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Nitrogen – Element with Impacts

An Integrated Target Value Sets a New Framework

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1 Introduction

Nutrition, mobility, energy generation, the production and consumption of goods, recreation and leisure – nitrogen plays an important role in almost all facets of modern life. Meeting the demand for nitrogen on the one hand and reducing excessive nitrogen inputs into the environment on the other are important goals in the global sustainability debate. In light of the growing world population, nitrogen as a plant nutrient is essential for sufficient food production. At the same time, harmful releases of reactive nitrogen compounds already exceed the "planetary boundary" for future life on our planet (Steffen et al., 2015). Important Sustainable Development Goals (SDGs) of the United Nations are closely linked to the nitrogen cycle. The following nine goals are directly related to the human use of nitrogen: 1 No Poverty, 2 Zero Hunger, 3 Good Health and Well-being, 6 Clean Water and Sanitation, 11 Sustainable Cities and Communities, 12 Sustainable Consumption and Production, 13 Climate Action, 14 Life below Water, 15 Life on Land.

If these sustainability goals are to be achieved, an effective nitrogen management is required. To this end, ways of using the resource of nitrogen more sustainably will need to be found. It is necessary to develop processes and technologies to minimise unwanted nitrogen releases and advance innovations for efficient recovery and utilisation of previously unusable nitrogen compounds. Last but not least, a change in lifestyles and everyday habits can contribute to solving the nitrogen problem. However, sustainable management also requires conscious political control and implementation of measures and programmes – on all spatial scales from the local to national to global level. This is because nitrogen is an element that circulates on a large scale. Once released into the environment, nitrogen can form various compounds with the potential to endanger air, water bodies, terrestrial ecosystems, the climate and human health.

Figure 1

Symbols of UN Sustainable Development Goals (SDG) directly related to human use of nitrogen and its compounds

Source: https://17ziele.de/downloads.html

Achieving the sustainability goals is also an overarching maxim of the German Federal Government. The Federal Ministry for the Environment is following a recommendation by the German Advisory Council on the Environment (SRU, 2015) and is working on preparing an integrated action programme for reducing nitrogen. In 2017 – as a first step – the first nitrogen report of the German Federal Government was published (BMUV, 2017). The German Environment Agency is supporting this process through several research projects (Bach et al., 2020b; Heldstab et al., 2020a; Oehlmann et al., 2021). This background paper summarises the results of these projects: It introduces the benefits and environmental impacts of nitrogen and its compounds, provides a summary of information on nitrogen-related substance flows, statistics and limit value exceedances in Germany and underpins the need for an overarching view of the nitrogen cycle. A key element is the proposal of an integrated nitrogen target for Germany as a guideline for future nitrogen policy in Germany.

2 Nitrogen, How An Element Changes the World

Nitrogen: Essential Nutrient, Basic Chemical Substance and Pollutant

As a plant nutrient and in order to maintain the soil's fertility, nitrogen is an indispensable component of productive agricultural systems. Nitrogen is directly absorbed by plants from the soil in the form of ammonium (NH_4^+) and nitrate (NO_3^-) and contributes to protein synthesis in plants. At present, nitrogenous fertilisers are indispensable when it comes to ensuring high crop yields. Humans and animals need nitrogen for their metabolism as well. They absorb nitrogen in the form of plant and animal protein and use it for life-sustaining bodily functions.

In the past, nitrogen for agricultural production could only be obtained from natural sources (e.g. manure, guano, saltpetre deposits). Today, the industrial production of mineral fertilisers makes it possible to provide a sufficient supply of nitrogen for crops.

In 1909, the chemist Fritz Haber[1] made one of the most important discoveries in human history at the Technical University of Karlsruhe: He developed the artificial synthesis of ammonia (NH_3). At the Badische Anilin- und Soda-Fabrik (Baden Analine and Soda Factory – BADF), Carl Bosch developed the process further and prepared the basis for an industrial process. Since then, atmospheric nitrogen can be used in almost unlimited quantities for the production of fertilisers, and food production can be increased. At the same time, however, too much mineral fertilisation and the high energy consumption of ammonia synthesis produce negative environmental effects.

Today, ammonia synthesis and fertiliser production account for approx. 2% of the global energy demand (Smil, 2000; Licht et al., 2014). In 2017, annual global ammonia production was reported to be 142 million tonnes of nitrogen (U.S. Geological Survey, 2019). The world population grew from 1.6 billion people in 1900 to 8 billion people in 2022 (United Nations, 2022). Nevertheless, there are still regions of the world where there are not enough nitrogen resources for productive agriculture and where people are also suffering from malnutrition for this reason. As the world's population continues to grow, additional ammonia will be needed for agricultural production.

Humanity's hunger for meat is also growing. The consumption of animal products in Europe is associated with nitrogen emissions around 10 times higher than the consumption of plant products (Leip et al., 2014). This is primarily due to the fact that animals being fattened can only absorb part of the nitrogen in the feed, while excreting the rest again. In addition, nitrogen is lost in fodder cultivation. For this reason, in regions with intensive livestock farming that is not tied to the area, there is often more manure than can be used on the agricultural land in the region (manure surplus). Even if these surpluses are officially regulated by manure exchanges and manure transport, there are locally increased amounts of nitrate (NO_3^-) entering the soil and groundwater and of ammonia (NH_3) entering the air. Part of the nitrogen from livestock farming also escapes as ammonia (NH_3) into the air from livestock housing and storage facilities of farm manure.

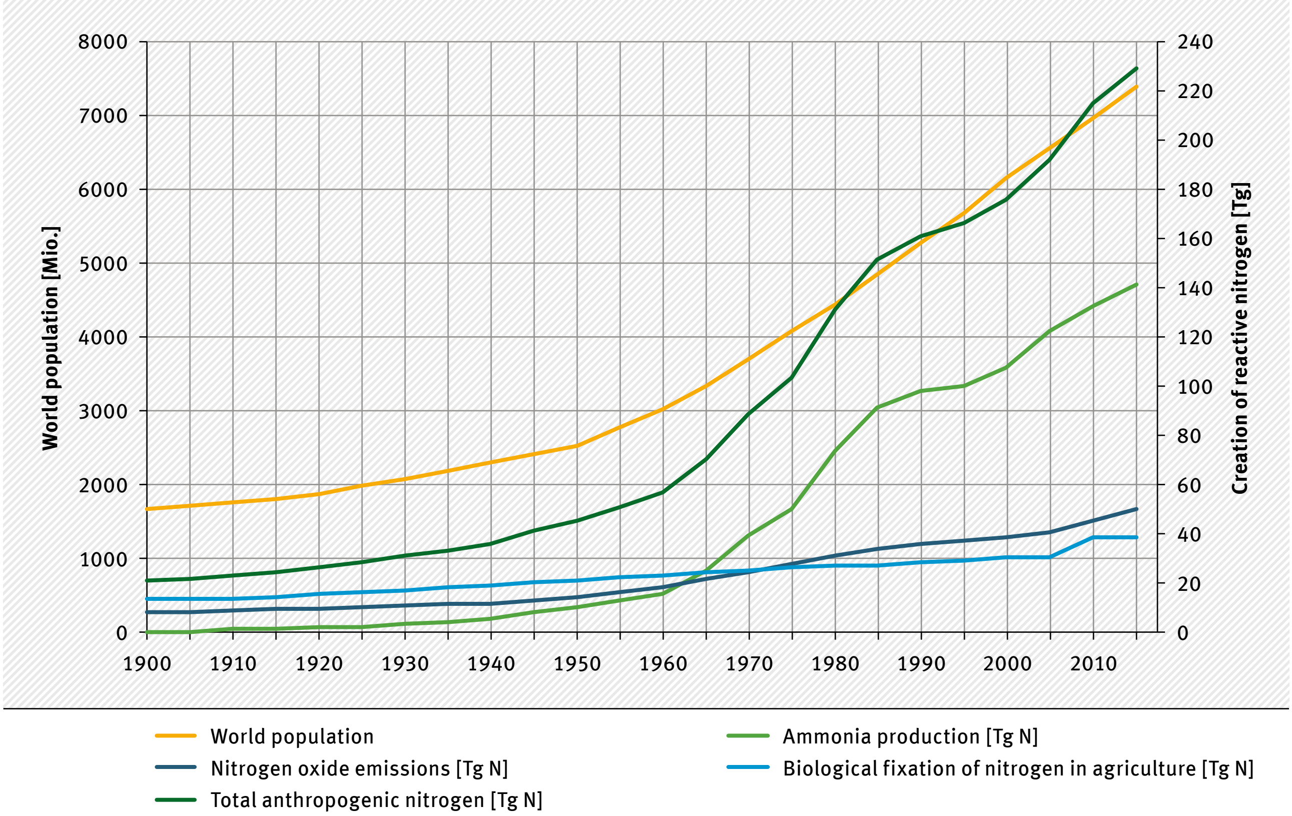
In addition, today's industrial livestock farming controls large global flows of nitrogen, as the feed demand cannot be met by the local cropland. An example for that is nitrogen bound in soya containing feed.

Humanity's current need for mobility, electrical energy and industrial products also causes large-scale, undesirable release of nitrogen oxide emissions (NO_x) from combustion processes. Nitrogen oxides are formed during combustion processes by conversion of the molecular atmospheric nitrogen contained in the air on the one hand and from the nitrogen contained in the fuel on the other. Particularly in the case of hard coal and lignite combustion, the nitrogen content of the coal plays a large part in the total release of nitrogen oxides. In contrary, 100% of nitrogen oxides released with petrol and diesel combustion result from the oxidation of atmospheric nitrogen. Both transport and traffic as well as large and medium-sized combustion plants in industry and the energy sector are the most significant causes of

1 The scientific work of Fritz Haber in the period of the First World War and the period between the world wars is characterised by great controversies that must not be ignored. For more information, see Friedrich, B. (2019). Fritz Haber at One Hundred Fifty: Evolving views of and on a German Jewish Patriot.

Figure 2

Global development of reactive nitrogen creation and world population



Source: Galloway, J. N., et al. (2003). „The nitrogen cascade.“ BioScience 53(4):341–356.
Original Datenreihe erweitert mit Herridge, D. F., et al. (2008); Li, J. and Y. Wang (2019); United Nations (2019); U.S. Geological Survey (2019).

nitrogen oxide emissions. As a result, high levels of nitrogen dioxide pollution can occur in inner cities, especially at locations with a high traffic density (German Environment Agency, 2022). When it comes to combustion and exhaust gas purification, today's technology is far advanced, allowing for large quantities of the nitrogen oxides contained in the flue gas to be converted directly in engines and motors back into harmless atmospheric nitrogen.

Never before in the history of humanity have people had such a profound impact on the nitrogen cycle as they have today (Ertl & Soentgen, 2015).

The global development of nitrogen emissions in connection with the world population is displayed in Figure 2. Due to anthropogenic activities, the amount of reactive nitrogen in the environment has doubled globally and even tripled in Europe (Sutton et al., 2011; Fowler et al., 2013). In order to reduce the unequal distribution of nitrogen as a resource and simultaneously minimise the many negative effects associated with releasing nitrogen into the environment, it will be necessary to have global, regional and also national control processes.

Environmental and Health Effects of Nitrogen Compounds

Oxygenated and hydrogenated nitrogen compounds enter the environment via various pathways. Excessive input into the environment can cause adverse ecological and health effects. An overview of impacts can be found in Table 1.

Table 1

Environmentally relevant nitrogen compounds, their formation and their effects

Nitrogen Compound	Main Source / Formation	Greatest Impact
Unreactive, Elemental Nitrogen		
N_2	At 78%, it is the main component of the atmosphere	None
Reactive Nitrogen Forms		
NO_x (nitrogen oxide)	Combustion processes ▸ Traffic ▸ Energy production and use ▸ Industry	▪ Precursor substance for the formation of substances harmful to health, such as ground-level ozone and secondary fine particulate matter ▪ Formation of methaemoglobin from NO ▪ Short-term: Irritant effect of NO_2 on the respiratory tract ▪ Long-term: Increase in cardiovascular mortality due to NO_2 ▪ Contribution to acidification and eutrophication of soils and ecosystems (nutrient imbalances, threats to biodiversity, shifts in the range of species)
NO_3^- (nitrate)	Conversion product from other nitrogen oxides, organic N-compounds and from ammonia or ammonium ▸ Arable farming, use of animal excreta and mineral fertilisers ▸ Industrial and municipal waste water ▸ Deposition of atmospheric nitrogen compounds	▪ Groundwater and surface water pollution ▪ Eutrophication of marine and coastal ecosystems ▪ Health problems due to heavily contaminated drinking water (nitrosamines, methaemoglobin) ▪ Acidification and eutrophication of soils and ecosystems (nutrient imbalances, threats to biodiversity, shifts in the range of species)
NH_3/NH_4^+ (ammonia/ ammonium)	Conversion and emissions ▸ Livestock husbandry in agriculture (handling of farm manure) ▸ Fertiliser production and its use ▸ Waste water discharge into surface waters	▪ Acidification and eutrophication of soils and ecosystems (nutrient imbalances, threats to biodiversity, shifts in the range of species) ▪ Health effects through secondary fine particulate matter ▪ Fish poison ▪ Damage to plant tissue
N_2O (nitrous oxide)	Microbial conversion processes in soils and water bodies (denitrification) ▸ Agriculture (use of fertilisers) ▸ Semi-natural ecosystems polluted with nitrogen ▸ Soil compaction ▸ Industrial processes	▪ Highly effective greenhouse gas (greenhouse effect) ▪ Contributes to the depletion of the stratospheric ozone layer

Nitrogen compounds can become health risks via the air. Nitrogen dioxide (NO_2), which mainly enters the environment as exhaust gas from combustion processes, irritates the mucous membranes, thereby reducing lung function, impairing the cardiovascular system and contributing to increased cardiovascular mortality in the long term (World Health Organisation, 2021; Faustini et al., 2014; Guarnieri & Balmes, 2014; Schneider et al., 2018). Furthermore, it is a precursor substance for the formation of ground-level ozone and, together with gaseous ammonia (NH_3), contributes to the formation of secondary particulate matter (von Schneidemesser et al., 2016).

Nitrate (NO_3^-) in drinking water can be a health risk, as it is the starting point for a toxic compound, secondary nitrite (NO_2^-), which is formed by reduction. The intake of nitrate through drinking water is predominantly associated with two health hazards for humans: acute "blue baby syndrome" (methaemoglobinaemia) and the formation of carcinogenic N-nitroso compounds. However, drinking water suppliers consistently monitor the quality of drinking water in Germany to ensure that the legal limit of 50 mg nitrate per litre is not exceeded. Nevertheless, some water suppliers are already being forced to drill deeper wells, relocate wells or mix uncontaminated and contaminated raw water to guarantee drinking water quality, because nitrate contamination in easier-to-reach layers of the groundwater is too high (WHO, 2016; German Environment Agency, 2017).

As a nutrient, nitrogen not only facilitates production in agricultural systems, but also leads to eutrophication and biodiversity loss in ecosystems. In semi-natural terrestrial ecosystems, such as heaths, grasslands or even forests, the continuous deposition of nitrate and ammonium as dust and via precipitation promotes an accumulation of nutrients. This elevated abundance of nutrients impairs the competitiveness of plant species adapted to nutrient-poor conditions (Bobbink et al., 2022; Riecken et al., 2006; German Federal Agency for Nature Conservation (BfN), 2016; Schaap et al., 2018), thereby shifting the range of local plant species. Due to close plant-insect interactions, changes in the plant community also impact insect populations. Insects that are primarily dependent on low-nitrogen and open habitats are particularly affected, as they find fewer breeding and host plants (German Environment Agency, 2019). Finally, nitrogen inputs contribute to soil acidification.

In high concentrations, ammonia (NH_3) has direct toxic effects on leaf organs (Cape et al., 2009). Lichens and mosses are particularly sensitive to ambient ammonia. Ammonia is produced primarily in agriculture, both in livestock farming and during fertilisation of farm fields. Ammonia can diffuse directly into plant tissues through stomata or it is deposited in dust and precipitation to ecosystems as ammonium, where it likewise has eutrophying and acidifying effects.

Besides terrestrial ecosystems, the aquatic environment is affected by excessive nitrogen input as well. A surplus of nutrients in aquatic ecosystems causes eutrophication and associated massive algae growth. In freshwater, phosphorus is usually the limiting nutrient for plant or algae growth. In marine and coastal ecosystems, nitrogen has a limiting effect. Excessive algae growth has aesthetic effects and is thus detrimental to the tourism sector. Algae growth facilitate summertime oxygen depletion, thereby affecting biodiversity, fish stocks and fishing quotas (HELCOM, 2018). Dissolved ammonium (NH_4^+) and nitrite (NO_2^-) have a toxic effect on the aquatic fauna.

The nitrogen compound nitrous oxide (N_2O) is a highly effective greenhouse gas. According to the 5th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), N_2O has about 300 times the warming potential of carbon dioxide (CO_2) per unit of quantity. In 2010, nitrous oxide emissions accounted for 6.2 per cent of total global greenhouse gas emissions in carbon dioxide equivalents (IPCC, 2013). Nitrous oxide is mainly produced in nitrogen-intensive agricultural systems.

In addition, nitrous oxide is long-lasting in the atmosphere and rises to great heights in our atmosphere because it is lighter than air. In the stratosphere, it contributes to the depletion of the ozone layer, which protects against excessive UV radiation. Currently, nitrous oxide has the greatest role in depleting the ozone layer relative to other ozone-depleting compounds (Ravishankara et al., 2009).

Lastly, atmospheric nitrogen contamination combined with other air pollutants damages building material and monuments and results in considerable additional maintenance or restoration costs every year. For example, nitrogen compounds, especially nitric acid (HNO_3), may account for more than fifty per cent of the weathering of limestone or the contamination of glass surfaces (ICP Materials, 2018).

3 Nitrogen Cycle in Germany

Quality Targets and Limit Values for Protecting Humans and the Environment

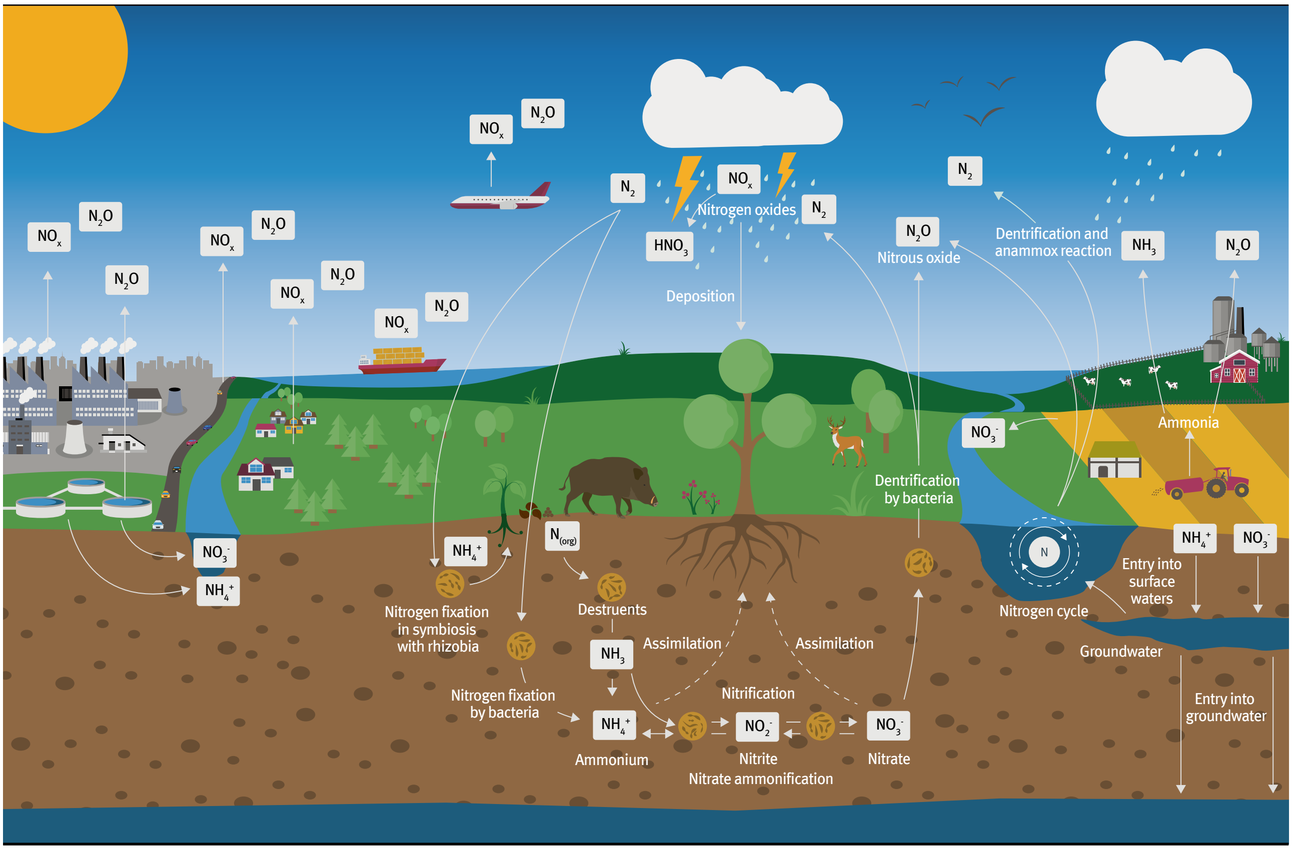
There are numerous nitrogen-related environmental targets for protecting humans and the environment. Limit values are defined either as concentration values of certain nitrogen compounds to ensure desirable air or water quality, or as substance-related reduction commitments/emission ceilings established to reduce the amount of nitrogen entering air, water bodies and ecosystems. In groundwater, for example, the German concentration limit value is currently 50 mg l^{-1} for nitrate. In air, the German concentration limit value for nitrogen dioxide (NO_2) is an annual average of 40 µg m^{-3} to protect health. For terrestrial ecosystems in Germany, ecosystem-specific critical loads are applied to assess and limit eutrophication. Such limit values are part of international protocols, stipulated in EU directives, or laid down in binding form in national regulations.

Where these limit values cannot be met, there is a justified risk that it will not be possible to adequately guarantee environmental quality due to the entry of excessive inputs of reactive nitrogen. An overview of the nitrogen-related environmental quality targets can be found in Table 3, Section 4.

Due to inadequate handling of the resource nitrogen characterised by losses to the environment in agriculture and through the release of nitrogen compounds into the atmosphere during combustion processes, many nitrogen-related environmental targets in Germany are not achieved at all or only insufficiently. Three examples among many for nitrogen related problems are limit value exceedances of nitrate in groundwater in intensively used agricultural areas with a simultaneously high potential of nitrogen leaching into groundwater-bearing strata, critical load exceedances for nitrogen inputs in areas with

Figure 3

Schematic illustration of the most important processes and cross-relationships of the nitrogen cycle



Source: kopfarbyte UG/Bosch & Partner GmbH, Umweltatlas Reaktiver Stickstoff
https://www.umweltbundesamt.de/umweltatlas/reaktiver-stickstoff/einfuehrung/gestatten-reaktiver-stickstoff/wie-veraendert-der-mensch-den-natuerlichen

sensitive ecosystems and high nitrogen deposition, or NO_2 limit value exceedances in cities with a high traffic density (https://www.umweltbundesamt.de/en/data/air/air-data).

As a result of this situation, Germany has been facing multiple EU infringement proceedings [2]. Currently ongoing EU infringement proceedings concern insufficient implementation of the EU Nitrates Directive and the Air Quality Directive, specifically with regard to insufficient compliance with the nitrate limit values and the annual NO_2 values. Since July 2019, infringement proceedings have been ongoing with regard to the Habitats Directive, since Germany has not taken sufficient measures to prevent the deterioration of species-rich grassland[3], and the conservation status of characteristic species in the affected habitat types is threatened due to the increased presence of nitrogen among other factors.

The Nitrogen Cycle

Nitrogen is a mobile element that can build multiple compounds. Reactive nitrogen in oxidised or reduced form enters the environment from various sources and is transported along different pathways through the environmental media of soil, air, water, plants, animals and humans, where it can produce adverse effects. For example, a nitrogen atom released as ammonia (NH_3) in agriculture can pass through different forms and have different effects: it can be wet deposited by rain as ammonium (NH_4^+) to a nearby forest. In the soil, ammonium can be converted to nitrate (NO_3^-) by microorganisms. Nitrate can be assimilated by plants or flushed out into a stream after a rain event. From there it enters the sea and is absorbed by algae which, after blooming, are decomposed by bacteria. In the course of these processes, the nitrogen atom is incorporated into a nitrous oxide molecule (N_2O), which escapes into the atmosphere. Many other pathways and processes of the nitrogen cycle are known (Figure 3). Focusing only on individual parts of the nitrogen cycle can therefore lead to important interactions being overlooked. A comprehensive understanding of the cross-relationships within the nitrogen cycle is thus a basic prerequisite for effective nitrogen management.

2 https://ec.europa.eu/atwork/applying-eu-law/infringements-proceedings/infringement_decisions/
3 Habitat Directive habitat types 6510 and 6520

Numbers, Data, Nitrogen Flows

In order to grasp nitrogen flows in Germany in quantitative terms, the most relevant national nitrogen fluxes were inventoried (Bach et al., 2020). Results of this inventory provide insights to different contributions of polluters to the nitrogen problem and illustrate which environmental media are polluted by different areas of societal activity. Such quantitative data are a prerequisite for effective action planning to reduce problems.

The data basis for quantifying nitrogen flows is the Guideline for the Preparation of National Nitrogen Budgets of the Expert Panel on National Nitrogen Budgets of the Geneva Convention on Long-range Transboundary Air Pollution (CLRTAP), 2013. This guideline demands that incoming and outgoing national nitrogen flows are calculated or compiled for a total of eight pools, which are interrelated (Figure 4).

The nitrogen flow data used were either borrowed directly from statistical reports, publications, etc. or calculated as the product of the amount of substance transported or converted and its mean nitrogen content. All in all, around 150 nitrogen flows were quantified in this way for Germany. The collected data relates to the years 2010–2014. All results were given as the mean value of this 5-year period.

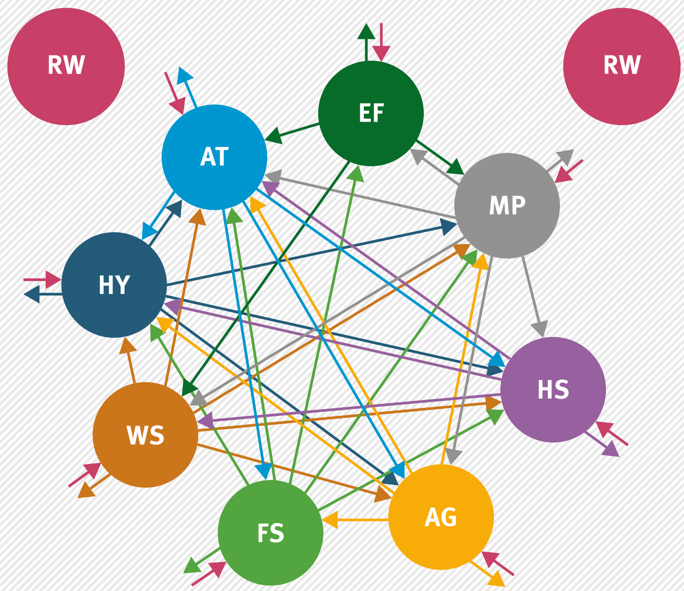
In summary, the balance shows that 6,275 kilotonnes (kt) of reactive nitrogen are introduced into the biogeochemical nitrogen cycle in Germany each year (Figure 5 and Bach et al. (2020)). 43% of this nitrogen input originates from ammonia synthesis, 37% from domestic production and imports of nitrogenous fossil fuels (lignite, hard coal, crude oil), 5% from natural nitrogen fixation and 12% from food and feed imports.

In contrast, 4,650 kt per year are removed from the national biogeochemical nitrogen cycle (Figure 5 and Bach et al. (2020)). The most significant quantifiable removal (i.e. outgassing of inert elemental nitrogen N_2 from the reactive nitrogen cycle) happens in flue gas denitrification during the combustion of fossil and renewable energy sources and in the processing of crude oil to petroleum products (60%). One quarter of elemental nitrogen (N_2) removed from the reactive nitrogen cycle originates from natural microbiological

Figure 4

Overview of the nitrogen pools of the national inventory of nitrogen flows and their cross-relationships to each other

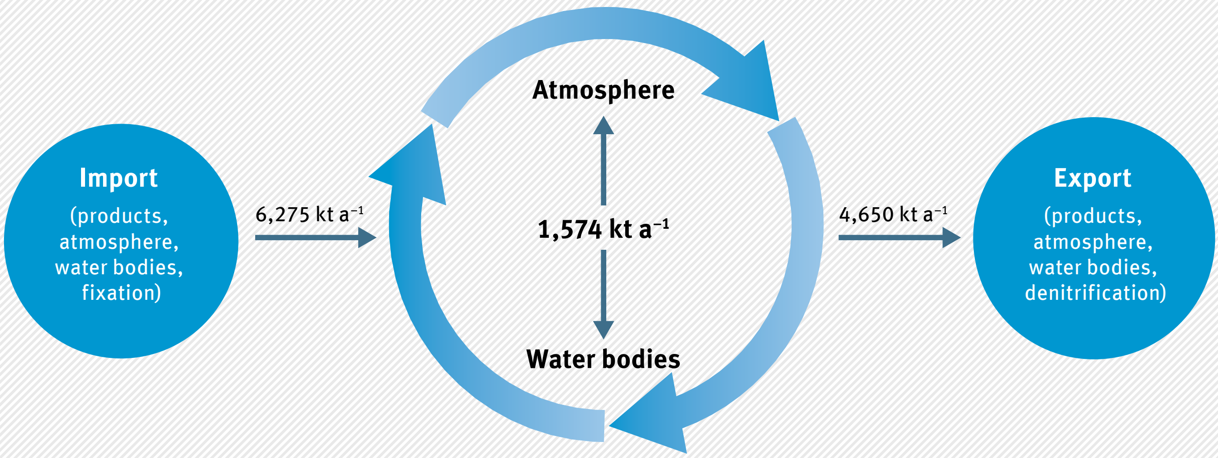
Pool-ID	Name of nitrogen pool
AT	Atmosphere
EF	Energy and fuels
MP	Material and products in industry
HS	Humans and settlements
AG	Agriculture
FS	Forest and semi-natural vegetation
WS	Waste management and sewage disposal
HY	Hydrosphere
RW	Import and export



Source: German Environment Agency

Figure 5

Quantified import and export of the German nitrogen cycle along with emissions as cycle-internal flows given as mean values of for 2010–2014 (Bach et al., 2020)



Source: German Environment Agency

process in waters and soils that convert nitrate to N_2 (denitrification). This removal process is also used in sewage treatment plants. The remaining amount of nationally removed reactive nitrogen is exported to neighbouring countries and coastal seas via the atmosphere and water runoff.

The difference between the input of reactive nitrogen into the cycle through extraction, production and import and the removal or export of reactive nitrogen from the cycle is approximately 1,625 kt of reactive nitrogen annually. This balance allows for two possible conclusions: Either this value equals the annual national nitrogen surplus, hereby increasing the

Table 2

Absolute quantities and percentages of polluter sectors and nitrogen compounds in the nitrogen cycle in Germany (Bach et al., 2020) *

Emission Range	Atmosphere			Surface Waters	Total	Percentage
	NO_x kt N a^{-1}	NH_3 kt N a^{-1}	N_2O kt N a^{-1}	NO_3^- kt N a^{-1}	kt N a^{-1}	%
Agriculture	36.0	558.0	65.4	381.9	1041	67 %
Traffic	159.6	11.5	3.0	0.0	174	11 %
Industry, energy industry	184.2	16.6	11.7	29.9	242	16 %
Households, waste water management	0.1	2.9	2.1	84.4	90	6 %
Total	380	589	82	496	1547	
Percentage	25 %	38 %	5 %	32 %		100 %

* In this aggregation, the groundwater-borne input into surface waters are attributed entirely to agriculture, thereby neglecting other inputs from agriculture via the soil-water pathway, that remain in the soil or that are degraded.

amount of reactive nitrogen in Germany by this load each year, or the difference owes to the difficulties and uncertainties in determining N flows.

Emissions of reactive nitrogen into the atmosphere and inputs into water bodies are of particular significance within the German nitrogen cycle, as they cause adverse effects in environmental media. The total annual emission of gaseous nitrogen compounds or nitrate into the environment in Germany amounts to 1,547 kt N a^{-1} (Figure 5; Table 2). This value is based on emission inventories and is therefore regarded as being relatively reliable. 67 % of reactive nitrogen emissions are released by agriculture, 11 % by the transport sector, 16 % by industrial and energy processes and 6 % by households, wastewater management and surface runoff. Most of reactive nitrogen inputs into the environment happen as ammonia emissions into the air, followed by nitrate input into surface waters, NO_x emissions and the release of nitrous oxide into the atmosphere (Table 2).

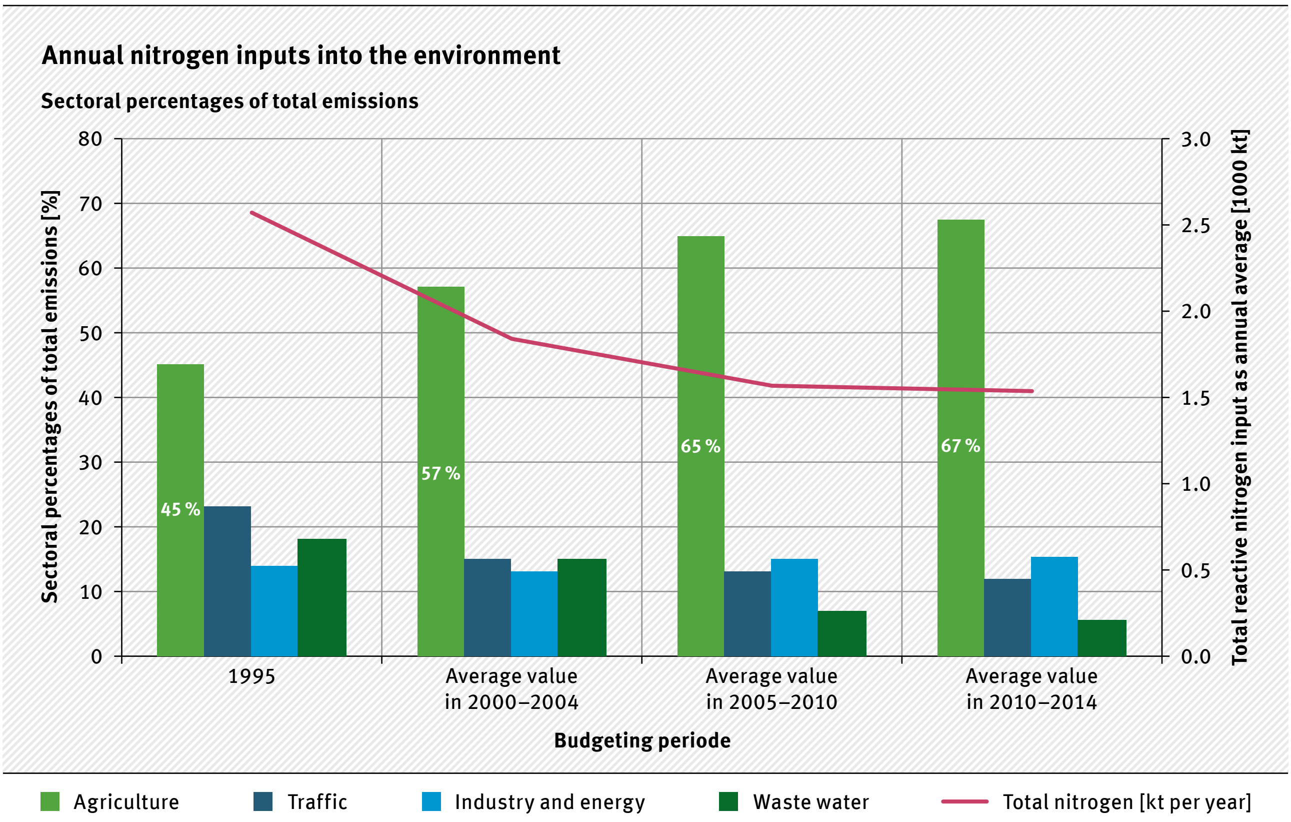
Four cross-sectoral inventories of reactive nitrogen output flows since 1995 are now available (Figure 6). Over the past 25 years, annual nitrogen output flows have decreased for Germany in total from 2,572 kt per year to 1,547 kt per year. The temporal resolution of this decrease, however, reveals a stagnation of total nitrogen outputs during the last 10 years. This stagnation can be explained by a concurrent decrease in the percentage of waste-water-related and traffic emissions since 1995 and an increase in the percentage of the industrial and energy sectors and especially in agriculture.

For this reason, the agriculture pool occupies a central place in the current nitrogen inventory, since nitrogen flows into and out of the agriculture sector are responsible for the largest turnover amount of reactive nitrogen in the environment (Figure 7). Related data on agricultural nitrogen predominantly stem from the statistics of the German Federal Ministry of Food and Agriculture (BMEL). The total nitrogen input flow into the reactive nitrogen cycle in Germany related to agriculture equals 3,320 kt of nitrogen per year, mainly through industrial feed, seed, mineral and agricultural fertilisers or through biological fixation. Within the agricultural pool, nitrogen cycles between the sub-pools soils, farmed animals and biogas plants contained in agricultural products such as substrate, plant feed and farm manure. Overall, there is a high domestic turnover of nitrogen. The process of balancing the cycle is then based on the justified assumption that the amount of nitrogen supplied to agriculture in various ways must also leave it again, either as a component of agricultural products or as emissions. Nitrogen in market products and nitrogen in atmospheric emissions can be quantified to a fairly reliable extent. On this base, nitrogen discharges into water bodies are derived as the difference between the total nitrogen flow into agriculture and all other calculated outgoing nitrogen flows. Please note that the conversion of reactive nitrogen to elemental atmospheric nitrogen (N_2) in seepage water or groundwater is assigned to the Hydrosphere pool and is therefore not included in Figure 7.

As shown by the example "Agriculture pool", individual nitrogen pools illustrate pathway dependencies and sector responsibilities for emissions, thereby helping to make a complex system visible. Illustration of flows related to additional pools are found in the "Reactive Nitrogen Flows in Germany 2010–2014 (DESTINO Report 2)" study by Bach et al. (2020). The overview of all pools allows the system to be understood as a complex cycle with many cross-relationships (see Figure 4).

Figure 6

Development of the percentages of the various polluter sectors in total nitrogen emissions over time*

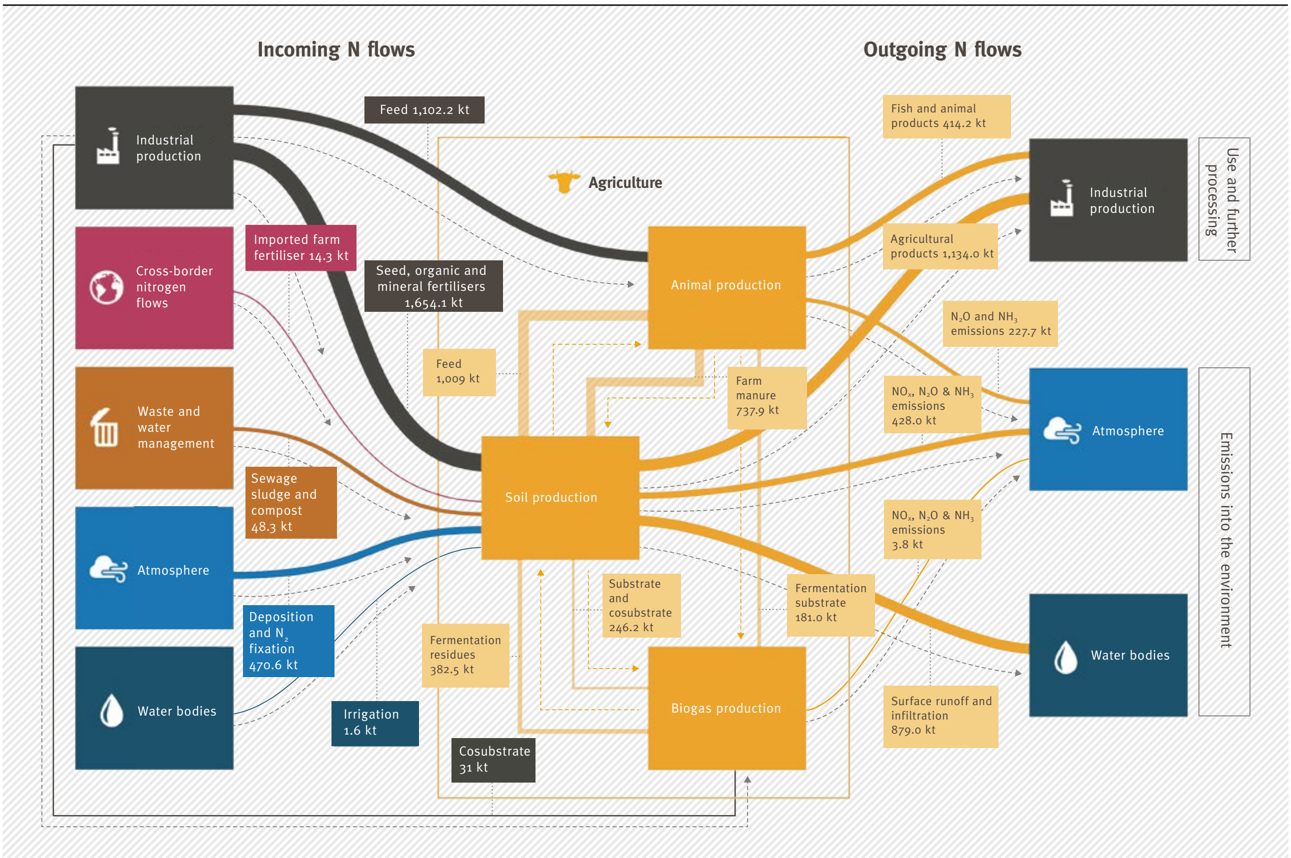


* For better comparability of the studies, the results on the input from agriculture into surface waters in the 1995 budgeting period were adjusted with the aid of the German Environment Agency (2019a).

Source: Alfred Töpfer Academy for Nature Conservation (NNA) (1997); German Environment Agency (2009); German Environment Agency (2015); German Environment Agency (2019a); and Bach et al. (2020)

Figure 7

Agriculture pool and its sub-pools and incoming and outgoing N flows in kt N a^{-1} averaged over 2010–2014 (Bach et al., 2020)



Source: Data from Bach et al. (2020); graphic realisation by Bosch & Partner and kopfarbyte, Thematic Environmental Atlas project https://www.umweltbundesamt.de/umweltatlas/reaktiver-stickstoff/einfuehrung/gestatten-reaktiver-stickstoff/welche-rolle-spielt-die-landwirtschaft-in-der

4 An Integrated Approach for Germany

Why an Integrated Approach is More Effective than Sectoral Considerations

Due to the complexity of the nitrogen problem, it is best practice to consider all polluter sectors and affected environmental media together. Independent assessments of individual nitrogen-related environmental problems – such as adverse effects on water or air quality – entail the risk of overlooking important interactions. For policy-makers, an integrated approach to the problem of nitrogen is desirable, as a cross-departmental, uniform political understanding is a prerequisite for joint action. Recognising, understanding and communicating the problem as a whole can increase the willingness to change lifestyles and thus support social transformation processes in the areas of nutrition, mobility and energy use. This would be a positive development because changes in these areas can contribute to a reduction of nitrogen surpluses in the environment. Even within an individual sector, an integrated approach supports effective solutions, as an overarching view allows synergetic effects of measures to be identified. In the case of nitrogen-reducing measures in agriculture, for example, it is expedient to assess the potential for air pollution control, climate protection and water protection in equal measure in order to identify efficient combinations of measures.

Integrated assessments of the nitrogen problem in Germany were first conducted in the 1990s as part of the nitrogen reduction programme of a joint working group of the Conference of Agriculture Ministers and Environment Ministers (Alfred Töpfer Academy for Nature Conservation (NNA), 1997). Since the publication of the special report "Nitrogen: Solution Strategies for a Pressing Environmental Problem" (SRU, 2015) by the German Advisory Council on the Environment, the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) has been working on the development of a national action programme for reducing nitrogen. The first nitrogen report of the German Federal Government was published in 2017 under the leadership of BMUV (BMUV, 2017). It identified the advantages of addressing nitrogen issues across sectors. Correspondingly, the nitrogen report of the federal government reads:

"An integrated nitrogen strategy is desirable because the total amount of reactive nitrogen in the system must be reduced in order to bring about ecologically and economically appropriate and balanced solutions and reduction requirements. Combining activities across departments permits avoiding redundant work and taking advantage of synergy effects. A complete overview of the various measures able to be utilised independently of one another in the different departments is necessary in order to use synergies as effectively as possible and to balance reduction deficits. Only an integrated approach allows economic cost-benefit assessments to be conducted across all the social and economic sectors concerned. Furthermore, only integrated solutions can effectively prevent problem areas from being shifted from one sector to another or from one environmental medium to another ("pollution swapping"). Since nitrogen emissions do not stop at national borders and the anthropogenic influence on nitrogen flows is a serious problem throughout Europe and the world, solutions at the single-sector or national level are not sufficient. An overarching national strategy therefore needs to be embedded in European and international activities. In summary, coherence and consistency, effectiveness and efficiency must be the success criteria of a successful policy approach, and this can best be achieved with comprehensive, integrated cooperation. Finally, the different facets and interrelations of the nitrogen problem can be communicated more readily to the public with an overall perspective. A broad awareness of the problem is needed to initiate and support sustainable change processes in agriculture, mobility, energy and consumption."

The Integrated National Nitrogen Target for Achieving Legal Requirements

In order to visualise the extent of the necessary reduction of reactive nitrogen in Germany, the German Environment Agency derived an impact-oriented, integrated national nitrogen target as part of a research project. The integrated action target marks the maximum annual amount of nitrogen permitted to be released in Germany in order to achieve the currently set environmental and health goals. It therefore sets a quantitative framework for reasonable handling of nitrogen compounds in the various economic sectors, without emphasising any single sector. The integrated goal allows for an accounting of the successes or failures of societal action to reduce nitrogen. At the same time, it facilitates communicating the problem situation to policy-makers and the public, thereby strengthening public awareness and sensitivity for political measures (Heldstab et al., 2020; Geupel et al., 2021). The national integrated nitrogen target therefore serves a similar communicative function as the planetary boundaries at the global level (Rockström et al., 2009; Steffen et al., 2015) or the 1.5 °C climate protection target of the Global Climate Change Alliance (UNFCCC, 2015). The German Environment Agency proposes that the integrated target be included in the nitrogen action programme.

As explained in greater detail below, this goal builds on certain policy action and interim targets by the year 2030. Achieving the set nitrogen target therefore does not yet guarantee a sustainable environmental condition, but it is to be regarded as an interim goal. For example, although the contamination situation in terrestrial ecosystems will be improved by the reduction in excessive emissions set for 2030, ecosystems still will not enjoy comprehensive protection from excessive inputs of nitrogen from the atmosphere. To better protect humans and the environment, the release of nitrogen should nevertheless be limited to 1,000 kt N a^{-1} (or 1 million t) annually for Germany as a first step. Compared to the current release level displayed in chapter 3, the total annual release of reactive nitrogen would have to be reduced by about one third. With 83 million inhabitants, this means limiting the release of nitrogen to about 12 kg N per year per person.

Method of Calculating the Integrated Nitrogen Target

For deriving the target, effects in different environmental media and reduction requirements in different emission and economic sectors were integrated into a common value. Specifically, this value includes impact indicators for six environmental sectors, with the maximum amount of nitrogen inputs per year calculated for each of the sectors in order to achieve corresponding quality targets on a spatial average for Germany (Table 3). The underlying quality targets of the respective impact indicators were taken from the existing legal situation. This involves concentration or emission limit values or maximum input loads, which are intended to protect air, water and living organisms from excessive nitrogen pollution. Taking the six environmental sectors into account, maximum release rates for ammonia (NH_3), nitrate (NO_3^-), nitrogen oxide (NO_x), nitrous oxide (N_2O) and total nitrogen (N) were calculated under the assumption that the concentration or quality targets in Germany are achieved on average (see Table 3). The integrated nitrogen target is the sum of the respective lowest maximum allowable nitrogen release rates per nitrogen compound, expressed as total nitrogen.

Table 3

Environmental sectors, quality targets and resulting N release rates / integrated nitrogen target (kt N per year) (Tables 12 and 17 in Heldstab et al. (2020) , adjusted to the current reference situation)

No.	Environmental Sector	Quality Target	Nitrogen Compound	*Integrated Nitrogen Target* and scaled max. release rates per environmental sector; in brackets: actual release situation in base year 2015
1.	**Terrestrial ecosystems –** eutrophication (deposition)	Reduction of the exceedance of critical loads for eutrophication by 35 % from 2005 to 2030 (European Commission, 2013; European Union, 2016)	NH_3 and NO_x emissions	**359** (563) NH_3-N **155** (375) NO_x-N
2.	**Surface waters** for preventing eutrophication of coastal waters	Total nitrogen concentration for protecting the North Sea, (2.8 mg N l^{-1}) and the Baltic Sea (2.6 mg N l^{-1}) (German Federal Government, 2016)	Total N load	**300** (356) N_{total}
3.	**Groundwater quality** affected by nitrate	NO_3^- concentration in groundwater: 50 mg l^{-1} (European Council, 1991)	NO_3 leaching	**121** (148) NO_3-N
4.	**Climate** affected by nitrous oxide emissions	N_2O emissions: long-term target reduction, 80–95 % (BMUV – German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2016)	N_2O emissions	**65** (83) N_2O-N
5.	**Vegetation** affected by NH_3 concentration	NH_3 critical level for higher plants: 3 µg m^{-3} NH_3 (Convention on Long-Range Transboundary Air Pollution (CLRTAP), 2017)	NH_3 emissions	**416** (625) NH_3-N
6.	**Human health** affected by nitrogen dioxide	NO_2 concentration: WHO threshold level for the background: 20 µg m^{-3} (World Health Organisation, 2013)	NO_x emissions	**223** (361) NO_x-N
Integrated Nitrogen Target (∑1.–4.)				**1,000** (1,525) kt N a^{-1}

* Only environmental sectors 1-4 highlighted in light blue are included in the integrated nitrogen target; all values have been adjusted with regard to the updated reference scenario, which, in contrast to the scenario in the research report, factors in measures that have already been adopted, such as the Climate Protection Act (2019) or the Fertiliser Ordinance (2020).

For the environmental sector "Eutrophication of Terrestrial Ecosystems" (1), the targets of the national air pollution control programme have been adopted. This programme implements the new EU Directive on the Reduction of National Emissions of Certain Air Pollutants (NEC Directive)[4] in Germany by specifying ammonia and nitrogen oxide reduction obligations, among other pollutants. Model calculations estimated the area of ecosystems affected by excessive nitrogen deposition in 2030 to reduce by 35 % compared to 2005 under the emission reductions agreed in the NEC Directive.

For the environmental sector "Surface Waters and Coastal Ecosystems Affected by Eutrophication" (2), the targets of the Surface Water Ordinance (German Federal Government, 2016) were taken as a basis. At the transfer point between limnic and marine systems, the nitrogen concentration to protect against eutrophication is 2.8 mg l^{-1} for the North Sea and 2.6 mg l^{-1} for the Baltic Sea. The German Working Group on Water Issues of the Federal States and the Federal Government (LAWA) has analysed data from the river basin communities and calculated target loads and the reduction required to comply with the concentration limit values. These results have been incorporated into the nitrogen target.

The average nitrate concentrations in the seepage water of the groundwater monitoring sites of the German states for the years 2010–2017 were used for the environmental sector "Groundwater Quality Affected by Nitrate" (3). For agricultural areas where a measuring point indicated an exceedance of the limit value of 50 mg l^{-1} of the Nitrate Directive[5], it was assumed that the necessary reduction of the nitrate concentration in the seepage water was proportional to the necessary reduction of the soil surface N-budget surplus of the respective agricultural area. From a precautionary point of view, the seepage water concentration was equated with the groundwater concentration and, for the sake of simplicity, it was assumed that the groundwater concentration of nitrate is only influenced by agricultural activities.

For the environmental sector "Climate" (4), the permissible amount of nitrous oxide released was calculated based on the long-term targets for greenhouse gas emissions of the German Federal Government's 2050 Climate Protection Plan (BMUV 2016). To this end, mandatory greenhouse gas reduction rates (in % of CO_2 equivalents) were converted in a simplified way to mandatory N_2O reductions. For precautionary reasons, the calculated value for 2050 has been used in the target. Due to the small absolute size, scaling through 2030 would not have an effect on the final result.

For the environmental sector "Vegetation Affected by Atmospheric Ammonia Concentration" (5), the critical limit concentration for ammonia (3 µg m^{-3}) recommended by the UNECE Clean Air Convention in the Gothenburg Protocol[6] for the Protection of Higher Plants was taken as a basis. By correlating time series of concentration and emission values over Germany and based on the assumption that ammonia mainly affects vegetation at short distances after it is released, it was possible to calculate maximum permissible average ammonia emissions for compliance with the specified limit concentration.

For the environmental sector "Human Health Affected by Nitrogen Dioxide in the Air" (6), the background concentration value for nitrogen dioxide of 20 µg m^{-3} proposed by the World Health Organisation (WHO) as an annual mean was used as the standard. The legally defined value of 40 µg m^{-3} cannot be used to derive an integrated target, as concentrations of this magnitude only occur in small areas on roads with heavy traffic, and these exceedances cannot currently be modelled with sufficient accuracy throughout Germany. Assuming that NO_2 concentrations at background measuring stations are proportional to the sum of national NO_x emissions[7], a nationally admissible maximum emission was calculated for compliance with the target.

4 DIRECTIVE (EU) 2016/2284 OF THE EUROPEAN PARLIAMENT AND OF THE EUROPEAN COUNCIL of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC

5 COUNCIL DIRECTIVE (91/676/EEC) of 12 December 1991 on the protection of water bodies against pollution caused by nitrates from agricultural sources

6 Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone

7 The calculation was based on the assumption that only 98 % of the background measuring stations are exclusively influenced by large-scale, national emissions, while 2 % of the stations (those with the highest measured values) are also influenced by local factors

The nitrogen compounds ammonia and nitrogen oxide each occur twice in different impact indicators. To avoid double counting, only the more sensitive maximum release rate from each of the two impact indicators was included in the integrated nitrogen target. For this reason, the ammonia value of the quality objective (5) that is less sensitive than the one for the environmental sector “Eutrophication of Terrestrial Ecosystems” (1) was not considered for the overall target. Likewise, the nitrogen oxide value for the quality target (6) of human health was not considered for the overall target, as the resulting target for nitrogen oxide in the environmental sector “Eutrophication of Terrestrial Ecosystems” (1) based on the National Clean Air Programme is stricter. Table 3 shows the four impact indicators included in the nitrogen target with light blue shading.

The target was derived by factoring in the current political framework conditions through 2030 in Germany. The value of 1,000 kt per year therefore reflects the reduction required under current legislation by 2030. The proposed integrated nitrogen target is to be understood as a political action target and not interpreted as a comprehensive environmental quality target.

Classification of the Integrated Nitrogen Target

The method described above and the resulting target value of 1,000 kt nitrogen per year harbour uncertainties related to the selection of the indicators, data basis, quality targets and methodology definition. Nevertheless, the value provides a reliable order of magnitude towards which social action and political action planning need to strive. The magnitude of the nitrogen target agrees well with other national targets, such as those of the NEC Directive[4]. In addition, the resulting per capita rate of around 12 kg of nitrogen per year[8] closely matches the historical global average per capita release at the beginning of the industrial era (Galloway et al., 2014).

Integrating quality objectives for ammonia, nitrogen oxide, nitrate and nitrous oxide enabled a uniform value for total nitrogen (N) to be derived. The integrated objective does not include a regional or local resolution but applies to the national level. In contrast, nitrogen-related environmental impacts show local or regional patterns and characteristics or are caused by specific nitrogen compounds. The national value therefore cannot be used on its own to ensure that measures are taken where limit value exceedances continue to be a problem. Nevertheless, the integrated target sets a new national framework for the overarching need for action. This framework needs to be supported by existing spatially resolved indicators and spatially explicit action planning. As such, existing indicators based on spatially detailed monitoring networks or detailed modelling approaches (https://www.umweltbundesamt.de/en/data) are not to be replaced but must be part of the action programme for reducing nitrogen. In addition, the sub-targets for ammonia, nitrogen oxide, nitrate and nitrous oxide should always be reviewed independently of each other to prevent a missed target in one environmental sector from being compensated by overachievement in another sector.

The integrated nitrogen target illustrates the urgent need for action to reduce nitrogen and fosters awareness raising for the nitrogen problem. Concurrently, it helps to monitor the success of social efforts and make them visible. The integrated target of a maximum release of 1,000 kt of nitrogen per year (1 million t N a^{-1}) can therefore set the future framework for further action planning within the action programme for reducing nitrogen.

Expected Emissions Development and Target Gaps in 2030

In the areas of air pollution control, climate protection and agriculture, political action packages have already been initiated that are expected to reduce nitrogen inputs into the environment by 2030.

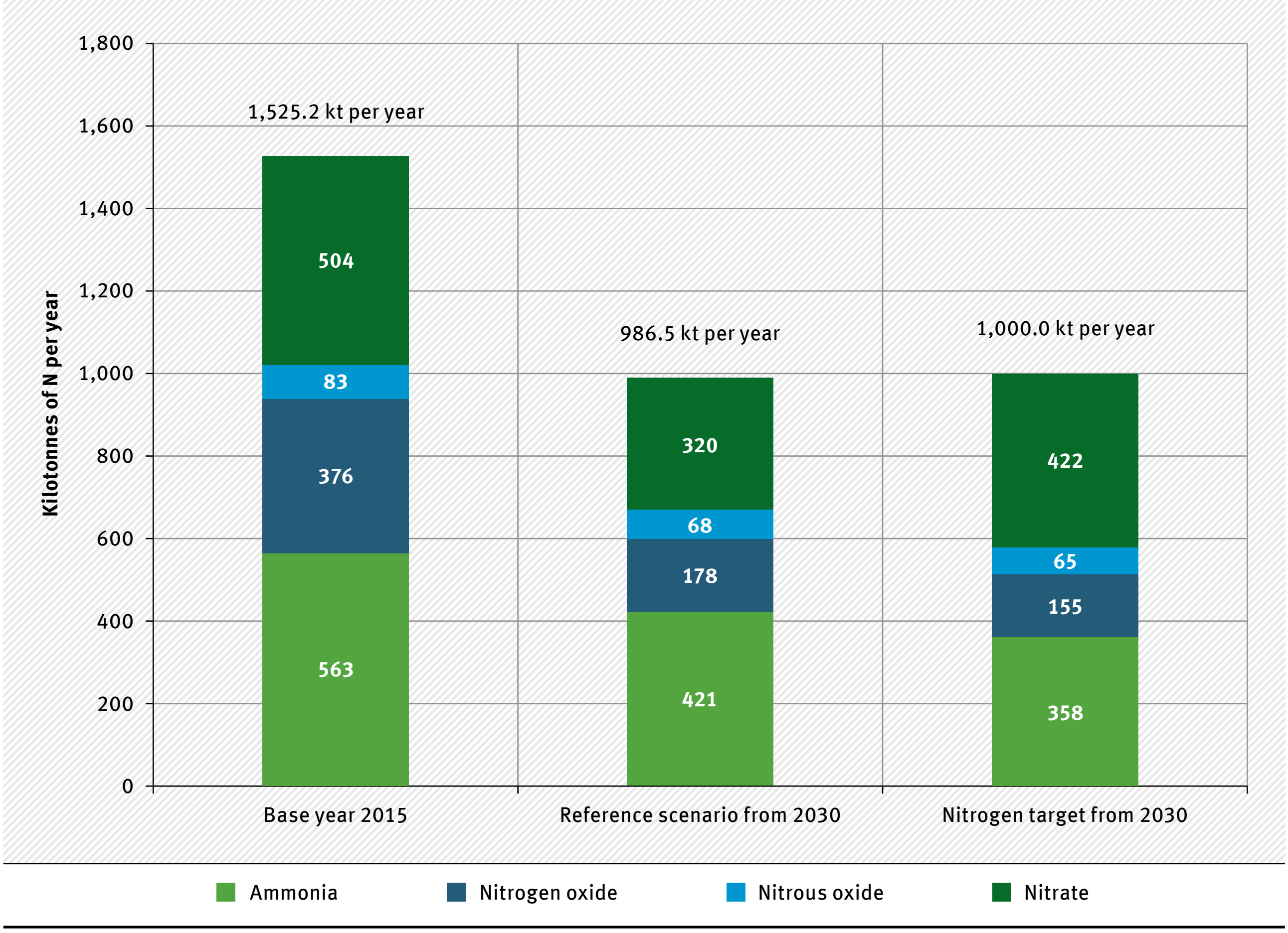
To visualise expected progress, an updated reference scenario was drawn up for the year 2030, building on the report “Proposed Measures for an Action Programme for Integrated Nitrogen Reduction” (Oehlmann et al., 2021). To this end, expected emission reductions for air pollutants (NO_x and NH_3), greenhouse gases (involving N_2O here) and nitrate loads (NO_3^-) were simulated through the year 2030. This is based on the updated air pollutant projections for the National Clean Air Programme for the NEC Directive[9], the nitrous oxide projections taking into account the

8 1000 kt / 83 million inhabitants = 12 kg/inhabitant

9 https://cdr.eionet.europa.eu/de/eu/nec_revised/projected/envygydvq/

Figure 8

Nitrogen flows in base year 2015 and in the reference scenario in 2030 compared to the target values in 2030 (see also Table 3)[10]



Source: German Environment Agency

2030 Climate Protection Programme (on 29 January 2020) (Harthan et al, 2020) and current assumptions for estimating the effectiveness of Fertiliser Ordinance updated in 2020 (German Federal Government, 2020) with regard to the development of agricultural nitrate discharges (Haß et al., 2020). Figure 8 visualises that the target value of 1,000 kt N a^{-1} is exceeded by nitrogen flows of 1,525 kt N a^{-1} in the base year 2015[10] and that current policy action packages can be expected to meet the overall management target by 2030.

Regardless of the overarching target, the sub-targets also need to be achieved (see above). In particular, the amended Fertiliser Ordinance and the associated assumptions on the possible development of national nitrate losses suggest that no further measures are required to achieve the aggregate sub-target on nitrate proposed here. According to current estimates, further measures urgently need to be implemented for nitrous oxide, nitrogen oxides and ammonia within the framework of the nitrogen reduction action programme in order to also to achieve the sub-targets in this respect.

10 The value of 1,525 kt differs from the 1,574 kt presented in Section 3 because it is based on different times (2010–2014 average vs. 2015 annual value) and because the method according to the Convention on Long-Range Transboundary Air Pollution (2013) was used to quantify the baseline situation in Section 3, while only national and legal requirements were used in Section 4.

The reference developments recorded here only allow for an estimation on a national level. While those developments in fact indicate that Germany is on the right track for nitrate on the national level, the important question of the extent to which nitrate concentration target values can be achieved with the amended Fertiliser Ordinance, even at individual measuring points, cannot be predicted here.

In addition to the consistent implementation of the above-mentioned action packages, regular monitoring of actual nitrogen emission developments related to target values is indispensable on a regional and local level.

Measure Assessment for a Nitrogen Reduction Action Programme

In order to prepare the development of the nitrogen reduction action programme and to justify the selection of measures, UBA has commissioned a comprehensive, cross-sectoral inventory of measures as part of an additional research project (Oehlmann et al., 2021). For the inventory, existing catalogues of measures along with other national and, above all, international literature sources were evaluated.

All measures included in the inventory were assessed uniformly according to the criteria of effectiveness, efficiency, technical feasibility and potential trade offs with other environmental sectors. In addition, a legal assessment of the intervention options was conducted and their feasibility assessed. In addition, estimates of the social and political acceptance were made and potential relocation effects abroad taken into account.

Potential measures that were highly effective and, at the same time, highly efficient were identified primarily in the transport and agriculture sectors. Measures in the energy sector and in households and industry are less effective and more expensive in comparison.

In the agricultural sector, this includes the introduction of a nitrogen surplus levy to further reduce ammonia, the introduction of space-dependent livestock farming, stricter upper balance limits in the Material Flow Balance Ordinance, nutrient-adapted multiphase feeding in pig and poultry farming, along with other mandatory requirements for the spreading of farm manure.

Measures that are particularly efficient and effective to further reduce NO_x in the transport sector include aligning the tax rate for diesel with that for petrol, abolishing the distance allowance, introducing a maximum speed of 120 km/h on federal motorways, a nationwide mileage-based car toll, reforming the company car privilege and extending the truck toll to all roads and all trucks over 3.5 tonnes.

In the final discussion of the action programme, additional evaluation criteria such as social and political acceptance plus technical and legal feasibility need to be considered, the results of which may also make other measures advisable, such as promoting e-mobility.

Ultimately, it is up to policy-makers to choose the appropriate measures to achieve regional and national nitrogen emission reduction targets ideally by 2030. The German Environment Agency's catalogue of measures provides a suitable set of instruments for drawing up an action programme for reducing nitrogen.

Civil Dialogue – Nitrogen Concerns Us All

Even though our dietary, consumption and mobility behaviour influences our personal "nitrogen footprint", society's awareness of the issue is still insufficient. This lack of awareness is at odds with the manifold effects of nitrogen on the environment and health and the fact that nitrogen is an essential resource in food production. Due to existing information deficits and local differences in the extent and nature of the impact, the nitrogen problem has only been grasped in part by the population. In the context of a broad civil dialogue initiated by BMUV and UBA, participants were sensitised to the overarching issue, and ideas and suggestions for reduction measures were collected. In particular, the local-specific, creative and external view of the citizens in focus was addressed. The purpose of the participation process was to find out which measures and instruments are preferred by the participants in order to reduce nitrogen emissions.

A total of 110 participants were randomly selected with the aim of achieving a group composition that was as heterogeneous as possible and invited to take part in four dialogue events in September and October 2019.

The participants developed their own proposals for reducing nitrogen emissions in four thematic regional conferences held in Weimar, Duisburg, Oldenburg and Stuttgart. With the aid of different discussion formats, they developed a total of 31 proposals on how nitrogen emissions can be reduced in the polluter sectors of "private consumption", "industry and freight transport", "agriculture" and "mobility". The proposed measures range from taxes, financial subsidies and bans to standard setting, improved vocational and school training and information campaigns. During a final two-day conference, the 31 proposals of the regional conferences were brought together by 23 delegates drawn by lot and discussed in the overall context. In the end, 16 proposals for measures were aggregated or selected and elaborated in depth. In February 2020, the Citizens' Proposal resulting from the conferences was published and subsequently submitted to the Federal Minister for the Environment (BMUV, 2020). Core elements of this proposal are to be incorporated into the nitrogen action programme of the German Federal Ministry for the Environment.

Cost-Benefit Analysis

The input of nitrogen into the environment is associated with costs and benefits. Nitrogen fertilisation increases yields in agricultural production and thus comes along with an economic benefit exceeding the costs of fertilisers and their application. Besides these directly computable costs and benefits, however, nitrogen deposition also causes damage to the environment and human health. For society, these impacts (e.g., contamination of drinking water, loss of biodiversity) are associated with costs. Measures to reduce nitrogen releases into the environment will lessen the negative environmental impacts and associated social costs.

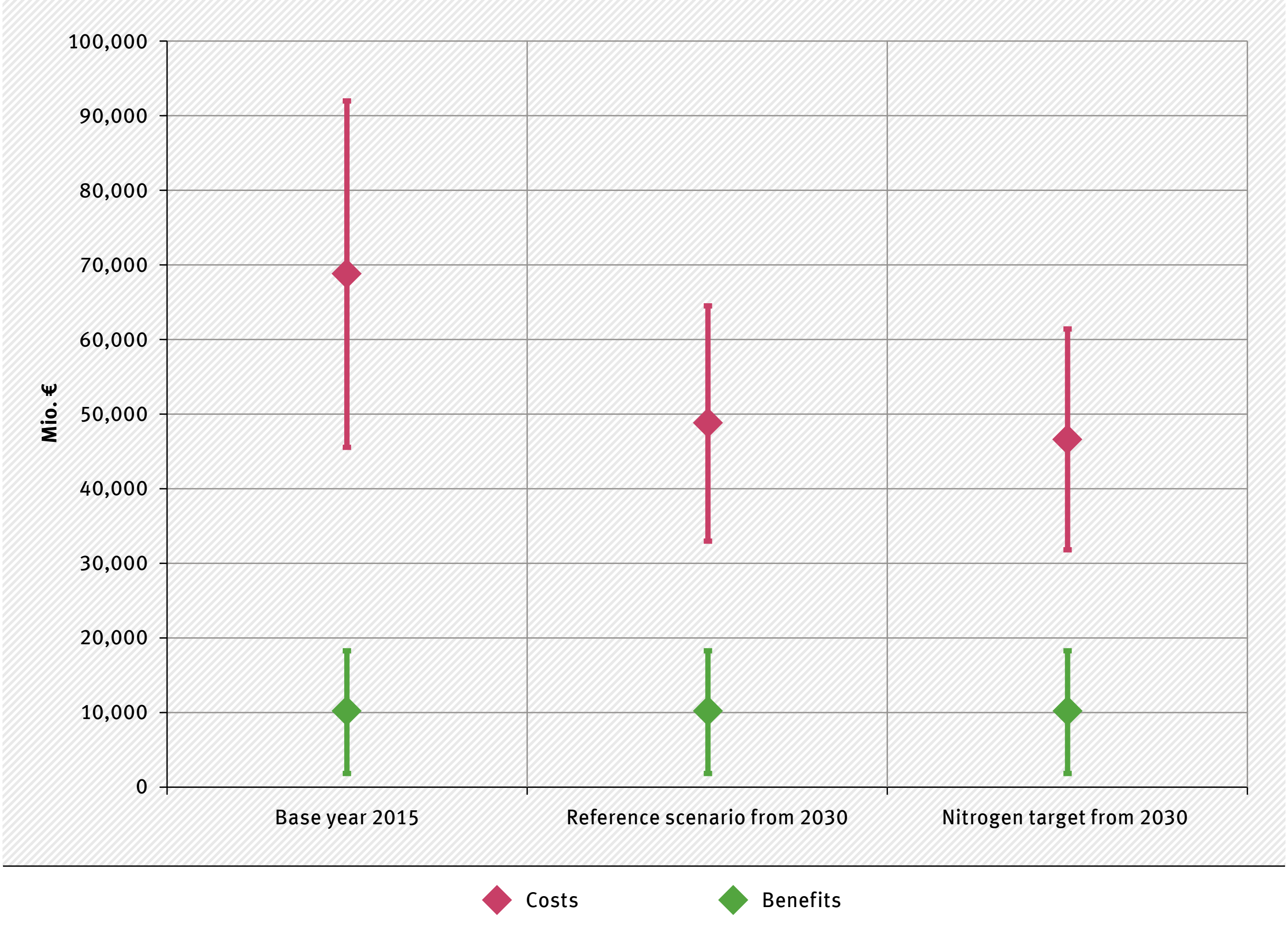
An economic cost-benefit analysis for nitrogen makes a transparent comparison of all relevant costs and benefits possible. It therefore provides yet another important decision-making basis for developing a nitrogen action programme.

As part of the aforementioned research project (Oehlmann et al., 2021), the costs and benefits of managing nitrogen in Germany were estimated. The analysis supports the conclusion that the economic costs – caused by, among other things, harmful effects on the environment and health costing around €70 billion – are multiple times greater than the benefits, which were mainly derived from agricultural yields and amounted to around €10 billion in 2015. Figure 9 shows that the consistent implementation of the currently adopted action packages is expected to lead to a slight improvement in the cost-benefit ratio by 2030. However, the analysis also shows that, even if annual nitrogen inputs are limited to 1,000 kt of nitrogen, the costs due to damage are still greater than the benefits. This underscores the fact that the 2030 nitrogen target is only to be regarded as an interim target: one that reduces negative impacts but does not yet provide adequate protection of the environment and human health. For more extensive, comprehensive protection, not only the nitrogen target but also the underlying environmental quality targets would have to become stricter in future.

The costs and benefits of nitrogen were calculated according to the method published by van Grinsven et al. 2013. The costs of the environmental and health impacts were determined based on the German Environment Agency's data for the economic assessment of environmental damage (Bünger & Matthey, 2020).

Figure 9

Costs and benefits from reactive nitrogen in Germany [in millions of euros] for the year 2015, for the 2030 reference scenario and for the nitrogen target of 1000 kt N per year



Source: adapted from Oehlmann et al., 2021

5 Fulfilling Social Responsibility through Smart Measures

The preceding analysis demonstrates that Germany still has deficits in how to handle nitrogen. It is necessary to further reduce nitrogen emissions from combustion processes and to optimise the use of nitrogen as a resource in agriculture in order to achieve the integrated national nitrogen target of 1,000 kt N a^{-1} by 2030 as developed by the German Environment Agency.

From the point of view of the German Environment Agency, the first and most important step is to adopt an integrated action programme for reducing nitrogen emissions. Within this integrated programme, the German Federal Government should commit to joint collaborative efforts of all ministries to exploit synergies and operate efficiently. The measures analysis commissioned by the German Environment Agency revealed that there exist sufficient suitable, sector-specific individual measures for achieving the integrated minimum nitrogen target and its sub-targets.

The embedding of such an action programme in a sustainable, interdepartmental strategy in a next step brings about the necessary commitment for medium to long-term action and long-term change towards sustainable nitrogen management at national level. In the long term, transforming society in the particularly relevant sectors of food and mobility is only possible with additional accompanying measures and processes, allowing society to reduce the individual nitrogen emissions and other negative environmental impacts associated with individual actions. Above all, it is personal dietary and mobility behaviour that influences personal "nitrogen footprints". In particular, restrained use of motorised private transport or air travel or moderating consumption of animal food products can have a positive effect on the nitrogen cycle.

Both behavioral changes also bring about synergies for climate protection, as the transition to a nitrogen-efficient society and nitrogen-conscious behaviour also protects the climate. Supportive in this context would be processes ranging from educational and advisory concepts for general and specialised schools to optimisations of the existing legal framework. Particularly for developing a political strategy for nitrogen reduction, the large synergies that are to be expected with protecting the climate need to play a significant role.

As nitrogen is of interest when it comes to environmental, economic and food policy in Europe and globally, it is therefore necessary for an overarching national strategy to be embedded in European and international activities. Nitrogen does not stop at borders through atmospheric transport of pollutants for example. Recently, the Netherlands declared a "nitrogen crisis" and resorted to drastic measures to better protect ecosystems from airborne nitrogen pollution caused by agricultural and combustion-related emissions. The reason for these measures was the inadequate implementation of the EU Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora by the Netherlands[11]. Due to the trade in farm manure, nitrogen does also not stop at the border between Germany and the Netherlands.

At the global level, the global network of scientists of the International Nitrogen Initiative (INI) is concerned with seeking and implementing integrated solutions for the complex system of the nitrogen cycle. The 8th Global Conference of the INI took place online in June 2021. The German Environment Agency and the Ministry for the Environment, Nature Conservation and Nuclear Safety hosted this event.

11 Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora.

The conference was held under the heading of "Nitrogen and the UN Sustainable Development Goals" (www.ini2021.com). The conference was an important component in the development of globally sustainable nitrogen management. By hosting the conference, Germany aimed to underscore its efforts to develop integrated solutions and, at the same time, facilitate the gathering of international experts in order to optimise national ways to reduce nitrogen and raise national public awareness of the nitrogen cycle.

The "INI2021" conference connects to the "Nitrogen Resolution" on sustainable nitrogen management of the Fourth UN Environment Assembly (UNEA-4) (UNEP, 2019). The environment ministers of the United Nations are also using this resolution to express that cross-sectoral and cross-media cooperation within the United Nations – aiming to optimise the use of nitrogen – can make an important contribution to achieving the Sustainable Development Goals mentioned above in the introduction.

Glossary

Acidification	Reduction of the pH value of a system (e.g., soil or water bodies); this reduction is caused by acidifying substances.
Anthropogenic	Caused by humans
CLRTAP	Convention on Long-Range Transboundary Air Pollution
Critical loads	Measure for assessing the sensitivity of ecosystems. This involves scientifically based pollution limits for atmospheric pollutant inputs per unit of area and time.
Denitrification	Microbiological conversion processes in water bodies and soils, during which nitrate is converted into atmospheric molecular nitrogen (N_2).
Deposition	The deposition of air pollutants; air pollutants are carried into ecosystems in gaseous form, as particles or dissolved in precipitation and atmospheric moisture.
Eutrophication	An accumulation of nutrients in ecosystems
Habitats Directive	EU Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora
Geneva Convention on Air Pollution	Convention on Long-Range Transboundary Air Pollution
kt	Kilotonne, 1000 tonnes
kt N a^{-1}	Kilotonnes of nitrogen per year
mg l^{-1}	Milligrammes per litre
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_x	Nitrogen oxide
N_2O	Nitrous oxide
NEC Directive	Directive (EU) 2016/2284 of the European Parliament and of the European Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC
Reactive nitrogen	Nitrogen compounds that are very reactive: They combine in different compositions with organic and inorganic substances and are able to change these compounds quickly.
UNECE	United Nations Economic Commission for Europe
µg m^{-3}	Microgrammes per cubic metre

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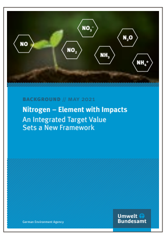

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