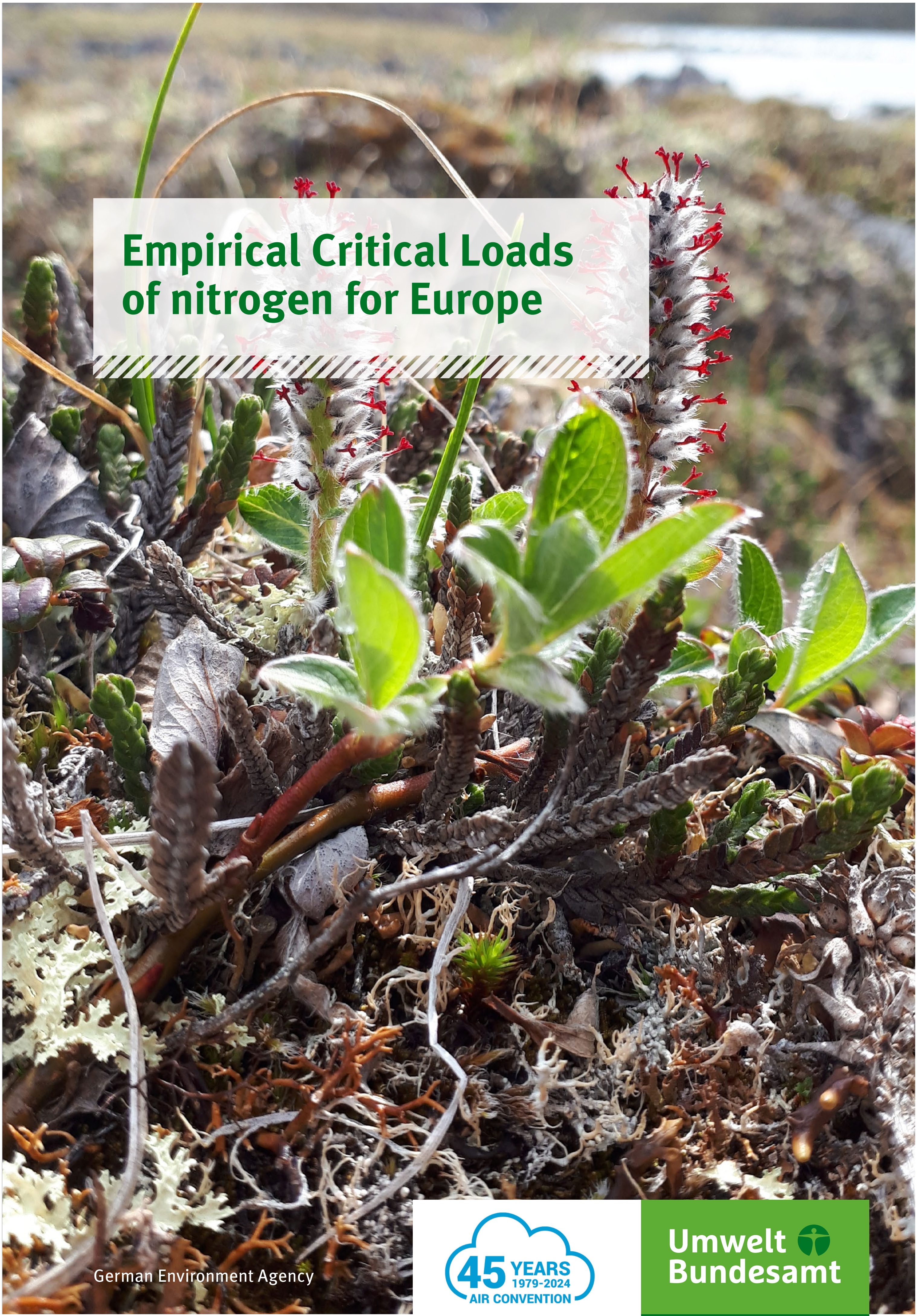
Empirical Critical Loads of nitrogen for Europe



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Empirical Critical Loads of nitrogen for Europe

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Umweltbundesamt
1974–2024

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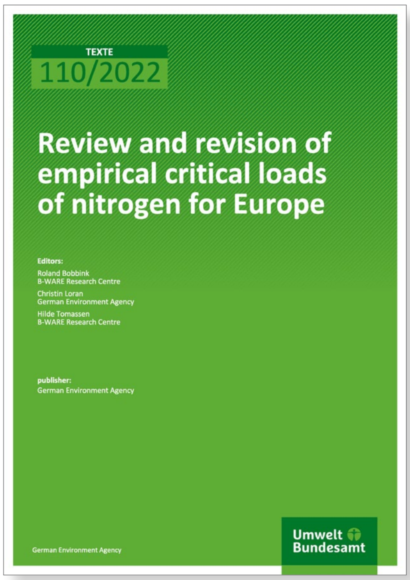
1 Introduction

Ecosystems that are affected by air pollution often show negative impacts on flora and fauna. Air pollution in this context is described as contamination of the ambient air by chemical substances that alter the natural properties of the atmosphere. Important chemicals are, for example, reactive forms of sulfur (S) and nitrogen (N). When these pollutants are excessively deposited from the atmosphere, they impair the ability of ecosystems to function and grow. One consequence is acidification, which affects the ability of ecosystems to provide ecosystem services, such as nutrient and carbon cycling, as well as supply with clean water on which the planet and human life depend.

Another effect of deposition is eutrophication, a process of accumulating nutrients, including nitrogen. As ecosystems degrade, so does biodiversity. Biodiversity loss impacts ecosystem resistance and resilience. Ecosystem stress is accompanied by a reduction in air quality, clean water, and healthy soils.

A suitable tool to scientifically support European policies aiming at effective emission reductions on air pollutants are critical loads (CL). *CL are quantitative estimates of exposure to one or more pollutants below which significant adverse effects on specified sensitive elements of the environment do not occur based on current knowledge* (CLRTAP, 2023). Crtitcal loads can be used to assess the risk of air pollution and the resulting risk to ecosystems and their structure and function. CL can be empirically estimated or modelled values. Empirical critical loads ($CL_{emp}N$) are based on measurable changes in ecosystem structure and function as determined by field observations, experiments and gradient studies.

The most recent update of the empirical critical loads of nitrogen for Europe is the result of expert collaboration within the Working Group on Effects (WGE) of the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). In June 2020 the Coordination Centre for Effects (CCE) started a project to bring the $CL_{emp}N$ up to date. The report "Review and revision of empirical critical loads of nitrogen for Europe" (Bobbink et al. 2022) provides $CL_{emp}N$ for harmful nitrogen inputs to natural and semi-natural ecosystems. The report also represents a revision and update of formerly published values of a previous report from the year 2011 (Bobbink and Hettelingh). The identified $CL_{emp}N$ now also include an analysis of new scientific data from the past 10 years by a team of 45 leading European nitrogen and ecosystem experts.



Picture of report Bobbink et al. 2022 as (UBA Texte 110/2022) published 10/2022

The updated list contains $CL_{emp}N$ for 51 different receptors in Europe:

- Marine habitats (3 $CL_{emp}N$)
- Coastal habitats (5 $CL_{emp}N$)
- Inland surface water habitats (5 $CL_{emp}N$)
- Marsh and fen habitats (16 $CL_{emp}N$)
- Heathland and tundra habitats (8 $CL_{emp}N$)
- Forest habitats (14 $CL_{emp}N$)

$CL_{emp}N$ for natural and semi-natural ecosystems were first presented in a background document at the 1992 workshop on critical loads staged during the UNECE Convention in Lökeborg (Sweden). Since then, they have been continuously developed on the basis of the latest scientific findings over the past 30 years. They pursue a harmonised, scientific approach developed with international experts. Based on field evidence, $CL_{emp}N$ are derived from observed N addition studies and N gradient studies which identify dose-effect relationships. The original rationale behind developing the $CL_{emp}N$ was to include the growing empirical evidence of negative nitrogen effects and increasing the credibility of nitrogen CL in policy support and regulation.

Nine new ecosystems could be added to the list of sensitive receptors, based on new scientific studies published between 2010 and 2021. Among them are Alpine and sub-Arctic lakes with clear water, Mediterranean beech forest on acidic soil as well as Temperate and sub-Mediterranean juniper shrubs.

More than 40% of ecosystem types reviewed are expected to be more sensitive to nitrogen inputs than assessed in 2010. Therefore, $CL_{emp}N$ had to be adjusted downwards (more sensitive).

This brochure summarises the current knowledge on empirical critical loads as published in the report "Review and revision of empirical critical loads of nitrogen for Europe" (Bobbink et al. 2022), which was elaborated in international cooperation under the CLRTAP with with ICP Forest, ICP Waters, ICP Vegetation and ICP Integrated Monitoring. It illustrates the wealth and diversity of European nature and underpins its sensitivity towards anthropogenic, atmospheric inputs of reactive nitrogen. Thus, the brochure shall support the broad understanding that nitrogen deposition is a severe risk for European biodiversity and of the importance for sustainable management of the nitrogen cycle to maintaine the European nitrogen-sensitive biodiversity."

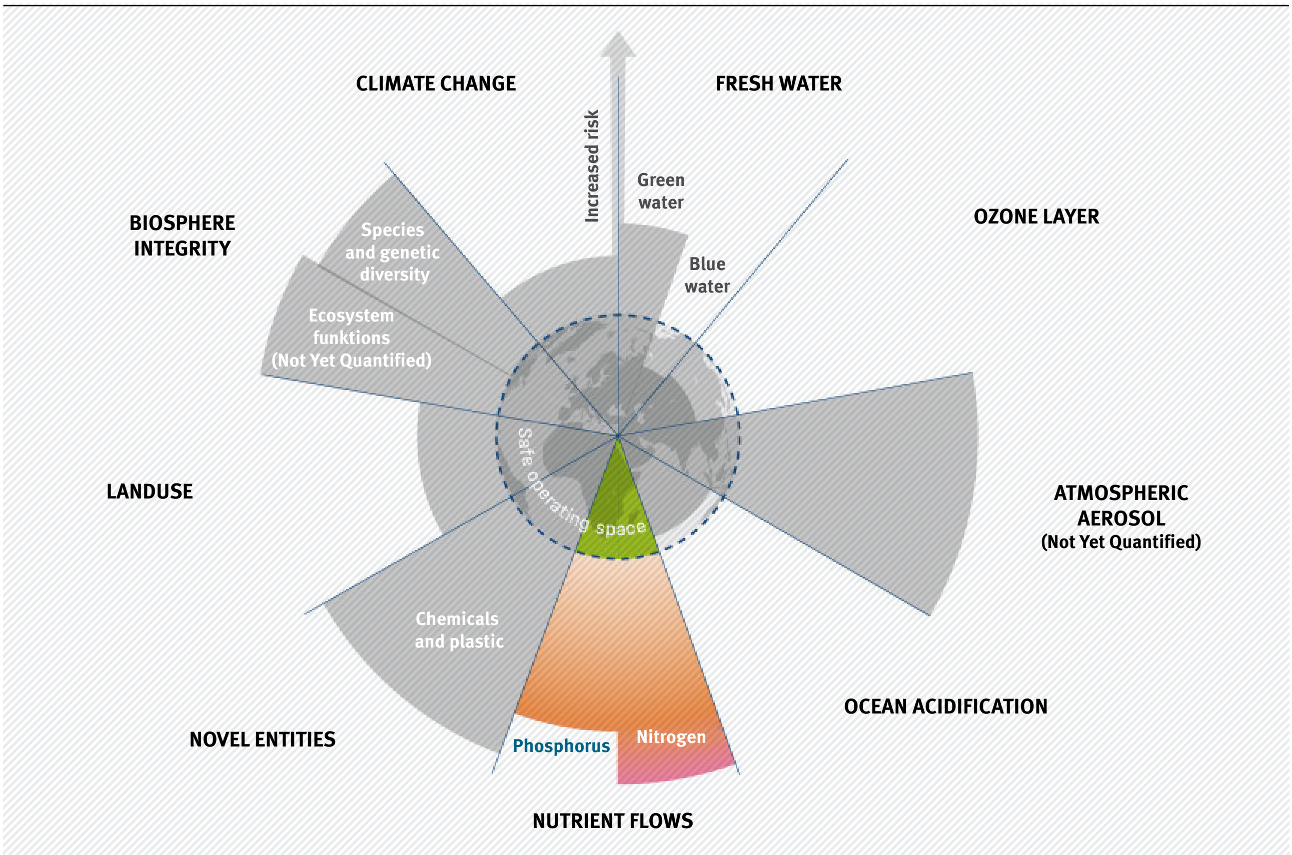
2 Nitrogen – element of life and threat to our environment

A large part of our planet's nitrogen supply is found as gaseous nitrogen compounds in the atmosphere. By far the largest part of this is elemental nitrogen, which is inert. It makes up 78 % of the air we breathe. Only a few natural processes convert elemental nitrogen into reactive forms: A few strains of bacteria, for example, can break down elemental nitrogen, making it available to plants. Since the industrial revolution, however, human processes have converted significantly more elemental nitrogen into reactive forms. The most important conversion processes are

- the combustion of fossil fuels and the associated emission of nitrogen oxides (NO_x),
- the synthesis of ammonia (NH_3) using the Haber-Bosch process (mainly for fertilizer production) and
- the cultivation of legumes.

Figure 1

Planetary boundaries exceedance for reactive N



Safe operation space · Planetary boundary exceeded

Source: Adapted figure originally produced by Azate for Stockholm Resilience Centre, based on analysis in Wang-Erlandsson et al., 2022, Persson et al. 2022 and Steffen et al. 2015

Part of the reactive nitrogen is released unused into the environment as an emission.

Excess reactive nitrogen inputs disturb the nitrogen balance of ecosystems and endanger plant communities, soils, and biodiversity. Due to anthropogenic emissions, the current global biogeochemical flows of reactive nitrogen have been shifted far beyond the proposed planetary boundary (Figure 1), which is among other set to avoid the risk of generating irreversible changes to ecosystems and their biodiversity due to nitrogen pollution.

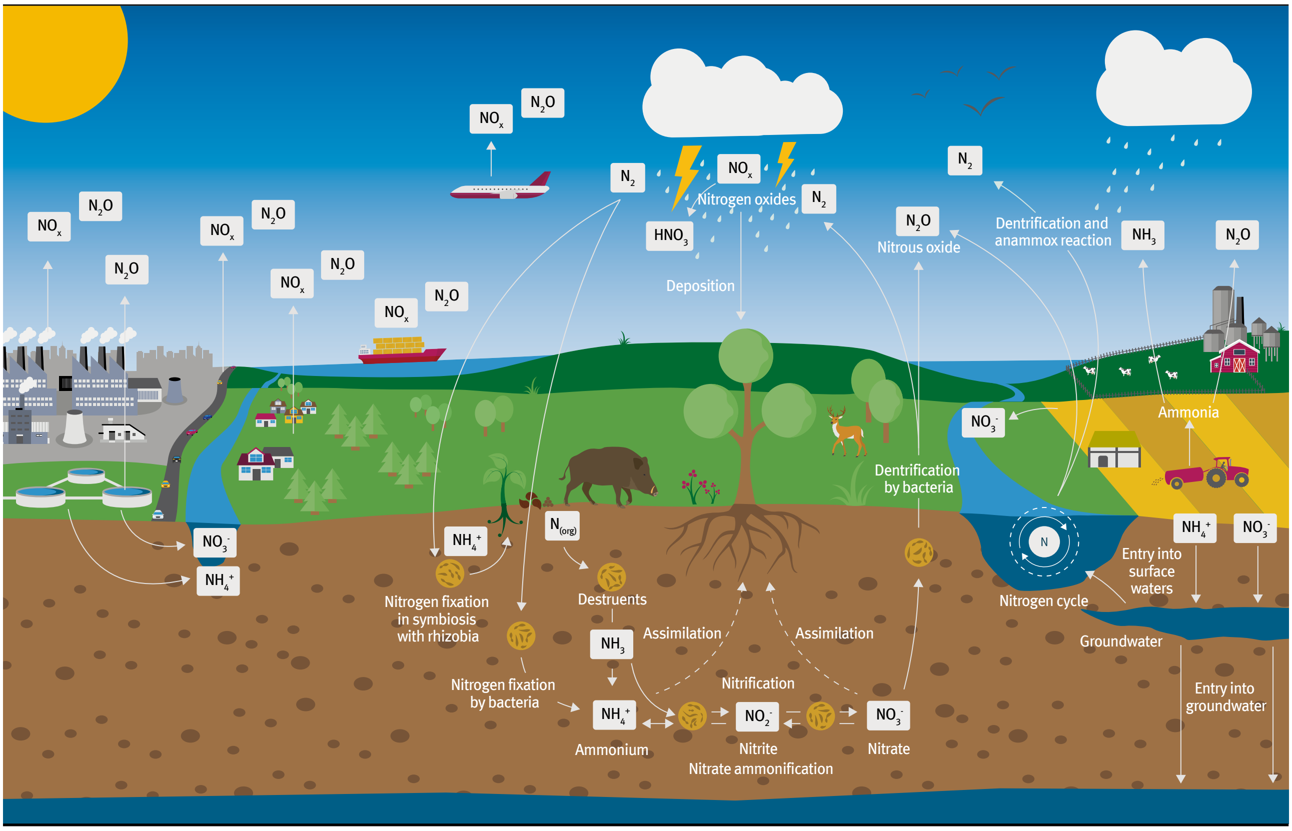
Reactive nitrogen compounds in the environmental context, relevant in the nitrogen cycle (Figure 2) are: nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O) nitrate (NO_3^-) which occur in dissolved form and in atmospheric particulate matter, nitrite (NO_2^-), nitric acid (HNO_3), ammonia (NH_3) which occurs in gaseous form and in atmospheric particulate matter or as ammonium salt (NH_4^+).

Exemplary effects of reactive N exceedances on ecosystems are:

Widespread nutrient oversaturation (eutrophication) and acidification of ecosystems have lasting consequences, such as loss of biodiversity. Elevated ammonia concentrations in the atmosphere cause widespread damage to sensitive plants in Europe.

Figure 2

Reactive 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

The most obvious effects of increased N deposition are significant changes in the N cycle, vegetation composition and biodiversity, e.g. species richness in vegetation (Bobbink et al. (1998, 2010), Dise et al. (2011) and Stevens et al. (2020)). Acidification and eutrophication (mainly caused by NH_3, NH_4^+, NO_3^- and NO_x) of soils and ecosystems lead to nutrient imbalances, threats to biodiversity and causes shifts in the habitats of species. Besides terrestrial ecosystems, the aquatic environment is affected by excessive nitrogen input as well. A surplus of nitrogen nutrients in coastal and marine ecosystems causes eutrophication and associated massive algae growth. Also, some freshwater ecosystems are sensitive towards elevated nitrogen inputs (ICPW Report 2022).

In general, biological diversity is the term used to depict the variety of life on earth. It encompasses all organisms, species, and populations, the genetic variation among them and their complex assemblages of communities and ecosystems (UNEP, 2017). Each species within an ecosystem has its own niches and requirements. Changes in the ability to access these requirements – in this report through changes in nitrogen availability – affect the population size of a species resulting in changes to the composition of biological communities and ecosystems (CSS, 2020).

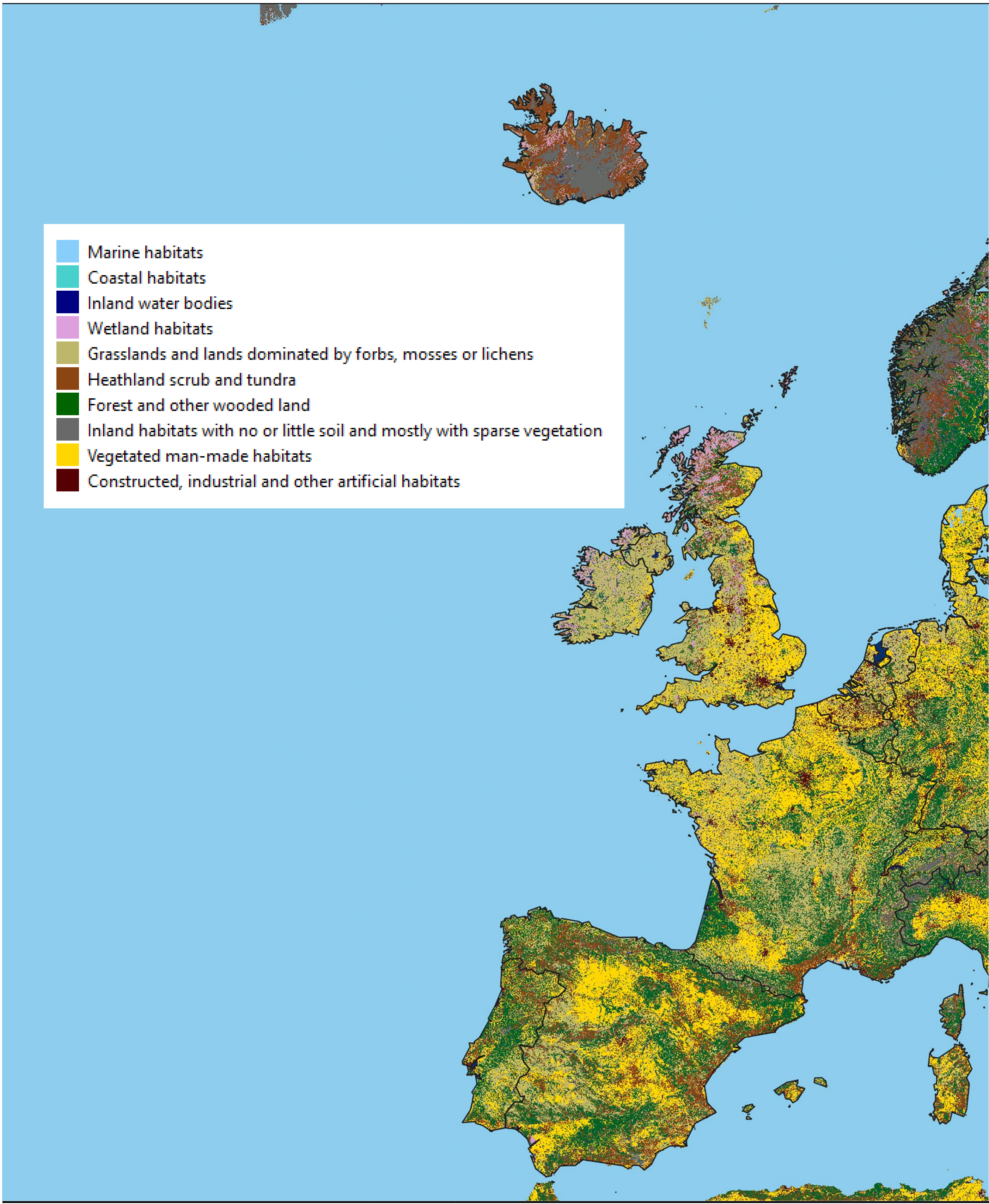
Threats to ecosystems from nutrient imbalances, high nitrogen saturation, and biodiversity loss have become an increasingly important issue under the Geneva Air Convention. The Long-term Strategy 2020–2030, which was adopted in 2018, specifically identifies the protection of biodiversity and the prevention of biodiversity loss as a goal. Indeed, this strategy states that the “disruption of global and regional nitrogen cycles is one of the most important environmental challenges (...) and that current and future exceedances of critical loads of nitrogen as an indicator of biodiversity loss over large areas are dominated by ammonia emissions from agriculture (...)” [Long-Term Strategy Decision 2018/5: p. 7].

3 Habitat classes

The habitat or biotope is the inanimate environment that, together with a community of organisms of different species, forms the ecosystem. An ecosystem means a biogeophysical environment in which organisms interact. Biotic (organisms) and abiotic factors (compartments) are thus mutually dependent in an energy and a nutrient cycle. Ecosystems are dynamic, but approaching a state of equilibrium. Disturbances in the form of pollution or over-nutrition can be absorbed by a functioning system that proves resilient. However, if the state of equilibrium is missed, resilience is lost and impacts such as eutrophication and other consequences occur. For the $CL_{emp}N$ the European Nature Information System (EUNIS) and the subdivision into classes described therein are used to describe all habitats. The $CL_{emp}N$ are derived at different EUNIS levels (levels 2-4) for the habitats. Exemplary, for coastal habitats $CL_{emp}N$ are derived on level 3, e.g. Shifting coastal dunes (N13) or on level 4, e.g. Dune-slack pools (N1H1). This is due to the fact that information, e.g. empirical and/or gradient studies, are available at different levels of habitats.

Figure 3

Distribution of ecosystems across Europe (designated for EUNIS Level 1)



Source: Gebhardt, S. (2023)

Marine habitats (MA)

Summary and indication of exceedance:

Marine habitats are directly connected to the sea. Salt marshes develop along coast lines and are intertidal. For marine habitats, the focus is on littoral biogenic habitat types. Dominant plants are rooted macrophytes and shrubs. When the $CL_{emp}N$ is exceeded, late successional species and species productivity may increase, positive indicator species decrease.

MA223: Atlantic upper-mid salt marshes;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

MA224: Atlantic mid-low salt marshes;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

MA225: Atlantic pioneer salt marshes;
$CL_{emp}N$ 20-30 kg ha^{-1} a^{-1}

Overview of the recent update of values:

The $CL_{emp}N$ for the two Atlantic coastal salt marshes, the Atlantic upper-mid salt marshes (MA223) and the Atlantic mid-low salt marshes (MA224) have been revised based on the results of the latest gradient studies. These two studies indicate that the $CL_{emp}N$ should be lowered. No new data is currently available for the review of the $CL_{emp}N$ of Atlantic pioneer salt marshes (MA225).

Coastal habitats (N)

Summary and indication of exceedance:

Soils of Coastal dunes with sand, shringle or rock as underlaying substrate are nutrient poor and therefore sensitive to the impacts of both eutrophication and acidification. Coastal dune grasslands (N15) are stable with dominant life forms of herbs and graminoids, and also bryophytes in certain areas in the north/western. Natural coastal dune heaths (N18, N19) are mostly dominated by typical dwarf shrub. Moist to wet dune slacks (N1H1/N1J1) are hot spots of plant biodiversity in the sandy dune regions of Europe. Dune slack vegetation dries out in most years in summer. Dune-slack pools have a water of ¾ of the year and were less than half year with an open water body. They show a high succession rate towards large heliophytes and shrubs. In general, as a result of N exceedance in coastal habitat classes, biomass may generally increase, and as terrestrial N leaching increases, root biomass will subsequently decrease. Oligotrophic species decrease while graminoids and mesophilic forbs increase. Also, the rate of succession may increase.

N13, N14: Shifting coastal dunes;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

N15: Coastal dune grassland (grey dunes);
$CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

N18, N19: Coastal dune heaths;
$CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

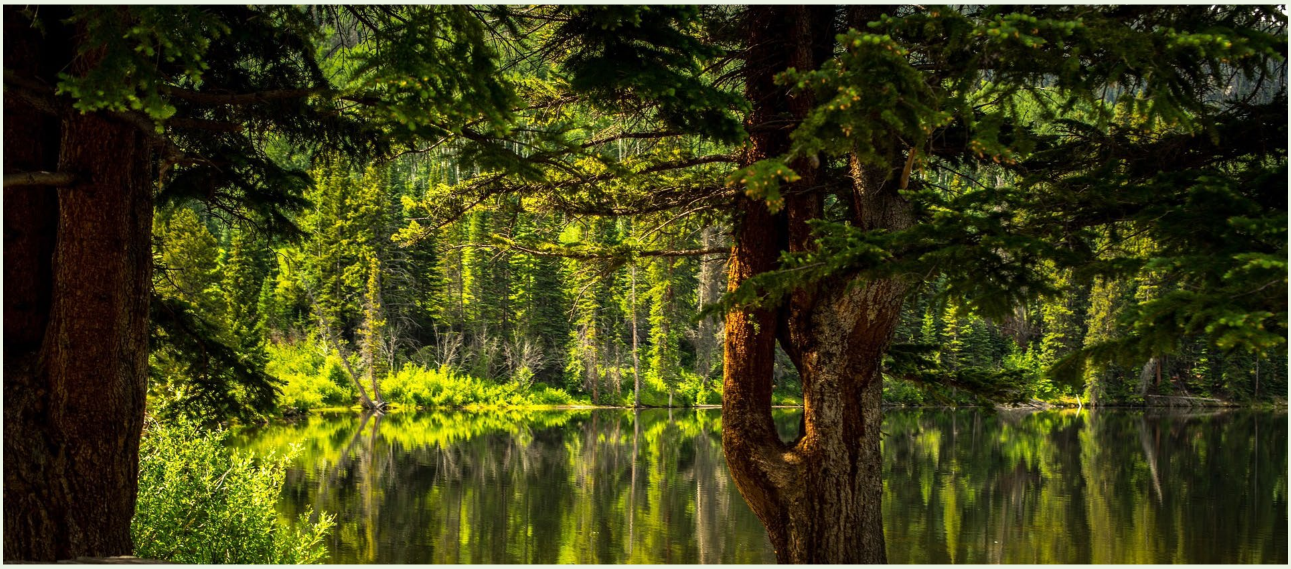
N1H: Moist and wet dune slacks;
$CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

N1H1, N1J1: Dune slack pools;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

New evidence for nitrogen effects only exists for some EUNIS categories under N1 (Coastal dunes and Sandy shores). Evidence for Shifting coastal dunes (N13 and N14) as coastal, mobile sand habitats come from gradient studies and experimental studies with N addition rates and low ambient N deposition. For Dune grasslands (N15) evidence comes from N-manipulation experiments and gradient studies. For natural Coastal dune heaths (N18/N19) a new N manipulation study has led to a lower $CL_{emp}N$ upper end of the range for this habitat. Gradient studies and field surveys on Dune slacks (N1H1/N1J1) show, that they are sensitive to N deposition. Due to little new evidence for this habitat, the $CL_{emp}N$ remains unchanged."

Inland surface water habitats (C)



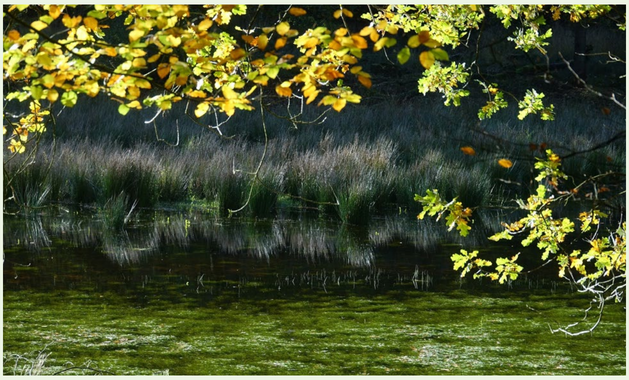
Summary and indication of exceedance:

The focus, looking at freshwater ecosystems, is on standing inland surface water habitats (C1). The different nutrient statuses of these surface standing waters lead to the following subdivision:"

- Oligotrophic lakes, ponds and pools (C1.1)
- Mesotrophic lakes, ponds and pools (C1.2)
- Eutrophic lakes, ponds and pools (C1.3)
- Dystrophic lakes, ponds and pools (C1.4) rich in humic substances.

The most dominant effect for inland surface waters of increased nitrogen availabilty is the increased algal productivity and the shift in nutrient limitation of phytoplancton from nitrogen (N) to phosphor (P). Another visible effect is the change in species composition of macrophyte communities.

C1.1: Permanent oligotrophic lakes, ponds and pools; $CL_{emp}N$ 2-10 kg ha^{-1} a^{-1}



C1.1 (elements of C1.2) Atlantic soft water bodies; $CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

C1.1 Alpine and sub-Arctic clear water lakes; $CL_{emp}N$ 2-4 kg ha^{-1} a^{-1}

C1.1 Boreal clear-water lakes; $CL_{emp}N$ 3-6 kg ha^{-1} a^{-1}

C1.4: Permanent dystrophic lakes, ponds and pools; $CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

Field surveys and experimental studies of soft water systems show that an increase in acidic and acidifying compound in the atmospheric deposition directly led to acidification of lakes and streams. Currently, critical loads for acidification of surface waters consider acidifying effects of S and N deposition. Evidence on N and P limitation in aquatic ecosystems on effects of eutrophication by atmospheric N is available. As a consequence, new $CL_{emp}N$ ranges are proposed for C1.1. For the permanent dystrophic class (C1.4), the lower end of the $CL_{emp}N$ range has been increased.

Mire, bog and fen habitats (Q)

Summary and indication of exceedance:

The wetland habitats under the EUNIS class Q (mire, bog and fens) are the most sensitive to nitrogen deposition. To define the $CL_{emp}N$ for these habitats, new experimental studies and numerous published gradient studies were reviewed. The general effect from N exceedance for these ecosystem types under EUNIS class Q are negative effects on bryophytes, either a decrease or an effect on species composition can be observed. In the long term, there is a risk that vascular plants, sedges and graminoids will increase.

Q1: Raised and blanket bogs;
$CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

Q2: Valley mires, poor fens and transition mires;
$CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

Q3: Pals and polygon mires;
$CL_{emp}N$ 3-10 kg ha^{-1} a^{-1}

Q41-Q44: Rich fens;
$CL_{emp}N$ 15-25 kg ha^{-1} a^{-1}

Q45: Arctic-alpine rich fens;
$CL_{emp}N$ 15-25 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

Whilst for Raised and blanket bogs (Q1) and Rich fens (Q4) the $CL_{emp}N$ could be confirmed for Valley mires, Poor fens and Transition mires (Q2) evidence led to a reduction of the low end of the $CL_{emp}N$. For Pals and polygon mires (Q3) a $CL_{emp}N$ was derived for the first time.

Grassland and tall forb habitats (R)

Summary and indication of exceedance

EUNIS class R habitats are grasslands and lands dominated by forbs, mosses and lichens. These ecosystems show a wide variety from dry to wet habitats, acidic to alkaline conditions, inland saline soils and different climatic regimes. Negative effects of too high nitrogen deposition are a general biomass growth with a decrease in diversity and decline in typical species. Soil nutrient cycling may change, mineralization, N leaching and surface acidification increase. Also, the dominance of graminoids and the decrease of lichens and bryophytes can be observed.

R1A: Semi-dry perennial calcareous grassland;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

R1D or R1E or R1F: Mediterranean closely grazed dry grasslands or Mediterranean tall perennial dry grassland or Mediterranean annual-rich dry grassland; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

R1M: Lowland to montane, dry to mesic grassland usually dominated by *Nardous stricta*; $CL_{emp}N$ 6-10 kg ha^{-1} a^{-1}

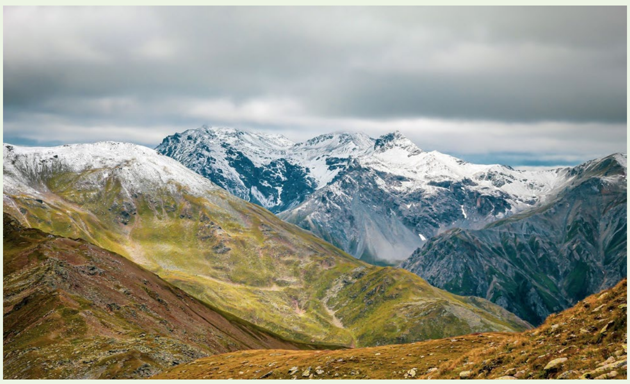
R1P or R1Q: Oceanic to subcontinental inland sand grassland on dry acid and neutral soils or Inland sand drift and dune with siliceous grassland; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

R22: Low- and medium altitude hay meadows;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

R23: Mountain hay meadows;
$CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

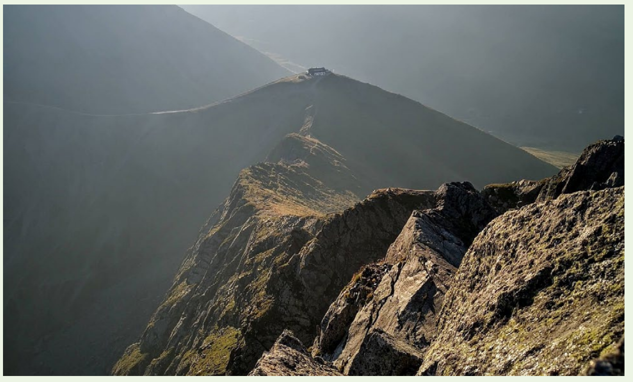
R35: Moist or wet mesotrophic to eutrophic hay meadow;
$CL_{emp}N$ 15-25 kg ha^{-1} a^{-1}

R37: Temperate and boreal moist and wet oligotrophic grasslands;
$CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}



R43: Temperate acidophilous alpine grasslands;
$CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

R44: Arctic alpine calcareous grassland;
$CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}



Earlier E4.2 – not classified yet but would be best represented in R42: Moss and lichen dominated mountain summits; $CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

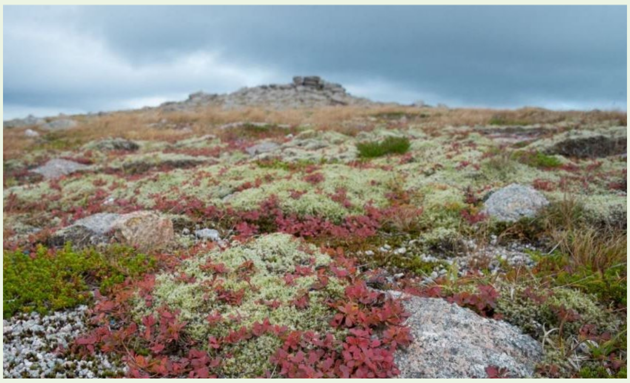
Based on experimental studies with N addition and also gradient studies the $CL_{emp}N$ were revised and partly updated where necessary. Findings from gradient studies and spatial analysis as well as several experimental studies (e.g. fertilizer study) show the need for lowering the $CL_{emp}N$ under R1 grasslands and R2 meadows (for 6 habitat $CL_{emp}N$) to prevent these ecosystems from negative effects. For Moist or wet mesotrophic to eutrophic hay meadow and Temperate and boreal moist and wet oligotrophic grasslands (R3) and Temperate acidophilous alpine grasslands, Arctic alpine calcareous grassland and Moss and lichen dominated mountain summits (R4) the $CL_{emp}N$ remain unchanged.

Heathland, scrub, and tundra habitats (S)

Summary and indication of exceedance:

Heathland, scrub and tundra habitats form the EUNIS class S include all dry and seasonally wet inland vegetation dominated by shrubs and scrubs. The term heath applies here to a plant community of small- leaved dwarf shrubs that form a canopy at one meter or less above soil surface. In heathlands the heath community occur together with grasses, forbs, lichens and mosses. Indicators of exceedances of the empirical critical load for nitrogen deposition for EUNIS class S habitats and the ecosystems are often changes in biomass and community composition, species richness and plant biochemistry. A result of N excesses a decrease in heather dominance, a decline in lichen species richness and general lichens, mosses, bryophytes and evergreen shrubs can be observed.

S1: Tundra, $CL_{emp}N$ 3-5 kg ha^{-1} a^{-1}



S2: Arctic, alpine and subalpine scrub habitats; $CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

S31: Lowland to montane temperate and submeterranean *Juniperus* scrub; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

S411: Northern wet heath – either *Calluna* (upland) or *Erica tetralix* (lowland) dominated wet heath; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

S42: Dry heaths; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

S5: Maquis, arborescent matorral and thermo-Mediterranean scrub; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

S6: Garrigue; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

Experimental N addition studies and gradient studies have clearly shown, that the input of reactive N highly impacts these ecosystems and needs to be lowered for most sensitive systems to prevent negative effects. Every $CL_{emp}N$ for all reviewed EUNIS S classes were lowered, due to current experimental data, except Tundra habitat (S1).

Forest habitats (T)

Summary and indication of exceedance:

Forests and other wooded land build up EUNIS class T. Forest ecosystems consist of different compartments which may be affected differently by increased N deposition. The soil plays an important role in mediating N effects on the whole forest ecosystem.

Important processes are:

a. **Soil eutrophication** from a surplus of N

b. **Nitrate leaching** to the groundwater if no uptake by plants or incorporation microbial biomass occurs

c. **Soil organic matter decomposition and carbon a nutrient cycling** – adverse C:N ratio – fine root biomass per tree decreases

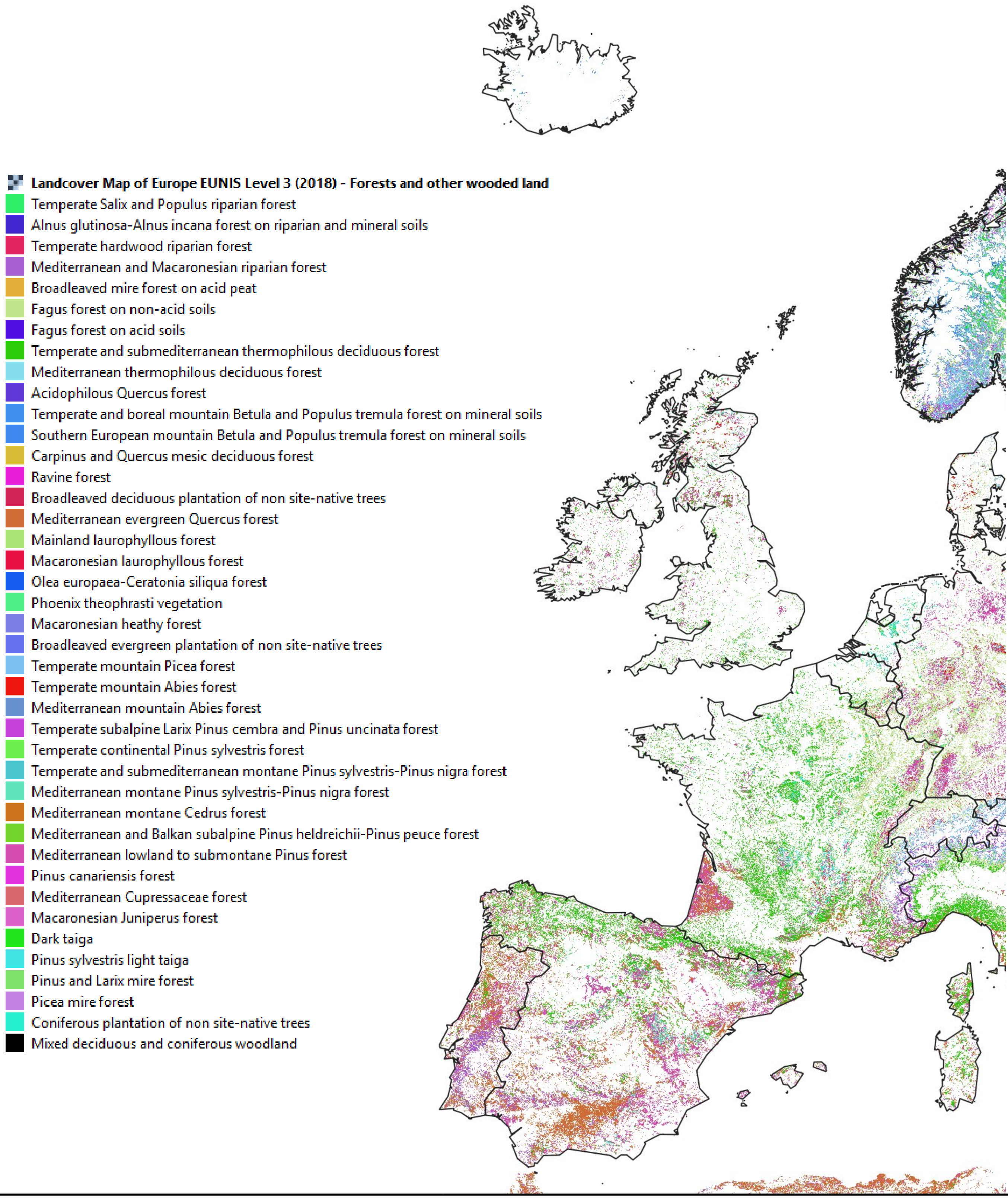
d. **Exchange of trace gases between soils and the atmosphere** due to microbial nitrification/denitrification

e. **Soil acidification** as a result of nitrification of NH_4^+ and leaching of NO_3^-

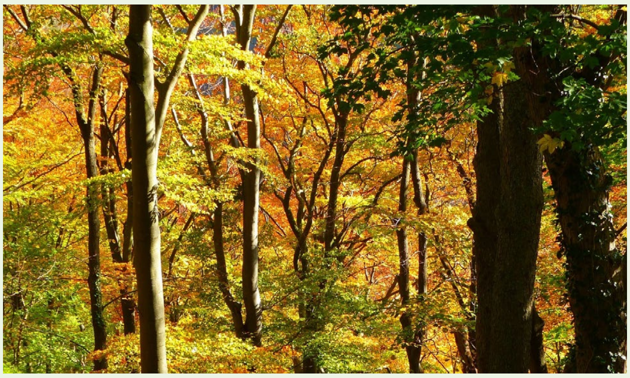
General effects of N deposition on trees are on growth, nutrition, physiology and parasite attacks. Spruce and taiga woods (here T3F and T3G) frequently show changes in epiphytic lichen and ground layer bryophyte communities and a general decline in N-fixation. The consequences for N excess in Mediterranean forest ecosystems (here T18 / T 21 / T33 / T37 / T3A) are divers. Heights and volume of tree growth is negatively affected, lichen community changes and also changes in soil microorganism communities do occur. In general, the most frequent effect of N excess for forests and wooded land are changes in soil processes, ground vegetation and fauna and the composition of mycorrhiza and also their decrease. Nutrient imbalances disturb the tree physiology. The loss of epiphytic lichens and bryophytes may occur.

Figure 4

Distribution of forest ecosystems across Europe (designated for EUNIS Level 3)



Source: Gebhardt, S. (2023)



T1: Broadleaved decidous forest; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T17, T18: *Fagus* forest on non-acid soils; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T18: Mediterranean *Fagus* forest on acid soils; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T1B: Acidophilous *Quercus* forest; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T1E: *Carpinus and Quercus* mesic decidous forest; $CL_{emp}N$ 10-20 kg ha^{-1} a^{-1}

T21: Mediterranean evergreen *Quercus* forest; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T3: Coniferous forests; $CL_{emp}N$ 3-15 kg ha^{-1} a^{-1}

T31, T32: Temperate mountain *Picea* forest, Temperate mountain *Abies* forest; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T33: Mediterranean mountain Abies forest; $CL_{emp}N$ 10-15 kg ha^{-1} a^{-1}

T35: Temperate continental *Pinus sylvestris* forest; $CL_{emp}N$ 5-15 kg ha^{-1} a^{-1}

T37: Mediterranean montane *Pinus sylvestris-Pinus nigra* forest; $CL_{emp}N$ 5-17 kg ha^{-1} a^{-1}

T3A: Mediterranean lowland to submontane *Pinus* forest; $CL_{emp}N$ 5-10 kg ha^{-1} a^{-1}

T3F: Picea abies, dark taiga; $CL_{emp}N$ 3-5 kg ha^{-1} a^{-1}

T3G: *Pinus sylvestris* light taiga; $CL_{emp}N$ 2-5 kg ha^{-1} a^{-1}

Overview and basis of the recent update of values:

No new experimental studies were conducted, but a number of existing gradient studies with modeled values of total N deposition, for example, were reviewed. A number of analysed studies suggested, that upper level of several $CL_{emp}N$ of EUNIS class T habitats were too high. This was also the case with the previous $Cl_{emp}N$ for Deciduous forests (T1) and for Evergreen deciduous forests (T2). The $Cl_{emp}N$ were therefore adapted. Information on N effects on lichens and on N leaching led to a lowering of $CL_{emp}N$ of Coniferous forests (T3). New forest types were included in EUNIS class T like Mediterranean Fagus forest on acid soils (T18), Mediterranean mountain abbies (T33) or Mediterranean montane Pinus silvestris-Pinus nigra forest (T37).

4 Use of empirical critical loads of nitrogen in risk assessment and nature protection

Current estimations of nitrogen deposition indicate wide-spread exceedance of modelled critical loads across Europe (EMEP 2023). Also, the updated $CL_{emp}N$ for the investigated habitats can be visualized in a map and then compared and evaluated with the existing nitrogen deposition. The preparation of a detailed exceedance map with $CL_{emp}N$ is embodied in the ICP Modelling and Mapping workplan for 2024/2025 and risk assessments for biodiversity are part of the scenarios for the revision of the Gothenburg Protocol of CLRTAP.

The revised $CL_{emp}N$ values emphasize even more the need of a sustainable nitrogen management and to reduce the amount of reactive nitrogen entering the environment. Nitrogen is primarily emitted from agriculture, i.e. from livestock manure and fertilized fields (primarily as ammonia), but also from combustion processes in vehicles and industry (as nitrogen oxides). Mitigation is most urgently needed where sensitive ecosystems are located within or around agricultural regions with intensive farming of livestock or close to high-traffic motorways or heavy industry.

In Europe, $CL_{emp}N$ are mainly used by Parties to the Geneva Convention on Air Pollution to quantify risks to ecosystems from air pollution; to develop emission reduction targets, and to assess risks for biodiversity (e.g. National Biodiversity Strategy Germany).

Implementation levels range from a more general national use in national risk assessments to specific regional and local applications in several countries to support decisions and authorization on new and existing emission sources near protected habitats.

In the Netherlands, the country with the highest livestock density in Europe, the government recently announced plans to compensate farmers for reducing their number of livestock in order to lower nitrogen pollution, in response to a court decision. This may serve as an example for other countries with high livestock densities, which also need to increase their efforts to reduce nitrogen pollution to protect sensitive ecosystems.

5 Outlook and further needs

More research and empirical data (e.g. with EU wide and structured measuring campaigns) is required to establish $CL_{emp}N$ for all habitats, to refine them and to further improve the understanding of the long-term effects of increased N deposition on habitats/ecosystems. Additionally, the interactive effects of climate change and nitrogen deposition on ecosystem functioning need to be investigated. Continuous experimental and survey work is essential to further improve the robustness of $CL_{emp}N$, and to establish $CL_{emp}N$ for habitats that have not yet been studied.

Further needs to comply with these tasks in future are:

- Fine resolution maps of sensitive ecosystems of high conservation value for each country
- Need on information on relative effects of oxidized and reduced N deposition (different impacts) More $CL_{emp}N$ for semi-natural ecosystems needed
- Interaction studies needed (climate (change) impact and N deposition) Studies on reversibility of nitrogen deposition
- Studies on long term effects of increased N deposition needed

Biodiversity refers to the variety of ecosystems and species. Consequently, it is necessary to protect the variety of ecosystems from unacceptable risks from air pollutants and thus the habitat for many different species in order to preserve biodiversity.

Glossary

Acidification Reduction of the pH value of a system (e.g. soil or water bodies); this reduction is caused by acidifying substances.

Biotope The biotope is a particular habitat of a biotic community in an area.

bryophytes group of non-vascular land plants comprising the liverworts, hornworts and mosses

CCE Coordination Centre for Effects. The CCE is a Program Center of the International Cooperative Program (ICP) on Modelling & Mapping under the Geneva Convention on Long-Range Transboundary Air Pollution (CLRTAP).

CL Critical load

$CL_{emp}N$ Empirical critical load of nitrogen

CLRTAP Convention on Long-Range Transboundary Air Pollution

Critical load Measure for assessing the sensitivity of ecosystems. This involves scientifically based pollution limits for atmospheric pollutant inputs per unit of area and time [kg ha^{-1} a^{-1}].

C:N ratio of bio-available carbon to nitrogen

Deposition The deposition of air pollutants; air pollutants are carried into ecosystems in gaseous form, as particles or dissolved in precipitation and atmospheric moisture.

Ecosystem An ecosystem consists of a community of organisms of several species and their inanimate environment, called a habitat or biotope.

Natural ecosystem This is an ecosystem, that has not been noticeably altered by human activities.

Semi – natural ecosystem This is an ecosystem that has been altered by human intervention but still contains significant native elements.

EMEP Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe.

EUNIS European Nature Information System (EUNIS) and the subdivision into classes described therein are used to describe all habitats.

Eutrophication An accumulation of nutrients in ecosystems.

Geneva Convention on Air Pollution Convention on Long-Range Transboundary Air Pollution.

graminoid refers to a herbaceous plant with a grass-like morphology

Habitat Habitat is understood as the habitat used by a selection of animal or plant species from the biotic community of a biotope. Habitats thus form partial habitats in biotopes.

HNO_3 nitric acid

ICP International Cooperative Programme

ICP Modelling and Mapping ICP M&M - International Cooperative Program on Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends.

kg ha^{-1} a^{-1} Unit for the deposition of air pollutants: kilogram per hectare and year.

NH_3 Ammonia

NH_4^+ Ammonium

N_2 nitrogen

NO nitric oxide

NO_2 nitrogen oxide

NO_2^- Nitrite

NO_3^- Nitrate

NO_x Nitrogen oxide

N_2O Nitrous oxide

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.

Receptor means ecosystem

UNECE United Nations Economic Commission for Europe

WGE Working Group on Effects. This is a working group under the UNECE Air Convention. WGE studies air pollution effects in the pan-European area and in North America based on international cooperation on research, monitoring, modelling and mapping.

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