Arbejdsrapport fra DMU nr. **121**

Critical Loads Copenhagen 1999

21st - 25th November 1999

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Miljø- og Energiministeriet, Danmarks Miljøundersøgelser

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Conference Report Prepared by Members of the Conference's Secretariat, the Scientific Committee and Chairmen and Rapporteurs of its Workshops in Consultation with the UN/ECE Secretariat

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The Conference was held under the UN/ECE Convention on Long-Range Transboundary Air Pollution and was sponsored by:

Nordic Council of Ministers
Danish Environmental Protection Agency
National Environmental Research Institute
Danish Farmers Union
Danish Power companies ELSAM and Elkraft

The Conference was organised by:

National Environmental Research Institute, Denmark

Miljø- og Energiministeriet
Danmarks Miljøundersøgelser
2000

Data sheet

Title:	Critical Loads Copenhagen 1999. 21st – 25th November 1999
Subtitle:	Conference Report prepared by members of the Conference's secretariat, the Scientific Committee and chairmen and rapporteurs of its workshops in consultation with the UN / ECE secretariat. Critical Loads
Authors:	Hans Løkke, Jesper Bak, Roland Bobbink, Keith Bull, Chris Curtis, Ursula Falkengren-Grerup, Martin Forsius, Per Gundersen, Mike Hornung, Brit Lisa Skjelkvåle, Michael Starr, Knud Tybirk Addresses of authors are shown in Annex 7.
Serial title and number:	Arbejdsrapport fra DMU nr. 121
Publisher:	Ministry of Environment and Energy National Environmental Research Institute©
URL:	www.dmu.dk
Date of publication:	February 2000
Layout:	Birgit Nygaard Sørensen
Drawings:	Kathe Møgelvang
Please quote:	Løkke, H., Bak, J., Bobbink, R., Bull, K., Curtis, C., Falkengren-Grerup, U., Forsius, M., Gundersen, P., Hornung, M., Skjelkvåle, B.L., Starr, M. & Tybirk, K. (2000): Critical Loads Copenhagen 1999. 21st – 25th November 1999. Conference Report Prepared by Members of the Conference's Secretariat, the Scientific Committee and Chairmen and Rapporteurs of its Workshops in Consultation with the UN / ECE Secretariat. Critical Loads. National Environmental Research Institute, Denmark. 48 pp. – Arbejdsrapport fra DMU nr. 121.
Keywords:	Critical loads, criteria, indicators, validation
ISSN (print):	1395-5675
ISSN (electronic):	1399-9346
Printed by:	Silkeborg Bogtryk EMAS Reg. No, DK-S-0084
Paper quality:	Cyclus Print
Circulation:	300
Pages:	48
Supplementary notes:	The report is available as PDF-file from the National Environmental Research Institutes web site.
Price:	DKK 50,- (incl. 25% VAT, excl. freight)
For sale at:	National Environmental Research Institute Vejlsøvej 25, PO Box 314 DK-8600 Silkeborg, Denmark Phone +45 89 20 14 00 Fax +45 89 20 14 14

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1. Introduction

1.1 Background of the Conference

The implementation of science based reduction targets has contributed towards producing remarkable reductions in air pollution loads in Europe and Northern America. Detecting recovery from acidification and eutrophication in terrestrial and aquatic ecosystems is therefore increasingly important, and needs good quality and representative methods and data. These requirements are even more important in implementing the Multi-pollutant, Multi-effects Protocol to abate acidification, eutrophication and ground-level ozone, signed in Gothenburg on December 1st 1999.

The acidification and eutrophication of forests, lakes and natural areas were one of the main issues, addressed at the Critical Load Conference, held under the UN/ECE Convention on Long-range Transboundary Air Pollution from 21st to 25th November 1999 in Copenhagen, Denmark. Scientists, administrators and experts from Europe and North America were assembled to review the present knowledge and to develop further the methods for assessing the impact of air pollution on the environment.

The use of soil and water chemistry models to calculate critical loads provides a practical tool aimed at obtaining simple and operational mapping procedures useful for administrative and regulatory purposes. However, during the implementation of abatement protocols and in validation of environmental recovery following emission reductions, attention needs to be given to a broad range of indicators of change in ecosystem structure and function, both biological indicators and chemical changes in the environment, and in particular cause-effect relationships.

Valid cause-effect relationships have been derived in some cases and applied in the development of critical load methodologies. However, for some terrestrial ecosystems, in particular forests, robust biological indicators have yet to be identified which make it possible to detect changes within a shorter period (10-20 years) and for which dose-response relationships can be derived. This is a key issue and the Conference received reports of current research on this topic.

135 participants from 17 countries attended the Conference. The UN/ECE secretariat, the Nordic Council of Ministers Workgroup on Sea and Air, the International Co-operative Programmes (ICPs) on Waters, and on Integrated Monitoring participated. The Co-ordination Centre for Effects (CCE), the Task Force on Mapping and several of its National Focal Centres (NFCs) were also represented.

1.2 Aims and structure of the Conference

The aims of the Conference were to

- Present the state of the art.
- Critically review methodologies for calculating critical loads for acidification and eutrophication.
- Strengthen the relationship between calculated exceedances and the observed biological and ecological effects in the field.

The presentation and discussion of recent advances in the field of biological responses to acidification and eutrophication should be used to develop further the critical loads approach in order to improve the relationship between calculated exceedances and the observed biological and ecological effects in the field. The purpose was to reach beyond empirical experiences – how can changes in ecosystem structure, composition and function be assessed, and how are they related to calculated exceedances. The Conference dealt with methods and models in terrestrial as well as in aquatic ecosystems. In particular the issues of biological indicators, modelling, and methods for validation calls for attention in order to further improve and develop science based critical loads as a tool in the abatement of long-range transboundary air pollution.

The Conference consisted of:

- Plenary sessions with keynote presentations.
- Thematic workshops with presentations, posters and in depth discussions, resulting in conclusions and recommendations (workshop reports attached in this document).
- Common conclusions and recommendations from in plenary sessions.
- Production of a draft conference report.
- Preparation of peer reviewed publication aimed for a special issue of the international journal Water Air, and Soil Pollution (WASP).

The organisers prepared an abstract book of all posters, presentations and scientific publications, which is available from the Danish National Environmental Research Institute.

1.3 Scientific programme

To provide for an in-depth discussion of the issues of the Conference, a number of keynote presentations in plenary overviewed existing information and outlined innovative methods and theories. The scientific programme was the following:

Sunday, 21 November

14.00 - 14.10 Welcome address from NERI
Dr. Hans Løkke, Department of Terrestrial Ecology, National Environmental Research Institute, Denmark

14.10 - 14.45 Historical development of the critical load concept. The way ahead after the EU Acidification Strategy and the UN/ECE multi-pollutant, multi-effect protocol
Prof. Keith Bull, Institute of Terrestrial Ecology, Monks Wood, United Kingdom

14.45 - 15.15 The European critical loads mapping programme, structure and results
Dr. Heinz Gregor, Federal Environmental Agency, Germany

15.45 - 16.15 Aims and outline of the conference
Dr. Hans Løkke, Department of Terrestrial Ecology, National Environmental Research Institute, Denmark

16.15 - 16.45 Effect-based control strategies - what do we need in the future?
Dr. Peringe Grennfelt, Swedish Environmental Research Institute, Sweden

16.45 - 17.30 Current methods in calculating critical loads
Prof. Harald Sverdrup, Department of Chemical Engineering, University of Lund, Sweden

17.30 - 18.00 General discussion

Monday, 22 November

09.00 - 09.30 Danish policy and visions on air pollution
Mr. Svend Auken, Minister of Environment and Energy, Denmark

09.30 - 10.15 Effects of atmospheric nitrogen on (semi-)natural ecosystems
Prof. John Lee, Department of Animal and Plant Science, University of Sheffield, United Kingdom

10.30- 11.15 How do we distinguish acidification-induced effects from natural variability? Examples from Fennoscandia
Prof. Peter Högberg, Swedish University of Agricultural Sciences, Sweden

11.15 - 12.00 Temporal and spatial uncertainties in use of biological responses to nitrogen
Dr. Ursula Falkengren-Grerup, Department of Ecology, University of Lund, Sweden

12.00 - 12.45 Statistical approach to assess effects of meteorological stress and air pollution on forest crown condition in Europe
Dr. Caroline van der Salm, Winand Staring Centre for Integrated Land, Soil and Water Research, the Netherlands

12.45 - 12.50 Introduction to the workshops

13.00 - 17.00 Workshops

Tuesday, 23 November

09.00 - 09.45 Steady state methods for calculating critical loads of acidity to surface waters.
Where do we stand today?
Dr. Arne Henriksen, Norwegian Institute for Water Research, Norway and Dr. Maximilian Posch, RIVM, the Netherlands

10.00 - 10.45 Evaluation and revision of acidification targets in the Netherlands
Dr. Caroline van der Salm, Winand Staring Centre for Integrated Land, Soil and Water Research, the Netherlands

10.45 - 12.00 Report from chairmen, workshops

13.00 - 17.00 Workshops

Wednesday, 24 November

09.00 - 09.45 Nitrogen status and impact of nitrogen input in forests – indicators and their possible use in critical load assessment
Dr. Per Gundersen, Forest and Landscape Research Institute, Denmark

10.00 - 10.45 Empirical N critical loads for (semi-)natural ecosystems: possibilities and constraints
Dr. Roland Bobbink, Landscape Ecology, Department of Geobiology, Utrecht University, the Netherlands

10.45 - 12.00 Report from chairmen, workshops

13.00 - 17.00 Workshops

Thursday, 25 November

09.00 - 12.00 Report from chairmen, discussion of the synoptic report

A number of posters provided additional information on the topics.

In-depth discussions continued in five individual workshops dealing with **criteria, methods, indicators, validation,** and **freshwaters**, respectively. An inter-disciplinary approach was used to address the main topics of the workshops. All workshops treated problems related to uncertainty of parameters and variables.

Workshop 1
CRITERIA was chaired by Dr. Ursula Falkengren-Grerup. This workshop dealt with ecosystem state and change, and addressed a variety of criteria and their possible alternatives. The use of different criteria for different species or ecosystems was addressed.

Workshop 2
METHODS was chaired by Dr. Michael Starr. This workshop addressed the links between chemical and biological variables, time lags and the use of dynamic modelling.

Workshop 3
ECOLOGICAL INDICATORS was chaired by Dr. Roland Bobbink. This workshop addressed ecosystem structure and function, and the selection of organisms or processes with good relationships to atmospheric deposition.

Workshop 4
VALIDATION was chaired by Dr. Mike Hornung and dealt with relations between statistical large-scale field data and modelled critical loads, dynamic modelling, and extrapolation.

Workshop 5
FRESHWATER was chaired by Dr. Brit Lisa Skjelkvåle. This workshop addressed a broad range of questions, in particular the links between catchment characteristics and surface waters, lake sensitivity, dose/response relationships, and chemical criteria and biological indicators.

2. Conclusions and recommendations of the workshops

A number of conclusions and recommendations elaborated by the individual workshops were discussed and approved by the plenary session. The participants also agreed on a number of overall conclusions of the Conference.

2.1 Workshop 1: CRITERIA

2.1.1 *Conclusions*

The workshop discussed and proposed several criteria for assessing effects of nitrogen and acidity in different compartments of terrestrial and aquatic ecosystems. Some of the proposed criteria require further research.

The workshop agreed that research is needed particularly in the following areas:

- Reassessment of existing limits and empirical critical loads using both old information and new data.
- Linking of critical limits to:
  - Mycorrhizal function (trees);
  - Tree species / succession (trees);
  - Wood quality (trees);
  - Plant functional types (other plants);
  - Soil fauna (soil).
- Consideration of historical land use and management, which may have a profound effect on several ecosystem processes and vegetation.
- Development of risk assessment methodologies using distributions of limits, allowing probabilities of critical load exceedances to be estimated.
- Development of dynamic models describing recovery rates in different compartments.
- Development of integrated models describing plant competition, and multistress interactions (nitrogen compounds, acidity, water stress).

2.1.2 *Recommendations*

- Revise present critical load definition in order to take into account sustainability of ecosystems (changes in italics):
  - Critical load means a quantitative estimate of an exposure to one or more pollutants *above* which significant *adverse* effects on specified sensitive elements of the environment *may* occur, according to present knowledge.
- Provide better guidance in the mapping manual (UBA, 1996) on the selection of different criteria (and their ranges) in order to improve international harmonisation of critical load calculations.
- Further develop methodologies for dynamic risk assessment of ecosystem effects.
- Develop combined critical load and risk assessment procedures. Apply critical loads for verified chemical and biological indicators and criteria across specific ecosystem compartments, soils and aquatic systems and use risk assessment methodologies where parameters are adequate. Conduct further research to link soil processes to ecosystem health.

2.2 Workshop 2: METHODS

2.2.1 *Conclusions*

- Present methods to estimate critical loads are: empirical approaches, simple mass balance (SMB) calculations, and dynamic models.
- The mapping of critical loads to-date has mostly been based on SMB calculations. Reduction in S-emissions and uncertainties in the SMB method means that there is now a need for a reappraisal and for a higher level of accuracy.
- The uncertainties associated with scaling (grid sizes) in the mapping of critical loads are of particular concern.
- More reliable input data is required for some components of the SMB equation and improved documentation on methodologies.
- Components of the SMB equations need more reliable input data and improved documentation.
- The importance of nitrogen compounds in critical loads has increased and there is an increasing amount of data available.

2.2.2 *Recommendations*

- In the case of terrestrial ecosystems, more emphasis should be given in the future to empirical and dynamic modelling approaches, and coupling acidification with the nitrogen cycle.
- There is a need for better accessibility and use of existing monitoring data on soil conditions, fluxes and biological indicators in order to improve and develop empirical relationships and models. Long-term monitoring should be secured.
- Uncertainty related to scale in mapping should be quantified and parameterisation of the major fluxes improved, in particular weathering, base cation deposition, N-immobilization in soils, and the toxicity and chemistry of aluminium.
- The role of land-use and forest management on base cation removal at harvesting should be included in order to compare with the effects of acidification from deposition.
- To reflect the uncertainties, ranges and probabilities for critical loads estimates should be given. Multiple criteria (related to different receptors) should be presented.
- Efforts to improve basic understanding of the nitrogen cycle in terrestrial ecosystems should be continued.
- An updated critical review of the evidence concerning aluminium toxicity in relation to base cations (BC) and forest ecosystem biological indicators should be made.

2.3 Workshop 3: ECOLOGICAL INDICATORS

The following working definition of an indicator was used: a structural or functional characteristic of an ecosystem, which may be affected by changes in acidifying and eutrophying atmospheric deposition.

2.3.1 *Main conclusions*

It was concluded that several studies during the last 4-5 years have increased the reliability of indicators and several of the empirical critical loads for nitrogen set in Lökesberg (1992) and Geneva (1995).

The main conclusions concerning the specific indicators discussed can be summarised in the following four groups of indicators. They can be used to set critical loads for nitrogen deposition in a large range of natural and semi-natural ecosystems, including forests:

- Chemical composition of the shoots (N content and related factors, such as N-rich amino acids, N ratios with P, K or Mg) give a good indication of the nitrogen status of the ecosystem. The actual levels, however, depend on the ecosystem type.
- Vegetation composition. Changes in abundance's of key species (e.g. dominants) and/or impacts on endangered species (red listed/nutrient stress indicators/functional groups) have been identified as reliable indicators of exceedance of N critical loads.
- Decomposition of organic matter, including nutrient mineralization and immobilization. Changes in rates of these indicators are clearly observed with increased nitrogen inputs.
- Acidification effects of N (decrease of nitrification and mineralization, changes in nitrogen form, base saturation).

2.3.2 *Recommendations*

- The empirical critical loads should be applied with confidence in the calculation and mapping procedures of individual countries.
- All countries should use the empirical N critical loads approach for natural and semi-natural ecosystems in addition to the SMB models. For this, detailed maps of sensitive ecosystems at the appropriate landscape scale (10x10, 1x1 km) have to be derived.
- Vegetation databases should include the most important ecosystem types and should be combined with the empirical critical values for production of critical load maps to demonstrate the probabilities of biodiversity losses more explicitly and adequately.

2.4 **Workshop 4: VALIDATION**

2.4.1 *Conclusions*

- Validation is needed at all levels to gain the users confidence and to support further development of the critical load programme.
- Some promising attempts at validation have been demonstrated in national studies.
- The existing European datasets cannot be used to validate effects on a site level.
- For acidification more confidence can in general be put on models and predictions for aquatic systems compared to terrestrial. For the terrestrial ecosystems, indicators and criteria are probably more robust for eutrophication than for acidification.
- Several criteria should be used in parallel when determining critical loads. The applied indicators / criteria should match users aims and be field validated.

- As deposition declines, deposition targets based on a gap closure in exceeded area becomes increasingly uncertain and the calculated exceeded area will tend to be underestimated.
- Dynamic modelling and dynamic impact evaluation of the biological responses are crucial for enhancement of the understanding of recovery. The present understanding of biological recovery is weak.

2.4.2 *Recommendations*

- Maintain monitoring and increase the use of data from intensive / integrated sites. Where needed monitoring protocols should be revised, especially for the extensive programmes.
- Include assessment of uncertainty in the national reporting to the CCE on the basis of common guidelines, and use the data in assessment of the implications for European calculations and for integrated assessment modelling. The appropriate scale for target setting should be considered.
- Change the emphasis of the mapping programme towards mapping of probability of exceedance and damage and include mapping of recovery. Methods may be tested on intensive sites, but the possibilities for European scale calculations with simple and generalised dynamic models should be explored.

2.5 **Workshop 5: FRESHWATER CRITICAL LOADS**

2.5.1 *Conclusions*

- Continued work is required on the quantification of spatial, temporal and biological uncertainty in static critical loads models and exceedances.
- Dynamic modelling is essential for the assessment of recovery times and the relative benefits of emissions reductions at different times and to different levels.
- Continued monitoring is essential for the assessment of effects of emissions reductions and to feed back into model development and improvement.
- Dose-response relationships used to select the critical chemical value are not necessarily transferable between regions or types of water body.

2.5.2 *Recommendations*

- Develop definitions of exceedance to include interpretations of the probability / risk of damage, the degree of damage, and the potential time lags between exceedance and damage or non-exceedance and recovery i.e. to incorporate uncertainty.
- Develop methods for the quantification of spatial (site) representativeness including GIS techniques to provide inventories of the population of ecosystems and to model the distribution of critical loads and exceedances amongst the whole population.
- Strongly encourage the wider application of freshwater models using appropriate regional dose-response relationships.
- Develop methods to improve understanding and modelling of biological recovery processes.

3. Overall conclusions of the Conference

The participants in the plenary sessions of the Conference:

- Noted the important results of ongoing activities on calculating and mapping critical loads and their substantial contribution to the development and implementation of air pollution control measures under the Convention.
- Agreed that the dose-response relationships used to select the critical chemical value are not necessarily transferable between regions (i.e. countries) or related ecosystems (e.g. streams and lakes), so countries should be encouraged to select or develop specific criteria where possible.
- Suggested a shift in emphasis to identify recovery following decrease in transboundary air pollution.
- Identified the need to pay more attention to nitrogen processes in terrestrial and aquatic systems, because critical loads for nitrogen load will still be exceeded in widespread areas of Europe.
- Noted the need to bring together more data to describe natural variability across Europe and North America, and to improve their accessibility.
- Recommended continued scientific work and monitoring to improve methodologies and data for assessing the status of terrestrial ecosystems, soils, freshwaters and ground water, in particular in relation to their protection from acidifying and eutrophying pollutants.

The participants of the Conference concluded that while there is a continuing need for international co-operation and harmonisation in monitoring activities and in deriving and mapping critical loads, more work is needed on:

- Proper use of indicators and criteria for specific receptors.
- Empirical approaches on critical loads for nitrogen to provide for protection of biodiversity and natural processes.
- Assessing critical load uncertainties at appropriate scale.
- Reduction of uncertainties due to site conditions and history.
- The generation of representative data.
- The evaluation and mapping of risk assessment and recovery of ecosystems.
- The further elaboration and application of dynamic models.
- Comprehensive assessment, explanation and validation of links between critical loads exceedances, violation of criteria, and possible damage and recovery of ecosystems.

Annex 1. Report from Workshop 1: CRITERIA

Chairman: Ursula Falkengren-Grerup
Rapporteur: Martin Forsius

Participants: *B. Andersen, U. Bertils, R. Chrast, E. Dambrine, B. Emmet, R. Finlay, A. Göransson, J. Hall, K. Hicks, M. Hovmand, P. Högberg, T. Johannessen, J. Kubiznakova, H. Løkke, G. Matschonat, R. Pauls, E. Selin Lindgren, H. Sverdrup, C. Ågren*

Background

The workshop was attended by 21 participants from 10 countries. The expertise of the participants covered a wide range including soil science, plant physiology, microbiology, chemistry, modelling and policy development. The discussion was structured around five substantive presentations and several shorter comments.

Topics covered

Some questions were posed in the conference programme as a starting point for the discussions within the workshop:

- How to relate/select criteria to ecosystem state and change?
- Why base cation/aluminium ratio=1 as the only criteria used in calculation of critical loads for acidity?
- Are the present choice of criteria acceptable and are there alternatives?
- Should different criteria be chosen for different species or ecosystems?

The group identified other questions to be discussed through a brain storming session on the first day and as a result of points raised in plenary and group talks or from questions raised in other working groups. The relatively short time available restricted the discussions to overarching questions and neither existing nor new values/limits for critical loads could be dealt with in the working group.

- The current definition of critical loads was discussed on the first day and some weaknesses identified and adjusted, as further presented below.
- Choice of biogeochemical and ecological criteria was discussed along with their usefulness for acidity and nitrogen critical loads. The significance of critical load calculations incorporating time delay between load and ecological response was stressed in several groups.
- Criteria for nitrogen received considerable attention in both plenary sessions and working groups and a substantial part of the discussions were devoted to existing criteria and a variety of new criteria, which were suggested for immediate or future use.
- Interactive-effects of various environmental factors were acknowledged but not discussed deeply. Effects of acidity and nitrogen and the issue whether conflicting criteria could arise were discussed in detail.

Main aspects to consider when deriving/defining criteria

As a starting point for the discussion the features of a relevant criterion were defined. It was concluded that a good criterion should:

- Reflect the relevant processes.
- Reduce complexity (correlate well with other parameters of interest).
- Be simple ("easy to determine").
- Be justified in relation to receptors.
- Be possible to validate.

It was concluded that it is also essential to consider several other factors like:

- Time lags in response / damage.
- Past and present management practices.
- Historical changes in land use.
- Interaction between acidification and N processes (e.g. on competition of plant species).

Proposal to revise definition of critical loads

When setting the framework for deriving relevant criteria, the workshop discussed the present definition of critical loads. It was felt that the current definition does not take into account sustainability of ecosystems, and that the uncertainty in the predictions and effects also should be reflected. A new definition was therefore proposed (changes from the current one are shown in italics):

- 'Critical load means a quantitative estimate of an exposure to one or more pollutants *above* which significant *adverse* effects on specified sensitive elements of the environment (*including ecosystem resources, structure and function*) *may* occur, according to present knowledge'.

For comparison, the current definition reads (Nilsson & Grennfelt, 1988):

- 'Critical load means 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'.

Framework for selecting criteria for Mass Balance Calculations and empirical values

The discussion within the working group was mostly focused upon new indicators and criteria rather than upon evaluating those available in the present manual. However, some talks in the plenary and working group meetings showed the variation in calculated critical load which could result from applying different criteria and their limits. The variability could be due to weaknesses in the available input data or because the methodology as defined made unjustified assumptions about the level of knowledge of the persons carrying out the calculations. The working group suggests that better guidance is given in the manual on how to choose criteria and appropriate limits.

The focus upon new criteria arose from the character of the Conference. Several participants supplied data from basic research they found were of importance for calculation of critical loads. These suggestions often need to be further studied or compiled from existing data, which is marked in the below tables. The current criteria and limits were not examined in the working group and were thus neither approved of nor rejected. There are, therefore, few numbers given for limits in the tables. Considerable time would be needed to derive limits from new data and scrutinize their soundness. This would be suitable for a specific workshop and few specific suggestions are noted below in the tables.

Framework for selecting nitrogen criteria.

Ecosystem	**Compartment**	**Ecosystem feature: Resources Structure Function**	**Indicator**	**Criteria/ limit**
Terrestrial Types depending on e.g. landuse, management	Trees	Vitality Growth Biodiversity	Growth rate Biomass partitioning Macro nutrients Nutrient ratios Aluminium in solution Free amino acids Leaching Wood quality # Species diversity # Algal shading effects on PAR # Pathogens # Mycorrhizal function for nutrient uptake # $d^{15}N$ #	 e.g. N/P [N]
	Other plants	Vitality Biodiversity	Community shifts Plant functional types Indicator species Loss of stock Leaching $d^{15}N$ #	[1)] f(pH, Al, N) [N]
	Soil	Quality	C/N ratio N concentration Leaching Soil fauna # Net mineralization and immobilization # $d^{15}N$ #	
	Ground water	Quality	Corrosion pH Aluminium in solution NO_3	ANC/SO4
Water -surface -brackish -marine			Chlorophyll Oxygen saturation N/P Plankton concentration Turbidity Soft bottom fauna # Species diversity #	

Suggested indicators for which databases are not yet compiled.
[1)] Data compiled from the Forest Inventory in Sweden was presented by H. Sverdrup. This gave empirical critical loads for nitrogen of 6 to 9 kg ha^{-1} yr^{-1} for changes in lichen and herb abundance.

Framework for selecting acidity criteria.

Ecosystem	Compartment	Ecosystem feature: Resources Structure Function	Indicator	Criteria/ limit[1]
Terrestrial Types depending on e.g. landuse, management etc.	Vegetation	Growth Vitality	Soil pH, Al^{3+} Soil BC / Al (species specific) Plant macro nutrients (species specific) # Biomass partitioning Mycorrhiza function for plant nutrition #	BC / Al 0.8[1)] (preliminary)
		Forest yield	Base saturation	
	Soil	Stability	No depletion of structure and bearing structure Mycorrhiza diversity #	$W_{Al}>Al_L$
Human	Ground water	Drinking water quality	Corrosion	$ANC/SO_4>$ pH> $Al^{3+}<$
Waters - surface - brackish - marine	Lakes	Fish stocks	ANC pH Al-concentration Episode parameters	f(pH,Al,t)
	Streams	Fish breeding	Al-concentration	

Suggested indicators for which data bases are not yet compiled.
[1)] E.g. Sverdrup & Warfvinge, 1993.

Framework for setting empirical criteria

Presentations in plenary and working group stressed the importance of taking the total changes caused by nitrogen or acidity inputs into account when defining the change under consideration. The chartflow below therefore includes a step where the unaffected, “satisfactory” status of the ecosystem feature is defined and then used as a reference in the definition of change. Another step allows division of an ecosystem into subgroups where changes in one group could be driven by acidity and the other by nitrogen.

It was also stressed that changes due to present and historical external pressure must be taken into account. Such effects could be former land use and varying intensity of present management. Results show that grazed vegetation may be more sensitive to nitrogen input than ungrazed systems, that forests on former agricultural land retain a high nitrogen mineralization for centuries and that intensity of forest management has profound effects on several ecosystem components. These pressures on indicators must be considered in the definition of change.

Step-by-step procedure for setting empirical critical loads (refer to text above).

Ecosystem	Ecosystem types	Definition of unaffected (satisfactory) vegetation type	Definition of change ↑ Pressures on indicators affecting degree of change: e.g. grazing, past and present management, other environmental factors	Empirical critical loads

Inclusion of a risk assessment approach in critical load calculations

During the final concluding discussions a new concept was introduced by H. Løkke for carrying out an assessment procedure based on critical thresholds (Figure 1). The basic feature of this approach is to make separate critical load calculations for ecosystems, soils and groundwater, using well-established and verified criteria. Differences may still be combined by the use of dynamic modelling. However, due to lack of data, heterogeneity and large time lags, it is not possible to establish cause-effect relationships by the use of simple steady state models. Additional risk assessment can be applied to selected topics where data are appropriate e.g. for toxicity of pH, aluminium, heavy metals, or POPs.

With this approach no direct link between soil quality and ecosystem protection needs to be established. The soil would be protected by using specified soil quality criteria using chemical and / or biological indicators aiming at long-term sustainability. Ground water protection should be established by a similar approach using chemical indicators for leaching of acidity, nitrate, heavy metals etc. Ecosystem protection should mainly be based on empirical criteria derived for specific ecosystems, or by use of dynamic modelling, where sufficient data are available.

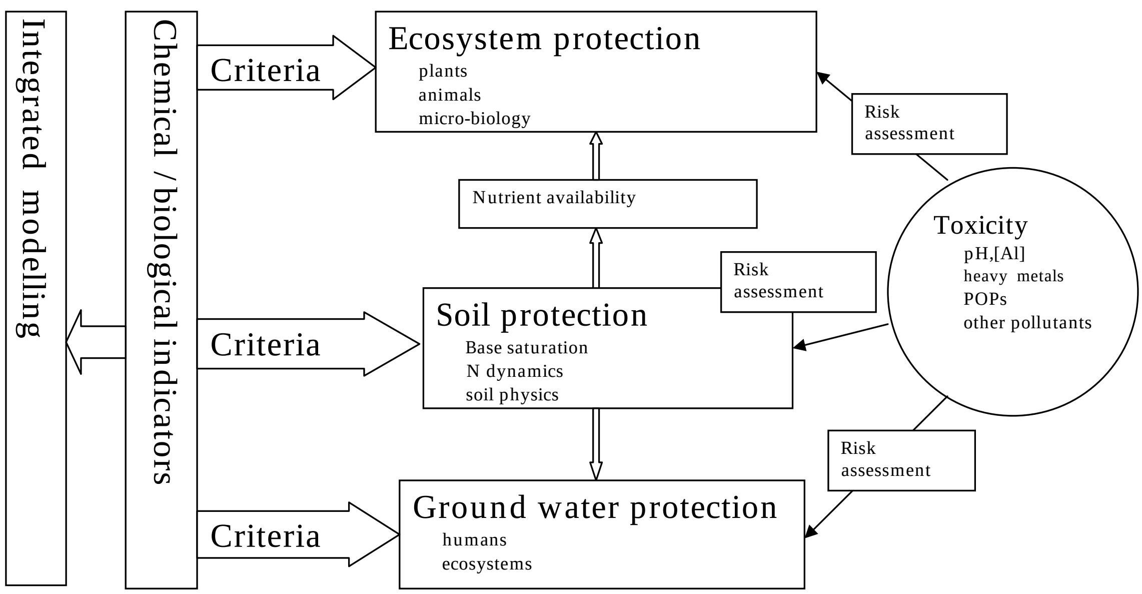

Figure 1. Suggested concept for the assessment procedure, involving separate critical load calculations for ecosystems, soils and groundwater, and additional risk assessment of specific toxic impacts.

Annex 2. Report from Workshop 2: METHODS

Chairman: Michael Starr
Rapporteur: Per Gundersen

Participants: *J. Aherne, M. Alvetag, J. Bille-Hansen, P. Blaser, B. Bosman, J. Derome, N. Dise, K. Foster, K. Hansen, M. Holmberg, H. Ilvesniemi, P. Kram, H.L. Kristensen, D. Kurz, S. Langan, A.-J. Lindroos, U. Lundström, E. Matzner, J. Mulder, K.E. Nielsen, M. Niklinska, R. Ouimet, L. Pardo, L. Rasmussen, B. Reynolds, R. Skeffington, T. Spranger, A. Stuanes, V. Vanderheyden, S. Watmungh, H. de Wit*

Introduction

33 persons from 13 countries attended Workshop 2. Expertise in the group covered soil science, soil chemistry, forest ecologists, forest ecosystem monitoring, critical load modelling, and critical load mapping. During the course of the workshop 13 presentations were made and there were 4 posters on display. Topics covered by the presentations and posters included weathering, aluminium chemistry, chemical criteria, modifications to the SMB critical load model, field applications, biological links, and various aspects of nitrogen. The approach during discussions was based on a "is it broke; can we fix it" philosophy with three main questions: 1) is there anything wrong with the present methodologies for calculating critical loads? 2) If so, what is wrong? and 3) How can we correct or improve it?

Background

At present three methods are used to estimate critical loads for nitrogen and acidity in terrestrial ecosystems:

- Empirical approaches.
- Simple mass balance (SMB) calculations.
- Dynamic models.

Empirical models use data from different locations and relate data on deposition to various observed effects. The advantage is that results are based on observed / measured data. They are effect based and directly link effects to deposition. Disadvantages are problems of representativeness, shortage of comparable data and limited possibilities for prediction.

SMB models use long-term average fluxes to calculate the critical deposition rate in a mass balance equation. Advantages are that maps can be drawn at the European scale and they account for aspects related to sustainable development. They represent long-term predictions of ecosystem fluxes and ecosystem structure. The main disadvantage of the SMB method is that calculations of current exceedances are not easily related to current effects. The uncertainties in the various fluxes and uncertainty related to scaling during mapping are very high.

Dynamic models are based on parameterisation of those processes considered most important for the functioning of the whole ecosystem. Advantages are that they cover various time-scales, have predictive capabilities and can analyse scenarios of different deposition. Also time lags between impact and effect can be resolved including recovery aspects. Disadvantages are that they can only be applied to well-documented sites and are thus difficult to upscale to the European level.

All three methods were discussed during the conference, presentations and discussions. In Workshop 2 most emphasis was on the SMB, since this method is most commonly used in the LRTAP work[1] on mapping of critical loads. The empirical models are mainly used for aspects of the nitrogen cycle and effects of nitrogen deposition. Examples of dynamic models dealt with recovery from acidification.

SMB methodology

The SMB methodology was important and suitable as a basis for responding to the urgent need for emission reduction strategies. However, as sulphur emissions have been reduced greater precision and accuracy are needed in the critical load and exceedance predictions. The present accuracy of the models is not sufficient to guide further emission reduction policy (but improvements suggested below may help). While the workshop suggested a number of improvements to the SMB method and the need for representative data, most benefits are likely to come from putting more emphasis on empirical and dynamic modelling approaches and methods.

Of particular concern were the uncertainties related to scaling (different grid size for different parameters) in the mapping of critical loads and exceedances. The systematic errors associated with scaling urgently needs to be addressed, since this may overshadow other uncertainties. The use of a smaller grid size in mapping and the use of ranges on all parameters in the critical load calculations should improve the situation.

For empirical models it is recommended that better use is made of available data such as the ICP[2] Forest Level 1 and 2, ICP Integrated Monitoring, and other integrated monitoring data. This clearly calls for increased data accessibility, a point where action is urgently needed. There is also a need for extension of the existing databases and continuation of long-term monitoring programmes. Generally the monitoring should include more biological indicators than in the past (see Workshop 3). Empirical models can be used in the validation and improvement of dynamic models, and in testing the validity of chemical criteria (C/N ratio, BC/Al ratio) and links with biological indicators.

The existing dynamic models of acidification rely mostly on chemical processes and have been relatively simple to parameterise. Since an increasing proportion of acidification derives from nitrogen deposition, a coupling of nitrogen process models and acidification models is needed. There is still a lack of understanding of major nitrogen processes, which call for fundamental studies in a range of ecosystems. Field manipulation experiments may be helpful in this respect. Dynamic models should be applied with different deposition scenarios to sites with large and quality datasets and where an integrated ecosystem approach has been adopted. The variation of soil chemical criteria and variables (e.g. BC/Al, BS, pH) with time can be seen as well as the time required to reach defined criteria (e.g. time to recovery, to N saturation (C/N-ratio<25), to BC/Al ratio<1).

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[1] LRTAP = Long Range Transboundary Air Pollution
[2] ICP = International Co-operation Programme

Most of the recommendations from Workshop 2 were focussed on improving the SMB model, but they are also relevant to the other modelling approaches and methods. The recommendations below are therefore organised around the main components of the SMB model equations.

Key parameters

The weathering rate is probably the most important term in the critical load calculation for acidity. The use of min-max weathering rate values was recommended to produce an envelope of estimates or use ranges/distributions as input to weathering models. It was noted that the 'Skokloster' weathering classes were rather crude estimates (Nilsson & Grennfelt, 1988). A compilation is recommended of a database on weathering rates and mineralogies in relation to parent material and method of calculation. The potential role of mycorrhizal weathering was demonstrated, and their effect should be included in the present depletion methods for estimating weathering rates, but not those based on dissolution kinetics of minerals, e.g. PROFILE (see Sverdrup & Warfvinge, 1993).

Base cation deposition is changing. A regional distribution of base cation deposition might be derived by application of a canopy exchange model on available precipitation and throughfall data from the Level 2 sites.

To better represent the role of biomass uptake (base cations and nitrogen removal at harvesting averaged over the growth period) scenarios on land-use and forest management (harvesting methods) should be included in order to compare with deposition rates. A database on biomass concentrations and tissue densities for different species, soil types and regions should be established to allow more accurate and comparable estimates of base cations and N accumulation and removal at harvest. In the critical load mapping manual (UBA, 1996), better documentation of default values should be given.

An aluminium-organic complexation model should be used to calculate the acidification related chemical criteria (ANC[3] leaching, BC/Al, pH) instead of the gibbsite model. Better criteria are needed for organic soils (an ad hoc working group from the workshop has agreed to tackle this problem via e-mailing). Leaching of organic anions should be included, especially for organic soils. Calculations should include several criteria to account for different soils and ecosystems. This can show the range of ANC leaching and allow the most appropriate and/or sensitive value for the soil type/ecosystem to be used.

For calculation of critical loads for nitrogen, most uncertainty is associated with nitrogen immobilization in the soil. Long-term values have so far been estimated at 1-2 kg/ha/yr, but it has been reported that soils may accumulate an order of magnitude more. Clearly more data on long-term development of soil carbon and nitrogen pools are needed and the controls including the interactions of both elements. Higher rates may be acceptable in N poor systems (North Scandinavia, heathland forest, N 'depleted' forests, i.e. litter raked, burned), but the critical limit is not known. Use of empirical relationships in dynamic models of N may provide estimates of time to saturation.

[3] ANC = Acid Neutralising Capacity

Contradictory evidence was presented concerning the phytotoxicity of aluminium. An updated critical review of the evidence concerning aluminium toxicity in relation to base cations should be made, including consideration of possible species / ecosystem specific values. Field-scale manipulation experiments to validate the aluminium toxicity hypothesis with mature trees should be made.

The higher nitrogen deposition sites are dominated by ammonium input. However, it is not known to what extent the fate of deposited nitrogen and its biological effects are dependent on the form of nitrogen. Further research is needed in this context.

For all models, there is a general need for reliable and representative data, standardisation of methods for sample collection and analysis, and harmonisation of the use of derived parameters (e.g. cation exchange capacity, base saturation). The criteria and calculation methods in the critical load mapping manual (UBA, 1996), including default values needs better documentation and clarification.

Annex 3. Report from Workshop 3: ECOLOGICAL INDICATORS

Chairman: R. Bobbink
Rapporteur: K. Tybirk

Participants: K. Enns, J.G.M. Roelofs, J.A. Lee, T. Riis-Nielsen, M. Risager, M. Johansson, H. Pleijel, F. Bussotti, L. Ericsson, T. Näsholm, J. Persson, J. Strengbom, B. Ackermann, A. Davidson, P. Cudlín, H. Staaf, B. Münzenberger, M. Quist, E. Hiltbrunner, Y. de Kluizenaar, S. Power, D. de Zwart, H. Vereecken, H.B.M Tomassen, A. Nordin

Introduction

The purpose of the workshop was to discuss previously proposed indicators of empirical critical loads for nitrogen and present the state of the art on relevant ecosystem research, enabling the Conference to strengthen the links between critical loads and observed effects in natural and semi-natural ecosystems.

The following working definition of an indicator was adopted by this workshop:

- 'A structural or functional characteristic of an ecosystem which may be affected by changes in acidifying and eutrophying atmospheric deposition'.

The characteristics of good indicators were illustrated and taken into account.

The workshop used a combination of oral presentations and intense discussions. 27 participants from 11 countries participated actively in the workshop by giving 10 oral presentations and informal reports of recent research data and through the discussion sessions. It was concluded with a session to structure the many ideas and suggestions by writing them separately on paper, sticking them at the wall and inviting all participants to organise and prioritise their conclusions. For this session the workshop was split into two groups to give a more effective decision-making procedure and dynamic discussions, one group on forested ecosystems and one group on open land natural and semi-natural ecosystems. Finally, consensus was reached in a general discussion.

Specific indicators for various ecosystems

As a basis for deriving the overall indicators, specific indicators for each ecosystem were selected and included in the discussions. Numerous characteristics of indicators were mentioned and used for the selection, such as specificity, signal/noise ratio, sensitivity, ease of application, possibility for application at many locations, public appreciation, non-destructiveness, time/concentration integration, reversibility, speed of response and costs.

Natural ecosystems
Natural nutrient poor ecosystems can be used directly to indicate changes due to excess nitrogen, which often represent the only human induced change to these ecosystems.

Bogs (unmanaged)
Short term
- Leaf chemistry (Chlorophyl concentration in *Sphagnum*, > 0.6% N in *Sphagnum*, N-rich amino acids, with respect to associated pests / pathogens).

Long term
- Cover of *Sphagnum* and composition of peat moss layer.
- Vascular species composition.

More research is clearly needed for clarification of the relationship between decrease in percentages of hollows (of the typical hummock-hollow structure of raised bogs) and N load, and research on net peat formation is also needed.

Soft water lakes
- Species composition - decrease in (rare) submerged macrophytes (isoetids).
- NH_4 / NO_3 ratio > 1 (mol / mol ratio) in sediment pore water.
- N content of water.
- Increase in algae (epiphyton).

Because of the relative quick changes in this group of ecosystems after increased N loads, no early and late warning indicator has been distinguished. This issue has also been addressed in Workshop 5.

Managed semi-natural ecosystems
The importance of habitat management must be recognised for semi-natural ecosystems. It is indeed essential for maintenance of these ecosystems and their conservation values. The extent and frequency of management processes, which remove nitrogen and other nutrients from the ecosystem, will influence the critical loads. Dynamic ecosystem models show that critical loads for lowland heathlands will be reduced if mowing or burning managements are used, as compared with sod cutting. Such calculations should be undertaken for all semi-natural ecosystems and be taken into account for both the loads and the indicators of changes due to nitrogen.

Heathlands
Short term indicators
- Leaf chemistry (N / P or N / Mg ratios, N-rich amino acids, these indicators can also be used as risk assessment for pests / pathogens).
- Species composition (changes in lichens and bryophytes).
- Bryophytes (N%).

Longer term indicators
- Species composition: increases in grasses, decreases in dwarf shrubs (‘grass index’).
- Net decomposition rates, including N-mineralization and immobilization.

To improve the definition of existing indicators and identify new ones, more research is needed on:
- Quantification of indicators for nutrient limitation in different heathland ecosystem.

- The influence of differential management effects on indicator performance with respect to nitrogen loads.
- Pests / pathogens.
- Changes in gap structure of the vegetation in relation to N loads.

Managed grasslands
- Abundances of dominant graminoids (increase in grasses or sedges).
- Species composition (decrease in subordinate species).
- Decomposition and N- mineralization.
- Clarification of a useable indicator (N / P or N / K) for non-N limited grassland ecosystems.

Forests
It became clear during discussions that it would be better to consider separately indicators for forests for protection of production values (trees) and for nature conservation (biodiversity). However, it was decided to focus the workshop discussion mainly on the natural values, but often they cannot - and should not - be separated. Time did not allow for a discussion of all different forest types, climate zones and management regimes, and therefore the following indicators should be further interpreted with respect to the specific forest and soil types.

The emphasis was put on protection of species (biodiversity) of the forests, including the characteristic functional groups, with focus on key species status and general attention on ground vegetation composition. Importance of succession during forest rotations and under different management strategies was not included.

The discussions were separated between indicators with potential as short, medium and long term indicators of changes due to nitrogen and associated effects of acidification. The indicators with potential for early warning are:
- Leaf chemistry (N concentration, nutrient imbalances, amino acids, and associated pests / pathogens).
- N-fixing lichens (reductions / disappearance of populations).

Indicators deemed more suitable for changes on an intermediate time scale are:
- Ground vegetation changes, including the relatively sensitive bryophytes and lichens.
- Pathogen infestation.
- Mycorrhizal infestation and status of fine tree roots.
- Tree vitality.

Indicators that will only provide good evidence of changes over a long term perspective are:
- Wood production.
- Base saturation (pH).
- Parasite / pathogen infestation.
- NO_3 leaching.
- C / N ratios.

Development of the work with indicators with respect to N critical loads

It was concluded that a number of studies carried out during the last 4-5 years have increased confidence of several of the indicators and levels of empirical nitrogen critical loads identified in Lökesberg (Grennfelt & Thörnelöf, 1992) and explored further at subsequent conferences. The recent research has increased the reliability considerably of these indicators and thereby the confidence with which they can be used for the setting and mapping of critical loads of the individual countries.

The participants of the workshop advise all countries to use the empirical N critical loads approach for natural and semi-natural ecosystems, including forests with nature values in addition to the steady state mass balance models. For an optimal use of the approach, detailed maps of sensitive ecosystems at the appropriate landscape scale (10x10, 1x1 km) has to be developed. Vegetation databases should be extended to include the most important terrestrial and wetland ecosystem types, and should be combined with the empirical critical values for production of exceedance maps. This will demonstrate more explicitly and adequately the probabilities of biodiversity losses than the present mapping used for negotiations.

Links to criteria, mapping, validation
The workshop did not explicitly discuss the links to the other workshops, but during plenary sessions the interactions were illustrated. For instance the Workshop 1 on criteria presented a discussion of ecosystem subdivision, definitions of unaffected ecosystem types and definition of changes - where the indicators of this workshop should be used for the empirical N setting.

Research needed on indicators

In addition to the general recommendations already mentioned, the workshop has also revealed numerous gaps in our knowledge:

- Development of dynamic ecosystem models integrating abiotic and biotic components of the ecosystems.
- The development of probabilistic multivariate models for vegetation and abiotic factors to establish critical loads for nitrogen and acidity at European scale.
- The differential importance of reduced or oxidized nitrogen in the observed changes in response to increase of total N deposition .
- The importance and variation of nitrogen immobilization should be further clarified and quantified for use in critical load setting.
- The development of methods to get realistic indications of non-nitrogen limitation in nutrient poor ecosystems.
- Additional research on the relationship between mycorrhiza, pathogens / parasites infestation, soil fauna (acidification and N effects) and nitrogen enrichment is needed.
- Critical loads for nitrogen have to be developed for numerous ecosystem types, such as tropical and subtropical, Mediterranean ecosystems, (sub)arctic, (sub)alpine.
- The importance of management on the effects of nitrogen in semi-natural ecosystems.
- The natural recovery of (deteriorated) ecosystems after reduced inputs should be further investigated, including restoration aspects.

Annex 4. Report from Workshop 4: VALIDATION

Chairman: Mike Hornung
Rapporteur: Jesper Bak

Participants: *M. Johansson, J. Jacobsen, F. Kennedy, S. Brickwood, A. Colles, J. Meykens, L. Mortensen, P. Warfvinge, J. Ahonen, F. Moldan, L. Nyberg, K. Tørseth, S. Braun, H. Gregor, J. Nilsson, P. Grennfelt, C. van der Salm, A.H. Legge, G. Fenech, D. Wright*

Discussion topics

The starting point for the workshop discussions was a list of questions presented by the chairman:

1. Can we validate critical loads - and how?
2. Can we validate models - and if so, how?
3. Do we have the data needed for validation?
4. Do we have suitable indicators / criteria to allow validation?
5. Static ↔ dynamic models.
6. Are there thresholds in dose responses?
7. Will reduction below the critical load produce recovery?

Introduction

The question of validation is connected to the definition of the term, which was therefore discussed. In principle steady state critical loads cannot be validated because ecosystems are not in steady state and will not be so in foreseeable time. In addition the complexity of natural ecosystems and the inherent limitations in data and understanding will probably mean that it will be impossible to validate critical loads as strict thresholds. Two answers to this were discussed. Firstly less stringent terms like testing or evaluating might be more suitable. Testing can be done at all levels from process descriptions and models to cause effect relationships. Secondly a shift in the perception of critical loads towards risk assessment was proposed. If critical loads are perceived as limits between different classes of risk, validation can be performed with statistical methods.

Five presentations were given as basis for the discussion in the workshop. *Fiona Kennedy, UK,* presented results from application of the SMB model at a number of British sites. At some of these sites very different results were obtained when different estimates of the key input parameters were used. Some of the heavy clay soils in UK have low weathering rates but large pools of exchangeable bases and are therefore not expected to reach equilibrium in hundreds of years. Discussion considered whether critical loads should be set for different time scales. *Sabina Braun, CH,* presented a national study on relationships between tree status, ecological factors and pollution load. Multi variate statistics was used to separate adverse effects of air pollution from natural variation and positive growth effects of nitrogen. A decrease in the growth and crown transparency of beech at base saturation's below 40% was demonstrated. *Jesper Bak, DK,* presented an assessment of the influence of uncertainty and spatial variation on large-scale assessment of critical load exceedances and the possibilities of validation. It was concluded that European datasets cannot be used to test critical loads or exceedances at individual sites but can be used to test the area protected. However, as deposition decline deposition targets based on a gap closure in exceeded area becomes increasingly uncertain. *Matti Johansson, FI*, presented lessons learned from a comparison of three Finish integrated model systems. From this study the following ranking of variability was given: emissions < effects, deposition < emissions, critical load < single parameters, critical load method < parameters, critical load soils < lakes, steady state < dynamic. It was concluded that know how exists for confirmation. *Johanna Ahonen, FI*, presented a comparison between different methods for critical load calculations. In southern Finland critical loads have been calculated with both the dynamic model SMART and the SMB model using parameters obtained from the SMART calculations. These calculations were compared with the range of critical loads calculated with the SMB model for the EMEP50 grid. All results were comparable.

Caroline van der Salm's plenary presentation regarding a 'Statistical approach to assess effects of meteorological stress and air pollution on forest crown condition in Europe' provided further inspiration for discussions in the workshop. A comparison between crown condition and a number of biotic and abiotic stress factors at roughly 2000 level I forest plots in Europe had, in the study presented, not revealed strong relationships between crown condition and critical load exceedances. The dominating explanatory variables were country and stand age. Other parameters made a very limited contributed to the explanation of variation in crown condition. One of the problems is probably the different reference tree used in the individual countries. Because of this difference 'country' was included as a separate parameter in the statistical analysis. This might have weakened the analysis because of cross correlation to e.g. deposition.

The lack of success in large-scale validation studies is problematic because these exercises are important in preserving users confidence. Different reasons for and answers to this problem were discussed. It was agreed that the indicators and criteria currently used for acidification of forest soils are not very robust and the range of indicators and criteria used should be expanded and differentiated for the different ecosystem types. European datasets cannot be used to test critical loads or exceedances at individual sites, but some national studies show better relationships. Substantial time lags can be anticipated between exceedance of critical loads and violation of the chemical criteria, and it will probably be necessary to include dynamic aspects in effect assessment at the European scale.

Conclusions and recommendations from the workshop have been summarised in five categories: 1) the critical load concept, 2) validation, 3) status, 4) uncertainty, and 5) recovery.

Overall conclusions and recommendations

The critical load concept
Critical loads are not thresholds but should be perceived as a separation between deposition levels with different risk / probability of damage.

Validation

- Increases users confidence and helps in further development of the critical load programme.
- Validation is needed at all levels from the conceptual to process description.

- Data from large-scale manipulation experiments, intensive integrated monitoring and from surveys should be used.
- European datasets cannot be used to test critical loads or exceedances at individual sites but can be used to test the proportion of sites (area) protected.

Status

- There is more confidence in models and predictions for acidity in aquatic systems compared to terrestrial, mainly because of the more robust criteria.
- Indicators and criteria for terrestrial ecosystems are probably more robust for eutrophication than for acidification.
- The links from model derived chemical parameters to biological response are weak for terrestrial systems, especially regarding the effects of acidification. The empirically based critical loads for eutrophication are probably reliable.
- Several criteria should be used in parallel. The applied indicators/criteria should match users aims and be field validated. Biodiversity will probably in the future be a more important indicator than tree growth, both because of a shift in political interest and because of the problems in validating cause-effect relationships for trees.

Uncertainty

- Inclusion of uncertainty in critical load and exceedance calculations increases openness.
- Inclusion influences the predicted area of exceedance. For acidification the exceeded area will increase unless large unknown biases are identified.
- As deposition declines deposition targets based on a gap closure in exceeded area become increasingly uncertain.
- Uncertainty assessment suggests we may have to reconsider how to set targets. The influence of uncertainty is scale dependent. The resolution for target setting should not necessarily be the same as in exceedance calculations.
- Uncertainty analysis could guide national teams in improvement of national databases.

Recovery

- Exceedance of critical loads and violation of the chemical criterion is not synchronous. There can be substantial time lags.
- Systems will not return to a pristine state so we might need to define targets for recovery or reversal.
- A deposition target for recovery can be different from a target set to avoid further damage.
- The impact of new protocols on anticipated recovery rates should be assessed. This information could be presented as maps of present status and maps of time to 50% recovery for different scenarios.
- Dynamic modelling is crucial. Methods may be tested on intensive sites, but the possibilities for European scale calculations with simple and generalised models should be explored.
- The observed chemical reversal in aquatic systems gives confidence in models and methods. Soil system recovery will be slower.
- The present understanding of recovery from eutrophication and on the relationship between chemical recovery and biological recovery is weak.
- Policy and industrial users of critical load information expect to see recovery following reductions in emission/deposition.

Recommendations

- Critically evaluate criteria and indicators on the basis of field data.

- More can be learned from further assessment of available data and studies.
- There is a need for long term integrated monitoring and large-scale manipulation experiments. Monitoring data from extensive networks are also needed, but there is a need to re-evaluate monitoring protocols.
- Include assessment of uncertainty in national reporting of critical load data on the basis of common guidelines, e.g. prepared by the CCE.
- Develop methods to map probability of exceedance and damage.
- Change the emphasis of the mapping programme towards mapping of probability of exceedance and damage and include mapping of recovery. Methods may be tested on intensive sites, but the possibilities for European scale calculations with simple and generalised dynamic models should be explored.
- Workshops on dynamic modelling and on recovery are needed.
- Encourage further research on recovery from eutrophication and on quantitative relationships between loads and the responses of criteria and indicators.
- Improve data on the status of receptors.
- Maintain monitoring, but evaluate protocols for extensive networks.

Annex 5. Report from Workshop 5: FRESHWATERS

Chairman: Brit Lisa Skjelkvåle
Rapporteur: Chris Curtis

Participants: *K. Bishop, K. Bull, R. Collins, J. Cosby, P. Dillon, C. Evans, B. Ferrier, A. Henriksen, A. Jenkins, A. Kammerud, M. Kernan, F. Moldan, D. Monteith, M. Posch, L. Rapp, B. Reynolds, S. Sandøy, J. Ullyett, A. Wade, A. Wilander, D. Wright*

Several questions were proposed as the basis for the theme of the workshop, and these were expanded by a preliminary discussion to decide the major issues for consideration, which are listed below.

Questions for discussion in the workshop

1. How representative are the water bodies selected for national mapping?
2. How representative is the water chemistry data used (seasonal and longer term patterns)?
3. How appropriate is the use of weathering rate for the critical load?
4. Is the SSWC method a suitable basis for the static critical loads models (i.e. to give weathering)?
5. Is ANC the best chemical criterion and if so, what ANC_{limit} should be used?
6. How can exceedance be related to current chemical and biological status?
7. How good are the estimates for N processes, in particular, in-lake retention?
8. What is the role of dynamic modelling?
9. How can the uncertainties in critical load and especially exceedance be expressed?

These questions were used to structure the workshop discussions over the 3 days. Brief outlines of the presentations are given (with the presenting author only) and the major discussion issues are summarised. Details may be found in the book of abstracts and the special volume of Water, Air and Soil Pollution from the Conference. The main conclusions after each discussion are listed for each day and overall conclusions presented after all three workshop reports.

Basis of static critical load models, temporal uncertainty and the interpretation of exceedance

Presentations

Anders Wilander(Sweden): How are results from critical load calculations reflected in lake water chemistry?
For the Swedish national freshwaters dataset, exceedance was compared with ANC/pH and showed a very good correlation with current chemical state, i.e. most exceeded sites had also violated their critical chemical criteria. A few sites are found with low pH (<6) or ANC (<0.05 $meql^{-1}$) and no exceedance, while a few more sites are exceeded but have high pH/ANC. Using minimum rather than mean values, there are more low pH values which are not exceeded, but fewer negative ANC values which

are not exceeded. This may be explained by naturally low pH values in humic lakes where the ANC is elevated by the presence of organics.

Arne Henriksen (Norway): SSWC - "state of the art" and links with current conditions
In Norway a similarly good correlation was found between exceedance and current violation of the variable ANC limit. The latest formulation of the SSWC model was presented, and illustrated the correct method for incorporation of base cation deposition and uptake. The critical load for freshwaters was re-expressed in terms of the weathering rate. Data were also presented to show the very good correlation between critical loads calculated from yearly weighted mean chemistry and those calculated from a single autumn water sample from the same sites.

Chris Curtis (UK): The link between exceedance of acidity critical loads for freshwaters and biological damage: a re-interpretation
The conceptual basis of the SSWC model was presented, and the relationship between exceedance of critical load and current chemical status was discussed. It was agreed that critical load exceedance in the SSWC model is essentially a prediction of steady-state ANC when the exceedance flux is converted into a concentration in the water. Maps for Great Britain were presented which showed the large number of sites exceeding their critical load but with a positive ANC, making up 47% of all exceeded sites. The disparity between exceedance and current chemistry was shown to be a function of the "F-factor", which explained the greater disparity for British sites (compared with Swedish and Norwegian sites) where high values of F are common. The implication is that there is a greater proportion of sites in Britain, which are not at or near steady state, and therefore not yet showing violation of the critical chemical criterion (which for the UK is zero ANC).

Don Monteith (UK): Large-scale decadal variability in freshwater critical loads calculations derived from long-term monitoring data for the UK
Data from the UK national freshwaters monitoring programme (the UK Acid Waters Monitoring Network) were presented to illustrate the issues of seasalt effects on critical load calculations and the association of seasalt and climatic influences with the North Atlantic Oscillation, particularly in western parts of the country. The implication is that periodic climatic factors can affect the calculated critical load depending on the sampling year within the period of oscillation, and these effects are independent of long term changes in climate. The problem of seasalt correction factors in the UK was illustrated with a map of the extensive areas in which one or more of the major ions becomes negative when corrected with the standard correction factors. It was pointed out that this problem also occurs in regions of Sweden and other countries.

Lars Rapp (Sweden): Uncertainties in SSWC model applications
Data for a Swedish lake were presented which showed the close correlation between critical load and measured ANC over a 10 year period, i.e. as for the UK sites, critical load varied from year to year. This was agreed to be a modelling problem, and highlighted an area of uncertainty in the SSWC model.

Conclusions

- The static critical load models should be based on the weathering rate.
- The SSWC model appears to give realistic estimates of weathering rate.
- There is a good correlation between exceedance and damage in Sweden and Norway, but not for all areas of the UK.
- The time of sampling to obtain water chemistry for critical loads calculation is very important, and while annual mean data are recommended where possible, a single autumn sample provides a good estimate for lakes in Norway.

- The SSWC model critical load is not necessarily stable from year to year, and may be affected by e.g. climatic influences. The associated temporal uncertainty needs to be quantified.
- Exceedance is a measure of predicted ANC but not necessarily of current ANC.
- Seasalt inputs are not adequately dealt with in static models.

Critical chemical criteria, static model uncertainties and dynamic modelling

Presentations

Lars Rapp (Sweden): Is PROFILE a potential alternative to SSWC?
The PROFILE model was proposed as a possible alternative to the SSWC model for the calculation of weathering rate. The model was applied to a cluster of lake sites in Sweden and optimized for soil depth to account for hydrological routing. The PROFILE model calculated a weathering rate of 180 eq ha^{-1} yr^{-1} which compared well with the SSWC model figure of 210 eq ha^{-1} yr^{-1}. It might therefore provide a potential alternative to the SSWC model, although its data requirements are much greater and so it is unlikely to be applied nationally. For another group of Swedish sites there was a very poor correlation between palaeolimnologically derived pre-industrial ANC and the value derived using the SSWC model. Again, the uncertainties associated with the various methods need to be quantified.

Rob Collins (UK): Incorporation of seasonal nitrogen dynamics within a long-term acidification model
The importance of seasonal variations in chemistry, in particular nitrate and ANC was discussed. The results of a MAGIC model run for a monthly timestep were presented. The model provided a good reproduction of seasonal ANC variation, though not for extreme events. The model has a potential role in predicting changes in minimum as well as mean chemistry.

Kevin Bishop (Sweden): Seasonal and episodic effects on critical load exceedance in Sweden
Spring is a very important period in Sweden, since 50% of runoff occurs and it is biologically very significant. The spring pH decline may be 1-2 pH units. A project looking at anthropogenically induced ANC decline in spring found a very good correlation with the sulphur content of pre-melt snow cover. Since episodic extreme events can result in severe biological damage, the change in minimum (extreme) ANC and pH can be more important than the change in mean values. It is also important to consider the toxicity of episodic inorganic aluminium peaks in organic rich streams where low pH values may coincide with relatively high ANC. The problem of non steady-state conditions during episodes was discussed, and it was concluded that all models are unreliable for predicting chemical or biological effects during storm events, in particular those related to inorganic aluminium.

Andrew Wade (UK): A dynamic end-member mixing model for predicting alkalinity
A new model, which predicts streamwater alkalinity from flow data, was presented. The model is based on end-member mixing, and requires data on soilwater and groundwater alkalinity under high and base flow conditions. If the flow data are available, it can predict daily changes in alkalinity. There may be scope for application of the model in conjunction with other dynamic models like MAGIC to determine episodic responses in water chemistry.

General discussion - episodicity

In the detailed discussion of episodicity which followed, the merits of using mean ANC as the critical chemical criterion were considered in relation to the more biologically significant minimum ANC. However, for national scale modelling, it is considered unlikely that sufficient data could be collected to determine minimum values for critical chemical criteria. It was concluded that for lakes, dose-response relationships were based on annual mean chemistry, which implicitly accounted for the effects of episodicity, but for streams the relationships are less well quantified, largely because of the much greater temporal variability. In a study of streams in Virginia, no fish were found where mean ANC was less than zero, whereas the widely used trout-ANC response function of Lien and co-workers for Norwegian lakes suggested only a 50% probability of damage to trout populations with zero ANC. It was suggested that the lack of refugia and greater episodicity in streams indicated a requirement for a greater ANC_{limit} than for lakes, and also that dose-response functions are not necessarily transferable between regions. In addition, biological status was found to be poorly related to single water samples both for invertebrate communities in Sweden and for fish in the USA. However, biological status was much more strongly linked to longer-term mean chemistry. It was agreed that there is a definite need for uncertainty analysis related to episodicity, which can feed back into model improvements.

General discussion – future prospects

For the static model incorporating N processes (FAB), the potential effects of future N saturation and increased N leaching are key factors in the calculation of critical load. However, it is the terrestrial (soil and vegetation) scientists who must provide the data for terrestrial processes (uptake/removal, immobilization, denitrification). Freshwater scientists need to improve the understanding of in-lake retention processes which will become increasingly important if N leaching to surface waters does increase as currently predicted.

The vital role of dynamic modelling in the assessment of recovery processes was agreed, particularly in relation to the effects of the timing of deposition reductions and the acceleration of chemical recovery by reducing deposition below the critical load. Again, the need for data from terrestrial scientists on N dynamics was highlighted, since these are required to improve the parameterisation of N processes in dynamic models like MAGIC. The problem of modelling hysteresis in recovery needs to be addressed. In future reviews of the success of international protocols and potentially in the consideration of further measures, both monitoring data and dynamic modelling will be essential.

The sensitivity of freshwaters, their widespread distribution in many European countries and the relative simplicity of their dose-response relationships make them particularly suitable for critical loads modelling and mapping. The wider use of freshwater critical load models is strongly encouraged.

Conclusions

- The use of alternative models (e.g. PROFILE) for freshwater critical loads should be encouraged for comparison with current static models, but the uncertainty in each model should be taken into account.
- Seasonality and episodicity are of major biological significance but are difficult to measure and model on a national scale, in particular because of the lack of steady-state conditions during extreme events.

- Dynamic models can improve understanding of the effects of temporal variability and episodicity, and may provide a means of accounting for their effects in critical or target loads.
- Because of extreme episodic events in streams and the possible lack of refugia, higher critical chemical values may be required than for lakes in the same region.
- Dose-response relationships derived for one region are not necessarily transferable to another.
- The future increases in nitrate leaching predicted by simple mass balance models will have severe impacts on freshwaters if they are realised - better estimates of steady-state rates for N processes are therefore required.
- More data on N dynamics are required for the parameterisation of dynamic models.
- Monitoring data are essential for model development and detection of change (especially recovery).
- Dynamic modelling is essential for the assessment of recovery times under different scenarios, and for quantifying the benefits (in terms of faster recovery) of either reductions beyond the critical load, or over different timescales.
- The wider use of freshwater critical loads models throughout Europe should be strongly encouraged.

Predictions using empirical and dynamic models

Presentations

Jackie Ullyett (UK): Investigating the use of larger scale maps for mapping the potential sensitivity of surface waters to acidification
GIS techniques were used to explore the relationship between UK freshwater sensitivity classes (5 classes from non- to very sensitive, used for mapping and site selection) based on a combination of soils, geology and land-use data, with the critical loads of water bodies having catchments containing the various mapped sensitivity classes. It was found that the correlation between sensitivity class and critical load class (from the widely used mapping classes 0-0.2, 0.2-0.5, 0.5-1.0, 1.0-2.0 and > 2.0 keq ha^{-1} yr^{-1}) was not improved by using greater resolution soils and geology data to generate the freshwater sensitivity maps. A major problem with the approach is the large overlap between sensitivity and critical load classes.

Martin Kernan (UK): Predicting freshwater critical loads from catchment characteristics
The presentation examined the potential for prediction of critical loads using nationally available datasets for the UK representing a range of catchment characteristics. Initially, the development of a global regression model for predicting freshwater critical load across a broad spectrum of catchment types (from lowland agricultural to mountain lake) was assessed. The global model was found to have less predictive power when applied to more specific catchment types (e.g. upland, non-arable), and cannot necessarily be applied for predictions within a narrow regional context. Separate analyses on regional subsets (based on 100km grid squares) using backward selection regression showed that the variables emerging as significant predictors varied substantially across the regions, as did the predictive power of the models.

Chris Evans (UK): Development of a method for mapping critical loads across a river network
The PEARLS (PrEdiction of Acidification and Recovery on a Landscape Scale) model was presented, with an example of an application to the catchment of the River Dart, Southwest England. The model uses GIS to incorporate datasets including a Digital Terrain Model (DTM), spatial landcover data, runoff and stream chemistry, which are

then used to predict characteristic water chemistry from defined landscape types. These data are in turn used to predict critical load for hydrological response units (HRU's) and enable the mapping of, for example, stream reaches exceeding the critical load. Mixing is taken into account so that exceeded reaches can extend beyond the most sensitive landscape types downstream into less sensitive areas. The model can be applied in a regional mode to generate percentile critical loads for whole stream / river networks.

Andrew Wade (UK): Predicting N fluxes with the INCA model
A dynamic model for the prediction of N leaching (INCA) was presented. The model operates on a daily timestep and uses a DTM, land use data, deposition data etc. and terrestrial and instream N process dynamics to predict N fluxes for a given point in a river network. Point source inputs can be accounted for, and scenarios for changes in e.g. hydrology, temperature, deposition and vegetation cover can all be modelled. The model has a potential role in a critical loads context in the prediction of N fluxes down a river network, but is very data intensive and therefore unlikely to be applicable on a national scale.

Richard F. Wright (Norway): Use of the MAGIC model to predict time required to achieve steady-state following emissions reductions
The dynamic model MAGIC was applied to two rivers in Norway with long data series, both now limed. The model was used to test the effects of a multi-effect protocol, which includes a 50% reduction in N deposition. Nitrate leaching was ramped up to the value predicted by the simple mass balance model FAB over 50 years. Despite a 10-20 year time lag in the recovery of river sulphate concentrations relative to deposition reductions, recovery to the ANC_{limit} was predicted over the 50 year period. The link between the required timescale of recovery and the need for a "safety margin" (reduction of deposition below the critical load) was demonstrated. Recovery was found to be very slow if deposition is reduced only as far as the critical load.

Filip Moldan (Sweden): Modelling recovery at Lake Gårdsjön with MAGIC
The relationship between soil recovery (in terms of base saturation and exchangeable calcium) and surface water recovery (as ANC) was explored for the Gårdsjön catchment, through application of the MAGIC model. It was shown that exchangeable calcium can decline even as surface water ANC recovers under "clean rain", because of the "pumping" away of calcium from the catchment via a combination of tree growth uptake, throughfall leaching and runoff. Reduced ionic strength under 'clean rain' slowed the recovery process through reduced ion exchange in the soil.

Conclusions

- Empirical models can be developed to predict water chemistry and critical loads from catchment characteristics and national datasets (e.g. soils, runoff, land cover) but relationships vary on a regional basis.
- Dynamic models can predict water chemistry and hence critical loads (and exceedance) for stream networks, and allow the calculation of percentile critical loads for stream lengths - however their heavy data requirements may preclude their use for national modelling applications.
- Modelling the spatial representativeness of critical loads will become more important as the number of exceeded sites declines under deposition reductions.
- Dynamic models can be used to determine the necessary "safety margin" for deposition reductions, either in terms of the problem of prevention of recovery because of episodic effects, or for recovery within given timescales.

Conclusions and recommendations

After the final workshop presentations, an open discussion of the requirements for future work followed. The overall conclusions and recommendations from the workshop are listed below, first those of more general relevance, and then those specific to freshwater critical loads.

Conclusions - General

1. There is considerable, but still unquantified, uncertainty associated with all aspects of critical loads modelling, including sampling period for data used in critical load calculations (temporal representativeness), population or area of sites affected (spatial representativeness), deposition estimates, critical load model assumptions, effects of seasalts, probability of exceedance, probability of damage associated with a given level of exceedance, and understanding of biological change and recovery processes. Quantification of this uncertainty will become more important as deposition declines towards the critical load and exceedances become very small.

2. There may be a time lag between exceedance and damage, and also between reduction of deposition to, or below, the critical load and recovery.

3. Dynamic modelling is essential for the assessment of recovery times and the relative benefits of emissions reductions at different times and to different levels.

4. There is a need for communication of the meaning of critical loads and exceedances to users, to avoid misinterpretation and misuse of models.

5. Continued monitoring is essential for the assessment of effects of emissions reductions and to feed back into model development and improvement.

Conclusions - Freshwaters

1. The weathering rate provides the most suitable basis for current static freshwater critical loads models (SSWC, FAB and Diatom models), which continue to have a role in the national assessment of critical loads and exceedance.

2. The dose-response relationships used to select the critical chemical value are not necessarily transferable between regions (i.e. countries) or types of water body (lakes, streams and rivers).

3. Episodicity is a very significant factor in determining biological response, particularly in streams, but is difficult to predict or model and therefore to use in setting critical chemical values.

4. Exceedance of SSWC or FAB model critical load is an indication of the steady-state value of ANC and may therefore not reflect current chemical conditions, current damage or biological status where the system is not near steady state.

5. Acidification of surface waters will still be an extensive problem after implementation of the Gothenburg Protocol.

Recommendations - General

1. Continue work on the quantification of spatial (site) representativeness by developing techniques (especially GIS) to provide inventories of the population of ecosystems and to model the distribution of critical loads and exceedances amongst the whole population.

2. Develop definitions of exceedance to include interpretations of the probability / risk of damage, the degree of damage, and the potential time lags between exceedance and damage or non-exceedance and recovery.

3. Continue national (and other) monitoring programmes to provide a continuous measure of the state of ecosystems in terms of damage or recovery, to validate models and improve parameterisation, and to assess the success / effectiveness of implemented reductions in emissions.

4. Continue the development and application of dynamic models to predict *chemical* damage or recovery and to determine potential timescales of damage or recovery associated with scenarios which include the reduction of deposition below the critical load and the reduction of deposition over different time periods.

5. Continue work to improve understanding of biological recovery processes, including the identification of potential recovery targets, determination of the effects of hysteresis and episodicity on recovery processes, and the identification of confounding factors (e.g. natural random variation, climatic influences) in the measurement of recovery.

Recommendations - Freshwaters

1. Carry out uncertainty analysis of models, which should include work to improve links between the biological effects of episodicity and the critical chemical value, to quantify the *temporal uncertainty* associated with the use of limited water chemistry data to determine critical load, and to incorporate the probabilistic nature of links between the critical chemical value and biological response (the dose-response function).

2. Continue the development and improvement of static models in current use, and encourage the testing of alternative models (e.g. PROFILE) to determine weathering rate and hence freshwater critical loads.

3. Strongly encourage the wider application of freshwater models, because dose-response relationships and critical load models for freshwaters are relatively well understood and simple to apply, while sensitive freshwater ecosystems are widely distributed in many more countries than actually submit data via National Focal Centres.

4. Consider the potential impacts of non-acidification effects of S and especially N deposition (e.g. eutrophication, direct ammonium toxicity in freshwaters), and develop methods to quantify the effects of “multiple drivers” (e.g. acidification, climate, heavy metals).

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