# Chapter 50
# The Critical Loads and Levels Approach for Nitrogen

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**Abstract** This chapter reports the findings of a Working Group to review the critical loads (CLs) and levels approach for nitrogen (N). The three main approaches to estimating CLs are empirical, mass balance and dynamic modelling. Examples are given of recent developments in Europe, North America and Asia and it is concluded that other countries should be encouraged to develop basic assessments using soil, land cover, and deposition map overlays in order to determine what regions might exceed nitrogen CLs. There is a need for increasing the certainty of critical load

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(CL) estimates by focusing on empirical data needs, especially for understudied ecosystems such as tropical or Mediterranean, high elevation environments, and aquatic systems. There is also a need to improve steady-state mass balance parameters, especially soil solution terms, such as nitrate leaching, used to determine the

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CL, and denitrification, which is an equation parameter. Improved dynamic models are needed for predicting plant community changes, and work should continue on existing models to determine CL values. Dynamic models require more data and are more complex than simple calculated CLs but offer more information and allow the development of 'what if?' scenarios. Optimal use of CLs requires expert knowledge of ecosystem values to provide reference states so that safe deposition amounts can be determined. Increased interaction between CL and biodiversity specialists to identify critical biodiversity limits would help provide better CL assessments.

**Keywords** Critical loads • Empirical • Exceedance • Modelling • Nitrogen deposition

## 50.1 Introduction

The main purpose of the Working Group was to assess the state of the art for the setting of regional critical loads (CLs) for reactive nitrogen ($N_r$) as a cause of eutrophication and acidification. Critical loads are a well established, effects-based approach to evaluating emission reductions in the analysis of the effects of air pollutants, as they are used to determine "tolerable" deposition amounts (see also Hettelingh et al. 2014, Chap. 30; this volume). For example, sulphur (S) and nitrogen (N) CLs are currently used by policy makers for objectively setting emissions reduction targets for sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$) and ammonia ($NH_3$) in the Gothenburg Protocol. Setting CLs can be challenging, however, as calculating them requires knowledge which can change with improvements in the

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science, thus sometimes making CLs moving targets. Critical loads can also be difficult to develop and apply because the data required are not always available.

The Working Group reviewed where current N critical load (CL) approaches for eutrophication and acidity were lacking and how improvements could be made. Five main questions were identified for discussion:

a. Can existing CL approaches be improved? There has been extensive use of $N_r$ CLs in the past 10 years, particularly in European countries, so what have practitioners learnt from that experience?
b. Could new, simplified approaches be developed for estimating CLs in regions where there is little information?
c. How could the CL approach be used to assist policy makers in better dealing with issues relevant to the Convention on Biological Diversity (CBD)?
d. Currently, all inorganic $N_r$ species (especially $NO_x$, $NH_3$) deposited into landscapes are lumped together to produce total N deposition estimates. Is it necessary to separate reduced from oxidized species in the calculations? Do we have the knowledge to do this? Critical loads have usually been set as deposition values. Should more work be done estimating critical levels for air concentrations relevant to sensitive taxa such as lichens?
e. Currently, all $N_r$ critical load maps are calculated for terrestrial ecosystems. Is there a need to develop freshwater CLs for N?

## 50.2 Review of Critical Load Approaches

There are three main approaches for estimating CLs which are described here: empirical, mass balance and dynamic modelling. Empirical CLs are based on knowing the deposition or ambient $N_r$ levels below which specific detrimental effects do not occur according to current knowledge. These are based on field or experimental observations of direct impacts to biota, such as changes in tree growth or changes in vegetation (biodiversity). These values can be estimated over large areas from map layers, if adequate information exists on soil chemistry and plant communities. However, the data required can sometimes be taken from examples collected elsewhere and may offer a relatively easy way to get a first approximation of N sensitivity of catchments. A number of reports have summarized tolerances to $N_r$ of plant species, such as Bobbink et al. (2003) and Pardo et al. (2011), and these form the basis for maps describing ecosystem N tolerances in Europe and the United States (USA). More detail and examples of how critical loads can be calculated are found in Hettelingh et al. (2008).

Mass balance CLs are based on equations which assess the ability of a landscape to retain deposited N. A formal definition was provided by the German Ministry of the Environment (UBA 2004) where critical loads of nutrient N are defined as 'a quantitative estimate of an exposure to deposition of N as $NH_3$ and/or $NO_x$ below which no harmful ecological effect is detected'.

This can be stated quantitatively from the N balance:

$$N_{dep} = N_i + N_u + N_{de} + N_{le} \quad \text{(Eq. 50.1)}$$

where $N_{dep}$ is total deposition of N, $N_i$ net immobilization, $N_u$ removal by plant biomass, $N_{de}$ denitrified to $N_2$ or $N_2O$ gases and $N_{le}$ is N leaching from soils (Hettelingh et al. 2008). The critical N load for the soil can thus be described as:

$$CL_{nut}(N) = N_i + N_u + N_{de} + N_{le,crit} \quad \text{(Eq. 50.2)}$$

where $N_{le,crit}$ is the acceptable leaching level. When N deposition exceeds N removal plus soil immobilization, the CL is said to be exceeded and a problem is identified.

Simple mass balance (SMB) CL approaches for both $NO_3$ leaching and changes to biodiversity have been applied in the European context. Nitrogen CLs are related to other stressors, such as pH and sulphur (S) from acidification. Critical loads can be calculated using dynamic geochemical models. These require more data and are more complex than simple calculated CLs but offer more information and allow the development of 'what if?' scenarios. Chemical CL critical limits or criteria need more research regarding specific ecosystem effects to allow more accurate assessments. In view of biodiversity issues, the distinction between acidity and nutrient N critical loads should be abandoned as it is potentially misleading, with eutrophication and acidification effects on biodiversity often difficult to disentangle (see Baron et al. 2014, Chap. 49; this volume). Moreover, multiple critical limits, which allow the assessment of multi-pollutant effects, can and should be constructed when the situation requires it, such as areas receiving both S and N deposition.

Dynamic CL models based on plant competition and succession have been run in polluted areas. Using estimated relationships between site-specific plant N, S and climate tolerances, Sverdrup et al. (2014, Chap. 40; this volume), have reconstructed historical plant communities in areas which are now affected by atmospheric pollution. Using plant-nutrient-climate relationships, predictions have been made of future plant community composition based on potential future climate and nutrient addition scenarios. Using this approach, other environmental stressors, such as fire and browsing animals can also be taken into account. The approach requires good quality information on plant-environment interactions, but has the ability to show the dynamic nature of plant communities over time.

Current knowledge of ecosystem responses to N inputs for the USA has been compiled by Pardo et al. (2011). The report synthesizes research collected in order to estimate N critical loads for ecoregions across the USA. The synthesis includes information from refereed as well as technical publications and could be used to identify ecosystems at risk for land managers and policy makers. The data are organized by ecoregions and include changes in biodiversity and species composition and in tissue N concentration, as well as N leaching from soils. The approach allowed the identification of receptors, responses, and thresholds, and the extrapolation to other regions or ecosystems. This allowed the estimation of empirical N CLs relevant to the major USA ecoregions. More data are continually being collected and synthesized in order to improve the assessment of atmospheric N pollution effects on USA ecosystems.

Efforts to coordinate CL research as a tool for supporting policy development and assessment in the USA are being developed. The objectives of these efforts are to: (a) facilitate sharing of technical information; (b) identify gaps in CL development, and develop strategies to fill them; (c) provide consistency in development and use of CL in the USA and (d) develop communications tools to help those working on or interested in CLs, to share a common understanding about CL terms and goals. It is hoped that these efforts will ultimately result in the USA being able to develop CL maps using commonly understood protocols, and share them with the UNECE and other interested groups. An overview of organizational models used to develop national N critical loads in other jurisdictions has been developed in order to see what would work best in the USA situation. The USA scientific expertise and funding is more widely dispersed than in most other countries and thus requires a new collaborative model for assembling the data needed to produce a coherent picture for a very large country.

Empirical CL maps for two typical Chinese ecosystems have been developed (Duan et al. 2014, Chap. 35; this volume). Sulphur dioxide emissions have increased in China over the past two decades to the highest levels in the world. The trend was subsequently reversed with a 4 % reduction in 2007, 6 % reduction in 2008 and a 10 % reduction goal from 2005 levels was set for 2010 by government authorities. Despite reductions in S, $NO_x$ and $NH_3$ emissions are rapidly increasing. In order to assess $N_r$ effects on Chinese ecosystems, the SMB soil model has been used to calculate CL for $NO_x$ and a large exceedance hot spot was identified in north-central China. Before there can be greater confidence in the data, more work must be carried out on longer time scales, and taking S deposition into consideration. China is a large country which also contains ecosystem types, such as sub-tropical regions, where no CLs have yet been estimated, again pointing out the unique situations which have to be understood. Moreover, large areas of China currently receive high N deposition, making it difficult to estimate pre-pollution conditions.

The view was expressed by some experts that globally land use and climate change present the greatest threats to biodiversity, even when N deposition is an important stressor. Moreover, the impacts of nutrient N on biodiversity may be assessed using critical load approaches. From this it was clear that there is currently considerable focus on developing empirical and dynamic approaches. Despite being the basis of 'acidification' assessments, mass balance approaches have fallen by the way-side in the race to determine CLs for nutrient N (Posch et al. 2011). Nonetheless, they may be the most practical (higher-level) approach for large regions, such as Canada. Currently, empirical approaches are the only viable option for large regions, despite there being a clear need to harmonize land cover maps between regions or jurisdictions. There is also a need for the development of more empirical critical limits (i.e., relationship between N deposition and receptor response), especially for low deposition areas.

Measurements and model-based assessments (Julian Aherne, personal communication) indicate that approximately 10 % of Canada receives N deposition

>10 kg N $ha^{-1}$ $year^{-1}$ (with the caveat that ammonia deposition may be greatly underestimated in some regions). Moreover, empirical assessments suggested that exceedance of CLs for nutrient N may be confined to a few regions across Canada: south-western British Columbia, northern Alberta, southern Ontario and Quebec where agricultural and industrial activities are intense.

## 50.3 Discussion and Recommendations

It is clear that the context for CL science is different than 10 years ago: (i) Climate change has a much higher profile, (ii) science and modeling methods have improved, (iii) linking environmental stressors to changes in biodiversity is very important, (iv) more regions of the world (USA, Canada, China, Brazil, India) are involved in CL science, in addition to Europe. Taking these points into consideration, the participants arrived at several conclusions.

### *50.3.1 How Can Existing Critical Load Approaches Be Improved?*

Using empirical and modelling approaches (meso-modelling) in a combined way rather than in three separate approaches (empirical, steady state, dynamic modelling) will most likely create the most informative results. Dynamic modelling identifies what factors may be most important in empirical studies. Moreover, modelling results can be used when no field measurements are available.

More information is needed on the soil geochemical dynamics of $N_r$, in particular N loss by denitrification, immobilization and leaching. Any improvement in quantifying individual model terms will be useful in improving models, especially as denitrification is sometimes ignored or identified as "retained in the catchment". More information is also needed on the climate variables which should be measured to improve our understanding of N soil chemistry.

Current models use and predict average values. How can we deal with deviations in extreme events such as significant storms which are important but are not well modelled? Is there a way to deal with this? We also need better spatial data for more ecosystems, such as Mediterranean, tropical and sub-tropical areas, polar and semi-desert ecosystems.

### *50.3.2 Can Simplified Models Provide Useful Information to Policy Makers and Scientists?*

Despite the need to increase the sophistication of CL approaches, there is still a large need for robust tools which can give reasonable approximations of conditions when few data are available. The Working Group agreed that it is important to encourage countries to develop rough map overlays for use with the 'Simple Mass Balance' model (for example) and to encourage development of empirical relationships relevant to their regions. It is important to manage expectations, but primitive models can be useful to identify problems and future data needs, as well as providing information on which areas are most likely to be adversely affected. This approach is especially useful to engage countries where currently little information is available (e.g., countries in South America and Asia).

For countries where more empirical data is available, but where spatial regions covered are very large (e.g., USA, Canada, and China), simple models allow scientists and managers to identify region which need further attention. It is important to note that low deposition areas are very important in developing empirical data and mass balance critical load values.

### *50.3.3 How Could the Critical Load Approach be Used to Better Deal with Issues Relevant to the Convention on Biodiversity (CBD)?*

Air pollution causes acidification as well as eutrophication and both are factors potentially modifying biodiversity. Thus, CL and vegetation dynamic modeling approaches are useful tools for predicting potential changes in biodiversity. However, the CL community lacks sufficient understanding of specific CBD goals or biodiversity limits, which are required to better link CL studies to CBD needs. Meetings like the INI Edinburgh Workshop are a good way to build the links between CBD and the LRTAP Conventions.

An important step in linking CL approaches to biodiversity is identifying reference states. What are the desired ecosystem states? What are the historical references? What are expected future reference states? In Europe, for example, plant community reference states have been identified for a year 2000 condition by EU scientific committees. Scientists can define probable CL levels in general, but it is most important that a more widely held consensus be developed to define biodiversity reference goals. We must better understand how to define desired characteristics of a reference state before we can calculate the CL necessary to achieve that state. Plant dynamic models should continue to be developed or improved to better assist in this task.

With good information on CLs, biodiversity specialists can support policy makers in setting priorities on where to spend resources to greatest effect for protecting key ecosystems or ecosystem components. The issue is further complicated by the fact that a number of regions, such as the Netherlands and parts of Great Britain may not be able to return to 'pristine' conditions for the foreseeable future. For example, central Britain lost most of it natural lichen communities 160 years ago. Is it reasonable to assume that we could ever return to that state? The interaction between CL and biodiversity specialists will be most important in addressing such highly subjective scientific issues.

### *50.3.4 Is There a Need for Calculating Separate Critical Loads for Oxidized and Reduced Nitrogen?*

Evidence for differential effects of reduced and oxidized species is beginning to appear, but is not well developed, as only a few grassland and heathland experiments have been conducted that show differences. The feeling of the Working Group was that it may be premature to set separate limits for reduced and oxidized N at this stage. However, there are some ecosystems where $NH_4^+$ is important (acid soils, poorly buffered grasslands); in those cases, it may make sense set CLs at the lower end of the deposition range (see Dise et al. 2011 for latest information).

There is sufficient information on the other hand, to set gaseous concentration $NH_3$ critical levels (as opposed to critical loads). Lichen studies in California and in the UK have developed good concentration-effects relationships which can be used to assess whether existing plant communities are damaged by airborne N. Moreover, relative $NO_3$ and $NH_4$ concentrations in air, soils and water are not static, as there are a number of chemical conversion pathways possible. Further, the $NH_3$ and $NO_3$ impact on plants in soils solution is governed by soil pH, so that acidification must be considered together to some extent. Nevertheless, $NH_3$ CLs are beginning to be used in the European government agencies to assess the impacts of changes in agricultural zoning and practices.

### *50.3.5 Is There a Need to Develop Nitrogen Critical Loads for Freshwater Systems?*

There is a great need for improvement in this area. In particular, empirical CLs for nutrient N in high elevation montane regions as well as estuarine/coastal areas currently need to be addressed. Phosphorus also needs to be included as a eutrophication driver, just as N and S are considered together for acidification modelling in surface waters. There is some empirical data available to assess aquatic N CLs in high elevation systems in the USA, but it is only available for limited geographic areas. A major shortcoming in this field of study is that no predictive modelling tools are currently available for nitrogen CL in freshwater systems.

## 50.4 Conclusions

The consensus was that first approximation empirical CL maps for nutrient effects are useful. Countries should be encouraged to develop basic assessments using soil, land cover, and deposition map overlays in order to determine what regions might exceed N CLs. There is a need for increasing the certainty of CL estimates by focusing on empirical data needs, especially for understudied ecosystems such as tropical or Mediterranean, high elevation environments, and aquatic systems. There is also a need to improve steady-state mass balance parameters, especially soil solution terms, such as nitrate leaching, used to determine the critical load, and denitrification, which is an equation parameter. There is also a need for improved dynamic models for predicting plant community changes, and work should continue on existing models to determine CL values.

Nitrogenous air pollution is one of the many threats to natural plant and animal communities, along with factors such as climate change, land-use change, overexploitation and invasive species. CL science can be most useful once biodiversity reference goals are identified. Therefore, we need assistance from ecosystem value specialists to determine what future states are "desirable" in order to determine what N pollution pressure is 'tolerable'. Though the stressors and their effects are often difficult to separate out, CL analysis provides a tool which can help sort out the contribution of air pollutants to community disturbance. Increased interaction between CL and biodiversity specialists to identify critical biodiversity limits would help provide better CL assessments.

Generally, expert soil chemistry opinion was that, under most conditions, the nitrification of $NH_4$ to $NO_3$ occurs very rapidly in most soils and that the long-term biological effects of these two ions could not be separated from each other. Exceptions might occur under wet, anoxic conditions, but these would be locally, not regionally important. However, differences in effect have been observed in the few available experimental studies, while the concentrations of different atmospheric species of N are important for direct effects on lichens and mosses.

The CL approach has shown itself to be a useful tool for assessing the ability of current ecosystems to deal with $N_r$. There is still room for improvement in the formulation of the approaches or the assessment of limits, but the approach still can be a useful exploratory tool even when little data is available. Optimal use of CLs does require expert knowledge of ecosystem values to provide reference states so that safe deposition amounts can be determined.

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