, responses to stressors such as nitrogen are non-linear. Beyond a certain critical limits, there may be "tipping points" at which abrupt changes may occur in the structure and function of ecosystems. Rockström et al (2009) proposed a number of planetary boundaries based on the lower bound of estimated critical limits, and concluded that these boundaries have been crossed on climate change, biodiversity and the nitrogen cycle (part of a boundary with the phosphorus cycle).

6. Figure 1 summarizes the five environmental issues (and key N_r compounds) that have been identified as the most important in the ***European Nitrogen Assessment*** (ENA). It can be seen that nitrogen integrates many different aspects of global environmental change, including the main environmental threats. The different effects of N_r on the environment can be mitigated through several strategies, which should focus on reducing the ***creation of N_r***, and increasing the efficiency with which it is used and recycled. Such strategies may include increasing the efficiency of N use in food production, altering human diets and improving the treatment of animal and human waste.

[1] All the bold italic words are explained in a glossary (in the back of this document)

Figure 1 Summary of the five key societal threats of excess reactive nitrogen highlighted by the European Nitrogen Assessment (ENA, 2011)



2. Options for nitrogen indicators

7. Until recently, the focus in using nitrogen indicators has been on component sources and effects rather than on gauging its overall impact as a headline indicator. For example, the OECD has established its agri-environmental indicator on ***gross nitrogen balance***, while the Convention on Biological Diversity has used atmospheric N deposition as an indicator of threat to biodiversity. Such approaches now need to be extended and combined, so that they are able to reflect the consequences of all the major sources. Recently, the ENA has made advances by establishing comprehensive N budgets of all major sources for several European countries. While this detailed approach needs to be further developed, there is also the need to refine an operational headline indicator that can be speedily implemented across OECD countries.

8. Overall, this task requires the collation of information from different sectors: industry, traffic, agriculture food consumption, waste water, etc. Based on existing indicators and datasets as much as possible, this asks for a 'building block approach': the first step being 'simple & doable', while the following steps would lead to a more comprehensive system (as in the N budget system developed in the ENA). This also allows for testing and verification by comparing the simpler and more detailed approaches.

9. The options for an operational nitrogen indicator could include, among others:

- *Index of N_r emissions* (analogy: GHG emissions): NO_x, N_2O and NH_3 emissions to air; N_r release to freshwater from agriculture (linked to N surplus), as well as from sewage systems; N_r emissions related to food consumption.
- *Index of new N_r creation* (analogy: fossil fuel supply): Haber-Bosch from fertilizer data; N_r from fossil fuel use; biological fixation from N-surplus indicator. Required N-fixation for non-fertiliser products and N-fixation in non-agricultural systems. This probably needs to be restricted to anthropogenic N-fixation.
- *Index of animal protein consumption per capita* (in analogy to GDP): Can be derived from FAO data and e.g. protein content is used in the underlying calculations. The consumption of protein is largely driving the overall food related losses of nitrogen.
- *Index of N use efficiency*: Integrating sources from agriculture (exists already in OECD dataset), as well as from combustion (N emitted per GJ fuel).

10. In the first instance, these calculations focus on direct national calculations, though 'national footprints' (i.e., including embedded emissions, based on national consumption) may also be considered (section 6, page 20).

3. Data requirements for the nitrogen indicators

11. In order to allow indicators to be derived for countries of very different levels of underlying statistical data, we propose a tiered approach in data assessment:

- Tier 1 would represent an easily implementable approach based on internationally available statistics;
- Tier 2 would represent a refined version based on national statistical information.
- Lastly, Tier 3 would combine national statistics with national conversion parameters (e.g., emission factors and N-contents of important goods). The following preliminary comments on data requirements can be made[2]:

Data input needed for Tier 1:

- FAO data as basis for agriculture / waste / consumption
- Global dataset on fossil fuel consumption, to calculate NO_x emissions
- Global dataset on biological and industrial nitrogen fixation
- OECD data for agricultural 'nitrogen balance'[3]

Data input needed for Tier 2:

National data/statistics on:

- Food consumption
- Waste related to food consumption
- Industry (production / energy use)
- Traffic (energy use, intensity)
- Trade of agricultural and non-agricultural products
- Fishery (amount caught)
- Data completing the agricultural "gross nitrogen balance" (i.e., feed purchase, animal and crop products); needs to be discussed how far this is available already for N-surplus indicator
- Afforestation/Deforestation/Forest degradation/Forest growth/use of forestry products
- Nitrogen emissions to the environment (water, air, soil) by different sources

Data input needed for Tier 3
(additional to those listed in Tier 2):

National information on

- Animal N excretion rates
- Manure handling systems
- N contents in key agricultural products
- Emission rates/factors in combustion
- Denitrification efficiency of wastewater plants

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[2] Note: some of the datasets do not provide information on Nr loss directly, but are rather used as input for such Nr loss calculations.

[3] See the OECD/Eurostat Handbook: Eurostat (2013). Nutrient Budgets – Methodology and Handbook. Version 1.02. Eurostat and OECD, Luxembourg.

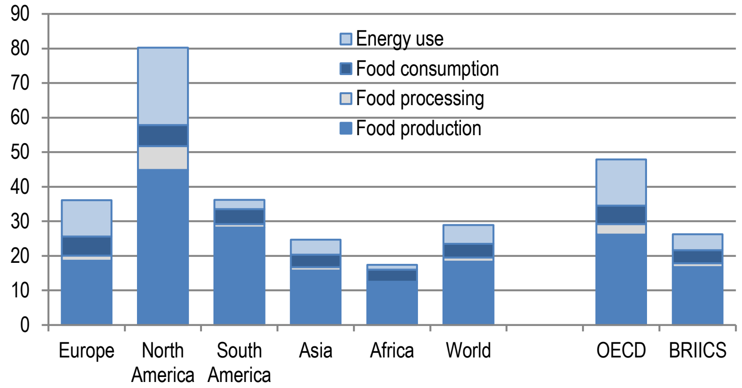
12. Tier 3 information represents a sound prerequisite to create full national ***N budgets***. Next to the mentioned data inputs needed for this Tier 3 approach, a thorough check of all different pools, fluxes and sinks not listed and estimated should be performed. In principle this will be part of the overall detailed methodology description of the Tier 3 approach, which will also consist of an extensive uncertainty evaluation. Once fully developed, the Tier 3 approach can relatively easy 'deliver' the various indicators that were mentioned in Section 2 (Index of N_r emissions, Index of new N_r creation, Index of animal protein consumption per capita, Index of N use efficiency). While the Tier 3 approach as such is not an indicator in itself, it provides the basis for the separate indicators mentioned above (+ possible additional indicators) addressing nitrogen in a more integrated way. Section 5 describes the Tier 3 approach in more detail.

13. Although the Tier 1 approach can be implemented relatively easy using existing and available data, the Tier 2 and 3 approaches need further work in developing the respective indicators based on country specific data from various sources. The next section will mainly focus on the Tier 1 approach and will describe its methodology, the data requirements and data availability.

4. Tier 1 approach

14. As mentioned before, the Tier 1 approach is easily implementable and is based on internationally available statistics. At present this specific approach is also used in the context of the Convention on Biological Diversity and is included in their list of potential new indicators related to the Aichi Target 8[4] ("By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity"). In the context of the CBD Target 8, this indicator is called: Loss of reactive nitrogen to the environment[5]. It shows the reactive ***nitrogen loss*** for different regions of the world as a result of the production and consumption of food and the use of energy (e.g. for electricity production, industry and transport), and is expressed as the reactive nitrogen loss per capita per year, without making a distinction between losses to air, soil and water. This loss is a surrogate measure of potential reactive nitrogen pollution; the actual pollution depends on environmental factors and the extent to which the waste flows at production and consumption of food and energy are being reused.

Figure 2 Average loss of reactive nitrogen per inhabitant, world regions, 2008



15. Figure 2 shows an example of the indicator for different regions in the world. These results for the different regions are averages for the underlying countries, for which separate calculations have been performed. The graph shows that in 2008 the global production and consumption of food and energy results in an average reactive nitrogen loss of 29 kg of nitrogen per inhabitant per year. Of the total loss, 5 kg is the result of energy use, 18 kg is from food production (agriculture), 1 kg due to food processing and

[4] http://www.cbd.int/sp/targets/

[5] More information about this indicator is available via http://www.bipindicators.net/nitrogenloss

4 kg is released during food consumption. The European reactive nitrogen loss per person is about 10 kg higher than the global average loss and is almost half of that in North America, but twice as high as in Africa. The energy component is relatively large in industrialized countries, while the contribution of food production and consumption is large in countries with an extensive livestock sector and high levels of meat consumption.

16. The sections below will describe the Tier 1 methodology and its data requirements and availability.

4.1 Methodology

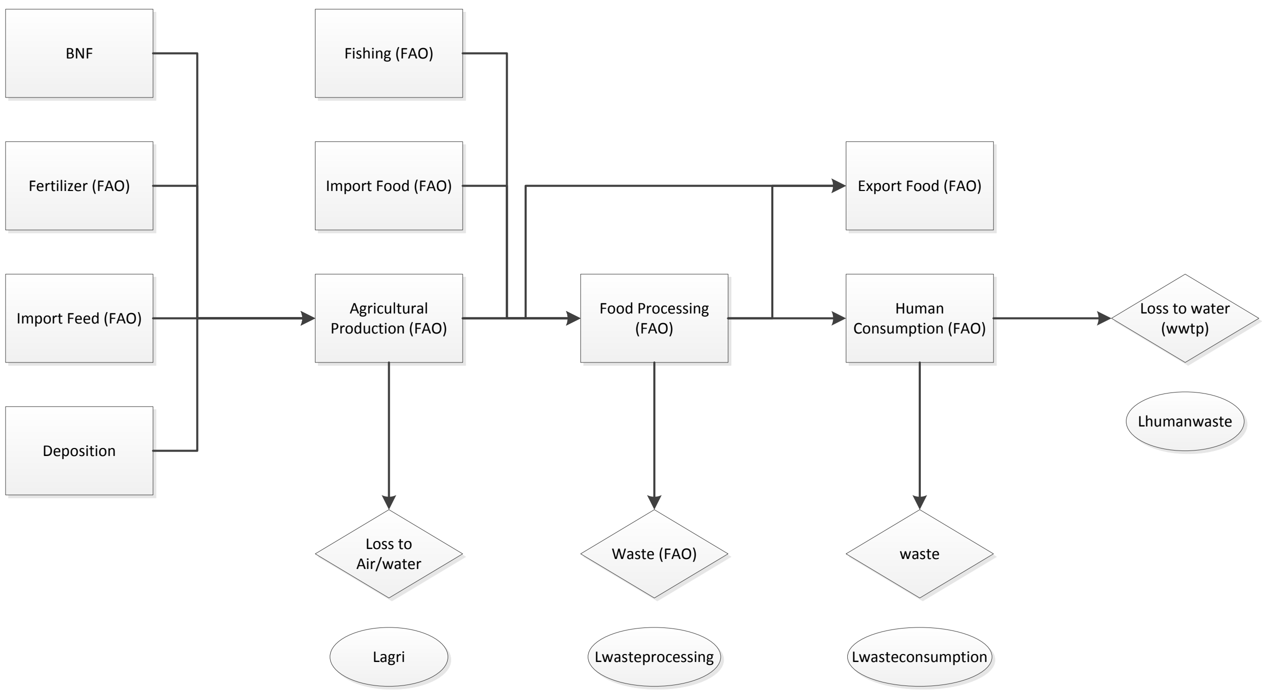
17. The CBD indicator shows the reactive nitrogen loss for different countries/regions of the world as a result of the production and consumption of food and the use of energy (e.g. for electricity production, industry and transport), and is expressed as a surrogate for reactive nitrogen “loss” per capita per year, without making a distinction between losses to air, soil and water when estimating the losses. To compare losses for individual countries with each other and/or with regions/the world, data are required that are comparable for these regions/countries. Although comparability increases, this will cause some restrictions with respect to the accuracy of the results.

18. The starting point for the overall methodology are national data for the topics ‘food’ and ‘fossil fuel’. These topics are now described separately.

Food

19. For the topic ‘food’ the global database of FAO is used, which is available via FAOSTAT. Important datasets are: ‘food balance’, fertilizer use’ and ‘trade’. Figure 3 gives a general overview of the various parts that are included in the food section of the Tier 1 approach.

Figure 3 Overview of the food section of the Tier 1 approach



20. For the food section, calculations start from the 'food balance' and 'fertilizer consumption' datasets. These are used for calculating the loss of reactive nitrogen during the agricultural production process in a country. With the fertilizer consumption per country as a basis, the total amount of nitrogen in agricultural products (based on that fertilizer) is then subtracted. The difference is the surplus of N_r as the potential of N_r loss to the environment.

21. However, fertilizer is not the only input into the system at a national scale. Also nitrogen deposition and biological nitrogen fixation (BNF) can form substantial nitrogen sources. These two topics are, however, not available via FAO and thus have to be taken from another data source. FAO, however, does provide information on different crops, and BNF to some extent can be estimated by extrapolating from the yield of leguminous plants. Nitrogen deposition can only be derived from atmospheric models, but even here at least scientific literature is available also globally (not a specific year, though). For the total production process also the use of animal manure is of importance. However, for the methodology described here, the assumption is that fertilizer is the starting point of the process and animal manure is in fact only an 'intermediate product' and therefore not considered as a separate part in the calculations. The same is true for the production of fodder (such as grazed grass), for which no robust statistical information exist.

22. Please note that where FAO is mentioned as a data source, also OECD could be mentioned. When for individual countries more accurate data are available on the items mentioned here (e.g. fertilizer consumption, agricultural production), FAO data can be easily replaced with OECD data here.

23. The first step towards and average potential to N_r emissions and loss during the production of agricultural products could be an expanded gross nitrogen balance and is calculated as follows:

Fertilizer + imported feed/seed + BNF + deposition – production = loss (N_r surplus)

24. An important part of the overall calculation is the conversion of the amounts of FAO product to amounts of nitrogen and N_r loss rate. This is done by using the available amount of product and protein per product group and country in the FAO database. Based on these data, and the assumption of 0.16g N/g protein, the conversion to nitrogen content of that N_r pool can be made.

25. The second part of the food part is relatively easy, because the necessary numbers are available via the FAO food balance dataset. The parts that are needed for this are 'waste' and 'processing'. These two items for crops and meat give the total amount of nitrogen by which the N_r pool is reduced on the way from production (on the farm and in the food industry) to the consumer. The problem with these number, however, is that we don't know to what extent these losses are really 'lost', or perhaps via a detour enter the production system again (e.g. in the form of compost, animal feed, etc.).

26. The last part is now the nitrogen lost during (and after) consumption. We assume a loss of 25% before consumption, where again there is a question about the fate of this 'loss': is it really lost or e.g. recycled as compost. Depending on the sewage treatment system, part of the nitrogen entering the treatment will be converted back to atmospheric N_2, and is thus not harmful to the environment anymore. At the moment this conversion back to N_2 is not included in the Tier 1 approach. However, when more information about this process is available from more detailed national data (Tier 2/3), this last step can be easily implemented in the calculation of the overall loss (which will thus decrease).

27. The total change in nitrogen pools (L) due to the 'food' part (Lfood), is then a combination of the above mentioned three parts:

Lfood =Lagri + Lwasteprocessing + Lwasteconsumption + Lhumanwaste

with: Lagri =Nfertiliser + Nimportedfeed + Nbnf + Ndeposition - Nfood
Lwasteprocessing =waste + processing

Lconsumption =75% food (Lhumanwaste-waste water) + 25% food (Lwasteconsumption– food waste)

Fossil Fuel

28. For the 'fossil fuel' section, things are a bit more complicated, mainly due to the limited availability of relevant data. However, in terms of the actual calculation it is much easier. When data related to energy- or fuel consumption are available, the calculation is mainly a combination of those data with ***emission factors***. Release of Nr (to the atmosphere) mostly takes the form of nitrogen oxides (NO_x or N_2O), which is formed from N contained in the fuel (e.g. in coal, oil or biomass), but previously not considered as N_r – the so-called "fuel-NO_x" – and from oxidation of molecular N_2 from combustion air at very high temperatures only, the "thermal NO_x" (a third pathway, via reaction of hydrocarbons with molecular nitrogen, is less relevant). Emission factors cover the gross total of all these processes, but the importance of "thermal NO_x" makes it critical to differentiate between use of fuels in high temperature processes (e.g., internal combustion engines) and low temperature combustion (e.g., heating). Also process use of fuels (e.g. natural gas in fertilizer production) may be associated with completely different emission factors. Finally, the release into the atmosphere is critically dependent on pollution abatement devices. Catalytic converters and non-catalytic reduction technology are able to remove >95% of the NO_x released originally, thus strongly decreasing the ultimate "loss" to the atmosphere.

General remarks

29. The uncertainty with respect to the results for individual countries is large. However, for a comparison between the different countries this will be much smaller. The latter is also caused by using consistent datasets and identical assumptions related to N_r content, N_r emission factors, decline rate to N_2 of pools, etc.

30. Please note that for some terms there is so far no difference between different countries in the various regions of the world. This introduces an additional uncertainty in the results per individual country. Because of the method that is used, the number of these 'terms' is limited. An example of this is the percentage 'waste' used in the calculations. This will not be the same for every country, depending on the development stage of waste collecting systems (and figures), but was set to 25% for the method described here.

31. For many OECD countries, high quality data on emissions to the atmosphere are being derived regularly. For these countries, existing emission datasets should be used. Some of the most uncertain parts, specifically the level of emission abatement, are mostly associated to countries that do have high concern on their atmospheric emissions, and would equip their emission sources even with continuous measuring devices which feed into high quality emission data.

4.2 Data requirements and availability

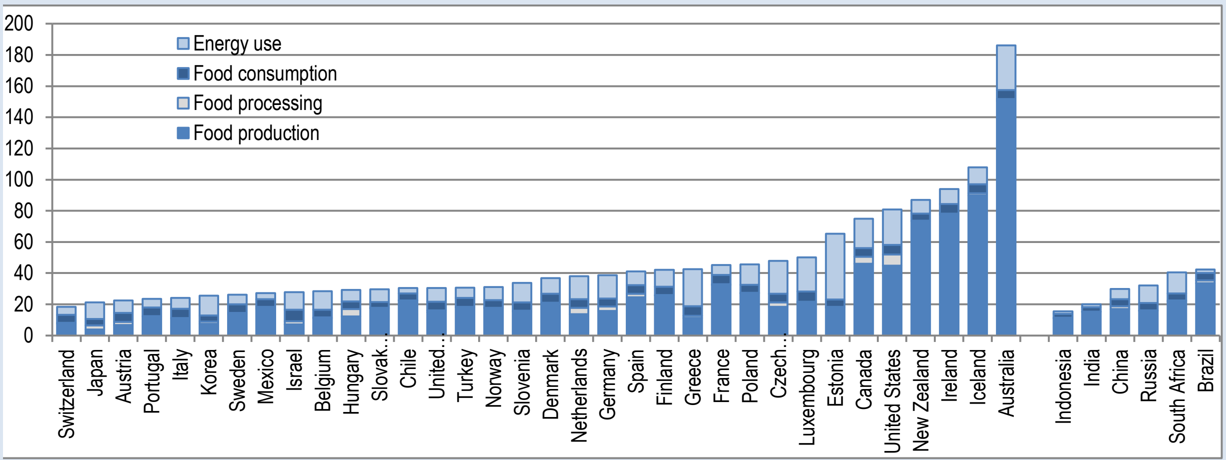
32. Next to describing the overall methodology, section 4.1 already gave a bit of an overview of the data that were used for the calculations. Here the overall datasets that were used for the calculations shown in Figure 2 are listed:

- *FAOSTAT*: global database with food balance and fertilizer data (1962 – 2010*)*
- *PBL-IMAGE*: global database with IMAGE data on Biological Nitrogen Fixation and Deposition (2010)
- *International Energy Statistics*: global database with country data on fossil fuel consumption and primary energy production (2006-2010).

33. Tier 1 results for OECD and BRIICS countries are presented in Box 1 (Source: INI).

Box 1 Tier 1 results for OECD and BRIICS countries

Average loss of reactive nitrogen per inhabitant, OECD and BRIICS countries, in kg N/cap/year



Country	Food production	Food processing	Food consumption	Energy use	Total Loss
Australia	150.6	1.1	5.7	28.8	**186.2**
Austria	6.7	2.0	5.7	8.0	**22.5**
Belgium	11.1	0.5	4.9	12.0	**28.5**
Canada	46.0	4.6	5.4	18.9	**75.0**
Chile	22.4	0.1	4.4	3.6	**30.5**
Czech Republic	18.5	2.9	5.4	21.2	**47.9**
Denmark	20.5	0.6	5.8	10.0	**36.9**
Estonia	17.9	0.5	4.7	42.3	**65.4**
Finland	25.5	0.5	5.3	10.9	**42.2**
France	32.3	0.8	5.9	6.2	**45.2**
Germany	15.7	2.9	5.2	14.8	**38.6**
Greece	11.3	1.4	6.0	23.9	**42.7**
Hungary	12.2	4.8	4.9	7.4	**29.2**
Iceland	89.9	1.3	5.9	10.9	**108.0**
Ireland	77.4	0.7	6.3	9.6	**94.0**
Israel	7.1	2.0	7.4	11.3	**27.8**
Italy	11.0	0.3	5.9	7.0	**24.2**
Japan	3.8	2.8	3.9	10.6	**21.2**
Korea	7.6	1.3	3.9	12.8	**25.6**
Luxembourg	21.3	0.2	6.7	21.9	**50.2**
Mexico	17.2	1.2	4.9	3.9	**27.2**
Netherlands	13.6	4.2	5.4	14.9	**38.1**
New Zealand	73.3	0.5	4.6	8.8	**87.0**
Norway	17.6	0.2	5.0	8.3	**31.1**
Poland	27.0	0.4	5.1	13.1	**45.6**
Portugal	12.0	0.4	5.6	5.6	**23.6**
Slovak Republic	17.3	0.5	3.8	8.1	**29.6**
Slovenia	15.3	0.5	5.5	12.3	**33.7**
Spain	24.5	2.3	5.4	8.9	**41.2**
Sweden	13.5	1.0	5.5	6.2	**26.2**
Switzerland	7.5	0.7	5.0	5.1	**18.3**
Turkey	18.0	0.5	5.7	6.6	**30.7**
United Kingdom	14.9	1.3	5.4	9.0	**30.5**
United States	44.8	7.1	6.1	22.8	**80.8**
OECD total	**26.2**	**3.0**	**5.4**	**13.3**	**47.9**
Brazil	33.5	1.9	4.7	2.3	**42.4**
China	16.9	2.0	4.5	6.5	**29.9**
India	15.1	0.2	2.9	1.8	**20.0**
Indonesia	10.9	0.5	2.5	1.7	**15.6**
Russia	15.8	0.3	4.8	11.3	**32.2**
South Africa	21.8	0.7	4.3	13.7	**40.6**
BRIICS total	**16.8**	**1.1**	**3.8**	**4.5**	**26.2**
World	**18.3**	**1.2**	**4.0**	**5.4**	**28.9**

4.3 Moving from Tier 1 to Tier2/3

34. While the above mentioned Tier 1 approach is rather straight forward, using available datasets on global scale, the Tier 2 and 3 approaches require some more explanation. The Tier 2 approach is, in principle, equal to Tier 1 with the exception that Tier 2 uses country specific data instead of information from the global datasets used for Tier 1. While results from the Tier 1 approach can be obtained without the assistance of the individual countries, the Tier 2 approach requires countries to deliver their country specific data for the calculation of their national nitrogen loss. An overview of the required data is given in the description of the Tier 1 approach.

35. The Tier 3 approach requires more detailed methodologies and datasets. Developing this approach asks for a simultaneous development of the methodology and an inventory of available country data. By doing this, the methodology development can be done in such a way, that it best reflects the country data that are available from different sources. Such a data inventory and methodology description could then form the basis for the operational methodology to be used by the OECD, together with the necessary data sources. The methodology development and data inventory will be based on previous work performed as part of the activities of the Expert Panel on Nitrogen Budgets under the Task Force on Reactive Nitrogen. This is described in the next section.

5. Tier 3 approach[6]

36. In this section guidance is provided in the calculation of nitrogen budgets, nitrogen use efficiency, and nitrogen surpluses and their improvements within the OECD countries. It is important to understand that "budgets" as defined here will not be limited to describe the flows across given system boundaries, but cover also stock changes and internal flows. All concepts are developed to allow guidance also for a broader range of nitrogen budgets at different scales and also for economic entities.

5.1 Introduction to Nitrogen Budgets

37. Nitrogen budgets (NBs) respond to the needs of policy makers and national experts to coordinate activities assessing potentially adverse nitrogen flows in and to the environment. National and international regulations require the collection of relevant information about such flows or about the resulting environmental state. Often such information is specifically compiled for the agricultural sector, recognizing the importance of nitrogen (N) as plant nutrient, while not fully reflecting the complete picture of the environmental nitrogen cascade. NBs overcome this problem (Leip et al., 2011):

1. NBs are an efficient instrument for visualizing the N cascade and its potential impact and thus help to raise awareness;
2. NBs provide policy makers with information for identifying intervention points and developing efficient emission reduction measures;
3. NBs can provide a tool for monitoring the impact and environmental integrity of implemented policies;
4. NBs are useful for comparisons across countries; and
5. NBs can help pinpoint knowledge gaps and thus contribute to improving our scientific understanding of the N cascade.

[6] Based on the 'Guidance document on national nitrogen budgets', annex to the draft decision on adoption of the guidance document by the Executive Body for the Convention on Long-range Transboundary Air Pollution (Geneva, 11-13 December 2012).

38. This section provides guidance to build NBs with a focus to the national scale (NNBs). The NNBs will support validation of environmental nitrogen flows (by way of identifying inconsistencies), guide the identification of intervention points to regulate environmental nitrogen emissions or releases and to optimize N use and to form the basis for the indicators that were mentioned in Section 2. In order to fulfill these goals, a minimum number of pools and flows considered is needed, which also requires harmonization between countries.

39. To this purpose, this section (a) provides a clear terminology to be used when constructing NNBs and (b) gives a description of the elements (pools) that must be included in any NNB taking into account the need to integrate existing structures and available documentation. Once NNBs become operative, additional descriptions and details for each of the pools will be developed.

5.2 Terminology

40. The following terms are described here in order to provide a better understanding of nitrogen budgets. They are therefore presented in a logical rather than alphabetical order:

1. *A nitrogen budget* consists of the quantification of all major nitrogen flows across all sectors and media within given boundaries, and flows across these boundaries, in a given time frame (typically one year), as well as the changes of nitrogen stocks within the respective sectors and media. NBs can be constructed for any geographic entity, for example at supra-national level (e.g. Europe), sub-national level (regions, districts), for watersheds or even individual households or for economic entities (such as farms) NNBs use the borders of a country including its coastal waters as system boundaries, such that the atmosphere above and the soil below this country are also included;

2. *Pools*: Nitrogen pools are elements in a nitrogen budget. They represent "containers" which serve to store quantities of nitrogen (these quantities may be referred to as nitrogen stocks). Exchange of nitrogen occurs between different pools via nitrogen flows. Nitrogen pools can be environmental media (e.g., atmosphere, water), economic sectors (e.g., industry, agriculture) or other societal elements (e.g., humans and settlements). Selection of pools may differ between budgets. For a NNB, all relevant pools to describe the nitrogen budget at a country-level shall be included;

3. *Sub-pools*: Pools can be further divided into sub-pools if sufficient data are available. For example, the pool "inland water" can be divided into groundwater, lakes, rivers, etc., with additional nitrogen flows across these sub-pools to be quantified;

4. *Stocks* represent real-world accumulations. Each pool can store a quantity of nitrogen, for example, as mineral or organic nitrogen in soils (for instance as in agriculture or semi-natural lands/pools). This quantity is the nitrogen stock. Nitrogen stocks may be very large with respect to nitrogen flows (e.g., for soil pools), and often N stocks are difficult to quantify. However, the most relevant parameter for the NB is a potential stock change, i.e. a variation over time of the respective accumulation, rather than the nitrogen stock itself. Nitrogen stocks can be composed of N in any nitrogen form. For NB, only stocks and stock changes of reactive nitrogen are relevant;

5. *Flow*: Nitrogen flows describe the transport of nitrogen over time between the various pools of an NB, or between the sub-pools within a pool. They also link any pool with the pools outside the system boundaries, the 'rest of the world' (RoW), in the form imports or exports (e.g. trade, atmospheric transport, riverine export). Flows of nitrogen can occur as reactive nitrogen (N_r) or

di-nitrogen (N_2). In addition, flows during which the transformation of nitrogen from reactive nitrogen to molecular N_2 or vice versa need to be considered. These flows include fixation (biological nitrogen fixation by plants and technical fixation by combustion processes or ammonia synthesis) as well as conversion of N_r to N_2 (resulting from denitrification and the anammox processes in soil biology, or from recombination during combustion). Flows must be represented in the same unit, e.g. in tons of N per year, or in tons of N per km^2 per year (also termed "flux");

6. *Balance*: Ideally, the balance of a pool, a sub-pool, or a full NB is closed, i.e. all nitrogen flows can be explained as input, output or stock changes. The balance equation is then $N_{output} + N_{stock\_change} - N_{input} = 0$. Such a closed NB-balance is theoretically possible for each pool defined and for a full NB. In practice, a closed balance is not a requirement of an NB and the balance becomes a value different from "0", with the difference referring to un-accounted nitrogen flows, including any errors. Un-accounted nitrogen flows indicate that contradicting/inconsistent data sources are used or that some data are missing. Both cases point to a need of better integration of the scientific understanding;

7. *Uncertainty*: Provides a quantitative estimate on the influence of imperfect information on the quantity of a nitrogen flow or stock change. Uncertainty assessment helps to set the priority for improving nitrogen budgets and is an important element of quality assurance in NBs. According to standards set by the Intergovernmental Panel on Climate Change (IPCC) which should be used here, too, a quantitative description of an uncertainty range should cover 95% of the total sample space. Uncertainty quantification typically will not cover bias, as any bias will be corrected as soon as it gets discovered.

5.3 Pools in national nitrogen budgets

41. A NNB must include all relevant pools that store nitrogen in N-stocks and exchange nitrogen with other pools or the RoW. An example has been established by Leip et al. (2011) as a contribution to the European Nitrogen Assessment (ENA). It contains a set of national nitrogen budgets, as well as a European budget (Figure 4).

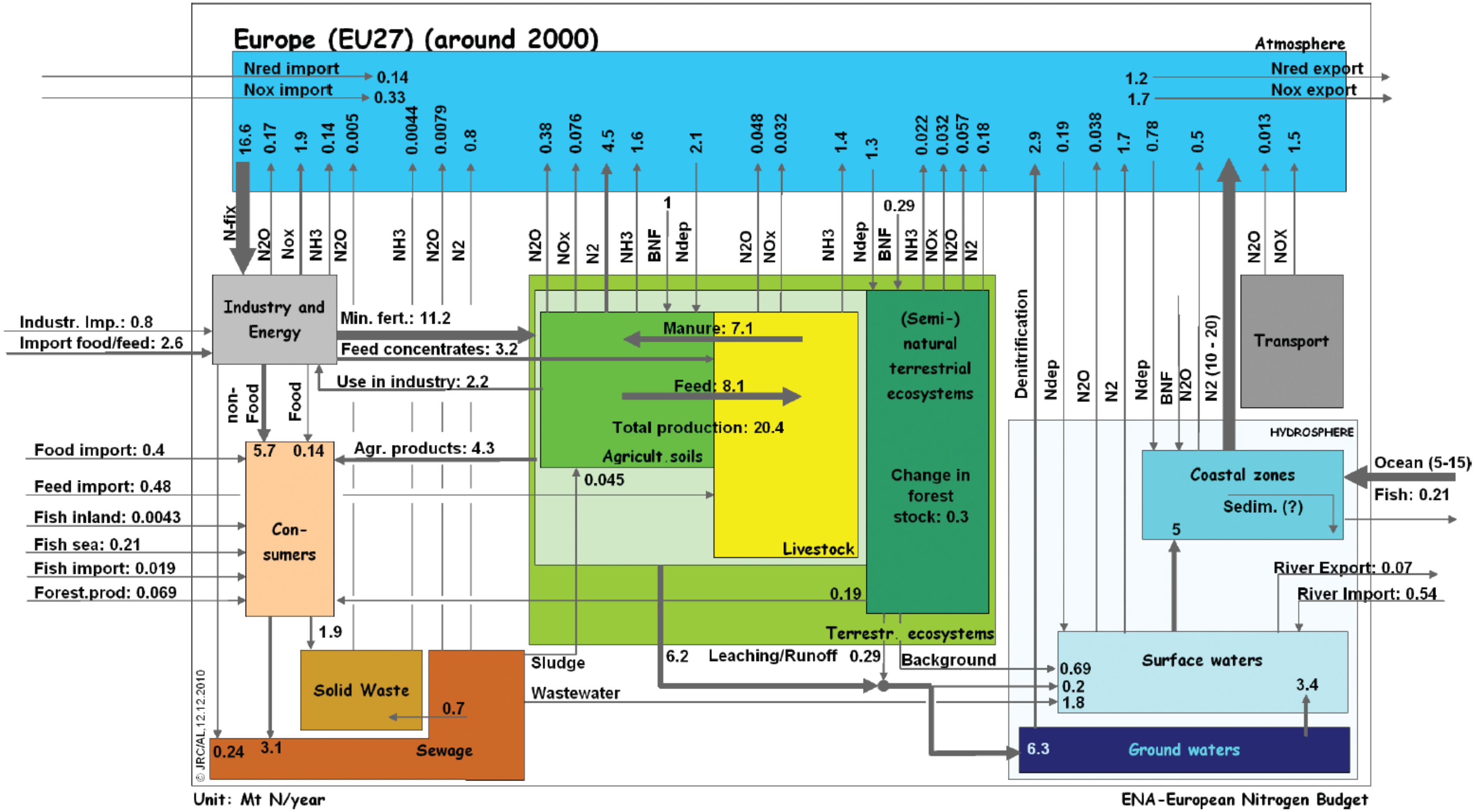
42. The European NB provides a comprehensive picture of nitrogen flows in Europe and can thus serve as a reference. However, the challenge of this section consists in building upon existing and well-established schemes, which provide appropriate information on a range of scales. For NNBs it is important to take advantage of existing structures, and to remain fully compatible with each of these activities while minimizing resources to close the remaining gaps towards a NB. Specifically of interest in the context of NNBs are national balances, as well as reporting obligations for national emissions of Nr for which guidance has already been developed and which are successfully applied in many countries:

a) The OECD, in cooperation with Eurostat, developed a handbook on gross nitrogen balances in agriculture (OECD, 2007) and is estimating the agricultural gross nitrogen surplus at a regular basis for OECD countries. The handbook on agricultural nutrient budgets was recently revised and expanded (Eurostat, 2013).

b) The EMEP/EEA air pollutant emission inventory guidebook (EEA, 2009) provides guidance on estimating emissions from both anthropogenic and natural emission sources of NO_x and NH_3.

c) The IPCC guidelines for National Greenhouse Gas Inventories (IPCC, 1997, 2006) provide guidance on the quantification of anthropogenic N_2O emissions.

Figure 4 European nitrogen budget (Leip et al., 2011)



43. In order to benefit, as much as possible, from the detailed data available from the air pollutant and greenhouse gas inventories submitted to EMEP (EEA, 2009) and the UNFCCC (see IPCC, 2006 and 1997), their structure is integrated closely. This also entails maintaining IPCC notation for reasons of consistency, expect that classification focusses on pools in contrast to the economic sectors used in the IPCC guidelines.

44. A NNB must be composed of eight essential pools (Table 1). For some pools, information on sub-pools must be provided. This concerns the Energy, Agriculture and the Waste pools, for which additional detail is required in order to include important flows occurring to- or from sub-pools and to provide a fully comparable national system. The definition of the sub-pools has been done according to IPCC definitions, thus data will be readily available.

45. The aim is for the list of pools to be comprehensive, i.e., any conceivable significant nitrogen flow between (sub-)pools can be accommodated into this scheme.

Table 1 Essential pools and sub-pools to be included in a NNB

Pool-ID	*Sub-pool*	*(Sub)Pool-Name*
1		**Energy and fuels**
1	A1+B	Energy conversion (includes flaring and fugitive emissions from fuels)
1	A2	Manufacturing Industries and Construction
1	A3	Transport
1	A4	Other energy and fuels (e.g., residential)
2		**Material and products in industry (processes)**
3		**Humans and settlements**
4		**Agriculture**
4	A	Animals
4	B	Manure / manure management
4	C/D/E/F	Crops & agricultural soils
5		**Forest and semi-natural vegetation including soils**
6		**Waste**
6	A	Solid waste disposal
6	B	Wastewater handling
6	C	Waste incineration
6	D	Other waste
7		**Atmosphere**
8		**Hydrosphere**
8	A	Inland waters (including ground water)
8	B	Coastal and marine waters

5.4 Description of the pools

Energy and fuels

46. The ‘Energy and fuels’ pool encompasses the flows of nitrogen of energy conversion sites, industry, transport and other uses of energy and fuels. The flows of nitrogen to be quantified include input flows (N-fixation) and output flows (N_r emissions). Input of nitrogen occurs both by ‘activating’ nitrogen contained in the fuels and through thermal generation of N_r at high temperatures during the burning process. Distinction between these two flows is difficult, however, and not required.

47. Emissions of Nr are linked to fuel use in the sub-pools, as reflected in national energy statistics and their implementation in reporting under the United Nations Framework Convention on Climate Change (UNFCCC). This is relevant to nitrogen pollution and emission flows which are generally well covered in atmospheric greenhouse gas (GHG) inventories. Even the questions of international transport and allocation of emissions in cross-boundary transport have been addressed in such inventories.

Material and products in industry

48. Typically, statistical information (energy statistics) differentiates between fuel combustion and feedstock use of fuels. IPCC deals with the latter case under “industrial processes”, a convention that is mimicked in NNBs.

49. Main input flows are nitrogen fixation processes, such as the Haber-Bosch ammonia synthesis. Industry processes use also nitrogen in agricultural products and imported products. Output flows that need to be quantified are fertilizers, compound feed products, food products, and non-food chemical products (nitric acid, melamine, caprolactam, etc. as used for example in explosives, plasticisers and nylon).

Humans and settlements

50. A separate sector in the IPCC guidance covers the use of compounds that are subsequently released into the atmosphere. For NNBs, this concept needs to be extended, to subsume “humans” as a pool encompassing various sub-pools:

a) The human body with intake of nitrogen in food from agriculture, fishery, industry, and output of nitrogen mainly to sewage systems;

b) The ‘material world’ made of chemical products from industry which accumulate in the ‘humans’ pool or are disposed of, incinerated or otherwise managed in waste system;

c) The ‘organic world’ with products from agriculture and forestry, including non-consumed food and wood and paper products, but also flowers, package material etc. These products are entering various waste streams, i.e. sewage systems, landfills, waste incinerators, are composted or deposited in other ways;

d) Non-agricultural animals (pets) that are fed on agricultural products.

51. The ‘humans’ pool in linked to the RoW through trade of products. Also the flows to and from the atmosphere (deposition, emissions) may need consideration. Output flows must be quantified to the different sub-pools of the ‘waste’ pool. Output flows to other pools are usually small, but should be quantified if significant.

Agriculture

52. Agriculture is a key pool for a NNB, and is a key driver for the global nitrogen cycle. Emissions of Nr from agricultural sources are important elements in environmental assessments. Agricultural flows are typically large and associated with high uncertainty. A NNB should differentiate the following sub-pools, as defined in analogy to the reporting framework for the sector “agriculture” under the Convention on Long-Range Transboundary Air Pollution as well as under the United Nations Framework Convention on Climate Change (UNFCCC):[7]

[7] Guidelines for reporting emission data under the Convention on Long-Range Transboundary Air Pollution: http://www.unece.org/fileadmin/DAM/env/documents/2008/EB/EB/ece.eb.air.97.e.pdf ; List of annexes:

a) Animal husbandry (corresponding to category 4A[8]). Input of nitrogen to livestock occurs through grazing, and feeding of crops/fodder and imported feed (concentrates). Output flows of nitrogen from livestock are in products (meat, milk, eggs, wool, etc.), non-carcass retained nitrogen in the animal body, and manure. Also emissions of Nr from animal housing systems might occur;

b) Manure management and manure storage systems (corresponding to category 4B). Input to manure management and storage systems is, first of all, from animal husbandry. The concept extends to N input to biogas plants even when limiting to material from energy crops (consistent with approaches taken by EEA, 2009). Main output flows are emissions to the atmosphere and hydrosphere and application of manure on soils. If import/export of manure is a significant flow in a country, it should be quantified as well. Manure management and storage systems are important for emission mitigation measures;

c) Soil-based agricultural pools. This includes rice cultivation (category 4C), cultivation of upland crops (category 4D) including grazing by ruminants, and prescribed burning of savannahs and field burning of agricultural residues (categories 4E and 4F). Input flows are the application of mineral fertilisers, nitrogen in manure that has been applied to fields (i.e., following spreading or from grazing livestock), nitrogen in other organic fertilisers (including crop residues), seeds, and N in atmospheric deposition and biological fixation. Output flows are harvested crop products, crop residues, and emissions of N to the atmosphere or hydrosphere.

53. In addition to IPCC's definition of agriculture, NNBs consider not only soil processes, but also stock changes in animal husbandry, manure management and storage systems, and cropland and grassland soils.

54. In contract to IPCC methodology, *indirect* emissions from agricultural sources are not included here, as they are not considered as an output flow from the agricultural pool. Instead, emissions of N following volatilization and deposition of Nr are quantified for the pool where the atmospheric deposition happens (forests and other non-agricultural vegetation and soils, settlements, or inland or coastal/marine waters). Equally, emissions of agricultural N towards the hydrosphere are "followed" along its path. This constitutes a deviation from IPCC's approach but maintains consistency in the NNB.

55. The "Gross Nitrogen Balances" of the OECD (2007) have been used successfully to describe the nitrogen flows in the agriculture pool. More detailed information, supporting the development of some of the national coefficients used in the OECD approach, is being compiled by national authorities to fulfill the requirements of national GHG or air pollutant inventories. The DireDate project (Oenema et al., 2011) discusses the respective reporting requirements and data on agricultural nitrogen in detail and serves as an input to EUROSTAT's activities to align the methodology for estimating Gross Nitrogen Balances with other international reporting obligations. Guidance provided here takes account of these existing activities and strives to harmonize, as much as possible, the different needs while taking advantage of existing activities. This will allow for a reassessment of data needs at all levels with respect to not only present

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http://www.ceip.at/ reporting-instructions/annexes-to-the-reporting-guidelines/; Cooperative Programme for "Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP)/European Environment Agency (EEA) guidebook for reporting under the Convention on Long-Range Transboundary Air Pollution: http://www.eea.europa.eu/themes/air/emep-eea-air-pollutant-emission-inventory-guidebook/emep; updated UNFCCC reporting guidelines on annual GHG emission inventories: http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600003988, 1996 IPCC Guidelines for National Greenhouse Gas Inventories: http://www.ipcc-nggip.iges.or.jp/public/gl/invs4.html and Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories: http://www.ipcc-nggip.iges.or.jp/public/gp /english/index.html.

[8] Reference to this and the following codes is contained in the documents listed in footnote 1

nitrogen flows, but also potential flows under conditions of emission abatement. Integrating such options is important for the use of NBs to study intervention points.

Forest and semi-natural vegetation including soils

56. While the IPCC sector "Land use, land use change and forestry" focuses on carbon stock changes, the corresponding NNB pool assesses the related change in nitrogen stocks in biomass and non-agricultural soils. This comprises all natural and semi-natural terrestrial ecosystems, according to the CORINE land cover class 3 "Forests and semi-natural areas" (EEA, 2007). Input flows are atmospheric deposition, biological N-fixation, and application of mineral or organic fertilizer. Output flows are harvesting of products to industry, to the humans, or as a fuel to 'energy', as well as emissions to the atmosphere and the hydrosphere.

Waste

57. This sector is another major contributor of environmental nitrogen. By separation specifically between waste disposal, wastewater treatment, incineration of waste, and other waste streams, NNBs follow the same concept as IPCC. Due to coverage of multiple environmental media, several flows additional to the ones covered by IPCC need consideration. These include, specifically, waste and sewage produced by humans, application of sludge to fields and release of wastewater to surface waters.

Atmosphere

58. Atmosphere is used mainly as a transport medium, as the atmosphere serves to collect, to deposit and to transport reactive nitrogen under various chemical forms. Even though most of the available nitrogen is stored here in the form of inert molecular N_2, only the fraction present as N_r or being converted to or from N_r must be quantified. The quantification of conversions between compounds of different possible atmospheric sub-pools (e.g., oxidized or reduced N_r-species) is not required, except for N_2 fixation to NO_x due to lightning, which is considered as an input flow. Other input flows are atmospheric import of N_r, as well as emissions from all other pools in a NNB. Also fluxes of N_2 from pools to the atmosphere are regarded as input flow. Output flows are biological and technical N-fixation, export of N_r by atmospheric transport and N_r-deposition to land-based pools.

Hydrosphere

59. The hydrosphere needs to be considered in addition to the existing IPCC categories. Water bodies not only provide a major environmental transport pathway but are also an important element in the nitrogen cascade. Some transformation processes, e.g. aqueous formation of the greenhouse gas N_2O actually take place here. Thus it is consistent to assign the "indirect" emissions due to leaching of agricultural nitrogen (in IPCC terminology) to the water pool, together with similar transformation of other water-available N_r. Again this difference to the IPCC approach is need for consistency. Several other flows, most of which bear prime responsibility for water pollution, are specifically relevant for NNBs, as is the split into the individual pools describing inland waters (groundwater and surface water) and marine waters (such as coastal lagoons and estuaries). The quantification of imports and exports via surface and ground waters is of special importance for NNBs. These processes may play a dominant role for closing balance equations of the water pools.

5.5. Specific guidance on each nitrogen pool of a NNB

60. This section contains the framework under which specific guidance to each of the eight pools listed including the required sub-pools can be developed (later to be added as Annexes to this document). For each pool, the following subsections should be considered:

a) Introduction, main known features of the pool (compared to other pools);

b) Definition: detailed description of activities/flows encompassed by the pool; clear definition of boundaries, separate description for all potential nitrogen species involved;

c) Internal structure: possible reference to sub-pools and their structure;

d) Pool description: flows of N_r into and out of the pool; flows of N_2 formed or used when undergoing conversion (e.g., fixation or denitrification); stock changes within the pool; “unlocking” (of other relevant fixed nitrogen) into N_r, if relevant; conversion of N_r species, if needed. The pool definition requires keeping the balance of the pool conceptually closed;

e) Underlying data: suggestions of data sources to be used (e.g. reference to other guidelines);

f) Factors and models: detailed descriptions of calculation algorithms for quantitative flow (and stock change) information, labeling of flows that are determined as residual from closing balance equations;

g) Uncertainties, data quality issues and other items critically affecting results; indication of potentially missing flows;

h) References, bibliography, further reading;

i) Document version, author contact information.

6. Way Forward

61. In a separate document the methodology of deriving the indicators mentioned in Section 2 will be described. The extent to which all the indicators can actually be addressed depends on the availability of necessary data (see Section 5). This needs to be explored in the coming period.

62. Once the Tier 3 approach has been set up, there are also opportunities for its further development as a means to highlight national impacts on the environment. Such extension should explore:

a) The calculation of national nitrogen footprints[9], including the consequences of embedded/imported national consumption differences.

b) The calculation of a global nitrogen indicator, and comparison with an aggregate for all OECD countries.

c) Refining the link between nitrogen losses to nitrogen threats (further comments below).

d) Extending the easier approaches to more detailed approaches, including consideration of detailed data sources, data harmonization, comparison of detailed/simple approaches.

e) The relationship between the different indicator options and further work to define possible planetary boundaries for reactive nitrogen.

63. In order to link the high-level nitrogen indicator information (e.g. total reactive nitrogen loss – Tier 1 & 2 approach) back to the threats, further development might use a scheme for redistributing the total loss to its different compounds (i.e. which part goes to N_2O, NH_3, N_2, NO_3, NO_x). An initial scheme of this kind was used to link nitrogen footprint estimates (in terms of nitrogen losses) of different regions (Figure 2) with the different compounds. Based on determining the overall losses in terms of the individual compounds, linking them to threats becomes relatively straight-forward.

[9] Note: footprint in this context is expressed as loss of nitrogen to the environment due to consumption. Import/export of nitrogen losses is not considered (yet) to calculate the overall footprint.

GLOSSARY

Creation of reactive nitrogen	Conversion of unreactive nitrogen (N_2) into a reactive form (N_r)
Emissions	Emissions are the ‘act or materials being sent or thrown out’. In this context it is nitrogen in some form being ‘thrown out’ or released into the environment. While this can, in principle, mean that it is emitted into the air, soil or water, in the context of this note they are referred to as atmospheric emission
Emission factor	An emission factor (or emission intensity) is the average emission rate of a given pollutant from a given source relative to the intensity of a specific activity (e.g. Grams of nitrogen oxides released/emitted per distance travelled by car).
European nitrogen assessment	The European Nitrogen Assessment was the major outcome of the European Science Foundation programme ‘Nitrogen in Europe’ (nine) and addresses current nitrogen issues, the cascade effects and the interactions and feedbacks. The ENA provides governments and other stakeholders insight in the balance between the benefits of fixed nitrogen to society, against the different adverse effects of excess nitrogen in the environment. The ENA is available via www.nine-esf.org/ENA.
Haber-Bosch process	The Haber-Bosch process is the industrial implementation of the reaction of nitrogen gas and hydrogen gas. It is the main industrial route to ammonia.
Nitrogen loss	Nitrogen loss is the release of reactive nitrogen from the various processes (e.g. Agriculture, industry, traffic) to the environment, irrespective of its route (air, water, soil)
Reactive nitrogen	Reactive nitrogen is a term used for a variety of nitrogen gases that are highly (chemically/biologically) reactive, such as nitrogen oxides (no_x), ammonia (NH_3), nitrous oxide (N_2O), nitrate (NO_3^-), urea, and organic N compounds. The compounds are produced via the Haber-Bosch process, as a negative side effect of burning fossil fuels, or via lightning, converting unreactive nitrogen (atmospheric N_2) into its reactive forms.
N_r pools and N_r bulks	Environmental and economic bulk units such as soil, water, fertilisers, etc. With natural and influenced increased of content of N_r in different forms (NO_x, NO_3^-, NH_3, HNO_x).
Soil nitrogen balance	Soil nitrogen balance estimates the magnitude of nitrogen loss/gain of agro-eco systems and provides information about the release of nitrogen into the environment as a consequence of e.g. Agricultural practices.
Unreactive nitrogen	Unreactive nitrogen is atmospheric nitrogen (as N_2) that is not biologically/chemically active. Reactive nitrogen can become unreactive again via the process of denitrification

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