Mapping Manual chapter updated 12.November 2007

5.2 Empirical Critical Loads

5.2.1 Empirical critical loads for nutrient nitrogen

5.2.1.1 Introduction

The emissions of ammonia (NH_x) and nitrogen oxides (NO_y) have strongly increased in Europe in the second half of the 20th century. Because of short- and long-range transport of these nitrogenous compounds, atmospheric nitrogen (N) deposition has clearly increased in many natural and semi-natural ecosystems. The availability of nutrients is one of the most important abiotic factors, which determine the plant species composition in ecosystems. Nitrogen is the limiting nutrient for plant growth in many natural and semi-natural ecosystems, especially of oligotrophic and mesotrophic habitats. Most of the plant species from such conditions are adapted to nutrient-poor conditions, and can only survive or compete successfully on soils with low nitrogen availability. In addition, the N cycle in ecosystems is complex and strongly regulated by biological and microbiological processes, and thus many changes may occur in plant growth, inter-specific relationships and soil-based processes as a result of increased deposition of air-borne N pollutants.

The series of events which occurs when N inputs increase in an area with originally low background deposition rates is highly complex. Many ecological processes interact and operate at different temporal and spatial scales. As a consequence, high variations in sensitivity to atmospheric nitrogen deposition have been observed between different natural and semi-natural ecosystems. Despite this diverse sequence of events, the following main effect “categories” can be recognised:

(a) Direct toxicity of nitrogen gases and aerosols to individual species (see N critical levels);
(b) Accumulation of nitrogen compounds, resulting in increased N availability and changes of species composition;
(c) Long-term negative effect of ammonium and ammonia;
(d) Soil-mediated effects of acidification;
(e) Increased susceptibility to secondary stress and disturbance factors such as drought, frost, pathogens or herbivores.

Recent experimental evidence, and practical field experience in ecosystem restoration, suggests that, once the process of altered species composition and increased N mineralisation occurred, spontaneous recovery of the vegetation may happen only over very long time scales, or with very active management intervention to decrease nitrogen status and cycling. This emphasises the need for caution in setting critical loads at which these major changes in vegetation composition and nitrogen cycling do not occur.

5.2.1.2 Data

Within the Convention on Long-range Transboundary Air Pollution (LRTAP), empirical procedures have been developed to set critical loads for atmospheric N deposition. Empirical critical loads of N for natural and semi-natural terrestrial ecosystems and wetland ecosystems

were firstly presented in a background document for the 1992 workshop on critical loads held under the UNECE LRTAP Convention at Lökeberg (Sweden) (Bobbink et al. 1992). After detailed discussion before and during the meeting, the proposed values were set at that meeting (Grennfelt and Thörnelöf 1992). Additional information from the period 1992–1995 was evaluated and summarised in an updated background paper (Bobbink et al. 1996) and published as Annex III in the previous version of the Mapping Manual (UBA 1996). The updated N critical loads were discussed and accepted at an expert meeting held in December 1995 in Geneva (Switzerland). They were also used in the Air Quality Guidelines for Europe (2^{nd} edition) of the World Health Organisation (WHO 2000). It became clear that considerable new insights into, and data on, the impacts of N deposition on natural and semi-natural ecosystems have become available since the compilation of the last values in the mid-1990s. Therefore, new information from the period 1996–2002 on the impacts of increased nitrogen deposition on the structure and function of natural and semi-natural ecosystems was evaluated and evaluated in a fully adapted background paper (Bobbink et al. 2003). The updated N critical loads were discussed and approved by full consensus at the November 2002 expert meeting held under the LRTAP Convention in Berne (Switzerland, Achermann and Bobbink 2003). Values for areas with low N deposition were updated by a CLRTAP workshop on critical loads of nitrogen in low-deposition areas (Stockholm, Sweden, March 2007) and adopted by ICP M&M and WGE in 2007.
The resulting values are given in Table 5-1.

<u>Approach:</u>
Based on observed changes in the structure and function of ecosystems, reported in a range of publications, empirical N critical loads were evaluated for specific receptor groups of natural and semi-natural ecosystems in both 1992 and 1996. In the 2002 and 2007 updating procedures a similar 'empirical approach' was used as for the earlier background documents. For this purpose, recent European publications on the effects of N in natural and semi-natural ecosystems were collected as completely as possible. Peer-reviewed publications, book chapters, nationally published papers and 'grey' reports of institutes or organisations, if available by request, were incorporated. Results from field addition experiments and mesocosm studies, from correlative or retrospective field studies, and, in few cases, dynamic ecosystem modelling was relevant in this respect.

<u>Ranges and reliability:</u>
The empirical N critical loads were established within a range for each ecosystem class, because of: (i) real intra-ecosystem variation between different regions where an ecosystem has been investigated; (ii) the intervals between experimental additions of nitrogen; and (iii) uncertainties in presented total atmospheric deposition values, although the latter have been checked by local specialists on atmospheric N deposition. Some additional information has been given on how to interpret this range in specific situations for an ecosystem. For every group of ecosystems, the empirical N critical loads are given with an indication of exceedance and of their reliability.

The reliability of the presented N critical load figures is indicated as before (Bobbink et al. 1996):
- <u>reliable</u> ##: when a number of published papers of various studies show comparable results;
- <u>quite reliable</u> **#**: when the results of some studies are comparable;
- <u>expert judgement</u> **(#)**: when no empirical data are available for this type of ecosystem. The N critical load is then based upon expert judgement and knowledge of ecosystems, which are likely to be more or less comparable with this ecosystem.

5.2.1.3 Ecosystem classification

To facilitate and harmonise the mapping procedure, the receptor groups of natural and semi-natural ecosystems were classified and ordered according to the EUNIS habitat classification for Europe (Davies and Moss 2002, http://eunis.eea.eu.int/index.jsp). For an introduction of EUNIS classification with respect to empirical N critical loads (see Hall et al. 2003). In general, the ecosystems used in the 2002 updating procedure, were classified down to level 2 or 3 of the EUNIS hierarchy. The following habitats groups (with EUNIS level 1 code between brackets) were treated:

- Woodland and forests habitats **(G)**
- Heathland, scrub and tundra habitats **(F)**
- Grassland and tall forb habitats **(E)**
- Mire, bog and fen habitats **(D)**
- Inland surface water habitats **(C)**
- Coastal habitats **(B)**
- Marine habitats **(A)**

In general, a good agreement was found between the previously used classification of ecosystem groups (Bobbink et al. 1996) and the EUNIS habitat classification now adopted. A main limitation for the use of many subcategories of the EUNIS classification was, unfortunately, a lack of research and data on N impacts for those habitats. Finally, it was at this moment not possible to use the EUNIS classification with respect to the setting of empirical N critical loads for forest ecosystems below level 1. It was only possible to set values of three broad EUNIS classes (G1, G3 & G4) for forest, with, however, some separation for grouping of forest types, such as coniferous versus deciduous and boreal versus temperate. Even within G1, G3 and G4 there are several types, e.g. wet-swamp forest and Mediterranean forests for which no data were available and thus left out. As before, studies based on pure plantation stands were (if possible) not accepted in the forest section, because the N critical loads of these intensively used systems are obtained via the steady-state mass balance method (see section 5.3). An overview of the old and new classification is presented in Table 5-3 to assist the shift to the EUNIS classification.

Table 5-1: Empirical critical loads for nitrogen deposition (kgN/ha/yr) to natural and semi-natural groups of ecosystems classified according EUNIS (except for forests). Reliability: ## reliable, # quite reliable and (#) expert judgement.

Ecosystem type	EUNIS-code	Critical load (kg N/ha/yr)	Reliability	Indication of exceedance
Forest habitats (G)				
Soil processes				
Deciduous & coniferous	-	10-15	#	Increased N mineralisation, nitrification
Coniferous forests	-	10-15	##	Increased nitrate leaching
Deciduous forests	-	10-15	(#)	Increased nitrate leaching
Trees				
Deciduous & coniferous	-	15-20	#	Changed N/macro nutrients ratios, decreased P, K, Mg and increased N concentrations in foliar tissue
Temperate forests	-	15-20	(#)	Increased susceptibility to pathogens and pests, change in fungistatic phenolics
Mycorrhiza				
Temperate and boreal forests	-	10-20	(#)	Reduced sporocarp production, changed/reduced below-groud species composition

Ground vegetation				
Temperate and boreal forests	-	10-15	#	Changed species composition, increase of nitrophilous species, increased susceptibility to parasites
- in low deposition areas:		<10	#	
Lichens and algae				
Temperate and boreal forests	-	10-15	(#)	Increase of algae, decrease of lichens
Overall				
Temperate forests	-	10-20	#	Changes in soil processes, ground vegetation mycorrhiza and increased risk of nutrient imbalances and susceptibility to parasites
Boreal forests - in low deposition areas:	-	10-20 5-10	#	Changes in soil processes, ground vegetation mycorrhiza and increased risk of nutrient imbalances and susceptibility to parasites
Heathland, scrub and tundra habitats (F)				
Tundra	F1	5-10[a]	#	Changes in biomass, physiological effects, changes in species composition in moss layer, and decrease in lichens
Arctic, alpine and subalpine scrub habitats	F2	5-15[a]	(#)	Decline in lichens mosses, and evergreen shrubs
Northern wet heath	F4.11			
‘U’ *Calluna*-dominated wet heath (upland moorland)	F4.11	10-20[a]	(#)	Decreased heather dominance, decline in lichens and mosses
‘L’ *Erica tetralix* dominated wet heath	F4.11	10-25[a,b]	(#)	Transition heather to grass
Dry heaths	F4.2	10-20[a,b]	##	Transition heather to grass; decline in lichens
Grasslands and tall forb habitats (E)				
Sub-atlantic semi-dry calcareous grassland	E1.26	15-25	##	Increase tall grasses, decline in diversity; increased mineralisation and N leaching
Non-mediterranean dry acid and neutral closed grassland	E1.7	10-20	#	Increase in graminoids, decline typical species
Inland dune pioneer grasslands	E1.94	10-20	(#)	Decrease in lichens, increase biomass
Inland dune siliceous grasslands	E1.95	10-20	(#)	Decrease in lichens, increase 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 graminoids; changes in diversity
Moist and wet oligotrophic grasslands	E3.5			
Molinia caerulea meadows	E3.51	15-25	(#)	Increase in tall graminoids; decreased diversity; decrease of bryophytes
Heath (*Juncus*) meadows and humid (*Nardus stricta*) swards	E3.52	10-20	#	Increase in tall graminoids; decreased diversity; decrease of bryophytes
Alpine and subalpine grasslands	E4.3 and E4.4	10-15	(#)	Increase in nitrophilic graminoids; biodiversity change
Moss and lichen dominated mountain summits	E4.2	5-10	#	Effects upon bryophytes or lichens

Mire, bog and fen habitats (D)				
Bogs and poor minerotrophic mires in low-deposition areas	D1	<8	#	Changed species composition, N induced damage on Sphagnum spp.
Raised and blanket bogs	D1	5-10[a,c]	##	Change in species composition, N saturation of *Sphagnum*
Poor fens	D2.2 [d]	10-20	#	Increase sedges and vascular plants; negative effects on peat mosses
Rich fens	D4.1[e]	15-25	(#)	Increase tall graminoids, decrease diversity, decrease of characteristic mosses
Mountain rich fens	D4.2	15-25	(#)	Increase vascular plants, decrease bryophytes
Inland surface water habitats (C)				
Permanent oligotrophic waters	C1.1			
Softwater lakes	C1.1	5-10	##	Isoetid species negatively affected
Dune slack pools	C1.16	10-20	(#)	Increased biomass and rate of succession
Coastal habitat (B)				
Shifting coastal dunes	B1.3	10-20	(#)	Biomass increase, increase N leaching
Coastal stable dune grasslands	B1.4	10-20	#	Increase tall grasses, decrease prostrate plants, increased N leaching
Coastal dune heaths	B1.5	10-20	(#)	Increase plant production; increase N leaching, accelerated succession
Moist to wet dune slacks	B1.8	10-25	(#)	Increased biomass tall graminoids
Marine habitats (A)				
Pioneer and low-mid salt marshes	A2.64 and A2.65	30-40	(#)	Increase late-successional species, increase productivity

[a)] use towards high end of range at P limitation, and towards lower end if P is not limiting;
[b)] use towards high end of range when sod cutting has been practised, use towards lower end of range with low intensity management;
[c)] use towards high end of range with high precipitation and towards low end of range with low precipitation;
[d)] for D2.1 (quaking fens and transition mires): use lower end of range (#) and for D2.3 (valley mires): use higher end of range (#);
[e)] for high latitude or N-limited systems: use lower end of range.

5.2.1.4 Use of empirical critical loads

Most of the Earth's biodiversity is present in semi-natural and natural ecosystems. It is thus crucial to control the atmospheric N loads, in order to prevent negative effects on these semi-natural and natural systems. The empirical N critical loads updated in 2002 and 2007 (Table 5-1) should be used to revise critical load databases. High-resolution maps of the sensitive ecosystems of high conservation value are needed per country to map N critical loads for these systems. It is advised to use both the mass balance and empirically derived N critical loads for forest ecosystems and other ecosystems for which data needed for the application of steady state models is available. If the two approaches yield different values, the one with the lowest values should be used until the background for this difference has been clarified. Furthermore, it is suggested to the different countries, where insufficient national data for specific national ecosystems are available, to use the lower, middle or upper part of the ranges of the N critical loads for (semi-)natural ecosystem groups according to the general relationships between abiotic factors and critical loads for N as given in Table 5-2.

Table 5-2: Suggested action for using lower, middle or upper part of the set critical loads of terrestrial ecosystems (excluding wetlands), if national data are insufficient.

Temperature/ Frost period	**Soil wetness**	**Base cation availability**	**P limitation**	**Management intensity**	**Action**
Cold/long	Dry	Low	N-limited	Low	Move to lower part
Intermediate	Normal	Intermediate	Unknown	Usual	Use middle part
Hot/none	Wet	High	P-limited	High	Move to higher part

Countries are advised to identify those receptor ecosystems of high sensitivity within the mentioned EUNIS classification relating to their individual interest. Effort should be directed to produce fine resolution maps of sensitive ecosystems of high conservation value. At this moment the empirical N critical loads have been set in values of total atmospheric N (kgN/ha/yr). More information is needed on the relative effects of oxidised and reduced N deposition. It was emphasised during the last two UNECE expert meetings that there is increasing evidence of NH_x having greater effects than NO_y. Particularly, bryophytes and lichens in a number of ecosystems, and several, mostly weakly buffered, ecosystems of EUNIS class F, E, C and B are (probably) more sensitive to deposition of reduced N. It is, however, at present not possible to set critical loads for both forms of N, separately.

5.2.1.5 Recommendations

Serious gaps in knowledge exist on the effects of enhanced N deposition (NO_y and NH_x) on semi-natural and natural ecosystems, although considerably progress has been made in several habitat groups in recent years. The following gaps in knowledge have been recognised as most important:

- research/data collection is required to establish a critical load for the following ecosystems: steppe grasslands, all Mediterranean vegetation types, wet-swamp forests, many mire & fens, several coastal habitats and high altitude systems;
- more research is needed in all distinguished EUNIS items with expert judgement or few research;
- impacts of N enrichment in (sensitive) freshwater and shallow marine ecosystems needs further research and are sometimes overlooked;
- additional effort is needed to allocate observed N effects to the appropriate EUNIS forest subtypes (division 2 & 3);
- the EUNIS classification needs clarification/adjustment with respect to some grasslands groups, Nordic bogs and mires and surface water habitats;
- the possible differential effects of the deposited nitrogen species (NO_y or NH_x) are insufficiently known to make a differentiation between these N species for critical load establishment;
- in order to refine current critical loads, long-term (> 3–5 years) N addition experiments with a high resolution of treatments between 5 and 50 kgN/ha/yr at low background regions or in mesocosms are useful. This would increase the certainty of deriving critical loads when the lowest treatment level considerably exceeds the critical load;

In conclusion, it is crucial to understand the long-term effects of increased N deposition on ecosystem processes in a representative range of ecosystems. It is thus very important to quantify the effects of nitrogen loads by manipulation of N inputs in long-term ecosystem studies in unaffected and affected areas. These data are essential to validate the set critical loads and to develop robust dynamic ecosystem models and/or multiple correlative species models, which are reliable enough to calculate critical loads for nitrogen deposition in (semi-) natural ecosystems and to predict (natural) recovery rates for N-affected systems.

Table 5-3: Cross-comparison between the ecosystem classification used in the 2002 and 2007 empirical N critical load setting (according to the EUNIS system) and the classification previously used (Bobbink et al. 1996) (with n.d. = not distinguished).

Ecosystem classification 2002 / 2007	EUNIS	Ecosystem classification 1996
Heathland, scrub and tundra habitats	**F**	**Heathlands**
Tundra	F1	n.d.
Arctic, alpine and subalpine scrub	F2	Arctic and Alpine heaths
Northern wet heaths		
• 'U' *Calluna* dominated wet heath	F4.11	Upland *Calluna* heath
• 'L' *Erica tetralix* dominated wet heath	F4.11	Lowland wet heathlands
Dry Heaths	F4.2	Lowland dry heathlands
Grasslands and tall forb habitats	**E**	**Species-rich grassland**
Sub-atlantic semi-dry calcareous grasslands	E1.26	Calcareous grasslands
Non-mediterranean dry acid and neutral closed grasslands	E1.7	Species-rich heaths and neutral acidic grasslands (partly)
Inland dune pioneer grasslands	E1.94	n.d.
Inland dune siliceous grasslands	E1.95	n.d.
Low and medium altitude hay meadows	E2.2	Neutral-acid grasslands (partly)
Mountain hay meadows	E2.3	Montane-subalpine grasslands
Moist and wet oligotrophic grasslands	E3.5	Neutral-acid grasslands (partly) Mesotrophic fens (partly)
• *Molinia caerulea* meadows	E3.51	n.d.
• Heath (*Juncus*) meadows and humid (*Nardus stricta*) swards	E3.52	n.d.
Alpine and subalpine grasslands	E4.3 and E4.4	Montane-subalpine grasslands (partly)
Moss and lichen dominated mountain summits	E4.2	n.d.
Mire, bog and fen habitats	**D**	**Wetlands**
Raised and blanket bogs	D1	Ombrotrophic bogs
Poor fens	D2.2	n.d.
Rich fens	D4.1	Mesotrophic fens
Montane rich fens	D4.2	n.d.
Inland surface water habitats	**C**	**Wetlands**
Permanent oligotrophic waters	C1.1	n.d
• Softwater lakes	C1.1	Shallow softwater bodies
• Dune slack pools	C1.16	n.d.
Coastal habitats	**B**	n.d
Shifting coastal dunes	B1.3	n.d.
Coastal stable dune grasslands	B1.4	Neutral-acid grasslands (partly)
Coastal dune heaths	B1.5	n.d.
Moist to wet dune slacks	B1.8	n.d
Marine habitats	**A**	n.d.
Pioneer and low-mid salt marshes	A2.64 and A2.65	n.d.

5.2.2 Empirical Critical loads for acidity

Empirical approaches assign an acidity critical load to soils on the basis of soil mineralogy and/or chemistry. For example, at the Critical Loads Workshop at Skokloster (Nilsson and Grennfelt 1988) soil forming materials were divided into five classes on the basis of the dominant weatherable minerals. A critical load range, rather than a single value, was assigned to each of these classes according to the amount of acidity that could be neutralised by the base cations produced by mineral weathering (Table 5-4). Other methods of estimating base cation weathering are discussed in Chapter 5.3.2.

Table 5-4: Mineralogical classification of soil materials and soil critical loads.

Minerals controlling weathering	**Critical load range** (eq/ha/yr)
Quartz, K-feldspar	<200
Muscovite, Plagioclase, Biotite (<5%)	200–500
Biotite, Amphibole (<5%)	500–1000
Pyroxene, Epidote, Olivine (<5%)	1000–2000
Carbonates	>2000

In addition, a number of modifying factors were identified that would enable the critical load value to be adjusted within the ranges (Table 5-5, after Nilsson and Grennfelt 1988). For example, some factors could make the soil more sensitive to acidification, requiring the critical load to be set at the lower end of the range; while other factors could make the soil less sensitive, setting the critical load at the upper end of the range.

Table 5-5: Modifying factors causing an increase or decrease in critical loads.

Modifying factor	**Effect on critical load:**	
	Decrease	***Increase***
Precipitation	High	Low
Vegetation	Coniferous forest	Deciduous forest
Elevation, slope	High	Low
Soil texture	Coarse-sandy	Fine
Soil drainage	Free	Impeded
Soil sulphate adsorption capacity	Low	High
Base cation deposition	Low	High

The classification of soil materials developed at Skokloster (Table 5-4) used a relatively small range of primary silicate minerals and carbonates. A larger range of minerals has been classified by Sverdrup and Warfvinge (1988) and Sverdrup et al. (1990). The following mineral classes have been identified:

Very fast weathering minerals (carbonates) include minerals that have the potential to dissolve very rapidly, in a geological perspective. The group includes calcite, dolomite, magnesite and brucite.
Fast weathering minerals include the silicate minerals with the fastest weathering rate. The group comprises minerals such as anorthite and nepheline, olivine, garnet, jadeite, diopside. A soil with a major content of these minerals would be resistant to soil acidification.
Intermediate weathering minerals include enstatite, hypersthene, augite, hornblende, glaucophane, chlorite, biotite, epidote, zoisite.
Slow weathering minerals include albite, oligoclase, labradorite, illite. Soils with a majority of such minerals will be sensitive to soil acidification.
Very slow weathering minerals include K-feldspar, muscovite, mica, montmorillonite, vermiculite. Soils with a majority of these minerals will be sensitive to soil acidification.
Inert minerals are those that dissolve so slowly or provide so little neutralising substance that they may be considered as inert for soil acidification purposes. This includes minerals such as quartz, rutile, anatase, kaolinite, gibbsite.

For each of the above mineral classes, weathering rates for soils with different mineral contents have been proposed (Table 5-6, Sverdrup et al. 1990).

Table 5-6: Weathering rates (in eq/(ha·m)/yr) for four selected mineral classes of soil material based on a soil depth of one meter – to convert to critical load values multiply by soil thickness in meters.

Mineral class	**Average soil mineral class content**			
	100%	30%	3%	0.3%
Very fast weathering	25000	15000	10000	3000
Fast weathering	15000	10000	3000	300
Intermediate weathering	10000	3000	300	30
Slow weathering	600	200	20	-
Very slow weathering	300	100	10	-
Inert	100	100	-	-

The information provided in Tables 5-4 to 5-6 above provide the basis on which empirical acidity critical loads can be assigned to soils. If mineralogical data are available for the units of a soil map, critical loads can be assigned to each unit and a critical loads map produced.

An example of the development of a critical load map at the national scale using empirical approaches is given by Hornung et al. (1995). In the UK this approach has been used to define acidity critical loads for non-forest ecosystems, by setting a critical load that will protect the soil upon which the habitat depends (Hall et al. 1998, 2003). The critical load is effectively the base cation weathering rate, with the leaching of acid neutralising capacity (ANC) set to zero (see section 5.3.2), and can be used in the calculations of the maximum critical loads of sulphur and nitrogen (see section 5.3.3).