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Impact of atmospheric nitrogen deposition on biodiversity

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1 Policy context

The disturbance of the global nitrogen (N) cycle in general and reactive[1] nitrogen deposition in particular are serious pressures on the environment. This has been recognized by the adoption and implementation of international and national policies aimed at reducing air pollution. Despite these efforts more still needs to be done (Sutton et al., 2011).

At the international level, the Convention on Long-Range Transboundary Air Pollution (UNECE, 1979) addresses long-range and transboundary impacts of air pollution. The Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (1999, amended 2012) sets out country-based emission limits to be achieved by 2020. In the EU, a range of directives tackle emissions of N pollutants to the air, including the National Emissions Ceilings (NEC) Directive (EC, 2001), the Industrial Emissions Directive (EC, 2010) and the Air Quality Directive (EC, 2008). The NEC Directive implements the 1999 Gothenburg Protocol in the EU. It sets upper limits for each Member State for the total emissions in 2010 of ammonia (NH_3) and oxides of nitrogen (NO_x) (and other pollutants) which contribute to N deposition, but leaves it largely to the Member States to decide which measures – on top of Community legislation for specific source categories - to take in order to comply.

In December 2013, the European Commission published a Clean Air Policy Package. This includes a Clean Air Programme for Europe (EC, 2013a) which sets the direction for EU air quality policy up to 2030 (replacing the 2005 Thematic Strategy on Air Pollution), a proposal for a revised NEC Directive, and a proposal for a Decision to ratify the 2012 amendment to the Gothenburg Protocol on behalf of the EU. The Package aims for the EU ecosystem area exceeding critical loads for eutrophication to be reduced by 35 % by 2030, relative to 2005 (EC, 2013a).

[1] Reactive nitrogen is collectively any chemical form of nitrogen other than di-nitrogen (N_2). Reactive nitrogen (N_r) compounds include NH_3, NO_x, N_2O, NO_3^- and many other chemical forms, and are involved in a wide range of chemical, biological and physical processes. In this paper the term 'nitrogen' is used to mean 'reactive nitrogen'.

Critical load exceedance for nitrogen

The availability of nutrients is one of the most important abiotic factors that determine plant species composition in ecosystems. Nitrogen is the limiting nutrient for plant growth in many natural and semi-natural ecosystems. Most of the plant species from oligotrophic and mesotrophic habitats are adapted to nutrient-poor conditions, and can only survive or compete successfully on soils with low nitrogen availability. High nitrogen deposition causes changes in vegetation composition and vegetation structure. These changes in turn affect the fauna composition.

High variations in sensitivity to atmospheric nitrogen deposition have been observed between and within different natural and semi-natural ecosystems. Critical loads are used to describe this sensitivity. A critical load is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson and Grennfelt, 1988). Exceedances of critical loads by current or future nitrogen loads indicate risks for adverse effects on biodiversity.

Source: (EEA, 2012)

A range of other policy areas, including agriculture, transport and climate change policies, influence the emissions of nitrogen. Furthermore, whilst NO_x and NH_3 are transboundary pollutants, there is potential for significant local impacts in source areas, particularly for ammonia. Measures to address nitrogen deposition impacts need to account for the local scale through to the transboundary scale.

The EC Biodiversity Strategy to 2020: Our life insurance, our natural capital (EC, 2011) is the key EU policy for action in the field of biodiversity until 2020. It includes six headline targets of which Target 3 zooms in on the role that agriculture and forestry play in maintaining and conserving biodiversity. Target 1 reinforces the importance of the Habitats and Birds Directive towards species and habitat protection, whereas Target 2 promotes a proactive approach towards keeping ecosystems in a better state with a restoration approach and green infrastructure. The Habitats Directive (EC, 1992), together with the Birds Directive (EC, 2009), promotes the protection of biodiversity in Europe. It requires Member States to take measures to maintain at, or restore to, favourable conservation status, the natural habitats and species of community importance.

2 Nitrogen deposition threatens Europe's biodiversity

2.1 Reactive nitrogen and emissions

Nitrogen is a key natural component of the earth's atmosphere, making up 78 % of it. This form of nitrogen (di-nitrogen, N_2) is unreactive and cannot be directly processed by organisms. They need reactive forms of nitrogen (N_r) for sustaining essential life processes. These reactive forms are in short supply under natural circumstances.

Since the end of the 19th century shortages of reactive nitrogen for crop production have been supplemented by mined forms of nitrogen (e.g. from guano). In the beginning of the 20th century industrial processes were developed that were able to fix N_2 into N_r on large scales. This has increased global N_r production and availability extensively, especially since the mid-1950s (Sutton and van Grinsven, 2009).

Three main processes cause the excessive amounts of reactive nitrogen having entered the global environment: industrial conversion of unreactive nitrogen into reactive nitrogen through the production of ammonia (Haber-Bosch process); nitrogen fixation by leguminous plants; and emissions of reactive nitrogen from the combustion of fossil fuels and burning of biomass (UWE Science Communication Unit, 2013). It is the excess supply of reactive nitrogen (additional to the natural nitrogen cycle) which causes environmental pollution by nitrogen in various forms (Sutton et al., 2009).

The enormous increase in production and use of reactive nitrogen comes with side effects that are undesirable for human health, the environment and biodiversity. Reactive nitrogen is extremely mobile. The processes of production and use are therefore accompanied by unintended emission of gaseous air pollutants such as nitrogen oxides (NO_x) and ammonia (NH_3). It also results in water pollution through leaching of nitrates (NO_3^-), nitrites (NO_2^-) and ammonium (NH_4^+).

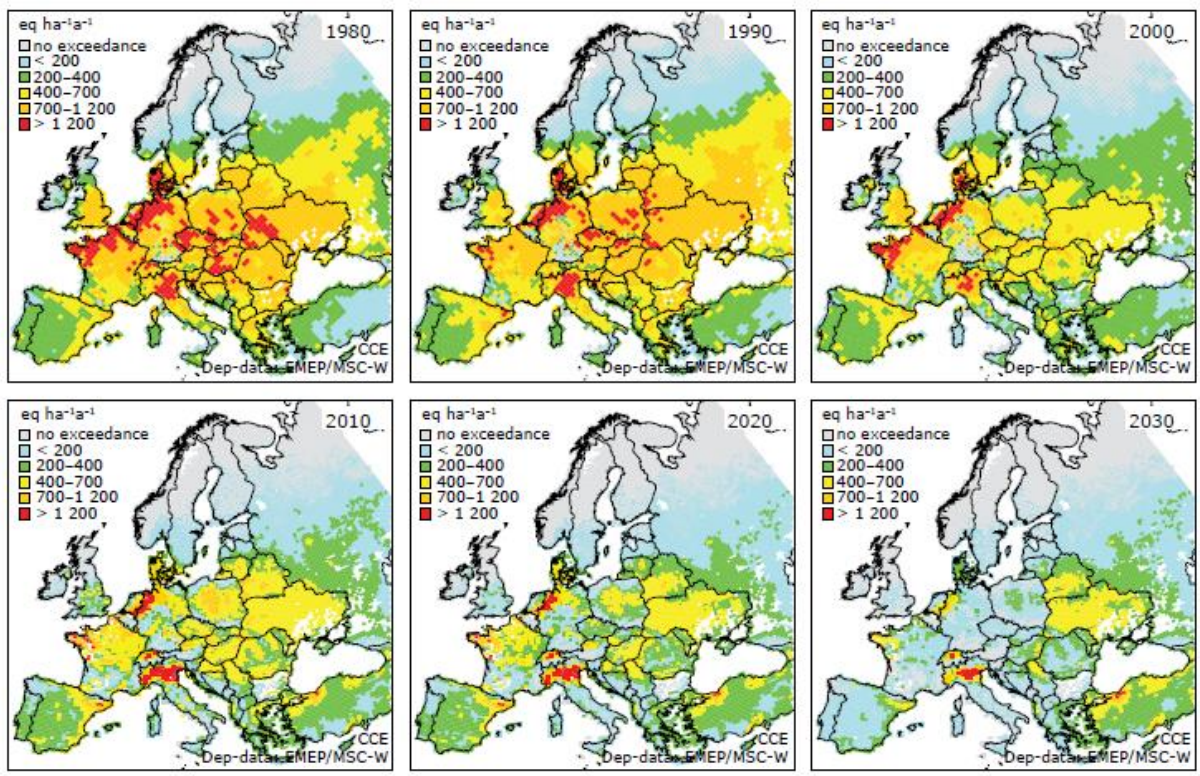
2.2 Nitrogen deposition and critical load exceedance

The emissions are dispersed in the air and finally deposited either directly (dry deposition of gases or particulate matter) or indirectly (wet deposition through precipitation) on the Earth's ecosystems. Together, this is commonly referred to as nitrogen deposition, which comprises oxides and reduced forms of nitrogen.

Through this cascade of anthropogenic nitrogen fixation, use, emission and deposition the global nitrogen cycle has become at least as, if not more, out of balance than the carbon cycle (UWE Science Communication Unit, 2013). Moreover, Rockström et al. (2009) have identified the nitrogen and phosphorous cycles as belonging to the nine planetary processes that should be kept within environmental limits to avoid destabilizing conditions for life. They claim that the nitrogen cycle is already disrupted beyond safe limits, second only to biodiversity loss.

Critical loads for eutrophication due to the deposition of nutrient nitrogen are exceeded in large parts of Europe (Map 2.1). West-France, North-Belgium, the Netherlands and the Po delta in Italy stand out as areas with highest critical load exceedance, coinciding with areas of most intensive agricultural land use in Europe (EEA, 2013c).

Map 2.1: Areas where critical loads for eutrophication are exceeded by nitrogen depositions caused by emissions between 1980 (top left) and 2030 (bottom right)



Note: The maps show the average accumulated exceedance (AAE) of critical loads for eutrophication in 1980 (top left), 1990 (top centre), 2000 (top right), 2010 (bottom left), 2020 under the revised Gothenburg Protocol (GP-CLE scenario) emission reduction agreements (bottom centre), and in 2030 assuming maximum technically feasible reduction (MTFR scenario) (bottom right). Source: (EEA, 2014a).

2.3 Impacts on the environment

The main processes causing impacts of nitrogen deposition on ecosystems are (Bobbink and Hettelingh, 2011):

- direct toxicity of N gases and aerosols to individual species;
- eutrophication;
- acidification;
- differences in effects of oxidised versus reduced N;
- increased susceptibility to secondary stress and disturbance factors.

The impacts of these processes on ecosystems (mainly on vegetation) include: a loss of sensitive species, increased growth of species that benefit from high nutrient levels, changes to habitat structure and function, the homogenisation of vegetation types, geochemical and biochemical imbalances including acidification, and diminished resilience against biotic and abiotic stresses (Dise et al., 2011). Some reductions in faunal diversity have been linked to nitrogen deposition, but knowledge of effects on fauna is still limited (Dise et al., 2011). It should be noted that N deposition is only one of the pressures on biodiversity and that cumulative or combined effects with other pressures may aggravate or buffer for certain impacts.

Critical loads vary considerably between ecosystem types. An overview of empirical critical loads of nitrogen deposition to natural and semi-natural ecosystems is provided in Table 2.1.

Table 2.1: Summary overview of possible impacts of exceedance of critical loads of nitrogen deposition on key ecosystem types.

Ecosystem type	Examples of impacts of critical load exceedance
Marine habitats	Increase in dominance of grasses; increase in late-successional species, increase in productivity
Coastal habitats	Biomass increase; increased N leaching; increase in tall grasses, decrease in prostrate plants, soil acidification, loss of typical lichen species; increase in plant production, accelerated succession
Inland surface water habitats	Change in the species composition of macrophyte communities; increased algal productivity and a shift in nutrient limitation of phytoplankton from N to P; increased biomass and rate of succession
Mire, bog and fen habitats	Increase in vascular plants; altered growth and species composition of bryophytes; increased N in peat and peat water
Grasslands and lands dominated by forbs, mosses and lichens	Increase in tall grasses, decline in diversity, increased mineralisation, N leaching; surface acidification; increased production; decline in typical species; decrease in total species richness; decrease in lichens; increased succession;
Heathland, scrub and tundra habitats	Changes in biomass, physiological effects, changes in species composition in bryophyte layer, decrease in lichens; decreased heather dominance; increased N leaching; increased sensitivity to abiotic stress
Woodland, forest and other wooded land	Changes in ground vegetation and mycorrhiza; nutrient imbalance; changes in soil fauna and flora; loss of epiphytic lichens and bryophytes; decreased biomass of fine roots; increased N_2O and NO emissions; ammonium accumulation; increased algal cover

Note: based on full overview table in annex. Adapted from Bobbink et al. (2011).

It is also recognised that nitrogen deposition can have both positive and negative effects on a wide range of ecosystem services. Specific connections have been identified for supporting, provisioning, regulating, and cultural services (e.g. Hettelingh et al., 2009; Jones et al., 2014). However, a direct linkage between N deposition, biodiversity and ecosystem service delivery is yet hard to establish. A useful overview of a range of ecosystem services affected by N deposition is included in Table 2.2.

Table 2.2: Links between the exceedance of nitrogen critical loads and the impairment of ecosystem services

Ecosystem service	Examples of nitrogen effects	Causal link with nitrogen deposition
Provisioning services		
Food	Decline in food quality	Nitrogen induced soil acidification increases Cadmium (Cd) availability leading to Cd contents in crops exceeding food quality criteria.

Ecosystem service	Examples of nitrogen effects	Causal link with nitrogen deposition
	Increase in food production	Nitrogen deposition increases crop growth in N-limited systems (low N fertilizer inputs).
	Decrease in food production	Excess atmospheric N oxides driving high levels of tropospheric ozone may cause crop losses.
Fibre/wood	Increased growth loss of timber	In N-limited systems, N increases forest growth and wood production. Acidification may increase uprooting of trees by storms.
Fresh water	(see regulating services)	
Regulating services		
Air quality regulation	Decline in air quality	Nitrogen deposition is correlated with increased concentrations of N oxides (NO_x), ozone (O_3) and particulate matter (PM10 and PM2.5), all affecting human health.
Water quality regulation	Decline in ground water and surface water (drinking water) quality	Nitrogen eutrophication and N induced soil acidification increases NO_3, Cd and Al availability, leading to NO_3, Cd and Al concentrations in groundwater and surface water exceeding drinking water quality criteria. There is increasing consensus about links between aluminium in drinking water and dementia. Higher levels of nitrate-N fed to infants may cause the 'blue baby syndrome'. Long-term exposure to nitrate (nitrite plus nitrate as nitrogen) at concentrations as low as 2-4 mg per liter in drinking water has possible links to bladder and ovarian cancer and non-Hodgkin's lymphoma. Fish dieback by algal blooms and anoxic zones (eutrophication) and aluminium affect fish gills (acidification).
Soil quality regulation	Decrease in acidity buffer	Nitrogen-induced soil acidification decreases the exchangeable pool of base cations, that may ultimately lead to reduced forest growth (unsustainable use) and affects the aluminium pool reducing soil structure.
Water quantity regulation	Increased flooding	Excess nitrogen may cause a lower Leaf Area Index due to defoliation caused by aluminium toxicity or pests/diseases, leading to an increased precipitation excess.
	Increased drought stress	Excess nitrogen causes an increased need for water by an increased growth and an increased sensitivity for drought stress by an increase in the ratio of above versus below ground biomass.
Climate regulation Greenhouse gas balance	Increased carbon sequestration in forests.	In N-limited systems, nitrogen increases forest growth and the related carbon sequestration. It also causes a reduced decomposition, leading to soil carbon sequestration.
	Increased carbon sequestration in peat lands.	At low N deposition, additional atmospheric nitrogen deposition may stimulate net primary productivity.

Ecosystem service	Examples of nitrogen effects	Causal link with nitrogen deposition
	Decreased carbon sequestration in peat lands	At high rates of N deposition, species composition changes lead to loss of peatland forming species and changed microbial activity causing degradation of peatlands.
Pest/disease regulation	Increased human allergic diseases	Increasing N availability can stimulate greater pollen production, causing human allergic responses, such as hay fever, rhinitis and asthma.
Cultural services		
Recreation/aesthetic values	Stinging nettles Algal blooms	Nitrogen induces the increase in nitrophilic species such as stinging nettles and algal blooms reducing recreational and aesthetic values of nature.

Source: Hettelingh et al. (2009)

Nitrogen deposition represents a major threat to European biodiversity, including sensitive habitats and species listed under the Habitats Directive (EEA, 2010; Dise et al., 2011; Hicks et al., 2011; Whitfield and McIntosh, 2014). It is estimated that 63 % of European ecosystem areas and 73 % of the area covered by Natura 2000 protected sites were exposed to air pollution levels that exceeded eutrophication limits in 2010 (EEA, 2014a).

Based on the most recent reporting by EU Member States, air pollution (including N deposition) is one of the key pressures to the habitats that are protected under the EU Habitats Directive (ETC/BD, pers. comm.). As long as deposition levels are not substantially reduced, achieving the objectives of favourable conservation status of these habitats is jeopardized.

3 What are current trends

3.1 Emissions

EU-28 emissions of NO_x fell by 51 % between 1990 and 2012, primarily as a result of fitting three-way catalysts to petrol fuelled vehicles (EEA, 2014c; 2014d). In 2012, the road transport sector emitted 39 % of total NO_x, the energy production and distribution sector 22 % and ‘Commercial, institutional and households' sectors 14 %. Emissions from passenger cars have decreased most since 1990 (-69.1 %) (EEA, 2014c).

Emissions of ammonia have decreased by 28 % between 1990 and 2012 in EU-28, reasons for this being a reduction in livestock numbers in the agricultural sector (especially cattle) since 1990, changes in the handling and management of organic manures and from the decreased use of nitrogenous fertilisers (EEA, 2014c). Agricultural emissions represent 93 % of total ammonia emissions (EEA, 2014c). However, there are large differences between countries, with some showing an overall decrease. Figure 3.1 shows the trend in anthropogenic reactive nitrogen inputs to the EU since 1900.

3.2 Nitrogen deposition and critical load exceedance

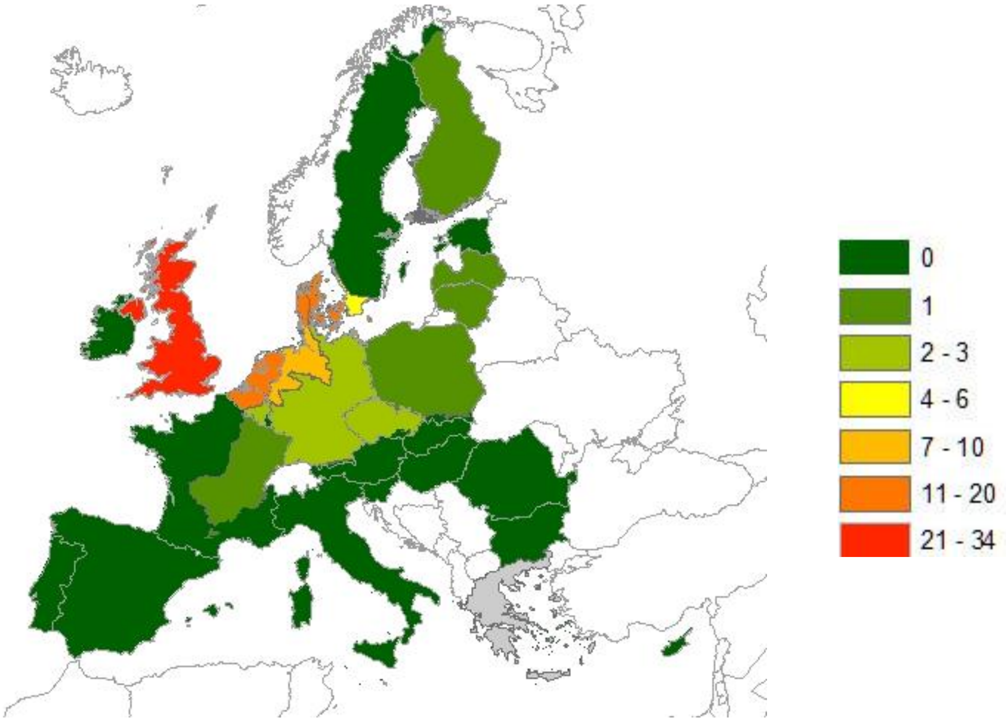
According to the scenarios assessed in a recent EEA report (EEA, 2014a) ‘critical loads for eutrophication peaked with 79 % of the EU-28 ecosystem area having exceedances in 1990. This percentage is projected to decrease to 54 % in 2020 under the amended Gothenburg Protocol. As the amount of nutrient N that is deposited per hectare per year is expected to decrease, the absolute magnitude of exceedances may also be reduced considerably in most areas. The exceptions to this are a few 'hot spot' areas in western France and the border areas between the Netherlands, Belgium and Germany, as well as in northern Italy. When computed for Natura 2000 areas alone, the extent of eutrophication critical load exceedances is projected to be 65 % in 2020.' The EEA concludes that 'even if all technically feasible reduction measures are implemented, the area at risk of eutrophication will still be 51 % in the EU-28 in 2030.'

3.3 Ecosystem impacts

Regional surveys across Europe have shown reductions in species richness with increasing nitrogen deposition (e.g. Stevens et al., 2010) and N-driven changes in species occurrence (e.g. Henrys et al., 2011). However, it is likely that biodiversity has been in decline in parts of Europe for many decades due to nitrogen deposition (Dise et al., 2011; Emmett et al., 2011). Several long-term studies have shown a decline in species characteristic of low-nutrient conditions and an increase in nitrogen-liking species over recent decades (e.g. Duprè et al., 2010; Bobbink et al., 2011; Dise et al., 2011).

Under Article 17 of the Habitats Directive, the EU Member States have to report each six years on the conservation status of the habitats and species listed in the annexes to the Directive. The latest report covers the period 2007-12 and includes reporting on threats and pressures using a hierarchical typology. Approximately one in five habitat reports (one per biogeographical region per country) note as pressures either type H04 Airborne pollution or type H04.02 Nitrogen input. These pressures are frequently noted in dunes, heaths and mires and they are mainly reported in NW Europe, as shown in Map 3.1.

Map 3.1: Number of habitat assessments with H04 Airborne pollution or H04.02 Nitrogen input reported as 'Highly important' per region & country



Note: no data received from Greece

Source: Article 17 reports for the period 2007-2012 (http://www.eea.europa.eu/data-and-maps/data/article-17-database-habitats-directive-92-43-eec-1)

It can be expected that the Atlantic part of France should have the same level of reporting as in UK and Belgium. However, it appears that France has reported this pressure under agriculture, particularly as A08 Fertilisation as the pollution is agricultural in origin.

4 What does the future bring

4.1 Emissions

The United Nations Economic Commission for Europe Gothenburg Protocol contains a series of measures that the Parties shall employ for the control of ammonia emissions from agricultural sources. Measures include for example new emission ceilings for NO_x, tight limit values for specific emission sources (e.g. electricity production), and requires best available techniques to be used to keep emissions down (UNECE, 2012). It also requires Parties to establish, publish and disseminate an advisory code of good agricultural practice to control ammonia emissions.

The Clean Air Programme for Europe proposes a directive on the reduction of national emissions of certain atmospheric pollutants and amending the National Emission Ceilings Directive of 2001. Among others, the proposal includes an objective to reduce for EU-28 the emission of ammonia and nitrogen oxides with 27 % and 69 % respectively by 2030 relative to the situation in 2005 (EC, 2013b). It also includes an annex containing cost-effective measures to achieve the new emission ceilings.

4.2 Critical load exceedance

The 2013 Clean Air Programme for Europe includes an objective to reduce the areas of ecosystems exposed to eutrophication by 35 % relative to the situation in 2005 (EC, 2013a). Despite some reduction in the area of sensitive ecosystems in Europe affected by eutrophication since 1990, the predictions for 2020 indicate that the risk is still widespread over Europe and the above target will not be met (EEA, 2014a). Based on full implementation of current legislation a 22 % reduction in ecosystem area exceeding eutrophication limits is expected by 2030 (EC, 2013a). Even when assuming a scenario where all *technically* feasible reductions are applied, the extent of critical load exceedances remains high (EEA, 2014a).

4.3 Implications for habitat management

Little is known about recovery of ecosystems from nitrogen deposition. Evidence suggests the cumulative load of N deposition is important (Bobbink et al., 2011). Therefore, reductions in nitrogen deposition will have delayed effects, due to the persistence of N in soils and vegetation. Full recovery in response to reduced N is likely to be slow, especially in highly impacted systems (Bobbink et al., 2011; Dise et al., 2011). Some positive effect of reduced N deposition on bogs was demonstrated by means of N-content in *Sphagnum* tissue, reducing to normal levels within 15 months and indicating potential for recovery in bog ecosystems (Limpens and Heijmans (2008) in Bobbink et al., 2011).

However, with regard to recovery of ecosystem services with reduced N deposition there is growing evidence that effects are positive. For the UK, for example, Jones et al. (2014) have calculated a net benefit in ecosystem service delivery of £ 65 million as a consequence of the decline in reactive N in the atmosphere with 25 % in Europe since 1990. The assessment covered only six ecosystem services as knowledge is missing for economic valuation of many services, which may underestimate the benefits of reducing N deposition (Jones et al., 2014).

Opportunities for further improvement, especially at the local level and in Natura 2000 sites, relate mainly to targeted measures on local sources, particularly agricultural sources (Whitfield et al., 2014). For example, increasing nitrogen use efficiency can lead to reduced nitrogen pollution as well as bringing financial benefits to farmers. Many measures are being explored and implemented to reduce nitrogen emissions from agriculture in Europe, based on low emission animal housing, management and feeding strategies, low emission manure/slurry management and storage, and low emission land spreading/soil management techniques.

Less mainstream forms of agriculture could also be applied, some of which may reduce N emissions, such as organic farming, agro-ecology, conservation agriculture, restoration agriculture, permaculture, minimal tillage, intercropping, cover crops, catch crops, green manures, broad crop rotation, effective use of crop residues, and landscape planning (Sutton et al., 2011), and other measures deploying functional agrobiodiversity (Bianchi et al., 2013). Furthermore, Sutton et al. (2011) suggest in addition to technical measures to reduce emissions there needs to be a greater awareness of the problems of reactive nitrogen to inform societal choices about consumption patterns.

On a wider scale, it should be noted that nitrogen management requires a holistic approach because environmental consequences become independent from the sources through the N cascade. The countries (e.g. the Netherlands) that have made most progress with tackling nitrogen deposition have both national strategies and local plans which are integrated (Whitfield et al., 2014).

5 Annex

Table A.1: Overview of empirical critical loads of nitrogen deposition (kg N ha^{-1} yr^{-1}; as revised in 2010) to natural and semi-natural ecosystems, classified according to EUNIS habitat classification[2]. A selection of effects that can occur when critical loads are exceeded is presented in the last column.

Ecosystem type	EUNIS code	Critical load kg N ha^{-1} yr^{-1} ([a])	Indication of exceedance
Marine habitats (A)			
Mid-upper salt marshes	A2.53	*20-30*	Increase in dominance of grasses
Pioneer and low-mid salt marshes	A2.54 and A2.55	*20-30*	Increase in late-successional species, increase in productivity
Coastal habitats (B)			
Shifting coastal dunes	B1.3	*10-20*	Biomass increase, increased N leaching
Coastal stable dune grasslands (grey dunes)	B1.4 ([b])	8-15	Increase in tall grasses, decrease in prostrate plants, increased N leaching, soil acidification, loss of typical lichen species
Coastal dune heaths	B1.5	*10-20*	Increase in plant production, increased N leaching, accelerated succession
Moist to wet dune slacks	B1.8 ([c])	*10-20*	Increased biomass of tall grasses
Inland surface water habitats (C)			
Permanent oligotrophic lakes, ponds and pools (including soft-water lakes)	C1.1 ([d])	**3-10**	Change in the species composition of macrophyte communities, increased algal productivity and a shift in nutrient limitation of phytoplankton from N to P
Dune slack pools (permanent oligotrophic waters)	C1.16	*10-20*	Increased biomass and rate of succession
Permanent dystrophic lakes, ponds and pools	C1.4 ([e])	*3-10*	Increased algal productivity and a shift in nutrient limitation of phytoplankton from N to P
Mire, bog and fen habitats (D)			
Raised and blanket bogs	D1 ([f])	**5-10**	Increase in vascular plants, altered growth and species composition of bryophytes, increased N in peat and peat water
Valley mires, poor fens and transition mires	D2 ([g])	10-15	Increase in sedges and vascular plants, negative effects on bryophytes

[2] http://eunis.eea.europa.eu/habitats.jsp

Ecosystem type	EUNIS code	Critical load kg N ha^{-1} yr^{-1} ([a])	Indication of exceedance
Rich fens	D4.1 ([h])	*15-30*	Increase in tall grasses, decrease in bryophytes
Montane rich fens	D4.2 ([h])	*15-25*	Increase in vascular plants, decrease in bryophytes
Grasslands and lands dominated by forbs, mosses and lichens (E)			
Sub-Atlantic semi-dry calcareous grasslands	E1.26	**15-25**	Increase in tall grasses, decline in diversity, increased mineralisation, N leaching; surface acidification
Mediterranean xeric grasslands	E1.3	*15-25*	Increased production, dominance by grasses
Non-Mediterranean dry acidic and neutral closed grasslands	E1.7 ([c])	**10-15**	Increase in grasses, decline in typical species, decrease in total species richness
Inland dune pioneer grasslands	E1.94 ([c])	*8-15*	Decrease in lichens, increase in biomass
Inland dune siliceous grasslands	E1.95 ([c])	*8-15*	Decrease in lichens, increase in biomass, increased succession
Low and medium altitude hay meadows	E2.2	*20-30*	Increase in tall grasses, decrease in diversity
Mountain hay meadows	E2.3	*10-20*	Increase in nitrophilous grasses, changes in diversity
Moist and wet oligotrophic grasslands			
• *Molinia caerulea* meadows	E3.51	*15-25*	Increase in tall grasses, decreased diversity, decrease in bryophytes
• Heath (*Juncus*) meadows and humid (*Nardus stricta*) swards	E3.52	10-20	Increase in tall grasses, decreased diversity, decrease in bryophytes
Moss- and lichen-dominated mountain summits	E4.2	5-10	Effects on bryophytes and/or lichens
Alpine and subalpine acidic grasslands	E4.3	5-10	Changes in species composition; increase in plant production
Alpine and subalpine calcareous grasslands	E4.4	5-10	Changes in species composition; increase in plant production
Heathland, scrub and tundra habitats (F)			
Tundra	F1	3-5	Changes in biomass, physiological effects, changes in species composition in bryophyte layer, decrease in lichens
Arctic, alpine and subalpine scrub habitats	F2	5-15	Decline in lichens, bryophytes and evergreen shrubs
Northern wet heath	F4.11		
• ‘U’ *Calluna*-dominated	F4.11 ([f, i])	10-20	Decreased heather dominance, decline in

Ecosystem type	EUNIS code	Critical load kg N ha^{-1} yr^{-1} ([a])	Indication of exceedance
wet heath (upland moorland)			lichens and mosses, increased N leaching
• 'L' *Erica tetralix*-dominated wet heath (lowland)	F4.11 ([f, i])	*10-20*	Transition from heather to grass dominance
Dry heaths	F4.2 ([f, i])	**10-20**	Transition from heather to grass dominance, decline in lichens, changes in plant biochemistry, increased sensitivity to abiotic stress
Maquis, arborescent matorral and thermo-Mediterranean brushes	F5	*20-30*	Change in plant species richness and community composition
Woodland, forest and other wooded land (G)			
Fagus woodland	G1.6	*10-20*	Changes in ground vegetation and mycorrhiza, nutrient imbalance, changes in soil fauna
Acidophilous *Quercus*-dominated woodland	G1.8	*10-15*	Decrease in mycorrhiza, loss of epiphytic lichens and bryophytes, changes in ground vegetation
Meso- and eutrophic *Quercus* woodland	G1.A	*15-20*	Changes in ground vegetation
Mediterranean evergreen (*Quercus*) woodland	G2.1	*10-20*	Changes in epiphytic lichens
Abies and *Picea* woodland	G3.1	*10-15*	Decreased biomass of fine roots, nutrient imbalance, decrease in mycorrhiza, changed soil fauna
Pinus sylvestris woodland south of the taiga	G3.4	5-15	Changes in ground vegetation and mycorrhiza, nutrient imbalances, increased N_2O and NO emissions
Pinus nigra woodland	G3.5	*15*	Ammonium accumulation
Mediterranean *Pinus* woodland	G3.7	*3-15*	Reduction in fine-root biomass, shift in lichen community
Spruce taiga woodland	G3.A	**5-10**	Changes in ground vegetation, decrease in mycorrhiza, increase in free-living algae
Pine taiga woodland	G3.B	5-10	Changes in ground vegetation and in mycorrhiza, increase in occurrence of free-living algae
Mixed taiga woodland with *Betula*	G4.2	*5-8*	Increased algal cover
Mixed *Abies-Picea Fagus* woodland	G4.6 ([j])	*10-20*	
Overall			
Broadleaved deciduous woodland	G1 ([l])	**10-20**	Changes in soil processes, nutrient imbalance, altered composition mycorrhiza and ground

Ecosystem type	EUNIS code	Critical load kg N ha^{-1} yr^{-1} ([a])	Indication of exceedance
			vegetation
Coniferous woodland	G3 ([l])	**5-15**	Changes in soil processes, nutrient imbalance, altered composition mycorrhiza and ground vegetation

([a]) Reliability, qualitatively indicated as reliable (bold); quite reliable (normal); and expert judgement (italic)

([b]) For acidic dunes, the 8 to 10 kg N ha^{-1} yr^{-1} range should be applied, for calcareous dunes this range is 10 to 15 kg ha^{-1} yr^{-1}

([c]) Apply the lower end of the range to habitats with a low base availability; and the higher end of the range to those with high base availability

([d]) This critical load should only be applied to oligotrophic waters with low alkalinity with no significant agricultural or other human inputs. Apply the lower end of the range to boreal, sub-Arctic and alpine lakes, and the higher end of the range to Atlantic soft waters.

([e]) This critical load should only be applied to waters with low alkalinity with no significant agricultural or other direct human inputs. Apply the lower end of the range to boreal, sub-Arctic and alpine dystrophic lakes.

([f]) Apply the high end of the range to areas with high levels of precipitation and the low end of the range to those with low precipitation levels; apply the low end of the range to systems with a low water table, and the high end of the range to those with a high water table. Note that water tables can be modified by management.

([g]) For EUNIS category D2.1 (valley mires): use the lower end of the range.

([h]) For high-latitude systems, apply the lower end of the range.

([i]) Apply the high end of the range to areas where sod cutting has been practiced; apply the lower end of the range to areas with low-intensity management.

([j]) Included in studies that were classified under G1.6 and G3.1.

([l]) For application at broad geographical scales.

Adapted from Bobbink et al. (2011).

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