A National Nitrogen Target for Germany

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Abstract: The anthropogenic nitrogen cycle is characterized by a high complexity. Different reactive nitrogen species (NH3, NH4+, NO, NO2, NO3-, and N2O) are set free by a large variety of anthropogenic activities and cause numerous negative impacts on the environment. The complex nature of the nitrogen cycle hampers public awareness of the nitrogen problem. To overcome this issue and to enhance the sensitivity for policy action, we developed a new, impact-based integrated national target for nitrogen (INTN) for Germany. It is based on six impact indicators, for which we derived the maximum amount of nitrogen losses allowed in each environmental sector to reach related state indicators on a spatial average for Germany. The resulting target sets a limit of nitrogen emissions in Germany of 1053 Gg N yr−1. It could serve as a similar means on the national level as the planetary boundary for reactive nitrogen or the 1.5 °C target of the climate community on the global level. Taking related uncertainties into account, the resulting integrated nitrogen target of 1053 Gg N yr−1 suggests a comprehensible INTN of 1000 Gg N yr−1 for Germany. Compared to the current situation, the overall annual loss of reactive nitrogen in Germany would have to be reduced by approximately one-third.

Keywords: reactive nitrogen; planetary boundary; nitrogen; emission ceiling

1. Introduction

Reactive nitrogen (Nr) is essential and beneficial for plant production. Our understanding of Nr includes and focuses on total nitrogen (N), ammonia (NH3), ammonium (NH4+), nitrogen monoxide (NO), nitrogen dioxide (NO2), nitrogen oxide (NOx), nitrate (NO3−), and nitrous oxide (N2O) [1]. At present, the anthropogenic production of mineral fertilizer through industrial ammonia fixation ensures the feeding of about 50% of the global population [2]. However, through agricultural production and also through combustion processes, anthropogenic reactive nitrogen unintentionally also enters the environment, resulting in several severe environmental impacts [3]. Currently, about half of the year-to-year globally fixed nitrogen is resulting from anthropogenic sources [1]. The consequences of an increased availability of reactive nitrogen include biodiversity loss, health impacts, reduced air and water quality, and impacts on the climate [4]. Therefore, the urgent need for a sustainable nitrogen management has recently been identified by several institutions at the global level [5–7]. Rockström et al. [8] and Steffen et al. [9] included a planetary boundary for anthropogenic nitrogen fixation into their concept of keeping the earth system in a safe operating space and identified the alteration of the nitrogen cycle as
one of the three most urgent fields of action. The current boundary for nitrogen, based on an original work by de Vries et al. [10], is currently clearly transgressed.

In contrast to the climate issue, nitrogen not only affects global biogeochemical pathways but also takes effect on smaller scales nearby its source. Regional and local problems also suggest the search for solutions at smaller scales. That is why numerous assessments of the nitrogen cycle at the regional and national level, for example, in Europe, India, or California, have been published recently that included recommendations for better nitrogen management [11–13].

In Germany too, the release of reactive nitrogen to the environment poses different environmental threats. A quantification of the German nitrogen cycle with a description of the most urgent problems has been published by the German Environment Agency [14]. The agricultural sector is the major sector responsible for reactive nitrogen losses (67%), followed by industry and energy (16%), transports (11%), and urban runoff and wastewater disposal (6%) [15]. Among others, the loss of biodiversity through reduced and oxidized nitrogen species deposition, the pollution of groundwater and coastal ecosystems by nitrate, and the ongoing exceedances of health-oriented concentration limits for nitrogen dioxide at traffic-related monitoring sites result from these losses. This is reflected in recent infringement decisions against Germany’s insufficient implementation of the European Union’s Nitrate and Air Quality Directive [16,17]. To overcome the problems, the Federal Government launched the development of a national nitrogen strategy [18], which endorses the need for an integrated nitrogen action program.

However, the acknowledgment of a certain risk for humans and the environment and the acceptance of political measures and strategies by the general public and relevant stakeholders depend greatly on the tangibility of the problem to be solved. On the global level, the Planetary Boundary Concept [8] or the 1.5 °C target of the climate community [19] are examples that successfully illustrate complex problems in an easily understandable way.

For reactive nitrogen, such a comprehensive concept is missing so far on the national level [20], and the German Advisory Council on the Environment suggests the development of an integrated nitrogen strategy for Germany through the Federal Government [21]. These suggestions comprise the development of an integrated nitrogen target for Germany.

With this study, we present an attempt to develop such an integrated national target for nitrogen (INTN) for Germany. In line with the suggestions from Salomon et al. [20], we expect such a target to facilitate communications with the general public and policymakers and to be a core indicator for the success of political measures. Our objective is to develop a national complement to the nitrogen planetary boundary on the global level. To create confidence in such a value and to implement it most effectively in environmental policies, we are confident that relating a national nitrogen limit to existing environmental critical target values, such as concentration limits or deposition loads, for example, is a promising procedure.

2. Materials and Methods

To calculate the INTN, the six most relevant impact indicators affected by excessive amounts of reactive nitrogen were chosen: (1) vegetation affected by NH₃-concentration, (2) terrestrial ecosystems affected by eutrophication, (3) surface water quality and (4) groundwater quality affected by nitrate, (5) nitrous oxide emissions affecting climate change, and (6) human health affected by NO₂ concentration. For each of these impact indicators, critical target values exist for Germany. In most of the cases, these are concentration limits to protect air, water, and living beings from excessive nitrogen pollution. We selected those target values reflecting the current legislative situation in Germany or, where no legal value was available, those reflecting the latest scientific knowledge. Sectors and targets are shown in Table 1. Our basic approach was to calculate a maximum permitted nitrogen loss per year on the national level for each impact indicator, such that related quality targets, herein referred as state indicators, are met in Germany at the spatial average. Where such
values for maximum loss rates were available from current legislation, we adopted those directly as target values. By the coverage of the six impact indicators, we obtained maximum loss rates for reactive nitrogen species, such as nitrate (NO\textsubscript{3})\textsuperscript{−}, nitrous oxide (N\textsubscript{2}O), nitrogen oxide (NO\textsubscript{x}), ammonia (NH\textsubscript{3}), and total nitrogen (N\textsubscript{total}). Those rates were given uniformly in gigagram nitrogen per year (Gg N yr\textsuperscript{−1}), converting species-related values into normalized nitrogen values by applying conversion factors related to the molecular weight per species.

Table 1. Overview of selected impact indicators and related state indicators to calculate the national nitrogen target as the sum of the related maximum permitted nitrogen losses per pressure indicator.

| Number | Impact Indicator | State Indicator | Pressure Indicator (Nitrogen Loss Rate) |
|--------|-----------------|-----------------|-----------------------------------------|
| (1)    | Vegetation affected by ambient NH\textsubscript{3} concentration | NH\textsubscript{3} critical level for higher plants: 3 µg m\textsuperscript{−3} | NH\textsubscript{3} emissions |
| (2)    | Terrestrial ecosystems affected by eutrophication (deposition) | 35% reduction of exceedance of the Critical Load for eutrophication from 2005–2030 | NH\textsubscript{3} and NO\textsubscript{x} emissions |
| (3)    | Surface water quality (to prevent coastal water from eutrophication) | N\textsubscript{total} concentration to protect North Sea: (2.8 mg N l\textsuperscript{−1}) and Baltic Sea: (2.6 mg N l\textsuperscript{−1}) | N\textsubscript{total} load |
| (4)    | Groundwater quality affected by nitrate | NO\textsubscript{3} concentration in groundwater: 50 mg l\textsuperscript{−1} | NO\textsubscript{3} leaching |
| (5)    | Nitrous oxide emissions affecting climate change | N\textsubscript{2}O emission: long-term goal reduction 80–95% | N\textsubscript{2}O emissions |
| (6)    | Human health affected by atmospheric NO\textsubscript{2} | NO\textsubscript{2} concentration: WHO effects level for the background: 20 µg m\textsuperscript{−3} | NO\textsubscript{x} emissions |

To derive INTN, we calculated the sum of the lowest maximum allowable nitrogen loss rates per nitrogen species.

2.1. Vegetation Affected by NH\textsubscript{3}-Concentration

We calculated the maximum annual emission rate of NH\textsubscript{3} to protect vegetation against a critical concentration of 3 µg m\textsuperscript{−3} (critical level, short CLev, recommended by the Geneva Convention on long-range transboundary air pollution [22]) from modelled NH\textsubscript{3} emission and concentration data at a spatial resolution of 0.03125° longitude and 0.015625° latitude. Due to the high deposition velocity of NH\textsubscript{3} [29], we assumed that the concentration in a grid cell is influenced primarily by the emission in the same grid cell. The emission data is based on the reported national submission of NH\textsubscript{3} emissions to the European Environment Agency (EEA) in the year 2015 [30]. As the spatially resolved ambient concentrations and emissions are strongly correlated, the maximum allowable NH\textsubscript{3} emission per grid cell (Em\textsubscript{NH3max}) can therefore be derived from a linear regression of the spatially resolved data (Equation (1))

\[
Em_{\text{NH3max}} = \left(\frac{\text{CLev} - b}{a}\right) \left[\text{Gg yr}^{-1}\right]
\]

with CLev = 3 µg m\textsuperscript{−3} NH\textsubscript{3} and a, b regression parameters. The sum of the positive differences between the modelled emission (Em\textsubscript{NH3,i}) and the resulting maximum allowable emission (Em\textsubscript{NH3max,i}) per grid cell (N = number of grid cells = 6314) corresponds to the reduction of the related total NH\textsubscript{3} emissions (R\textsubscript{NH3}) that is required to remain below the critical concentration in each grid cell (eq 2). To obtain a value for NH\textsubscript{3}–N, the CLev of 3 µg m\textsuperscript{−3} NH\textsubscript{3} for vascular plants and the underlying concentration and emission data were converted to the fraction of nitrogen in the ammonia molecule with a factor of 14/17.

\[
R_{\text{NH3}} = \sum_{i=1}^{N}(Em_{\text{NH3},i} - Em_{\text{NH3max},i}) \left[\text{Gg yr}^{-1}\right]
\]
2.2. Terrestrial Ecosystems Affected by Eutrophication

To protect terrestrial ecosystems from eutrophication and resulting loss of biodiversity, the deposition of reactive nitrogen from atmosphere into ecosystems needs to be reduced. Emission reduction requirements for NH\(_3\) and NO\(_x\) for Germany are defined within the framework of the European Union’s directive on the reduction of national emissions of certain atmospheric pollutants, the so-called NEC Directive [24]. Assuming a successful implementation and compliance with the directive’s requirements until 2030, the area where critical loads for sensitive ecosystems are exceeded will decline by about 35% compared to the area in 2005 [23]. For the purpose of deriving a national nitrogen target, we adopted the current reduction requirements for Germany for NH\(_3\) (29%) and NO\(_x\) (65%) between 2005 and 2030, and calculated maximum allowable NH\(_3\) and NO\(_x\) emissions in 2030 based on the emission reporting submitted in 2017 [30].

2.3. Surface Water Quality

Increased inputs of reactive nitrogen put surface waters under severe pressure by unbalancing the ecosystem. The result is eutrophication, which can lead to hypoxia of surface waters and cause further release of toxic compounds [31]. However, primary production of fresh water ecosystems in Germany is predominantly controlled by phosphorous and only to a lesser extent by nitrogen [32]. In contrast, productivity of coastal and marine ecosystems is limited by nitrogen, which puts them at high risk for eutrophication by total nitrogen loads from rivers (N\(_{\text{total}}\), mainly as nitrate). To reduce nitrogen inflow with rivers into coastal ecosystems, maximum allowable concentration levels to protect North Sea (2.8 mg N l\(^{-1}\)) and Baltic Sea (2.6 mg N l\(^{-1}\)) coastal ecosystems are defined for estuary areas in the German clean water legislation [25]. The German Federal States are the authorities responsible for reducing nitrogen inputs into rivers, such that the concentration limits mentioned above can be met. The river basin associations of the Federal State authorities calculated maximum allowable total nitrogen loads (N\(_{\text{total}}\)) for the river basins Rhine, Elbe, Ems, Weser, Eider, Schlei-Trave, and Warnow-Feene to meet these concentration limits for North Sea and Baltic Sea [33]. The given river basins cover most of the area, except south-eastern Germany, which is covered by the Donau-basin. The calculations were based on long-term measurement data of concentration and loads in the given river basins under the basic assumption that the annual mean of the total N concentration is proportional to the total annual N load in these surface waters. We added these river-related computed loads up and transferred the sum directly into our database for the purpose of deriving a national nitrogen target.

2.4. Groundwater Quality Affected by Nitrate Concentration

The Nitrate Directive of the European Union aims to protect groundwater from nitrate pollution from agricultural sources and defines a quality threshold of 50 mg NO\(_3\) l\(^{-1}\). Nitrogen budget surpluses from agricultural activities need to be reduced to diminish nitrate leaching with seepage water. To calculate the maximum permissible loss of nitrogen from agricultural land use through leaching to the groundwater, the Federal State data of nitrate monitoring in groundwater was evaluated in combination with regionalized modelled nitrogen soil surface budget surpluses. In a first step, a high-resolution Germany-wide map of nitrate concentrations in groundwater (1 × 1 km) was produced based on measured nitrate concentrations from some 5414 groundwater Federal State groundwater-monitoring stations, regionalized using the “Random Forest” modelling method based on spatial data (maps) for hydrogeology, land use, and further parameters [34]. As a simplification, we neglected the denitrification and retention potential and assumed that the nitrate concentration in groundwater equals nitrate concentration in seepage water and is predominantly due to inputs of nitrate through leachate from agricultural areas. The rationale behind this assumption is based on the precautionary principle. For each grid cell \(j\) with nitrate concentration \(c_j > 50\) mg NO\(_3\) l\(^{-1}\), the relative reduction of the NO\(_3\) concentration, \(\Delta c_j\) (%), necessary to comply with the quality standard of 50 mg NO\(_3\) l\(^{-1}\) was
calculated. In a second step, these grid-specific relative reduction values were transferred to the gridded dataset of nitrogen budget surpluses [35], and we assumed that the necessary reduction in the nitrate concentration in seepage water and groundwater was proportional to the necessary relative reduction in the nitrogen surplus (\(n_s\)) of the respective agricultural area (Equation (3)).

\[
\Delta(n_s)_j[\%] = \Delta c_j[\%]
\]

The reduction in the absolute nitrogen surplus per grid cell \(\Delta(NS)_j\) in kilogram nitrogen per year (kg N yr\(^{-1}\)) for each grid cell can then be calculated from the absolute nitrogen surplus data, the necessary relative reduction and the used agricultural area per grid cell: the sum of the absolute necessary reductions per grid cell (\(N = \text{number of grid cells} = 357,582\)) corresponds to the required overall reduction of the nitrogen surpluses (\(R_{NS}\)) to remain below the critical nitrate concentration in each grid cell (Equation (4)).

\[
R_{NS} = \sum_{j=1}^{N} NS_j \left[ Gg \text{ yr}^{-1} \right]
\]

2.5. Nitrous Oxide Emissions Affecting Climate Change

We calculated maximum permissible N\(_2\)O emissions based on targets defined in the national Climate Action Plan 2050 of the German Federal Environment Ministry [27]. All calculations were based on the reported greenhouse gas emission 2017 [36]. As a long-term objective for 2050, the Action Plan defines a reduction of total greenhouse gas emissions in Germany (in CO\(_2\) equivalents) by 80–95% as compared to 1990 and a corresponding interim reduction target for 2030 of 55%, which is also defined in terms of sectoral reduction targets. The action plan does, however, not define a specific target for nitrous oxide emissions. Therefore, we used the existing sectoral targets for 2030 to derive a target for nitrous oxide emissions in 2050. For N\(_2\)O emissions from the energy sector, an average reduction in line with the long-term target for total greenhouse gas emissions is assumed (~87%, as compared to 1990). For N\(_2\)O emissions from the waste sector, we assumed that the interim target corresponds to the long-term target (~87% as compared to 1990). For N\(_2\)O emissions from agriculture, the interim target for 2030 (32.5%) was extrapolated linearly to 2050, resulting in a necessary reduction of 40% compared to 1990. Comparing these three sectoral reduction targets to the N\(_2\)O emission situation in 2015 [36] provides a target for maximum allowable N\(_2\)O emissions, which we included in the national nitrogen target. Since in the industrial sector nitrous oxide emissions were already reduced by 95% between 1990 and 2015, we assumed that the emissions remain at the level of 2015 in this sector.

2.6. Human Health Affected by NO\(_2\) Concentration

To protect human health from pollution by nitrogen dioxide, a concentration limit of 40 \(\mu g\) m\(^{-3}\) as an annual mean is defined in the European Air Quality directive [37]. However, this limit mainly addresses hotspots with heavy traffic. Background concentrations are well below this concentration limit. Deriving a maximum allowable NO\(_x\) emission at the national scale from concentration measurements at hotspots that are strongly affected by local sources (i.e., traffic or industry) is therefore not adequate. At a measurement site exposed to heavy traffic, cutting local emission from traffic will likely lead to compliance with the concentration limit. Therefore, our approach for deriving a national emission target focusses on a limit value of 20 \(\mu g\) m\(^{-3}\) at background stations, proposed by the World Health Organization [28]. Measurements at background sites are influenced by emission sources at a wider range and are not exposed to specific local sources [38,39]. We therefore assume that they are representative of the emissions at the national scale and can therefore be used to derive a national target. We evaluated measurement data available for 179 background stations in Germany for the years 2002–2015. We assumed that the 98th percentile value of NO\(_2\) measurements from all background stations is approximately proportional to the national NO\(_x\) emissions. The 98th percentile value was chosen, because
the set of evaluated background stations should fulfill the requirement as far as possible to be unaffected by local emission sources. However, this requirement cannot be guaranteed for all background measurement sites over the entire time period considered, for which reason the choice of the 98th percentile acknowledges that some of the background measuring stations could also be affected by local emission sources. With \( A(t) \) being the 98th percentile of background concentrations measurements in the year \( t \) and \( E(t) \) as Germany’s national NO\(_x\) emissions for the year \( t \), the target emission \( E_{\text{max}} \) is calculated as follows:

\[
E_{\text{max}} = A_{\text{max}} \left( \frac{E(t)}{A(t)} \right) \left[ \text{Gg yr}^{-1} \right]
\]

where \( A_{\text{max}} = 20 \ \mu\text{g m}^{-3} \) and \( \frac{E(t)}{A(t)} \) denotes the average proportion between NO\(_x\) emissions and 98th percentile of NO\(_2\) concentration measurements over the time period 2002–2015.

3. Results

3.1. Vegetation Affected by NH\(_3\) Concentration

The maximum permissible NH\(_3\) emissions per grid cell for compliance with the critical level can be derived from a linear regression between ambient ammonia concentrations and ammonia emissions per grid cell. NH\(_3\) emission and NH\(_3\) concentration maps are shown in Figure 1. The linear regression between emission and concentration data is shown in Figure 2.

![Figure 1](image_url)
Figure 2 shows that to meet the critical level of 3 µg NH₃ m⁻³ (2.47 µg NH₃ m⁻³), the annual NH₃ emissions per grid cell must not exceed a maximum of 0.12 Gg NH₃–N yr⁻¹. The sum and therefore the national total of the resulting maximum allowable emissions per grid cell therefore is 441 Gg NH₃–N yr⁻¹.

3.2. Terrestrial Ecosystems Affected by Eutrophication

The absolute target values for NH₃ and NOₓ for the year 2030 are based on the reduction requirements for Germany under the NEC Directive between 2005 and 2030. The underlying emission data is based on the German emission report 2017. The report shows 558 Gg NH₃–N yr⁻¹ and 479 Gg NOₓ–N yr⁻¹ for the year 2005 [30]. The reduction requirement for Germany of 29% NH₃ between 2005 and 2030 [24] results in an absolute target value of 396 Gg N yr⁻¹. The reduction requirement for Germany of 65% NOₓ [24] results in an absolute target value of 168 Gg N yr⁻¹.

3.3. Surface Water Quality

Table 2 shows a total annual N load of 356.2 Gg N yr⁻¹ from the inflows from Germany into the North Sea and Baltic Sea and the outflow of the Rhine into the Netherlands. Note the different reference periods for the individual river basins. To comply with the target values at the limnic/marine transition points and at the Bimmen/Lobith border point to the Netherlands, the associations of the river basins reported an overall necessary reduction by 42.2 Gg N yr⁻¹.
Table 2. Nitrogen reduction requirement in German river basins flowing into the North Sea and Baltic Sea, to comply with target concentrations; various time periods (Gg N yr\(^{-1}\)) [33].

| River Basin      | Current Load | Target Load | Reduction |
|------------------|--------------|-------------|-----------|
|                  | North Sea — target concentration 2.8 mg N l\(^{-1}\) |             |           |
| Rhine            | 198.3\(^{b}\) | 196.6       | –1.7      |
| Elbe             | 78.8\(^{b}\) | 66.6        | –12.2     |
| Ems              | 15.1\(^{c}\) | 7.8         | –7.3      |
| Weser            | 44.4\(^{b}\) | 28.5        | –15.9     |
| Eider            | 5.7\(^{b}\)  | 4.7         | –1.0      |
| Sub-total North Sea | 342.3     | 304.2       | –38.1     |
| Baltic Sea — target concentration 2.6 mg N l\(^{-1}\) |             |           |           |
| Schlei/Trave     | 6.3\(^{b}\)  | 4.0         | –2.3      |
| Warnow/Peene     | 7.6\(^{d}\)  | 5.8         | –1.8      |
| Sub-total Baltic Sea | 13.9      | 9.8         | –4.1      |
| Total            | 356.2        | 314.0       | –42.2     |

Note: \(^{b}\) normalized mean nitrogen load 2012–2016; \(^{c}\) mean nitrogen load 2008–2012; \(^{d}\) mean nitrogen load 2012–2015.

3.4. Groundwater Quality Affected by Nitrate Concentration

The frequency distribution of the grid map of nitrate concentration in groundwater in Germany (Figure 3) shows that 8.8% of the area (grid cells) has a concentration above 50 mg NO\(_3\) l\(^{-1}\) (Figure 4). The mean NO\(_3\) concentration in grid cells that exceed the threshold is 59.4 mg NO\(_3\) l\(^{-1}\). Following that, for these cells, the mean necessary reduction of the N surplus is 15.8% or 9.1 kg N ha\(^{-1}\) yr\(^{-1}\). The sum for all these grid cells gives a necessary reduction of the N surplus in Germany of 21 Gg N yr\(^{-1}\). In comparison to the total soil surface balance N surplus (annual mean 2011–2014) of 148 Gg N yr\(^{-1}\), this leads to an overall reduction target of 127 Gg N yr\(^{-1}\).
Figure 3. Distribution of the nitrate concentration in groundwater in Germany (1 × 1 km grid), predicted using the random forest classification [34].
3.5. Nitrous Oxide Emissions Affecting Climate Change

The assumptions made in chapter 2.5 lead to the fact that in 2050, compared with 1990 levels, nitrous oxide emissions have to be reduced by 66%. Relative to the nitrous oxide emissions in 2015, which is the basis for our calculation of our maximum permitted nitrogen loss rates, this corresponds to a reduction of 43%. In 2015, nitrous oxide emissions amounted to 83.4 Gg N$_2$O–N yr$^{-1}$. The resulting maximum annual nitrogen loss therefore is 48 Gg N$_2$O–N yr$^{-1}$.

3.6. Human Health Affected by NO$_2$ Concentration

In Figure 5 the 179 background NO$_2$ monitoring stations with complete data from 2002 to 2015 are shown. Of these, 78 stations are in urban areas, 47 in sub-urban areas, 23 in rural areas, 11 stations are rural/peri-urban, 14 stations are rural/regional, and 6 stations are remote rural. Figure 6 shows that the NO$_2$ ambient concentrations show widespread compliance with the annual limit value (40 µg m$^{-3}$), except at exposed locations, where values are still too high. The resulting mean target emission of NO$_x$ of 236 Gg NO$_x$–N shown in Table 3 is based on equation 5, which gives the relation between yearly values of reported NO$_x$–N emissions and the 98 percentile value of NO$_2$ measurements from all background stations.
Figure 5. Locations of NO$_2$ background measurement stations with continuous data for 2002–2015 [41].

Table 3. Relation between yearly values of reported NO$_x$ emissions, the 98th percentile value of NO$_2$ measurements from all background stations, and the mean target emission of NO$_x$ based on Equation (5).

| Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Mean |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| a    | 538  | 522  | 501  | 479  | 474  | 451  | 429  | 398  | 406  | 399  | 386  | 385  | 371  | 361  |      |
| b    | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   | 20   |      |
| c    | 39   | 43   | 41   | 40   | 39   | 38   | 37   | 38   | 37   | 34   | 34   | 33   | 32   | 33   |      |
| d    | 274  | 242  | 243  | 238  | 246  | 239  | 234  | 209  | 222  | 232  | 229  | 236  | 234  | 221  | 236  |

Note: a: reported emission (Gg NO$_x$–N yr$^{-1}$) [30]; b: WHO threshold value (µg NO$_2$ µm$^{-3}$) [28]; c: 98th percentile value of NO$_2$ measurements from all background stations [41]; d: resulting target emission (Gg NO$_x$–N yr$^{-1}$).
3.7. Summary of the Results

The maximum permissible nitrogen loss calculated for the six impact indicators is summarized in Table 4. The most sensitive (lowest) loss rates per nitrogen species were selected to derive the national nitrogen target by adding them up. Directly included indicators are “terrestrial ecosystems affected by eutrophication”, “surface water quality”, “groundwater quality”, and “nitrous oxide emissions affecting climate change”. The maximum loss rates for the impact indicators “vegetation affected by NH$_3$ concentration” and “human health affected by NO$_2$ concentration” based on quality targets set by the World Health Organisation (WHO) and the Convention on Long-Range Transboundary Air Pollution (CLRTAP) are only indirectly part of the national target, since the NO$_x$ and NH$_3$ reduction rates required to meet the regional limit values for “terrestrial ecosystems affected by eutrophication” are more ambitious. The resulting integrated national target for nitrogen (INTN) amounts to 1053 Gg N yr$^{-1}$ or 12.7 kg per capita and year accounting for 83 Million inhabitants in Germany.

Figure 6. Map of the modelled NO$_2$ ambient concentrations 2015 (combination of measurements and distribution model). Circles mark measurements from stations that are only locally representative (annual means). The annual limit value is 40 µg NO$_2$ m$^{-3}$. The WHO response threshold for background concentrations is 20 µg NO$_2$ m$^{-3}$ [42].
Table 4. Calculated maximum permitted pressure indicators (nitrogen loss rates per year) to comply with related concentration or impact targets in Germany for six impact indicators and the resulting national nitrogen target; selected indicators per species and INTN (integrated national target for nitrogen) shaded (in brackets, annual nitrogen losses for the year 2015 [34]).

| Method Number | Impact Indicator                                                                 | Maximum Annual Pressure Indicator (Nitrogen Losses in 2015) (Gg N yr\(^{-1}\)) |
|---------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 2.1.1         | Vegetation affected by NH\(_3\) concentration                                   | 441 (625) NH\(_3\)–N                                                            |
| 2.1.2         | Terrestrial ecosystems affected by eutrophication                                | 396 (625) NH\(_3\)–N                                                            |
|               |                                                                                  | 168 (361) NO\(_x\)–N                                                            |
| 2.1.3         | Surface water quality (to prevent coastal waters from eutrophication)           | 314 (356) N\(_{\text{total}}\)                                                   |
| 2.1.4         | Groundwater quality                                                               | 127 (148) NO\(_2\)–N                                                            |
| 2.1.5         | Nitrous oxide emissions affecting climate change                                  | 48 (83) N\(_2\)O–N                                                              |
| 2.1.6         | Human health affected by NO\(_2\) concentration                                 | 236 (361) NO\(_x\)–N                                                            |

Integrated national target for nitrogen (INTN) as the sum of the lowest loss rates per nitrogen species (2.1.2 – 2.1.5) 1053 (1574) N

4. Discussion

In Sections 2 and 3, we showed an approach to calculate a national nitrogen target from pressure indicators, for which maximum permissible values are deduced from quality target values.

Our selection of indicators and our simplified methods used to calculate maximum permissible nitrogen loss are characterized by heterogeneity. Calculated nitrous oxide emissions are based on percental greenhouse gas emission reduction requirements. For NO\(_x\) and NH\(_3\), proportionality between an approximation of quality targets and a related maximum emission was assumed. For eutrophication effects in terrestrial ecosystems, we relate our emission reduction requirements to results of the GAINS model [43], and the calculated N load into surface water is based on long-term correlation of concentration and N loads in rivers. We did not consider acidification of terrestrial ecosystems as a threat, because nitrogen-deposition-induced acidification is a minor threat in comparison with eutrophication [44], hence its consideration would lead to a minor reduction target in comparison with the “eutrophication target”.

The correlation between NH\(_3\) concentration and NH\(_3\) emission data was assumed on a spatial resolution of 0.03125\(^\circ\) * 0.015625\(^\circ\), which is acceptable due to the high deposition velocity of NH\(_3\) [29]. However, the selection of the underlying emission data and of the critical level substantially influence the resulting maximum NH\(_3\)–N loss rate. For example, picking the critical level of 1 \(\mu\)g m\(^{-3}\) (to protect most sensitive elements of the vegetation such as lichens and other cryptogams) instead of 3 \(\mu\)g m\(^{-3}\) for higher plants would lead to a much lower maximum NH\(_3\)–N loss rate of 96 Gg N yr\(^{-1}\) instead of 441 Gg N yr\(^{-1}\).

Additionally, the resulting maximum NO\(_x\) emission to protect human health from NO\(_2\) is influenced by our own assumptions: Picking, for example, a percentile value of 90 instead of 98 would lead to higher maximum NO\(_x\) emissions. In contrast, calculating the maximum NO\(_x\) emissions from a linear regression of the 98th percentile of the annual concentration measurement data at background stations and the annual NO\(_x\) emission data, which show a high correlation, would lead to lower maximum NO\(_x\) emissions.

Acknowledging the differences of the selected six different approaches, we are confident that integrating their results to our INTN is an acceptable simplification, comparable to the planetary boundary for N fixation by de Vries et al. [10]. We acknowledge that we face difficulties to prove our suggested value, but we are confident that the result is sufficiently robust for the purpose of an additional element for political communication.
Additionally, we admit that whereas five of our calculated maximum permissible nitrogen loss rates can be related to emission sources directly, in contrast, such a direct relationship to emission sources for the N load in surface waters cannot be established. This implies that necessary area-related emission reduction at the source is likely to be even larger than our load-related value. This denotes that our resulting INTN has to be interpreted as an interim target and that further in-depth assessments would lead to an even lower target value.

For human health effects of nitrogenous air pollutants, we focused only on the direct effects by NO\textsubscript{2}, although nitrogen in the atmosphere also influences the concentration of ozone and secondary inorganic particulate matter. We neglected those indirect effects and did not relate them to an acceptable nitrogen loss rate, as ozone concentrations and health effects of fine particulate matter are also driven by many other drivers and the establishment of a sound mathematical relationship to nitrogen emissions was not possible. However, by choosing a low-value background concentration of 20 µg m\textsuperscript{-3} as a state indicator, our approach is precaution-oriented, so that we are confident that our related maximum NO\textsubscript{x} emissions also improve human health exposition to those indirect effects.

The national nitrogen target is composed of independent targets, which we either calculated by applying a simplified approach or adopted from existing studies or directives. The methods applied are designed as such so that related state indicators or quality targets are met on a spatial average in Germany. Therefore, reaching the national nitrogen target does not guarantee that the six state indicators considered as spatial-dependent functions are reached everywhere. By integrating in the spatial dimension, our approach results in a target that only ensures compliance at the spatial average. The compliance with the nitrogen loss rate is therefore a necessary condition but is not sufficient to reach the environmental state indicators everywhere. For that, we recommend that neither our indicators nor the calculated national nitrogen target should fully replace existing indicators based on, for example, spatially resolved monitoring networks or detailed modelling approaches.

Against the background of the cascading mobility of reactive nitrogen, it cannot be excluded that a reduction of nitrate in groundwater will positively affect N concentration in surface waters, too. However, a double counting of nitrogen reduction requirements in a relevant order we believe is unlikely, because the groundwater-related quality target of 50 mg l\textsuperscript{-1} was neither designed to protect surface water downstream nor to protect marine and coastal ecosystems from eutrophication. The assumption of long-lasting travel times of nitrate in groundwater justifies our hypothesis that double-counting of N in the groundwater and surface water indicators can be neglected. Therefore, it seems likely that compliance with our “groundwater indicator” will not lead to a substantial lower “surface water indicator”.

By combining the resulting maximum nitrogen loss rates per indicator to an integrated national nitrogen target, we aggregated the different nitrogen species to the uniform unit of total nitrogen and summed them up. In that sense, a future compliance with the national nitrogen target on that aggregated level will not give information on how much the different indicators contribute to the emission reduction. For that reason, it is not sufficient to achieve compliance with the national nitrogen target only. We suggest instead that all indicators need to be reduced to their maximum allowable loss rates independently in order to achieve the related state indicator.

In terms of robustness, we did not quantify the uncertainties of our maximum pressure indicators and the national nitrogen target. Nevertheless, we acknowledge the overall uncertainty of our approach, as we recognize a certain scope in the selection of target values in terms of types and units of limit values (concentration limits, area of critical load exceedance, critical levels, quality thresholds, and emission reduction targets) and methods to calculate maximum nitrogen losses. Note also that our results depend on the national nitrogen emissions and losses. Considering that emission estimates regularly change due to adjustments in inventorying emissions, it is possible that our target value of
1053 Gg N yr\(^{-1}\) will change in the future. To avoid this feature, a relative national nitrogen target could be a helpful complement in the future.

Finally, our selection of state indicators also determines the scope and level of our national nitrogen target. We selected the underlying six state indicators by focusing on the current political framework for Germany in combination with scientific limit values defined by international agreement within WHO and CLRTAP. Directly included indicators in the INTN are based on German legislation, indirectly enclosed indicators are science-based quality targets of the WHO and the CLRTAP. Available indicators are heterogenous and do not all imply an absolute good environmental status when reaching them. The state indicators implemented in the German legislative framework reflect action targets. For example, the state indicator for eutrophication of terrestrial ecosystems aims at reducing the area affected by eutrophication by 35% compared to the status in 2005. At the same time, compliance with the included state indicator to prevent coastal waters from eutrophication probably will not finish eutrophication automatically, as the changing climate and its effects on coastal ecosystems probably require a further lowering of the current quality targets. Lower N concentrations than the ones we include to prevent aquatic ecosystems from eutrophication in the range of 1 \(\mu g\) l\(^{-1}\) have been discussed by Camargo and Alonso [31]. Therefore, the proposed INTN reflects the heterogenous reduction required under the current legislation rather than the reduction required to achieve a good status of the environment everywhere in Germany. Thus, the proposed INTN should be interpreted more as a political interim target than a comprehensive environmental quality target, which means that a future lowering of the INTN should not be excluded.

In summary, we acknowledge that all of our own approaches are simple and the results deserve no more than to be characterized as good estimates. Full-chain iterative model calculations, for example, analysis of the agricultural surplus reduction in combination with accompanying nitrate, ammonia, and nitrous oxide reductions or even model combinations of sectoral activity and emission models, media distribution, and transfer models and last but not least, spatial-resolved impact analysis would have been more sophisticated alternatives. However, such models themselves, their combinations, and scenario back-calculations contain also uncertainties, which could increase by combining them. Furthermore, the simple set-up based on existing national indicators also is advantageous and suggests that our approach could be a role model for similar exercises in other countries or regions with a comparable data availability.

Despite our simplifications and the strong dependence of the results from our methods and assumptions, the resulting order of magnitude of our INTN is in a reasonable range with existing emission reduction commitments [45]. This is supported by the finding that our resulting per capita value of 12.7 kg is in the same order of magnitude as global, historical per capita reactive nitrogen creation in the early decades of industrial times until 1950 [46]. In summary, the chosen methods seem robust enough to use the national nitrogen target as a complementary means for communication. Rounding the calculated value 1053 Gg N yr\(^{-1}\) to a value of 1000 Gg N yr\(^{-1}\) does not change this order of magnitude. The suggested rounding makes the value more stable towards changes in input data and the selection of methods and limit values. Certainly, on the one hand, this rounding underlines that our result is not more than a good estimation, however, on the other hand a rounded value allows a better means of complementary political communication.

5. Conclusions

Environmental problems related to excessive loss of reactive nitrogen in Germany are manifold. A large variety of sectors and anthropogenic activities contribute to these problems. Fragmented measures taken so far show only limited success and bear the risk that nitrogen pollution is shifted from one medium of the nitrogen cycle to another (“pollution swapping”). To enhance awareness for this issue and to support political action on the way to an integrated approach to solve the nitrogen problem, we present an integrated national target for nitrogen (INTN). The selected methods allow us to derive a quantitative
estimate of annual permitted nitrogen loss rates to the environment in Germany as an objective for political action that at the same time enhances the compliance with many of the media-related quality targets. Simultaneously it is as easily understandable and tangible for the addressed public and policy as the planetary boundary concept [8,9] or the 1.5 ◦C target of the climate community [19]. We are confident that the approach can be applied by other countries, although selected indicators might differ from one country to another and we suggest to use our findings as a role model for similar studies in countries or regions with comparable data availability.

Acknowledging the uncertainties and the scope of our approach and enhancing expressiveness of our concept, we propose to use 1000 Gg N yr⁻¹ as a national nitrogen target for Germany when it is used in the political communication (instead of the calculated 1053 Gg N yr⁻¹). As our target is linked to existing political reduction targets, which do not fully reflect the reduction requirements to achieve a good ecological status for all addressed impact indicators, it should be considered as an interim target. Comparing the result of our calculations under our selected assumptions to the current annual nitrogen losses to the environment in Germany amounting to 1574 Gg N yr⁻¹ [34], the overall annual loss of reactive nitrogen in Germany would have to be reduced by more than 500 Gg N yr⁻¹.

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