Chapter 30
Development of the Critical Loads Concept and Current and Potential Applications to Different Regions of the World

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Abstract The chapter addresses whether the critical load of nutrient nitrogen (N) is a relevant, necessary and sufficient indicator to address adverse effects of reactive nitrogen (N_r) on biodiversity in different regions of the world. Based on a description of the critical loads concept for nutrient N, and the relationship to biodiversity endpoints, applications of the critical load for nutrient N are summarized in the context of policies under the Long-range Transboundary Air Pollution (LRTAP)

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M. A. Sutton et al. (eds.), *Nitrogen Deposition, Critical Loads and Biodiversity,*
DOI 10.1007/978-94-007-7939-6_30,

Convention. Potential applications of critical loads are addressed with respect to the relevance of adverse effects of N under the Convention on Biological Diversity (CBD). The chapter considers the prospects for effect-based applications in different regions of the world and poses some questions that need to be addressed. Finally, the potential for a broader indicator for N (a 'threshold' rather than a 'load') that could apply to all forms and impacts of N is considered, as it could potentially increase the coherence between CLRTAP and CBD.

Keywords CBD • Critical loads • Dynamic models • LRTAP • Nitrogen deposition • Steady-state mass balance

30.1 Introduction

Excess atmospheric deposition of reactive nitrogen (N_r) compounds can cause adverse effects to biodiversity and thereby affect ecosystem structure and functions (see Bobbink and Hicks 2014, Chap. 14, this volume and de Vries et al. 2014, Chap. 41, this volume). These impacts are triggered by both acidification and eutrophication. However, acidification is not only caused by nitrogen (N) deposition, but also by sulphur (S) deposition as an important cause of the acidification risk to the health of ecosystems in many regions of the world. In the context of this workshop, the focus of this chapter is on the impacts of nutrient N.

When atmospheric deposition of N_r is at or below critical loads, it is assumed not to cause adverse effects to plant species diversity. Deposition that exceeds a critical load can affect biodiversity to the extent where provisioning, regulating, supporting and cultural services of nature (see de Vries et al. 2014, Chap. 41, this volume and Erisman et al. 2014, Chap. 51, this volume) are jeopardized. However, these endpoints may differ between regions of the world. Therefore, the global usefulness of the critical loads concept needs to be carefully addressed with respect to regionally specific importance of ecosystem services.

The main question addressed in this chapter is whether the critical load of nutrient N is a relevant, necessary and sufficient indicator to address adverse effects of N_r on biodiversity in different regions of the world. First a short description is provided of the concept of critical loads of nutrient N, and the relationship to biodiversity endpoints. Current applications of the critical load for nutrient N are then summarized in the context of policies in the field of air pollution under the Long-range Transboundary Air Pollution (LRTAP) Convention. Next, potential applications of critical loads are addressed, with respect to the relevance of adverse effects of N under the Convention on Biological Diversity (CBD). Finally, the chapter considers the prospects for effect-based applications in different regions of the world and poses some questions that need to be addressed. This synthesis is framed with reference to the Conventions addressed in this workshop, names the LRTAP Convention and the CBD.

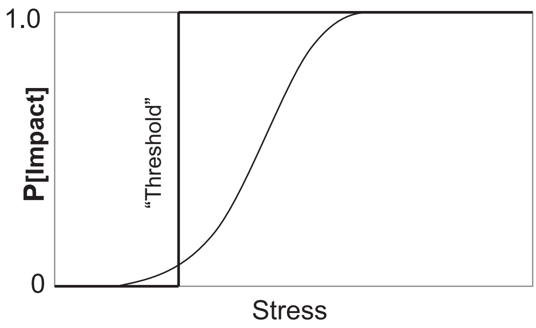

Fig. 30.1 The critical load as "threshold" in the context of damage functions

30.2 The Nutrient Nitrogen Critical Loads Concept and Biodiversity: A Summary

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). To understand the concept, one can think of a damage function, in which a threshold can be identified above which stress leads to a high probability of impact (Fig. 30.1).

There are two established ways to determine critical loads, i.e. empirical and modelled[1] (Fig. 30.2). Empirical critical loads are established through N addition experiments on sites at which bio-geochemical conditions and the effects of the N addition on species diversity can be compared to a control. The empirical approach is limited to situations where N inputs dominate the effects on biodiversity. Regional applications of empirical critical loads require the extrapolation of site-specific findings. Empirical critical load ranges have been assigned in relation to vegetation changes in European natural areas (Achermann and Bobbink 2003) classified following the European Nature Information System (EUNIS, Davies et al. 2004). European empirical critical loads have been adopted under the LRTAP Convention and included in the Mapping Manual (UBA 2004). In the USA, work is ongoing to derive empirical critical loads to ecoregions (Pardo et al. 2011). Furthermore, a first assessment of impacts of N deposition on ecosystems worldwide with related empirical critical N loads is described in Bobbink et al. (2010).

Modelled critical loads can be applied to all situations in which an environmental quality criterion exists. Concentrations of N in the soil solution have been used as environmental quality criterion to compute critical loads for nutrient N in relation to vegetation changes (Table 30.1). Apart from vegetation changes, N deposition can affect a number of ecosystem services of which a preliminary overview can be found in Hettelingh et al. (2008) and which are further addressed in part IV of this volume.

[1] Integrated bio-geochemical models can also be used to derive critical loads (see e.g. de Vries et al. 2007, 2010).

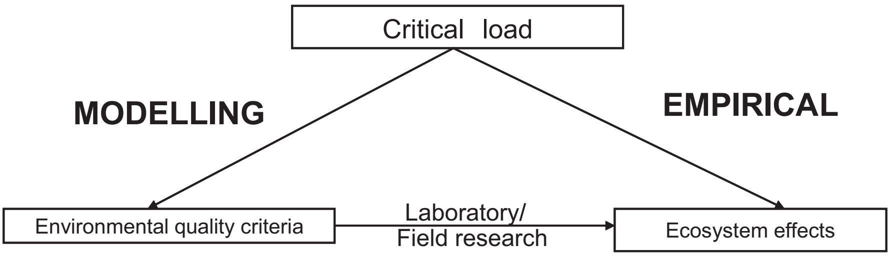

Fig. 30.2 Empirical and modelled approaches to derive critical loads (adapted from de Vries and Posch 2003)

Table 30.1 Critical N concentrations, $(N)_{crit}$, in soil solution. (Source: de Vries et al. 2007) to avoid specified changes of biological diversity

Impact	Critical N concentration (mg N.l^{-1})	
	UBA (2004)	de Vries et al. (2007)
Vegetation changes in Northern Europe		
Lichens to cranberry (lingonberries)	0.2–0.4	0.2–0.4
Cranberry to blueberry	0.4–0.6	0.4–0.6
Blueberry to grass	1–2	1–2
Grass to herbs	3–5	3–5
Vegetation changes in Western Europe		
Coniferous forest		2.5–4
Deciduous forest	–	3.5–6.5
Grass lands		3
Heath lands	–	3–6
Other impacts on forests		
Nutrient imbalances	0.2–0.4	–
Elevated nitrogen leaching/N saturation	–	1
Fine root biomass/root length	–	1–3
Sensitivity to frost and fungal diseases	–	3–5

The critical N concentration is used in the N mass balance to derive a critical load of nutrient N as follows:

$$CL_{nut}(N) = N_i + N_u + N_{de} + Q \cdot [N]_{crit} \tag{30.1}$$

Nitrogen immobilization, N_i, is approximated by the long-term immobilization of 0.5–1 kg N ha^{-1} year^{-1}. Nitrogen uptake, N_u, is the long-term average removal by harvesting (accompanied by a proportional removal of base cations), and denitrification, N_{de}, depends on the soil moisture. The runoff (Q) is assessed from the difference between precipitation and actual evapotranspiration and the acceptable N concentration is related to the natural leaching from a N-limited stand. For more details, we refer to Posch et al. (1993) and reviews and revisions thereof, as adopted in the Mapping Manual (UBA 2004).

The disadvantage of a simple steady-state soil model is that there is not a direct linkage between a critical N concentration in solution and plant species diversity. Furthermore, steady state models do not allow prediction of the temporal response of ecosystems to deposition scenarios, for example, in terms of impacts on plant species diversity. This requires the use of the dynamic integrated soil-vegetation models. Such models can also be used to assess critical loads, while accounting for differences in sensitivity to perturbation depending on their current state and recent history. In an overview report and paper, de Vries et al. (2007, 2010) describe the possibilities of multi-species models in combination with dynamic soil-vegetation models to (i) predict plant species composition or diversity as a function of atmospheric N deposition and (ii) calculate critical N loads in relation to an acceptable plant species diversity change. They also discuss the potential of linked biogeochemistry-biodiversity models to support pollution abatement policy, amongst others in view of the validation status of the models and the potential of the models to assess critical loads. In general, one can say that a combination of empirical critical N loads and integrated soil-vegetation models (as e.g. done by Van Dobben et al. 2006) is the most promising approach to assess reliable critical N loads in view of biodiversity impacts at a regional scale.

As mentioned before, N is one of the components that also causes acidification. Critical loads for acidification are computed using critical limits for indicators such as the ratio between base cations and aluminium or pH, with a strong emphasis on soil chemical requirements for environmental health. The relationship between soil chemical indicators and biodiversity is currently receiving increasing attention, but not addressed further in the context of this chapter. Critical loads for acidification have been computed and mapped in Asia (Hettelingh et al. 1995a). Critical loads for S, N and acidity in China were computed and mapped by Duan et al. (2001), and for Europe and northern Asia by Reinds et al. (2008). On a global scale, the Stockholm Environment Institute (SEI) has assessed the sensitivity of soils to acid deposition (Kuylenstierna et al. 2001), and Bouwman et al. (2002) derived and mapped critical loads of acidity and nutrient N for terrestrial ecosystems.

Critical loads of nutrient N have been mostly used in semi-natural areas in Europe to protect biodiversity, but may need more attention elsewhere. Agricultural areas are not addressed through the critical load approach. On the other hand, agricultural practices including the use of fertilizer are an important source of N inputs to nature in the form of ammonia. In Europe, ammonia deposition on natural receptors is the prevailing cause of critical load exceedance, although the deposition of oxidized N alone causes exceedance in many receptors as well.

In other parts of the world, the importance of oxidized N may be more important than in Europe, because of other energy mixes and emission abatement technologies. On the other hand, the substitution of nature by agricultural land, thereby affecting the geographical distribution of N receptors, may be more important in other regions of the world than in Europe. The relative importance of receptors, biodiversity-endpoints and N deposition in relation to one another varies among regions in the world. This has implications for the use of critical loads to support policies in the field of air pollution and biodiversity.

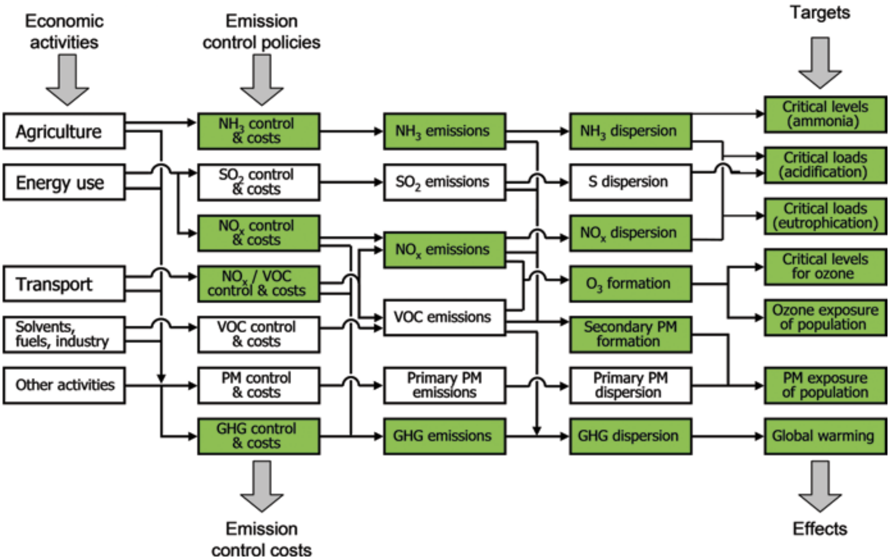

Fig. 30.3 Integration of nitrogen pressure-impacts in the GAINS model (adapted from Winiwarter et al. 2011)

30.3 Current and Potential Applications Under the LRTAP Convention

Critical load exceedances are used under the LRTAP Convention to assess impacts of emission abatements on the environment (Hettelingh et al. 1995b, 2001, 2007). In addition to critical loads for N in relation to eutrophication, use is made of critical acid loads (N and S) in view of acidification. Furthermore, critical levels (see UBA 2004) and health guidelines are important threshold indicators to protect human health and the environment.

The multiple relationships (green shading) by which N_r emissions and control-policies contribute to the risk of adverse effects, is illustrated in Fig. 30.3.

It can be seen from Fig. 30.3 (last column) that N relevant policy targets can be set based on critical levels for ammonia, critical loads for acidification, critical loads for eutrophication, critical levels of ozone for vegetation and WHO health guidelines for ozone and particulate matter. The link to global warming is reflected incompletely, as this would increase the complexity of the figure. Then, interactions would need to be addressed with carbon compounds from emissions that are currently not addressed under the LRTAP Convention.

Reductions of the exceedance of critical loads and levels has been an explicit policy target in establishing two effect-based LRTAP Convention protocols including the protocol to abate acidification, eutrophication and ground level ozone (Gothenburg Protocol 1999), as well as the National Emission Ceilings (NEC) Directive for European Union countries in 2001 (see: http://ec.europa.eu/environment/

air/pollutants/ceilings.htm). In short, in Europe the effect-based approach, involving both the use of critical loads and levels, has been applied successfully, although more still needs to be done to reduce current exceedance levels.

Note that biodiversity is adversely affected when any of the critical loads or levels are exceeded. In Europe the need to reduce emissions of reduced and oxidized N may be driven by regional (local) requirements to meet critical loads and levels. This might be even more so in other regions of the world, especially where urban air quality standards and WHO health guidelines drive air pollution abatement policies. The reason is that the improvement of urban air quality will, as a co-benefit, also reduce the exceedance of critical loads or levels in rural parts of these regions, and thus diminish the risk to biological diversity. But, what can be the role of critical loads when biodiversity is the prime policy target, such as under the Convention on Biological Diversity?

30.4 Current and Potential Applications Under the UN Convention on Biological Diversity

Biological diversity is defined by the 1992 United Nations Convention on Biological Diversity (CBD) as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species and ecosystems". The change of biodiversity comes in many forms including changes of species abundance, species richness and homogenization and is caused by a large variety of drivers, of which human activities have become of significance in approximately the last 100 years (see also Millennium Ecosystem Assessment 2005; EEA 2007). The importance of biological diversity for human well being is well established by its underpinning of ecosystem services which the Millennium Ecosystem Assessment has classified as provisioning, regulating, supporting and cultural services (see part IV of this volume). The CBD formulated a target to be reached in 2010 "to achieve a significant reduction of the current rate of biodiversity loss at the global, regional and the national level as a contribution to poverty alleviation and to benefit of all life on earth". In support of meeting its target in 2010, the CBD developed a number of indicators including the 'change of abundance of selected species'. The indicators are listed in Table 30.2. Nitrogen deposition is among the indicators, however without reference to a critical load for N. The scenario analysis in a modelling study of Ten Brink et al. (2007) has addressed main drivers of loss in biodiversity in 2050 relative to the Mean Species Abundance (MSA) in various regions in the world. Using a Business-as-usual scenario from the FAO, which focuses on land use changes, the study concludes that world MSA decreases from 70 % in 2000 to 63 % in 2050. The role of N turns out to be insignificant in comparison to the influence of the change to agricultural area. Nitrogen is mentioned to play a (minor) role only in Europe and South and East Asia. The question is to what

Table 30.2 Set of headline indicators agreed on the conference of the parties to the CBD through decision VII/30 and VIII/15. (Source: Ten Brink et al. 2007, pp. 23)[a]

Focal area	Indicator
Status and trends of the components of biological diversity	**Trends in extent of selected biomes, ecosystems, and habitats**
	Trends in abundance and distribution of selected species
	Coverage of protected areas
	Change in status of threatened species
	Trends in genetic diversity of domesticated animals, cultivated plants, and fish species of major socioeconomic importance
Sustainable use	Area of forest, agricultural and aquaculture ecosystems under sustainable management
	Proportion of products derived from sustainable sources
	Ecological footprint and related concepts
Threats to biodiversity	**Nitrogen deposition**
	Trends in invasive alien species
Ecosystem integrity and ecosystem goods and services	Marine Trophic Index
	Water quality of freshwater ecosystems
	Trophic integrity of other ecosystems
	Connectivity/fragmentation of ecosystems
	Incidence of human-induced ecosystem failure
	Health and well-being of communities who depend directly on local ecosystem goods and services
	Biodiversity for food and medicine
Status of traditional knowledge, innovations and Practices	Status and trends of linguistic diversity and numbers of speakers of indigenous languages
	Other indicator of the status of indigenous knowledge
Status of access and benefit-sharing	*Indictor of access and benefit-sharing*
Status of resource transfers	**Official development assistance provided in support of the Convention**
	Indicator of technology transfer

[a]Indicators shown in bold typeface have been assessed in Ten Brink et al. (2007). Indicators in italics are still under development

extent this result would change if the scenario had focused on drivers other than those where the substitution of nature for agricultural area is predominant.

In addition to the 2010 target of CBD the European Commission developed its Biodiversity Conservation Strategy (ECBS), which was adopted in 1998. In support of the ECBS, the European Environment Agency (EEA 2007) developed indicators to monitor the progress towards the CBD 2010 target in a project entitled “Streamlining European 2010 Biodiversity Indicators” (SEBI 2010). For this 26 indicators were proposed as summarized in Table 30.3. The exceedance of the critical load of N features as indicator 9.

From Tables 30.2 and 30.3 it is obvious that the critical load indicator is currently of moderate importance to the support of CBD policies.

A way to improve the use of critical loads in both Conventions is to address relationships between critical load exceedance and ecosystem services. A first attempt

Table 30.3 The 26 indicators proposed by the SEBI 2010 process. (Source: EEA 2007, p. 6)

The 26 indicators proposed by the SEBI 2010 process	
1	Abundance and distribution of selected species
2	Red List Index for European species
3	Species of European interest
4	Ecosystem coverage
5	Habitats of European interest
6	Livestock genetic diversity
7	Nationally designated protected areas
8	Sites designated under the EU Habitats and Birds Directives
9	Critical load exceedance for nitrogen
10	Invasive alien species in Europe
11	Occurrence of temperature-sensitive species
12	Marine Trophic Index of European Seas
13	Fragmentation of natural and semi-natural areas
14	Fragmentation of river systems
15	Nutrients in transitional, coastal and marine waters
16	Freshwater quality
17	Forest: growing stock, increment and fellings
18	Forest: deadwood
19	Agriculture: nitrogen balance
20	Agriculture: area under management practices potentially supporting biodiversity
21	Fisheries: European commercial fish stocks
22	Aquaculture: effluent water quality from finfish farms
23	Ecological Footprint of European countries
24	Patent applications based on genetic resources
25	Financing biodiversity management
26	Public awareness

was made in Hettelingh et al. (2008) and will be addressed further in de Vries et al. 2013, Chap. 41, this volume and Erisman et al. 2014, Chap. 51, this volume).

30.5 Prospects for Effect-Based Applications in Different Regions of the World

In support of the revision of air pollution agreements in Europe, both empirical and modelled critical loads are used, as schematically shown in Fig. 30.4.

Figure 30.4 illustrates the use of exceedances of computed (top route) and empirical critical loads (bottom route) in the effect-based support of N emission reduction alternatives. The relation to biodiversity and ecosystem functions depends on how effects of critical load exceedances propagate through ecosystems. For this both dynamic models and dose-response functions are used. Thus the use of both computed and empirical critical loads increases the robustness of scenario findings. An extension of Fig. 30.4 to include critical levels would further enhance the robustness of effect-based assessments under the LRTAP Convention.

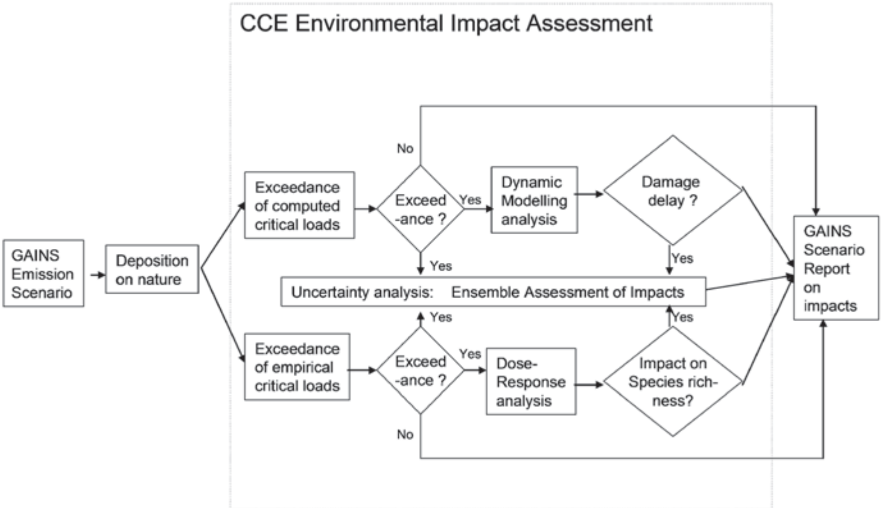

Fig. 30.4 The use of the exceedance of computed and empirical critical loads as part of an effect-based assessment of emission abatement scenario alternatives under the LRTAP Convention. (Source Hettelingh et al. 2008)

Further work is needed to extend Fig. 30.4 to include drivers and impacts that are relevant to other regions of the world.

30.6 Issues for Further Discussion

While biodiversity is an endpoint common to both the LRTAP Convention and the CBD, the development and use of critical loads is operational only under the LRTAP Convention. Convention on Biological Diversity indicators addressing N deposition do not include critical loads or exceedances. However, in Europe the implementation of CBD targets included exceedance of critical loads in its "Streamlining European 2010 Biodiversity Indicators" (SEBI 2010).

Other indicators related to excess ambient concentrations of N_r, i.e. critical levels of ammonia and ozone, relating to biodiversity and human health endpoints are included under the LRTAP Convention, but not used under either CBD or SEBI 2010. Conversely, other indicators that are relevant to express the risk to biodiversity have been included in the set of indicators of both CBD and SEBI 2010, but do not (yet) feature in the effect-based work of the LRTAP Convention. Moreover, the appropriateness of biodiversity endpoints and critical thresholds of N_r is not only delimited by these (and other) policy frameworks, but is also driven by regional and socio-economic differences.

To make the critical load concept more useful in the context of CBD, the following questions need to be addressed:

- Is it possible to assess empirical and (integrated) model based critical loads in different regions of the world?
- If yes, are changes in the critical load formulation needed to make them more relevant (e.g. sufficient to address N impacts to biodiversity) in other regions of the world?
- Should different critical thresholds (e.g. concentration levels, deposition levels) of ammonia, NO_x and ozone be accounted for in view of interacting impacts on growth and biodiversity?
- What is the possibility to make use of the most recent insights in soil-vegetation modelling?
- What could be the institutional framework for large scale regional applications of critical loads?

Further to this discussion, there is interest in the international community in developing a much broader indicator for N (a 'threshold' rather than a 'load') that could apply to N_r (reduced and oxidized forms, as well as the ozone formation potential of (oxidized) N). A move towards a threshold approach for N_r, with biodiversity and human health endpoints could potentially increase the coherence between CLRTAP and CBD approaches in an effect oriented policy context. For example, as stated above in Sect. 30.3, the improvement of urban air quality will, as a co-benefit, also reduce the exceedance of critical loads or levels in rural areas, and thus diminish the risk to biological diversity. Such a development may help the international community move towards a more integrated and holistic treatment of N impacts on human well-being and the environment.

See Clair et al. 2014, Chap. 50, this volume and Erisman et al. 2014, Chap. 51, this volume for the results of the working group discussions on these topics.

Acknowledgments This investigation has been performed by order and for the account of the Directorate for Climate Change and Industry of the Ministry of Housing, Spatial Planning and the Environment (2009). The work of the Coordination Centre for Effects (CCE) is partially supported by the trust fund for the funding of core activities, including effect-oriented work, of the Convention on Long-range Transboundary Air Pollution. The authors gratefully acknowledge support from the European Science Foundation under the NinE and COST729 programmes for attendance to present this chapter, the ÉCLAIRE project for underlying research support,

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