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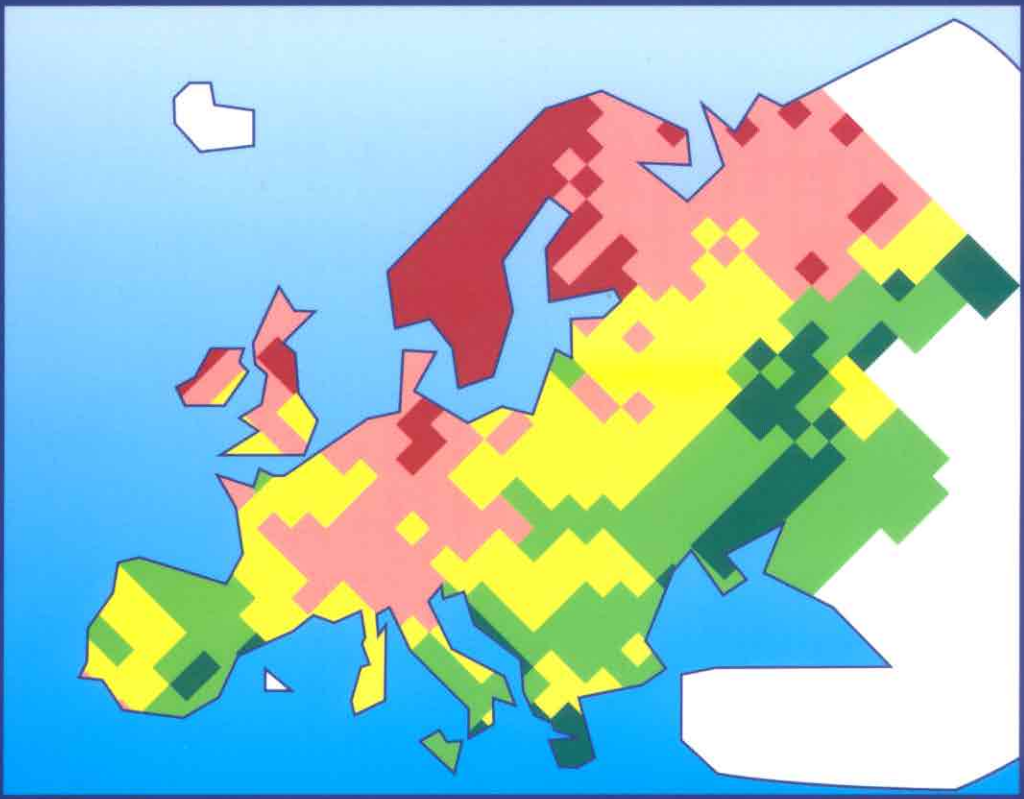

Status Report 1993

Coordination Center for Effects

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RIJKSINSTITUUT VOOR VOLKSGEZONDHEID EN MILIEUHYGIENE
NATIONAL INSTITUTE OF PUBLIC HEALTH AND ENVIRONMENTAL PROTECTION

Calculation and Mapping of Critical Loads in Europe:

Status Report 1993

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1. Introduction

R.J. Downing, J.-P. Hettelingh, and P.A.M. de Smet

1.1 Overview

This report summarizes the work of the RIVM Coordination Center for Effects (CCE) and National Focal Centers (NFCs) for Mapping over the past two years. The report includes European maps of critical loads of acidity and sulphur, produced for the United Nations Economic Commission for Europe's (UN ECE) Convention on Long-range Transboundary Air Pollution (LRTAP). The primary task of the critical loads mapping program during this period was to compute and map critical loads of sulphur in Europe.

Since the first European maps of critical loads were published in 1991 (Hettelingh *et al.*), a number of revisions and improvements have been made with respect to data and methodologies. Efforts were also undertaken to enhance the scientific foundations and policy relevance of the critical load program, and to foster consensus among producers and users of this information.

Three mapping workshops organized by the CCE during 1992-1993 (Bilthoven, January 1992; Katowice, September, 1992; and Madrid, March, 1993), as well as a workshop on critical loads of nitrogen (Lökeberg, April 1992) provided forums to review work conducted to date, and to discuss methods and other issues concerning future work.

The report describes the calculation methods used, and resulting critical loads maps, based upon the outcomes of these workshops. It provides the reader with a comprehensive overview of the current status of the work related to critical loads in Europe.

1.2 The critical loads concept

A critical load has been defined as "the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function" (Nilsson, 1986). Thus, a critical load is an indicator for sustainability of an ecosystem in that it provides a value for maximum allowable load of a pollutant at which risk of damage to an ecosystem is reduced. By measuring or estimating certain physical and chemical properties of an ecosystem, its sensitivity to acidic deposition can be calculated, and a "critical load of acidity", or the level of acidic deposition which affects the sustainability of an ecosystem, can be identified.

This information on ecosystem sensitivity can be compared with pollutant deposition data, to determine which areas currently receive deposition levels which exceed the area's critical load. These areas of "exceedance" indicate where present levels of pollutant deposition increase the risk of damage to ecosystems. Since 1991 critical load maps of sulphur have been given priority. Maps showing critical loads and exceedances of sulphur in Europe show which areas need to receive less sulphur deposition in order to protect ecosystems.

The critical load concept consists of using information on critical loads and exceedances by groups under LRTAP Convention to help develop strategies for reducing emissions of sulphur. The critical load concept is illustrated in Figure 1.1.

The critical load concept is a methodology in which critical load calculations are used as a criterion to assess the effect of emission reduction strategies on sensitive ecosystems, taking national emission reduction costs into account. As can be seen from Figure 1.1 (dotted line), the procedure is iterative.

First, an objective by which exceedances should be reduced (the so-called "gap closure") is formulated. This gap closure has been defined as a percentage of current exceedances, i.e. the excess of deposition over critical loads. The required emission reduction at minimum European costs are then computed. Finally, the remaining exceedances in different regions in Europe are expressed in terms of the extent to which the national area of ecosystems is protected. This procedure is repeated by changing the objective.

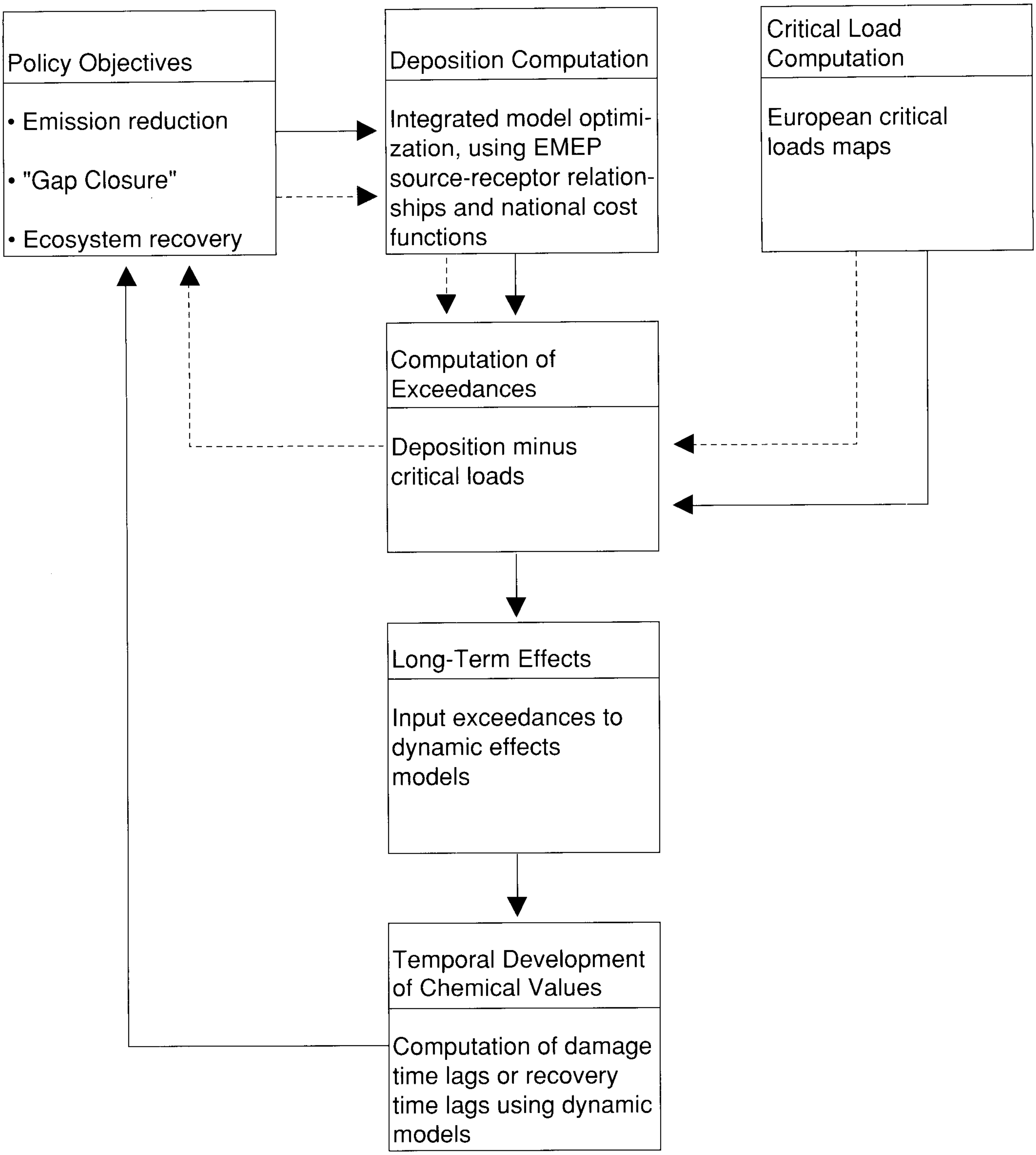

Figure 1.1. *The critical load concept consisting of: (1) iterating required emission reductions to meet critical loads and costs (short circle; dotted line), and (2) computing time horizons before ecosystem damage (continued critical load exceedance) or recovery (whenever exceedance ceases to exist). The computation of time horizons is represented by the solid line (long circle).*

This procedure led to the identification by groups under UN ECE LRTAP (i.e. Task Force on Integrated Assessment Modelling and the Working Group on Strategies) of the 60% gap-closure being an appropriate starting point of emission reduction negotiations. The intent of the 60% gap-closure strategy is to reduce the 1990 exceedances by 60% (meaning that parts of Europe will continue to have depositions which exceed critical loads. By definition, exceedances of critical loads may lead to "harmful effects", and the temporal aspect of these exceedances (i.e. estimating *when* these harmful effects will occur, or the "damage time lag"), becomes important.

These damage time lags can be investigated by using dynamic soil models, which simulate the temporal development of soil chemistry due to (excess) acid deposition. Conversely, it is also possible to assess recovery time of an ecosystem (the "recovery time lag") once emissions have sufficiently been reduced. This procedure is also part of the critical load concept (the solid line in Figure 1.1).

The dynamic part of the critical load concept has been initiated (see Hettelingh and Posch, 1993) but has not yet been part of the integrated assessment of emission reduction strategies within the UN ECE. It is expected, however, that the dynamic part of the critical load concept will become increasingly important as indications of target years for establishing required emission reduction vary over Europe. The computation and mapping of critical loads and their application as part of the critical load concept has proven to be successful in evaluating emission reduction alternatives in Europe.

1.3 Critical loads mapping activities

The RIVM's Coordination Center for Effects (CCE) was established by the Netherlands Ministry of Housing, Physical Planning and Environment, and began its work in 1990. One of CCE's primary tasks is to assist in the development and production of methods and maps of critical loads on a European scale, in cooperation with the Task Force on Mapping.

National maps of critical loads of acidity and sulphur have been produced by 15 European countries through National Focal Centers for Mapping appointed by each country. Where countries have not been able to calculate critical loads, the CCE has used European background data bases to calculate critical loads for these regions.

As outlined in its mandate, the CCE's main tasks in support of the critical loads mapping exercise are to:

- Provide guidance and documentation on the methods and data used in developing maps of critical loads of acidity, sulphur, and nitrogen, and critical levels for relevant pollutants;

- Collect and assess national and European data used in producing maps of critical loads of acidity, sulphur, and nitrogen, and critical levels for relevant pollutants. The Center will circulate draft maps for review and comments by National Focal Centers and it will update maps as appropriate;

- Produce reports and maps on critical loads and critical levels, documenting the mapping exercise, with the assistance of National Focal Centers and in cooperation with the Task Force on Mapping;

- Provide, upon request, the UN ECE Working Group on Effects, the Working Group on Strategies, and the Task Force on Integrated Assessment Modelling, with scientific advice regarding the use and interpretation of maps of critical loads and levels, and target loads and levels;

- Maintain and update relevant data bases and serve as a clearinghouse for data collection and exchange regarding critical loads and levels among parties to the Convention, in consultation with the International Cooperative Programs and EMEP;

- Conduct periodic training sessions and workshops to review activities and develop and refine methods used in the critical load and critical level mapping exercise.

Formal evaluation of the proposed methods and preliminary critical loads maps was obtained in meetings of the UN ECE Task Force on Mapping and the Working Group on Effects. Results of the work were submitted to the Task Force on Integrated Assessment Modelling to be used in scenario analysis of emission reductions on behalf of the Working Group on Strategies.

1.4 Structure of this report

Chapter 2 of this report contains the most recent maps (May 1993) of the critical load of acidity as well as the critical load of sulphur and critical sulphur deposition, which are derived from the critical load of acidity. The chapter also contains maps of the sulphur deposition in Europe in 1980 and 1990, and the resulting exceedances (i.e. the excess of present deposition levels above the critical load).

Chapter 3 describes the methods and equations used to derive the maps of critical loads and exceedances of acidity and sulphur with emphasis on the advances in the calculation methods used since the first European critical loads maps were produced in 1991 (Hettelingh *et al.*).

Chapter 4 presents the methods to be used to compute and map critical loads in the future. Rather than computing critical loads separately for sulphur and for nitrogen, the proposed method examines those combinations of sulphur and nitrogen deposition which do not lead to exceedances of the critical load of acidity and nutrient nitrogen. This method avoids the usage of a sulphur fraction, which was originally introduced to accommodate policy requirements for specifying the share of sulphur in the computation of the critical load of acidity.

Chapter 5 gives an overview of the data inputs provided by National Focal Centers, and the methods of data handling performed by the CCE to produce the current European maps of critical loads.

Chapter 6 describes the results of an uncertainty analysis which was performed on the critical loads computation methodology to assess the reliability of the computation results and the importance of the various input variables.

Chapter 7 provides some conclusions and recommendations resulting from the critical load mapping activities.

A list of the mathematical notation and acronyms used in this report follows the references section.

Appendix I contains the reports of the National Focal Centers for Mapping, detailing national mapping activities. A number of input variables from a variety of sources have been used to calculate critical loads and exceedances. Maps of several of these are contained in Appendix II.

Appendices III through V contain additional information to be used in calculating critical loads according to the mapping guidelines in Chapter 4.

Appendix VI contains the workshop reports from three CCE Mapping Workshops held in Bilthoven, Netherlands (January 1992); Katowice, Poland (September 1992); and Madrid, Spain (March 1993).

Appendix VII provides information on the contents and sources of the European background data bases used to calculate critical loads when no national data were submitted.

2. Maps of Critical Loads, Critical Sulphur Deposition, and Exceedances

J.-P. Hettelingh, R.J. Downing, and P.A.M. de Smet

This chapter contains European maps of critical loads of acidity and sulphur, critical sulphur deposition, and their exceedances. Details on the assumptions, calculation methods, and data used are contained in Chapters 3 through 5. Appendix I contains reports from national Focal Centers for Mapping and various national maps.

The current maps of critical loads of acidity and sulphur have been updated wherever possible to ensure consistency with the map of critical sulphur deposition used by the UN ECE LRTAP Convention. However, the European map of critical loads of sulphur and acidity have not consistently been subject to inputs from National Focal Centers (NFC's), due to the priority given to the computation and mapping of the critical sulphur deposition. Not all NFC's have submitted updated national computations of the critical load of acidity and sulphur, but instead submitted updated data directly as sulphur deposition computations.

The following points should be noted concerning the maps in this chapter.

Ecosystems mapped: Countries submitting national data calculated critical loads for either forest soils, surface waters, or a combination of the two. For countries not submitting national data, critical loads for forest soils were computed, using European data bases which are further described in Appendix VII.

Grid size: The Co-operative Program for the Monitoring and Evaluation of the Long-Range Transmission Air Pollutants in Europe (EMEP), which operates under the aegis of the UN ECE LRTAP Convention, oversees a monitoring network over an European grid with a cell resolution of 150 x 150 km^2. Modeling work conducted by EMEP to compute emissions and depositions of air pollutants in each grid cell, and by other institutions assessing proposed emission reduction schemes, is used in negotiations on emission reduction by parties of the Convention. To be consistent with this European EMEP grid, the critical loads have been mapped on the same resolution. This allows direct comparison between maps of critical loads and maps of loads of pollutant deposition.

Percentiles: The maps show the 5-percentile critical load, i.e. the deposition level needed to protect most sensitive 95 percent of ecosystem area in each grid cell. Sections 4.4 and 5.3 give further details on the statistical treatment of critical loads data.

Units: All critical load maps have been calculated in acid equivalents per hectare per year (eq ha^{-1} yr^{-1}). Maps of critical loads of sulphur, critical sulphur deposition, and their exceedances in Chapter 2, are also expressed in terms of milligrams of sulphur per square meter per year (mg S m^{-2} yr^{-1}).

Chapter 3 describes in further detail the reasons for the differences between these maps and those published in the CCE 1991 Technical Report (Hettelingh *et al.*)

2.1 Critical load of acidity

Figure 2.1 shows the critical load of acidity (5 percentile). The basic equation used to calculate this map is:

$$CL(A) = BC_w - Alk_{l(crit)}$$

where:
$CL(A)$ = critical load of (actual) acidity
BC_w = base cation weathering
$Alk_{l(crit)}$ = critical alkalinity leaching

The map shows that the areas which are most sensitive to acidic deposition are mainly in northern Europe. Large portions of Scandinavia and the north of Great Britain and Germany have critical loads of less than 200 acid equivalent per hectare per year. Approximately 14 percent of the land area surveyed falls into this most sensitive category.

A large band of slightly less sensitive soils extends through Germany, Austria, and northern Italy, as well as parts of France, Spain, Romania. In general, southern Europe is less sensitive than northern areas. This trend can be clearly seen in the former Soviet Union.

In comparison to the map of critical loads of acidity contained in the 1991 CCE Technical Report (Hettelingh *et al.*), large parts of Finland, Poland, and the former Soviet Union have a higher critical loads than before, due largely to updated national data and calculations conducted by NFC's.

In addition, parts of France and the Iberian peninsula appear more sensitive (i.e. with a lower critical load). These differences are due to a number of methodological changes which are described in Chapter 3.

A list of National Focal Centers which contributed national data included in this map can be found in Chapter 5 (Table 5.1).

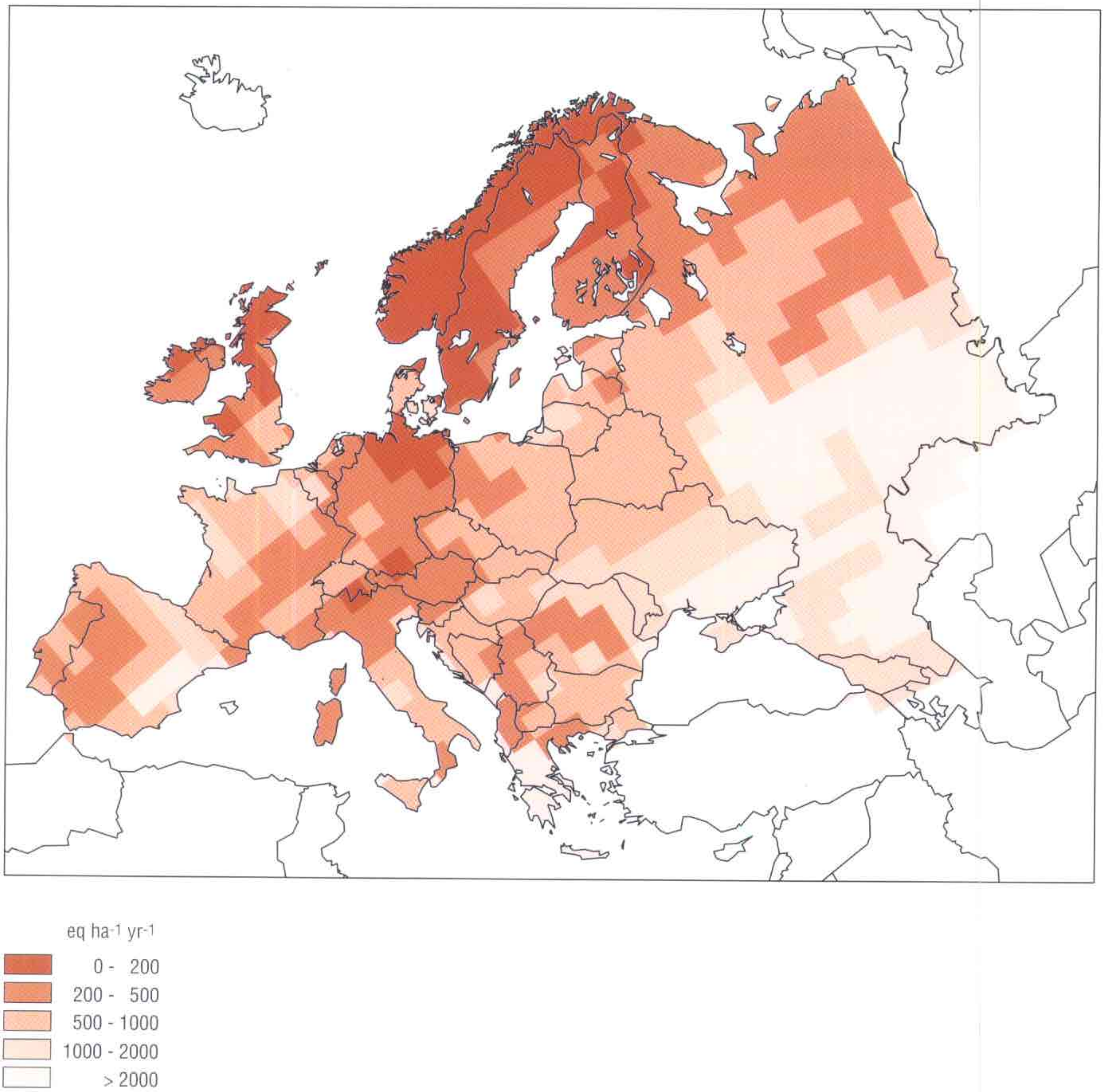

Figure 2.1. *Critical loads of acidity (5 percentile).*

2.2 Critical load of sulphur

Figure 2.2 was calculated using the critical load of acidity, and apportioning the acidic input to an ecosystem between sulphur and nitrogen, using the so-called *sulphur fraction*, described in Section 4.2.2:

$$CL(S) = S_f \cdot CL(A)$$

where:
$CL(S)$ = critical load of sulphur
S_f = sulphur fraction

The map shows that the ecosystems most sensitive to sulphur deposition include large parts of Scandinavia and Germany, northern England, and Alpine areas: parts of Switzerland, Austria and northern Italy. Roughly 18 percent of the European land area mapped falls into the most sensitive category, with a critical load of less than 200 acid equivalents per hectare per year (approximately 320 milligrams of sulphur per square meter per year).

Compared to the critical load of sulphur in the 1991 CCE Technical Report, increased ecosystem sensitivity (lower critical loads) are seen in an extended area in Portugal, Spain, France, Germany, Italy and the former Yugoslavia. These differences are due to a number of methodological changes which are described in Chapter 3.

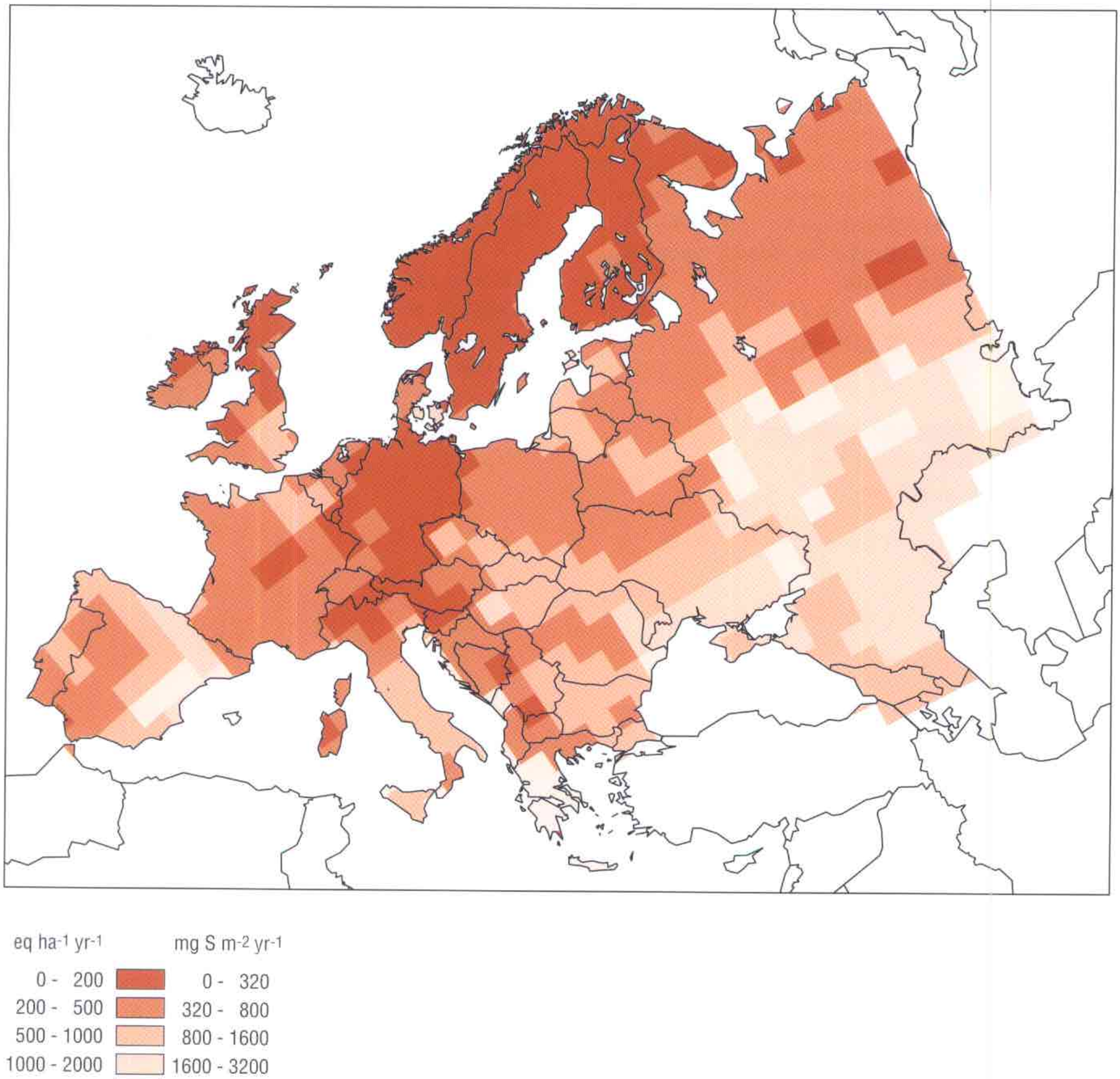

Figure 2.2. *Critical loads of sulphur (5 percentile).*

2.3 Critical sulphur deposition

Figure 2.3 shows the 5 percentile critical sulphur deposition for Europe. This map is calculated by including the effects of base cation uptake and base cation deposition to the critical load of sulphur. These variables were formerly included in the computation of the exceedance (Hettelingh *et al.*, 1991). The reason for including these variables with the critical load is (see also Chapter 3) that the map of critical sulphur depositions is compatible with the deposition maps produced and published by EMEP. Base cation deposition has an acid neutralizing effect, whereas uptake (by vegetation) reduces the amount of base cations available to neutralize acidic inputs. The sulphur fraction is used on these variables for reasons of consistency; as the critical load of acidity was assumed to be differentiated among sulphur and nitrogen so should variables which affect acidity. Thus:

$$CD(S) = CL(S) + S_f \cdot (BC_{dep} - BC_u)$$

where:
$CD(S)$ = critical sulphur deposition
BC_{dep} = base cation deposition
BC_u = base cation uptake

Some countries submitted national data for these modifying base cation factors. For other countries, European data bases were used. In most cases, the net effect of including these factors is an acid neutralizing influence; thus, the critical sulphur deposition values are generally higher than the critical load of sulphur for a given grid cell.

Similar to the map of critical loads of sulphur (Figure 2.2), the areas most sensitive to sulphur deposition include large parts of Scandinavia and northern Germany, and parts of Ireland and central England. The most sensitive category (with a critical load of less than 200 acid equivalents per hectare per year) comprises approximately 14 percent of the European land area.

This map was reviewed at the CCE workshop held in Madrid in March 1993, and has been used by the Task Force on Integrated Assessment Modelling and distributed in the Working Group on Strategies as endorsed by the Task Force on Mapping.

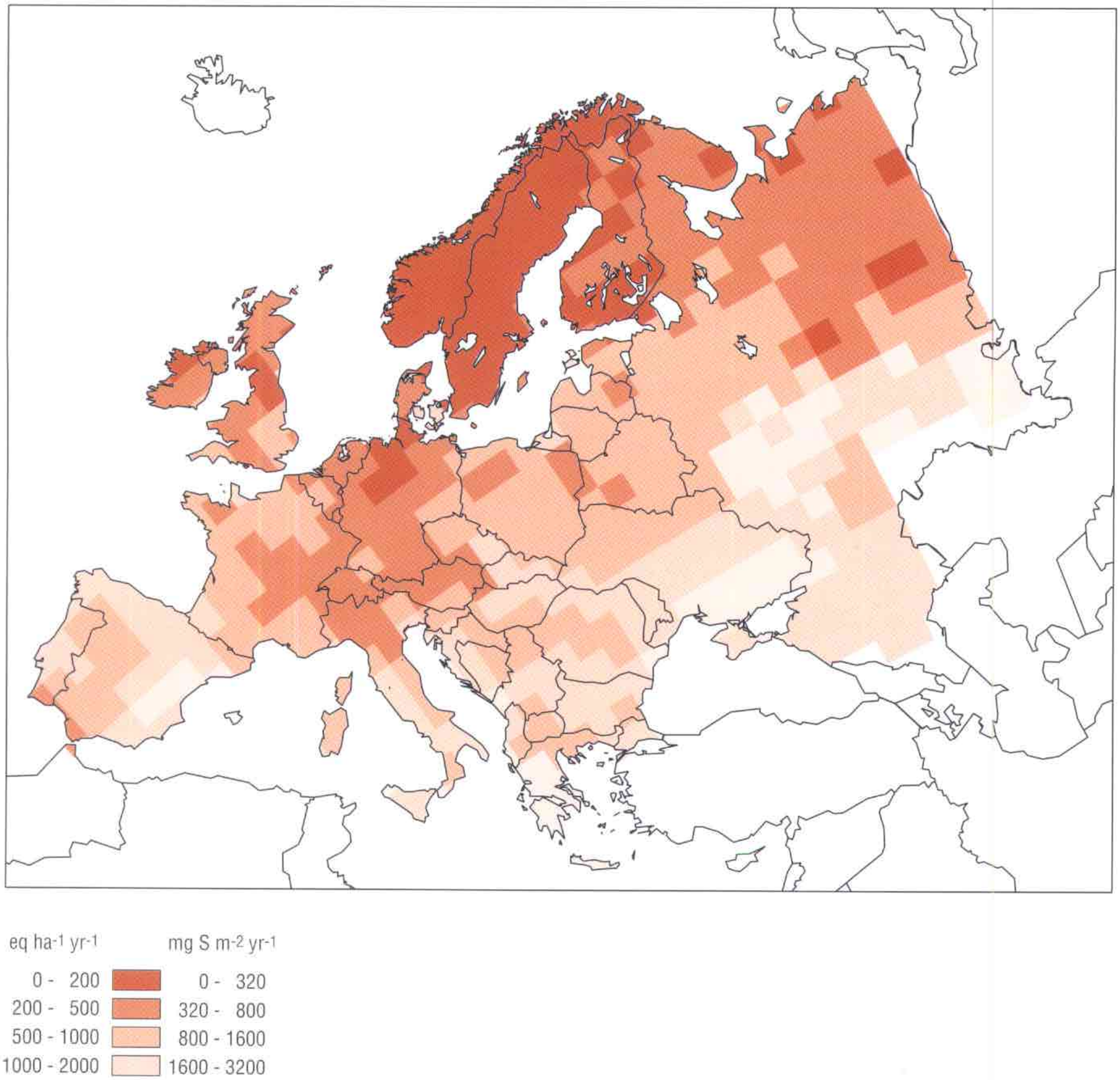

Figure 2.3. *Critical sulphur deposition (5 percentile).*

2.4 Present sulphur deposition (1990)

Sulphur deposition in 1990 (Figure 2.4) has been computed using national emissions of 1990. This deposition map serves as a basis to calculate exceedances of the critical load of sulphur, and to assess the results of emission reduction strategies (i.e. the "60 percent gap closure" scenario).

Transport and deposition is computed by the RAINS model, as used in TFIAM scenario analyses, using an average of the EMEP source-receptor relationships of 1985 and 1987–1990.

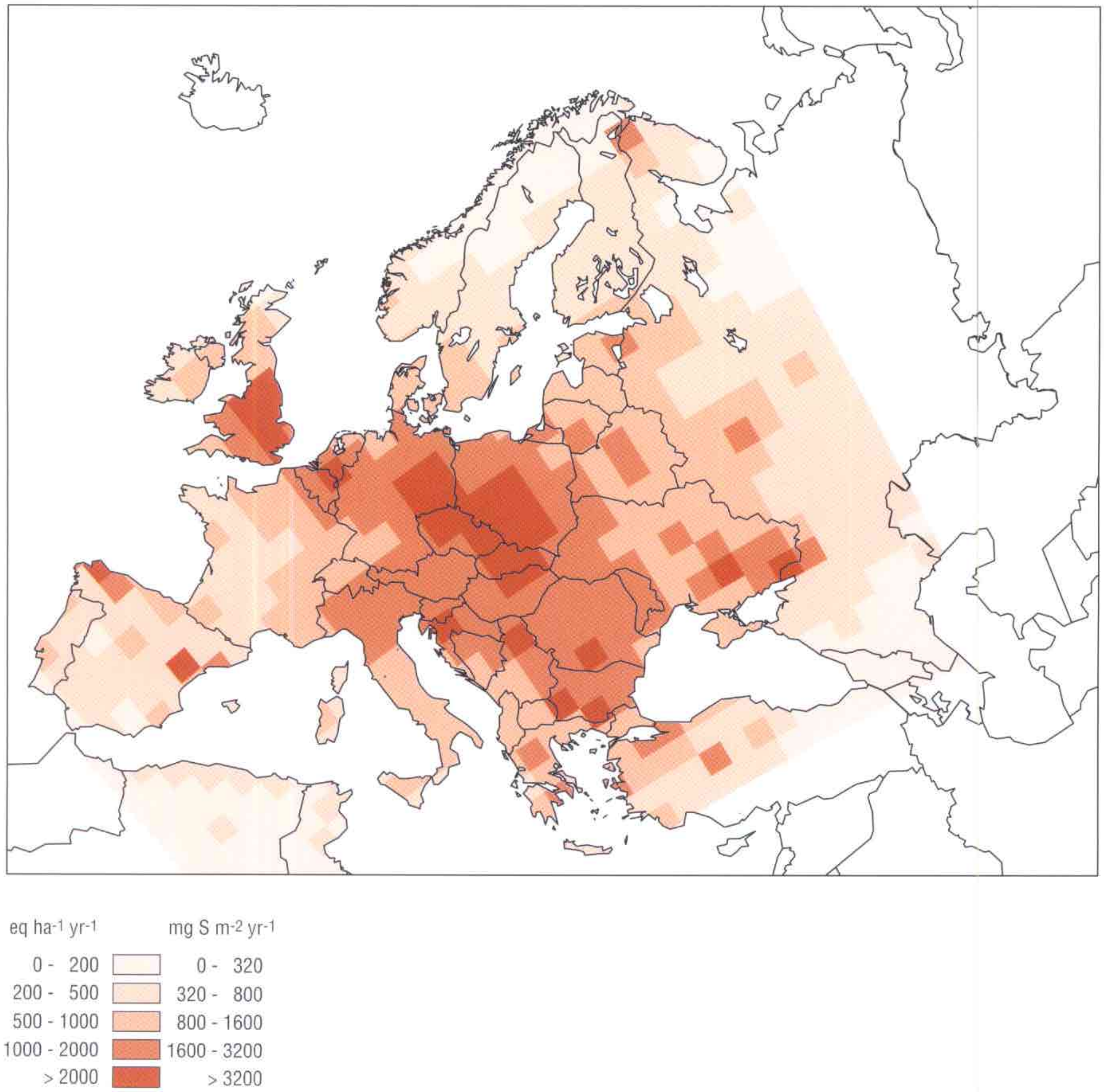

Figure 2.4. *Sulphur deposition in 1990.*

2.5 Exceedance of the critical sulphur deposition in 1990

Figure 2.5 compares the difference ("exceedance") between the present (1990) deposition of sulphur (from Figure 2.4) to the critical sulphur deposition (shown in Figure 2.3). Areas with a positive exceedance are currently receiving levels of sulphur deposition which could damage the most sensitive ecosystems in that area.

$$Ex(S) = PL(S) - CD(S)$$

where:
$Ex(S)$ = exceedance of the critical sulphur deposition
$PL(S)$ = present load of sulphur

Compared to the map of the exceedance of critical loads of sulphur in the 1991 CCE Technical Report, the area of highest exceedance is reduced. The pattern of exceedances over Europe is quite similar, with the highest exceedances occurring in the "Black Triangle" region of Central Europe.

Differences are especially due to the fact that filtering factors are no longer used, new national data, and a number of other methodological changes which are described in Chapter 3.

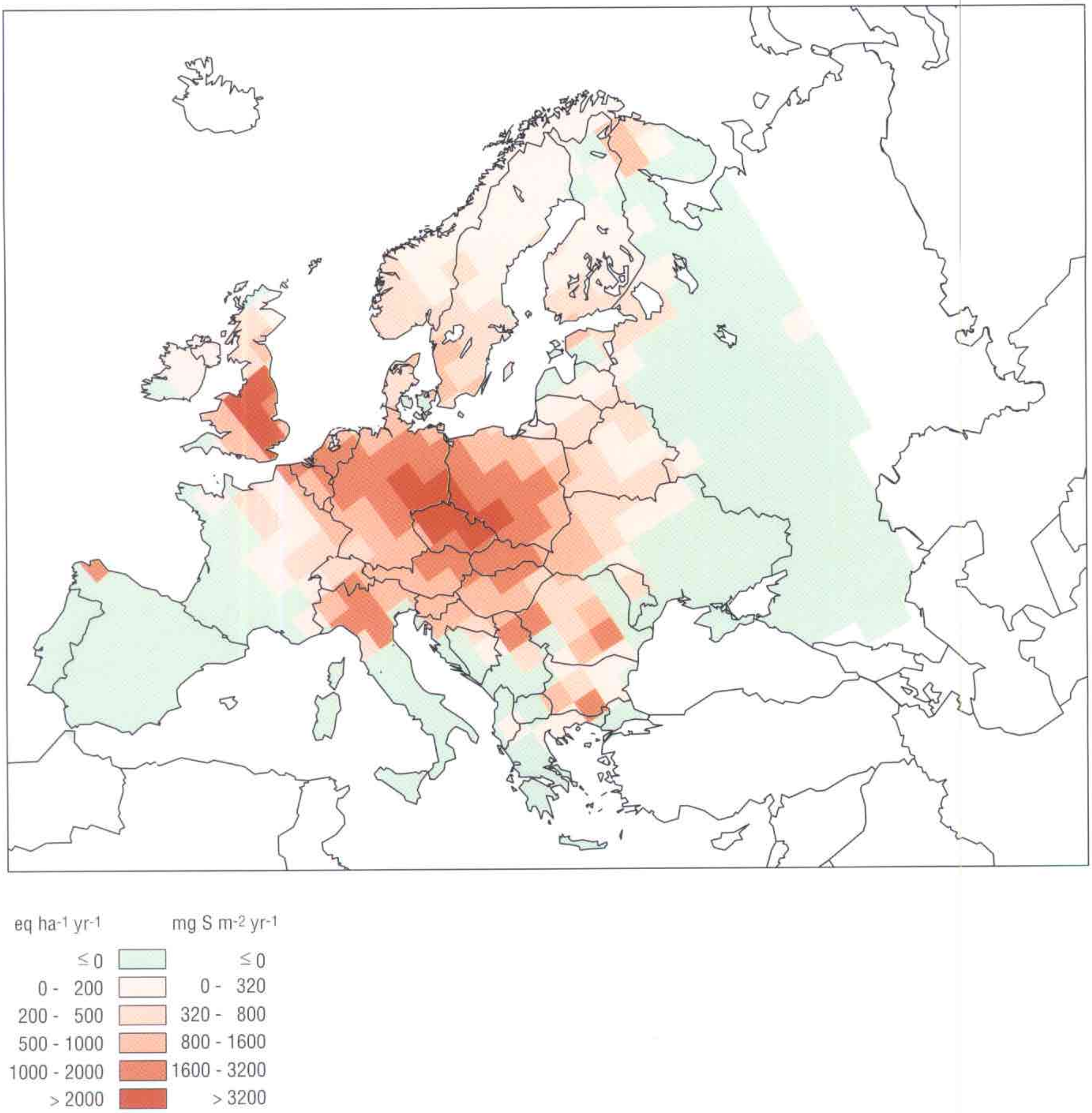

Figure 2.5. *Exceedance of critical sulphur deposition in 1990 (5 percentile).*

2.6 Sulphur deposition in 1980

Sulphur deposition in 1980 (Figure 2.6) is computed using national emissions estimates, as reported to the United Nations (Amann *et al.*, 1993). This deposition map serves as a basis to assess the results of proposed emission reduction strategies (e.g. the "60 percent gap closure" scenario).

Transport and deposition is computed by the RAINS model, as used in TFIAM scenario analyses, using an average of the EMEP source-receptor relationships of 1985 and 1987–1990.

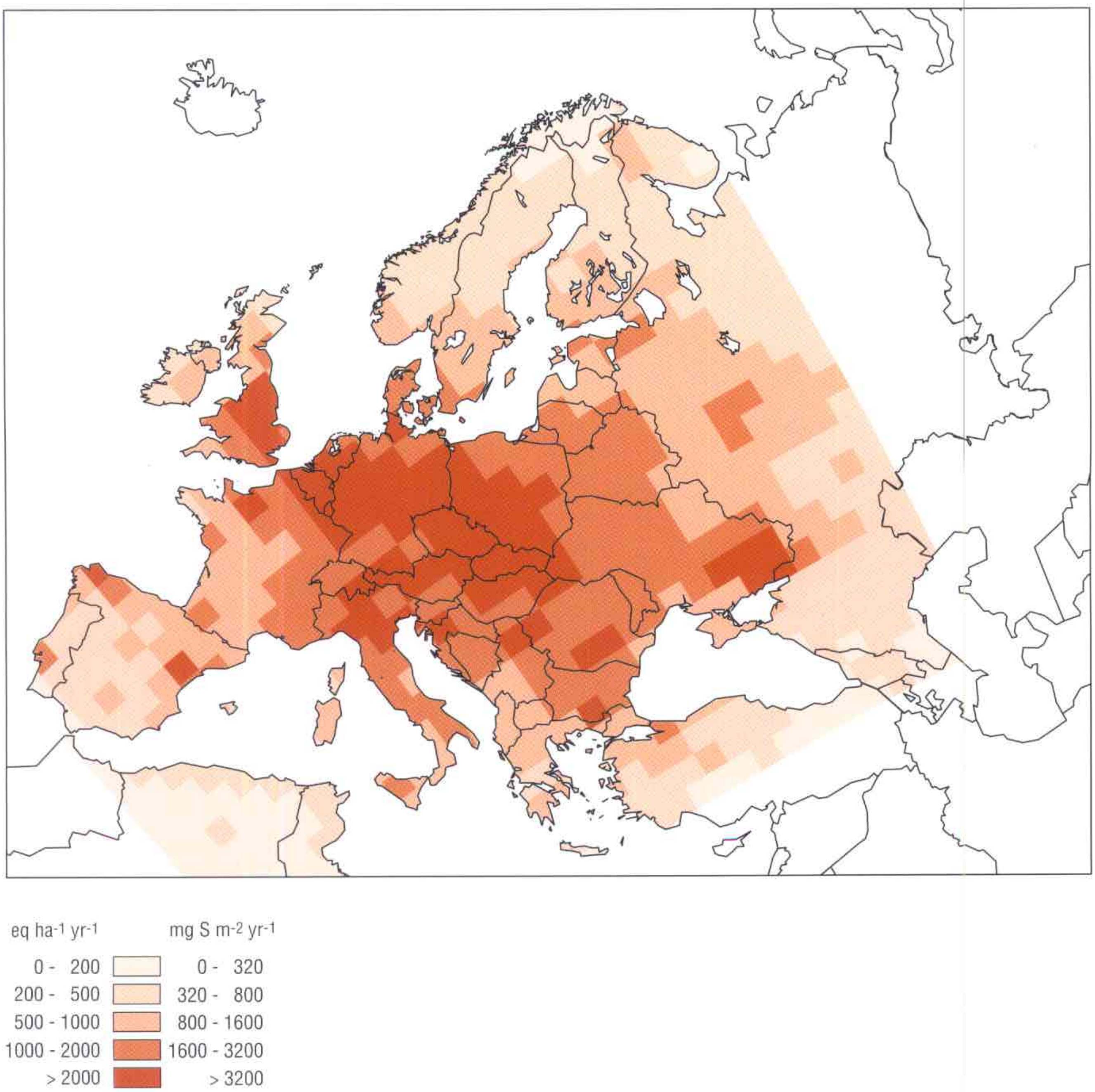

Figure 2.6. *Sulphur deposition in 1980.*

2.7 Exceedance of the critical sulphur deposition in 1980

Figure 2.7 compares the difference ("exceedance") between the sulphur deposition in 1980 (from Figure 2.6) to the critical load of sulphur (shown in Figure 2.3). Areas with a positive exceedance received levels of sulphur deposition which could damage the most sensitive ecosystems in that area.

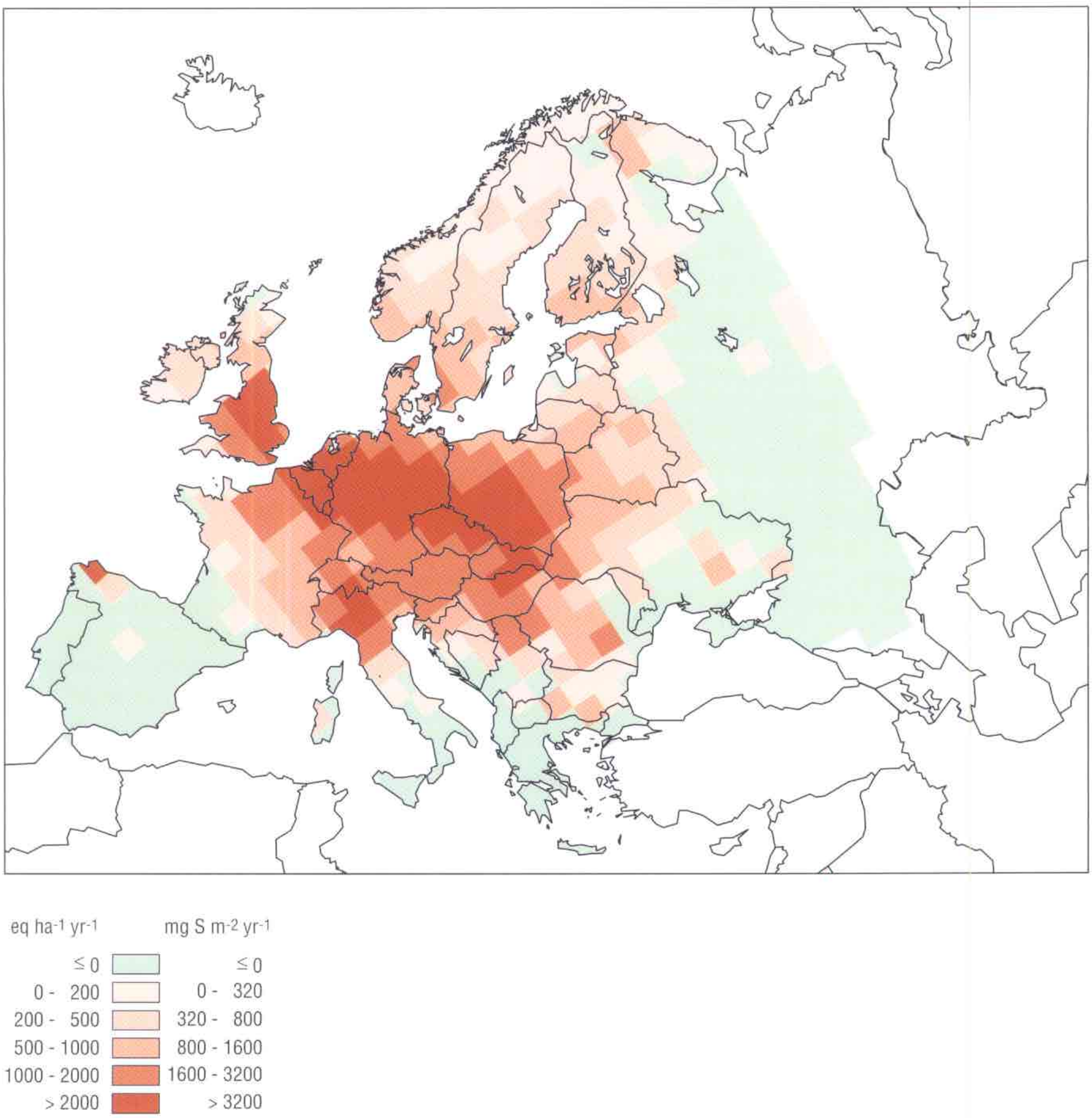

Figure 2.7. *Exceedance of critical sulphur deposition in 1980 (5 percentile).*

3. Computation of Critical Loads of Acidity and Sulphur and Critical Sulphur Deposition in 1992 and 1993

J.-P. Hettelingh, R.J. Downing, and P.A.M. de Smet

3.1 Overview

In 1992 and 1993 priority was given to computing critical loads of sulphur, to provide information for the negotiation of a second sulphur protocol under the LRTAP Convention, in particular the activities of the UN ECE Task Force on Integrated Assessment Modelling (TFIAM). The requests from the TFIAM for critical load data led to a number of adaptations to computations of critical loads and the submission of data. In addition, improvements were made with respect to methods and data quality at a number of NFC's (e.g. sampling, number of data points). A summary of the adaptations and changes in comparison to the critical loads maps published in 1991 is as follows:

1. Instead of the EMEP grid cell area, the *ecosystem* area within a grid cell was used as a basis for the computation of cumulative distribution functions of critical loads (see Section 3.2).

2. Factors which buffer acidity (e.g. dust) and those which increase acidification (i.e. base cation uptake) were included in the computation of critical loads, rather than in the computation of critical load exceedances. The ecosystem sensitivity computed in this way is termed the "critical sulphur deposition" (see Section 3.3).

3. The inclusion of forest filtering factors, which were designed to address the effects of throughfall and orography in the computation of exceedances, were abandoned by consensus of National Focal Centers, due to a lack of comparable data across Europe (see Section 3.3).

4. Some countries with regions which have a relatively high precipitation surplus adapted the computation of critical loads in high-elevation areas (see Section 3.4).

5. For a few grids, the calculated 5-percentile critical loads (i.e. protecting 95% of the ecosystems) were negative due to a small number of non-representative ecosystems with very particular conditions (e.g. natural acidification). For these grid cells, the level of background deposition was used as minimum critical load (see Section 3.5).

6. Nearly all countries which submitted national input data or critical loads calculations, have revised these data since 1991 on the basis of new monitoring results and improved methodologies.

This chapter summarizes the consequences of these adaptations. A detailed description of general critical loads methodologies can be found elsewhere (Hettelingh *et al.*, 1991; Hettelingh and de Vries, 1992; UN ECE, 1993b) whereas the current status of the method is included in Chapter 4.

3.2 Ecosystem rescaling

In order to directly compare the extent of ecosystem sensitivity in a region with present deposition levels, the EMEP grid resolution (150 x 150 km) is the basis of comparison between sulphur deposition and critical loads of sulphur. Previously, cumulative distributions were calculated for the area of each EMEP grid cell, and the 5-percentile critical load was chosen as a threshold for the protection of 95% of ecosystems in each EMEP grid cell.

However, the result of using the surface area of an EMEP cell is that a 5-percentile critical load would protect 95% of the EMEP grid cell, regardless of the actual ecosystem surface area in the cell. The advantage of this method was that the areal basis for computing percentiles was equal for all grid cells in Europe; however, the disadvantage was that the protection level for the actual ecosystems in a grid cell could be too low. This is particularly true for grid cells which contain relatively small areas of particularly sensitive ecosystems.

Therefore the revised maps are based on the total *ecosystem* area in each grid cell to compute critical load percentiles. The advantage of this approach is that the actual protection level is increased, as the ecosystem-based 5-percentile critical load is generally lower than the EMEP grid-cell-based 5-percentile critical load. The disadvantage is that the areal basis for the percentile computation varies over grid cells. Results of the scenario analysis performed in the TFIAM provide both the ecosystem and EMEP area rescaling methodology. A detailed description of methods used to compute percentiles is found in Sections 4.4.1 and 5.3.

3.3 Inclusion of background variables and exclusion of filtering factors

Background variables such as base cation deposition and uptake, nitrogen uptake, and nitrogen immobilization were previously included only when computing exceedances. Critical load computations thus were based only on variables describing soil chemistry and other ecosystem characteristics. In earlier computation methods, so-called filtering factors for coniferous and deciduous forests were incorporated, to reflect that forest throughfall measurements had been measured to be larger than computed deposition.

The exceedance of the critical load of acidity, *Ex(A)*, and of sulphur, *Ex(S)*, were therefore originally (Hettelingh *et al.*, 1991) defined as:

$$Ex(A) = f^{s}_{EMEP} \cdot S_{dep} + f^{n}_{EMEP} \cdot N_{dep} + BC_{u} - BC_{dep} - N_{u} - N_{i(crit)} - CL(A) \qquad (3.1)$$

and:

$$Ex(S) = f^{s}_{EMEP} \cdot S_{dep} + S^{f} \cdot (BC_{u} - BC_{dep}) - CL(S) \qquad (3.2)$$

where:
f^{s}_{EMEP} = sulphur filtering factor
f^{n}_{EMEP} = nitrogen filtering factor
S_{dep} = sulphur deposition
N_{dep} = nitrogen deposition
BC_{u} = base cation uptake
BC_{dep} = base cation deposition
N_{u} = nitrogen uptake
$N_{i(crit)}$ = critical nitrogen leaching

At the September 1992 workshop in Katowice (Poland), there was lengthy discussion about the potential misunderstandings among the various groups (scientists, modellers, and policymakers) using the current critical loads maps in the UN ECE framework. Much of the difficulty arises from an earlier decision by the mapping community to keep critical loads "clean"; i.e. to address only ecosystem properties, and to exclude any modifying factors such as base cation deposition and base cation uptake. These factors were only included when computing the exceedances of critical loads.

This approach had a number of disadvantages, such as: (1) modifying factors are sometimes available on a much higher than EMEP resolution, leading to a loss of information when used on an EMEP scale, and (2) the resulting critical load maps could not be directly compared with the deposition maps which are regularly published by EMEP's Meteorological Synthesizing Center-West (MSC-W).

It was therefore decided to include these modifying factors in calculating maps of a new *"critical sulphur deposition"*, which would then be directly comparable to EMEP deposition data. Similarly, critical acid deposition and critical nitrogen deposition maps can be obtained by also including nitrogen uptake, nitrogen immobilization and nitrogen fixation. (See Chapter 4.)

It was agreed among national Focal Centers to discontinue the use of filtering factors in view of the lacking possibilities to provide scientifically grounded values for various kinds of filtering (throughfall, orographic) which can be distinguished. As the current national data for these factors varies widely over Europe, inclusion of available data would have led to a divergence between countries of the basis for computing critical load exceedances.

In order to allow the direct comparison between ecosystem sensitivity (critical loads) and present deposition levels in the scenario analysis of the TFIAM, a decision was taken at the CCE Mapping Workshop held in Katowice, Poland in September 1992, to compute the critical sulphur deposition (a critical acid deposition has not been required). From equation 3.2 and excluding filtering the critical sulphur deposition becomes:

$$CD(S) = CL(S) + S_{f} \cdot (BC_{dep} - BC_{u}) \qquad (3.3)$$

The exceedance is then simply given by:

$$Ex(S) = S_{dep} - CD(S) \qquad (3.4)$$

3.4 High-precipitation areas

The original equation for computing critical loads of acidity which was predominantly used in Europe is based on a molar base cation : aluminum (BC : Al) ratio of 1 (Hettelingh *et al.*, 1991, p. 36):

$$CL(A) = ANC_w + 0.09 \cdot Q + 1.5 \cdot (ANC_w + BC_{dep} - BC_u) \quad (3.5)$$

where:
ANC_w = acid neutralizing capacity produced by weathering
Q = water flux from the bottom of the rooting zone ($m^3\ ha^{-1}\ yr^{-1}$)

Evidence became available that the result of equation 3.5 is a critical load which is too high for regions with high precipitation, primarily due to simplifications made to the original steady-state mass balance equation consisting of: (1) applying K_{gibb} = 300 $m^6\ eq^{-2}$, and (2) assuming that all base cations produced by weathering are available in the base cation : aluminum ratio. This problem was thoroughly investigated at a meeting organized by the Austrian National Focal Center for Mapping (Workshop on problems of mapping critical loads and levels in sub-Alpine and Alpine regions, Vienna, March 1992), which resulted in an adaptation of the computation methodology. Starting from the original mass balance equation, the revised equation for the critical load of acidity is derived as follows (Sverdrup, 1992):

$$CL(A) = ANC_w - ANC_{l(crit)} \quad (3.6)$$

$$ANC_{l(crit)} = -H_{limit} - Al^3_{limit} \quad (3.7)$$

$$Al^3_{limit} = 1.5 \cdot (0.8 \cdot ANC_w + BC_{dep} - BC_u - BC_{le(min)}) \quad (3.8)$$

$$H_{limit} = \left(\frac{Al^3_{limit}}{Q \cdot K_{gibb}} \right)^{1/3} \cdot Q \quad (3.9)$$

where:
H^+_{limit} = critical hydrogen leaching
Al^{3+}_{limit} = critical aluminum leaching
$BC_{le(min)}$ = minimum leaching of base cations which cannot be taken up

In equation 3.8 it is assumed that 20 percent of the weathered material is Na and therefore not active in the BC : Al ratio. With an average concentration of 15 μeq l^{-1}, $BC_{le(min)}$ becomes:

$$BC_{le(min)} = Q \cdot 0.015 \quad (3.10)$$

Substitution of equations 3.10, 3.9 and 3.8 into equation 3.7 yields the modified critical load equation which was used for areas with high precipitation (using K_{gibb} = 200 $eq^{-2}\ m^6$):

$$CL(A) = ANC_w + \left(1.5 \cdot \frac{0.8 \cdot ANC_w + BC_{dep} - BC_u - 0.015 \cdot Q}{200} \right)^{1/3} \cdot Q^{2/3} + 1.5 \cdot (0.8 \cdot ANC_w + BC_{dep} - BC_u - 0.015 \cdot Q) \quad (3.11)$$

Finally the critical load of sulphur is computed from equation 3.11 by using the sulphur fraction.

3.5 Treatment of very sensitive non-representative ecosystems

Critical loads and critical depositions have been computed on the basis of geochemical data of forest soils and surface waters. The critical ratio between base cations and aluminum have been found to be around 1 for forest soils (Sverdrup and Warfvinge, 1993), whereas for surface waters a critical ANC of 20 μeq l^{-1} has been used. The application of the critical ANC criterion to compute critical loads of 4515 lakes in Scandinavia led to negative values for 150 lakes, of which 128 lie in Norway (Henriksen *et al.*, 1993). Although the number of negative critical loads only represents 3% of the total number of sampled lakes, a problem emerged for the application of scenario analysis of sulphur reduction alternatives. The reason is that the 5-percentile critical load in some grid cells (listed in Table 3.1) identified this minority of ecosystems. To avoid that these ecosystems become binding in the scenario analysis, an alternative to the 5-percentile critical load became necessary.

The issue was raised among European scientists at the March 1993 CCE workshop in Madrid. The common characteristic of the grid cells in Table 3.1 is that the computed 5-percentile critical sulphur deposition is lower than the natural background deposition, and therefore these ecosystems cannot be protected by the reduction of anthropogenic emissions. However, not all ecosystems in these grid cells are so sensitive. Exclusion of these grid cells from the scenario analysis leads to giving up all ecosystems in these grid cells, including those for which a reduction of anthropogenic emissions would increase the number of protected ecosystems.

Instead of excluding entire grid cells from the optimization exercise, it was proposed that only naturally acidified ecosystems in these grid cells are excluded. This is done by taking the background deposition instead of the 5-percentile critical sulphur deposition.

The background deposition values fall within the range of critical loads which were computed in the eleven grid cells. Table 3.1 lists those grid cells for which substitutions have been made by the TFIAM.

Table 3.1. *Grid cells for which critical sulphur deposition calculations have been revised.*

Grid Cell	Country
14/27	Norway
14/30	Norway
15/24	Norway
15/25	Norway/Sweden
15/26	Norway/Sweden
15/30	Norway/Sweden
16/24	Norway/Sweden
16/25	Norway/Sweden
20/16	Germany/Netherlands*
20/17	Germany
21/23	Sweden

* For this cell the Dutch values of the critical load has been used for the entire cell.

4. Guidelines for the Computation and Mapping of Critical Loads and Exceedances of Sulphur and Nitrogen in Europe

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4.1 Background

The calculation and mapping of critical loads of acidity, sulphur and nitrogen form a basis for assessing the effects of changes in the emissions and deposition of these compounds. So far, these assessments have focused on the relationship between emission reductions of sulphur (and nitrogen) and the effects of the resulting deposition levels on terrestrial and aquatic ecosystems.

Critical loads of acidity have recently been mapped by the RIVM Coordination Center for Effects (CCE) in collaboration with National Focal Centers (NFC's) and other collaborating institutions throughout Europe. This work is designed to support the negotiations within the United Nations Economic Commission for Europe (UN ECE) on developing further protocols for reducing emissions of sulphur and nitrogen compounds.

Critical loads of acidity formed the basis for deriving a (separate) critical load of sulphur. A distinction between sulphur and nitrogen was needed to accommodate the UN ECE Convention on Long-Range Transboundary Air Pollution (LRTAP), which has addressed sulphur separately in the protocol currently under negotiation.

Future protocols may address both reductions of sulphur and nitrogen emissions simultaneously, to reduce acid deposition. Unlike sulphur, however, nitrogen deposition contributes to major environmental problems other than acidification. Thus an assessment of the effects of nitrogen compounds on ecosystems must consider both acidification and eutrophication effects. This paper considers primarily acidification and eutrophication of terrestrial ecosystems.

The starting point of the method proposed in this paper is that the ecosystem is indifferent with respect to whether its protection (i.e. achieving critical loads) results from sulphur or from nitrogen deposition reductions. The result is that trade-offs between emissions reductions of these two pollutants can be considered without exceeding the critical load of acidity and eutrophication. These different combinations of required deposition reductions to meet the critical load for a receptor can be expressed as a function, the so-called "exceedance indifference curve".

The EMEP model (Iversen *et al.*, 1991) is used to calculate deposition patterns over Europe. The model estimates total deposition of sulphur and nitrogen species on 150 x 150 km^2 grid cells covering Europe. Thus critical loads have to be aggregated to a single value for each EMEP grid cell. These European critical loads are based on nationally calculated critical loads which are usually computed for a much smaller grid scale (i.e. with higher resolution). Therefore, the task of the CCE to map critical loads for Europe requires procedures to derive a single critical load value for each EMEP grid cell from nationally calculated critical loads. Different emission reduction strategies in terms of their ecosystems impact are then evaluated by comparing deposition patterns, calculated with the EMEP model, with these European critical loads.

Methodologies to calculate critical loads have been described in Sverdrup *et al.* (1990) and de Vries (1991). The guidelines for the mapping of critical loads of acidity in Europe are described in an updated Mapping Vademecum (Hettelingh and de Vries, 1992) and the first results of the mapping exercise can be found in Hettelingh *et al.* (1991). The Mapping Vademecum describes a number of practicalities with respect to statistical procedures

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and calculation methodologies to be followed by national participants to achieve a consistent European map of critical loads of acidity.

The aim of this paper is to describe the treatment of total (sulphur plus nitrogen) exceedance. The calculation methodology of the critical load of nitrogen is consistent with the concepts described in the proceedings of the Lökeberg workshop (Grennfelt and Thörnelöf, 1992). While the results of the Lökeberg workshop do not affect the methodology to calculate critical loads of acidity (Hettelingh *et al.*, 1992), an adjustment of the calculated exceedances of critical loads of sulphur could emerge from the methodology described in this paper.

Section 4.2 summarizes the calculation methods for the critical load of acidity, as well as the current methods of calculating critical loads of sulphur and nitrogen. The section continues with the proposed method for calculating a critical load of nutrient nitrogen, with some emphasis on the mathematical treatment.

Section 4.3 focuses on the present and proposed methods to calculate exceedances of critical loads of acidity, sulphur, and nitrogen, and provides an illustrative example of applying these methods to calculate critical loads and exceedances of both sulphur and nitrogen simultaneously.

Section 4.4 describes the statistical methodology needed to produce critical load values in EMEP grid cells. In addition to the mapping of critical load values in grid cells, the new methodology also necessitates the grid cell mapping of ecosystem related functions. These functions describe the combination of sulphur and nitrogen values for which no exceedance of critical loads (acidity and eutrophication) occurs.

Section 4.5 discusses the consequences of the proposed methodology for current and future assessments of emission reduction scenarios conducted by the Task Force on Integrated Assessment Modelling (TFIAM) and other UN ECE bodies dealing with the development of future emission reduction protocols. Suggested values for various input variables used in calculating critical loads can be found in Appendix III.

Appendix IV includes a description of an empirical approach for deriving nitrogen critical loads for situations where a mathematical approach is infeasible; e.g. due to lack of data, and includes suggested values to be used. Appendix V summarizes the proposed method for calculating critical loads of sulphur and nitrogen for aquatic ecosystems.

4.2 Calculation of critical loads

This section summarizes the methods used to calculate critical loads of acidity, sulphur and nitrogen and their respective exceedance, both the methodology currently in use and proposed revisions resulting from a number of recent workshops. The concepts will be presented for forest soils only; the corresponding method pertaining to lakes is presented in Appendix V.

Note that all quantities provided in this chapter are expressed in eq ha^{-1} yr^{-1} (acid equivalents per hectare per year), unless otherwise noted.

4.2.1 Critical load of acidity

The critical load of actual acidity, $CL(A)$, is calculated according to:

$$CL(A) = ANC_w - ANC_{l(crit)} \quad (4.1)$$

where:
ANC_w = acid neutralizing capacity produced by weathering (Note that weathering was denoted by BC_w in former publications.)
$ANC_{l(crit)}$ = ANC consumed by the maximum acceptable alkalinity leaching at critical load

4.2.2 Critical loads of acidifying sulphur and nitrogen: current method

For the purpose of the sulphur protocol currently under negotiation, a critical load of sulphur, $CL(S)$, has been defined from the critical load of acidity by allocating a part of the allowable acidity deposition to the sulphur deposition:

$$CL(S) = S_f \cdot CL(A) \quad (4.2)$$

where S_f is the "sulphur fraction", defined as:

$$S_f = \begin{cases} \dfrac{S_{dep}}{S_{dep} + N_{dep} - N_u - N_i} & \text{if } N_{dep} > N_u + N_i \\ 1 & \text{otherwise} \end{cases} \qquad (4.3)$$

where:
S_{dep} = present sulphur deposition
N_{dep} = present nitrogen deposition
N_u = net uptake of nitrogen in the tree biomass
N_i = net immobilization of nitrogen in the root zone

A critical load of nitrogen, *CL(N)*, is derived by assuming that nitrogen deposition will lead to acidification when it is not taken up or immobilized:

$$CL(N) \;=\; N_u + N_i + (1 - S_f) \cdot CL(A) \qquad (4.4)$$

Note that denitrification is not considered in this formulation.

4.2.3 Critical load of nutrient nitrogen: proposed method

In addition to the acidifying aspect of nitrogen, the effects of nitrogen deposition on the nutrient status (eutrophication) of an ecosystem should be considered when determining critical loads and exceedances. The principle used is the steady-state mass balance for nitrogen. Considering sources and sinks of nitrogen, the mass balance used in the calculations is given by:

$$N_{dep} = \; N_u + N_i + N_l + N_{de} \qquad (4.5)$$

where:
N_l = nitrogen leaching
N_{de} = denitrification

and biological fixation of N_2 is subsumed in the N_i term.

In this formulation of the critical load, the nitrogen uptake, immobilization and leaching terms are the values at critical load:

$$CL_{nut}(N) = N_{u(crit)} + N_{i(crit)} + N_{l(crit)} + N_{de} \qquad (4.6)$$

where:
$CL_{nut}(N)$ = critical load of nutrient nitrogen
$N_{l(crit)}$ = critical nitrogen leaching

In order to calculate a critical load, the individual terms in equation 4.5 have to be estimated. Estimation methods for each of these terms are outlined below.

4.2.3.1 Nitrogen uptake

The estimation of nitrogen uptake is based on the minimum of critical and present uptake. Critical nitrogen uptake is based on the nutrient limitation concept, which implies that N_u is dependent on base cation weathering and deposition. The long-term nitrogen uptake is defined as that uptake which can be balanced by a long-term supply of base cations. The critical uptake is calculated from mass balances for the nutrient ions Mg, K, Ca and P separately. The production of different ions due to weathering can be calculated with a weathering model such as PROFILE, from total analysis of the soil, or estimated from soil type, parent material, temperature, texture and soil wetness. Taking deposition and weathering as the sources of these nutrients, and uptake and leaching as the sinks, the mass balance for the ion *X* becomes:

$$X_{u(crit)} = X_{dep} + X_w - Q \cdot [X]_{crit} \qquad (4.7)$$

where:
$X_{u(crit)}$ = critical uptake of element *X*
(*X* = Ca, Mg, K, P)
X_{dep} = atmospheric deposition of element *X*
X_w = production of element *X* from weathering
Q = water flux from the bottom of the rooting zone ($m^3\ ha^{-1}\ yr^{-1}$)
$[X]_{crit}$ = limiting concentration for uptake of nutrient *X* (eq m^{-3})

The limiting concentration is the level at which trees can no longer extract a nutrient from the solution. In the calculations, the limiting concentration for Ca and Mg has been set to 0.005 eq m^{-3}, and to zero for K and P (implying $[BC]_{crit}$ = 0.01 eq m^{-3}).

From the critical base cation uptake, the corresponding critical nitrogen uptake can be calculated from the ratio between each cation and nitrogen in the biomass:

$$N_{u(crit)} = min \left\{ \frac{Ca_{u(crit)}}{x_{Ca:N}}, \frac{Mg_{u(crit)}}{x_{Mg:N}}, \frac{K_{u(crit)}}{x_{K:N}}, \frac{P_{u(crit)}}{x_{P:N}} \right\} \qquad (4.8)$$

where:
$N_{u(crit)}$ = critical nitrogen uptake
$x_{X:N}$ = ratio of nutrient X to nitrogen during uptake (eq eq^{-1})

Nutrient ratios for the critical load calculations are given in Table 4.1. If weathering of separate ions is not available, then the total base cation weathering and a base cation : nitrogen ratio (last column in Table 4.1) can be used.

Table 4.1. *Approximate nutrient ratios (eq eq^{-1}) for the critical load calculations for preventing long-term nutrient imbalances for three major tree species.*

Tree species	$x_{Ca:N}$	$x_{Mg:N}$	$x_{K:N}$	$x_{P:N}$	$x_{BC:N}$
Norway spruce	0.60	0.20	0.20	0.20	0.90
Scots pine	0.50	0.15	0.12	0.20	0.70
European beech	0.40	0.20	0.20	0.20	0.70

Note that these ratios are different from optimal nutrient ratios.

Since tree growth may be limited not only by nutrient, but also by other stress factors (e.g. water availability), it is recommended to calculate nitrogen uptake as the minimum of the critical nitrogen uptake (cf. equation 4.8) and the present uptake. The nitrogen uptake used is thus the lower of either: (a) the limiting nutrient approach (at present, tree growth is too fast and nutrients in the soil are depleted by artificial or time-limited supply of nutrients, mobilized from exchange sites by acid deposition), or (b) the nutrient uptake approach (nutrients are not limiting tree growth but other stress factors, such as water availability, are).

4.2.3.2 Nitrogen immobilization

Nitrogen immobilization at critical load, $N_{i(crit)}$, can be approximated by the long-term, natural immobilization of 2 to 5 kg N ha^{-1} yr^{-1} (142 to 357 eq ha^{-1} yr^{-1}), which is assumed to be net immobilization, including fixation. Under present environmental conditions with acidified soils, acid rain and high growth due to elevated nitrogen deposition, immobilization may be substantially higher.

4.2.3.3 Critical nitrogen leaching

At steady state with a balanced nutrient supply, the nitrogen leaching should amount to the natural leaching from nitrogen-limited stands. In these calculations, $N_{l(crit)}$ can have different values.

Relatively small concentrations of nitrogen in the soil solution may be able to induce nutrient imbalances in coniferous forest stands. When nitrogen appears in significant amounts in the soil solution, plant species composition of the forest or ground vegetation may change. Lichen plant communities lose ground to lingon (*Vaccinium vitis idaea*) and heather (*Caluna spp.*) plant communities. These in turn lose ground to blueberry (*Vaccinium myrtillus*) type of ground vegetation, blueberry lose to grass, grass lose to herbs. Nitrogen-tolerant tree species may gain advantage over less tolerant species. The maximum permitted leaching is approximated by the water flux at the bottom of the root zone (i.e. runoff rate) and the critical nitrogen soil solution concentration:

$$N_{l(crit)} = Q \cdot [N]_{crit} \qquad (4.9)$$

where:
$[N]_{crit}$ = critical nitrogen soil solution concentration (eq m^{-3})

Values for $[N]_{crit}$ for some vegetation changes are given in Table 4.2.

4.2.3.4 Denitrification

Two methods to estimate denitrification are proposed in the following sections. The first uses a kinetic equation, while the second uses a constant denitrification fraction. In both methods, denitrification is dependent upon nitrogen deposition, and thus changes as deposition changes.

Dynamic denitrification fraction

In this method, denitrification, N_{de}, is calculated with a kinetic equation based on a Michaelis-Menten reaction mechanism (see Sverdrup and Ineson, 1993):

Table 4.2. *Suggested limiting concentrations of N for inducing vegetation changes.*

Change	$[N]_{crit}$ in mg N l^{-1}	$[N]_{crit}$ in eq m^{-3}
Coniferous trees → Nutrient imbalance	≤ 0.2	≤ 0.0143
Deciduous trees → Nutrient imbalance	≤ 0.2 - 0.4	≤ 0.0143 - 0.0276
Lichens → Cranberry	≤ 0.2 - 0.4	≤ 0.0143 - 0.0276
Lingon → Blueberry	≤ 0.4 - 0.6	≤ 0.0276 - 0.0429
Blueberry → Grass	≤ 1 - 2	≤ 0.0714 - 0.1429
Grass → Herbs	≤ 3 - 5	≤ 0.2143 - 0.3571

$$N_{de} = \begin{cases} \dfrac{k \cdot (N_{dep} - N_u - N_i)}{K + (N_{dep} - N_u - N_i)} & \text{for } N_{dep} > N_u + N_i \\ 0 & \text{otherwise} \end{cases} \tag{4.10}$$

where:
k = denitrification rate coefficient
K = saturation coefficient (2900 eq ha^{-1} yr^{-1})

The rate coefficient k is a function of temperature, soil wetness and pH:

$$k = k_0 \cdot f(T) \cdot g(w) \cdot h(pH) \tag{4.11}$$

where:
k_0 = kinetic rate constant (1710 eq ha^{-1} yr^{-1})
T = temperature (°C)
w = relative soil moisture saturation (Θ/Θ_s)
pH = soil solution pH

The modifying functions f, g and h are given by:

$$f(T) = 10^{5660\left(\frac{1}{281} - \frac{1}{273 + T}\right)} \tag{4.12}$$

$$g(w) = \frac{5.96w}{0.96 + w} \tag{4.13}$$

$$h(pH) = 0.408 \cdot pH^2 - 2.7808 \cdot pH + 5.15 \tag{4.14}$$

Temperature and soil wetness can have a substantial influence on the denitrification rate. When including the pH dependence of the denitrification rate, more elaborate and iterative models have to be used. Different acidity deposition levels will lead to different soil pH, causing the critical load to change with soil acidity. Therefore it is suggested to use $pH = 5.0$, leading to $h(pH) = 1$.

Constant denitrification fraction

An alternative function for denitrification is given in de Vries *et al.* (1992):

$$N_{de} = \begin{cases} f_{de} \cdot (N_{dep} - N_u - N_i) & \text{if } N_{dep} > N_u + N_i \\ 0 & \text{otherwise} \end{cases} \tag{4.15}$$

where f_{de} is the denitrification fraction. Note that in both methods proposed, denitrification is assumed to be zero (and $N_u + N_i = N_{dep}$) when $N_{dep} < N_u + N_i$.

In a European application (de Vries *et al.*, 1992), f_{de} has been related to soil type on the basis of data given by Steenvoorden (1984) and Breeuwsma *et al.* (1991), and proposed values can be found in Appendix III. Denitrification seems to be nearly negligible in deeply drained sandy forest soils (Klemedtsson and Svensson, 1988).

4.2.3.5 Derivation of critical loads of nutrient nitrogen

Using equations 4.5 for the steady-state mass balance for nitrogen, and the calculation methods for each of the input variables from Sections 4.2.3.1 through 4.2.3.4, a critical load of nutrient nitrogen can now be derived, according to each of the two methods to estimate denitrification described above.

Dynamic denitrification fraction

Using the kinetic denitrification fraction in equation 4.10, a critical load of nutrient nitrogen, $CL_{nut}(N)$, can be calculated by inserting equation 4.10 into equation 4.6:

$$CL_{nut}(N) = N_{u(crit)} + N_{i(crit)}$$

$$+ \frac{k \cdot (CL_{nut}(N) - N_{u(crit)} - N_{i(crit)})}{K + (CL_{nut}(N) - N_{u(crit)} - N_{i(crit)})} + N_{l(crit)} \quad (4.16)$$

Note that in this formulation of $CL_{nut}(N)$, the N_u is the nitrogen uptake at critical load, i.e. $N_{u(crit)}$, and the same holds true for N_i and N_l. Rewriting equation 4.16 yields the following quadratic equation for $CL_{nut}(N)$:

$$(CL_{nut}(N) - N_{u(crit)} - N_{i(crit)})^2$$
$$+ 2a\,(CL_{nut}(N) - N_{u(crit)} - N_{i(crit)}) - b = 0$$

where:

$$a = \frac{1}{2}\,(K - k - N_{l(crit)}) \qquad \text{and} \qquad b = K \cdot N_{l(crit)}$$

And the solution of this equation gives the following expression for the critical load of nutrient nitrogen:

$$CL_{nut}(N) = N_{u(crit)} + N_{i(crit)} - a + \sqrt{a^2 + b} \quad (4.17)$$

Constant denitrification fraction

From equation 4.5, and replacing the N_{de} term with the formulation from equation 4.15 and rearranging the terms, one obtains the following equation for the critical load of nutrient nitrogen:

$$CL_{nut}(N) = N_{u(crit)} + N_{i(crit)} + \frac{N_{l(crit)}}{1 - f_{de}} \quad (4.18)$$

4.3 Calculation of exceedances of critical loads

When calculating exceedances, both the acidifying aspects of sulphur and nitrogen and the nutrient (eutrophying) aspect of nitrogen have to be taken into account. The acidifying aspect is considered by the critical load of acidity.

4.3.1 Exceedances of the critical load of acidity

The exceedance of the critical load of acidity, *Ex(A)*, is obtained by subtracting the critical load from the deposited acidity and the acidity produced by soil processes:

$$Ex(A) = A_{dep} + A_{soil} - CL(A) \quad (4.19)$$

where:
A_{dep} = total acidity deposition
A_{soil} = total acidity produced by soil processes

Positive exceedance implies that there is too much acidity deposited.

The atmospheric acidity input to the ecosystem is defined as:

$$A_{dep} = S_{dep} + N_{dep} - BC_{dep} \quad (4.20)$$

where:
BC_{dep} = total non-marine base cation deposition

And the acidity produced by soil processes is given by:

$$A_{soil} = BC_u - N_u - N_i - N_{de} \quad (4.21)$$

where:
BC_u = net uptake of base cations in the tree biomass

4.3.2 Exceedances of critical loads of acidifying sulphur and nitrogen: current method

Exceedances of the critical loads of acidifying sulphur, *Ex(S)*, and nitrogen, *Ex(N)*, are defined as:

$$Ex(S) = S_{dep} + S_f \cdot (BC_u - BC_{dep}) - CL(S) \quad (4.22)$$

and:

$$Ex(N) = N_{dep} + (1 - S_f) \cdot (BC_u - BC_{dep}) - CL(N) \quad (4.23)$$

Again, note that denitrification is neglected in the current method.

Base cation deposition and uptake have been included in the calculation of the exceedances, and this has led to some misinterpretation related to whether they had to be taken into account when comparing critical loads with modelled sulphur deposition. Therefore, these variables are currently added to the critical loads to allow a direct comparison with modelled deposition patterns due to various emission reduction strategies. To distinguish these new critical values from the critical loads defined previously, they have been termed the *critical* *deposition of sulphur* and *critical deposition of nitrogen*, respectively, and are defined as:

$$CD(S) = S_f \cdot (CL(A) + BC_{dep} - BC_u) \tag{4.24}$$

and:

$$CD(N) = N_{u(crit)} + N_{i(crit)} + (1 - S_f) \cdot (CL(A) + BC_{dep} - BC_u) \tag{4.25}$$

Note that when $BC_{dep} < BC_u$, $BC_{dep} - BC_u$ should be set equal to 0.

The exceedances are then simply given by:

$$Ex(S) = S_{dep} - CD(S) \tag{4.26}$$

and:

$$Ex(N) = N_{dep} - CD(N) \tag{4.27}$$

4.3.2.1 Summary of current method

To consider exceedances of sulphur and nitrogen together, it is useful to introduce the notions of minimum and maximum critical loads of sulphur and nitrogen.

Substituting equations 4.20 and 4.21 (neglecting denitrification) into equation 4.19, we obtain the exceedance, *Ex(A)*, in terms of sulphur and nitrogen deposition:

$$Ex(A) = S_{dep} + N_{dep} - BC_{dep} + BC_u - N_{u(crit)} - N_{i(crit)} - CL(A) \tag{4.28}$$

The maximum critical load of one pollutant (either sulphur or nitrogen) can be derived by solving equation 4.27 for $Ex(A) = 0$ and setting the deposition of the other pollutant to zero. Thus, the maximum allowable sulphur deposition not causing exceedance of the critical load is:

$$CL_{max}(S) = CL(A) + BC_{dep} - BC_u \tag{4.29}$$

Note that $CL_{max}(S)$ is equal to the critical load of potential acidity defined in Hettelingh *et al.* (1991).

The minimum critical load of nitrogen is equal to uptake and immobilization:

$$CL_{min}(N) = N_{u(crit)} + N_{i(crit)} \tag{4.30}$$

The maximum critical load of nitrogen, $CL_{max}(N)$, not causing acidity exceedance can be calculated by setting $S_{dep} = 0$, and solving equation 4.28 for $Ex(A) = 0$:

$$\begin{aligned} CL_{max}(N) &= N_{u(crit)} + N_{i(crit)} + CL(A) + BC_{dep} - BC_u \\ &= CL_{min}(N) + CL_{max}(S) \end{aligned} \tag{4.31}$$

Figure 4.1 depicts the relationship between actual deposition, critical deposition and exceedance for a hypothetical forest soil. The critical deposition of sulphur and nitrogen, and consequently the critical loads, for given values of S_{dep} and N_{dep} are obtained by the intersection of the line of constant sulphur fraction (defined by equation 4.3) passing through (N_{dep}, S_{dep}) and the zero-exceedance line (thick line in Figure 4.1). Taking a calculated value of *CD(S)* and S_f (= 0.7), *CD(N)* can be read from the figure.

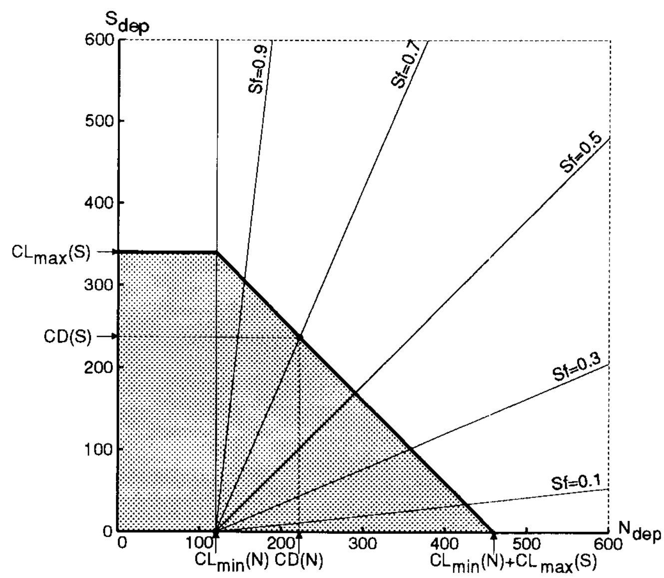


Figure 4.1. *Example showing the relationship between sulphur and nitrogen deposition, critical deposition and exceedance for a hypothetical forest soil. The gray area indicates those combinations of sulphur and nitrogen deposition values which cause no exceedance.*

4.3.3 Exceedances of sulphur and nitrogen deposition: proposed method

The disadvantage of the current formulation of critical loads (and critical deposition values) is that they do not depend on ecosystem properties alone, but also on the (current) deposition values, and

therefore should be recalculated whenever the deposition pattern changes. In addition, only the acidifying aspect of nitrogen has been considered.
Based on recent workshops, methods for calculating exceedances are suggested in the following sections which address these shortcomings.

While the expressions for $CL_{max}(S)$ and $CL_{min}(N)$ (see equations 4.29 and 4.30) remain the same in the proposed method, $CL_{max}(N)$ changes due to the inclusion of denitrification, using either of the methods described previously in Section 4.2.3.4.

4.3.3.1 $CL_{max}(N)$ using the dynamic denitrification fraction

Beginning from the exceedance of acidity defined in equation 4.19, and inserting equations 4.20 and 4.21, and the denitrification term defined in equation 4.10, yields the following:

$$Ex(A) = (S_{dep} + N_{dep} - BC_{dep}) + \left(BC_u - N_{u(crit)} - N_{i(crit)} - \frac{k \cdot (N_{dep} - N_{u(crit)} - N_{i(crit)})}{K + N_{dep} - N_{u(crit)} - N_{i(crit)}} \right) - CL(A) \qquad (4.32)$$

In the same way as $CL_{nut}(N)$ in section 4.2.3.5, the maximum critical load of acidifying nitrogen which will not lead to exceedance, is derived:

$$CL_{max}(N) = N_{u(crit)} + N_{i(crit)} - \bar{a} + \sqrt{\bar{a}^2 + \bar{b}} \qquad (4.33)$$

where:

$$\bar{a} = \frac{1}{2}(K - k - CL_{max}(S)) \qquad \text{and} \qquad \bar{b} = K \cdot CL_{max}(S)$$

and $CL_{max}(S)$ is given by equation 4.29.

4.3.3.2 $CL_{max}(N)$ using the constant denitrification fraction

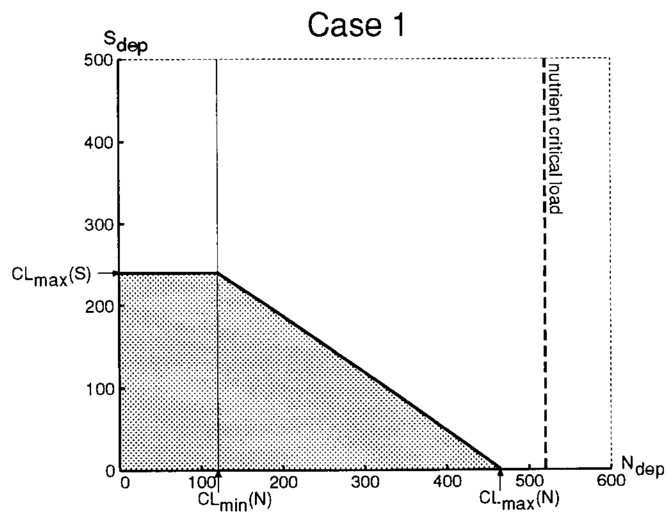
From equations 4.17 through 4.20, and substituting the N_{de} term from equation 4.15, we obtain:

$$Ex(A) = (S_{dep} + N_{dep} - BC_{dep}) + \left(BC_u - N_{u(crit)} - N_{i(crit)} - f_{de} \cdot (N_{dep} - N_{u(crit)} - N_{i(crit)}) \right) - CL(A) \qquad (4.34)$$

From this we obtain the maximum critical load of acidifying nitrogen which does not cause an exceedance:

$$CL_{max}(N) = N_{u(crit)} + N_{i(crit)} + \frac{CL_{max}(S)}{1 - f_{de}} \qquad (4.35)$$

The relationship between deposition and critical loads, derived by the above formulations, are illustrated in Case 1 of Figure 4.2. The thick lines in the figure indicate all possible pairs of critical loads of sulphur and nitrogen, and the slope of the tilted line is given by $1 - f_{de}$.



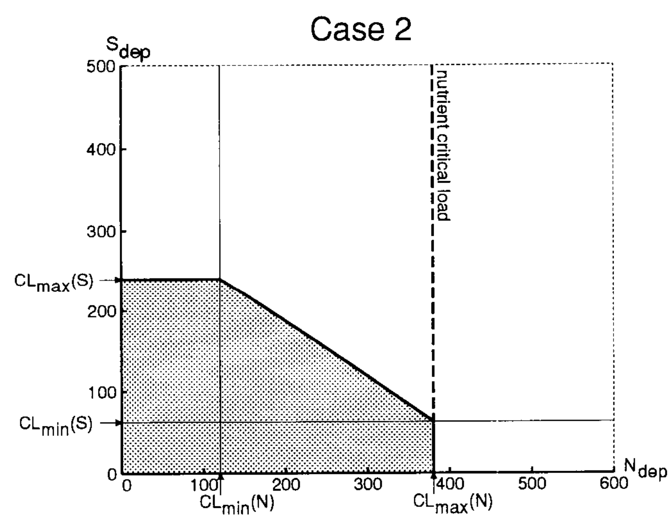


Figure 4.2. *Relationship between sulphur and nitrogen deposition and exceedance of acidity and nutrient nitrogen for a hypothetical ecosystem. The gray area marks those deposition values causing no exceedance.*

4.3.4 Illustration of proposed method including the critical load of nutrient nitrogen

Using the dynamic denitrification fraction, the exceedance of the critical load of nutrient nitrogen is defined as:

$$Ex_{nut}(N) = N_{dep} - N_{u(crit)} - N_{i(crit)} - \frac{k \cdot (N_{dep} - N_{u(crit)} - N_{i(crit)})}{K + N_{dep} - N_{u(crit)} - N_{i(crit)}} - N_{l(crit)} \quad (4.36)$$

and using the constant denitrification fraction, one obtains:

$$Ex_{nut}(N) = N_{dep} - N_{u(crit)} - N_{i(crit)} - f_{de} \cdot (N_{dep} - N_{u(crit)} - N_{i(crit)}) - N_{l(crit)} \quad (4.37)$$

Considering nutrient nitrogen and acidity together, two possibilities arise (see Figure 4.2):

Case 1: $CL_{nut}(N) \geq CL_{max}(N)$ or, equivalently, $N_{l(crit)} \geq CL_{max}(S)$:

In this case $CL_{nut}(N)$ is of no consequence and can be ignored, and $Ex(A) = 0$ (defined by equations 4.32/4.34), is the only constraint on nitrogen (and sulphur) deposition. This is shown in the upper diagram in Figure 4.2 where it can be seen how $CL_{nut}(N)$ is larger than the maximum nitrogen deposition permitted within the critical load of acidity. The exceedance function remains similar to that shown in Figure 4.1.

Case 2: $CL_{nut}(N) < CL_{max}(N)$ or, equivalently, $N_{l(crit)} < CL_{max}(S)$:

In this case $CL_{nut}(N)$ limits the maximum allowable nitrogen deposition. As shown in the lower diagram in Figure 4.2, the line for $N_{dep} = CL_{nut}(N)$ is cutting off the line describing zero exceedance of acidity.

If $N_{l(crit)} < CL_{max}(S)$, then $CL_{max}(N)$ is given by $CL_{nut}(N)$ (calculated by equation 4.17/4.18), and a minimal critical load of sulphur can be obtained by solving the equations $Ex_{nut}(N) = 0$ and $Ex(A) = 0$ simultaneously:

$$CL_{min}(S) = CL(A) + BC_{dep} - BC_u - N_{l(crit)} = CL_{max}(S) - N_{l(crit)} \quad (4.38)$$

All cases can be summarized in the following single exceedance function for sulphur and nitrogen deposition:

$$Ex(S_{dep}, N_{dep}) = \begin{cases} S_{dep} - CL_{max}(S) & \text{for } N_{dep} \leq CL_{min}(N) \\ Ex(A) & \text{for } S_{dep} > CL_{min}(S) \text{ and } N_{dep} > CL_{min}(N) \\ Ex_{nut}(N) & \text{for } S_{dep} \leq CL_{min}(S) \end{cases} \quad (4.39)$$

where $Ex(A)$ and $Ex_{nut}(N)$ are given by equations 4.32/4.34 and 4.36/4.37, respectively.

The above considerations show that, in general, it is not possible to define a unique critical load of sulphur and nitrogen which depends on ecosystem properties alone. Different combinations of sulphur and nitrogen depositions are possible to achieve zero exceedance. The thick line thus defines zero exceedance for all combinations of sulphur and nitrogen deposition; it has therefore been termed the "exceedance indifference curve" of the ecosystem.

4.4 Statistical procedures for mapping

The aim of this section is to describe how a single critical load value and a single exceedance function is obtained in an EMEP grid cell which contains a variety of ecosystems. The principle is to construct a cumulative distribution of critical loads and of exceedance functions, respectively. This section is based on earlier descriptions of the application of cumulative distributions for the mapping of critical loads (Hettelingh *et al.*, 1991; Posch *et al.*, 1993b).

4.4.1 Mapping critical load values in an EMEP grid cell

A cumulative distribution function (CDF), used to describe the cumulative occurrence of an ascending sequence of critical loads $x_1 < ... < x_n$ in an EMEP grid cell, is defined as:

$$F(x) = \begin{cases} 0 & \text{for } x < x_1 \\ \sum_{k=1}^{i} w_k & \text{for } x_i \leq x < x_{i+1} \\ 1 & \text{for } x \geq x_n \end{cases} \quad (4.40)$$

where:
$F(x)$ = the probability of a critical load being smaller than x
w_i = the weight assigned to critical load x_i
$(i = 1,...,n)$

The weight w_i represents the "importance" of the ecosystem with critical load x_i. This importance may reflect the area of an ecosystem or its intrinsic value. Since many EMEP grid cells cover two (or more) European countries, the critical load values provided by these countries have to be merged to obtain a single CDF for that grid cell. This requires the rescaling of the weights which is done in the following way: Let $W_1,...,W_n$ be the weights of the n critical load values of country 1, and $W_{n+1}, ..., W_{n+m}$ those of country 2. If no weights are provided, we set $W_i = 1/n$ for $i = 1, ..., n$ and $W_{n+i} = 1/m$ for $i = 1, ..., m$. Further, let A_k be the ecosystem area of country k ($k = 1,2$) in this grid cell ($A_1 + A_2 = A$). If the ecosystem area is not known, A_k is assigned the total land area of country k in that grid cell. The weights for the combined set of critical loads of countries 1 and 2 are then rescaled as:

$$w_i = \frac{A_1}{A} \cdot \frac{W_i}{S_1} \quad \text{for } i = 1, ..., n \quad \text{where } S_1 = \sum_{i=1}^{n} W_i \qquad (4.41)$$

and:

$$w_{n+i} = \frac{A_2}{A} \cdot \frac{W_{n+i}}{S_2} \quad \text{for } i = 1, ..., m \quad \text{where } S_2 = \sum_{i=1}^{m} W_{n+i} \qquad (4.42)$$

With this procedure the weights w_i, $i = 1, ..., n+m$, add up to 1 (100%). Finally the combined set of the $n+m$ critical load values is sorted in ascending order to construct the combined CDF for that grid. Note that the above procedure also covers the case where ecosystems overlap, e.g. country 1 contains forest soils with area F, other terrestrial ecosystems with area T and groundwater with area G such that $F+T+G$ is larger than the grid cell area. In this case A_1 is set equal to $F+T+G$. The generalization of this rescaling scheme to three or more countries is obvious and is just a matter of proper notation.

All ecosystems in a grid cell are protected by taking the minimum critical load value in this cell. For political reasons, but also to discard outliers, it has been agreed to use a (low) quantile of the CDF $F(x)$. The qth quantile ($0 \le q \le 1$) is denoted by x_q and is the critical load satisfying $F(x_q) = q$. Taking the qth quantile critical load protects a $(1-q)$th percentage of the ecosystems. Percentiles are obtained by scaling quantiles to 100, i.e. the pth percentile corresponds to the $(p/100)$th quantile.

4.4.2 Mapping exceedance functions in an EMEP grid cell

The proposed methodology described in Sections 4.2 and 4.3 leads to an exceedance indifference curve for each ecosystem in an EMEP grid cell. The question arises how to construct a single exceedance indifference curve representative for that grid cell. While percentiles have been used in the case of individual critical load (exceedance) values, the problem is more intricate for the proposed methodology, since the exceedance indifference curves do not necessarily allow a simple ordering, i.e. it is not always obvious which of two ecosystems is more sensitive than the other. For example, one ecosystem might by very sensitive to sulphur (low $CL_{max}(S)$), but – due to high denitrification – not very sensitive with respect to nitrogen (high $CL_{max}(N)$), whereas the opposite might be true for another ecosystem.

Ideally, a single exceedance indifference curve for a grid cell, Ex_p, derived from a set of individual exceedance indifference curves, should have the following properties: (a) it is monotonically decreasing, i.e. the higher the deposition value the smaller the function, and (b) if $Ex_p\ (S_{dep}, N_{dep}) < 0$ for a given sulphur and nitrogen deposition, the same is true for $(100 - p)$ percent of the original exceedance indifference curves, i.e. $(100 - p)$ percent of the ecosystems are protected. In other words, this "percentile exceedance indifference curve" serves the same purpose as does the percentile for a set of critical load values.

However, as can be shown by examples, an exceedance indifference curve fulfilling criterion (b) is not necessarily monotonous, i.e. it violates criterion (a). In addition, an algorithm for computing Ex_p according to criterion (b) in a finite number of steps is difficult to formulate, and therefore one has to resort to approximations. Furthermore, National Focal Centers will submit only data on $CL_{min}(S)$, $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$ for describing the individual exceedance indifference curves in a grid cell (even in case a non-linear formulation for [e.g.] denitrification had been chosen).

Therefore the following simple approach will be used by the CCE for computing the p-th percentile exceedance indifference curve for a grid cell. Let, e.g. $CL_{max,\,i}(S)$ (i = 1, ..., n) be the set of n maximum critical load values for sulphur in an EMEP grid cell. Then simply the p-th percentile of that values is computed by standard procedures; and the same is done for $CL_{min}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$. The four resulting values, $CL_{min,\,p}(S)$, $CL_{max,\,p}(S)$, $CL_{min,\,p}(N)$ and $CL_{max,\,p}(N)$, characterize the p-th percentile exceedance indifference curve Ex_p. When calculating this function, weights are taken into account in the same manner as described in Section 4.4.1.

Figure 4.3 shows a 5-percentile exceedance indifference curve on the EMEP grid computed from the European data base at the CCE. Note that Figure 4.3 is only an example to illustrate the method, and no conclusions should be drawn from the actual values.

Case 1 in Figure 4.3 illustrates a 5-percentile exceedance indifference curve in each EMEP grid cell in Europe when only acidification is considered. $CL_{max}(N)$ (the intercept of the exceedance indifference curve with the N_{dep} axis) reflects the maximum amount of nitrogen deposition which, assuming sulphur deposition is zero, will not increase risk of damage due to acidification. Similarly, $CL_{max}(S)$ (the intercept of the exceedance indifference curve with the S_{dep} axis) applies to sulphur deposition only. Where $CL_{max}(N)$ and $CL_{max}(S)$ are higher, ecosystems are less sensitive to acidity, and the 5-percentile exceedance indifference curve connecting these two values comprises a larger area. Therefore, the area below the exceedance indifference curve (i.e. the area of non-exceedance) in the illustration is smaller in northern Europe compared to southern and eastern Europe.

Case 2 (Figure 4.3) differs from case 1 in that critical load of nutrient nitrogen (see equation 4.36) is considered. It is illustrated that the critical load of nutrient nitrogen is lower than $CL_{max}(N)$ in nearly all EMEP grid cells. The result for the 5-percentile exceedance indifference curve is that the area of non-exceedance is vertically cut off. This figure is shown as an illustration only; it is expected that the incorporation of national calculations could change these results.

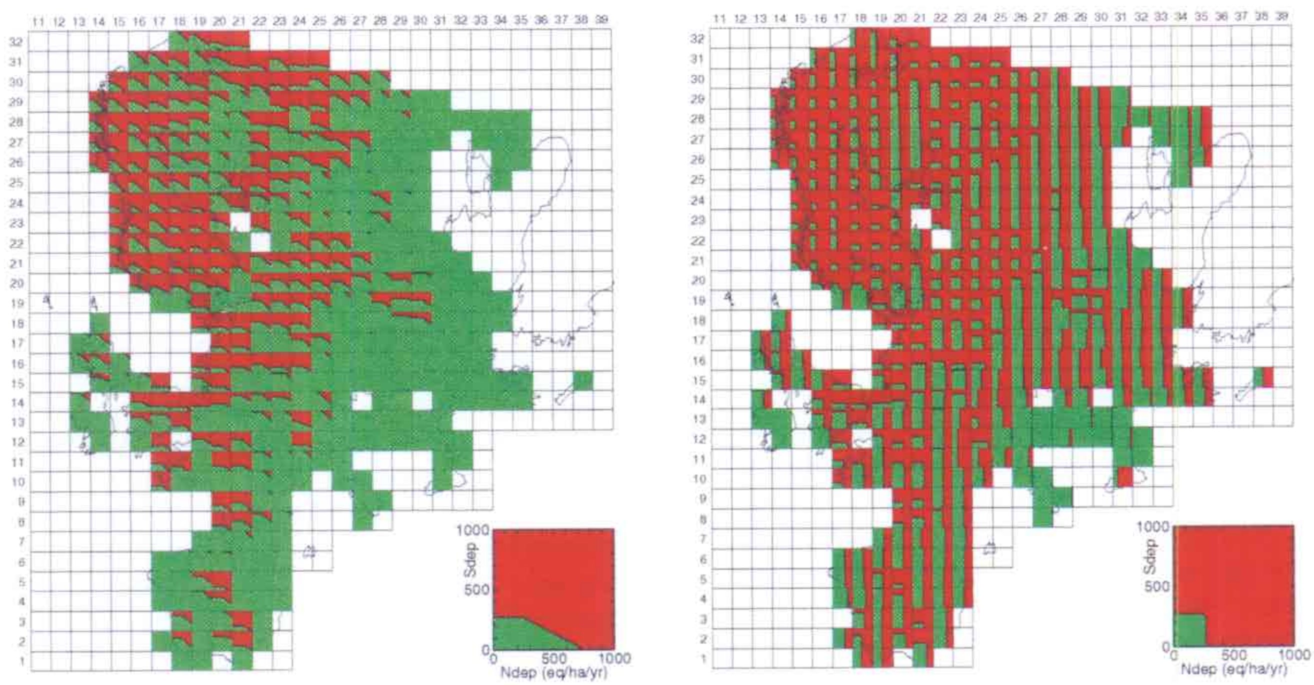


Figure 4.3. *An illustrative example of a 5-percentile exceedance indifference curve for EMEP grids, using the European data base. The figure on the left (Case 1) depicts the combined exceedance indifference curves for sulphur and nitrogen. The right-hand figure (Case 2) includes consideration of* $CL_{nut}(N)$*, as described in Section 4.3.4.*

4.5 Consequences of using the proposed nitrogen method for soils on integrated assessment modelling and future abatement policy

There are important consequences resulting from the use of the proposed method to calculate critical loads of nitrogen for soils. These are discussed here, together with their implications for other groups within the UN ECE.

Until now, using the sulphur fraction method, the critical load of sulphur (derived from the critical load of acidity and current net deposition levels of sulphur and nitrogen) and, more recently, the critical sulphur deposition (which incorporates base cation deposition), have been derived for use in integrated assessment modelling. Single values of these parameters (e.g. that protecting 95% of sensitive ecosystems) were determined for each EMEP grid square from the European critical loads map data. These values, or values related to them (e.g. 2 x critical load), were then used by the integrated assessment models as deposition values for the optimization procedure. The sulphur fraction approach has been the only method accepted within the UN ECE for considering the acidifying effects of sulphur and for deriving optimized strategies for controlling sulphur emissions.

The proposed method for acidity and nitrogen seeks to further develop and extend the sulphur fraction approach. For this, it not only takes into account the acidifying effects of both sulphur and nitrogen simultaneously, but also considers nitrogen processes in soils which are dependent on the deposition of nitrogen and sulphur. The method can also take into account eutrophication effects within the same calculations.

While details of the proposed methodology for nitrogen are considered in previous sections, it is easiest to consider the consequences of using the method by reference to simple examples. These can demonstrate the usefulness of considering sulphur and nitrogen together and highlight circumstances where emission reductions of sulphur and nitrogen may or may not benefit sensitive ecosystems. The examples are considered in relation to a simple sulphur/nitrogen exceedance indifference curve, similar to that depicted in Figure 4.2 (case 2), defined for all values of sulphur and nitrogen deposition (Figure 4.4). No exceedance occurs within the shaded ("protected") area which lies below the exceedance indifference curve.

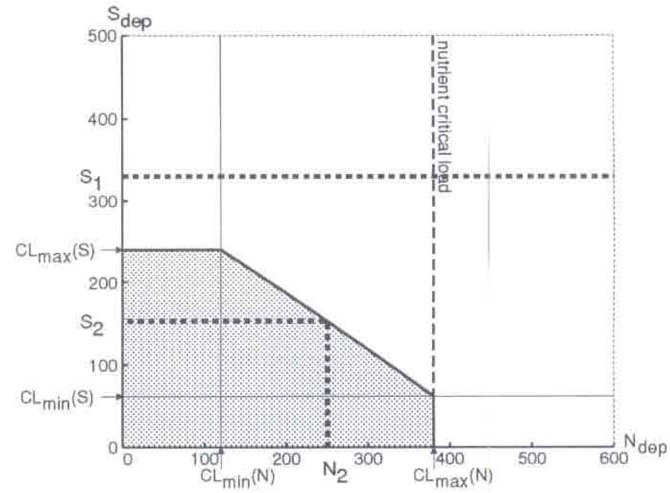


Figure 4.4. *Relationship between the exceedance function and various sulphur* (S1, S2) *and nitrogen* (N2) *depositions.*

The critical load of sulphur ranges between a maximum value, $CL_{max}(S)$, which is the critical load of acidity including base cation deposition less base cation uptake, and a minimum value $CL_{min}(S)$ (as defined in Section 4.3.4). The critical load of nitrogen ranges between a minimum value $CL_{min}(N)$ which is based on the capacity of the ecosystem to remove nitrogen (uptake, immobilization, denitrification) and, by including nitrogen leaching, a maximum value $CL_{max}(N)$ which is equal to $CL_{nut}(N)$ as defined in Section 4.2.3.

Example 1: A sulphur deposition, S_1, is defined which is greater than $CL_{max}(S)$, i.e. the critical load is not achieved (Figure 4.4). To minimize exceedance by reducing nitrogen alone, it is necessary to reduce nitrogen deposition to $CL_{min}(N)$. Even with this nitrogen reduction, the total critical load (which is for acidity in this example) will still be exceeded. Only when S_1 is reduced to become equal to $CL_{max}(S)$ is an exceedance of zero achieved. When the sulphur reduction to $CL_{max}(S)$ is not achieved, it is important to note that no further benefits result from any reduction of nitrogen below $CL_{min}(N)$; benefits can only be achieved by further reducing sulphur deposition.

Therefore the following simple approach will be used by the CCE for computing the p-th percentile exceedance indifference curve for a grid cell. Let, e.g. $CL_{max,i}(S)$ $(i = 1, ..., n)$ be the set of n maximum critical load values for sulphur in an EMEP grid cell. Then simply the p-th percentile of that values is computed by standard procedures; and the same is done for $CL_{min}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$. The four resulting values, $CL_{min,p}(S)$, $CL_{max,p}(S)$, $CL_{min,p}(N)$ and $CL_{max,p}(N)$, characterize the p-th percentile exceedance indifference curve Ex_p. When calculating this function, weights are taken into account in the same manner as described in Section 4.4.1.

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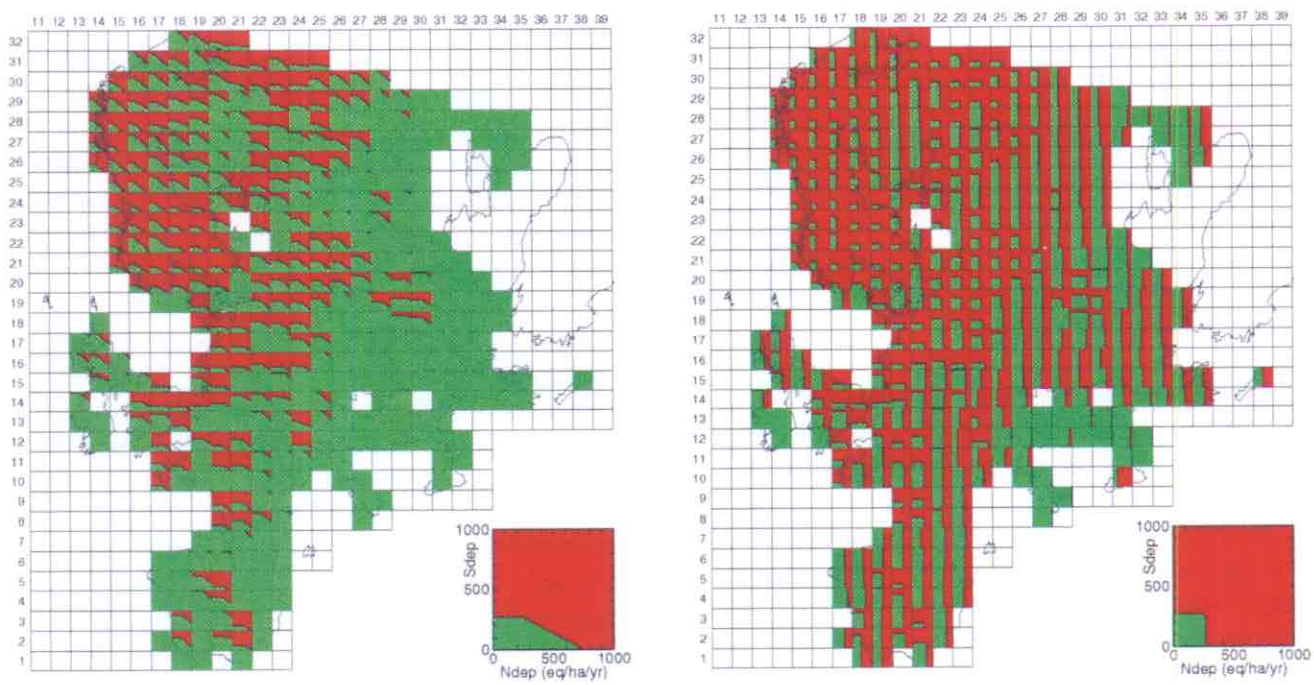

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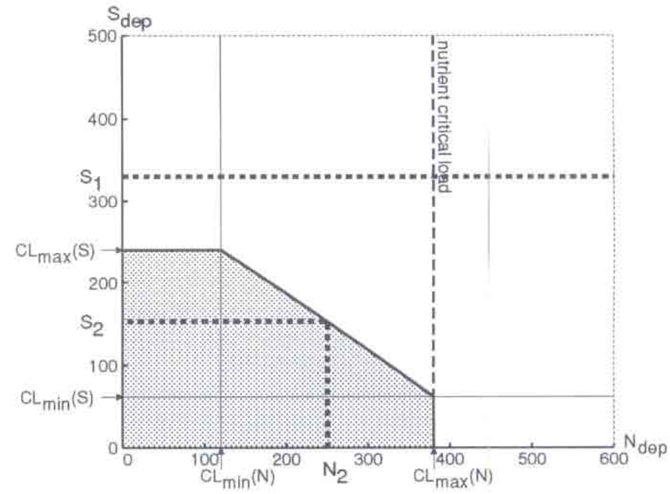
While details of the proposed methodology for nitrogen are considered in previous sections, it is easiest to consider the consequences of using the method by reference to simple examples. These can demonstrate the usefulness of considering sulphur and nitrogen together and highlight circumstances where emission reductions of sulphur and nitrogen may or may not benefit sensitive ecosystems. The examples are considered in relation to a simple sulphur/nitrogen exceedance indifference curve, similar to that depicted in Figure 4.2 (case 2), defined for all values of sulphur and nitrogen deposition (Figure 4.4). No exceedance occurs within the shaded ("protected") area which lies below the exceedance indifference curve.



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Example 2: Compared to Example 1, a lower sulphur deposition, *S2*, is defined. This sulphur deposition is less than $CL_{max}(S)$. Nitrogen now only needs to be reduced to *N2* to prevent exceedance of total critical load. Furthermore, any further reductions of sulphur deposition will lead to relaxation of the requirements for nitrogen reductions. Lower sulphur depositions will permit higher nitrogen deposition without exceeding the critical load. Note that when sulphur is reduced below $CL_{min}(S)$, no further increases in nitrogen deposition above $CL_{max}(N)$ is possible without exceeding the critical load. In turn, if nitrogen is reduced below $CL_{min}(N)$, then there is no additional benefit in reducing sulphur below $CL_{max}(S)$.

Eutrophication may still occur if sulphur deposition is lower than $CL_{min}(S)$ and the critical load of acidity is not exceeded; damage will always result from nitrogen levels greater than $CL_{max}(N)$. Indeed, it is clear that no benefits will result from reducing sulphur below $CL_{min}(S)$ since, in this region, only nitrogen makes a contribution to the total critical load. Similarly, there are no additional benefits from reducing nitrogen below $CL_{min}(N)$, since below this value the ecosystem can take up and immobilize all nitrogen.

In practice, because of the interdependence of ecosystem processes upon nitrogen and sulphur deposition, the shape of the exceedance indifference curve is likely to be more complex. The critical load for eutrophication will also vary by ecosystem independently of the acidity critical load (if the acidity critical load is lower then eutrophication can be ignored). A statistical treatment for summarizing exceedance indifference curves which relate to particular areas such as EMEP grids is therefore required (see Section 4.4). However, the consequences will be the same as the ones described above.

It is clear from the above discussion that future consideration of nitrogen emission/deposition reductions would benefit from taking account of exceedance indifference curves which combine the effects of both nitrogen and sulphur deposition. In this way it is possible to identify the combined effects and exploit the potential for considering alternative combinations of sulphur and nitrogen in abatement strategies.

It is therefore recommended that the Task Force on Integrated Assessment Modelling consider the above consequences at an early stage in its deliberations on nitrogen abatement. The proposed method for nitrogen strongly supports the suggestion that sulphur and nitrogen deposition should be modelled together and indicates that this is best done using exceedance indifference curves defined for each EMEP square. In this way an optimized approach for considering both sulphur and nitrogen together may be possible.

The policy implications resulting from the work suggested above would be a combined sulphur and nitrogen protocol. While this has been suggested in the past, it is only now that scientific knowledge has advanced sufficiently to consider the feasibility of such a policy.

Note that the sulphur fraction method which was used until now, does not lead to critical loads of sulphur which are incompatible with the range of critical loads derived for the proposed method for nitrogen. This can be seen by comparing the critical sulphur deposition (critical load including background variables) derived with the sulphur fraction method with the proposed range of critical loads (see Figure 4.1). Note from equations 4.24 and 4.29 that:

$$CD(S) = S_f \cdot CL_{max}(S) \leq CL_{max}(S) \quad (4.43)$$

since $S_f \leq 1$.

Therefore, scenario assessments to date (which have used critical loads of sulphur) have produced results which are included in the range of scenario outcomes which are to be generated using the exceedance indifference curve approach.

Finally, it should be noted that in addition to the critical load of nutrient nitrogen, other nitrogen-limiting aspects can also be included within the concept of the exceedance indifference curve. For example, another nitrogen limitation can be incurred by NO_x concentrations which are restricting the formation of tropospheric ozone.

Such limiting NO_x concentrations can be reflected in nitrogen deposition results, which can be graphed into the exceedance indifference curve as well. Thus, the use of this curve to assess required reductions of nitrogen-based deposition (NH_3 or

NO_x) and concentrations, would allow for the investigation of both direct (concentration-based) and indirect (deposition-based) risks of ecosystem damage. The investigation of synergisms between critical loads, levels, and effects provides a better understanding of required pollution thresholds to be estimated with respect to ecosystem protection. A more synergetic approach of effects in the near future would avoid scientific issues similar to those introduced by the estimate of a separate critical load of sulphur, which was subject to debate from an ecological point of view.

5. Data Processing and Mapping Procedures

P.A.M. de Smet and E. Heuvelmans[1]

5.1 Introduction

Producing European maps of critical loads (or critical deposition) consists primarily of applying a simple model and integrating the results into one map of critical loads for Europe. However, a number of incompatibilities must be addressed, such as: (1) different geographic resolutions of national input data and computation results, (2) source of data for countries which did not submit data, (3) the treatment of different ecosystems to obtain a mixed map of ecosystem critical loads, (4) ensuring comparability of EMEP deposition calculations to allow for scenario analysis, and (5) the treatment of national border areas. The objective of the data treatment is to obtain one single map with a critical load value in each EMEP grid cell.

This chapter provides a systematic description of the different procedures necessary to produce a single integrated map of critical loads on the EMEP grid cell resolution. This resolution is required to allow for comparison of EMEP-computed pollutant deposition and critical loads in scenario analysis for the support of the current UN ECE protocol negotiations.

The process of mapping critical loads (as well as critical deposition) on a European scale is described in Figure 5.1. The rows (1 to 5) of Figure 5.1 depict the steps required to process data submitted by National Focal Centers (NFC's) into a result to be integrated in the European map of critical loads. The columns (labelled A through E) in the figure reflect the different cases of geographical resolution at which data was made available to the CCE.

The result of combining steps 1 to 5 with cases A to E is a matrix with results of the data operations consisting of 18 different combinations (Figure 5.1). Section 5.2 describes the treatment of each combination in more detail.

All combinations of data processing steps and resolution cases converge into one cumulative distribution function (CDF) of critical loads in each EMEP grid cell (Box 5.A-E in Figure 5.1). A CDF provides information about the critical load value which will protect a predetermined percentage of ecosystems in each grid cell. A detailed description of CDFs is provided in Section 5.3.

The 5 data processing steps depicted in the rows of Figure 5.1 are summarized below:

Step 1. Data preparation consists of:
- importing national data bases into the CCE geographical information system (GIS) at the original national resolution
- data interpretation (including NFC comments)
- checking data quality
- computing critical loads, critical deposition, and other quantities as required
- contacting NFC's for any clarifications necessary.

Step 2. Resolution conversion includes the transformation of national data on ecosystem surface areas into surface areas expressed as a percentage of EMEP grid cells.

Step 3. Substitution of European background data with NFC data: the result of this step is a data base of EMEP grid cells, each of which are provided with a set of critical loads and related ecosystem surface areas.

Step 4. Computation of CDF and percentiles: a data base is created that contains critical load percentiles (ranging from 1 to 100) for each of approximately 650 EMEP grid cells.

Step 5. Substitution of percentiles by NFC percentiles: Substitution of results obtained in Step 4 is necessary when a country submits *only* percentile critical load values for each EMEP cell.

1. Geodan B.V., Amsterdam, the Netherlands.

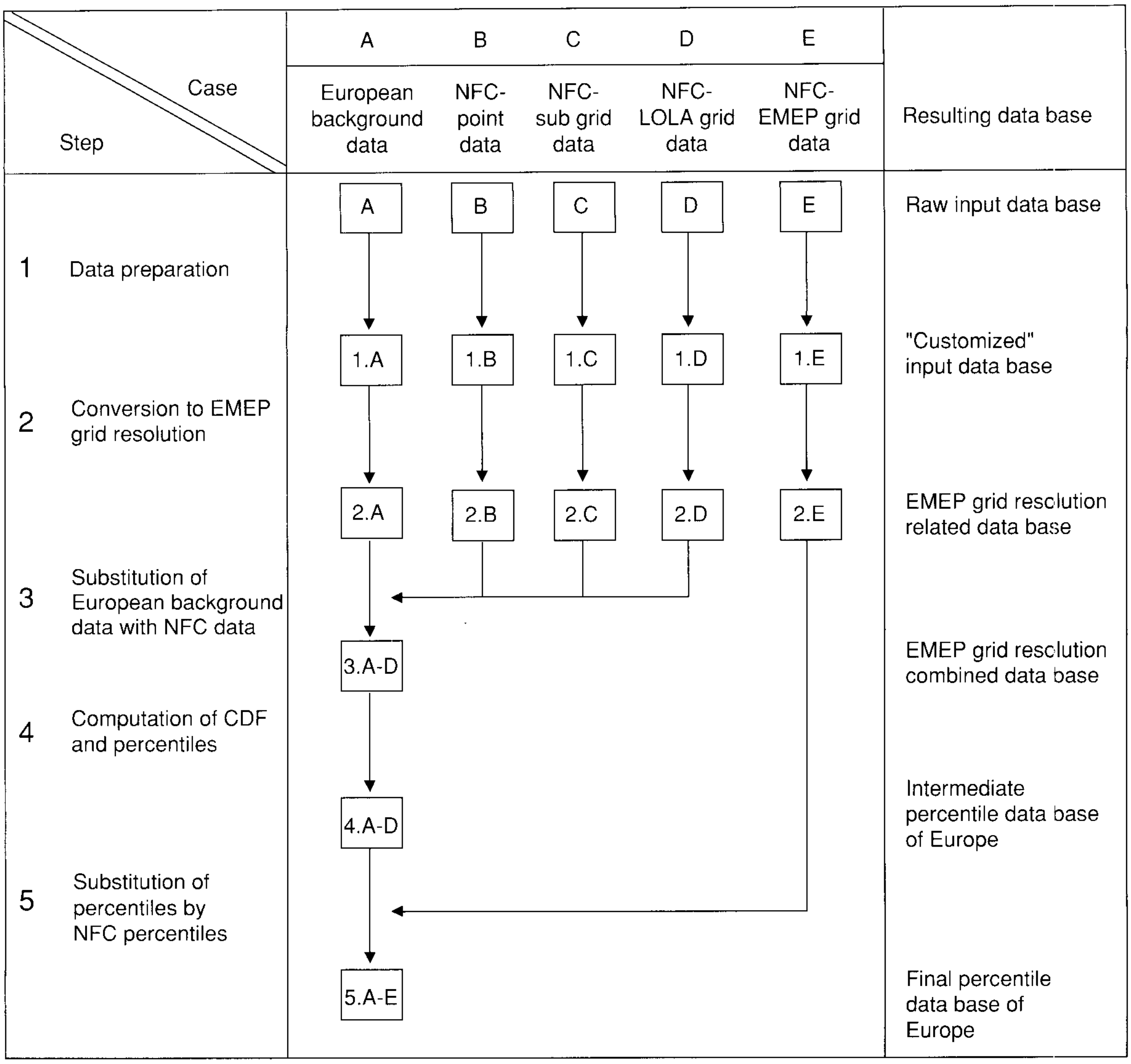

Figure 5.1. *The process of integrating national data into the European map of critical loads.*
Each row describes a step of data conversion which is required to finally obtain an EMEP map of critical loads (after step 5). The data bases resulting from each step are also listed. Each of the 5 columns describes a geographical resolution at which NFC data were submitted.

The five cases depicted in the columns of Figure 5.1 are the following:

Case A. European background data: European data bases were used for countries which did not submit background data or critical load calculations. The sources for, and structure of, this data base is described in Appendix VII.

Case B. Point data, sometimes including data on the area to which the critical load value should be applied.

Case C. National grid cell data which includes varying combinations of critical load values and related surface areas. Both the grid cell resolution and the data provided for each cell vary, e.g.:
- one critical load value per national grid cell, without surface area data;
- multiple critical load values and their related area as a percentage of the national grid cell area;
- multiple critical load values and their related area as a fraction of the national grid cell area, or
- multiple critical loads and their related area in km^2 (or ha) for each national grid cell.

Case D. Data provided for 1.0° longitude x 0.5° latitude ("LOLA") grid cells with varying combinations or grid resolutions, as in Case C.

Case E. EMEP grid cell data. A few NFC's provide a single (or very few) critical load percentile values for each EMEP cell.

Table 5.1 lists the sources and resolution of input variables and critical load calculations for each country.

5.2 Data cases and their processing

This section describes each combination of data processing steps 1 to 5, and grid resolution (cases A to E). The data processing starts with the European background data bases (Case A) followed by the national inputs (Cases B, C, D and E).

5.2.1 Case A: European background data

1.A Data preparation
The European background data base consists of a resolution of 1.0° x 0.5° longitude/latitude (LOLA) grid cells.

The data are first imported into the GIS and critical load software of the CCE. Critical loads and other quantities are then calculated, according to the Mapping Vademecum and the guidelines contained in Chapter 4 of this report.

2.A Resolution conversion
The LOLA grid cells contain critical load values and related surface area percentages for all ecosystems in the cell. A cross-section of the LOLA grid cells with the national areas and with EMEP grid cells (i.e. LOLA-nation-EMEP cross-section) is then created. The critical load value for each ecosystem and its surface area in the cross-section is stored separately in the data base. Substitution of national contributions takes place on the basis of this cross-section.

All the ecosystem areas in the cross-section are recalculated as percentage of the EMEP cell area. The conversion function applied is:

$$EP_{EMEP} = \frac{A_{LOLA}}{A_{EMEP}} \cdot EP_{LOLA} \qquad (5.1)$$

where:
EP_{EMEP} = ecosystem surface area of a LOLA cell as a percentage of the EMEP cell area (%)
A_{LOLA} = area of LOLA-nation-EMEP cross-section (km^2)
A_{EMEP} = area of EMEP cell (km^2)
EP_{LOLA} = ecosystem surface area of a LOLA cell as a percentage of the LOLA cell area (%)

3.A Substitution of European background by NFC data
Since Case A pertains to instances where no national data have been submitted, this step is unnecessary for Case A.

4.A Computation of CDF and percentiles
This step finalizes the data treatment required for each of the cases A through D, leading to a data base of cumulative distributions for each EMEP grid cell. Section 5.3 describes the computation of CDFs in more detail.

5.A Substitution of percentiles by NFC percentiles
Since Case A pertains to instances where no national data have been submitted, this step is unnecessary for Case A.

5.2.2 Case B: National point data

1.B Data preparation
The spatial distribution of data points throughout the nation is generally irregular. Some countries deliver several critical load values for each point, as more than one receptor type is monitored at that point (e.g. watershed sites). Each value is stored separately in the data base.

The national point data is then imported into the CCE software and GIS environment. The coordinates of point data from NFC's sometimes lead to a few points being assigned in neighboring countries or in the sea. The CCE reassigns these points to the nearest national territory which is represented by the NFC which submitted the data.

2.B Resolution conversion
National point data may or may not include information of the surface area for which each data point is applicable. Thus, two different methods are used:

Table 5.1. *Sources and resolution of input variables and critical load calculations for each country.*

The letter codes in the table refer to the cases A through E depicted in Figure 5.1, and listed below. The table summarizes the data used for the critical loads data produced for the new sulphur protocol.

Country	N_u	N_i	Q	BC_w	BC_u	BC_d [1]	Sf [2]	CL(A) [3]	CL(S) [3]	CD(S) [3]
Albania	A	A	A	A	A	A	A*	A*	A*	A*
Austria	C	A	C	C	C	C	C*	C	C*	C*
Belgium	A	A	A	A	A	A	A*	A*	A*	A*
Bulgaria[4]	D*	A	A	A	D*	A	D*	D*	D*	D*
Czech Republic[5]	A	A	A	A	A	A	A*	D	D*	D*
Denmark	C	A	C	C	C	C	C*	C	C*	C*
Finland	B	B	B	B	B	B	B	B	B	B
France[4]	D	A	D	A	D	A	D*	D*	D*	D*
Germany	C	C	C	C	C	C	C*	C	C	C
Greece	A	A	A	A	A	A	A*	A*	A*	A*
Hungary	A	A	A	A	A	A	A*	A*	A*	A*
Ireland	A	A	A	A	A	A	C	E	E*	E*
Italy	A	A	A	A	A	A	A*	A*	A*	A*
Luxembourg	A	A	A	A	A	A	A*	A*	A*	A*
Netherlands	C	A	C	C	C	C	C*	C	C	C*
Norway	D	A	A	A	D	A	D*	B*	B*	B*
Poland	C	A	C	C	C	C	C	C	C	C*
Portugal	A	A	A	A	A	A	A*	A*	A*	A*
Romania	A	A	A	A	A	A	A*	A*	A*	A*
Russian Federation[6]	D	A	A	D	D	D	E	E	E	E*
Slovakia[5]	A	A	A	A	A	A	A*	D	D*	D*
Spain	A	A	A	A	A	A	A*	A*	A*	A*
Sweden	B	B	A	B	B	B	B*	B	B*	B*
Switzerland	C	C	A	A	C	C	C	C	C	C
United Kingdom	E	A	A	A	E	A	E	E	E*	E*
Yugoslavia[7]	A	A	A	A	A	A	A*	A*	A*	A*

Key:
A = No national data submitted; European background data used.
B = National point data submitted.
C = National data submitted on sub-grid resolution.
D = National data submitted on LOLA grid resolution.
E = National data submitted on EMEP grid resolution.

* = Values calculated by the CCE.

Notes:
1. Several countries derived their base cation deposition data from the EMEP program. Some countries submitted data on total BC_d, while other submitted data for only wet deposition of base cations. A total base cation deposition value is derived from the data on wet base cation deposition from the EMEP program. (See also Figure A2.3 in Appendix II.)
2. The 50 percentile of national N_u data is used to derive S_f when no national S_f data was submitted. When no national N_u and S_f data were submitted, the value for S_f has been calculated from the European background data base.
3. For countries which did not submit calculated critical loads or critical depositions, these values were derived by the CCE from the national data wherever possible.
4. Submitted some modifications to European background data base.
5. Territory of the former Czech and Slovak Federal Republic.
6. Territory of the European part of the former USSR.
7. Territory of the former Yugoslavia.

(a) For point data without corresponding information on related surface areas:
As this information is required for computing CDFs, it is assumed that all points are equally distributed throughout the nation and represent an equal area portion of the EMEP cell. An area is assigned to each point for each ecosystem expressed as a percentage of the EMEP cell. The ecosystem area is computed as a percentage of the cross-section between an EMEP cell (j) and a country (C):

$$EP_{EMEP} = \frac{A_{EMNA,C,j}}{n_{C,j}} \cdot \frac{1}{A_{EMEP}} \cdot 100\% \qquad (5.2)$$

where:
$A_{EMNA,C,j}$ = area of nation C in EMEP cell j (km^2)
$n_{C,j}$ = number of data points in nation C and EMEP cell j

(b) Points with data on surface area:
Some countries which submit ecosystem data as points, also include an area weight factor for each EMEP grid cell. The factor expresses the ecosystem area represented by the point, as a ratio of the total area of all the points in the national territory of the involved EMEP cell.

To compute the ecosystem area as percentage of the EMEP cell for each point, the following conversion is performed:

First, the absolute surface area for each ecosystem point is computed:

$$W_{C,j,i} = \frac{w_{C,j,i}}{\sum_{i=1}^{n} w_{C,j,i}} \cdot A_{EMNA,C,j} \qquad (5.3)$$

where:
$w_{C,j,i}$ = area weight factor for ecosystem point i of nation C in EMEP cell j
$W_{C,j,i}$ = total ecosystem surface area at point i in nation C and EMEP cell j (km^2).

Subsequently, $W_{C,j,i}$ has to be converted to percentages related to the EMEP cell area:

$$EP_{EMEP} = \frac{W_{C,j,i}}{A_{EMEP}} \cdot 100\% \qquad (5.4)$$

where:
A_{EMEP} = area of EMEP cell j (km^2)
EP_{EMEP} = ecosystem surface area as a percentage of the total area of EMEP cell j (%)

3.B Substitution of European background data by NFC data
For countries which did not submit national data, the European background data are replaced with the NFC point data that are prepared according Steps 1.B and 2.B.

4.B Computation of CDF and percentiles
This step finalizes the data treatment required for each of the cases A through D, leading to a data base of cumulative distributions for each EMEP grid cell. Section 5.3 describes the computation of CDFs in more detail.

5.B Substitution of percentiles by NFC percentiles
Since Case B pertains to instances where national point data have been submitted, this step is unnecessary for Case B.

5.2.3 Case C: National data on a subgrid resolution

1.C Data preparation
The size of the national grid cells has to be known.

National Focal Centers submit data with varying combinations of critical load values and the ecosystem areas. The data consist of coordinates for the national grid cells, the grid cell size, and critical load data itself, in one of the following formats:
(a) One critical load value for each national grid cell, without surface area data;
(b) Multiple critical load values and their related area as a percentage of the national grid cell area;
(c) Multiple critical load values and their related area as a fraction of the total national grid cell area;
(d) Multiple critical load values and their related surface area in km^2 (or ha) for each national grid cell.

The CCE links the coordinates of the national grid cell (i.e. lower left corner) point) uniquely to one EMEP grid cell (or one EMEP-nation cross-section).

2.C Resolution conversion
Each combination (a) to (d) requires a specific conversion routine to establish ecosystem percentages related to the EMEP cell area (or EMEP-nation cross-section area):

(a) One critical load value in each national grid cell, without surface area data:
When no ecosystem surface area data is available, it is assumed that the critical load value is representative for the entire national grid cell. The conversion of the national grid cell area into a percentage related to the involved EMEP cell area is as follows:

$$EP_{EMEP} = \frac{A_{cell}}{A_{EMEP}} \cdot 100\% \qquad (5.5)$$

where:
A_{cell} = total area of the national grid cell (km^2).

(b) Multiple critical load values and their related area as a percentage of the total national grid cell area:
When critical loads and their ecosystem area is available as a percentage of the national grid cell, the conversion to an area expressed as a percentage of the EMEP cell area is as follows:

$$EP_{EMEP} = \frac{EP_{cell} \cdot A_{cell}}{A_{EMEP}} \qquad (5.6)$$

where:
EP_{cell} = ecosystem surface area as a percentage of the national grid cell area (%)

(c) Multiple critical load values and their related area as a fraction of the total national grid cell area:
When critical loads and their ecosystem surface area is available as a fraction of the national grid cell, the conversion to a surface area expressed as a percentage of the EMEP cell area is as follows:

First, the fraction is modified to a percentage of the national grid cell area:

$$EP_{cell} = EF_{cell} \cdot 100\% \qquad (5.7)$$

where:
EF_{cell} = ecosystem surface area as a fraction of the national grid cell area

Subsequently, the conversion proceeds according to equation 5.6.

(d) Multiple critical load values and their related surface area in km^2 (or ha) for each national grid cell:
When data on critical loads and their related ecosystem area is available in km^2 (or ha) for each national grid cell, the conversion to a surface area expressed as a percentage of the EMEP cell area is as follows:

First, the absolute area size is modified to a percentage of the subgrid cell area:

$$EP_{cell} = \frac{A_{eco}}{A_{cell}} \cdot 100\% \qquad (5.8)$$

where:
A_{eco} = ecosystem surface area in the national grid cell (km^2).

Subsequently, the conversion proceeds according to equation 5.6.

3.C Substitution of European background data by NFC data
For the nations of concern the European background data are replaced with the NFC grid data that are prepared according Steps 1.C and 2.C.

4.C Computation of CDF and percentiles
This step finalizes the data treatment required for each of the cases A through D, leading to a data base of cumulative distributions for each EMEP grid cell. Section 5.3 describes the computation of CDFs in more detail.

5.C Substitution of percentiles by NFC percentiles
Since Case C pertains to instances where national subgrid data have been submitted, this step is unnecessary for Case C.

5.2.4 Case D: National data on a longitude-latitude resolution

1.D Data preparation
Importing the data base into the GIS and critical load software of the CCE; the data base consists of a resolution of 1.0° x 0.5° longitude/latitude (LOLA) grid cells.

Some NFC's provided the CCE with a modified version of the European background data base as far as considered the national territory.

Critical loads and other quantities are then calculated, according to the Mapping Vademecum and the guidelines contained in Chapter 4 of this report.

2.D Resolution conversion
Generally, the LOLA grid cells contain critical load values and related surface area percentages for all the ecosystems in the cell. When only one critical load value, without ecosystem surface area data, is provided for each LOLA cell, the value is assumed to be representative for the entire national territory within the LOLA cell.

For conversion of the ecosystem surface area to the EMEP cell area refer to Step 2.A.

3.D Substitution of European background data by NFC data
For the nations of concern the European background data are replaced with the national LOLA data that are prepared according Steps 1.D and 2.D.

4.D Computation of CDF and percentiles
This step finalizes the data treatment required for each of the cases A through D, leading to a data base of cumulative distributions for each EMEP grid cell. Section 5.3 describes the computation of CDFs in more detail.

5.D Substitution of percentiles by NFC percentiles
Since Case D pertains to instances where national data have been submitted on the LOLA grid, this step is unnecessary for Case D.

5.2.5 Case E: National data on the EMEP grid resolution

For Case E, the NFC data can be divided into two categories:
(a) NFC data consisting of critical load classes and the area (as percentage of the EMEP grid cell) applied to each class;
(b) NFC data consisting of one (or very few) percentile critical load values for each EMEP grid cell.

The national data of category (a) and especially category (b) do not fit very well in the concept of computing critical load values for a full range of percentiles (1–100%), since a full CDF can not be computed.

1.E Data preparation
Category (a): critical load classes submitted with the area for each EMEP cell applied to each class

The area percentages must be cumulated in order to fit into the final percentile data base that results from Step 5.E.

Category (b): One percentile critical load value for each EMEP cell:

Only one (or a few) percentile(s) are submitted. Each value can directly be used for maps which display the critical loads at the percentiles which have been submitted.

2.E Resolution conversion
No conversion is needed for category (a) or (b).

3.E Substitution of European background data by NFC data
Step 3.E, contrary to steps 3.B, 3.C and 3.D, will never be performed. Instead, substitution of national critical load percentiles for categories (a) and (b) is performed in Step 5.E after Steps 1 to 4 for Cases A to D are conducted.

4.E Computation of CDF and percentiles
Since Case E pertains to instances where only percentile data have been submitted, this step is unnecessary for Case E.

5.E Substitution of percentiles by NFC percentiles
Substitution of national percentile critical loads for categories (a) and (b) is performed only after Steps 1 to 4 for Cases A to D:

Category (a): critical load classes submitted with the area for each EMEP cell applied to each class:

The national percentile critical loads, derived in Step 1.E from the critical load classes, are substituted into the data base with the computed percentiles for the entire European area (data base 4.A-D).

Category (b): One critical load percentile for each EMEP cell:

The CCE can only substitute the submitted critical load percentile values (one per EMEP cell) into the final data base, as other percentiles are not available. From the point of view of data treatment this substitution is not consistent with the substitutions performed on the other four data cases. Problems arise if two nations share the same EMEP cell and the first nation submits a large number of ecosystem critical load values for that cell but the second country submits only one critical load percentile value for the same cell. The critical load percentile values derived from the CDF based on the large number of data of the first country overrules the reliability of that single percentile critical load value submitted by the second country.

5.3 Cumulative distribution functions

To describe the relationship between critical loads and ecosystem surface area, *cumulative distribution function* (CDF) of critical loads of an EMEP grid cell is introduced.

5.3.1 Percentile critical loads

The CDF provides information about the critical load value at which a predetermined percentage of ecosystems will be protected in each EMEP cell. The predetermined percentage is known as the *percentile critical load.*

Percentiles for both EMEP cells and EMEP-nation cross-sections can be derived at the CCE. The percentiles for EMEP cells are used for the integrated European critical load maps. The percentiles for the EMEP-nation cross-sections are used to compile critical loads maps of each country separately, based on national data inputs.

Percentile critical loads are computed in two ways: (1) as a percentage of the total EMEP cell area (or EMEP-nation cross-section area), and (2) as a percentage of the total ecosystem area within an EMEP cell (or EMEP-nation cross-section). Section 3.2 describes the advantages and disadvantages of each of these two approaches. The following section describes the computation of the CDFs and percentiles in more detail.

5.3.2 Computation of CDFs related to the total EMEP cell area

As discussed in the previous sections of this chapter, all available national data are converted to the EMEP grid resolution. When an EMEP cell containing national borders includes one or more nations that contributed national data, only the submitted national data is used to compute cumulative distributions for that EMEP cell.

Figure 5.2 shows an example of a set of critical load data for an EMEP cell and its derived CDF. The critical loads of acidity are represented on the horizontal axis, and the cumulative percentages are represented on the vertical axis.

The hypothetical data used to calculate this CDF are shown in Table 5.2, which lists critical load values (column 1), the ecosystem surface areas as a percentage of the surface area of the EMEP grid cell (column 2), and the cumulative percentage of ecosystem surface areas (column 3).

Table 5.2. *Hypothetical example of critical load data for one EMEP grid cell, illustrated in Fig. 5.2.*

critical load value (eq ha^{-1} yr^{-1})	ecosystem percentage	cumulative percentage
452	13	13
748	8	21
1175	6	27
1493	6	33
1782	5	38
1855	14	52
2450	21	73

Figure 5.2 and Table 5.2 show that the ecosystems in this EMEP grid cell have critical loads ranging from 452 to 2450 eq ha^{-1} yr^{-1}, and cover a total of 73% of the EMEP grid cell surface area. The most sensitive ecosystem covers 13% of the EMEP grid area, and the least sensitive ecosystem covers 21%.

The lowest critical load in this EMEP cell (452 ha^{-1} yr^{-1}) is assigned to all percentiles lower than the percentage of the area covered by the most sensitive ecosystem (Figure 5.2, section A).

The highest critical load in this EMEP cell (2450 ha^{-1} yr^{-1}) is assigned to all percentiles higher than the percentage of the area covered by the least most sensitive ecosystem (Figure 5.2, section C).

Critical loads which exceed the minimal critical load but are smaller than the maximum critical load can be computed at any percentile by means of linear interpolation (figure 5.2, section B).

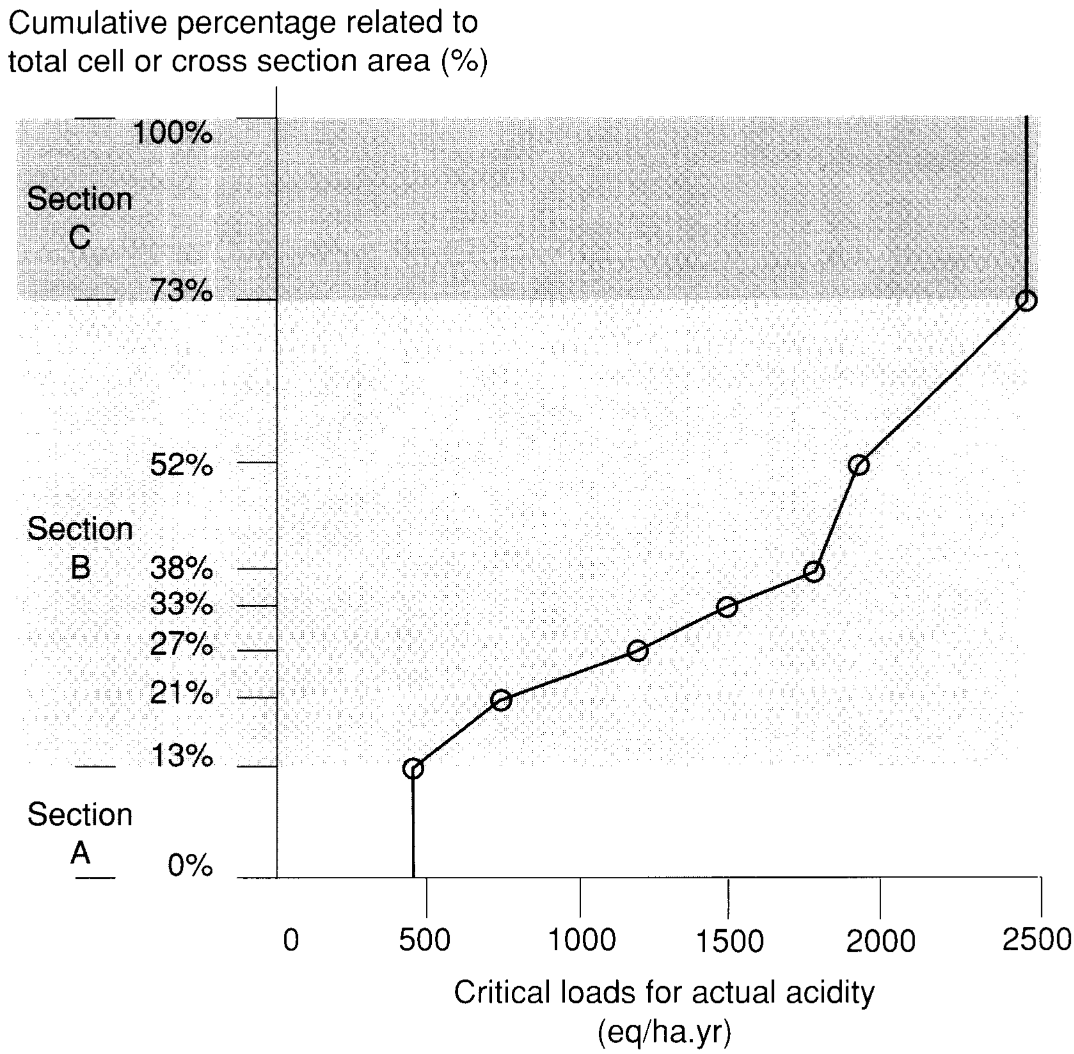

Figure 5.2. *Example of a cumulative distribution function for critical loads related to the total EMEP cell area.*

5.3.3 Computation of CDFs related to the total EMEP-nation cross-section area

The procedure described in section 5.3.2 is also applied for the cross-section of an EMEP cell with the area of a nation. This procedure results in separate data bases of critical load percentiles for the EMEP-nation cross-sections for each nation. These results have been used for NFC verification of CCE data treatment.

5.3.4 Computation of CDFs related to the total ecosystem area in each EMEP grid cell

The CDF and the percentile critical loads related to the total ecosystem area in an EMEP cell are computed by rescaling the percentile of the highest critical load to 100% and rescaling all the other cumulative percentages accordingly:

$$P_{i,eco} = \frac{P_{i,EMEP}}{P_{max,EMEP}} \cdot 100\,\% \qquad (5.9)$$

where:

$P_{i,eco}$ = cumulative ecosystem percentage related to the total ecosystem surface area of the EMEP cell at ecosystem *i*.

$P_{i,EMEP}$ = cumulative ecosystem percentage related to the total EMEP cell area at ecosystem *i*

$P_{max,EMEP}$ = cumulative ecosystem percentage related to the total EMEP cell area at the maximum national critical load value

The cumulative distribution function from Figure 5.2, after rescaling, is shown in Figure 5.3.

Rescaling means that 100% of the ecosystem surface area is chosen as the basis for the computation of percentiles. Thus, the 73% is rescaled to 100%. The minimum critical load of 452 now applies to 18% of the total ecosystem area in the grid cell.

The horizontal axis represents critical loads of acidity. Cumulative percentages before and after rescaling are represented on the left-hand and right-hand side of the vertical axis respectively. Note that rescaled percentages have been rounded in Figure 5.3.

5.3.5 Computation of CDFs related to the total ecosystem area per EMEP-nation cross-section

The rescaling of the cumulative percentages of the total EMEP-nation cross-section area into cumulative percentages of the total ecosystem area for each EMEP-nation cross-section is computed in a similar manner to the procedures described in Section 5.3.4.

$$P_{i,eco} = \frac{P_{i,EMNA}}{P_{max,EMNA}} \cdot 100\ \% \qquad (5.10)$$

where:

$P_{i,\ EMNA}$ = cumulative ecosystem percentage related to the total EMEP-nation cross-section cell at ecosystem i

$P_{max,\ EMNA}$ = cumulative ecosystem percentage related to the total EMEP-nation cross-section cell at the maximum national critical load value

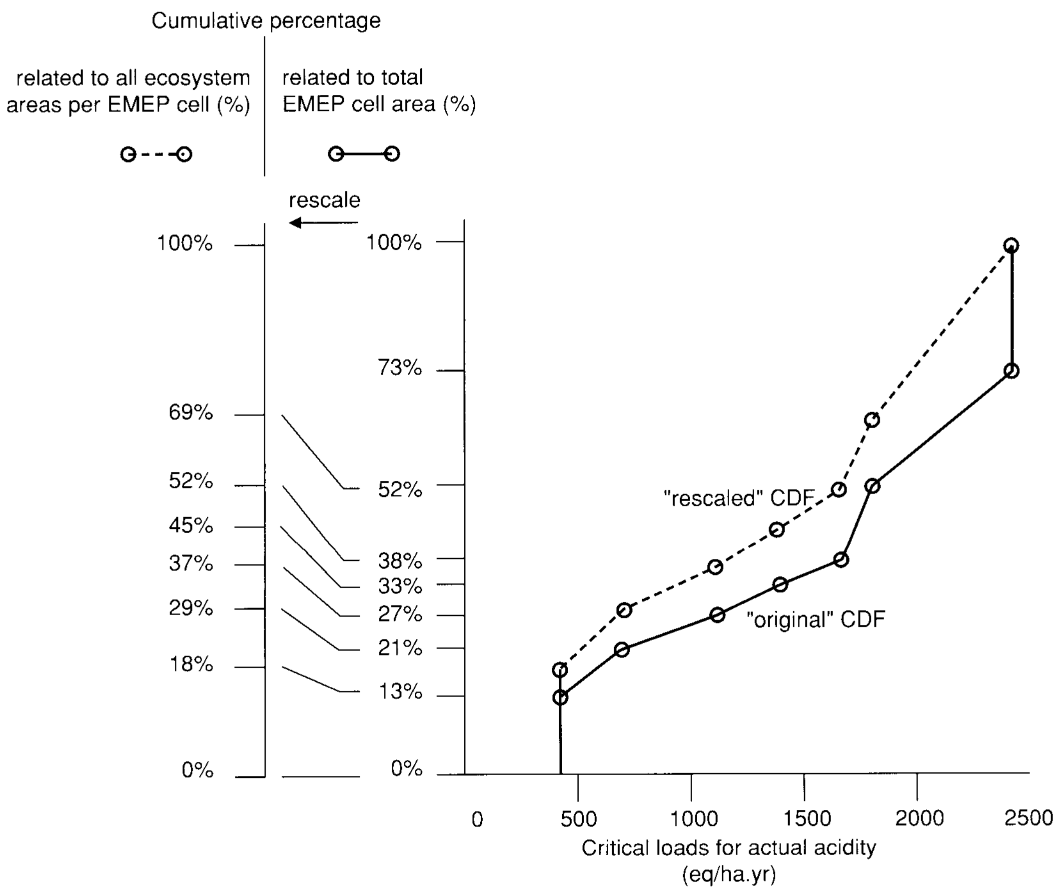

Figure 5.3. *Example of a cumulative distribution function of critical loads of acidity related to the total EMEP cell area (solid line) and related to the total ecosystem areas in the cell (dotted line).*

5.4 Conclusions and final remarks

This chapter described how a wide variety of NFC data types were processed at CCE to obtain a map of European critical loads on an EMEP resolution. Although efforts have been made to harmonize data submissions (Vademecum, CCE workshops) a great variety of data types had to be treated at CCE. This situation was satisfactory in a time period where CCE and NFC's initiated collaboration. However, in order to increase quality insurance and keep the current and future CCE data base manageable, NFC data will have to meet requirements which are the same for all participants. Therefore, at the Madrid CCE workshop in March 1993 (see Appendix VI), specific guidelines for data submission were agreed upon for the upcoming critical loads mapping activities.

6. Preliminary Uncertainty and Sensitivity Analysis of Computed Critical Deposition of Acidity in Europe

J.-P. Hettelingh and P. Janssen[1]

6.1 Introduction

This chapter describes the influence of the uncertainty of input variables of the Steady-State Mass Balance Model (SSMB) on the critical deposition of acidity computed for Europe. In general, reliability of predicted output variables such as critical deposition of acidity can be affected by:

- **errors in data:** Data measurements have been at the basis of critical load computations to an extent which varies over European contributors; some European nations did not contribute with measured data (see Chapter 5).
- **model structure:** the model principle was similar over most of Europe, but an adaptation was made to the model structure for high-precipitation areas and for watersheds.
- **the numerical treatment of data:** the numerical treatment involved aggregation of resolutions (see Chapter 5) to obtain critical load estimates on an EMEP grid cell resolution.

Uncertainty in this chapter is understood in a probabilistic sense, following Beck (1987). This means that erroneous assumptions or distributions of errors associated with observed or estimated quantities are regarded as random events which influence the variability of the computed critical deposition of acidity. The implication is that further differentiation of the SSMB approach to incorporate other processes, e.g. detailed ecological behavior, is not considered as a viable means of evaluating the current SSMB results. The reason is that the formulation of a more detailed model, if appropriate in the first place, would demand experimental observations throughout Europe which are currently not available nor technically feasible. Therefore, uncertainty analysis on model structure has not been performed.

Treating uncertainty in a probabilistic sense leads to Monte Carlo analysis to be a suitable instrument to investigate variability of computed critical deposition of acidity. This instrument has become common over the past two decades in environmental modeling in general (see for an overview Hettelingh, 1989, pp. 5-16 and 49-68) and on large regional scales in particular (see also Hettelingh *et al.*, 1992b). Monte Carlo analysis is a technique to repeatedly run a model using random numbers which are sampled from the data ranges to which each of the input variable values are restricted.

An exhaustive description of methods and techniques including computer codes for sampling from statistical distributions related to Monte Carlo can be found in McGrath *et al.* (1973), McGrath and Irving (1973a, 1973b), Gardner *et al.* (1983) and, based on the latter, at RIVM (Janssen *et al.*, 1992). The Monte Carlo method as developed further at RIVM has been used to perform a preliminary investigation of the critical loads uncertainty as computed for Europe by means of the Steady-State Mass Balance model.

6.2 Applying Monte Carlo analysis using Latin Hypercube sampling on three regions in Europe

Monte Carlo analysis is performed on the equation for the computation of the critical deposition of acidity which, as described in Chapter 4, implies the critical load of acidity including background variables:

$$CD(A) = BC_{dep} - BC_u + N_u + N_{i(crit)} + CL(A) \qquad (6.1)$$

CL(A) is computed as described in Section 3.1.

Note that the sulphur fraction has not been included in the analysis, in order to focus on ecosystem variables only.

The analysis was performed for critical loads computed in Europe as a whole, northern Europe (lati-

1. Center for Mathematical Methods, RIVM.

tudes 55.5° to 70°) , middle Europe (latitudes 45° to 55°) and southern Europe (latitude 35° to 44.5°). Europe has been divided into three regions to reflect the general geographical impression of critical loads being low in northern Europe and rather high in southern Europe. The exact latitudes at which Europe was divided were chosen arbitrarily.

The European data base for deciduous and coniferous forest soils (European background data; see Chapter 5) was used. Critical load computations for fresh waters in northern Europe were not included in this study for reasons of simplification and the fact that preliminary results are described elsewhere (Johansson and Janssen, 1993). The reason for not using national data in this preliminary analysis is that not all countries provided required background data. Therefore, the preliminary analysis described in this chapter does not provide insight in the uncertainty which might possibly be attributable to the differences by which national data were obtained and submitted to CCE (see Chapter 5).

Monte Carlo analysis using Latin Hypercube sampling, which ensures that each of the input variables is sampled efficiently and equally well over its entire range (see Hettelingh, 1989, pp.63-64), was applied with the software package UNCSAM (Janssen *et al.*, 1992) using a variety of distribution functions for the input variables in each of the three regions and total Europe. The input variables which are independent of the type of forest are base cation weathering (ANC_w), base cation deposition (BC_{dep}), the gibbsite constant (K_{gibb}) and base cation to aluminum ratio (BC : Al). Input variables which were distinguished for deciduous and coniferous forests respectively are: runoff (Q_{dec}, Q_{con}), base cation uptake ($BC_{u(dec)}$, $BC_{u(con)}$), and nitrogen uptake ($N_{u(dec)}$, $N_{u(con)}$). The shape of the distribution functions was rigorously tested against actual distribution statistics for each of the variables. The type of distribution function, the mean, standard deviation, minimum and maximum value of the data ranges for each of the input variables is given in Tables 6.1 to 6.4 for southern, middle, northern and total Europe respectively. Monte Carlo analysis consisted of (1) taking 500 samples from these data ranges by means of Latin Hypercube sampling, (2) an uncertainty analysis describing the importance of each of the input variables for the variability of the critical deposition of acidity, and (3) a sensitivity analysis which gives an indication of the percentage change of the critical deposition for acidity when the input variables are changed by 1% relative to their mean values. Correlation between input variables were not considered in this analysis.

The importance of each of the input variables for computed critical deposition for acidity is expressed as the contribution of each input variable to the coefficient of determination (R^2). The coefficient of determination is computed by applying linear regression treating the critical deposition for acidity as the dependent variable and the input variables ANC_w to the BC : Al ratio as the independent variables (sample size = 500).

Table 6.1. *Specification of distribution functions and data ranges in southern Europe for the input variables used in SSMB.*

Name	Type[1]	Mean	Standard Dev.	Min	Max.
ANC_w	nor	5302	4119	279	10000
Q_{con}	log	139	185	11	1962
Q_{dec}	log	197	217	18	2254
BC_{dep}	nor	859	619	116	2047
$BC_{u(con)}$	nor	261	142	0	564
$BC_{u(dec)}$	nor	588	233	0	928
$N_{u(con)}$	nor	278	151	0	600
$N_{u(dec)}$	nor	518	206	0	817
K_{gibb}	tri	595.58	---	300	950
$BC{:}Al$	log	1	1.2	0.1	10

1. nor = normal; log = log-normal; tri = triangular; lun = log-uniform.

Table 6.2. *Specification of distribution functions and data ranges in middle Europe for the input variables used in SSMB.*

Name	Type[1]	Mean	Standard Dev.	Min	Max.
ANC_w	lun	2632	3050	187	10000
Q_{con}	log	117	181	19	1743
Q_{dec}	log	182	210	20	2006
BC_{dep}	log	668	384	88	1964
$BC_{u(con)}$	log	269	138	0	854
$BC_{u(dec)}$	log	552	212	0	1006
$N_{u(con)}$	log	287	147	0	909
$N_{u(dec)}$	log	486	187	0	886
K_{gibb}	tri	595.58	---	300	950
$BC{:}Al$	log	1	1.2	0.1	10

1. nor = normal; log = log-normal; tri = triangular; lun = log-uniform.

Table 6.3. *Specification of distribution functions and data ranges in northern Europe for the input variables used in SSMB.*

Name	Type[1]	Mean	Standard Dev.	Min	Max.
ANC_w	log	1699	2966	158	10000
Q_{con}	log	201	271	12	2144
Q_{dec}	log	287	292	12	2418
BC_{dep}	log	321	195	52	939
$BC_{u(con)}$	nor	220	112	6	508
$BC_{u(dec)}$	nor	482	254	13	924
$N_{u(con)}$	log	167	100	4	479
$N_{u(dec)}$	nor	329	195	7	749
K_{gibb}	tri	595.58	---	300	950
$BC{:}Al$	log	1	1.2	0.1	10

1. nor = normal; log = log-normal; tri = triangular; lun = log-uniform

Table 6.4. *Specification of distribution functions and data ranges in total Europe for the input variables used in SSMB.*

Name	Type[1]	Mean	Standard Dev.	Min	Max.
ANC_w	lun	2950	3526	158	10000
Q_{con}	log	156	227	11	2144
Q_{dec}	log	229	254	12	2418
BC_{dep}	log	555	434	52	2047
$BC_{u(con)}$	nor	247	130	0	854
$BC_{u(dec)}$	nor	529	238	0	1006
$N_{u(con)}$	nor	234	142	0	909
$N_{u(dec)}$	nor	425	211	0	886
K_{gibb}	tri	595.58	---	300	950
$BC{:}Al$	log	1	1.2	0.1	10

1. nor = normal; log = log-normal; tri = triangular; lun = log-uniform

It should be noted that distribution types were conjectured to match the mean, minimum and maximum values which were extracted from the European data base for each of the input variables in the sub-regions. For most of the variables a satisfactory result was obtained. For base cation weathering it was more difficult to specify a distribution function reflecting the standard deviation from the European data base appropriately. This might lead to an underestimation of the importance of ANC_w in the computation of the critical deposition for acidity.

6.3 Results

Table 6.5 shows which of the input variables contributes most to the uncertainty, i.e. the variance of the critical deposition for acidity.

The contribution of ANC_w to the uncertainty of the critical deposition for acidity is most important in each of the three regions. In southern and middle Europe 93% or more of the uncertainty is explained by variation of ANC_w for both coniferous and deciduous forest soils. In northern Europe importance of ANC_w is decreasing explaining 89% and 87% of the uncertainty of critical deposition in coniferous and deciduous forest soils respectively.

Next, the variability of Q and BC_{dep} contribute most to the uncertainty of critical deposition for acidity. This is generally true for all European forest soils except in northern European deciduous forest soils where nitrogen uptake (N_u) takes over the, minor, role of BC_{dep}. Northern Europe also distinguishes itself from the other two regions by a more striking importance of Q in comparison to BC_{dep}.

Finally, note that the variability of K_{gibb} and BC : Al is of insignificant importance in the critical load assessment. The results with respect to ANC_w and Q are consistent with an uncertainty analysis focussing on a different regional breakdown (de Vries *et al.*, 1992).

The result of a sensitivity analysis is provided in Table 6.6, which shows that the computed critical deposition for acidity of coniferous forest soils will change by 0.79%, 0.71% and 0.67% due to a 1% change of ANC_w in southern, middle and northern Europe respectively. The changes are slightly less with respect to deciduous forest soils (0.78%, 0.68%, and 0.60%, respectively).

In southern and middle Europe BC_{dep} is contributing more to critical deposition sensitivity than in northern Europe where Q takes over. Note that Q is more sensitive for computed critical deposition of deciduous forest soils in comparison to coniferous soils, the latter for which BC_{dep} is more sensitive. Also note the relative importance of N_u in middle, northern and total Europe.

Table 6.5. *Uncertainty contributions of the input variables to the critical deposition for acidity computed for southern, middle, northern and total Europe (in percent).*[1]

	southern		middle		northern		total	
	coniferous	deciduous	coniferous	deciduous	coniferous	deciduous	coniferous	deciduous
ANC_w	94	93	94	94	89	87	93	93
Q	3	4	2	3	8	9	3	4
BC_{dep}	3	2	1	1	1	0	2	1
N_u	0	0	0	0	0	1	0	0
BC_u	0	0	0	0	0	0	0	0
K_{gibb}	0	0	0	0	0	0	0	0
$BC{:}Al$	0	0	0	0	0	0	0	0
R^2	1	.99	.99	.99	.98	.98	.99	.99

1. percentages have been rounded.

Table 6.6. *Absolute sensitivity contributions of a 1% change relative to the mean of the input variables to the critical deposition for acidity computed for southern, middle, northern and total Europe (in percent).*[1]

	southern		middle		northern		total	
	coniferous	deciduous	coniferous	deciduous	coniferous	deciduous	coniferous	deciduous
ANC_w	0.79	0.78	0.71	0.68	0.67	0.60	0.71	0.68
Q	0.06	0.08	0.09	0.12	0.19	0.23	0.11	0.14
BC_{dep}	0.14	0.12	0.18	0.14	0.11	0.05	0.15	0.11
N_u	0.04	0.07	0.08	0.12	0.06	0.12	0.07	0.11
BC_u	– 0.04	– 0.06	– 0.06	– 0.08	– 0.06	– 0.05	– 0.06	– 0.07
K_{gibb}	– 0.01	– 0.02	– 0.02	– 0.04	– 0.06	– 0.06	– 0.03	– 0.04
$BC{:}Al$	0.00	0.00	0.00	0.00	– 0.01	– 0.02	0.00	– 0.01

1. percentages have been rounded.

Finally, it has been observed that the results on overall variability as proposed in Table 6.5 and 6.6 generally hold when an analysis is focused on the 5-percentile critical deposition for acidity.

It is estimated that data on ANC_w and Q may vary by 50% and 25% respectively, compared to actual rates (de Vries, pers. commun.; see also de Vries, 1992) for a few areas in Europe. Q may be underestimated in central Europe, whereas BC_w may be overestimated in Southern Europe, but in general, estimates of these variables are reasonably reliable. However, taking the results of Table 6.6 into account, the effect of inaccurate estimates of ANC_w in southern Europe may be that the currently computed critical deposition for acidity in southern Europe is about 39% too high. Underestimation of Q might imply a current underestimation of the critical acid deposition in parts of central Europe in a range of 2% to 3%.

Also, data on base cation deposition needs to be improved. It is currently not clear how well BC_{dep} model inputs are consistent with real data. A better understanding of the convolution of natural and anthropogenic sources of BC_{dep}, including the effect of SO_2 abatement techniques, is required in order to improve the assessment of the uncertainty of critical deposition of acidity.

6.4 Conclusions and final remarks

Uncertainty analysis described in this chapter was limited to the critical deposition for acidity applied to three broadly defined parts of Europe using data from the European data base. The conclusion of ANC_w, Q and to some extent, BC_{dep} being most important variables is not surprising and consistent with other, independent, findings. The current knowledge of the quality of the data for the two variables does not lead to pessimism about the reliability of the critical deposition computation results which were used for designing alternative abatement strategies by the Task Force on Integrated Assessment Modelling. Current knowledge about the quality of the data for base cation deposition needs to be improved.

Further work with respect to uncertainty analysis will have to include:

- **computations of critical loads, critical deposition and exceedances:** with the upcoming necessity for a renewed nitrogen or acidification protocol it is necessary to apply uncertainty analysis to the results of the methodology applied in Chapter 4.

- **national data:** The application of European data was appropriate because of its consistency throughout Europe. However, it may be of interest to perform uncertainty analysis on national computations using national data. This would provide insight in the extent to which the reliability of results provided to CCE would vary over countries.

- **regions with specific characteristics:** The division of Europe into three distinct parts was obtained in a rather arbitrary way using the general indication of increased sensitivity of northern ecosystems in comparison to southern ecosystems as a guideline. Extending the analysis to include regions with very specific characteristics (e.g. very high precipitation, very high weathering, many watersheds) may allow for the identification of areas in Europe for which homogenous characteristics can be formulated (cf. Hettelingh *et al.*, 1992b). This could allow for targeted improvements of either data or computation methodologies.

- **regions where other methodologies for the critical load computations were applied:** In some parts of Europe critical loads have been computed with SSMB for watersheds. A few other countries used the so-called "Level 0" method to assess critical loads. Data treatment at National Focal Centers and data submission to the Coordination Center for Effects also show variation over Europe (see Chapter 5). These distinct approaches may lead to specific uncertainties.

- **specific ecosystem characteristics:** A recent report by Sverdrup (1992) gives a thorough overview of BC : Al ratios for many species. Although the current uncertainty analysis did not reveal significant importance of the BC : Al ratio for the computation of the critical deposition for acidity, the inclusion of other than forest soils may become important. This is especially true as the critical loads/level methodology will include other pollutants and other than indirect effects.

- **improved exchange of data, measurements and other research results obtained under the convention of LRTAP:** Exchange of data and research results have been intensified between research participants of the Convention on Long-range Transboundary Air Pollution (LRTAP). Future activities will increase the exchange of compatible data of ecosystem characteristics between ICP's, NFC's and CCE. The computation and mapping of critical loads may benefit from measurement programs conducted by ICP's to assess reliability of critical load computations. On the other hand, reliability of assumptions made by the critical load mapping community to accommodate for specific policy requirements (e.g. the application of a sulphur fraction based on 1990 deposition) also requires evaluation of other programs under the LRTAP convention. Intensified collaboration of EMEP and CCE will enhance applicability of computed critical loads for the assessment of current, future or, more recently, historical air quality. A recent analysis by the EMEP program with respect to the relationship between historical (1880) deposition and critical loads (Mylona, 1993) needs further attention. In this study, the use of a critical load of sulphur using a sulphur fraction based on 1990 sulphur and nitrogen deposition, and a current estimate of base cation deposition, to assess historical exceedances, needs to be addressed carefully.

7. Conclusions and Recommendations

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7.1 General conclusions

The European critical loads mapping activities conducted for the LRTAP Convention of the UN ECE have progressed notably in recent years. The concept of designing pollution control measures with the aim of protecting the most sensitive ecosystems led to the creation of the Task Force on Mapping and Coordination Center for Effects to implement these concepts on a European scale.

The methods used to produce the sulphur critical loads maps in this report are the result of an extended process of collaborative deliberation among a large number of scientists across Europe. These procedures were first assembled in the Mapping Manual produced by the Task Force on Mapping in 1989, and further elaborated in a Mapping Vademecum. Many recent developments have resulted from numerous workshops organized to achieve scientific consensus on the methods, data, and assumptions used in the mapping activities. The resulting maps of critical loads reflect the current state of scientific knowledge concerning the sensitivity of forest soils and surface waters in Europe.

The proposed methods outlined in Chapter 4 to calculate critical loads and exceedances of nitrogen and sulphur simultaneously allow both the identification of combined effects and the consideration of alternative combinations of sulphur and nitrogen deposition in abatement strategies which do not lead to exceedances (the exceedance indifference curve).

It is therefore recommended that the Task Force on Integrated Assessment Modelling consider the above consequences at an early stage in its deliberations on nitrogen abatement. The proposed method for nitrogen strongly supports the suggestion that sulphur and nitrogen deposition should be modelled together and indicates that this is best done using exceedance indifference curves defined for each EMEP square. In this way an optimized approach for considering both sulphur and nitrogen together may be possible. In addition, the effect of other nitrogen-limiting aspects (e.g. ozone) can be assessed using the exceedance indifference curve.

The critical loads work conducted to date has been used as the basis for assessing European sulphur emission reduction strategies within the UN ECE Convention on Long-range Transboundary Air Pollution. It is expected that this method will be applied for future international agreements under the Convention.

The policy implications resulting from the methods described in this report would support the development of an acidification protocol. While this has been suggested in the past, it is only now that scientific knowledge has advanced sufficiently to consider the feasibility of such a policy.

7.2 Preliminary conclusions from the sensitivity analysis

The initial sensitivity analysis described in Chapter 6 identified ANC_{w}, Q and to some extent, BC_{dep} being most important variables which influence the calculation of critical loads in three broadly defined areas of Europe. The conclusion of is not surprising and consistent with other, independent, findings. The current knowledge of the quality of the data for the two variables does not lead to pessimism about the reliability of the critical deposition computation results which were used for the formulation of alternative abatement strategies by the Task Force on Integrated Assessment Modelling. Current knowledge about the quality of the data for base cation deposition needs to be improved.

Further work with respect to uncertainty analysis will have to include:
- computation methods for critical loads, critical depositions, and exceedances
- the use of national data in European critical load calculations
- examination of regions with specific characteristics (e.g. high-precipitation areas)

• regions where other methodologies for the critical load computations were applied:
• specific ecosystem characteristics, and
• improved exchange of data, measurements and other research results obtained under the convention of LRTAP.

Discussions between the CCE and the various International Cooperative Programs which conduct monitoring and assessment programs for a variety of ecosystems and receptors, have begun and will continue. Efforts will be made to use the comprehensive data bases developed by the programs to the maximum extent practicable.

7.3 Future activities

The guidelines contained in Chapter 4 of this report will serve as the basis for beginning the process of examining the effects of two pollutants, sulphur and nitrogen, simultaneously. It is expected that future critical loads maps will address:
• additional ecosystem types
• critical levels (air concentrations)
• synergisms between and among pollutants
• temporal aspects of exceedances (i.e. damage time lags)
• continued quality control of methods and data

A CCE workshop to be held in early 1994 will review progress on implementing the mapping guidelines, and discuss future work. The first European critical loads maps for both sulphur and nitrogen will be produced and circulated for review in 1994.

In addition, a number of international workshops have been held recently to address issues concerning the calculation and mapping of critical levels for ozone. Possibilities for inclusion of ozone in the assessment of combined effects described in Chapter 4 will be investigated in 1994.

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List of Mathematical Notation and Acronyms

A_{cell} = area of the national grid cell (km^2)
A_{dep} = total acidity deposition
A_{eco} = ecosystem surface area in the national grid cell (km^2)
A_{EMEP} = area of EMEP cell (km^2)
$A_{EMNA,C,j}$ = area of nation C in EMEP cell j (km^2)
A_{LOLA} = area of LOLA-nation-EMEP cross-section (km^2)
A_{soil} = total acidity produced by soil processes
$Ac_{le(crit)}$ = critical leaching flux of acidity
$Al^{3+}{}_{limit}$ = critical aluminum leaching
Alk_{le} = alkalinity leaching
$ANC_{l(crit)}$ = acid neutralizing capacity consumed by maximum acceptable alkalinity leaching at critical load
ANC_{limit} = ANC threshold
ANC_{w} = ANC produced by weathering
$[BC]_0^*$ = original sea-salt corrected base cation concentration
$(BC:Al)_{crit}$ = critical base cation : aluminum ratio
BC_a = base cation availability
BC_{CaCO3} = weathering influenced by reaction with carbonate minerals
BC_{dep} = total non-marine base cation deposition
BC_{exch} = weathering influenced by exchangeable base cations in soil
BC_{gu} = growth uptake of base cations
BC_l = limiting concentration for uptake of base cations
BC_{le} = base cation leaching
$BC_{le(min)}$ = minimum base cation leaching
BC_u = net uptake of base cations in the tree biomass
BC_w = base cation weathering
BC_w^* = weathering of other soil minerals
BC_{wd} = wet base cation deposition
C_t = hydrothermal coefficient
$CD(N)$ = critical nitrogen deposition
$CD(S)$ = critical sulphur deposition
$CL(A)$ = critical load of acidity
$CL(Ac_{act})$ = critical load of actual acidity
$CL(Ac_{pot})$ = critical load of potential acidity
$CL(N)$ = critical load of nitrogen
$CL(P)$ = critical load of phosphorus to avoid an alteration of trophic level
$CL(S)$ = critical load of sulphur
$CL_{max}(N)$ = maximum critical load of nitrogen
$CL_{max}(S)$ = maximum critical load of sulphur
$CL_{min}(N)$ = minimum critical load of nitrogen
$CL_{min}(S)$ = minimum critical load of sulphur
$CL_{nut}(N)$ = critical load of nutrient nitrogen
C_{upt} = coefficient of nitrogen uptake by vegetation
EF_{cell} = ecosystem surface area as a fraction of the national grid cell area
EP_{cell} = ecosystem surface area as a percentage of the national grid cell area (%)
EP_{EMEP} = ecosystem surface area of a LOLA cell as a percentage of the EMEP cell area (%)
EP_{LOLA} = ecosystem surface area of a LOLA cell as a percentage of the LOLA cell area (%)
f = fraction of forested land in a catchment area
FW = water flux ($m^3\ ha^{-1}\ yr^{-1}$)
h = elevation (m)
$H^+{}_{limit}$ = critical hydrogen leaching
k = denitrification rate coefficient
K = saturation coefficient (2900 eq $ha^{-1}\ yr^{-1}$)
k_0 = kinetic rate constant (1810 eq $ha^{-1}\ yr^{-1}$)
K_{gibb} = gibbsite coefficient ($m^6\ eq^{-2}$)
$n_{C,j}$ = number of data points in nation C and EMEP cell j

$[N]_{crit}$ = critical nitrogen soil solution concentration
N_{de} = denitrification
N_{dep} = nitrogen deposition
N_{exp} = export of organic nitrogen out of the catchment
N_i = net immobilization of nitrogen in the root zone
$N_{i(crit)}$ = critical nitrogen immobilization
N_{gu} = growth uptake of nitrogen
N_l = nitrogen leaching
$N_{l(crit)}$ = critical nitrogen leaching
$N_{l(crit)w}$ = critical nitrogen leaching to avoid surface water eutrophication
N_{NMC} = actual nitrogen mineralizing capacity of soils
N_{ret} = in-lake retention of nitrogen
N_{td} = total nitrogen deposition
N_u = net uptake of nitrogen in the tree biomass
$N_{u(crit)}$ = critical nitrogen uptake
P_c = critical phosphorus concentration to subdivide trophic levels
pH = soil solution pH
$P_{i,\,eco}$ = cumulative ecosystem percentage related to the ecosystem area of an EMEP cell at ecosystem i
$P_{i,\,EMNA}$ = cumulative ecosystem percentage related to the total EMEP-nation cross-section cell at ecosystem i
$P_{i,\,EMEP}$ = cumulative ecosystem percentage related to total EMEP cell area at ecosystem i
$P_{max,\,EMNA}$ = cumulative ecosystem percentage related to the total EMEP-nation cross-section cell at the maximum national critical load value
$P_{max,\,EMEP}$ = cumulative ecosystem percentage related to the total EMEP cell area at the maximum national critical load value
ρ_N = in-lake nitrogen retention
ρ_S = in-lake sulphur retention
Q = water flux from the bottom of the rooting zone ($m^3\ ha^{-1}\ yr^{-1}$)
r = lake : catchment area ratio
S_{dep} = sulphur deposition
S_{ret} = in-lake retention of sulphur
t = period of water exchange (yr)
T = temperature (°C)
w = relative soil moisture saturation (Θ/Θ_s)
$w_{C,\,j,\,i}$ = area weight factor for ecosystem point i of nation C in EMEP cell j
$W_{C,\,j,\,i}$ = total ecosystem surface area at point i in nation C and EMEP cell j (km^2)
$W_{catchment}$ = weathering rate of base cations on the whole path (not only rooting zone) percolated by the runoff
$X_{BC:N}$ = ratio of cations to nitrogen in exported biomass
$[X]_{crit}$ = limiting concentration for uptake of nutrient X
X_{dep} = atmospheric deposition of element X
$X_{u(crit)}$ = critical uptake of element X (X = Ca, Mg, K, P)
X_w = production of element X from weathering
$x_{X:N}$ = ratio of nutrient X to nitrogen during uptake ($eq\ eq^{-1}$)
Y = nitrogen mineralizing capacity
z = average depth of water bodies (m)

Acronyms:

CCE = Coordination Center for Effects
CDF = cumulative distribution function
EMEP = Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe
GIS = geographic information system
LOLA = longitude-latitude
LRTAP = (Convention on) Long-Range Transboundary Air Pollution
NFC = National Focal Center
SSMB = Steady-State Mass Balance model
TFIAM = Task Force on Integrated Assessment Modelling
TFM = Task Force on Mapping
UN ECE = United Nations Economic Commission for Europe

APPENDIX I. National Focal Center Reports

AUSTRIA

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A. Critical Loads of Acidity

Receptor mapped:

Forest soils.

Calculation method:

Steady-state mass balance method.

Grid size:

2.75 x 2.75 km; approximately 11,000 receptor points, nearly 8000 of which are (partially) covered by forest.

Data sources:

Geographical: A number of regional parameters are required to determine the critical load for a given ecosystem. To date the following data bases have been identified as being useful for the model purpose:

- The inventory of soil types in Austria based upon Fink (1978).
- Geological data extracted from the "Geological Map of Austria" from the Austria Atlas.
- Soil types according to FAO classifications have been derived by overlaying the above-mentioned maps.
- Forest data have been taken from the "Austrian Forest Inventory 1971–80" on a 2.75 x 2.75 km grid.
- Precipitation patterns have been estimated on information provided by the Technical University Vienna (Behr, 1989).
- Evapotranspiration has been estimated by applying empirical relationships between altitude and evapotranspiration in the Alpine regions (Baumgartner *et al.*, 1983).

Ion deposition: Due to its orography, major local variations in acid deposition occur throughout Austria. Therefore, data on acid deposition had to be derived on a small scale for all of Austria. Relevant information is available from the Institute for Analytical Chemistry at the Technical University Vienna (Kovar *et al.*, 1991). However, in order to derive the local deposition from the EMEP-computed average grid deposition the following approach has been developed:

Wet deposition: The measured sulphur and nitrogen concentrations in precipitation were spatially interpolated and superimposed on a map of local precipitation, This precipitation maps was based on measurements and a digital surface model. Within this project, the described method has been tested and compared with the measured deposition at some EMEP measuring sites.

Dry deposition: The measured concentrations of air pollutants in rural areas have been spatially interpolated. Using empirical exponential functions, the altitude was taken into account in the calculations. Based on this regional distribution, dry deposition has been calculated with the aid of a velocity factor.

Occult deposition: Because of the lack of measurements, deposition loads from fog and clouds in forest are estimated by adding 50% of the wet deposition values to total deposition (Kovar *et al.*, 1991).

Evapotranspiration: Data from Baumgartner *et al.* (1983) has been corrected for deciduous (+240 mm yr^{-1}) and coniferous (+120 mm yr^{-1}) forests; for northward-oriented slopes (+67.5° from the north) with an inclination larger than 30%, a 30% lower evapotranspiration rate has been assumed. The corrections were adapted with a constant value so that the total water balance for Austria did not change.

Runoff: For slopes with an inclination larger than 30%, a surface runoff of 20% of the precipitation has been assumed. The runoff used in critical load calculation is therefore reduced by that amount. Runoff values are then checked to ensure that they are always positive.

Soil characteristics: The procedure for deriving soil characteristics applicable to the suggested modelling approach was discussed at an international expert meeting held at IIASA in spring 1990. The results of this meeting not only influenced the design of this study, but have directly been incorporated into the Mapping Vademecum (Hettelingh and de Vries, 1991).

Table A1.1 is based on the guidelines in the Mapping Vademecum. Data were checked and adapted for Austria together with Assistant Prof. Solar from the Universität für Bodenkultur, Vienna. This table enables the derivation of the model input data for soil characteristics from the available soil map.

Table A1.1. *Soil characteristics in Austria.*

Soil Type			Code	Class
Lithosol a. Kalk	Eutric Lithosols	Ie	488	10
Lithosol a. Kalk	Eutric Lithosols	Ie	488	1 (>1500m a.s.l.)
Lithosol sonst.	Dystric Lithosols	Id	493	2
Regosols	Calcaric Regosols	Rc	312	3
Rendsina (alpin)	Orthic Rendzinas	Eo	160	6
Rendsina (alpin)	Orthic Rendzinas	Eo	160	1 (>1500m a.s.l.)
Rendsina sonst.	Rendzinas	E	168	2
Parabraunerde	Orthic Luvisols	Lo	327	4
Schwarzerde	Chernosem	Ch	678	4
Braunerde a.K.	Eutric Cambisols	Be3	3	10
Braunerde sonst.	Dystric Cambisols	Bd1	320	1
Braunlehm, Rotlehm	Eutric Cambisols	Be1	319	4
Reliktboden a.K.	Eutric Cambisols	Be2	316	5
Reliktboden sonst.	Dystric Cambisols	Bd2	2	3
Podsol	Orthic Podsol	Po	570	1
Pseudogley + Rel. Pg.	Gleyic Luvisols	Lg	705	5
Semipodsol	Leptic Podsols	Pl	559	1
Paratschnernosem	Luvic Phaeozems	Hl	39	3
Feuchtschwarzerde	Haplic Phaeozems	Hh	676	2
Hochmoore	Dystric Histosols	Od	959	0
Niedermoore	Eutric Histosols	Oe	955	0
Auböden, grau	Eutric Fluvisols	Je	996	10
Auböden, braun	Dystric Fluvisols	Jd	998	3
Gleye a. Kalk	Eutric Gleysols	Ge	972	10
Gleye sonst.	Dystric Gleysols	Gd	707	5

Since comprehensive soil motoring is currently being undertaken in Austria, a later stage of the project will test, improve or partly replace this preliminary table with more precise information.

The values for the various weathering classes in this table are based on the report of the workshop on "Critical Loads for Nitrogen and Sulphur" held in Skokloster, Sweden (Nilsson, 1986). In order to reflect the very thin organic soil layers in high alpine regions – with in fact very little contact to the calcareous bedrock material – a very slow weathering rate was assumed for these soil types in altitudes above 1500 m above sea level (Stöhr *et al.*, 1989; see Table A1.1).

Biomass uptake: Biomass uptake of base cations and nitrogen can be estimated based on the canopy type by multiplying the annual biomass increment (from Nilsson and Sallnäs, in press) with the proper element contents (from de Vries, 1988; see Table A1.2). These data are available for trees in areas with moderate (or low) concentrations of elements in soil. At very high or very low concentrations of base cations or nitrogen in soil water, additional process become important, that may lead to systematic errors. In order to provide consistency for low concentrations, the computed potential uptake has been checked against the availability of nutrients in the soil. The base cation input minimum value was assumed as 50 (rather than 100) eq ha^{-1} yr^{-1}, which seems more appropriate for Austrian conditions.

Table A1.2. *Data on element contents in trees for Austria.*

Species	Forest increment (m^3 ha^{-1} yr^{-1})	Stem density (kg m^{-3})	Stem Content %				Branch Content %				Ratio Br/Stem
			N	Ca	Mg	K	N	Ca	Mg	K	
Scotch pine	5.0	490	0.11	0.09	0.02	0.05	0.40	0.24	0.05	0.20	0.15
Douglas fir	8.9	410	0.08	0.05	0.01	0.05	0.31	0.50	0.06	0.26	0.10
Norway spruce	10.0	450	0.10	0.12	0.02	0.06	0.57	0.34	0.07	0.37	0.15
Oak	7.0	740	0.19	0.20	0.05	0.13	0.37	0.50	0.05	0.19	0.38
Beech	7.0	860	0.13	0.09	0.03	0.09	0.44	0.27	0.03	0.16	0.23
Coniferous	10.0	500	0.10	0.08	0.02	0.05	0.35	0.35	0.05	0.25	0.15
Deciduous	7.0	700	0.15	0.10	0.04	0.10	0.45	0.50	0.05	0.20	0.20

B. Critical Loads of Eutrophication

Receptors mapped:
Forests and natural non-forest areas

Calculation method:
Steady-state mass balance and expert knowledge

Grid size:
2.75 x 2.75 km; approximately 11,000 receptor points, nearly 8000 of which are (partially) covered by forest.

General approach:
Due to the development of guidelines for the computation and mapping of critical loads and exceedances of sulphur and nitrogen, preliminary calculations of critical loads of eutrophication were made. From literature on field investigations and experimental results it is known that nitrogen reactions are highly variable, depending on dynamical characteristics of several environmental factors. Until now it is not possible to estimate ranges and probabilities of relevant data over large areas in Austria. Therefore it was decided to employ robust formulas for calculating critical loads of forest area. For ecosystems other than forest areas, only fixed values based on recommendations from the Lökeberg workshop were used. Because the ranges of the Lökeberg values are conditioned by uncertainties, in most cases median values were used.

Definition of receptors:
The same grid structure as for acidification was used to define and calculate eutrophication. It is therefore simple to combine acidification data with eutrophication data by geographical area. The predominating ecosystem in each 2.75 x 2.75 km grid unit was defined. To reduce the risks of secondary effects in alpine regions, lateral transport between

ecosystems were considered. Due to this relationship, the following ecosystems were classified because of their influences on other ecosystems:

- bare rocks, because of possible influences on alpine vegetation at lower elevation levels; and
- glaciers, because of possible influences on small alpine lakes.

Critical loads for these two ecosystems were defined similar to the critical loads of influenced ecosystems (Table A1.3).

Table A1.3. *Critical loads for land use types other than forests.*

Land Use Type	Critical loads (kg N ha^{-1} yr^{-1})
Alpine heathland	10
Lowland grassland on calcareous soils	19
Lowland grassland on non-calcareous soils	
precipitation < 800 mm yr^{-1}	10
precipitation > 800 mm yr^{-1}	25
Shallow lakes	7
Alpine bare rocks	10
Glaciers	7
Mesotrophic fens	20
Ombrotrophic bogs	5

Additional data sources:

To consider sensitive ecosystems and elevation influences, the data base was extended by:

- the digital elevation model of Austria.
- data on forest ecological areas, published by "Österreichischer Forstverein".
- digital map of bogs of Austria developed by the Federal Environmental Agency of Austria.

Calculation of critical loads for forests:

Calculations of critical loads for eutrophication were oriented on tree growth values from periods prior to 1950. Nitrogen uptake factors for deciduous forests and coniferous forests outside alpine areas were set as constant, depending on the dominant tree species. Critical loads of alpine coniferous forests were calculated by using an uptake function depending on elevation. This function was developed by using published growth factors of spruce in alpine regions and by adapting this function to uptake rates within an elevation range between 600 and 2000 meters above sea level (Table A1.4).

Table A1.4. *Factors used for calculating critical loads of eutrophication of forests. All terms except denitrification fraction are in kg N ha^{-1} yr^{-1}.*

Factor	Value
Denitrification fraction (see Section 4.2.3.4)	0.4
Critical nitrogen leaching:	
coniferous forest	4
deciduous forest	5
Nitrogen immobilization	3
Nitrogen uptake: (N_u)	
Beech	6
Oak	9
Spruce: region of Wald-, Mühlviertel	5
other areas outside alpine regions	7
alpine areas (600–2000 m above sea level):	*

* for alpine areas:
$N_u = 6 \cdot [3.664 - 0.501 \cdot \ln (h - 500)]$
where h = elevation (m)

Figures:

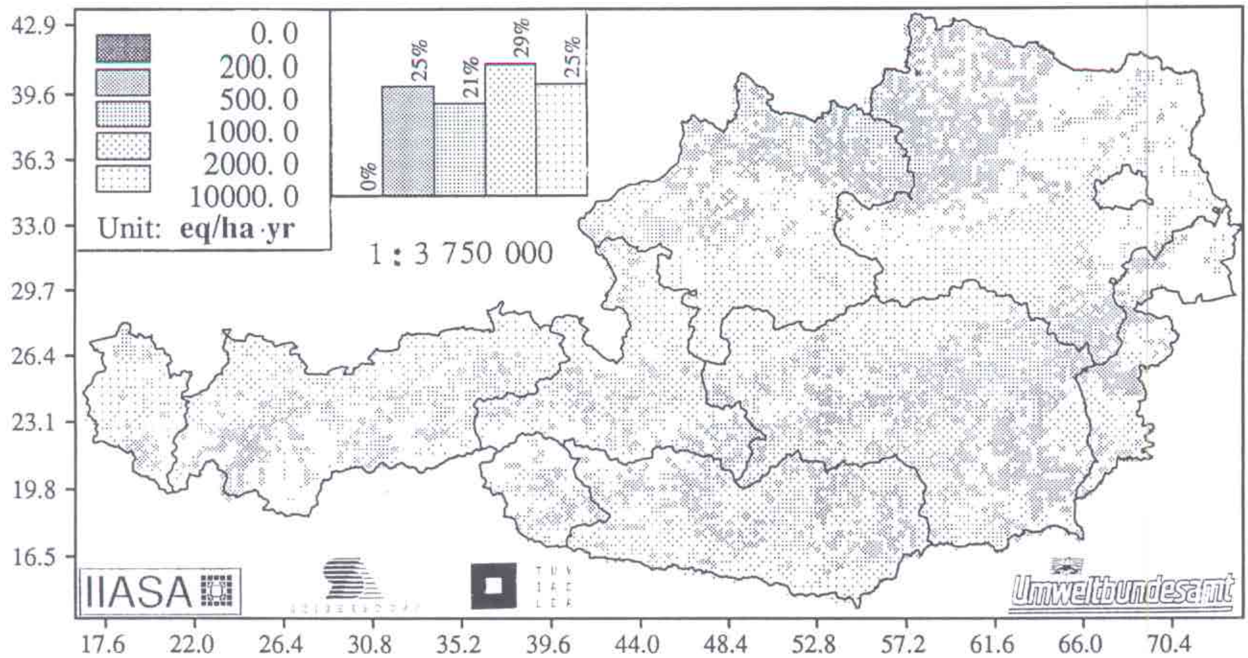

Figure A1.1. *Austria: Critical loads of actual acidity.*

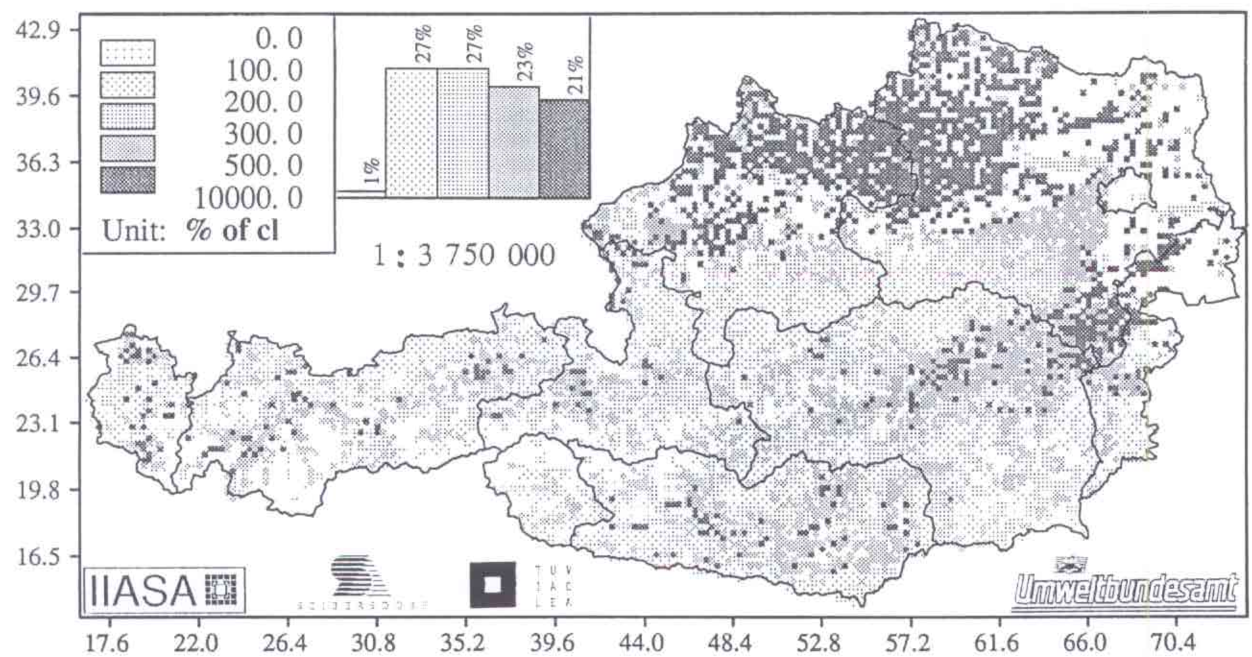

Figure A1.2. *Austria: Exceedance of critical loads of actual acidity.*

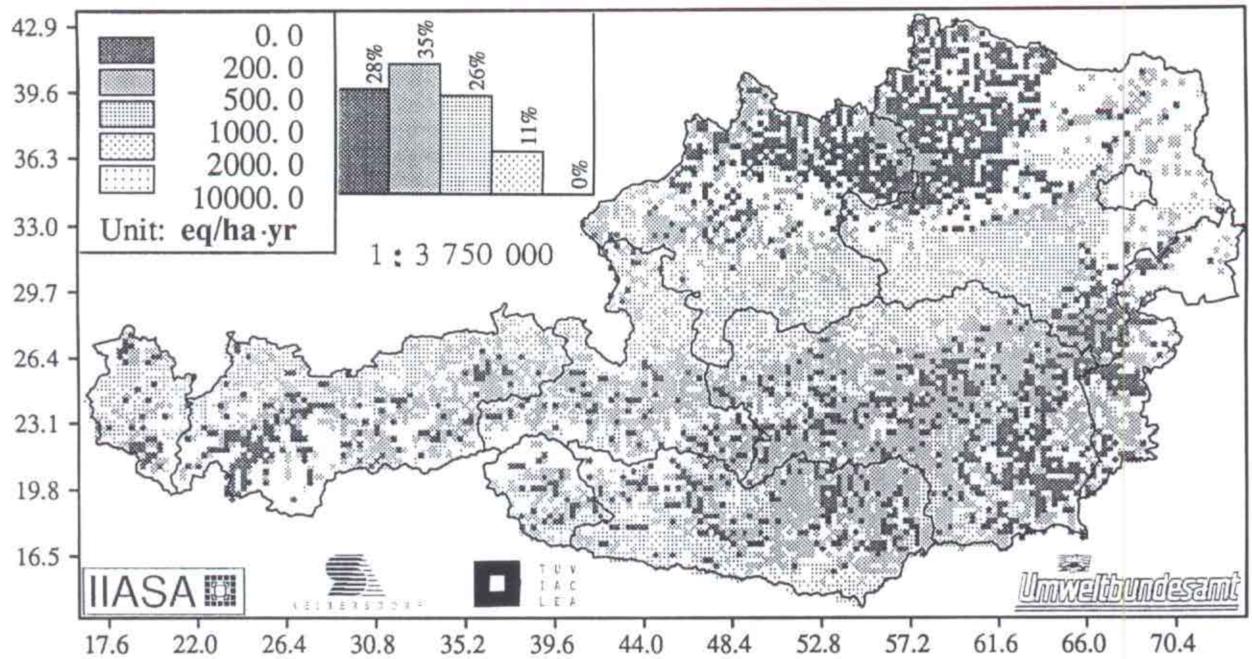

Figure A1.3. *Austria: Critical load of sulphur.*

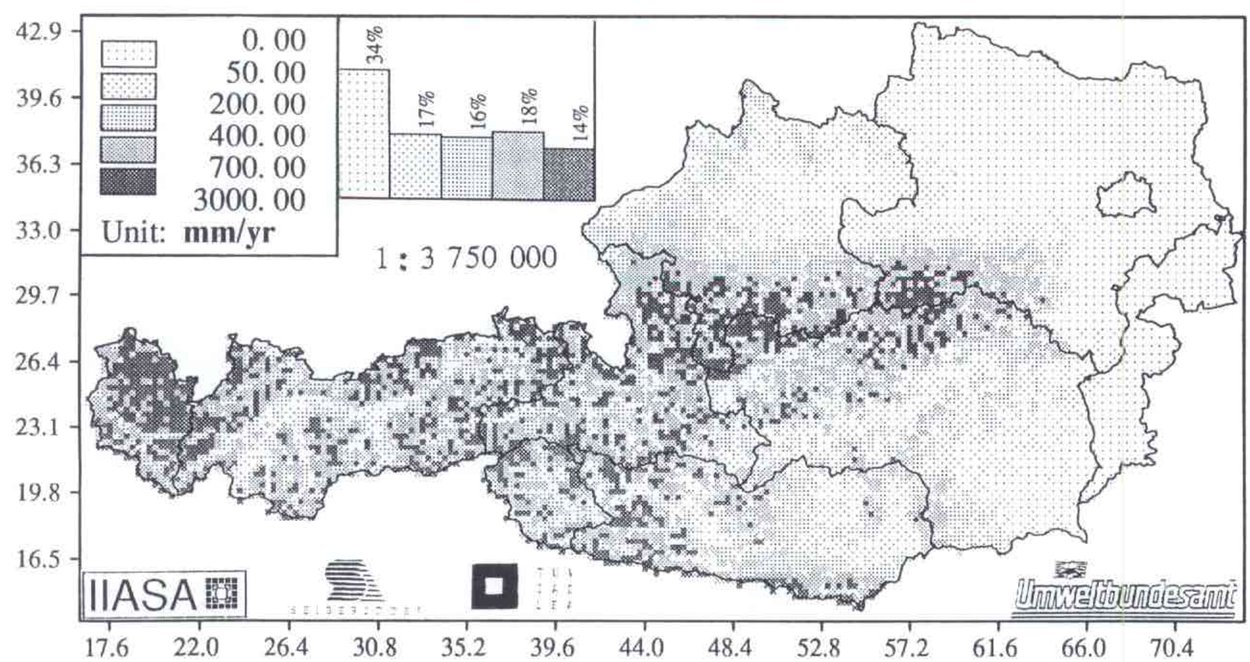

Figure A1.4. *Austria: Precipitation surplus.*

DENMARK

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Receptors mapped:

Forest soils, permanent grassland

Calculation method:

Steady-state mass balance method

The PROFILE model has been used for calculating the critical load values $CL_{min}(S)$, $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$ for acidification of soils. The criteria used is Ca : Al > 1 just below the root zone. This is a modification from the Mapping Manual (UN ECE, 1990), which states that the soil criteria has to be maintained everywhere in the root zone.

Calculations have been made for the following types of ecosystems:

- Beech-dominated forest
- Oak-dominated forest
- Spruce-dominated forest
- Pine-dominated forest
- Permanent, unmanaged grasslands

For each km^2, the following data have been collected or calculated:

- ecosystem cover
- soil mineral content for A/E and B horizons
- soil texture
- precipitation
- SO_4, NO_3, NH_4, BC and BC^* depositions
- removal of biomass by harvesting

The critical load values are calculated as 1, 5, 15 and 50 percentile values from ecosystem cover on a 5 x 5 km grid. As data are aggregated on a 1 x 1 km grid, the critical load values for an ecosystem can be calculated on a 1 x 1 km grid. The calculations are only performed for ecosystems covering more than 1% of the total ecosystem area in a 5 x 5 km grid cell, giving a total number of 20,000 calculations for the entire area.

To limit the number of calculations, the main variables have been divided into a limited number of classes, e.g. 6 classes of precipitation and 13 classes of mineral content. Only cells with a unique combination of input parameters have to be calculated, totalling 1500 model calculations.

Grid Size/Aggregation Methods:

Data have been collected from a number of existing sources. Where digital maps have been available, these maps have been used. Some data, such as soil mineral content are only available as point registrations. In these cases interpolation methods have been applied. From digital vector maps and point sources, raw data have been aggregated on a 100 x 100 m grid. From these grids, the basic data for the critical load calculations are aggregated to a 1 x 1 km grid.

The critical load calculations are performed on 1 x 1 km data. For each 1 x 1 km grid cell the percent cover of the mapped ecosystem types is calculated. For ecosystem types giving more then 1 percent ecosystem cover in a 5 x 5 km grid cell, critical load values are calculated. Percentile values of critical loads are calculated on a 5 x 5 km grid.

The sources and resolution of the data used in the Danish critical load mapping are shown in Table A1.5 below.

Table A1.5. *Sources and resolution of input data.*

Parameter	Resolution	Source
Soil mineralogy	60 points	DLD, literature
Soil texture	1 : 500,000	DLD
Geological type	1 : 500,000	DLD
Forest limits	1 : 500,000	DLD
Forest production and species composition	1 : 500,000 4000 registrations	DLD, DSO
Ecosystem cover	1 km grid	NERI
Unmanaged forests	point data	NFNA
Deposition	1.5 km grid	NERI, EMEP

DLD: Danish Institute of Plant and Soil Science, Dept. of Land Data
DSO: Danish Statistical Office
NERI: National Environmental Research Institute
NFNA: National Forest and Nature Agency

Data sources:

Deposition: Sulphur deposition is calculated from EMEP concentrations and deposition constants derived from data for throughfall and air concentrations from 10 sites in Denmark.

Base cation deposition has been calculated from a limited number of deposition data from Denmark and southern Sweden. The concentration of non-marine base cations in precipitation has been estimated to be 20 µg l^{-1}. The total non-marine base cation deposition has been calculated by multiplying the wet deposition by the ratio of sodium from throughfall to deposition for the different vegetation types. The marine deposition of Ca, Mg and K has been calculated based on an empirical relation between throughfall of sodium and the distance from the Danish North Sea coast.

A new set of model calculations of NH_x and NO_y has been performed for the critical load calculations (Asman, 1993). The model calculations have been validated on a set of measured depositions. The modelled NH_x wet and dry deposition, and NO_y dry deposition fits well with the measured data. For the NO_y wet deposition, the correlation is poorer, and the average measured wet deposition of NO_4 was used.

Vegetation: A total registration of the production in Danish forests was performed in 1979–1982 (Skovregistreringen, 1986). These data have been available on a digital basis. Although there has been a development in the forested area, the production figures from this registration still seems in agreement with new figures from the Danish Statistical Office. Removal of nitrogen and base cations by harvest is calculated by multiplying the production figures with the mean element content in stem and branches.

For permanent, unmanaged grasslands, where critical loads calculations are performed, a removal rate of 30 kg N ha^{-1} by extensive use for grazing is assumed. The figures for effective root depth and uptake used in the calculations are listed below.

Table A1.6. *Values used in critical load calculations.*

	Root depth (cm)	BC uptake (keq km^{-2})	N uptake (keq km^{-2})
Beech	70	5.4· PC	10.4· PC
Oak	90	6.8· PC	10.4· PC
Spruce	45	3.7· PC	3.9· PC
Pine	45	1.8· PC	3.4· PC
Grass	25	5.1	3.0

PC: Production class, m^3 ha^{-1} yr^{-1}

Soil mineral content: Maps are available of the geology and texture classes of Danish topsoils. However the mineral content in the soils have though only been analysed on a limited number of points. Data from 60 sites have been made available from published and unpublished sources.

A map with 11 different classes of topsoil geology has been constructed. Within each of these classes, point data for mineral content have been interpolated for the A/E and B horizons to give a total map coverage. Three different rules have been used in the interpolation:

- Where measured data are available, the measured value is used.
- Between measuring points, an inverse distance-weighted interpolation between the closest measuring points and a mean value for the geological class is used.
- In areas where no measurements are available within a distance of 70 km, the mean value for the geological class is applied.

The surface area of the soils are calculated from the texture classes. The surface area of the clay fraction has been estimated to range from 8 m^2 g^{-1} with 5% clay to 40 m^2 g^{-1} with 95% clay in the soil. This estimate gives a lower sensitivity of clayey soils than shown by former Danish computations.

Aggregation of data: Data have been aggregated in a limited numbers of classes in order to limit the number of calculations. The classes of data used are shown in Table A1.7.

Table A1.7. *Aggregation classes used.*

Class	1	2	3	4	5	6
Precipitation (mm yr^{-1})	< 575	575–625	625–775	775–875	> 875	
BC deposition (keq ha^{-1} yr^{-1})	< 0.2	0.2–0.3	0.3–0.4	0.4–0.8	0.8–1.6	>1.6
BC from non-marine sources (%)	< 30	30–60	60–80	> 80		
Production class (m^3 ha^{-1} yr^{-1}):						
Beech	< 5	5–7	7–8	8–9	9–12	> 12
Oak	< 5	5–6	6–7	> 7		
Spruce	< 5	5–10	10–12	12–14	14–18	> 18
Pine	< 4	4–5	5–6	6–9	>9	
Soil mineral content	13 classes based on principal component analyses of the content of 9 minerals					

Results:

The present calculations are made for acidification of forest soils and permanent grasslands. The critical load value for nitrogen will be set by the eutrophication criteria for most Danish terrestrial ecosystems. As this value also will set $CL_{min}(S)$, the presented calculations are for $CL_{max}(S)$, i.e. the critical load value for sulphur with a nitrogen deposition of 0 or sulphur fraction of 1.

The lowest critical load values are found in areas with oak and pine forest at the North Sea coast of Jutland. For these vegetations, critical load values below 0.1 are found. These values are lower than previous calculations which were based solely on beech and spruce.

The clayey soils on Funen and Seeland are relatively insensitive to acidification. Compared to earlier Danish computations, the sensitivity of these soils is lower. The influence on the critical load values for the Danish EMEP grids will, however, be limited.

Figures:

A1.5. Denmark: $CL_{max}(S)$ for forest soil and permanent grassland, 1 percentile.

A1.6. Denmark: $CL_{max}(S)$ for forest soil and permanent grassland, 5 percentile.

A1.7. Denmark: Ecosystem type setting $CL_{max}(S)$, 1 percentile.

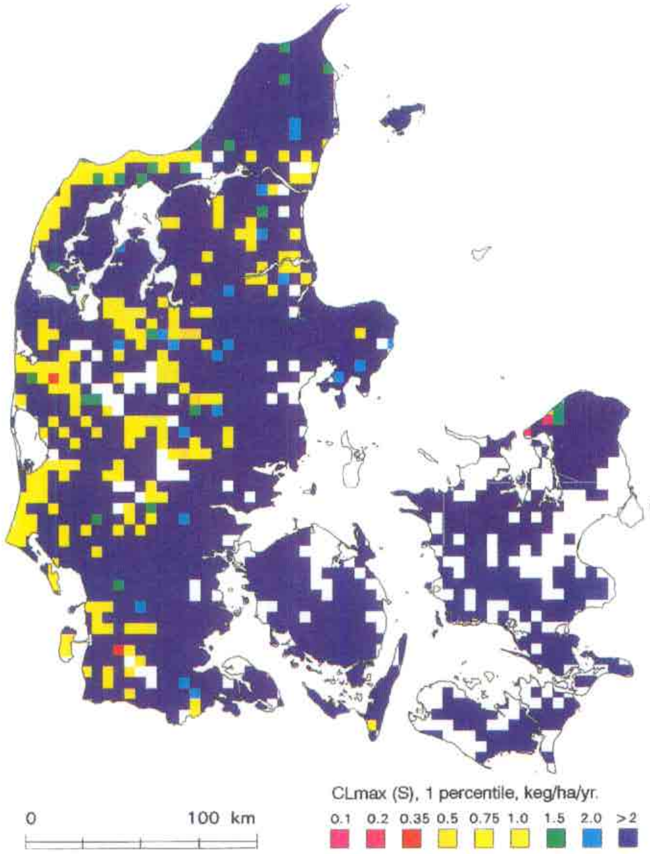

Figure A1.5. *Denmark:* $CL_{max}(S)$ *for forest soil and permanent grassland, 1 percentile.*

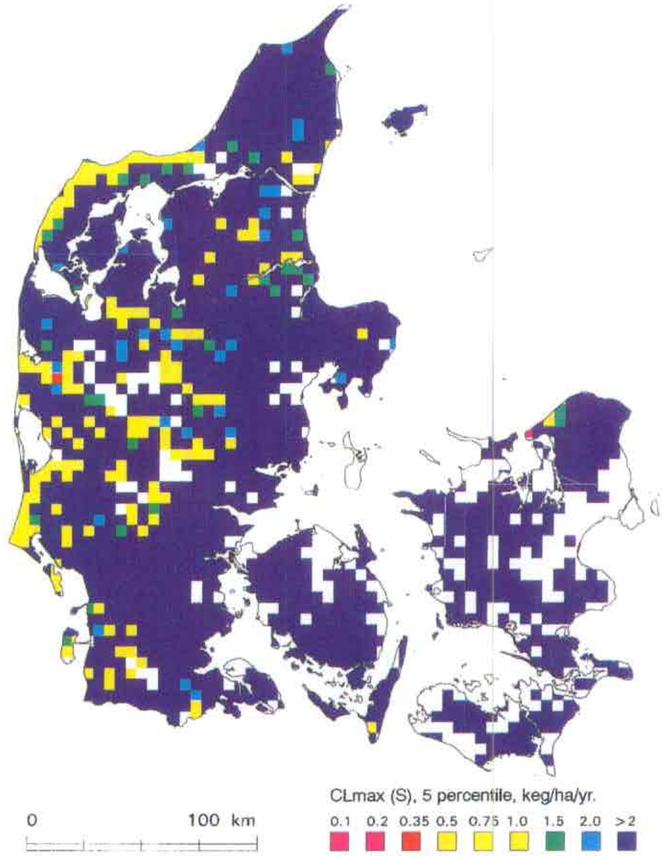

Figure A1.6. *Denmark:* $CL_{max}(S)$ *for forest soil and permanent grassland, 5 percentile.*

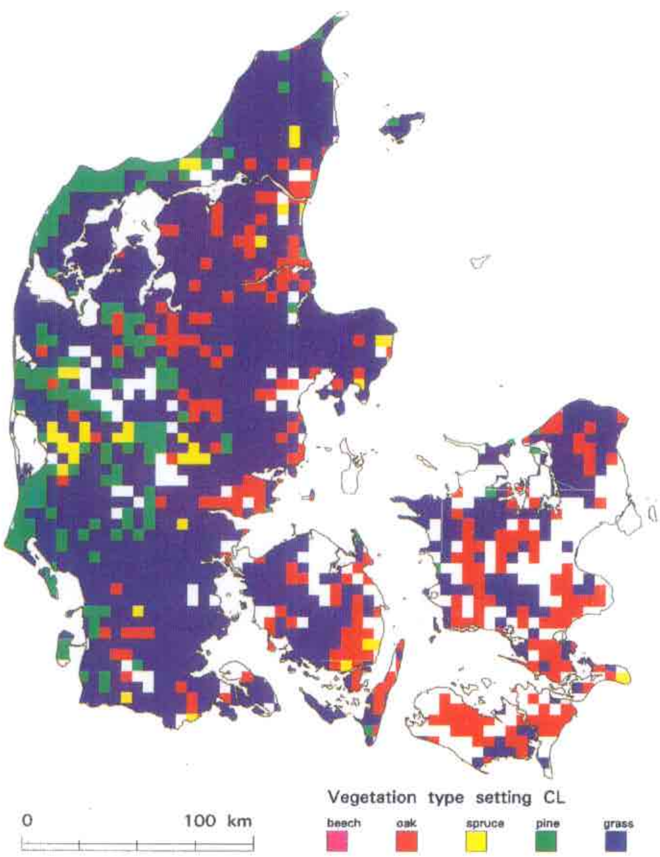

Figure A1.7. *Denmark: Ecosystem type setting* $CL_{max}(S)$*, 1 percentile.*

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Receptors mapped:

Forest soils and surface waters

Calculation method:

For both receptors mapped, the possible pairs of critical load of nitrogen and sulphur acidity are derived from acidity balance considerations. For the sum of nitrogen and sulphur deposition the following acidity balance is assumed (Kämäri *et al.*, 1992; Henriksen *et al.*, 1993):

$$N_{dep} + S_{dep} = f N_u + (1-r)(N_i + N_{de}) + N_{exp} + rN_{ret} + rS_{ret} + BC_{le} \quad (A1.1)$$

where the base cation leaching, BC_{le}, is given by:

$$BC_{le} = BC_{dep} + (1-r)\, BC_w - f\, BC_u - Alk_{le} \quad (A1.2)$$

where:
f is the fraction of forested land in the catchment area, r is the lake : catchment area ratio, N_u and BC_u are the net growth uptake of nitrogen and base cations, N_i is the immobilization of nitrogen in soils, N_{de} is the denitrification, N_{exp} is the export of organic nitrogen out of the catchment, N_{ret} and S_{ret} are the in-lake retention of nitrogen and sulphur, BC_w is the base cation weathering, and Alk_{le} is the alkalinity leaching. For lake catchments the term $(1-r)$ limits the influence of N_i, N_{de} and BC_w to the terrestrial area, and f limits the uptake to the forested area only. For forest soils one has to set $f=1$, $r=0$ and $N_{exp}=0$.

Inserting the deposition-dependent expressions for soil denitrification, and in-lake nitrogen and sulphur retention into equation A1.1, one obtains:

$$a_N N_{dep} + a_S S_{dep} = b_1 N_u + b_2 N_i + N_{exp} + BC_{le} \quad (A1.3)$$

where the dimensionless constants a_N, a_S, b_1, and b_2 are all smaller than one and depend on ecosystem properties only: denitrification fraction f_{de}, net mass transfer coefficients for sulphur and nitrogen, s_S and s_N, the lake's residence time, and runoff Q. For soils, BC_{le} at critical load is computed from equation A1.2; for lakes the net base cation leaching at critical load is computed from water quality data (cf. Henriksen *et al.*, 1992):

$$BC_{crit} = Q\,([BC]_0^* - [ANC]_{limit}) \quad (A1.4)$$

where $Q[BC]_0^*$ is the pre-acidification leaching of base cations from the catchment area, and $Q[ANC]_{limit}$ is the critical alkalinity leaching. The methods for the calculation of critical loads in Finland are the same as in the mapping guidelines contained in Chapter 4 of this report.

Input data:

For forest soils information is needed for BC^*_{dep}, BC_w, BC_u, N_u, N_{de}, N_i, and $Alk_{le,crit}$, i.e. Alk_{le} at critical load. BC^*_{dep} is interpolated from the data from the years 1986–88 of a nationwide network of stations measuring monthly bulk deposition (Järvinen and Vänni 1990). Results from measuring stations with a significant anthropogenic contribution have been excluded. The long-term average BC_w was estimated by the method of Olsson and Melkerud (1991), using the effective temperature sum (ETS) and the total element content (Ca + Mg) in the C horizon as input data. Total analysis data for 1057 plots were obtained from the Geological Survey of Finland. N_u and BC_u refer to the net uptake of nutrients in the stem and bark biomass via harvesting, and are estimated from annual forest growth and the element contents in biomass. Forest growth was calculated for each major tree species based on ETS, whereas element contents were taken from unpublished Swedish data (Rosén, pers. comm.). N_{de} was assumed proportional to the net incoming nitrogen, and the denitrification fractions were related to the soil type by linearly interpolating between a low value of 0.1 for podzolic mineral soils and a value of 0.8 for peat soils, depending on the soil type fractions (de Vries *et al.*, 1992). For N_i a value of 0.5 kg N ha^{-1} yr^{-1} as a long-term average was used for Finnish forest soils (Rosén *et al.*, 1992). $Alk_{le,crit}$ is calculated by adding the critical aluminum leaching, obtained from the molar Al : BC ratio of 1.0, and the hydrogen leaching, calculated from a gibbsite equilibrium. The runoff values needed for converting concentrations to fluxes were obtained from a digitized runoff map for 1961–1975 (Leppäjärvi, 1987).

For lakes, additional information is needed for f, r, N_{exp}, S_{ret}, N_{ret}, $[BC]_0^*$ and $[ANC]_{limit}$. The data for lakes were largely obtained from a national statistically based lake survey of 970 lakes conducted in 1987. The spatial distribution of the lake data set reflects the actual lake density in different regions. Both lake and catchment areas, as well as the forest fraction, were measured from topographic maps. N_{exp} was computed on the basis of organic nitrogen concentrations which were estimated as the difference between the total nitrogen and the sum of inorganic nitrogen species. S_{ret} and N_{ret} were computed from kinetic equations (Kelly *et al.*, 1987); and the mass transfer coefficients s_S and s_N were taken from retention model calibrations in North America (Baker and Brezonik 1988; Dillon and Molot 1990). $[BC]_0^*$ was estimated using the so-called F-factor, which relates the change over time in the leaching of base cations to long-term changes in inputs of strong acid anions in a lake, estimated as a function of the present base cation concentration. $[SO_4^{2-}]_0^*$ was estimated from the relationship between present sulphate and base cation concentrations from 251 lakes located in northern Fennoscandia receiving very low acidic deposition (Henriksen *et al.*, 1993). An $[ANC]_{limit}$ value of 20 ueq l^{-1} was selected as the chemical criterion based on results of a fish status survey conducted in Norway (Lien *et al.*, 1992).

Map displays:

The new fomulation of an exceedance function, i.e. the possibility of having the same exceedance for various combinations of sulphur and nitrogen deposition, does not allow the specification of a unique reduction strategy. It is possible, however, to specify an upper and lower bound for the required sulphur + nitrogen deposition reduction to achieve non-exceedance. Let Ex be the value of the exceedance function for the present (1990) sulphur and nitrogen deposition and (S_{red}, N_{red}) a pair of sulphur and nitrogen deposition reductions leading to zero exceedance, then the following equation holds:

$$a_S\, S_{red} + a_N\, N_{red} = Ex \tag{A1.5}$$

Since $a_S \le 1$ and $a_N \le 1$ it follows that Ex is a lower bound for the overall reduction $S_{red} + N_{red}$ (but not sufficient for achieving non-exceedance). This lower bound can be made sharper by observing that $a_N \le a_S$: dividing both sides in equation A1.5 by a_S we get:

$$S_{red} + N_{red} \ge S_{red} + \frac{a_N}{a_S} N_{red} = \frac{Ex}{a_S} =: Red_{min} \tag{A1.6}$$

This lower bound Red_{min} ($\ge Ex$) is the minimum reduction required to achieve non-exceedance. On the other hand, dividing by a_N we obtain:

$$S_{red} + N_{red} \le \frac{a_S}{a_N} S_{red} + N_{red} = \frac{Ex}{a_N} =: Red_{max} \tag{A1.7}$$

showing that Red_{max} is the maximum reduction required to achieve non-exceedance. The actual value of $S_{red} + N_{red}$ will depend on the selected emission reduction strategy, i.e. which pollutant is reduced to what extent. In Figures A1.8 through A1.11, the 95th percentiles of Red_{min} and Red_{max} are displayed for lakes and forest soils in Finland.

Figures:

A1.8. Red_{min}: Minimum reduction required to achieve non-exceedance for lakes (95th percentile).
A1.9. Red_{max}: Maximum reduction required to achieve non-exceedance for lakes (95th percentile).
A1.10. Red_{min}: Minimum reduction required to achieve non-exceedance for soils (95th percentile).
A1.11. Red_{max}: Maximum reduction required to achieve non-exceedance for soils (95th percentile).

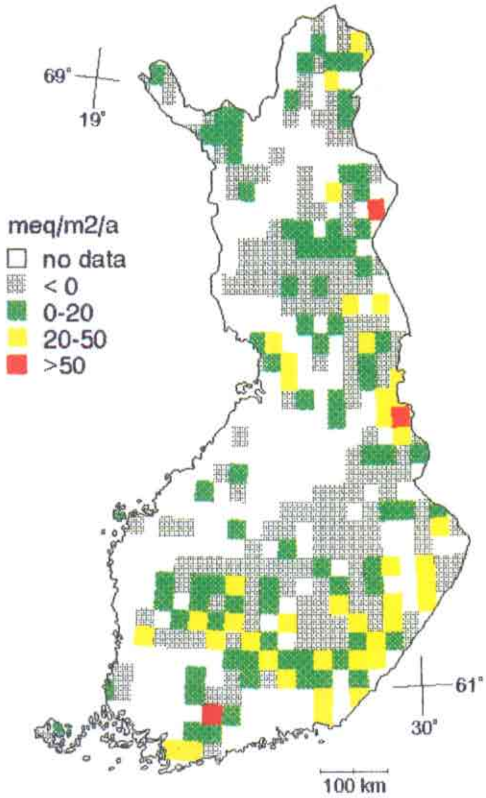

Figure A1.8. *Red$_{min}$: Minimum reduction required to achieve non-exceedance for lakes (95th percentile).*

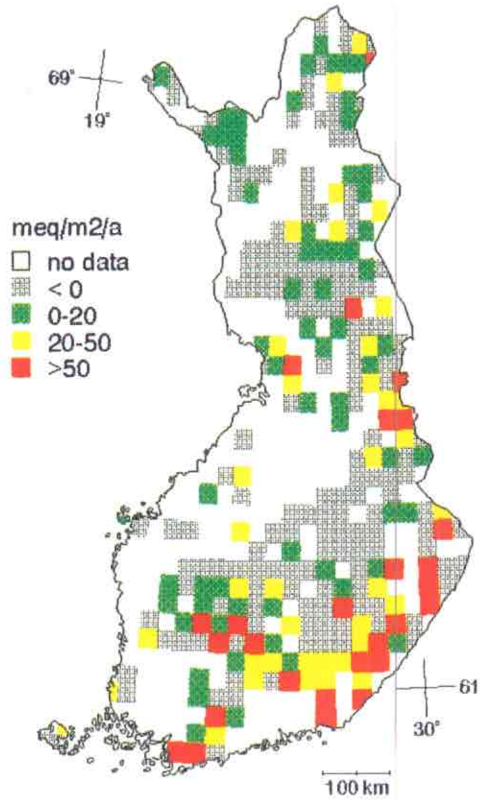

Figure A1.9. Red$_{max}$: *Maximum reduction required to achieve non-exceedance for lakes (95th percentile).*

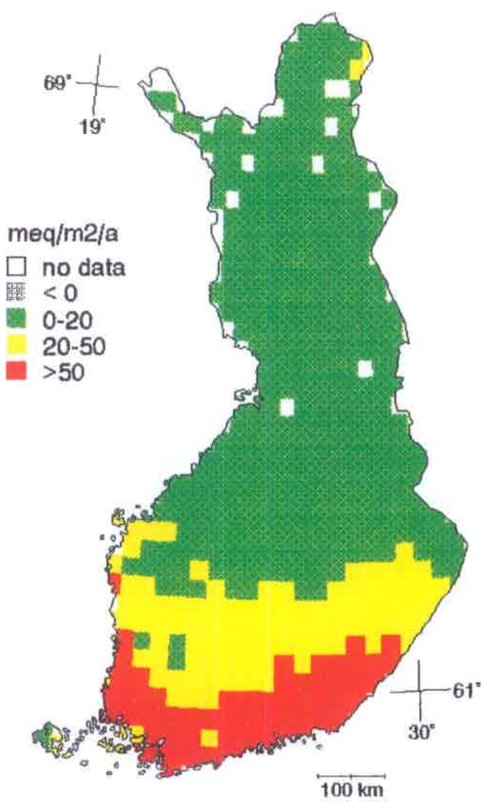

Figure A1.10. Red$_{min}$: *Minimum reduction required to achieve non-exceedance for soils (95th percentile).*

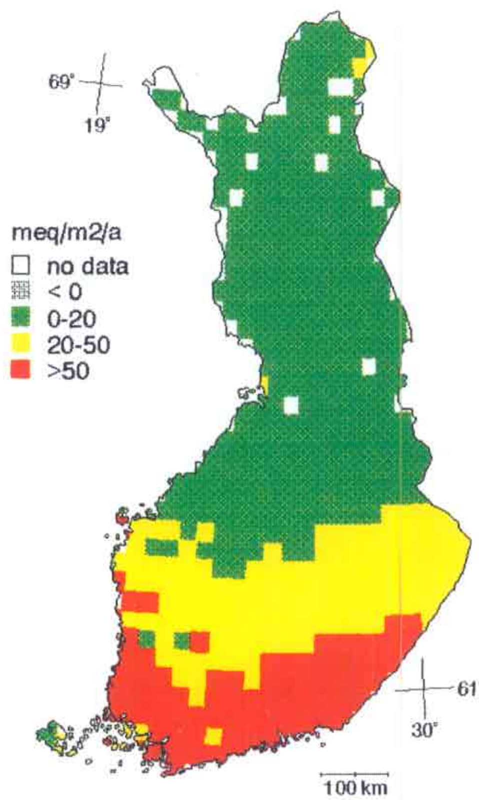

Figure A1.11. Red$_{max}$: *Maximum reduction required to achieve non-exceedance for soils (95th percentile).*

GERMANY

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Receptor mapped:

Forest soils

A. Critical Loads of Acidity

Calculation method:

For calculating the critical loads of acidity for forest soils the modified steady-state mass balance approach was used, with regard to problems with unrealistically high critical load values in high-precipitation areas (UN ECE, 1993b).

According to the explanations given in Chapter 4 of this report, the critical load of acidity was computed as:

$$CL(A) = ANC_w - ANC_{l(crit)}$$

where:

$$ANC_{l(crit)} = 1.5 \cdot \frac{BC_a}{K_{gibb}} \cdot Q^{2/3} + 1.5 \cdot BC_d \qquad (A1.8)$$

and:

$$BC_a = 0.8 \cdot ANC_w + BC_{dep} - BC_u - Q \cdot 0.015 \qquad (A1.9)$$

where:
BC_a = base cation availability
K_{gibb} = gibbsite coefficient (300 $m^6\ eq^{-2}$)

The assumption was made that the term describing the base cation availability in soil has to be greater then zero ($BC_a > 0$); otherwise the term was set to 1.

Furthermore the values of the critical load of sulphur and the critical sulphur deposition were calculated with the following equations:

$$CL(S) = S_f \cdot CL(A)$$

$$CD(S) = S_f \cdot (CL(A) + BC_{dep} - BC_u)$$

In the calculation of the critical sulphur deposition, *CD(S)*, some slightly negative values occurred due to the influence of base cation uptake (BC_u). The assumption has been made that such negative values reflect a kind of natural acidification that had to be excluded from consideration. Although this is true for a few ecosystems in Germany, there is a way to still regard them in the calculation by including the condition that the sum of $CL(A) + BC_{dep} - BC_u$ should not be smaller than the value of $CL(A)$ alone. Thus an overestimation of the influence of BC_u is avoided. Furthermore it has to be noted that BC_u is a value which is highly influenced by forestry practices.

The critical loads of nutrient nitrogen were calculated for forest ecosystems using the nitrogen mass balance approach as described in the mapping manual (UN ECE, 1993b):

$$CL_{nut}(N) = N_u + N_i + N_{de} + N_l$$

Grid size:

Calculations were made for about 26,000 polygon areas developed by overlaying the basic vector maps in the geographical information system Arc/Info. Forest ecosystems exist in approximately 15,700 of these polygons.

Data sources:

For the assessment of different input parameters for the mass balance equations for acidity and nitrogen critical loads, the following approaches were used:

Base cation release by weathering (ANC_w): The weathering classes were assigned to the categories of the soil map as proposed in the Mapping Vademecum. The weathering rate assigned to a certain weathering class was computed using equation 4.17 from Hettelingh *et al.*, 1992.

Net uptake of base cations in biomass (BC_u): This term was evaluated as a function of temperature as given in Sverdrup *et al.* (1990).

Nitrogen leaching (N_l) was set to fixed values according to the report of the Lökeberg workshop (Grennfelt and Thörnelöf, 1992). For deciduous forests, N_l was set to 3.5 eq ha^{-1} yr^{-1}; for coniferous forests to 4.5 eq ha^{-1} yr^{-1}.

Immobilization of nitrogen in soils (N_i) was assigned to the C:N ratio of soil types. For soils with a C:N ratio < 15, N_i was set to 0.5 eq ha^{-1} yr^{-1}; for soils with a C:N ratio between 15 and 25, to 1.5 eq ha^{-1} yr^{-1}; and for soils with a C:N ratio > 25 the value was set to 3.0 eq ha^{-1} yr^{-1}.

Denitrification (N_{de}): Two different methods were proposed for calculating denitrification. Both were used, and the results are presented in Figure A1.14. For method A, the constant denitrification fraction (equation 4.18 in this volume) was used; for method B, the dynamic denitrification fraction (equation 4.16) was used.

Net uptake of nitrogen in biomass ($N_{u(crit)}$): The nutrient limitation approach in a simplified version was used, jointly considering all relevant base cations.

$$N_{u(crit)} = \frac{BC_{dep} + ANC_w - BC_l}{X_{BC:N}} \qquad \text{(A1.10)}$$

where:
BC_l = limiting concentration for uptake of base cations
$X_{BC:N}$ = ratio of cations to nitrogen in exported biomass

Data bases: Sources and geographic resolution for maps used in the calculations are shown in Table A1.8.

Results:

The critical loads of acidity are mapped in Figure A1.12; the exceedances of these values in Figure A1.13.

Initial problems with high critical load values in high precipitation areas as described in the 1991 NFC report were solved mainly by using the modified steady-state mass balance method. 23% of the forested area shows values lower than 500 eq ha^{-1} yr^{-1}, 45% of the values rank between 500–2000 eq ha^{-1} yr^{-1}, and 30% have values above 2000 eq ha^{-1} yr^{-1}. The critical loads of acidity are exceeded in 85% of the area, in 50% of the area by more than 3000 eq ha^{-1} yr^{-1}.

First preliminary maps of critical loads of nitrogen are shown in Figure A1.14. Comparison between the two methods applied show that the inclusion of temperature in the calculations (as in dynamic method B) has an equalizing effect on denitrification values.

Future activities will aim at a further refinement of calculation methods and data bases, especially concerning the uptake and immobilization in biomass, which will be recalculated using more climatic parameters. Furthermore, characteristics of natural growing districts (Wuchsbezirke) will be included in the assessment of vegetation parameters.

Table A1.8. *Data used to calculate critical loads in Germany.*

Map	Type of Data	Items	Source and Resolution	Comments
Soil	Vector	FAO soil type, soil texture	Eastern part of Germany: Atlas GDR, 1 : 750,000 Western part: CORINE 1 : 1,000,000	Eastern part translated to FAO-systematic
Precipi-tation Surplus	Vector	annual mean precipitation surplus [mm]	Eastern part: 1 : 750,000 Western part: Hydrolog. Atlas, 1 : 1,000,000	
Forest	Raster cell	forest type (numeric code): 1 - coniferous 2 - deciduous	INS 1 km x 1 km	Developed using classification of NOAA/AVHR imagery
Tempe-rature	Vector	annual mean temperature [°C]	Eastern part: Atlas GDR, 1 : 750,000 Western part: BFANL	
Base cation deposition	Raster cell	total deposition [$eq\ ha^{-1}\ yr^{-1}$]	NILU 1° x 0.5°	
Anion Deposition	Raster cell	total deposition [$eq\ ha^{-1}\ yr^{-1}$]	INS 1° x 0.5°	Developed by spatial interpolation (Kriging)

Figures:

A1.12. Germany: Critical loads of acidity for forest soils.

A1.13. Germany: Exceedance of critical loads of acidity for forest soils.

A1.14. Germany: Critical loads of nitrogen for forest soils.

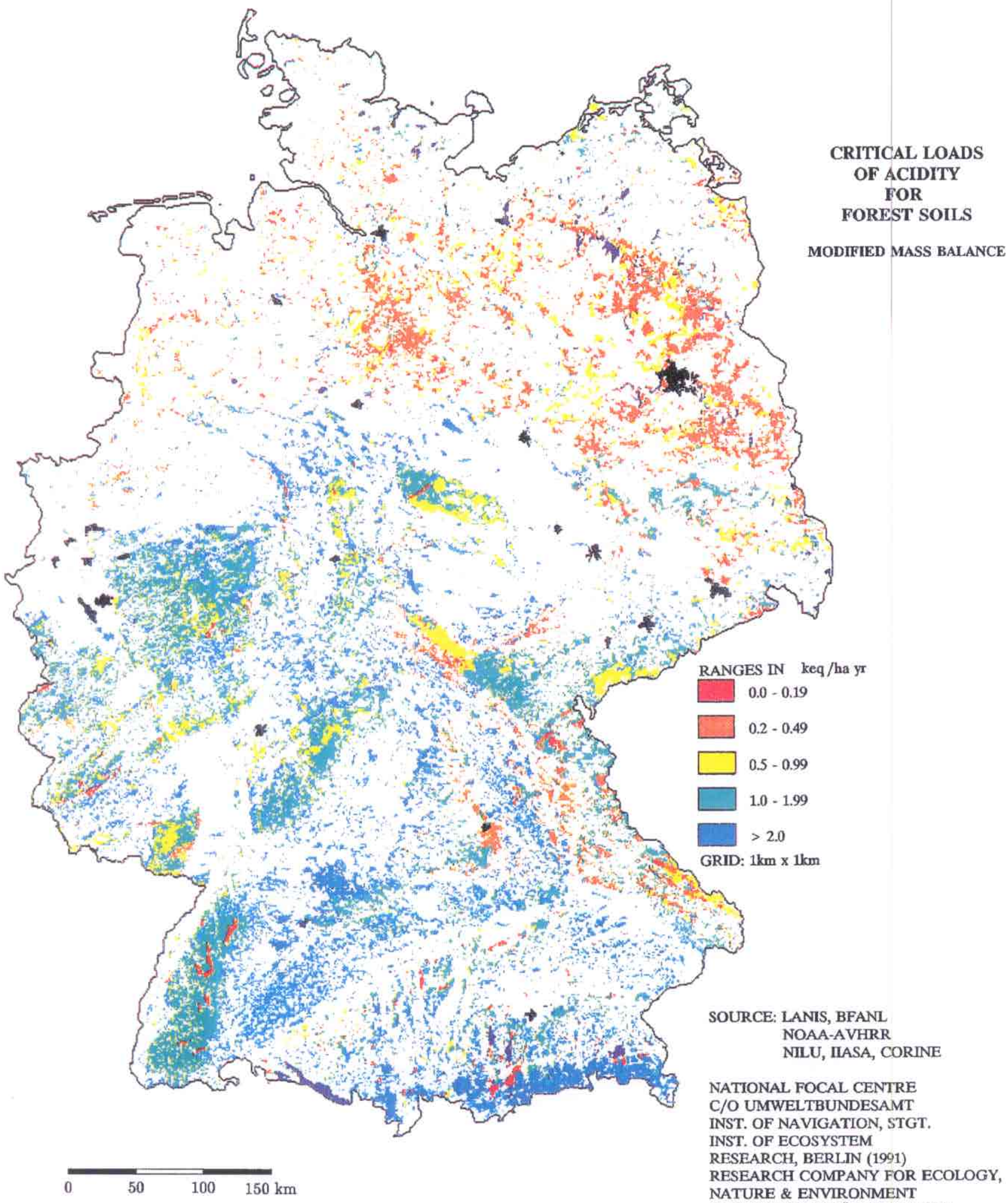

Figure A1.12. *Germany: Critical loads of acidity for forest soils.*

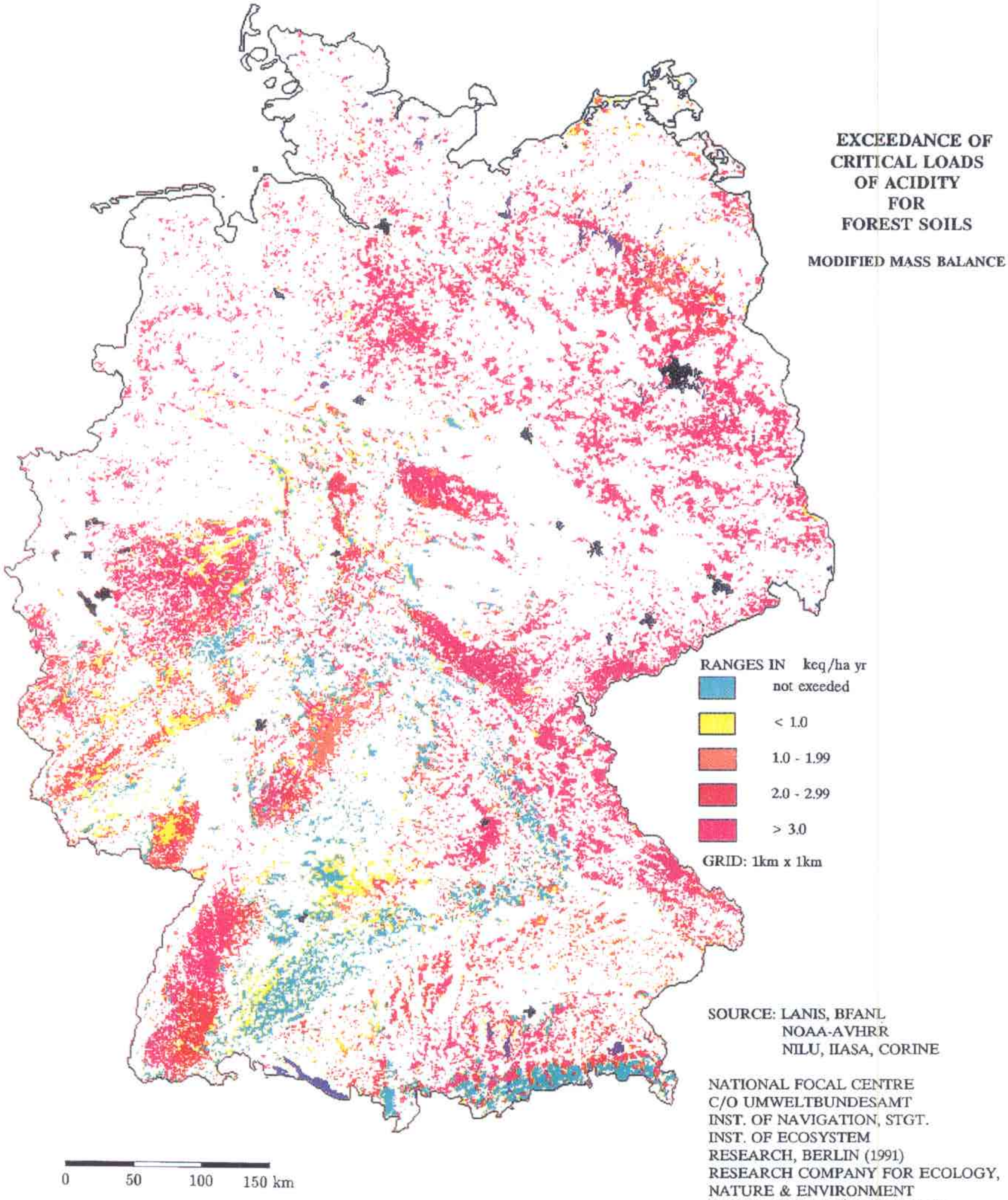

Figure A1.13. *Germany: Exceedance of critical loads of acidity for forest soils.*

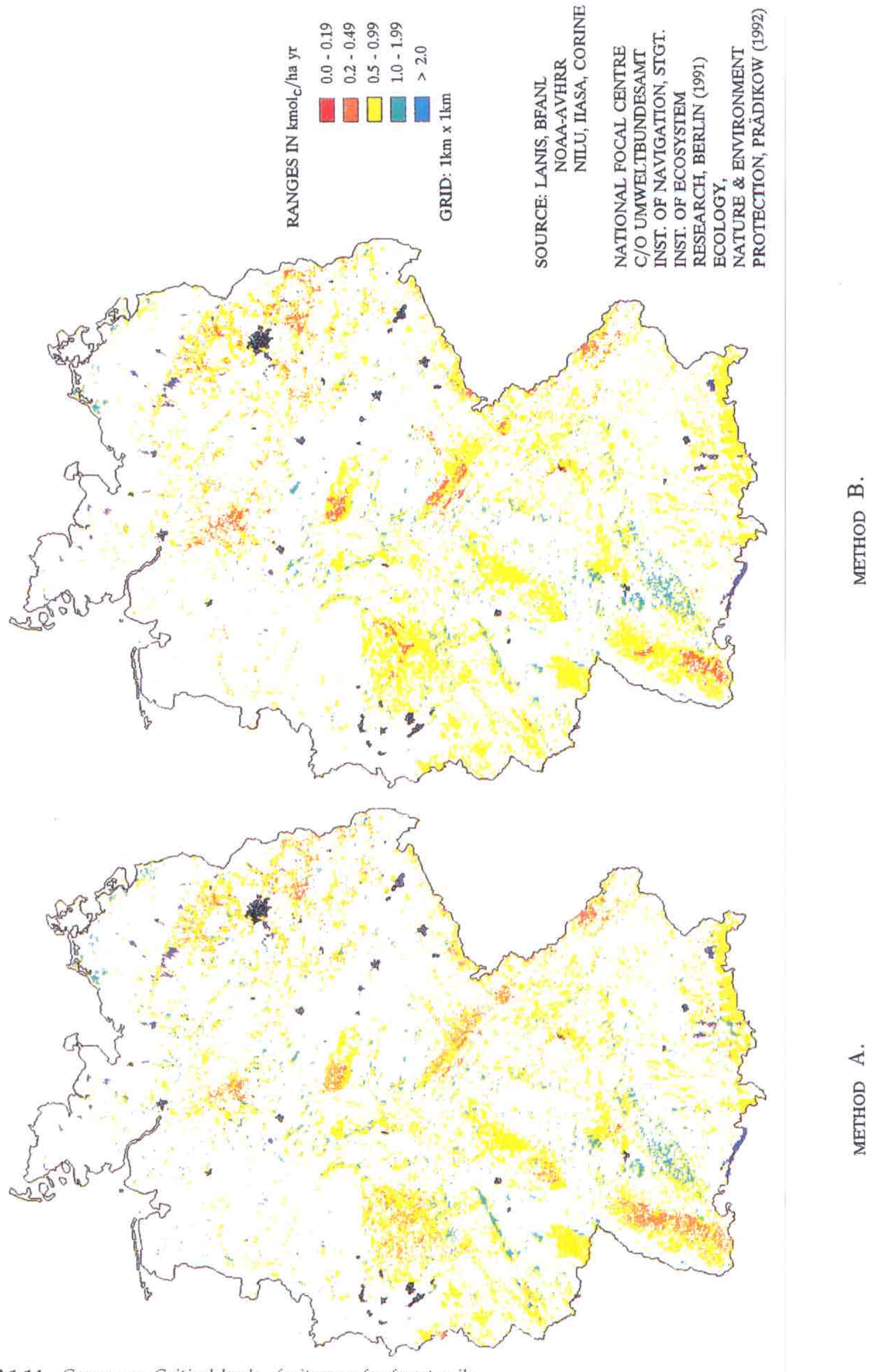

Figure A1.14. *Germany: Critical loads of nitrogen for forest soils.*

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Receptor mapped:

Forest soils

Calculation method:

Steady-state mass balance method, according to:

$$CL(Ac_{pot}) = BC_w - BC_{gu} + N_{gu} + N_{i(crit)} + Ac_{le(crit)} \quad (A1.11)$$

$$CL(Ac_{act}) = BC_w + Ac_{le(crit)} \quad (A1.12)$$

where:
$CL(Ac_{pot})$ = critical load of potential acidity
$CL(Ac_{act})$ = critical load of actual acidity
BC_{gu} , N_{gu} = growth uptake (net needed for forest growth) of base cations and nitrogen respectively
BC_w = base cation weathering
$N_{i(crit)}$ = long-term nitrogen immobilization
$Ac_{le(crit)}$ = critical leaching flux of acidity
The element fluxes in the above equation are all given in eq ha^{-1} yr^{-1}.

In the Mapping Vademecum, the potential acid load is defined as the sum of SO_x , NO_x and NH_x corrected for the total deposition of base cations not balanced by Cl. Using this definition, total seasalt-corrected base cation deposition, BC^*_{td} , was not included in the critical load calculation.

The critical acidity leaching flux was calculated as the sum of aluminum leaching and H leaching. Three options for calculating the critical aluminum leaching flux were used:

- a critical Al concentration of 0.2 mol m^{-3},
- a critical Ca : Al ratio of 1.0,
- no Al depletion,

and the minimum value taken.

The critical H leaching flux was calculated as:

$$H_{le(crit)} = FW \cdot [H]_{crit} \quad (A1.13)$$

where FW is the water flux in m^3 ha^{-1} yr^{-1}.

The critical H concentration was related to the critical aluminum concentration according to:

$$[H]_{crit} = \frac{[Al]_{crit}^{1/3}}{K_{gibb}} \quad (A1.14)$$

where K_{gibb} is the gibbsite equilibrium constant in mol_c^{-2} m^6. For K_{gibb} a value of $3 \cdot 10^2$ mol_c^{-2} m^6 (= 10^8 mol^{-2} l^2) was used.

The value of the critical aluminum concentration, $[Al]_{crit}$, is determined by the critical aluminum leaching flux divided by the water flux.

Separate critical loads of nitrogen and sulphur have been calculated according to:

$$CL(N) = N_{gu} + N_{im(crit)} + NO_{3,le(crit)} \quad (A1.15)$$

and:

$$CL(S) = BC_w - BC_{gu} + Ac_{le(crit)} - NO_{3,le(crit)} \quad (A1.16)$$

Summation of the critical loads of nitrogen and sulphur gives the critical load of potential acidity (from equations A1.11, A1.15 and A1.16). Again, the value of BC^*_{td} was not included in equation A1.16, but this term was accounted for by calculating the critical deposition of sulphur according to:

$$CD(S) = BC^*_{td} + BC_w - BC_{gu} + Al_{le(crit)} - NO_{3,le(crit)} \quad (A1.17)$$

Data sources:

Deposition areas have been defined by seeking an optimum between the number of areas and the spatial variability within each area. A 10 x 10 km grid has been used, as detailed information regarding tree species and soil types exists at this scale. The number of grids containing forests equal 434. A distinction has been made in twelve tree species and 23 soil types. Tree species included are *Pinus*

Sylvestris (Scotch Pine), *Pinus Nigra* (Black Pine), *Pseudotsuga Menziesii* (Douglas Fir), *Picea Abies* (Norway Spruce), *Larix Leptolepis* (Japanese Larch), *Quercus Robur* (Oak), *Fagus Sylvatica* (Beech), *Populus Spec* (Poplar), *Salix Spec* (Willow), *Betula Pendula* (Birch), *Fraxinus Nigra* (Ash) and *Alnus Glutinosa* (Black Alder). Soil types were differentiated in 18 non-calcareous sandy soils (mainly podzolic soils), calcareous sandy soils, loess soils, non-calcareous clay soils, calcareous clay soils and peat soils on the basis of a recent 1 : 250,000 soil map of The Netherlands.

Information on the area (distribution) of each specific forest-soil combination in a grid was derived by overlaying the digitized forest and soil data base. This was done by a grid overlay of the digitized 1 : 250,000 soil map with a spatial resolution of 100 x 100 m and a data base with tree species information with a spatial resolution of 500 x 500 m for each 10 x 10 km grid.

The total number of forest-soil combinations for all grids was 17,102 (12,514 on non-calcareous sandy soils and 4588 on all other soils). The number of forest-soil combinations in a grid ranges between 1 and 125.

Data that are needed to map critical loads and exceedances are the deposition, weathering and uptake of elements and the water flux. Long-term nitrogen immobilization has been neglected. These data are collected as a function of location, tree species and soil type as shown in Table A1.9.

Table A1.9. *The influence of location, tree species and soil type on input data as considered in the Dutch application.* ("x" = considered, "-" = not considered)

	Deposition	Weathering	Uptake	Precipitation Surplus
Location	x	-	-	x
Tree species	x	-	x	x
Soil type	-	x	x	x

An overview of the collection of the data determining the various fluxes of elements and water is given below.

Deposition: Total deposition of base cations has been calculated by multiplying the bulk deposition with a dry deposition factor. The bulk deposition of base cations (Ca, Mg, K and Na) and Cl has been derived from 22 weather stations in the Netherlands using interpolation techniques to get values for each grid. Dry deposition factors for base cations and chloride on each tree species have been derived from available data on Na in throughfall and bulk deposition.

Weathering rates: Base cation weathering rates are based on a correlation with total base cation contents. This correlation has been derived for nine non-calcareous sandy soils and six loess soils in the Netherlands. Weathering rates are based on information on base cation depletion rates in soil profiles, budget studies and on column and batch experiments, which have been conducted during five years on the most relevant non-calcareous sandy soils in The Netherlands. For clay and peat soils an indicative value has been derived from literature.

Uptake: Uptake rates are determined by forest growth and element contents in stems. Forest growth estimates for all relevant combinations of forest and soil type and contents of the elements N, K, Ca and Mg in stems are based on a literature survey for all tree species included.

Precipitation surplus: is determined by the precipitation rate minus the sum of interception, evaporation and transpiration (evapotranspiration). Precipitation estimates have been derived from 280 weather stations in The Netherlands, using interpolation techniques to obtain values for each grid. Interception fractions, relating interception to precipitation, have been derived from literature data for all tree species considered. Data for evaporation and transpiration have been calculated for all combinations of tree species and soil types with a separate hydrological model.

The range in model inputs for non-calcareous soils in The Netherlands is given in Table A1.10. The table shows that nitrogen uptake is the most important proton sink in peat soils. However, the uptake of nitrogen (proton sink) is largely compensated by base cation uptake (proton source). Consequently uptake is an unimportant proton sink. In sandy soils, the critical acidity leaching is the most important proton sink. For clay soils, the weathering rate

Table A1.10. *5%, 50% and 95% values of input data (eq ha⁻¹ yr⁻¹) for Dutch forests on non-calcareous soils.*

Soil type	BC* dry deposition 5%	50%	95%	BC weathering 5%	50%	95%	BC uptake 5%	50%	95%
Peat	145	220	570	200	200	200	118	256	366
Sand	147	231	554	180	300	580	187	311	545
Loess	172	541	1370	500	500	500	270	456	707
Clay	145	220	685	1000	1000	1000	118	396	994
All	146	229	602	200	300	1000	178	304	586

	N uptake 5%	50%	95%	NO_3 leaching 5%	50%	95%	Acidity leaching 5%	50%	95%
Peat	136	507	1142	39	191	251	114	304	520
Sand	221	409	680	39	223	323	116	419	746
Loess	309	557	918	58	234	321	173	635	941
Clay	136	507	1142	38	184	249	113	533	735
All	210	418	829	39	216	313	116	421	744

is most important. However, this value is rather arbitrary. As with peat soils the weathering rate of clay soils has been assigned on the basis of vary few data. Consequently, values have not been varied (see Table A1.10). In loess soils the dry deposition of base cations and the nitrogen uptake is nearly as important as acidity leaching. The large input of base cations (mainly calcium) on loess soils is due to their locations in the neighborhood of limestone quarries in the southern part of The Netherlands.

Figures:

A1.15. Netherlands: Critical loads of actual acidity for soils (mean, 5, 50, and 95 percentile).
A1.16. Netherlands: Critical loads of sulphur for soils (mean, 5, 50, and 95 percentile).
A1.17. Netherlands: Critical deposition of sulphur for soils (mean, 5, 50, and 95 percentile).

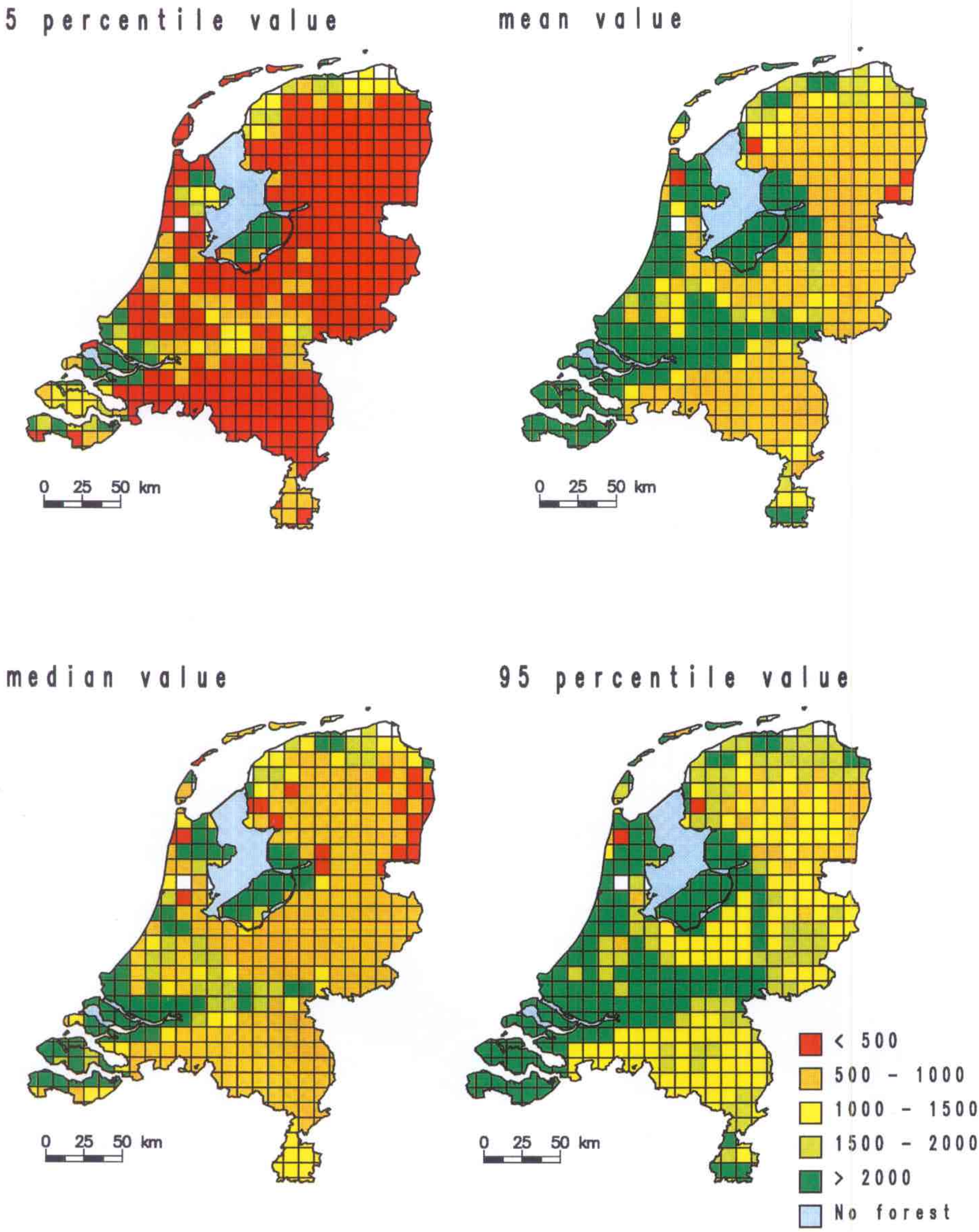

Figure A1.15. *Netherlands: Critical loads of actual acidity for soils (5 percentile, mean, median, and 95 percentile).*

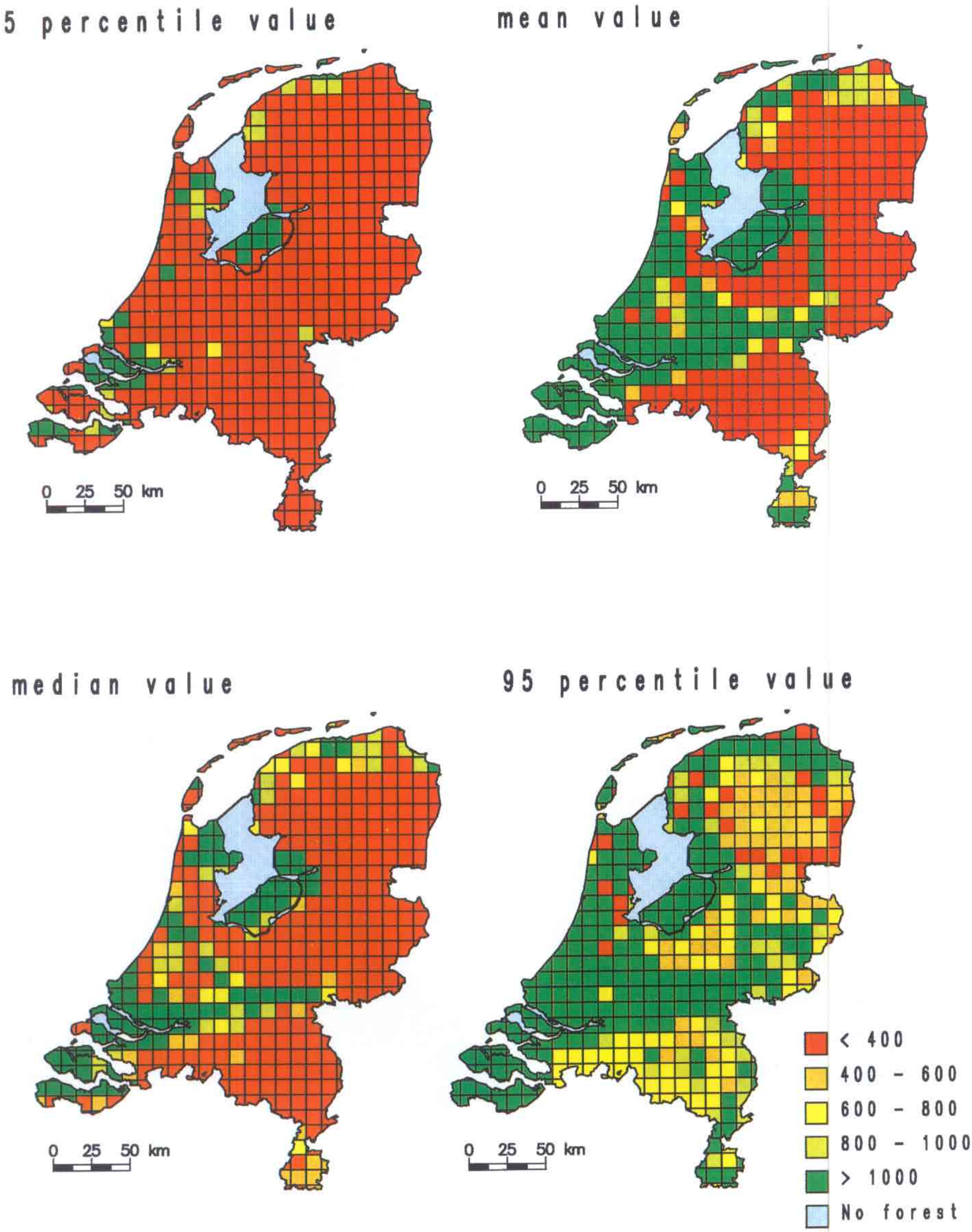

Figure A1.16. *Netherlands: Critical loads of sulphur for soils (5 percentile, mean, median, and 95 percentile).*

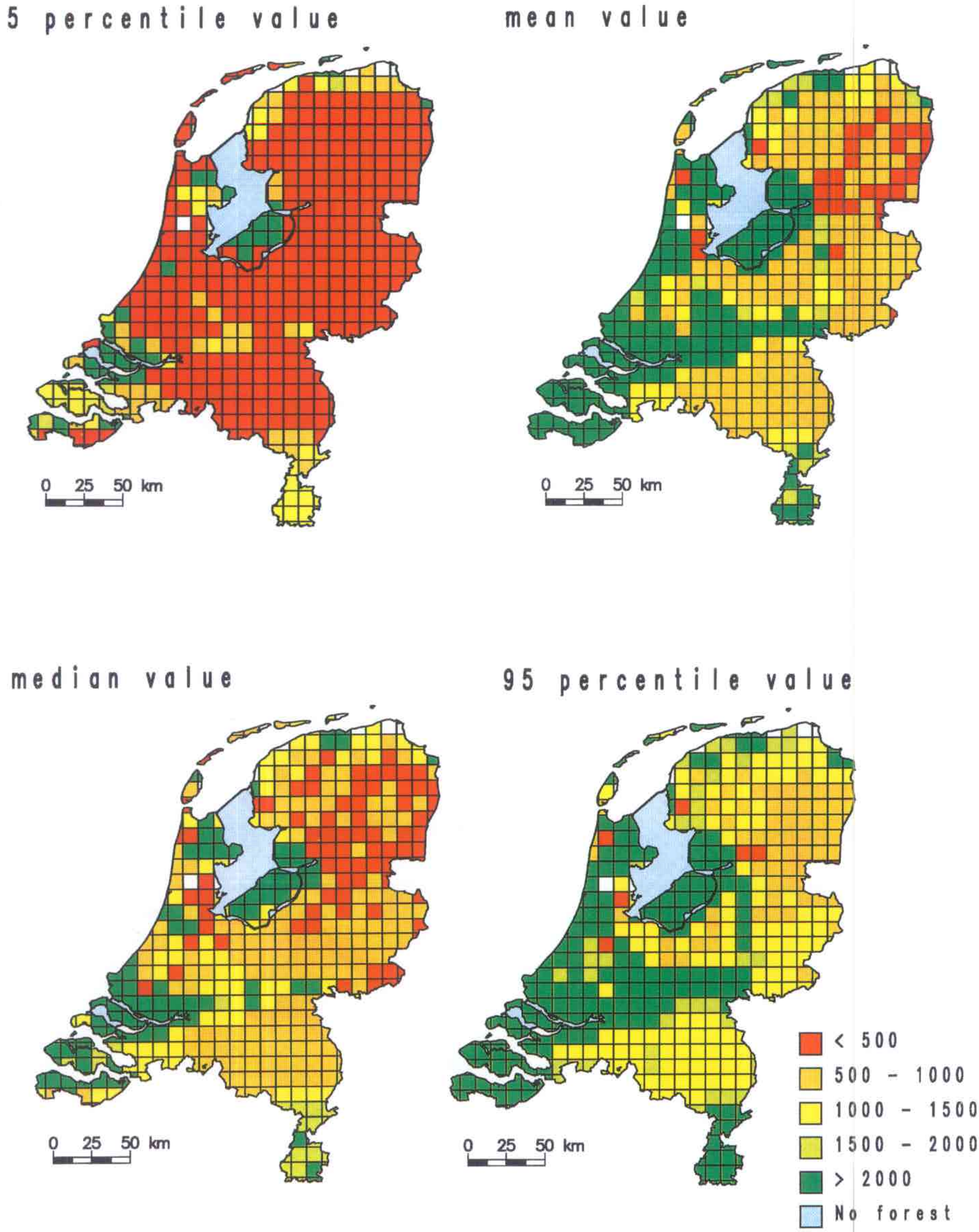

Figure A1.17. *Netherlands: Critical deposition of sulphur for soils (5 percentile, mean, median, and 95 percentile).*

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Receptors mapped:

Surface waters, forest soils.

Data sources:

National regional lake surveys and monitoring programs.

Precipitation: A weighted average total deposition value for each NILU grid (a 3 by 3 subdivision of an EMEP grid) has been calculated from ambient air concentrations and wet deposition taking land use data (coverage of different receptors) into account. Data for the period 1983–1987 were used. The deposition values for each of the surface water grids (see above) was estimated from the NILU grid data base.

Water: The chemistry of surface water within a subgrid was estimated by comparing available water chemistry data for lakes and rivers within each grid. The chemistry of the lake that was judged to be the most typical was chosen to represent the grid. If there were wide variations within a subgrid, the most sensitive area was selected, if it amounted to more than 25% of the grid's area. Sensitivity was evaluated on the basis of water chemistry, topography and bedrock geology. Geology was determined from the geological map of Norway (1 : 1,000,000) prepared by the Norwegian Geological Survey. Mean annual runoff data is from runoff maps prepared by the Norwegian Water and Energy Works.

A. Surface Waters

Calculation method:

The steady-state water chemistry method was used to produce maps of critical loads of acidity and critical load exceedance for sulphur and for present exceedance for sulphur and nitrogen.

Grid size:

Each 1° longitude by 0.5° latitude grid was divided into 16 subgrids, each covering about 12 x 12 km in southern Norway, and with decreasing grid width at higher latitudes. The land area covered by each of these 2315 grids has been calculated.

B. Forest Soils

Calculation method:

The dynamic MAGIC (Model of Acidification of Groundwater in Catchments) model was used to produce maps for critical loads of acidity and exceedance for sulphur and nitrogen to forest soils (Cosby *et al.*, 1985a, 1985b).

Grid size:

The same grid system as for surface water was used. Of these 706 grids are in productive forests both coniferous (spruce, pine) and deciduous (birch). The remaining grids cover unproductive forests and non-forested areas, for which critical loads for forest soils cannot be calculated.

Data sources:

National monitoring data.

Precipitation: The same data as for surface water was used.

Soil: The calculations are based on data from the NIJOS forest monitoring plots on a 9 x 9 km grid and on the surface water data base referred to above. All input data are aggregated to the 12 x 12 km grid net. The NIJOS soils data are from areas in productive spruce and pine forests. A soil pit was objectively located within the representative vegetation type five meters from the plot center in the 9 x 9 km grid. The soil pit was dug to at least 50 cm where possible. Soil profile samples were taken and analyzed according to standard procedures.

Figures:

A1.18. Norway: Critical loads of acidity for surface waters in Norway using ANC_{limit} = 20 $\mu eq\ l^{-1}$.

A1.19. Norway: Critical loads of acidity for forest soils using the MAGIC model. Criterion is the Ca : Al molar ratio 1.0 in upper 60 cm soil solution.

A1.20. Norway: Critical loads of acidity for the most sensitive ecosystems (based on minimum critical load of water and soil for grids with both sets of data, and critical load for waters for grids without soil data).

Note:

Harmonized maps for critical loads of acidity to surface waters have been prepared for Finland, Sweden and Norway using the steady-state water chemistry method. Also maps for critical load exceedance for sulphur have been prepared (Henriksen *et al.*, 1990a). Further, two models for calculating steady-state critical loads of nitrogen and sulphur acidity have been applied to Finnish, Norwegian and Swedish lake data bases. The first model was used for calculating present exceedances from the critical loads of acidity, and the second for assessing also the future situations (Henriksen *et al.*, 1993).

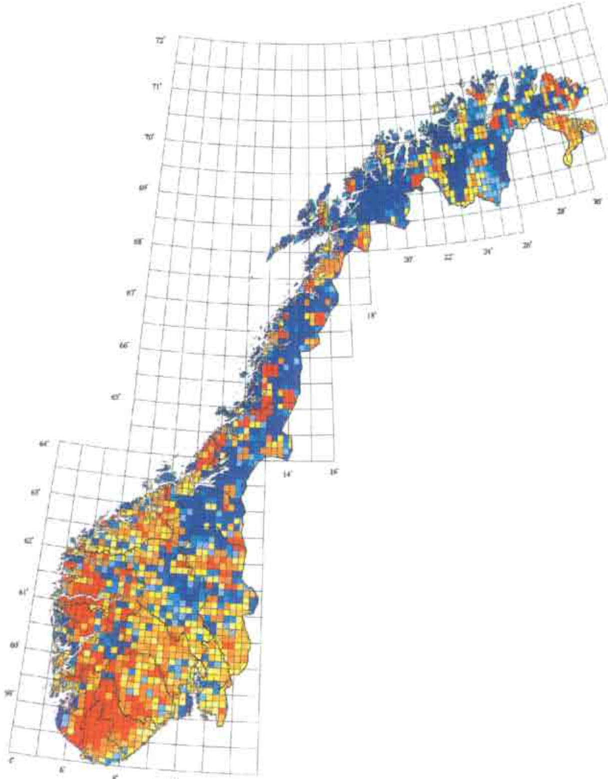


Figure A1.18. *Norway: Critical loads of acidity for surface waters in Norway using* $ANC_{limit} = 20\ \mu eq\ l^{-1}$.

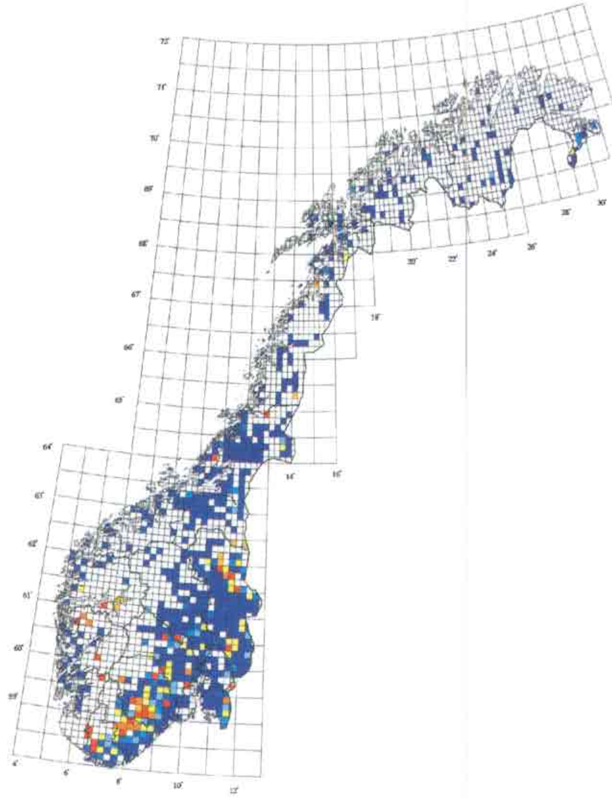
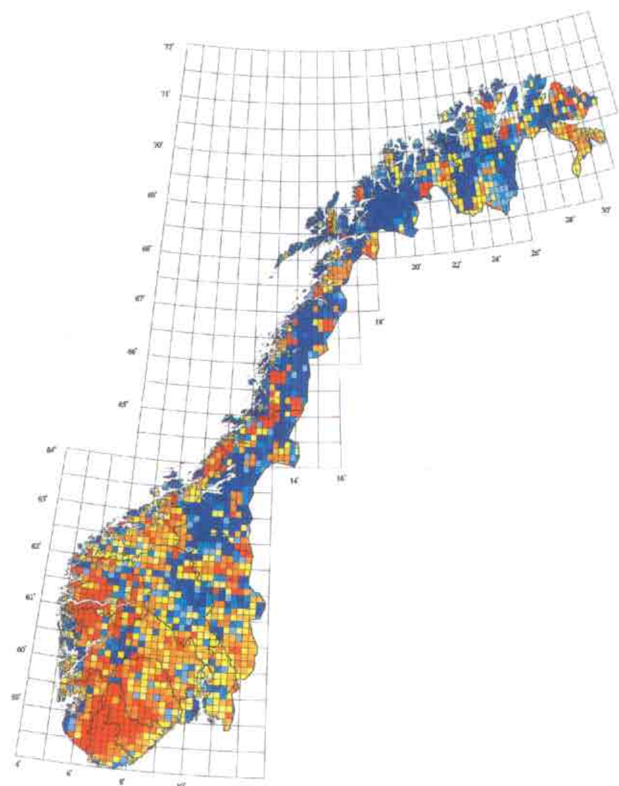


Figure A1.19. *Norway: Critical loads of acidity for forest soils using the MAGIC model. Criterion is the Ca : Al molar ratio 1.0 in upper 60 cm soil solution.*

$keq\ km^{-2}\ yr^{-1}$	$gS\ m^{-2}\ yr^{-1}$
0 - 12.5	0 - 0.19
12.5 - 25.0	0.20 - 0.39
25.0 - 37.5	0.40 - 0.59
37.5 - 50.0	0.60 - 0.79
50.0 - 62.5	0.80 - 0.99
62.5 - 75.0	1.00 - 1.19
75.0 - 87.5	1.20 - 1.39
87.5 - 100.0	1.40 - 1.59
100.0- 112.5	1.60 - 1.79
> 112.5	> 1.80

100 km



NIJOS NATURENS TÅLEGRENSER NIVA

Figure A1.20. *Norway: Critical loads of acidity for the most sensitive ecosystems (based on minimum critical load of water and soil for grids with both sets of data, and critical load for waters for grids without soil data).*

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Receptors mapped:

Forest soils and surface waters

A. Forest Soils

Calculation methods:

Steady-state mass balance method. For high mountain areas in Poland the critical loads were determined on the basis of procedures discussed during the workshop held in Vienna, 9-10 March 1992, and in Prädikow (Germany) 28 April, 1993.

Grid size:

Longitude/latitude 0.2° x 0.1° grids; 2170 receptor points, nearly 930 of which covered by forests.

Data sources:

Most geographical data used to determine the critical loads values were taken from national data sources (apart from branch to stem ratio and relative soil moisture saturation).

Soil Data: The dominating types of soil in particular grids were adopted on the basis of data from the *Polish Soil Atlas 1:300,000*. Forty types of predominant soils in Poland were applied for the calculations, and adequate values of base cation weathering were attributed to them.

Meteorological Data: The data concerning precipitation, runoff and average annual temperature were obtained from the *Hydrological Atlas of Poland* published by the Institute of Meteorology and Water Management for the years 1951 - 1975.

Forest Data: The data concerning the spatial location of forests were based on the *Forest Map of Poland*, edited by the Forest Management and Geodesy Office. The data concerning resources, forest growth and age of trees were obtained from the data bank of the Forest Management Office. For calculation of critical loads, the chosen forestry areas were those in which the percentage of forests in the grid surface was greater than twenty percent.

Uptake Data: Data for BC_u, N_u, N_i, and N_l were determined on the basis of forest growth in particular grids and the contents of particular elements in stems and branches. On the basis of national data, the rate of denitrification, N_{de}, and sulphur fraction, S_f, were calculated.

Deposition Data: The data concerning sulphur, nitrogen and base cation deposition were adopted from EMEP data provided by CCE-RIVM.

B. Surface Waters

Calculation method:

Using the steady-state water chemistry method the critical loads values were calculated for Tatra Mountains, as a most sensitive area in Poland. Lake sampling, data analysis and collection are now being conducted to calculate critical load and prepare maps, in cooperation with the NIVA (Oslo).

Data sources:

Most of geographical and chemical data used to determine the critical loads values were taken from national data sources.

Figures:

A1.21. Poland: Critical loads of actual acidity.
A1.22. Poland: Critical loads of sulphur.
A1.23. Poland: Critical loads of nitrogen.
A1.24. Poland: Critical deposition of sulphur.
A1.25. Poland: Critical deposition of nitrogen.
A1.26. Poland: Exceedance of critical loads of actual acidity.
A1.27. Poland: Exceedance of critical loads of sulphur.
A1.28. Poland: Exceedance of critical loads of nitrogen.

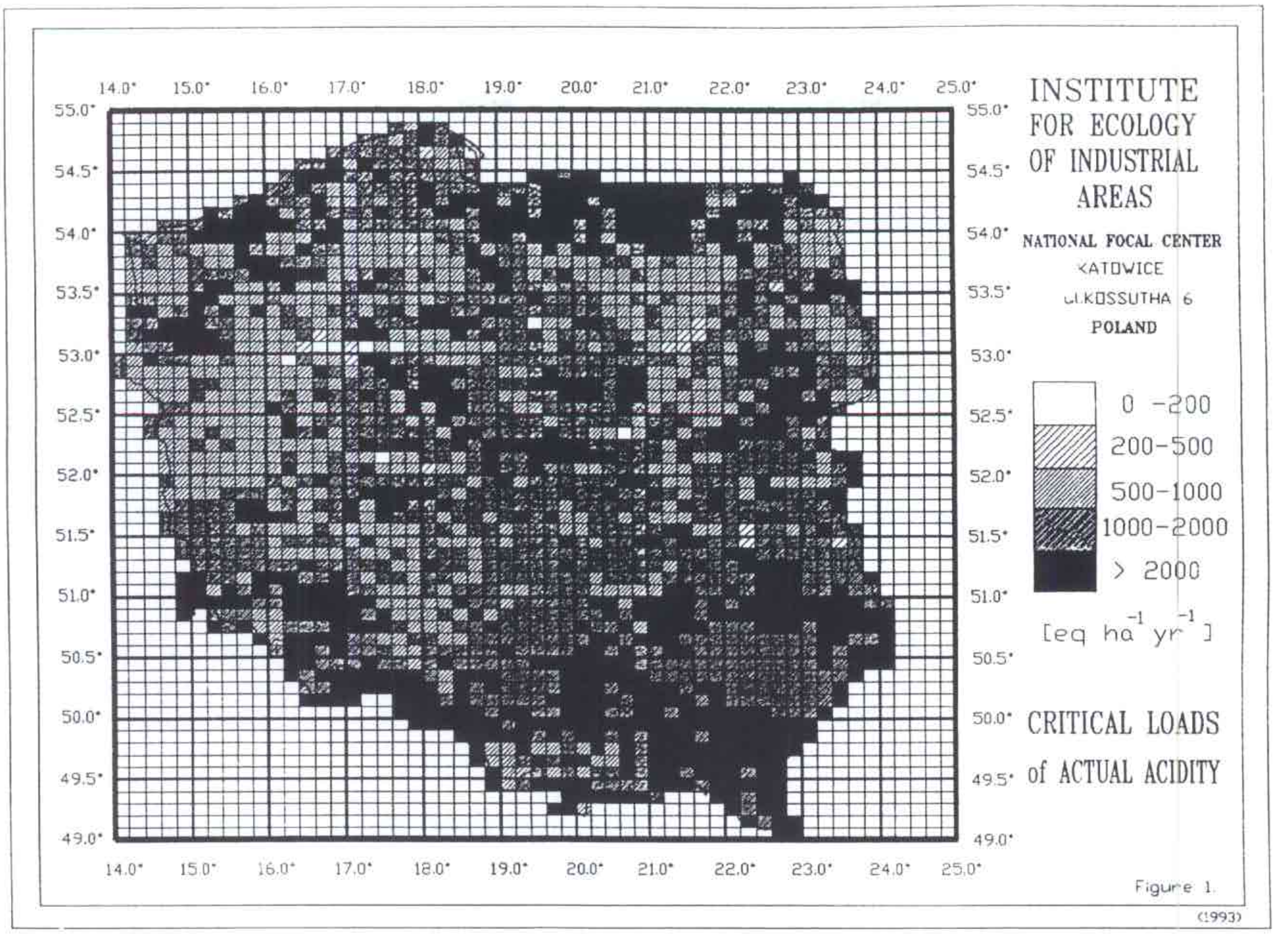

Figure A1.21. *Poland: Critical loads of actual acidity.*

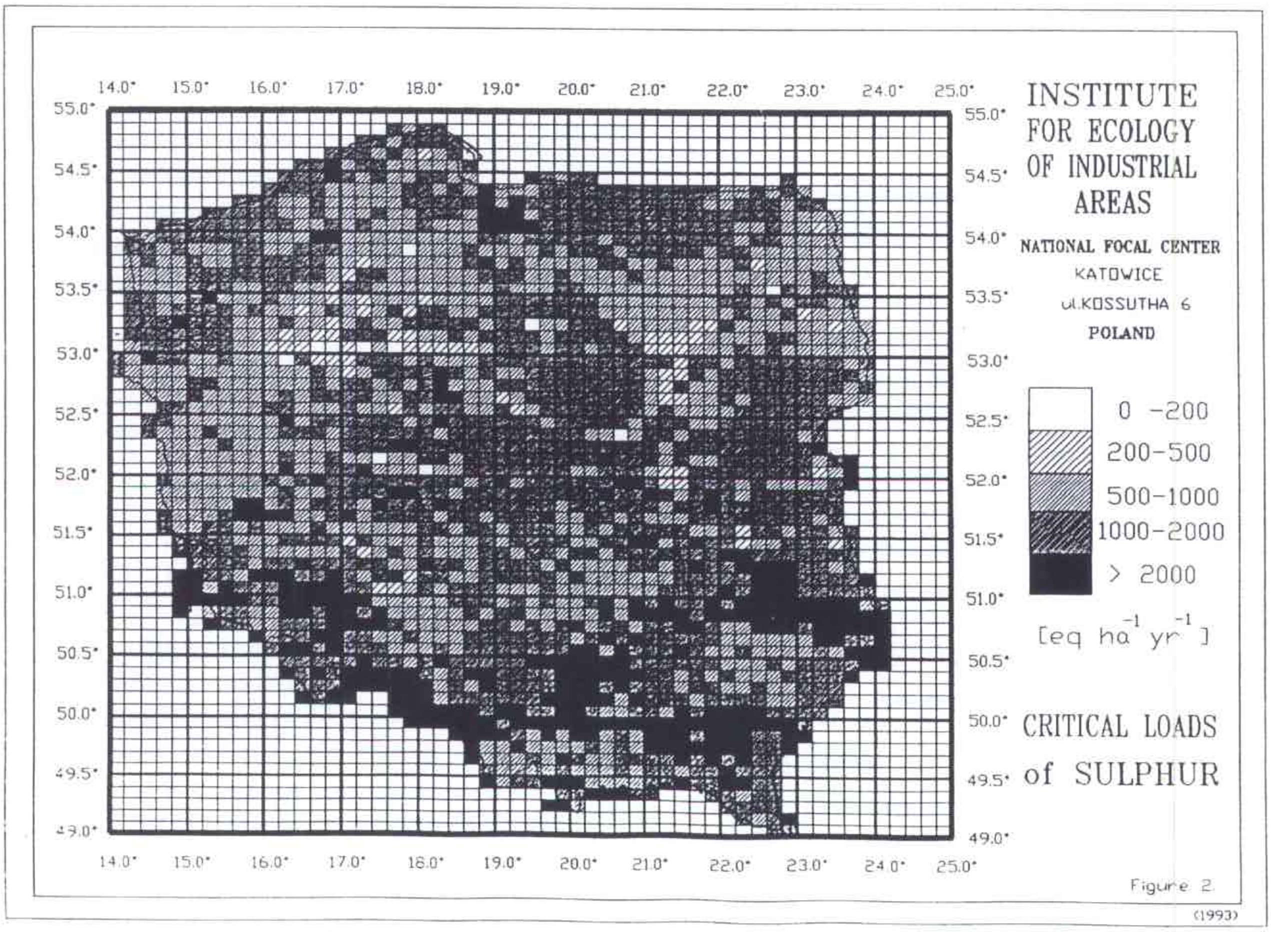

Figure A1.22. *Poland: Critical loads of sulphur.*

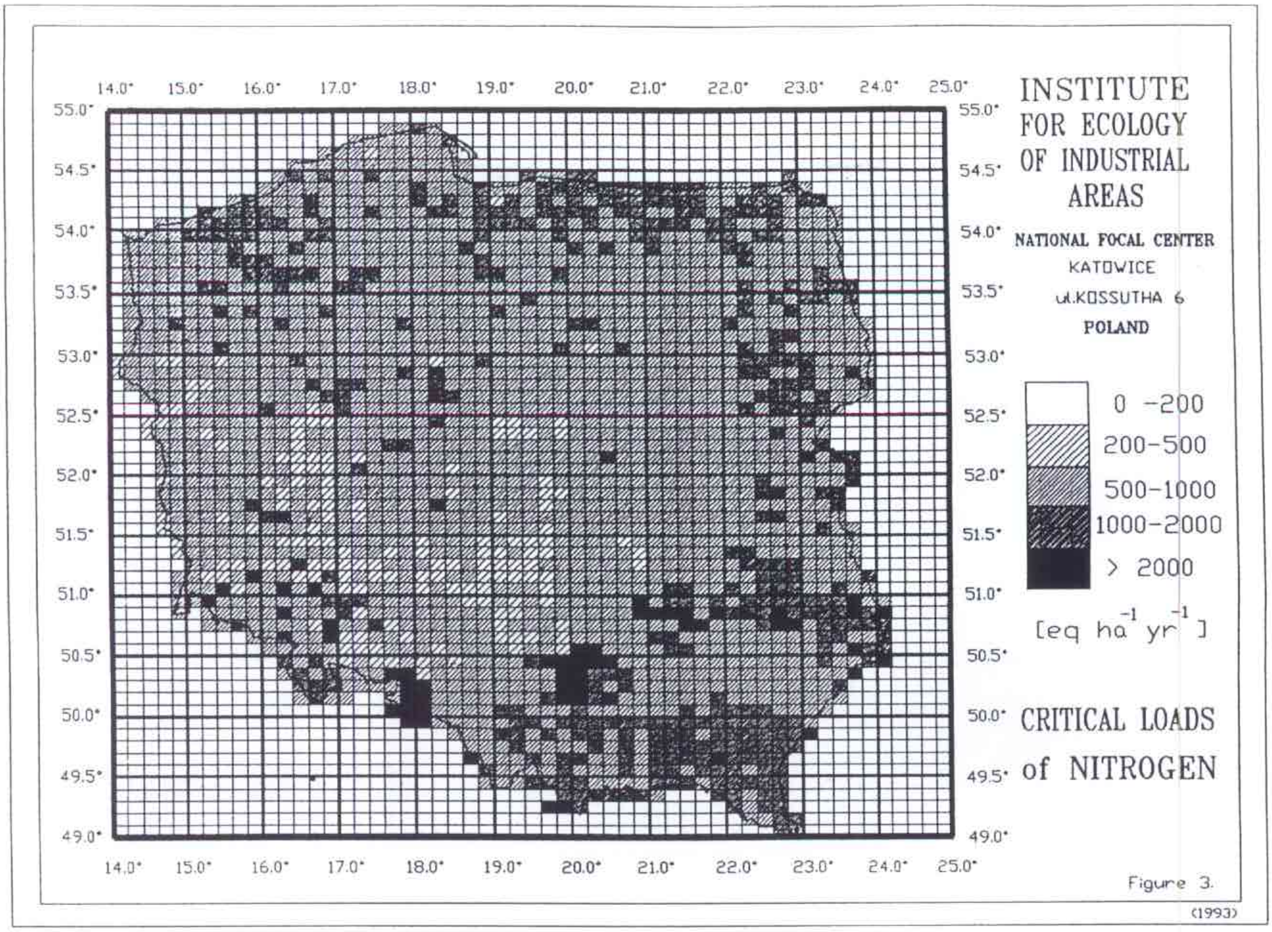

Figure A1.23. *Poland: Critical loads of nitrogen.*

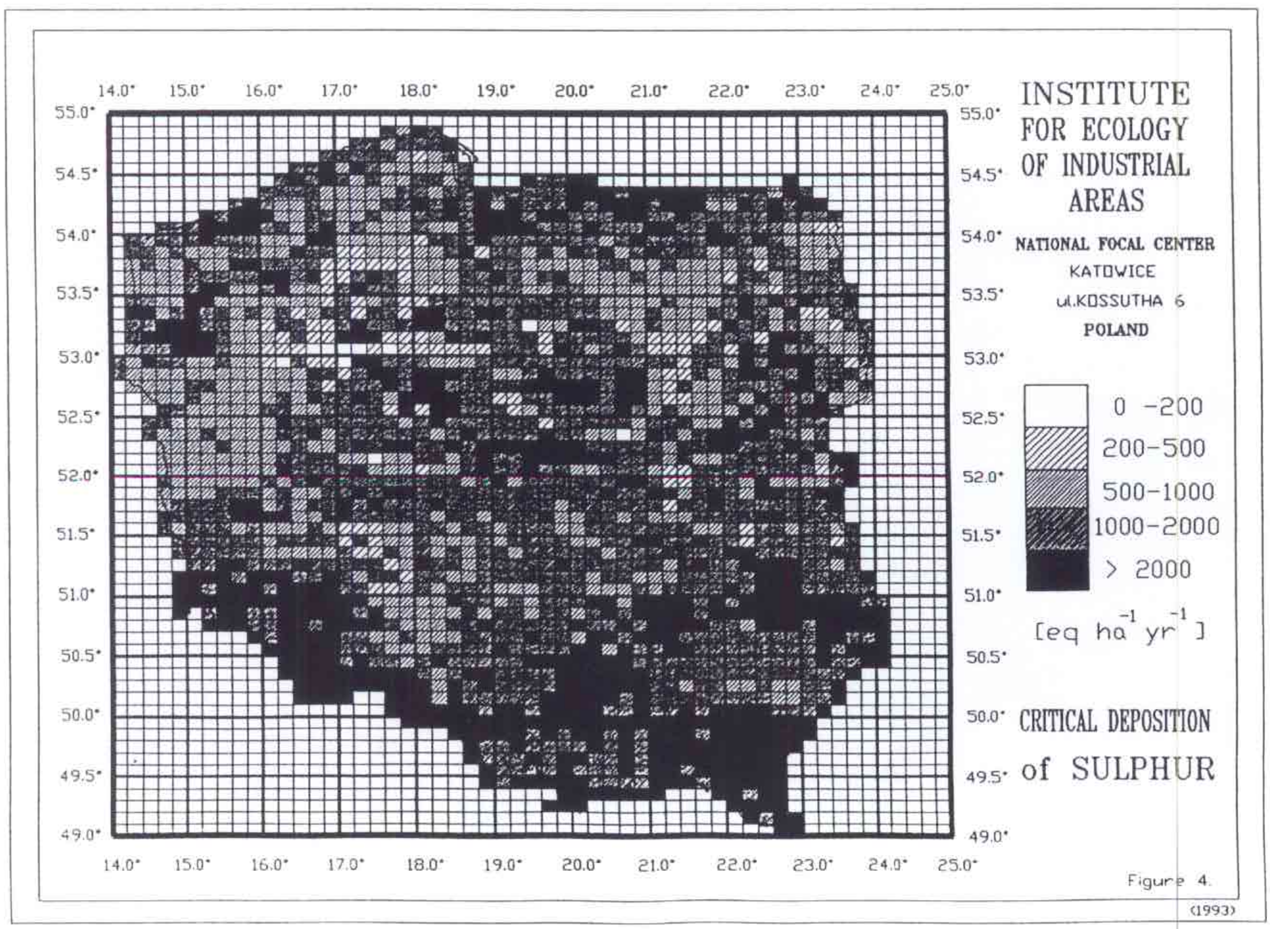

Figure A1.24. *Poland: Critical deposition of sulphur.*

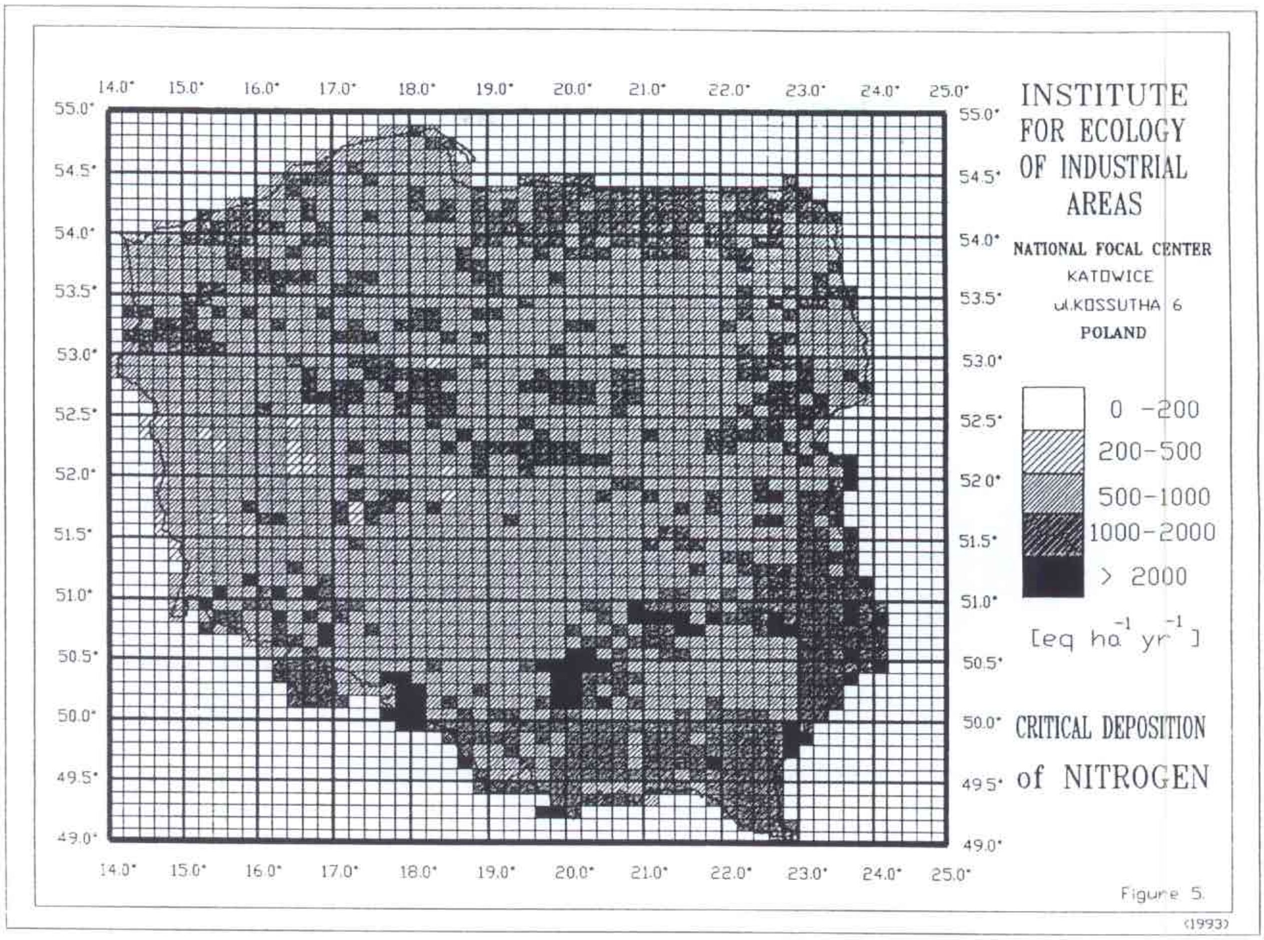

Figure A1.25. *Poland: Critical deposition of nitrogen.*

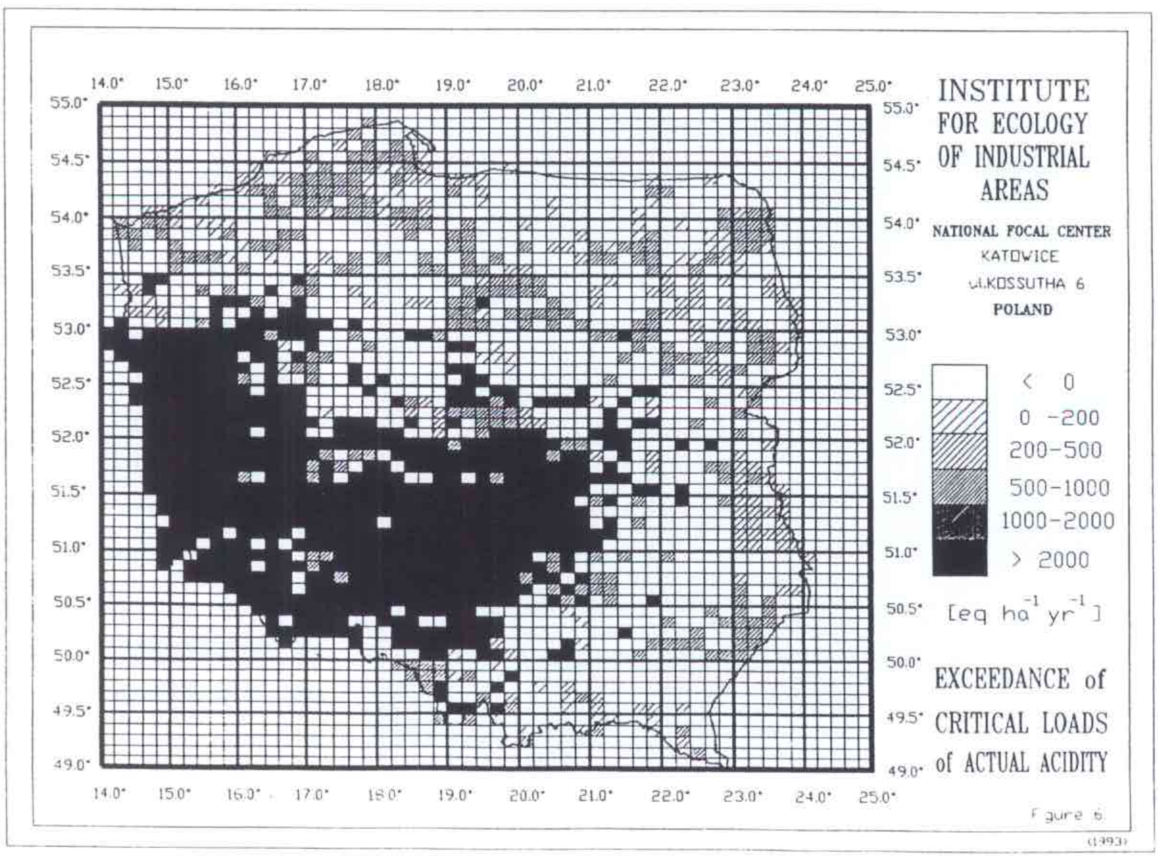

Figure A1.26. *Poland: Exceedance of critical loads of actual acidity.*

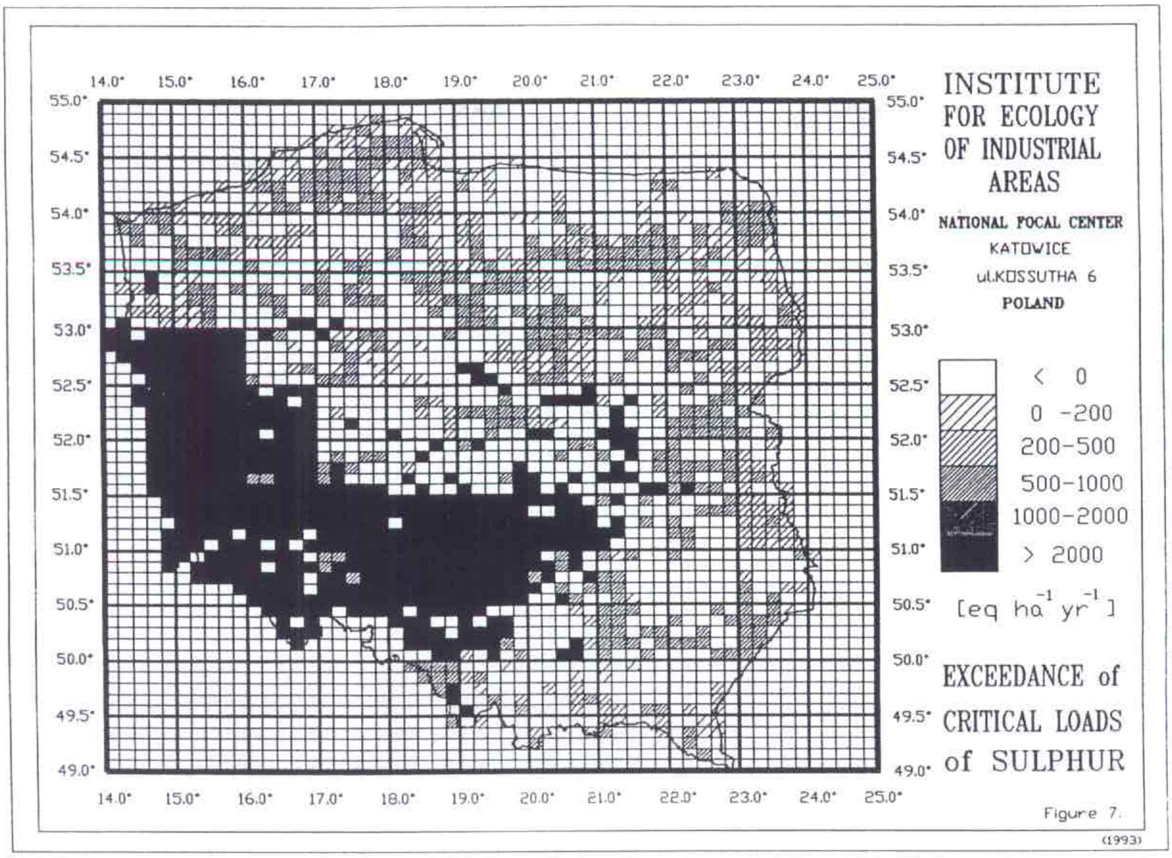

Figure A1.27. *Poland: Exceedance of critical loads of sulphur.*

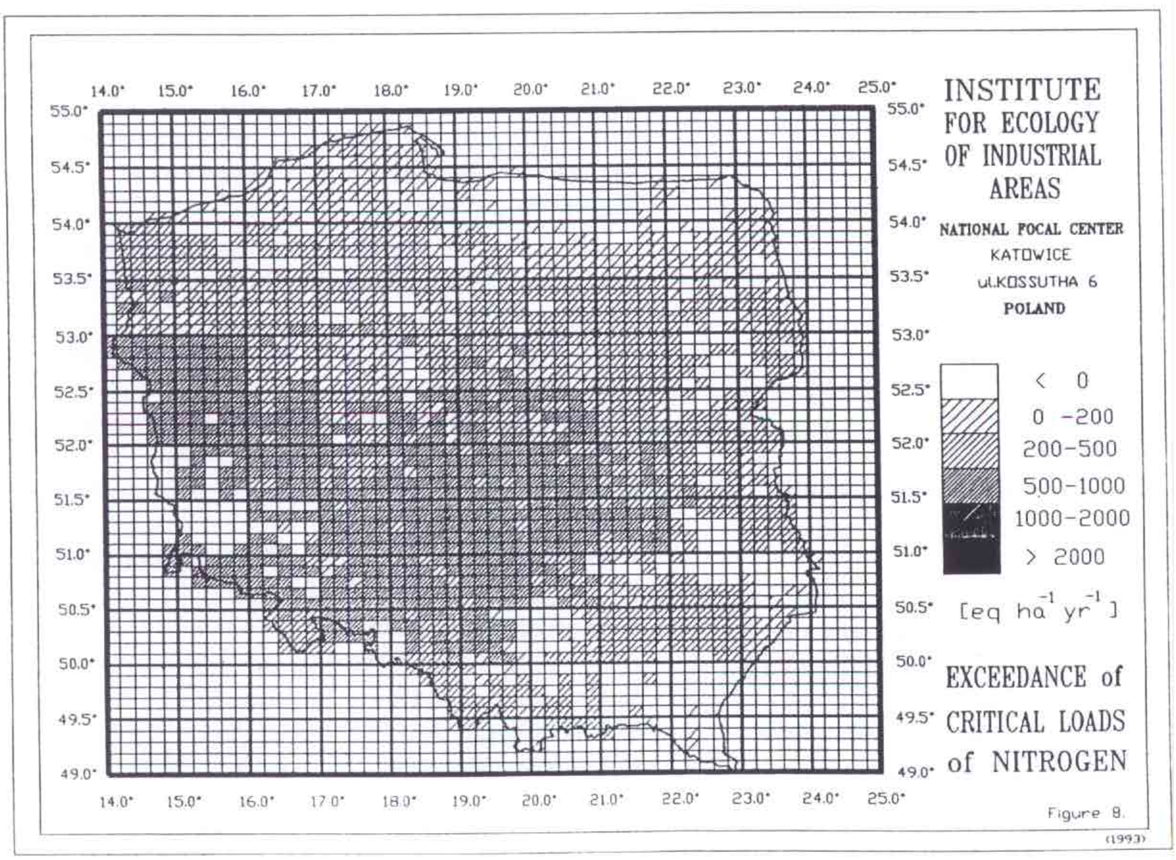

Figure A1.28. *Poland: Exceedance of critical loads of nitrogen.*

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Receptors mapped:

Forest soils; surface waters; forest ecosystems; mixed ecosystems

Calculation method:

The following parameters have been calculated on the basis of current methods summarized in Chapter 4:

- Critical deposition of acidifying sulphur and nitrogen (equations 4.24 and 4.25)
- Exceedances of critical deposition of sulphur and nitrogen (equations 4.26 and 4.27)
- Exceedance of nutrient nitrogen (equation 4.36/4.37).

The values of N_{de} were examined on the a basis of calculations described in the earlier discussion of denitrification.

- Exceedance of actual acidity (equation 4.28).

Grid size:

1° longitude x 0.5° latitude ("Lo-La" grid); 150 x 150 km (EMEP grid). Approximately 1400 receptor points, nearly 950 of which are (partially or wholly) covered by forest.

Data sources:

Geographical: The quantitative assessment and mapping of sulphur and nitrogen critical loads was carried out on the basis of number of regional parameters for a given ecosystem. For the European part of Russia the following data bases were identified:

- The inventory of soil types and subtypes (Liverovsky, 1974)
- The inventory of air self-purification capacity (Glazovskaya, 1976)
- The inventory of self-purification capacity and migration in surface water bodies (Glazovskaya, 1988)
- The inventory of values of surface runoff of nitrogen and phosphorus (Kondratjev and Koplan-Dix, 1988)
- The inventory of complex self-purification capacity of terrestrial and freshwater ecosystems (Glazovskaya, 1988)
- Hydrochemical regionalization of surface waters (Baranov, 1982)
- Biogeochemical regionalization of terrestrial and freshwater ecosystems (Kovalsky, 1974)
- Geological data for the European part of Russia (Geographical Atlas, 1980)
- Hydrochemical data for surface waters (Bikbulatov, unpublished data, 1993)
- Hydrobiological data for surface waters (Komov *et al.*, unpublished, 1993)
- Forest data (USSR Forest Atlas, 1973)
- Precipitation data (Gidrometeoisdat, 1989)
- Evapotranspiration data (Lvovich, 1974).

Ion deposition: The average deposition of nitrogen and sulphur compounds (wet and dry) have been taken from EMEP/MSC-E reports (Dedkova, 1992). The base cation content in precipitation have been taken from CCE data, as adapted from EMEP and IIASA. Due to a lack of available data on base cation deposition in a large area (see Figure A2.3), it has been assumed that $(BC_{dep} - BC_u) = 0$ for these areas.

Biomass uptake: Biomass uptake of nitrogen, calcium, magnesium, potassium, and sodium has been estimated on a basis of vegetation type and annual biomass increase (Bazilevich and Rodin, 1971; Manakov, 1972; Bashkin, 1987, 1992). Annual nitrogen uptake for various soil types and subtype as well as nitrogen : base cation ratios are shown in Tables A1.11 and A1.12. Values for nitrogen uptake range from 2 to > 150 kg ha^{-1} yr^{-1}, for calcium from < 6 to > 150 kg ha^{-1} yr^{-1}, for magnesium from < 1 to > 60 kg ha^{-1} yr^{-1}, for potassium from < 6 to > 150 kg ha^{-1} yr^{-1}, and for sodium from < 1 to > 8 kg ha^{-1} yr^{-1}. The average values of [N] : [Ca] are 1.1– 4.4, [N] : [Mg] are 7.8–35.0, [N] : [K] are 1.2–4.4, [N] : [Na] are 5.8–35.0, and [N] : [ΣBC] are 0.6–1.7.

Table A1.11. *Quantitative assessment of nitrogen utilization by natural plant biomass* (N_u) *for various soils (in kg N ha^{-1} yr^{-1}).*

Soil Type (FAO/Unesco classification)	C:N ratio	Nitrogen mineralizing capacity	Uptake coefficient		
				N deposition	
			N_{NMC}	NH_4	NO_3
Lithosols	14.0	25	0.1	0.2	0.3
Gleyic Podzoluvisols	9.0	47	0.15	0.2	0.3
Dystric Podzoluvisols	9.0	50	0.18	0.2	0.3
Albic Luvisols	10.4	83	0.2	0.2	0.35
Ferric, Humic and Dystric Podzols	21.4	71	0.15	0.15	0.4
Albi-Gleyic Luvisols	21.0	72	0.15	0.15	0.4
Luvic Phaerozems	11.9	87	0.25	0.25	0.5
Molic Chernozems	13.2	147	0.3	0.3	0.5
Haplic Chernozems	12.0	202	0.3	0.3	0.5
Deep Calcic Chernozems	11.9	166	0.3	0.3	0.5
Calcic Chernozems	11.8	185	0.3	0.3	0.5
Xeric Chernozems	11.6	138	0.3	0.3	0.5
Calcic Chernozems (mycelium)	12.0	150	0.25	0.25	0.4
Xeric Chernozems (mycelium)	12.0	150	0.25	0.2	0.35
Haplic Kastanozems	11.0	140	0.25	0.2	0.3
Luvic Kastanozems	9.5	90	0.25	0.2	0.3
Haplic Xerosols	9.0	53	0.2	0.15	0.3
Calcic solonetzic Xerosols	9.1	40	0.2	0.15	0.25
Gypsic luvic Yermosols	10.2	31	0.2	0.15	0.25
Rendzinas	10.0	90	0.25	0.2	0.3
Fluvisols	11.1	108	0.3	0.25	0.4

Base cation weathering (BC_w): The BC_w parameter is one of the most important in estimating critical loads of acidity, sulphur and nitrogen. The values of BC_w depend upon soil type, mechanical composition, parent material and they have been widely used during initial stage of our work (Krassilov *et al.*, 1991). It relates largely to the current CCE method of calculations (Hettelingh and de Vries, 1992).

However, further investigations have shown that the rate of chemical weathering depends to a greater extent on the total content of base cations, their exchangeable forms and, in particular, on hydrothermal conditions, which have not been taking into account directly under current calculation methods. Furthermore, in view of the great variety of soil and climatic conditions of forest and freshwater ecosystems in Russia, the factors mentioned above greatly influence the actual rate of weathering (Glazovskaya, 1989). These factors influence all soil types in the European part of Russia: sub-arctic and boreal belts as well as to sub-boreal and semi-humid ones. Consequently, in acid

Table A1.12. *Annual biomass uptake of biophilic elements in various vegetation types of the European part of Russia.*

Vegetation Type	kg ha^{-1} N	P	Ca	K	Mg	Na	average ratio N:P	N:Ca	N:K	N:Hg	N:Na	N:ΣBC
Moss and lichen tundra	< 11	1–3	6–10	6–10	1–2	1	7.5	1.9	1.9	10.0	15	0.8
Bush tundra	21–50	4–6	11–40	11–30	2–6	1	7.0	1.4	1.8	8.8	35	0.7
Forest tundra	21–50	4–6	11–40	11–30	2–6	1	7.0	1.4	1.8	8.8	35	0.7
Pine forest	21–50	1–3	6–10	6–10	1–2	1	17.5	4.4	4.4	23.3	35	1.7
Dark-conifers of northern taiga	21–50	1–3	11–40	11–30	2–6	1	7.0	1.4	1.8	8.8	35	0.7
Dark-conifers of middle taiga	51–75	4–6	41–70	31–50	6–10	1–2	12.6	1.1	1.6	7.9	42	0.6
Dark-conifers of southern taiga	51–75	4–6	41–70	31–50	6–10	2	12.6	1.1	1.6	7.9	42	0.6
Sphagnum swamps	21–50	1–3	6–10	6–10	1–2	< 1	17.5	4.4	4.4	23.3	35	1.7
Deciduous-dark conifers	101–150	10–15	71–100	51–90	11–15	2	10.0	1.5	1.8	9.6	62.5	0.7
Deciduous-pine conifers	101–150	10–15	41–70	51–90	6–10	2	10.0	2.3	1.8	15.6	62.5	0.9
Broad-leave forest	76–100	10–15	101–150	51–90	15–22	2	6.8	0.7	1.2	5.0	43.0	0.4
Flood-plain forest	301–400	10–15	101–150	121–150	45–60	2–4	29.1	2.8	2.6	6.7	116.7	1.1
Meadow steppe	101–150	10–15	41–70	91–120	12–21	4–6	10.0	2.3	1.2	7.8	25.0	0.9
Steppe forest and bushes	101–150	7–10	41–70	31–50	12–21	4–6	14.7	2.3	3.1	7.8	25.0	1.1
Dry steppe	76–100	4–6	11–40	11–30	2–6	6–8	17.4	5.0	6.2	31.2	17.8	1.4
Dry solonetz steppe	51–75	4–6	11–40	31–50	2–6	6–8	12.4	2.1	1.6	15.5	8.9	0.9
Desert steppe	76–100	1–3	11–40	11–30	1–4	2–4	43.3	2.9	4.4	35.0	29.2	1.7
Desert forest	21–50	1–3	6–10	11–30	< 1	6	17.5	4.4	1.8	> 35.0	5.8	1.0

and weak acid soils not saturated by base cations, the base cation weathering rate was calculated as:

$$BC_w = (BC_{exch} + BC_w^*) \cdot C_t \quad \text{(A1.18)}$$

and in neutral soils, saturated by base cations, on the basis of the following equation:

$$BC_w = (BC_{exch} + BC_{CaCO3} + BC_w) \cdot C_t \quad \text{(A1.19)}$$

where:
BC_{exch} = weathering influenced by exchangeable base cations in soil
BC_w^* = weathering of other soil minerals
BC_{CaCO3} = weathering influenced by reaction with carbonate minerals
C_t = hydrothermal coefficient

Thus the BC_w values in northern and moderate soils (Lithosols, Gleyic Podzoluvisols, Distric Podzoluvisols, Albic Luvisols, Ferric, Humic and Distric Podzols, Albi-Gleyic Luvisols) vary from 50 to 1000 eq ha^{-1} yr^{-1}. In southern soils (various types of Chernozems) these values are more than 20,000 eq ha^{-1} yr^{-1} and practically are not influenced by acid atmospheric deposition.

Calculation of critical loads:

Conceptual ideas: At present there are at least two approaches to the determination of critical load values:

1. The use of steady-state mass balance equations including a quantitative assessment of the maximum possible number of parameters of pollutant turnover in the limits of a specific, defined area (i.e. a watershed). Such an approach is the most applicable in comparatively small areas having high degree of information support for calculation of various parameters and constants of balance equations. This approach is used as a basis for calculation of critical loads for many European countries.

2. Use of various expert-modelling geoinformation systems using modern computers. These systems can operate using data bases and knowledge bases relating to the areas with very great spatial data

uncertainty. As a rule, the given systems include an analysis of various element cycles in the key plots, a choice of algorithm describing these cycles and corresponding interpretation of data. This approach requires numerous cartographic materials, for example, maps of soil cover, geochemical and biogeochemical structure, self-purification capacity of soil, water, atmosphere, etc. It is the most applicable approach for Russia because it is impossible to present adequate supporting information for the great spatial variability of natural and anthropogenic factors (Bashkin, 1987, 1992).

Taking into account these approaches as well as the need to use the unique European approaches for the quantitative assessment and mapping of critical loads, this research project was based on following methodology (Bashkin *et al.*, 1993):

a) All areas under study was divided into "elemental taxons" based on soil subdivision, biogeochemical regions and geochemical areas of self-purification.

b) As much acceptable information as possible was collected for each elemental taxon to give a quantitative assessment of various parameters and constants of balance equations for the cycling of sulphur, nitrogen, heavy metals, persistent organic pollutants, etc.

c) Taking into account the maximal sensitivity of freshwater ecosystems, this assessment of critical load values was made for watershed areas including all terrestrial and freshwater ecosystems.

d) Using expert-modelling systems and geographic information systems (GIS), the results obtained were interpreted on the whole areas of each elemental taxon.

e) The critical load values were corrected on a basis of hydrothermal peculiarities of active stages of geochemical and biogeochemical reactions.

A. Critical loads of acidity

The values of critical loads of acidity were calculated by two parallel approaches:

a) The critical load of actual acidity, $CL(A)$, is calculated according to equation 4.1 of the Mapping guidelines (see Chapter 4):

$$CL(A) = ANC_w - ANC_l$$

Calculations of ANC_l have been described earlier (Krassilov *et al.*, 1991).

b) The critical load of actual acidity were calculated on the basis of the following equation:

$$CL(Ac_{act}) = \frac{CL(N) - N_u - N_i}{1 - S_f} \qquad (A1.20)$$

The values of $CL(Ac)$ range from less than 100 to more than 20,000 eq ha^{-1} yr^{-1}. The differences between two techniques of calculation were in limits of ± 25 percent.

B. Critical loads of sulphur

The values of $CL(S)$ were calculated according equation 4.2 of the mapping guidelines (see Chapter 4), and range from 0.01 to 142.1 kg ha^{-1} yr^{-1} for the European part of Russia.

C. Quantitative assessment of nitrogen critical loads

The quantitative assessment of critical loads was carried out according to above-mentioned principles on a basis of steady-state mass balance equations for every "elemental taxon". In the European part of Russia, 23 soil types and subtypes, 12 zones of air self-purification capacity, 14 zones of self-purification capacity and migration in surface water bodies, 8 zones of values of surface runoff of nitrogen and phosphorus, 14 zones of complex self-purification capacity of terrestrial and freshwater ecosystems, 4 hydrochemical classes of surface waters were derived. Additionally 4 biogeochemical regions and many natural, technobiogeochemical, and agrogeochemical provinces were divided for an assessment of possible influence of acidification and eutrophication on the human health.

As a basic steady-state mass balance equation, the following equation was used, in accordance with proposed method for calculation European critical loads (see also Chapter 4):

$$CL(N) = N_u + N_{de} + N_i + N_{l(crit)} \cdot Ct \qquad (A1.21)$$

This equation allows for the calculation of a nitrogen balance for the whole watershed areas including terrestrial and freshwater ecosystems.

Nitrogen uptake (N_u): Values were assessed for every soil type and subtype subdivided on the area under study in accordance with the following equation:

$$N_u = (N_{td} + N_{NMC}) \cdot C_{upt} \qquad \text{(A1.22)}$$

where:
N_{td} = total nitrogen deposition
N_{NMC} = actual nitrogen mineralizing capacity of soils
C_{upt} = coefficient of nitrogen uptake by vegetation
This equation is a modified analog of equation 4.8 (see Chapter 4).

It is known that it is impossible to apply the term "weathering" to nitrogen due to its predominant accumulation in soil organic matter. This index was thus changed to an index "nitrogen mineralizing capacity of soils", i.e. the mineralization of soil organic matter under the influence of input of mineral nitrogen from deposition and/or from fertilizers (Bashkin and Kudeyarov, 1989). The values of nitrogen mineralizing capacity (N_{NMC}) were determined for the majority of soil types and subtypes in experimental trials. For those soils where experimental assessments were absent, the N_{NMC} values were calculated by following equation (Bashkin, 1987):

$$Y = 9.587 + 0.185\,(C:N) + 0.190\,(Ca^{2+}) - 0.790\,(Mg^{2+}) - 1.157pH + 0.080\,(P_2O_5) \qquad \text{(A1.23)}$$

where:
Y = nitrogen mineralizing capacity
$C:N$ = carbon to nitrogen ratio in forest and virgin soils
Ca^{2+}, Mg^{2+} = exchangeable cations, mg 100 g^{-1} soil
pH = content of H^+ ions in KCl extract
P_2O_5 = mobile phosphorus, mg 100 g^{-1} soil

Table A1.11 shows the N_{NMC} values and uptake coefficients for every soil division (types and subtypes). In accordance with this table, N_u values range from 9 to 180 kg ha^{-1} yr^{-1}, but in the majority of natural zones they are less than the values of perennial nitrogen accumulation in yearly biomass increase (Table A1.12). This means that the majority of terrestrial natural ecosystems have a nitrogen deficit, which is covered by nitrogen uptake from lower soil horizons (lower than 50 cm depth) and/or due to symbiotic and non-symbiotic nitrogen fixation.

Denitrification (N_{de}): It was found in numerous field and laboratory experiments with various forest and virgin soils (Podzols, Albic Luvisols, Luvic Phaeozems, Haplic and Calcic Chernozems, Harlic Kastanozems, Ferralic Arenosols, Rhodic and Haplic Nitosols, Cryic Fluvisols, Fluvisols etc.) that:

$$N_{de} = 0.145\,(N - N_{NMC}) + 6.477 \qquad \text{(A1.24)}$$

$n = 43$, $r = 0.847$.

It is well known that all biochemical and biological processes in soil do not depend on the type of nitrogen source (mineralized, fixed, from precipitation or fertilizers, etc.). Thus it is possible to assign a portion of the denitrification to that portion of nitrogen input received from precipitation (Bashkin, 1987). The denitrification values for soils under study range from 0.1 to 5 kg ha^{-1} yr^{-1}.

Nitrogen immobilization (N_i): Values of N_i were calculated on the basis of numerous experimental studies with main soil types in the territory of Russia. It was found that in the dependence of the C:N ratio there are following relationships:

where:

C:N < 10	then $N_i = 0.2\ NH_4^+ + 0.1\ NO_3^-$	
10 < C:N < 13.2	then $N_i = 0.3\ NH_4^+ + 0.2\ NO_3^-$	(A1.25)
C:N > 13.2	then $N_i = 0.4\ NH_4^+ + 0.3\ NO_3^-$	

where:
NH_4^+, NO_3^- = input of nitrogen from precipitation.
N_i values range from 2 to 7 kg yr^{-1}.

Critical nitrogen leaching:
a) Values for critical nitrogen leaching to avoid eutrophication of terrestrial ecosystems, $N_{l(crit)t}$, were calculated on the basis of the following assumptions:
- root zone depth = 0.5–1.0 m
- nitrogen concentration in inner soil waters = 0.2–2.5 mg l^{-1}
- surface and undersurface runoff = 50–600 mm ha^{-1} yr^{-1} and were equal to 1–12 kg ha^{-1} yr^{-1}.

b) According to numerous experimental data, the application of a critical load concept for nitrogen as a eutrophying factor must also consider phosphorus (Kämäri *et al.*, 1992; Kondratjev and Koplan-Dix, 1989; Bikbulatov *et al.*, 1993).

It has also been found that in phytoplankton biomass in general C : H : O : N : P ratios are close to the Redfield ratio 106 : 175 : 50 : 16 : 1 (by atoms). As a rule, C, H, and O in surface waters are in excess and phytoplankton biomass is determined by a N : P ratio of 16 : 1. At present in accordance with an analytical review (Bikbulatov, unpublished data, 1993), the predominant number of lakes and water reservoirs in the European part of Russia are strongly limited by phosphorus and only one, Pletscheevo lake in the Yaroslavl region, is limited by nitrogen, i.e. having a N : P ratio < 16. Based on these assumptions, it is possible to calculate critical nitrogen leaching in comparison with critical phosphorus loads presented in Table A1.13 (after Bikbulatov, 1993) for the main characteristic water bodies in various hydrochemical classes. Thus:

$$N_{l(crit)w} = 16 \cdot CL(P) \tag{A1.26}$$

where:
$N_{l(crit)w}$ = critical nitrogen leaching to avoid surface water eutrophication
$CL(P)$ = critical load of phosphorus to avoid an alteration of trophic level

Critical loads of phosphorus were calculated on a basis of the well-known Vollenweider model (1975):

$$CL(P) = Lc = P_c \cdot \frac{z}{t} \cdot (1 + t^{1/2}) \tag{A1.27}$$

where:
P_c = critical phosphorus concentration to subdivide trophic levels (usually 10 µg l^{-1})
z = average depth of water bodies (in meters)
t = period of water exchange (years)

Table A1.13 shows the values of N : P ratios, $CL(P)$ and $N_{l(crit)w}$ for various lake systems in the Russian area. It was shown that for various water bodies situated in different "individual taxons" the values of $N_{l(crit)w}$ are in the limits of 8 to 53 kg ha^{-1} yr^{-1}.

Table A1.13. *Values of N : P ratios, critical loads of phosphorus, and nitrogen critical loads in various Russian lakes.*

Region	N : P ratio	$CL(P)$ (mg m^{2} yr^{-1})	$N_{l(crit)w}$ (kg ha^{-1} yr^{-1})
Kareliya	16–33	29–67	0.9–9.4
Nonchernozemic belt	21–52	56–219	2.9–18.0
Chernozemic belt	17–54	104–600	24–54

It is necessary to note that transformation and migration nitrogen in soil-plant-water systems occur only during periods with active geochemical or biogeochemical reaction and processes. The duration of these periods varies greatly in the area under study, from less than 2 months in arctic zones, and up to 10 or 11 months in southern and southwestern zones. According to this figure, the corresponding coefficients (C_t) were used to take into account biogeochemically active periods. These coefficients, ranging from 0.25 to 0.83, were applied in calculating each component of nitrogen critical loads. Summing the results, the values of $CL(N)$ range from 0.05 to 120.5 kg ha^{-1} yr^{-1} for the European part of Russia.

Mapping critical load values and their exceedances in an EMEP grid cell:
On the basis of a longitude-latitude grid cell distribution, the values of $CD(S)$, $CD(N)$ and corresponding exceedances were recalculated for each EMEP grid cell. These values are shown in Table A1.14.

Table A1.14. *Distribution of values of critical deposition of sulphur and nitrogen in the European part of Russia.* Figures are given as percentage of total area.

Ranges	Critical deposition		Exceedances	
(eq ha^{-1} yr^{-1})	$CD(S)$	$CD(N)$	$CD(S)exc$	$CD(N)exc$
< 200	4.8	7.0	87.1	99.4
200–500	36.0	22.0	5.3	0
500–1000	26.9	15.1	5.3	0
1000–2000	19.9	22.0	2.3	0
> 2000	12.4	33.9	0	0.6

Conclusions:

The quantitative assessment and mapping of sulphur and nitrogen critical loads and deposition show that the minimal values (< 200 eq ha^{-1} yr^{-1}) are calculated for some plots of arctic and sub-arctic zones. The possible negative ecological problems are here connected with an acidification and eutrophication, because: (a) various types of podzols and lithosols have low buffering capacity to additional input of H^+ ions, and (b) most lakes are oligotrophic. These values are characteristic for 4.8 and 7.0% of the European part of Russia for sulphur and nitrogen, correspondingly.

In the northwestern part of the Kola peninsula, the values of atmospheric deposition of sulphur are high and exceed the values of *CD(S)*. The values of nitrogen deposition are not so high in these zones and at present there is no remarkable exceedances of *CD(N)*.

In the belt of conifers the values of *CD(S)* and *CD(N)* are in the ranges of 200–500 and partly 500–1000 eq ha^{-1} yr^{-1}. Exceedances of *CD(S)* and *CD(N)* are noted in the St. Petersburg region, although in other zones of this taiga-forest non-chernozemic belt, critical loads are seldom exceeded at existing levels of atmospheric deposition, but potentially this area is sensitive due to low buffering capacity of soils and the oligotrophic or partly mesotrophic state of water bodies. (In total, about 50% and 40% of area under study for sulphur and nitrogen, respectively.)

In other areas of the European part of Russia there are practically no exceedances of sulphur and nitrogen critical loads and critical deposition values. Potentially dangerous effects can be related to eutrophication aspects, especially in mixed forest-agricultural zones with large amounts of surface phosphorus runoff, e.g. in forest-steppe chernozemic biogeochemical region.

Figures:

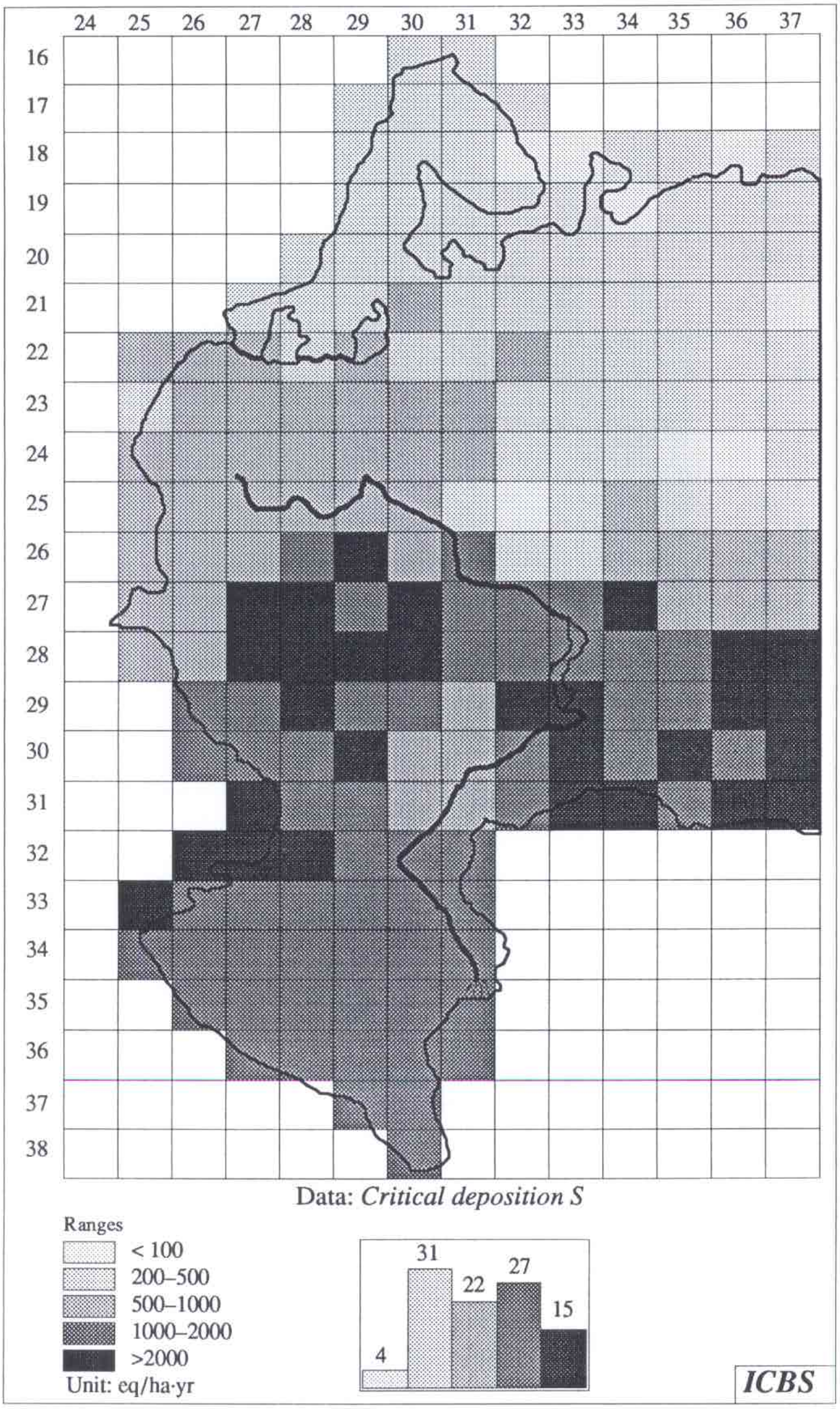

Figure A1.29. *Russia: Critical sulphur deposition.*

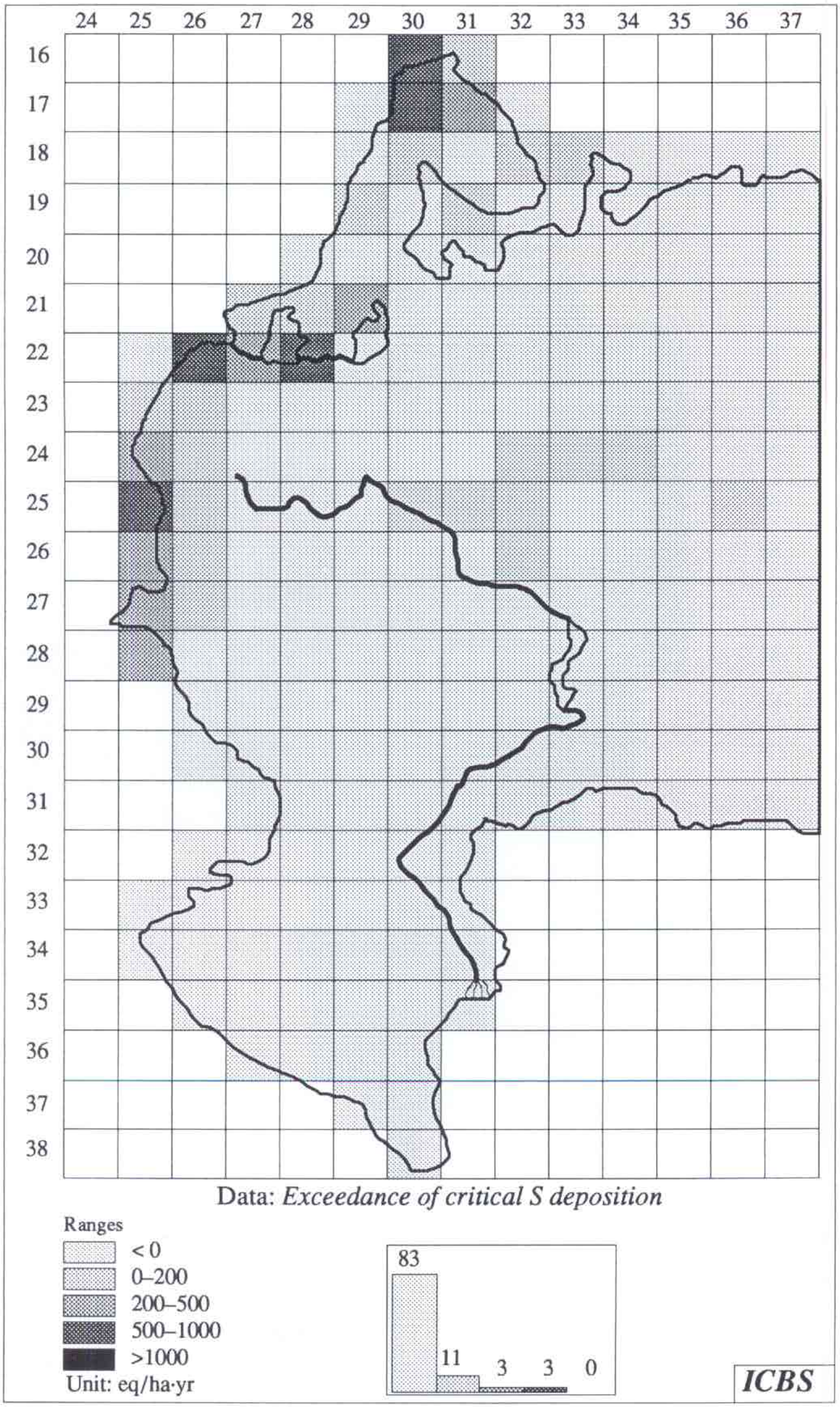

Figure A1.30. *Russia: Exceedance of the critical sulphur deposition.*

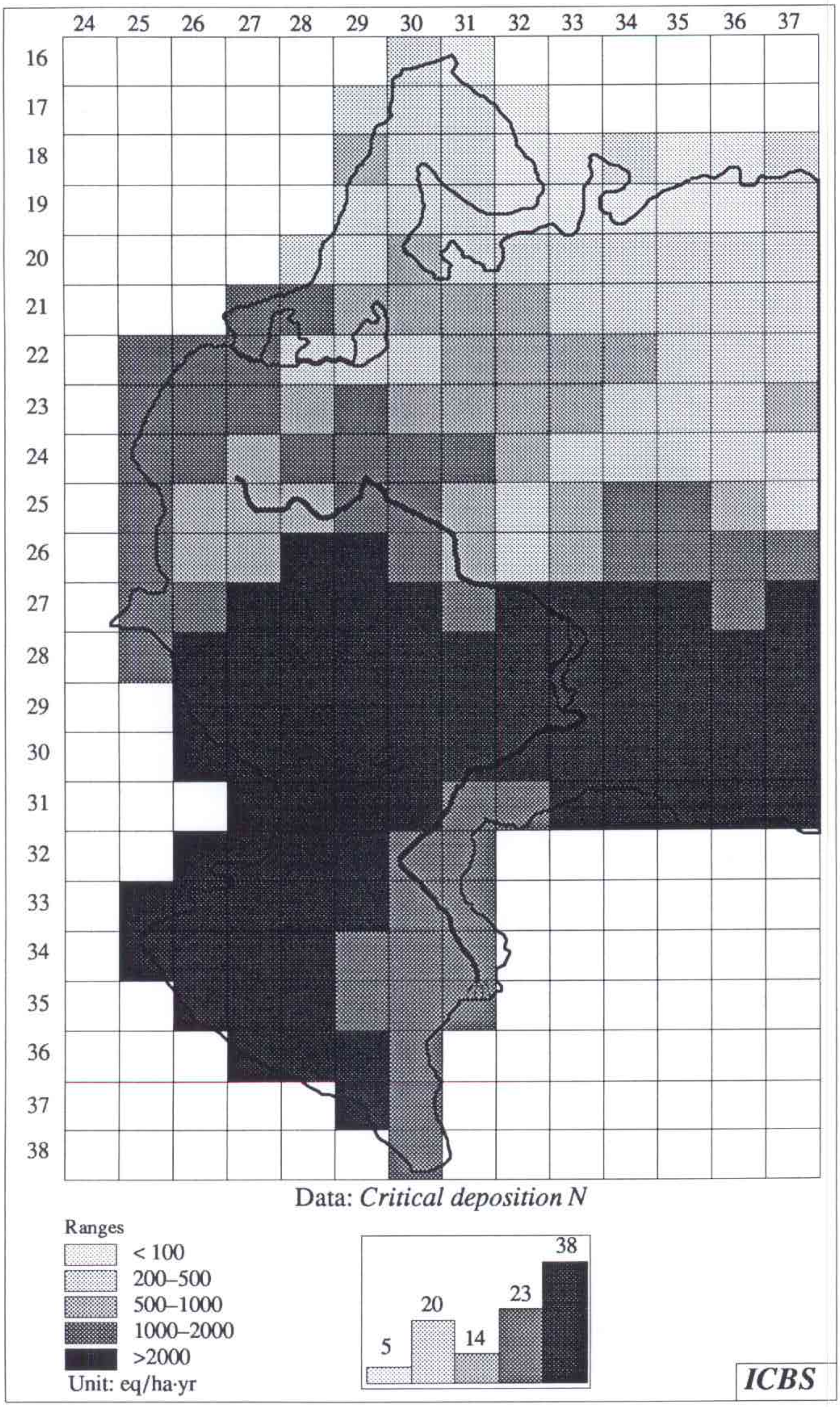

Figure A1.31. *Russia: Critical nitrogen deposition.*

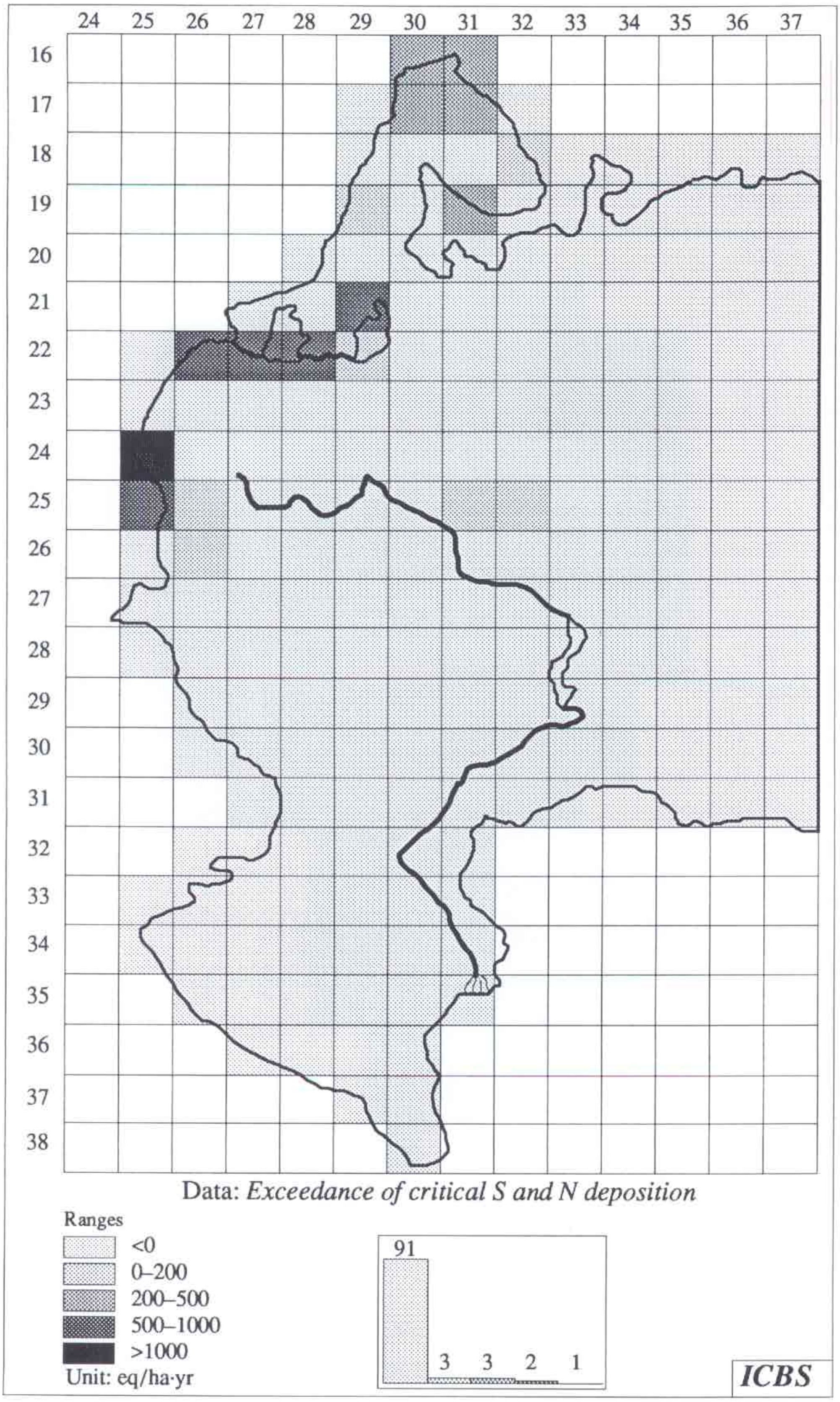

Figure A1.32. *Russia: Exceedance of the critical nitrogen deposition.*

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Receptors Mapped:

The forest critical load maps applies to all types of forests on moraine. The forest vegetation includes the Southern Swedish deciduous forest, the coniferous forest and the northern birch forest.

Program A. Deposition (G. Lövblad)

Calculation Method:

The deposition over Sweden has been mapped in cooperation with other Nordic countries. The main purpose of the joint Nordic effort was to obtain deposition estimates which as close as possible agree with monitoring data (throughfall measurements). Another main goal was to harmonize the national maps in order to avoid discrepancies along national borders. Deposition of sulphur and nitrogen was estimated based on monitoring results of wet deposition. Dry deposition was calculated from air pollution concentrations and dry deposition velocities. For sulphur deposition, velocities were derived from throughfall results, and for nitrogen from literature data. Deposition was mapped to specific ecosystems in order to compare it to critical loads. Land-use weighted deposition was calculated for 50 x 50 km EMEP subgrid net.

Data Sources:

Data used for calculating deposition of sulphur and nitrogen include:

- wet deposition monitoring data from the national monitoring network: 30 stations for precipitation chemistry and 700 for precipitation amount
- air concentration data from the six Swedish EMEP stations
- throughfall monitoring results from a network in southern Sweden (around 80 stations)
- snow cover data from the national meteorological network
- land use data from the Swedish University of Agricultural Sciences.

Program B. Acidity in Forest Soils

(H. Sverdrup & P. Warfvinge)

Calculation Method:

Steady-state mass balance appproach, implemented as the Apple MacIntosh version of the PROFILE model. Units used are keq ha^{-1} yr^{-1} if not otherwise specified. The soil profile is divided into four layers, using input data for the thickness of each soil layer. The criteria were applied for soil depths of

0–50 cm of the soil, assumed to be the tree rooting depth in Sweden.

Criteria:

The criteria Ca:Al > 1.0 was used for the calculation of critical loads. In the model base cation uptake will occur from each layer, but uptake is stopped if the base cation soil solution concentration falls below 15 $\mu eq\ l^{-1}$. Residual uptake is then moved to the next layer.

Data sources:

The calculations are based on 1804 individual points. The soil and vegetation data was taken from the data base of the Swedish National Forest Survey. For each site the net long-term uptake is specified, based on the measurements in the survey of base cation and nitrogen contents of stem and branch, combined with site-specific estimates of net long-term forest growth. Each tree is considered separately, and the total uptake weighted together for each calculation point. Weathering rate is calculated internally in the PROFILE model, primarily from mineralogy and texture.

The soil mineralogy was derived for 131 sites by measurement. For the remaining sites, the soil mineralogy was calculated using the total analysis, backchecked against the 131 measured mineralogy determinations. Texture was measured by granulometry and BET/adsorption. The texture for the remaining 1673 sites were read from the correlation using the field classification.

Annual average air temperature, precipitation and runoff was taken from official statistics for each NILU grid (3 x 3 subdivision of EMEP). Other input data were derived strictly in accordance with Sverdrup *et al.* (1990) and the Mapping Vademecum.

Program C. Nitrogen in Forest Ecosystems (P. Warfvinge & H. Sverdrup)

Calculation method:

The nutrient limitation concept, as described in the Grennfelt and Thörnelöf (1992), were applied in the PROFILE model. The map is calculated using stem uptake according to present land use patterns. Immobilization was assumed to be the fraction of litterfall not decomposed, modified with respect to soil pH, wetness and temperature. Immobilization range from 1.5–6 kg $ha^{-1}\ yr^{-1}$ under critical loads in a north-south gradient.

Criteria:

The critieria applied were in accordance with the nutrient limition concept. Growth and nitrogen uptake is limited by current growth rate or lessened according to the availability of base cations. No nitrogen is permitted in the percolating water at the bottom of the rooting zone at 50cm soil depth.

Data sources:

Critical loads of acidity data base. Calculations were based on 1804 points, ultimately derived from data of the Swedish Forest Survey.

Program D. Acidity of Lake Ecosystems

(H. Sverdrup & P. Warfvinge)

Calculation method:

The critical load was calculated using two complementary methods. The steady-state water chemistry method ("Henriksen method") was used for 4,000 lakes. The PROFILE model was applied to 1804 small catchments in forested areas.

Criteria:

For the steady-state water chemistry method, an ANC_{limit} of 20$\mu eq\ l^{-1}$ was used. The PROFILE model was used to reconstruct historical ANC in 1804 catchments. The critical limit applied was ANC_{limit} = 20$\mu eq\ l^{-1}$ or $ANC_{limit} = ANC_{historical} - 10\mu eq\ l^{-1}$ when $ANC_{historical} < 20\mu eq\ l^{-1}$. This procedure eliminates negative critical loads. The map based on the PROFILE calculation ignores lakes in agricultural areas and very large lakes.

Data sources:

Chemistry data from 4021 lakes was sampled in January to April 1990. The lakes were randomly selected from a size stratification of the lake population in Sweden. Data was corrected for liming. The data for the PROFILE model application is the forest critical loads data base supplemented with soil depth information from the Swedish Geological Survey and the Swedish Forest Survey.

Figures:

A1.33. Sweden: Seasalt-corrected deposition of S and N, and exceedance of S deposition over the critical loads:

a. Sulphur + nitrogen deposition.

b. Sulphur deposition in excess of the critical loads.

A1.34. Sweden: Critical loads and exceedance of acidity for forest soils:

a. Critical loads, 5 percentile.

b. Exceedance of critical loads, 5 percentile.

A1.35. Sweden: BC : Al ratios and forest growth:

a. Future BC : Al, present deposition continued (50 percentile).

b. Observed BC : Al, n=450 (50 percentile).

c. Estimated historic BC : Al (50 percentile).

A1.36. Sweden: Critical loads and exceedance of acidity for lakes:

a. Henriksen method (5 percentile).

b. PROFILE model (5 percentile).

c. Exceedance of critical loads, PROFILE model.

A1.37. Sweden: Critical loads and exceedance for nitrogen in forest ecosystems:

a. Critical loads of nitrogen, keq ha^{-1} yr^{-1} (5 percentile).

b. Exceedance of critical loads, keq ha^{-1} yr^{-1} (5 percentile).

c. Reduction required to reach critical loads (5 percentile).

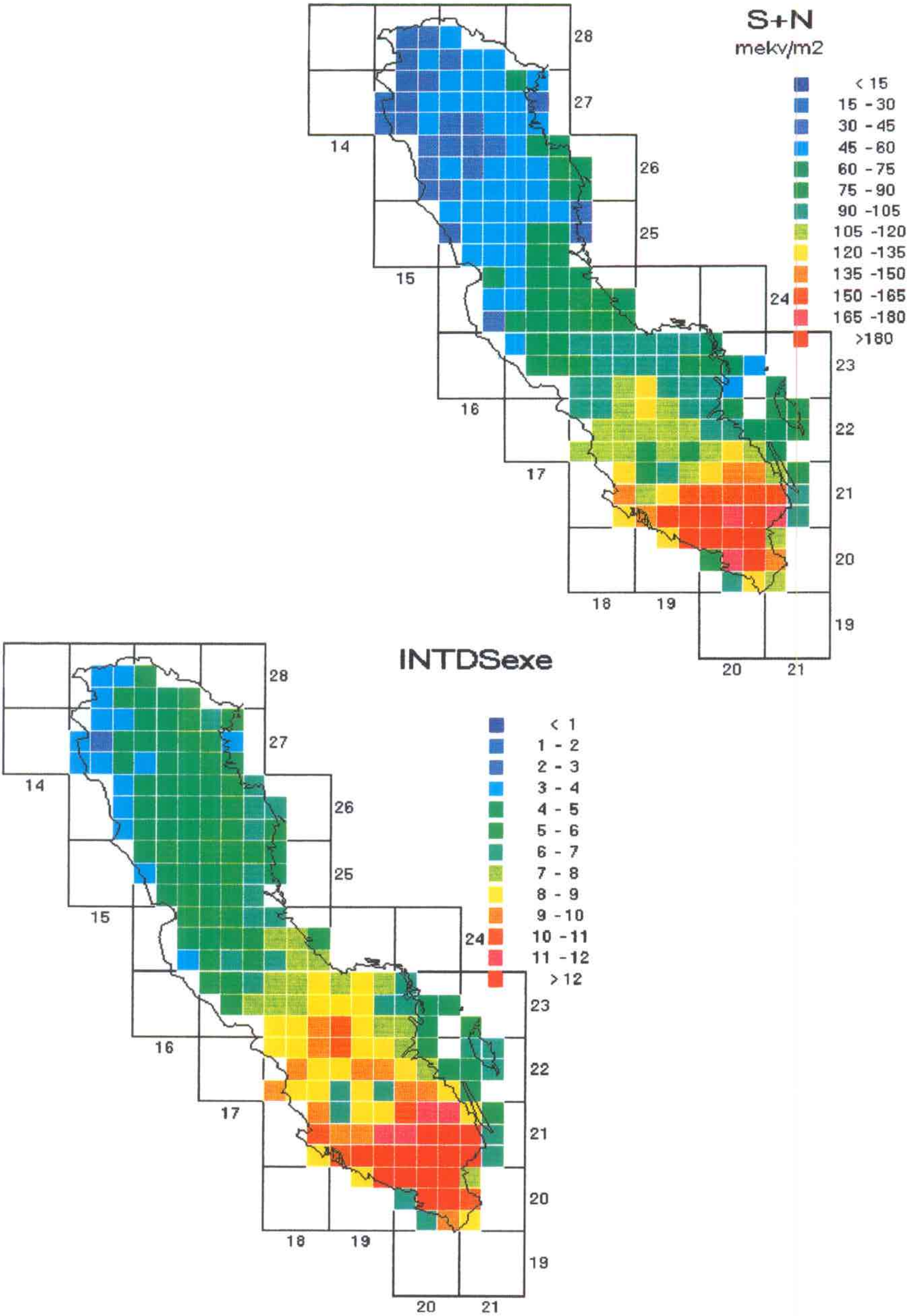


Figure A1.33. *Sweden: Seasalt-corrected deposition of S and N, and exceedance of S deposition over the critical loads. a. Sulphur + nitrogen deposition* (top); *b. Sulphur deposition in excess of the critical load* (bottom).

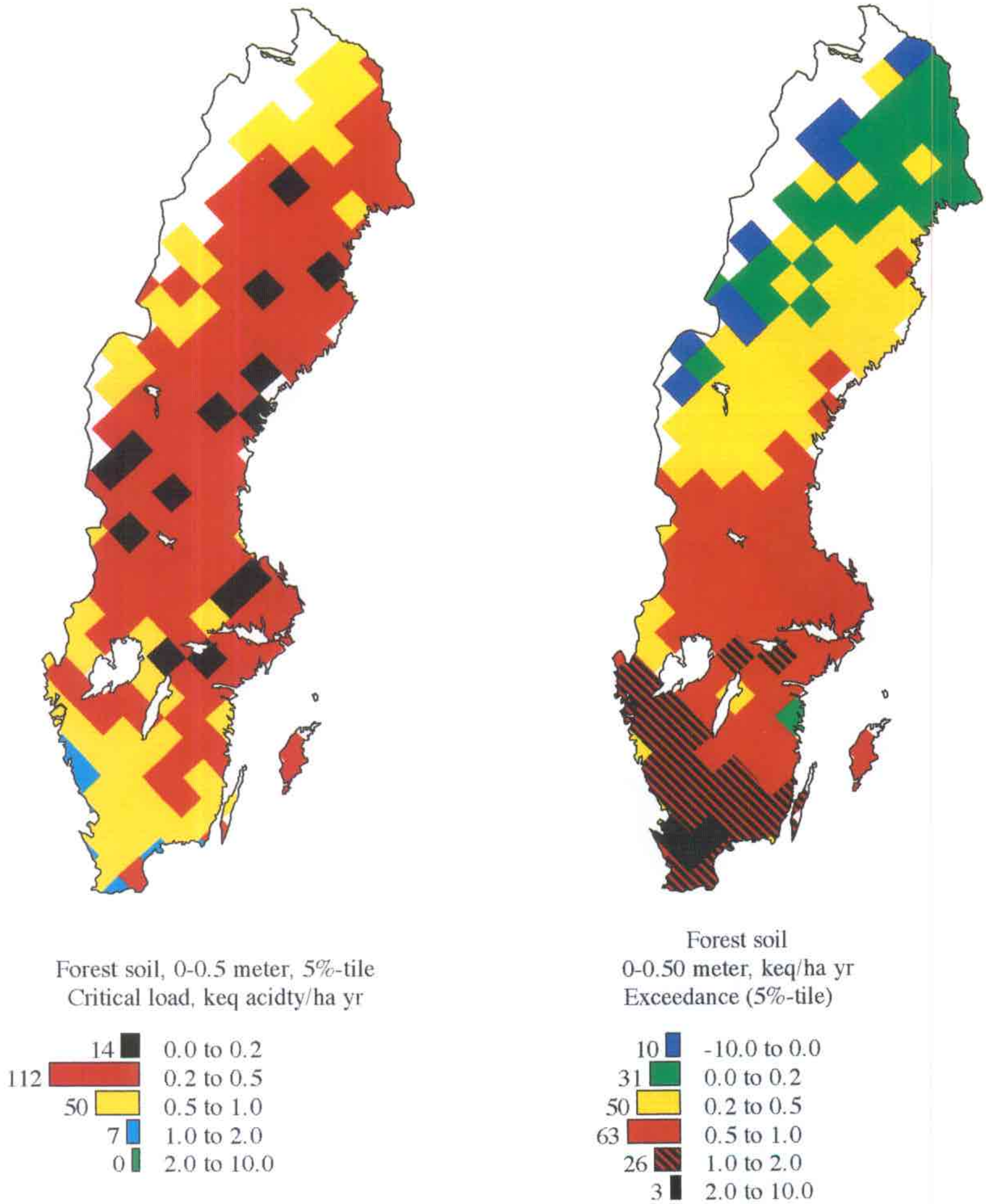


Figure A1.34. *Sweden: Critical loads and exceedance of acidity for forest soils.*
a. Critical loads, 5 percentile (left), *b. Exceedance of critical loads, 5 percentile* (right).

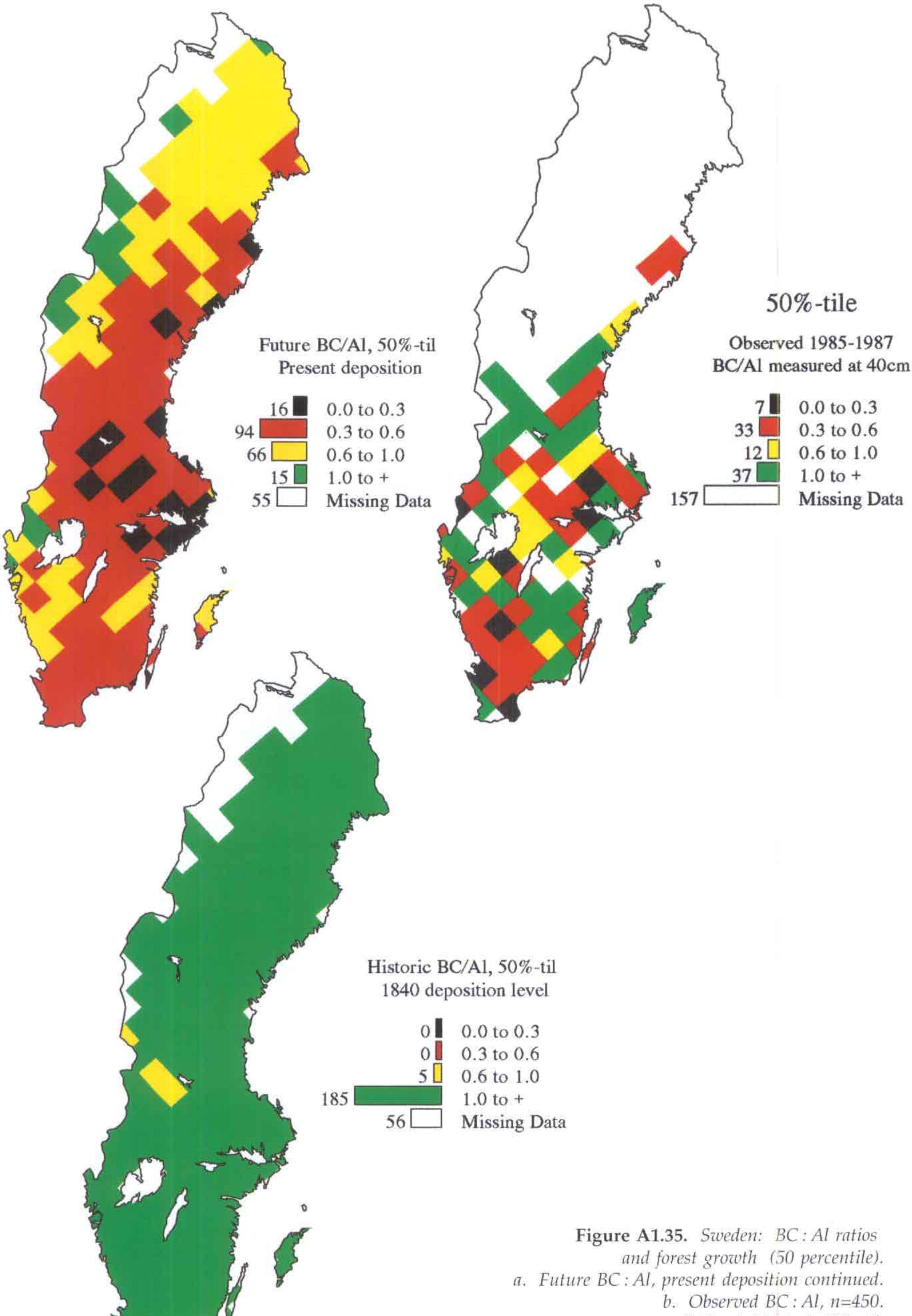
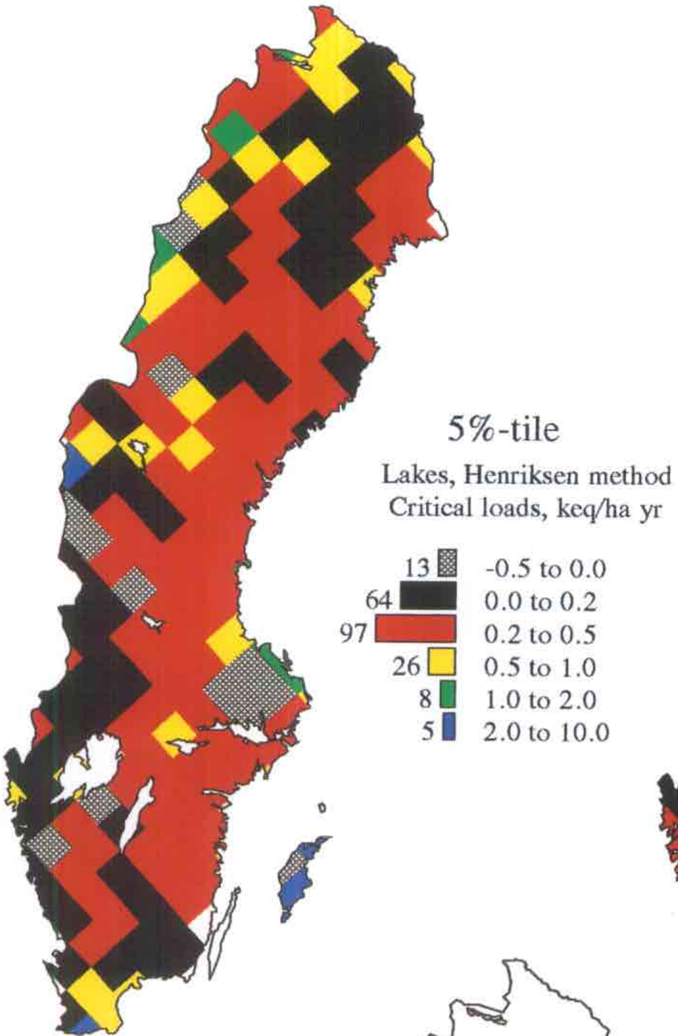
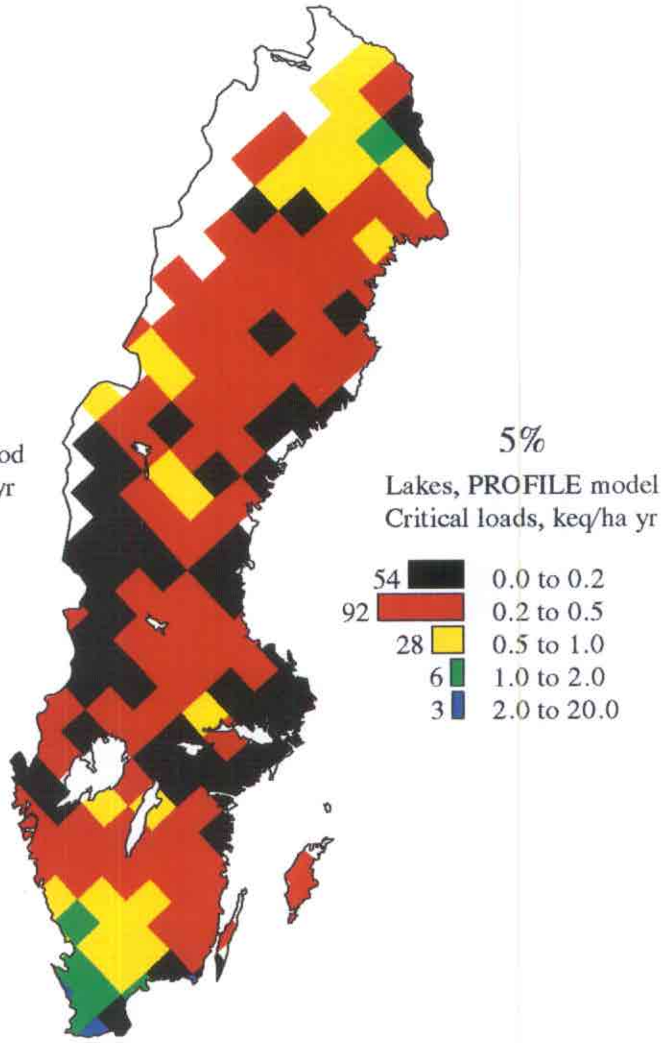


Figure A1.35. *Sweden: BC : Al ratios and forest growth (50 percentile).*
a. Future BC : Al, present deposition continued.
b. Observed BC : Al, n=450.
c. Estimated historic BC : Al.





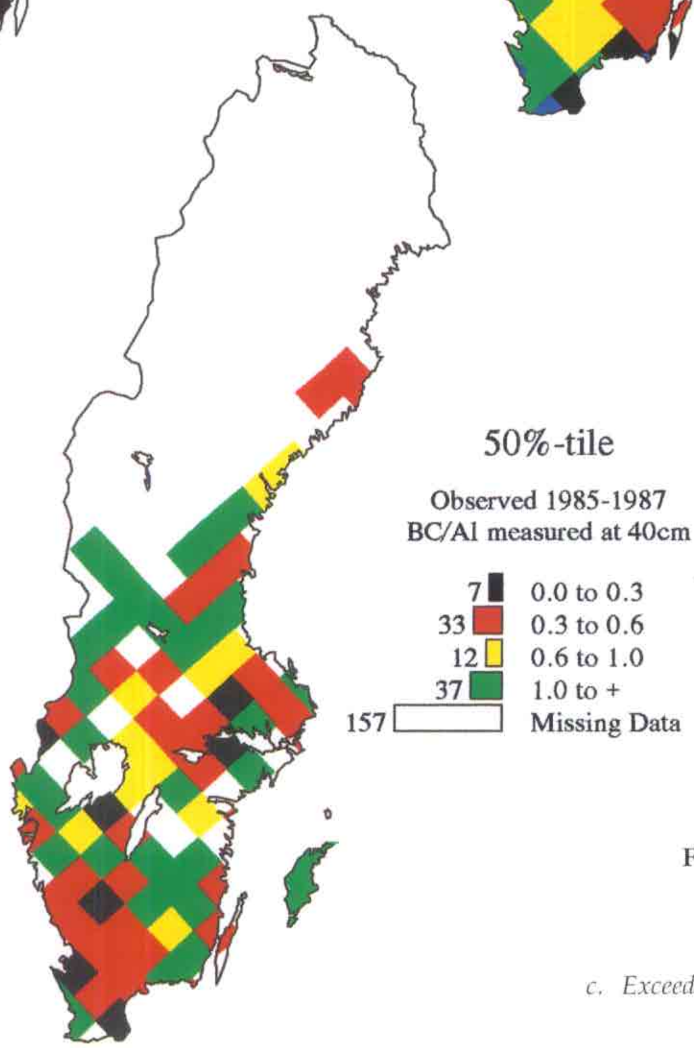


Figure A1.36. *Sweden: Critical loads and exceedance of acidity for lakes.*
a. Henriksen method (5 percentile).
b. PROFILE model (5 percentile).
c. Exceedance of critical loads, PROFILE model.

Figure A1.37. *Sweden: Critical loads and exceedance for nitrogen in forest ecosystems (5 percentile).*
a. Critical loads of nitrogen, keq ha^{-1} yr^{-1}.
b. Exceedance of critical loads, keq ha^{-1} yr^{-1}.
c. Reduction required to reach critical loads.

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A. Critical Loads of Acidity

Receptors mapped:

11,000 receptor points, each of them representing one square kilometer with one of the following receptor types:

- coniferous forests
- deciduous forests
- unmanaged forests
- alpine lake catchments, on slow-weathering bedrocks.

Calculation method:

As was mentioned in the NFC Report 1991, the map of critical loads of (actual) acidity for Switzerland was not satisfactory, as it showed unrealistic values in high-precipitation areas. In order to solve this problem a workshop was held in Vienna, 9-10 March 1992. Based on the results of this workshop a new map was produced and supplied to the CCE in March 1992. In this report the method used to calculate the new map will be described very briefly.

In general, surface waters and ground waters are well-buffered in Switzerland. However, there are some regions on slow weathering bedrocks situated between 1200 and 2800 m above sea level, where lakes are sensitive to acidic deposition and severe damages to fish populations have been observed.

The calculation method is the steady-state mass balance (SSMB) as described in the Vienna Workshop Report. For forest soils two criteria were applied and the lower of the two results was chosen:

1. Critical load of (actual) acidity for forests, applying the BC:Al criterion:

$$CL = W + \left(1.5 \cdot \frac{0.8 \cdot BC_w + BC_d - BC_u - BC_{le(min)}}{(BC{:}Al)_{crit} \cdot K_{gibb}}\right)^{1/3} \cdot Q^{2/3} + 1.5 \cdot \left(\frac{0.8 \cdot BC_w + BC_d - BC_u - BC_{le(min)}}{(BC{:}Al)_{crit}}\right) \qquad \text{(A1.28)}$$

2. Critical load of (actual) acidity for forests, applying the Al depletion criterion:

$$CL = 2.5 \cdot BC_w + \left(1.5\,\frac{BC_w}{K_{gibb}}\right)^{1/3} \cdot Q^{2/3} \qquad \text{(A1.29)}$$

For alpine lake catchments the critical load of (actual) acidity was calculated assuming a critical alkalinity of 0.02 eq m^{-3}:

$$CL(lakes) = W_{catchment} - 0.02 \cdot Q \qquad \text{(A1.30)}$$

where:
BC_w = weathering rate of the base cations Ca, Mg, K and Na (in eq ha^{-1} yr^{-1}). The factor 0.8 takes into account that approximately 20 to 25% of the base cations released by weathering is Na, not participating in the BC : Al ratio.
$W_{catchment}$ = Weathering rate of base cations on the whole path (not only rooting zone) percolated by the runoff (eq ha^{-1} yr^{-1}).
BC_{dep} = base cation deposition (eq ha^{-1} yr^{-1}).
BC_u = base cation uptake (eq ha^{-1} yr^{-1}).
Q = runoff rate, at the bottom of the rooting zone (m^3 ha^{-1} yr^{-1}).
$BC_{le(min)}$ = Minimum leaching of base cations corresponding to the leaching caused by the residual concentration of base cations that the trees cannot take up (= $Q \cdot 0.015$). The limiting concentration is in the range 10 to 20 µeq l^{-1}.
$(BC{:}Al)_{crit}$ = 1. Critical chemical value.
K_{gibb} = 200 (m^6 eq^{-2}). Gibbsite coefficient. The factor 1.5 derives from the conversion of critical loads and base cation concentrations in equivalents to the molar ratio.

In many cases the SSMB method returned slightly negative critical load values for alpine lakes. This may result from inaccurate input data and effects that are not included in the present model. Where this occurred, the critical load was set to a value of 100 eq ha^{-1} yr^{-1}, corresponding approximately to the natural background deposition of acidity.

Data sources:

• Digital Elevation Model (DEM):

A data set from the Federal Office of Statistics (GEOSTAT), with a resolution of one hectare, is available. It is an interpolated 250 x 250 m grid.

• National Forest Inventory (NFI):

This is a data base of the Swiss Federal Institute for Forest, Snow and Landscape Research, with a resolution of 1 x 1 km. It supplies information on tree species, forest type, soil properties (pH in topsoil, drainage conditions) and management (mean harvesting rates in five different regions).

Base cation uptake: was calculated by multiplying the long-term harvesting rate by values for the element content in stems (proposed by the CCE). Branches are not included according to the harvesting practice in Switzerland.

In the alpine and southern parts of Switzerland current harvesting rates are very low. A national programme has been establish to intensify forest management in those regions. With respect to this, the long-term harvesting rates are assumed to be higher than today (+30% in the alpine region, +100% in southern Switzerland).

Weathering rates: The 23 categories of the 1 : 500,000 soil map "Atlas der Schweiz", edited by the Federal Office of Topography, are assigned to weathering rate classes as proposed in the CCE Mapping Vademecum 1990. Some categories were not suitable to distinguish calcareous and non-calcareous soils. Therefore, soil acidity values from the NFI were used to recognize calcareous soils (surface pH > 6.2). Then the weathering rate, which is assigned to a certain weathering rate class, is corrected by the influence of soil temperature. The temperature is estimated by a linear regression with the altitude for two different climate zones.

• Hydrological Atlas of Switzerland: This atlas contains a precipitation data set with a resolution of 1 x 1 km. It was produced at the Swiss Meteorological Institute by processing a large set of measurement data with kriging interpolation methods. It shows the "mean annual corrected precipitation depths 1951–1980".

The precipitation surplus (water flux at the bottom of the rooting zone) is precipitation minus evapotranspiration. The evapotranspiration rate is calculated by empirical linear regressions with altitude for three different climate zones. Evapotranspiration values are then increased by 240 mm yr^{-1} for coniferous forests, by 120 mm yr^{-1} for deciduous forests and decreased by 30% for shady regions, which are evaluated on the digital elevation model.

Base cation deposition: EMEP data and dry deposition factors from the CCE.

• Atlas of Vegetation Types Worthy of Protection (VT): This data set, available at the Federal Office of Environment, Forests and Landscape, has a resolution of 1 x 1 km. It shows the spatial distribution of 97 ecologically relevant vegetation types. A subset of these data is used for determining critical loads of nutrient nitrogen by the empirical method.

• Federal Inventory of Raised and Transitional Bogs of National Importance (HM): This data set is available in vector form at the Federal Office of Statistics (GEOSTAT). It contains the outlines of raised (ombrotrophic) bogs digitized at a scale of 1 : 25,000. For the application in the empirical approach the vector data were rastered into a 1 x 1 km grid.

• Federal Inventory of Fens of National Importance (FM): This data set is available in vector form at the Federal Office of Environment, Forests and Landscape. It contains the outlines of eutrophic and mesotrophic fens digitized at a scale of 1 : 25,000. For the application in the empirical approach only the mesotrophic fens have been selected and the vector data were rastered into a 1 x 1 km grid.

B. Critical loads of Nutrient Nitrogen: Empirical Approach

Critical loads maps for nutrient nitrogen have been produced by applying both the empirical approach and the nitrogen Steady-State Mass Balance (SSMB) approach. The application of the empirical approach is based on highly resolved and detailed ecosystem inventories, which cover the whole territory of Switzerland. The resulting map reflects the sensitivity of natural and semi-natural ecosystem types in Switzerland based on empirically examined effects such as changes in vegetation and biodiversity according to the list developed at the UN ECE Workshop on Critical Loads of Nitrogen in Lökeberg (Sweden) in April 1992. The SSMB approach on the other hand is applied for managed forests only. Several possibilities of applying the SSMB approach have been evaluated by varying the input parameters to the mass balance equation within the ranges proposed by the Lökeberg Workshop and the mapping guidelines contained in Chapter 4.

The following data bases have been used to define critical load values according to the results of the Lökeberg Workshop, as presented in Appendix IV of this report:

- Atlas of Vegetation Types Worthy of Protection in Switzerland (VT)
- Federal Inventory of Raised and Transitional Bogs of National Importance (HM)
- Federal Inventory of Fens of National Importance (FM).

In order to produce a map of "most probable" critical load values, the middle of the ranges given in Appendix IV was taken, generally, as those ranges mostly reflect the uncertainty of the method. All data are compiled on the basis of a 1 x 1 km grid. If more than one ecosystem type exists within one grid cell, the most sensitive ecosystem determines the critical load of nutrient nitrogen for this grid point. The results are shown in Figures A1.38 through A1.41.

The critical load values are assigned as listed in Table A1.15, in kg N ha^{-1} yr^{-1}.

C. Critical Loads of Nutrient Nitrogen: SSMB Approach

The critical load is calculated by the steady-state nitrogen mass balance for 11,000 sampling points of the National Forest Inventory. Equation 4.18 from the mapping guidelines was used (see Chapter 4):

$$CL_{nut}(N) = N_{u(crit)} + N_{i(crit)} + \frac{N_{l(crit)}}{1 - f_{de}}$$

Most of these terms are quite uncertain. Therefore the influence of assumptions that must be made was evaluated by calculating different versions with the available data base. For this sensitivity analysis three versions have been calculated using the extremes and the middle of the ranges proposed by the mapping guidelines contained in Chapter 4:

Version 1 ("low version"): The lower bounds of the ranges proposed by the mapping guidelines for nitrogen immobilization, leaching and denitrification are used. The denitrification rate is assumed to be greater than zero even in socalled dry soils, because also these soils are assumed to be temporarily saturated by moisture during high precipitation periods or snow melting periods.

Version 2 ("middle version"): Values within the proposed ranges for nitrogen immobilization, leaching and denitrification are used.

Version 3 ("high version"): The upper bounds of the proposed ranges for nitrogen immobilization, leaching and denitrification are used.

The values used for each of these versions are summarized in Table A1.16.

The results of all three versions are presented in Figure A1.38 as cumulative frequency distributions for Switzerland. Version 2 (middle) has been submitted to the CCE for data processing at the European level, because the result of this versions might be the most plausible one, being based on less extreme assumptions than the other versions. The result of Version 2 is also presented in Figure A1.41.

Table A1.15. *Critical load ranges assigned for various ecosystem types in Switzerland.*

Ecosystem	Critical load range	Applicable ecosystems in Switzerland	Critical Load Assigned	Code
Acidic (managed) coniferous forest	15–20	Molinio-Pinion (Waldfoehrenwald auf tonigem Boden, montan)	17	VT157
		Ononido-Pinion (offener Kieferwald, sehr trocken)	17	VT158
		Cytiso-Pinion (Foehrenwald-Steppe)	17	VT159
Acidic (managed) deciduous forest	<15–20	Quercion robori-petraeae (bodensaurer Eichen-Birkenwald, naehrstoffarm)	15	VT249
		Quercion pubesc.-petraeae (thermophile Eichenwaelder)	15	VT267
		Orno-Ostryon (Hopfenbuchwald)	15	VT268
Calcareous forests	unknown	no values assigned		
Acidic (unmanaged) forests	unknown	no values assigned		
Lowland dry heathland	15–20	none		
Lowland wet heathland	17–22	none		
Species-rich lowland heaths/acid grassland	7–20	none		
Arctic and alpine heaths	5–15	Erico-Mugion (Bergfoehrenwald auf Kalk, subalpin)	10	VT149
		Erico-Pinion (Waldfoehrenwald auf Kalk, montan)	10	VT156
		Calluno-Pinion (Föhrenwald auf Silikat, montan)	10	VT247
Calcareous species-rich grass land	14–25	Mesobromion (Halbtrockenrasen, kollin u. unt. montan)	19	VT036
		Andropogonetum gryllii (Trockenrasen, Steilhaenge)	19	VT038
Neutral-acid species-rich grassland	20–30	Molinion (nasse Streu-Magerwiesen)	25	VT069
Montane-subalpine grassland	10–15	Seslerio-Bromion (Halbtrockenrasen, ob. montan)	12	VT037
		Festucion spadiceae (subalpin kalkarm, steile Trockenhaenge)	12	VT039
		Caricion ferrugineae (frische Rasen auf Kalk, subalpin)	12	VT056
		Stipo-Poion xerophilae (Walliser Schwingelrasen, Graubuenden)	10	VT046
		Oxytropido-Elynion (Gratrasen, alpin)	10	VT048
		Seslerion coeruleae (Trockenrasen auf Kalk, subalpin-alpin)	10	VT049
Shallow soft-water bodies	5–10	Littorellion (flache, oligothrophe See- und Teichufer)	7	VT019
Mesotrophic fens	20–35	Scheuchzerietalia (Scheuchzergras)	25	FM
		Caricion fuscae (Braunseggenried)	25	FM
		Caricion davallianae (Davallsseggenried)	25	FM
Ombrotrophic bogs	5–10	Sphagnion fusci (Hochmoor)	7	HM

Table A1.16. *Input values used for calculating critical loads of nitrogen for Switzerland (in kg N ha⁻¹ yr⁻¹).*

Factor	Version low	middle	high
Nitrogen uptake (N_u): derived from the long-term harvesting rate	0.7–7	0.7–7	0.7–7
Nitrogen immobilization (N_i):			
in Podzols and Histosols	2	3	3
in other soils	1	2	3
Critical nitrogen leaching ($N_{l(crit)}$):			
deciduous forests	4	4-5	5*
coniferous forests	2	2-4	4*
Denitrification rate (f_{de}): determined according to the drainage conditions given in the National Forest Inventory:			
all dry soils	0.1	0.2	0.3
dry soils with inhibited permeability	-	0.3	-
moist soils	0.5	0.5	0.5
moderately wet soils	0.7	0.7	0.7
wet soils	0.8	0.8	0.8

* depending on altitude.

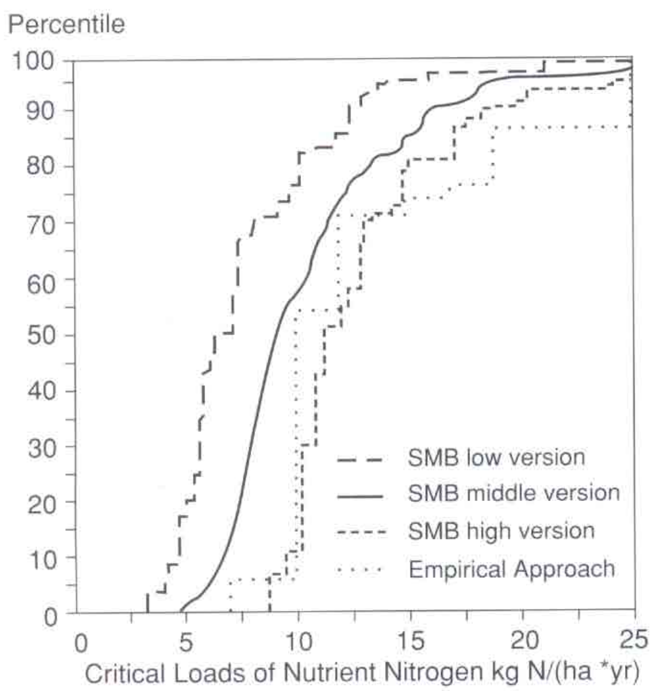

Figure A1.38. *Cumulative frequency distributions of critical loads of nutrient nitrogen for Switzerland. The three SMB versions were applied to forest ecosystems, the empirical approach to other natural and semi-natural ecosystems.*

Figures:

A1.39. Switzerland: Critical loads of actual acidity. Method: SMB with Al and BC : Al criteria (Vienna, March 1992). Receptors: Forest soils and Alpine lakes.

A1.40. Switzerland: Critical loads of nutrient nitrogen: empirical approach, based on the CCE Guidelines of May 1993. Receptors: Natural and Semi-natural Ecosystems.

A1.41. Switzerland: Critical loads of nutrient nitrogen: SMB approach, version 2 (middle), based on the CCE Guidelines of May 1993. Receptors: Forests.

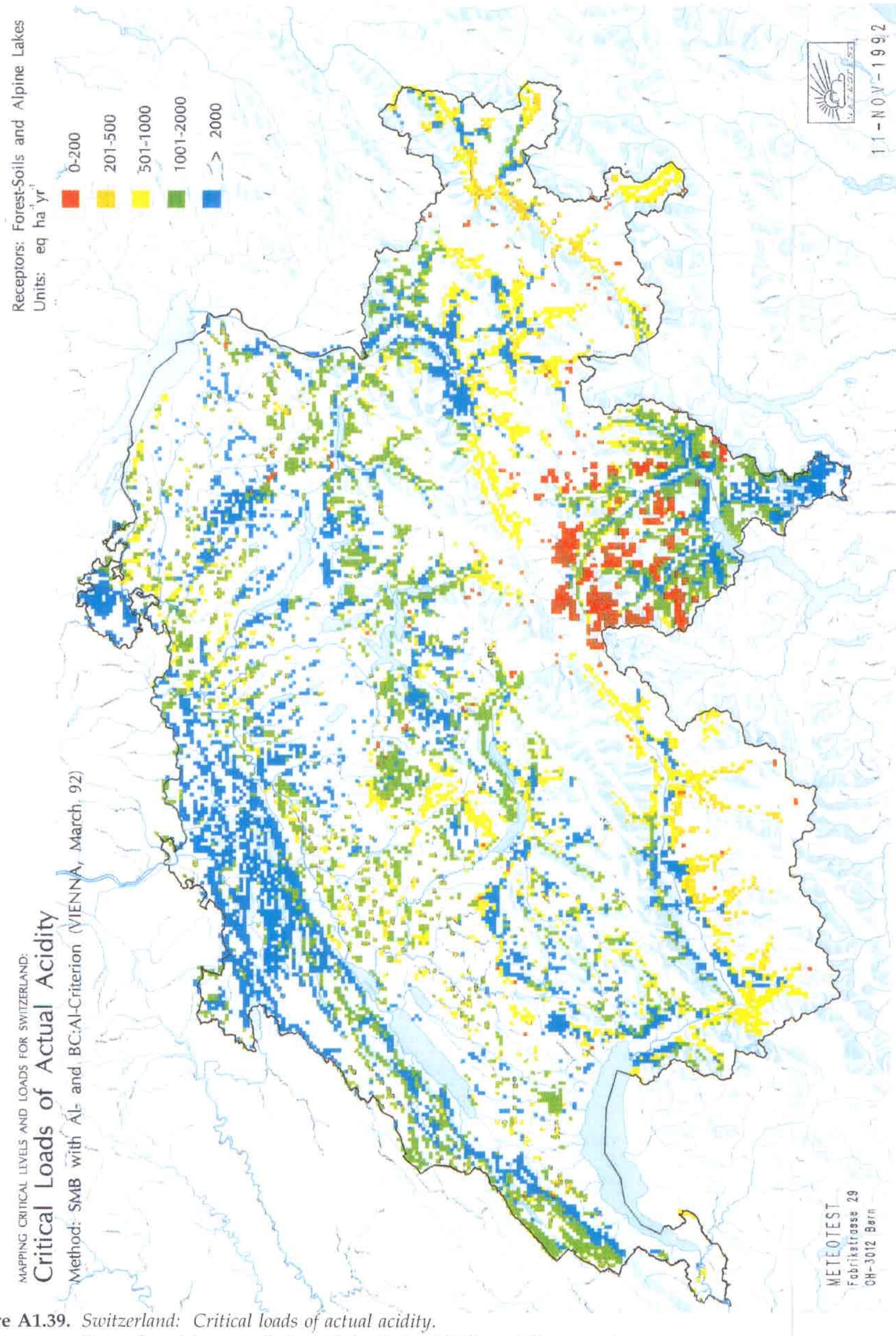

Figure A1.39. *Switzerland: Critical loads of actual acidity.*
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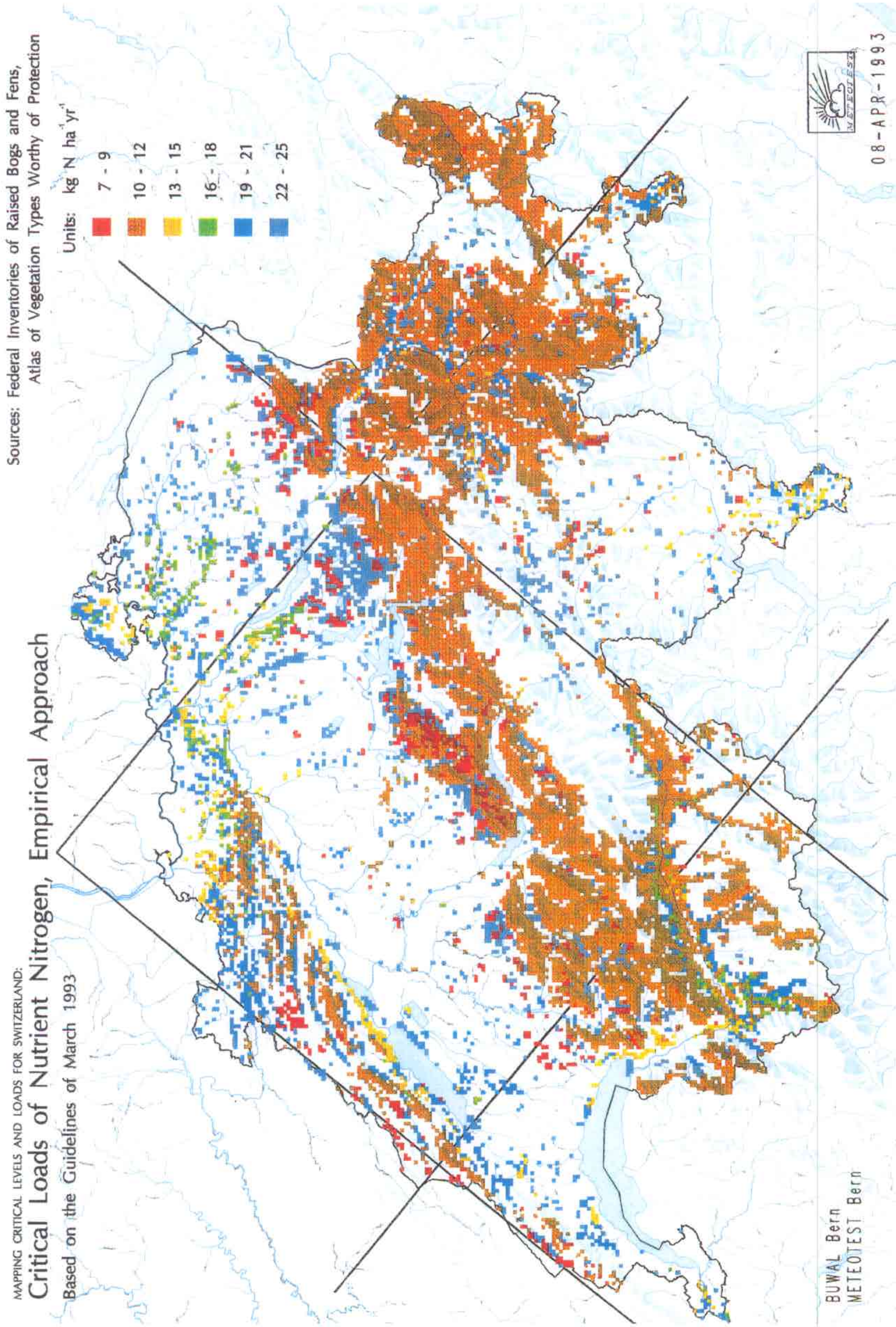

Figure A1.40. *Switzerland: Critical loads of nutrient nitrogen: empirical approach*
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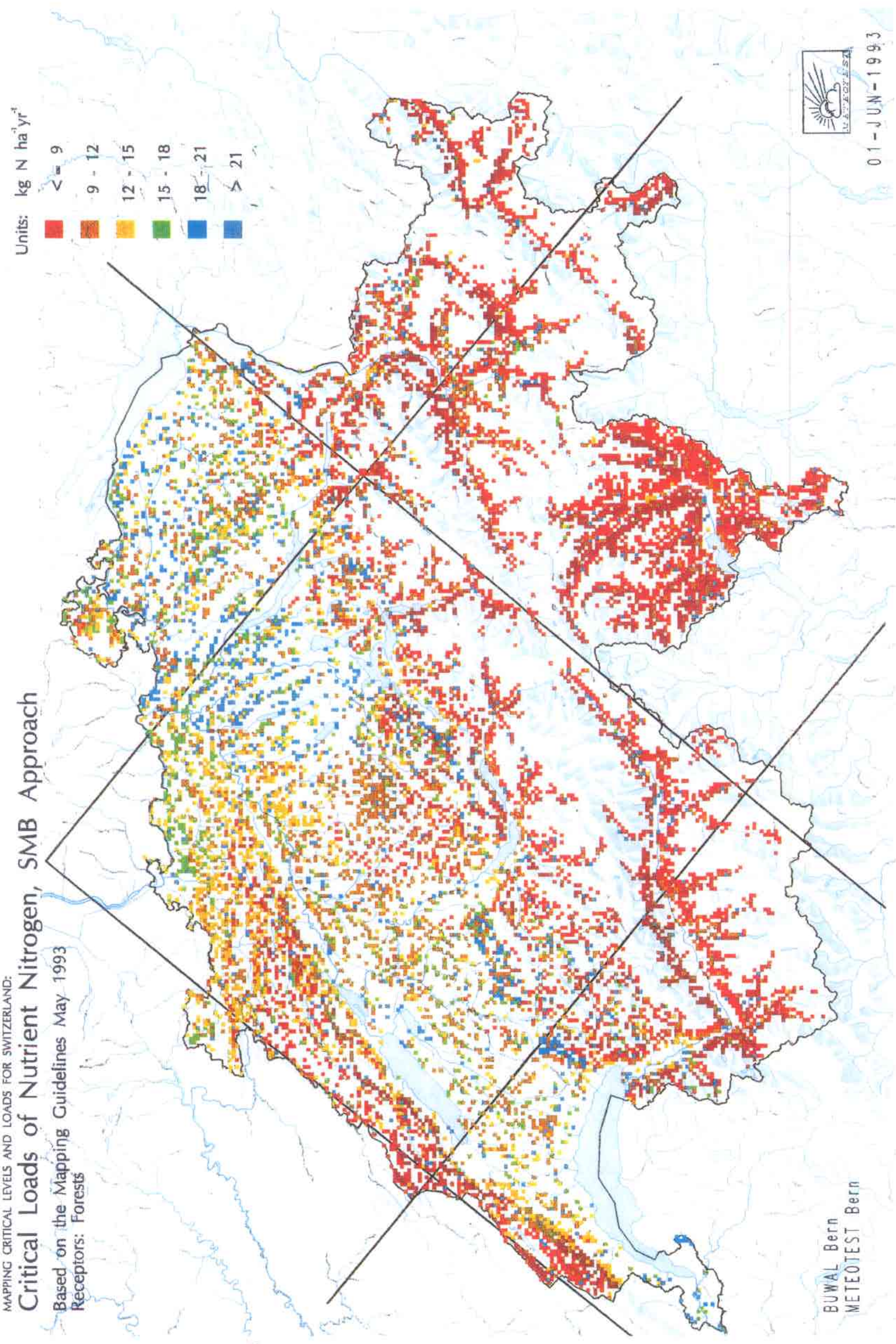

Figure A1.41. *Switzerland: Critical loads of nutrient nitrogen: SMB approach Version 2 ("middle").* Reproduced by permission of the Federal Office of Topography.

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Receptors mapped (and methods used):

Acidity: Soils (empirical, level zero), freshwaters (Henriksen), freshwaters (diatom model), soils (modified steady-state mass balance, single species maps and percentiles based upon land cover).

Nitrogen: Soils (mass balance single species maps and percentiles based upon land cover), vegetation (empirical).

Levels: Natural vegetation, forests, agricultural crops, lichens (sulphur dioxide); wheat, oil seed rape, white clover (ozone); bryophytes and lichens (wet acidic deposition).

Grid size:

1 km for soil and land cover vegetation maps, 10 km for freshwater and plant species maps.

Calculation methods:

A. Critical Loads of Acidity

Level zero: empirical method for soils: The method has been described in detail previously (Hettelingh *et al.*, 1991). Only minor changes have been made to the map, e.g. new data for the Isle on Man, revised organic soil critical loads values for some areas. The 1 km data set used for the map has been used for estimating the necessary percentile values for the UK area on the European maps of critical loads. The map has been studied in relation to critical loads estimates derived using different models, e.g. PROFILE. In addition, field studies are in progress which have used the map to define particular areas of interest. The critical loads data have also been used to assess impacts for a number of possible future deposition scenarios in the UK.

Steady-state mass balance method for soils: The steady-state mass balance equations originally proposed for calculating critical loads for soils were found to be unsatisfactory for the UK. Similar problems were encountered as for other high rainfall regions of Europe. Following the workshop on the "Problems of mapping critical loads and levels in sub-alpine and alpine regions", the UK has explored the use of modified mass balance equations. For a number of species, appropriate critical base cation : aluminium ratios have been selected, and, together with estimates of the necessary other parameters, critical loads have been calculated. The empirically derived soil critical loads values (unmodified for land use) have been used as weathering rate estimates, but with peat soils allocated a weathering rate of zero. Calculations are therefore again based upon 1 km grid areas of Britain. The individual species maps (e.g. Figure A1.42) show critical loads values assuming each species grows in all parts of Britain. The data for several species, together with a land cover map of Britain derived from LANDSAT satellite imagery, provide the necessary information to estimate cumulative distributions of critical loads values for each 1 km area. In this way, maps showing critical loads for the various percentiles of sensitive ecosystem areas will be drawn for the UK. Data relating to these ecosystems will be made available to the CCE in the coming year.

The Henriksen method for freshwaters: Critical loads for freshwaters have been derived, using the Henriksen model, from samples collected from each 10 km grid square of the UK. For sampling, a standing water body in the most sensitive area of each grid square was selected using available information on soils, geology, land use and altitude. If a standing water was not available, a low-order stream was sampled. For the calculations, an ANC value of zero has been used which relates to a 50% probability of occurrence of brown trout. Use of other ANC values will reflect different probabilities or the occurrence of other species. Investigations on the impacts to other species are continuing. The resulting critical loads map for ANC = 0 (Figure A1.43) is seen as a "case study" in view of the method of selection of sampling areas. It effectively shows the most sensitive freshwaters in Britain, but may not reflect the actual ecosystem areas across the country. Studies are in progress to compare soils and freshwaters critical loads maps.

The diatom model for freshwaters: This approach has been developed from the extensive use of lake sediments in the study of acidification in the UK. Using the same freshwater chemistry data collected for the Henriksen model, a method has been devised using diatom-based pH reconstruction.

The point at which the first diatom evidence for acidification occurs in a lake sediment is taken as the point at which the critical load is exceeded. Using contemporary sulphur deposition and freshwater calcium concentrations, a critical ratio may be defined which separates acidified from nonacidified waters. Critical loads are estimated using this ratio and the pre-acidification calcium value determined using the Henriksen "F" factor. The resulting map (Figure A1.44) shows lower critical loads values than the Henriksen model for many parts of the UK. This reflects the sensitivity of diatom changes to the impact of acidification.

B. Critical Loads of Nitrogen

Critical loads of nutrient nitrogen for soils: The steady-state methodology proposed at the Lökeberg workshop has been applied to a number of plant species in the UK. Using appropriate data for the parameters in the steady-state equation data, maps have been generated for critical loads of nitrogen (Figure A1.45). The same species are being investigated as for the mapping of critical loads of acidity described above. This will provide the basis for generating critical loads data for the same ecosystem areas and enable application of the mapping guidelines approach as detailed in Chapter 4 of this report.

Critical loads of nutrient nitrogen for vegetation: empirical method: An empirical approach to mapping critical loads of nitrogen was proposed at the Lökeberg workshop. (See Appendix IV). In the UK, this approach has been explored making use of the extensive records which are held for plant species at the Biological Records Center, Monks Wood. For each of the sensitive vegetation types identified at Lökeberg, a number of UK indicator species have been identified using the National Vegetation Classification. The presence of several indicator species within an area is taken to indicate the presence of the sensitive plant community. Preliminary maps have been drawn and work is continuing. Future studies will be aimed at the further selection and refinement of suitable plant species, and the development of criteria for determining presence of vegetation types. In addition, critical loads values will need to be identified from the ranges suggested at Lökeberg.

C. Critical Levels

Following the critical levels workshop at Egham in 1992, a number of approaches have been explored for mapping sensitive receptors for sulphur dioxide, ozone and wet acidic deposition.

For sulphur dioxide, the LANDSAT land cover map of Great Britain has been used to derive "level 1" critical levels maps for forests (coniferous and deciduous woodland), natural vegetation and agricultural crops. Distribution data for cyanobacterial lichens, which show higher sensitivity to sulphur dioxide, are being studied with a view to generating further critical levels maps. Bryophytes and lichen distributions are also being studied with a view to deriving maps of critical levels for wet acidic deposition. "Level 2" mapping is being explored using "effective temperature sum" modifications.

For ozone, land cover data is being linked with survey data to provide maps of individual crop species for Britain. Initially, maps for wheat, oil seed rape and white clover are being developed.

Figures:

A1.42. United Kingdom: Provisional 1km map of critical loads of acidity for soils assuming complete cover of Norway Spruce (*Picea abies*). Calculations are made using the simple mass balance equation from the current version of the Mapping Manual. The results presented are still subject to revision.

A1.43. Critical load map of sulphur for freshwaters using the "steady-state chemistry model" with $ANC_{crit} = 0$. 1139 mainly lowland squares known to have insensitive surface waters because of their base-rich soils and geology were not sampled. These squares are not differentiated on the map and are included in the >2 (blue) category. For nine sites where the pH was < 5.0 and the steady-state chemistry critical load resulted in a negative value, the critical load was set to zero. For 350 sites where sulphate values were >500 $\mu eq\ l^{-1}$, SO_4 was removed from the model calculation to avoid deriving improbably low critical load values for insensitive lowland sites. A full list of sites for which these adjustments were made is available from the ECRC. Values shown are subject to validation.

A1.44. Critical load map for UK freshwaters using the "diatom model" with the Ca : S ratio set to 94:1. 1139 mainly lowland squares known to have insensitive surface waters because of their base-rich soils and geology were not sampled. These squares are not differentiated on the map and are included in the >2 (blue) category. A full list of squares not sampled is available from the ECRC. Values shown are subject to validation.

A1.45. Provisional 1 km map of critical loads of nitrogen for soils assuming complete cover of Norway Spruce (*Picea abies*). Calculations are made using the simple mass balance equation.

Compiled and produced by the UK Critical Loads Mapping Center, Monks Wood from data provided by the Institute of Terrestrial Ecology (Grange-over-Sands and Edinburgh) and the Warren Spring Laboratory, Stevenage.

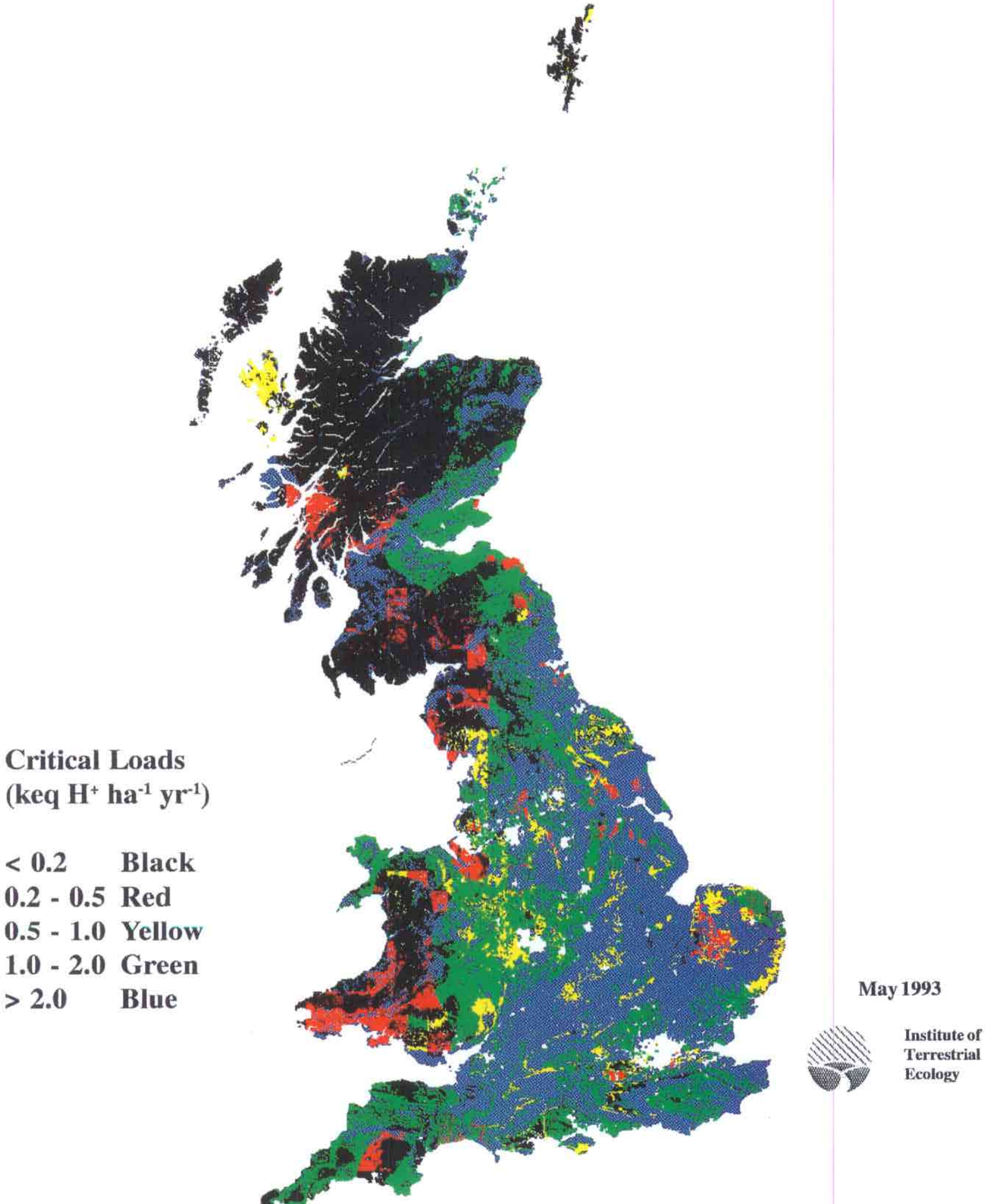
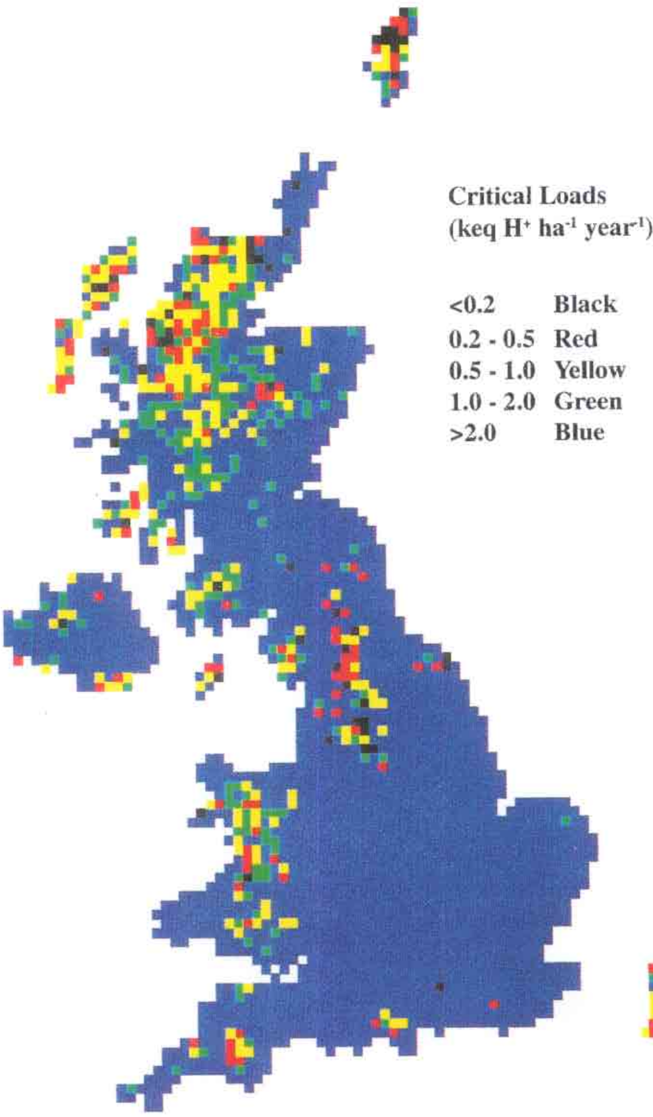
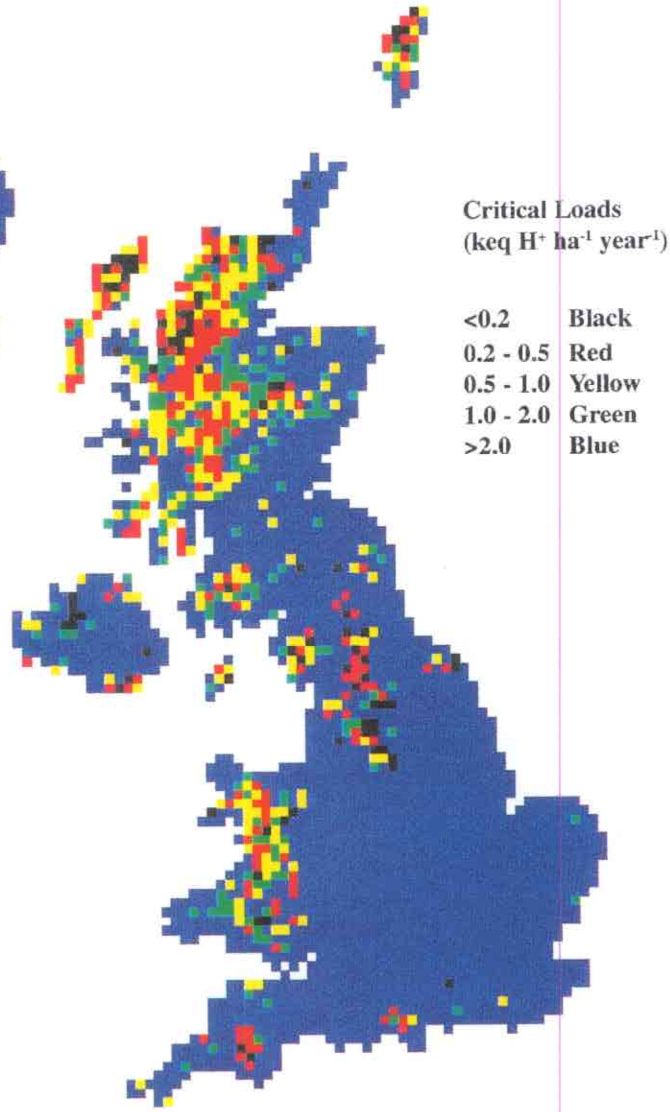


Figure A1.42. *United Kingdom: Provisional 1km map of critical loads of acidity for soils assuming complete cover of Norway Spruce* (Picea abies). *Calculations are made using the simple mass balance equation from the current version of the Mapping Manual. The results presented are still subject to revision.*





March 1993 Data

Institute of Terrestrial Ecology

Figure A1.43. *Critical load map of sulphur for freshwaters using the steady-state chemistry model with* $ANC_{crit} = 0$.

Figure A1.44. *Critical load map for UK freshwaters using the "diatom model" with the Ca : S ratio set to 94 : 1.*

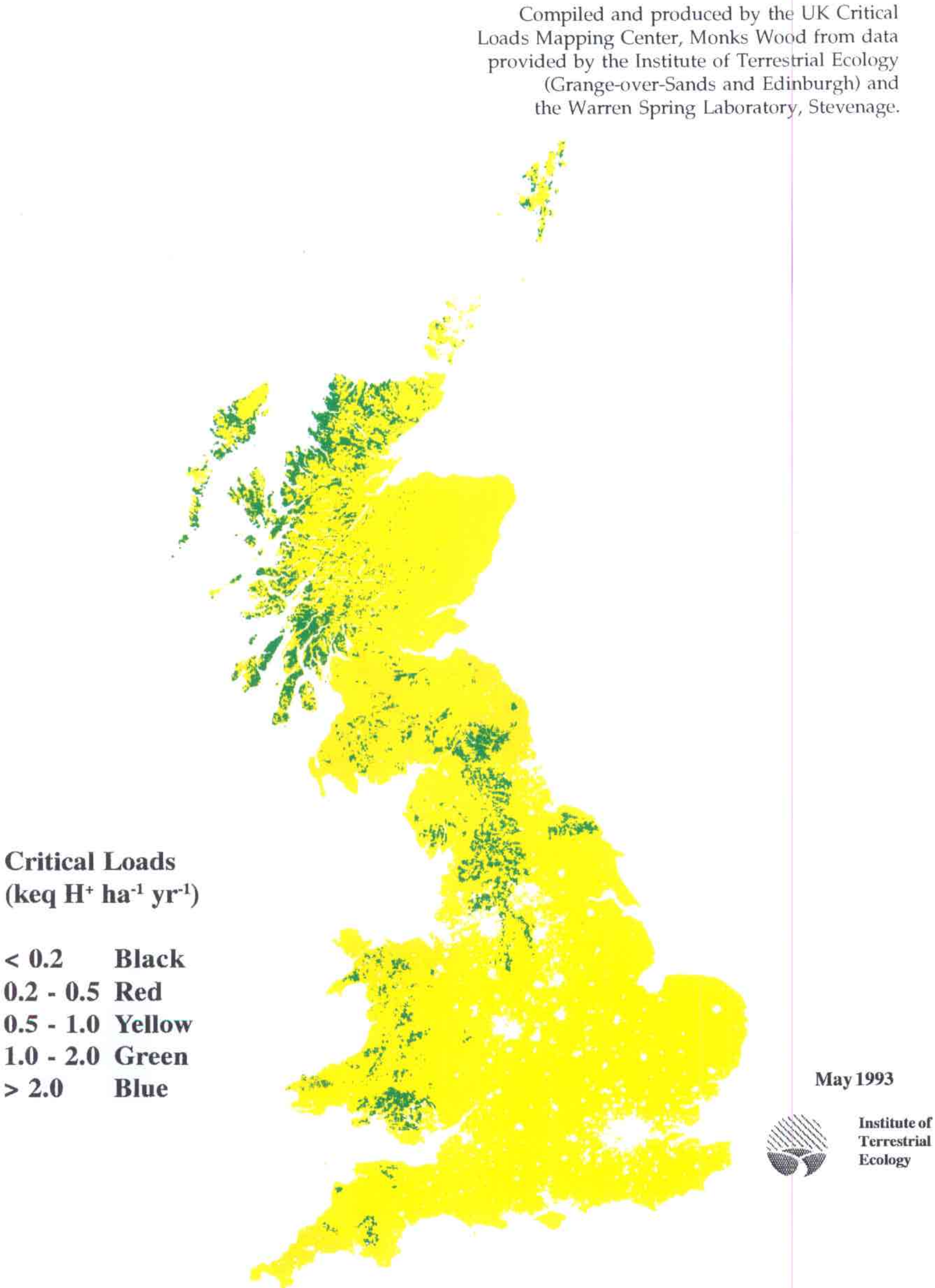


Figure A1.45. *Provisional 1 km map of critical loads of nitrogen for soils assuming complete cover of Norway Spruce* (Picea abies).

APPENDIX II. Additional Maps of Critical Loads and Background Variables

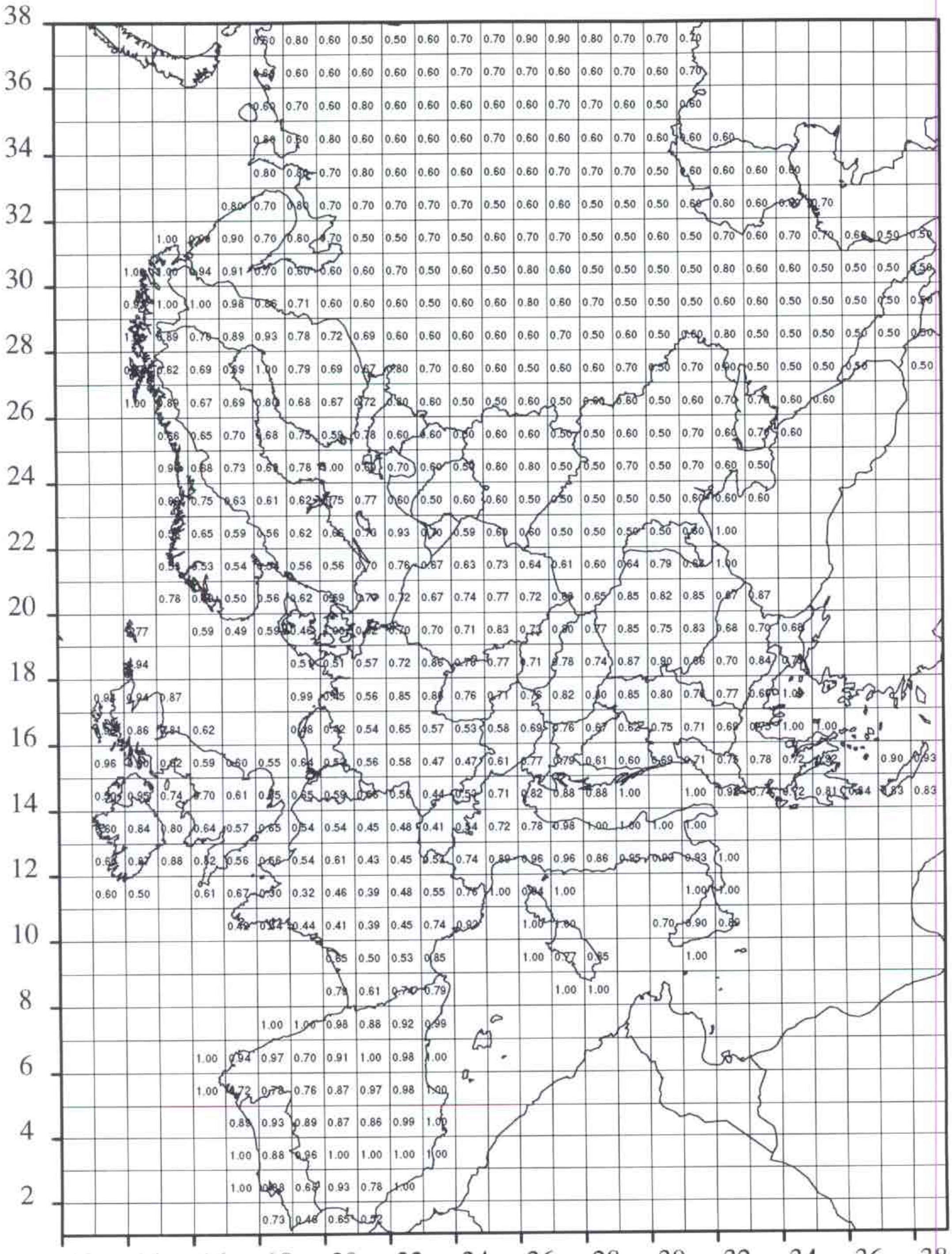


Figure A2.1. *Sulphur fractions.*

This map shows the 50-percentile sulphur fraction (S_f), calculated from national data submissions wherever available. The procedures used to compute these values for each format of national S_f data is described in Chapter 5. When no sulphur fraction was submitted, the CCE computed the S_f according to equation 4.3, using 1990 EMEP data for S_{dep} and N_{dep} and assuming N_i to be zero.

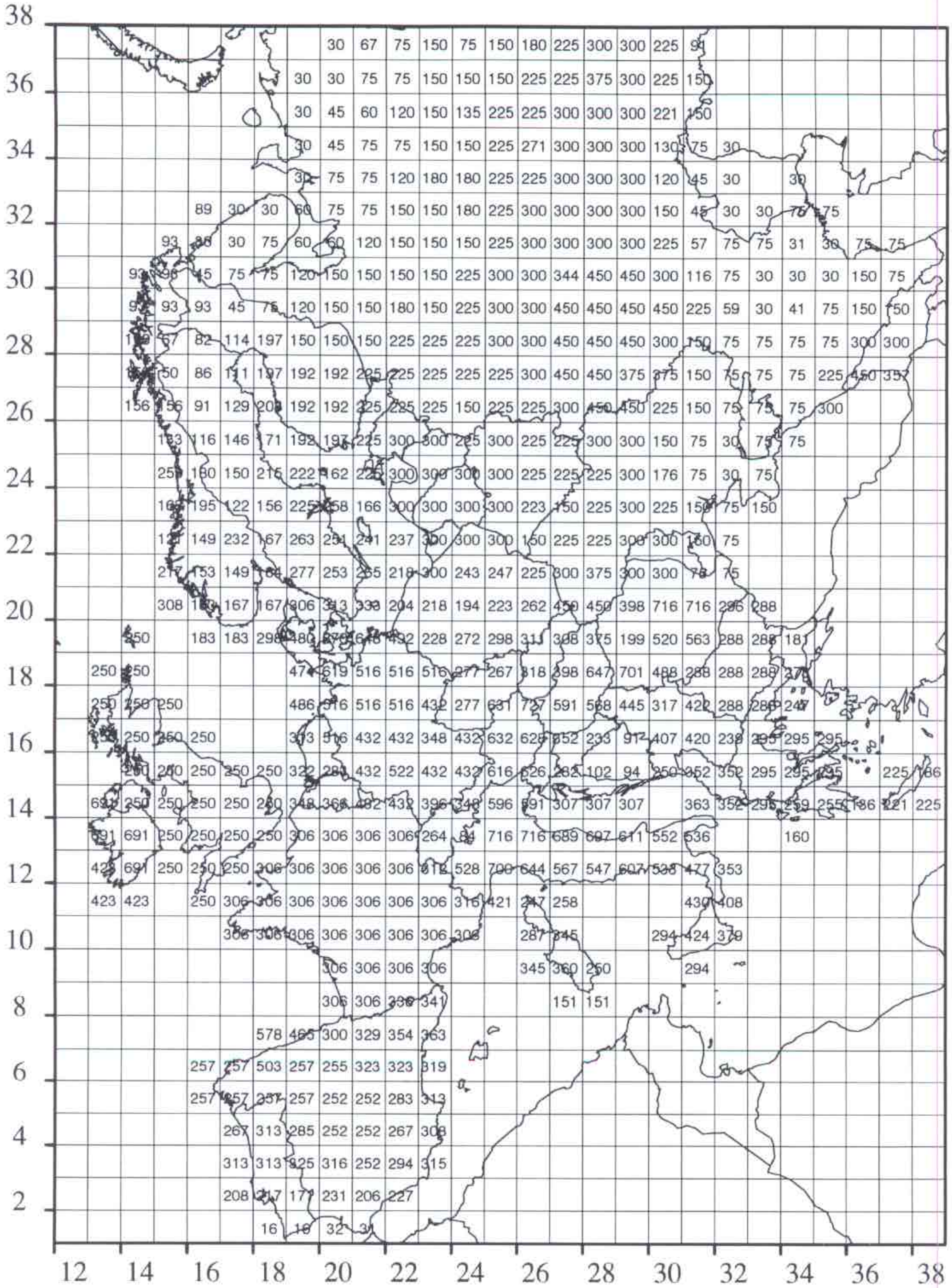


Figure A2.2. *Base cation uptake* (eq ha^{-1} yr^{-1}).

This map shows the 50-percentile base cation uptake of the combined national data submissions, related to the total ecosystem area per EMEP grid cell. Depending on the format of the submitted data the procedure applied to compute the 50-percentile numbers is according to the descriptions in Chapter 5.

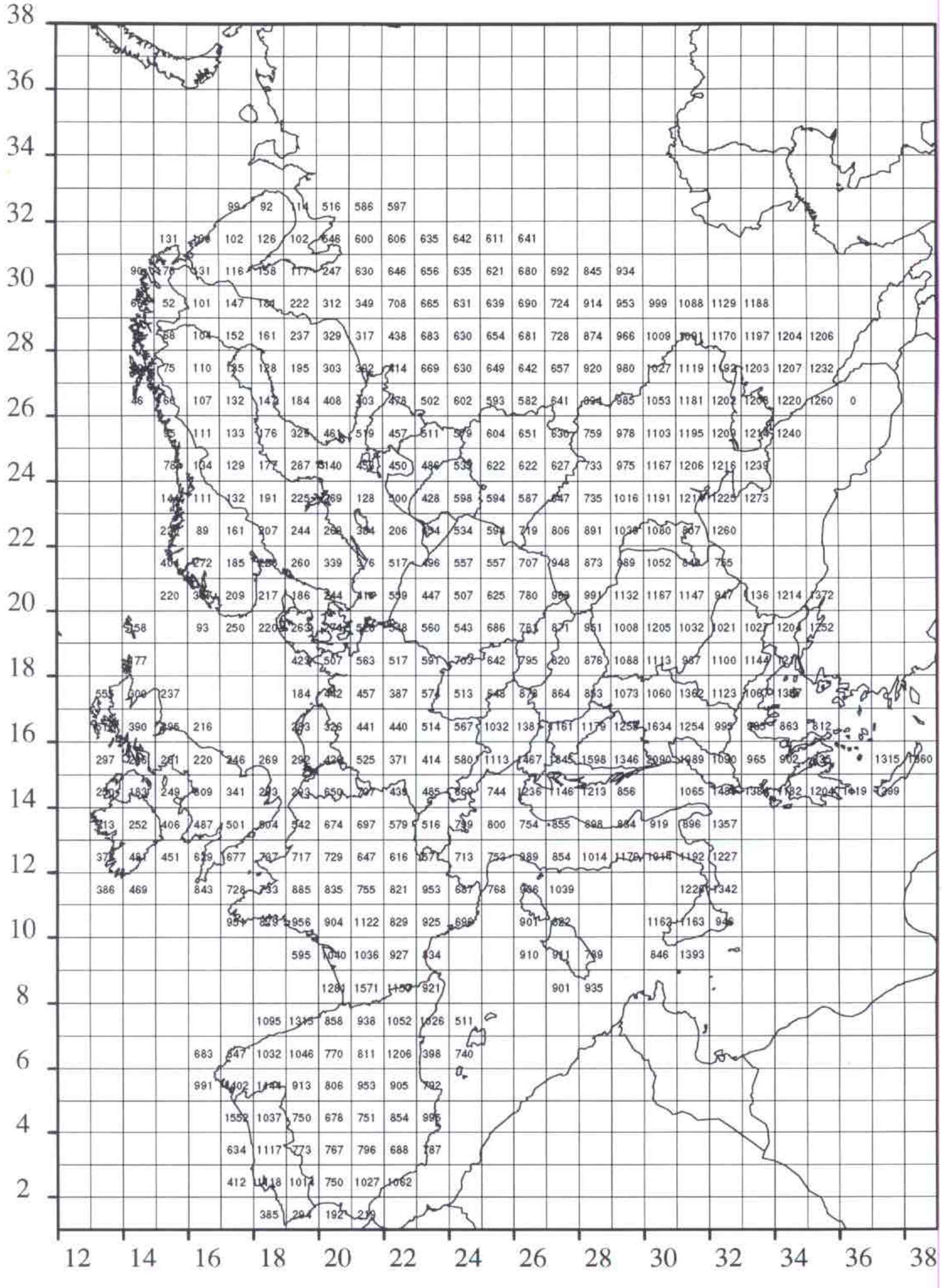


Figure A2.3. *Base cation deposition* (eq ha^{-1} yr^{-1}).

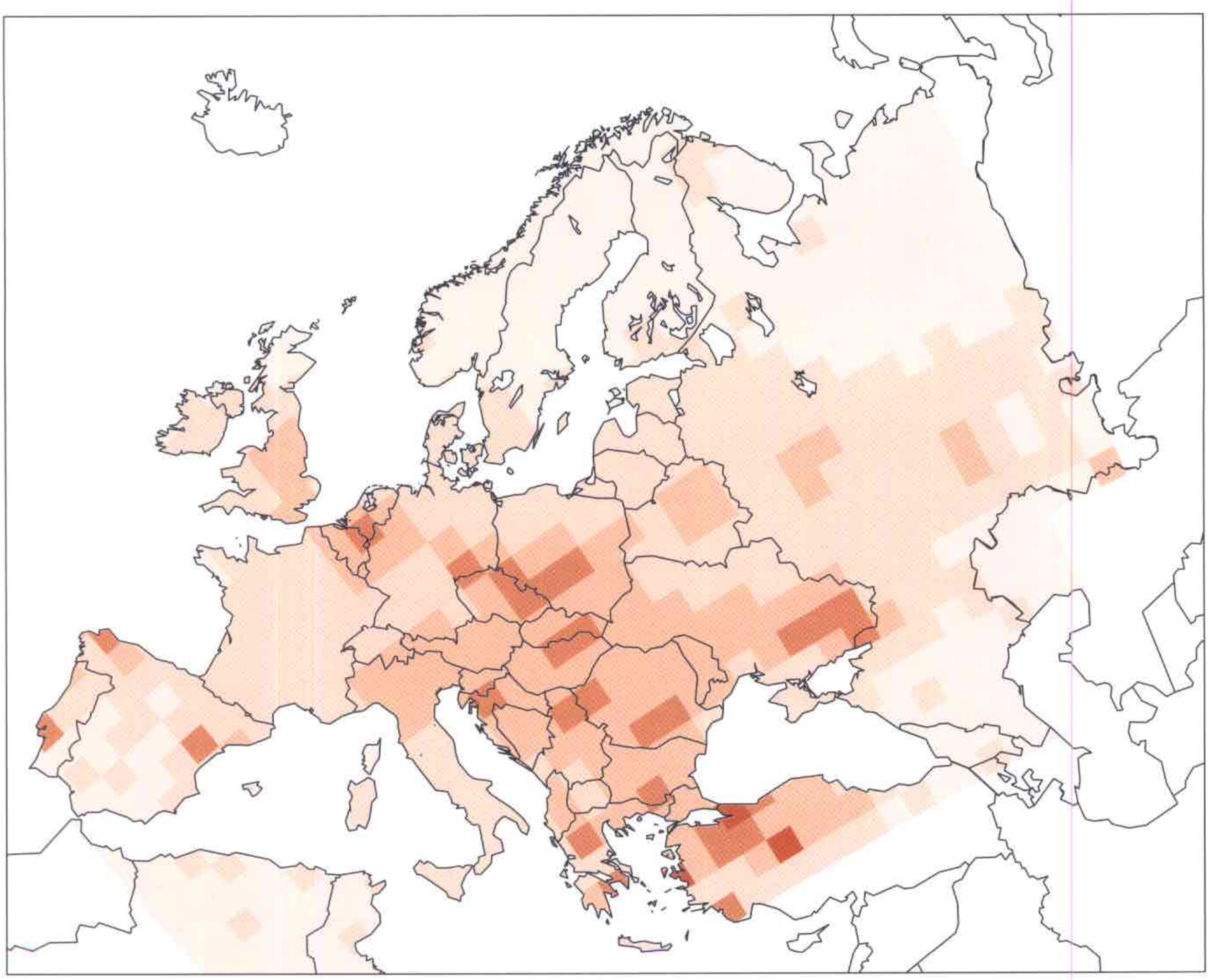
The numbers express the total base cation deposition, corrected for sea salt. The total base cation deposition is partly deposited as a wet fraction and partly as a dry fraction. The wet fraction used is the average of the 1988 and 1989 wet base cation deposition data of the EMEP Meteorological Synthesizing Center - West. Since data for the dry deposition is not available on a European scale, the total deposition including a dry deposition fraction is estimated as following:

$$BC_d = \begin{cases} 2 \cdot BC_{wd} & \text{if } BC_{wd} < 250 \text{ eq ha}^{-1} \text{ yr}^{-1} \\ 250 + BC_{wd} & \text{otherwise} \end{cases}$$

where:

BC_{wd} = 1988/1989 average wet base cation deposition

BC_d = total base cation deposition



eq ha^{-1} yr^{-1}	mg S m^{-2} yr^{-1}
0 - 200	0 - 320
200 - 500	320 - 800
500 - 1000	800 - 1600
1000 - 2000	1600 - 3200
> 2000	> 3200

Figure A2.4. *Resulting sulphur deposition pattern under "60 percent gap-closure" scenario.*

The intent of the 60% gap-closure strategy is to reduce the 1990 exceedances of the critical sulphur deposition by 60%.

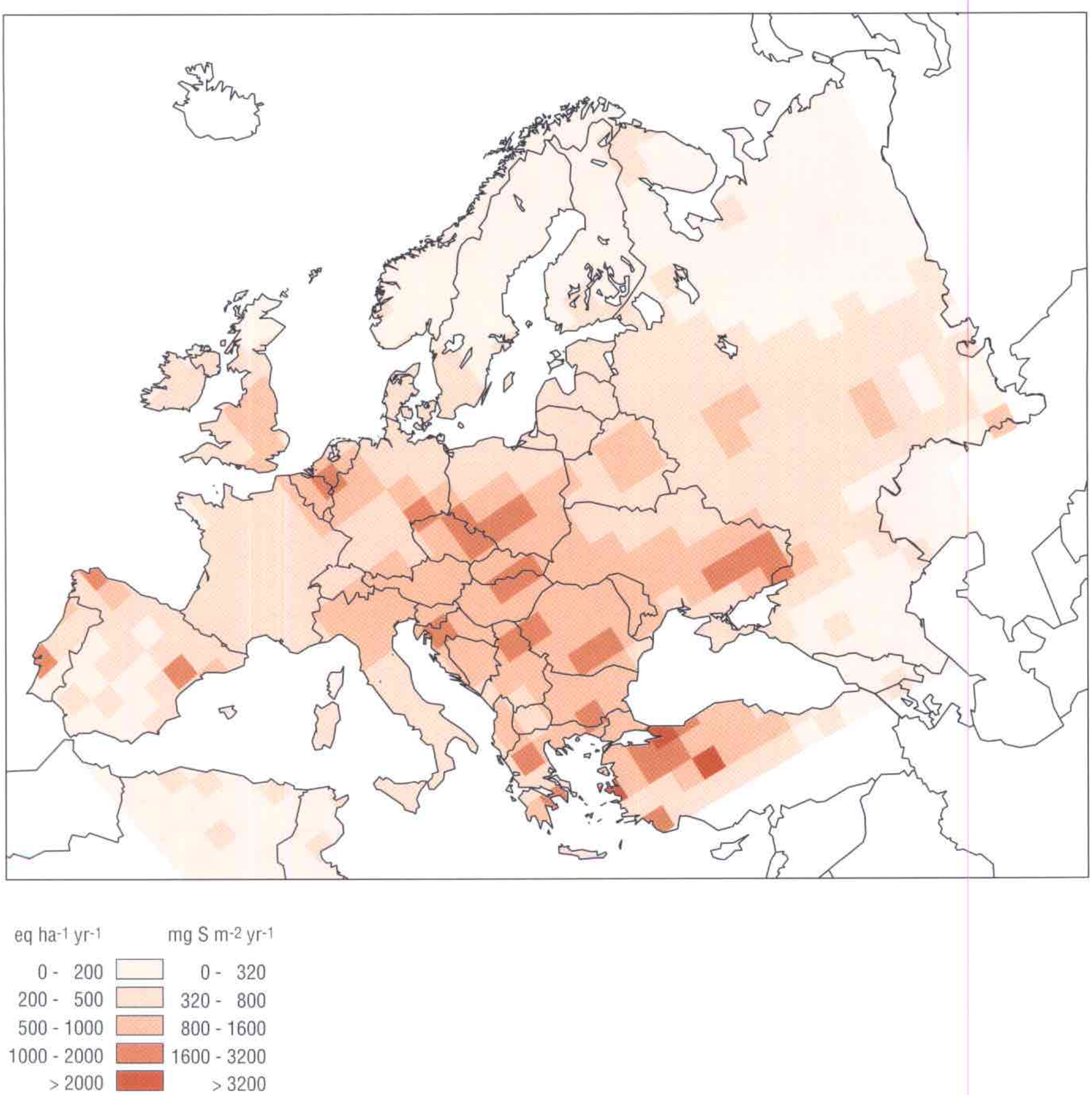


Figure A2.4. *Resulting sulphur deposition pattern under "60 percent gap-closure" scenario.*

The intent of the 60% gap-closure strategy is to reduce the 1990 exceedances of the critical sulphur deposition by 60%.

APPENDIX III. Values for Estimating Critical Loads of Nitrogen

Parameter	Values	Units
N_{de} [1]	0–1 aerated soils	kg N ha^{-1} yr^{-1}
	2–3 waterlogged soils and low deposition	kg N ha^{-1} yr^{-1}
	4–5 waterlogged soils and high deposition	kg N ha^{-1} yr^{-1}
f_{de} [2]	0.8 peat soils	–
	0.7 clay soils (FAO texture classes 2, 3 and 2/3)	
	0.5 sandy soils (FAO texture classes 1, 2 and 1/2) with gleyic features	
	0.1 loess soils and sandy soils without gleyic features	
pH soil[3]	5.0	–
T	Annual average temperature	°C
(Θ/Θ_s)[4]	Relative soil moisture saturation: well-drained 0.2; moderately well-drained 0.4; moderately drained 0.6; moderately poorly drained 0.8; poorly drained 0.9	–
$N_{l(crit)}$	tundra 0–1	kg N ha^{-1} yr^{-1}
	boreal conifers 1–2	kg N ha^{-1} yr^{-1}
	temperate conifers 2–4	kg N ha^{-1} yr^{-1}
	temperate deciduous 4–5	kg N ha^{-1} yr^{-1}
N_u	(See note 5.)	eq ha^{-1} yr^{-1}

1. It is recommended to use equation 4.10 or 4.15. Where the necessary data for these equations are lacking, values from the given range may be used.

2. Based on de Vries *et al.* (1992).

3. The dependence of the denitrification rate coefficient k on the pH is ignored in equation 4.16, and the function $h(pH)$ in equations 4.11 and 4.14 is set to 1.0. This happens at $pH = 5.0$.

4. Crude estimates of relative soil moisture saturation (Θ/Θ_s) related to FAO soil types are based on data from: FAO, 1987; de Vries *et al.*, 1992; and the Global Change department of RIVM. Soil moisture saturation also depends significantly on the soil texture and occurrence of gleyic features.

5. The mean nitrogen accumulation per year over a rotation based on the product of biomass and nitrogen concentration in removed timber should be used whenever equation 4.18 cannot be quantified.

APPENDIX IV. Empirical Approach for Critical Loads of Nutrient Nitrogen

An alternative approach to the mass balance method is to examine the effect of increased nitrogen loading on (semi-) natural ecosystems empirically. At the April 1992 UN ECE Workshop in Lökeberg, a list of critical loads for various ecosystems was assembled. The critical loads formulated there are based on observed changes in vegetation and biodiversity. The methods used to detect changes included experiments under controlled and field conditions, chemical analysis and comparisons of vegetation and fauna composition in time and space. While the mass balance method focuses on the nitrogen and proton budget within the existing ecosystem (e.g. forest stands), the empirical method enables inclusion of ecosystem types where biodiversity (changes in species composition) is the key criterion.

The advantage of this method is that cause-effect relationships need not be modelled; thus data requirements are modest. Only maps of the distribution of plant species or vegetation communities are necessary to apply the empirical method proposed here. These values must be adapted to the regional conditions for each application. This means choosing critical load values from the given ranges. Wherever possible, local studies or expert judgment should be used to select critical load values. The ranges partly represent uncertainty and partly reflect the variation of the ecosystem sensitivity under different conditions. For instance, in an earlier Swiss application (FOEFL, 1992) the range of 5-10 kg N ha^{-1} yr^{-1} for ombrotrophic bogs was interpreted as an altitude dependence. Where no further information on an ecosystem is available we suggest using the mean value of the range.

The critical loads achieved by the empirical method can be used in conjunction with results from the mass balance method (see Section 4.2.3), as a substitute for $CL_{nut}(N)$. However, the empirical method should be used with care. The values in Table A4.1 are based on knowledge including field measurements. It can not be excluded that some of the values include effects other than those related to acidification or eutrophication (e.g. climatic effects) which may lead to bias when the values are only regarded as critical loads.

Table A4.1. *Critical nitrogen loads (in kg N ha^{-1} yr^{-1}) for terrestrial ecosystems according to other than the steady-state mass balance methodology.*

Ecosystem	Critical load	Indication	Reference [1]
Acidic (managed) coniferous forest	15–20	Changes ground flora and fruit bodies, mycorrhizae	(a) #
Acidic (managed) deciduous forest	<15–20	Changes ground flora	(a) #
Calcareous forests	unknown	unknown	
Acidic (unmanaged) forests	unknown	unknown	
Lowland dry-heath land	15–20	Transition heather to grass	(b) ##
Lowland wet-heathland	17–22	Transition heather to grass	(b) ##
Species-rich lowland heaths/acid grassland	7–20	Decline sensitive species	(c) #
Arctic and alpine heaths	5–15	Decline lichens, mosses and evergreen dwarf shrubs, increase in grasses and herbs	(b) (#)
Calcareous species-rich grass land	14–25	Increase tall grass, decline diversity	(d) ##
Neutral-acid species-rich grassland	20–30	Increase tall grass, decline diversity	(d) #
Montane-subalpine grassland	10–15	Increase tall graminoids, decline diversity	(d) (#)
Shallow soft-water bodies	5–10	Decline isoetid species	(e) ##
Mesotrophic fens	20–35	Increase tall graminoids, decline diversity	(e) #
Ombrotrophic bogs	5–10	Decline typical mosses, increase tall graminoids	(e) #

1. This column provides information on where to find the reference (a to e) and the reliability of the data as follows: ## reliable; # quite reliable and (#) best guess. See Bobbink *et al.* (1992): (a) section 2.2; (b) section 3.1; (c) section 3.2; (d) section 4 and (e) section 5.

APPENDIX V. Proposed Method to Calculate Critical Loads for Aquatic Ecosystems

Similar to terrestrial ecosystems, the calculation of critical loads of acidity for aquatic ecosystems (lake + catchment) starts from the charge balance, but now also taking into account in-lake processes. While details of the derivation can be found in Kämäri *et al.* (1992) and Henriksen *et al.* (1993), one obtains for the critical loads of sulphur and nitrogen:

$$a_S\, CL(S) + a_N\, CL(N) = b_1\, N_{u(crit)} + b_2\, N_{i(crit)} + BC_{l(crit)} \tag{A5.1}$$

where the dimensionless constants a_N, a_S, b_1 and b_2 – all smaller than one – depend on ecosystem properties only, as follows:

$$a_S = 1 - \rho_S \tag{A5.2}$$

$$a_N = (\, 1 - f_{de}\,(1 - r)\,)\,(1 - \rho_N) \tag{A5.3}$$

$$b_1 = f\,(1 - f_{de})\,(1 - \rho_N) \tag{A5.4}$$

$$b_2 = (1 - r)\,(1 - f_{de})\,(1 - \rho_N) \tag{A5.5}$$

where f is the fraction of forests in the catchment area, r is the lake to catchment area ratio, and ρ_S and ρ_N refer to the in-lake sulphur and nitrogen retention, and are modeled by kinetic equations (see Kelly *et al.* 1987):

$$\rho_S = \frac{s_S}{\frac{Q}{r} + s_S} \quad \text{and} \quad \rho_N = \frac{s_N}{\frac{Q}{r} + s_N} \tag{A5.6}$$

and s_S and s_N are the net mass transfer coefficients for sulphur and nitrogen, respectively. Values for s_S have been given by Baker and Brezonik (1988), and for s_N by Dillon and Molot (1990). In the case of aquatic ecosystems, the critical base cation leaching is estimated by Henriksen *et al.* (1993), Sverdrup *et al.* (1990), Hettelingh *et al.* (1991):

$$BC_{l(crit)} = Q \cdot (\, [BC]_0^* - ANC_{limit}\,) \tag{A5.7}$$

where:
$[BC]_0^*$ = original sea-salt corrected base cation concentration
ANC_{limit} = ANC threshold

$[BC]_0^*$ can be estimated using the so-called F-factor from present-day water chemistry data (Brakke *et al.*, 1990) and the ANC_{limit} depends on the aquatic organism to be protected (see e.g. Lien *et al.*, 1991). Note, that in the above formulation of critical loads for lakes the linear formulation (from equation 4.15) for denitrification has been used. Similar to terrestrial ecosystems, a critical load of nitrogen related to eutrophication can be computed for lakes. Starting from the mass balance for nitrogen, one obtains: (see Kämäri *et al.*, 1992; Henriksen *et al.*, 1993):

$$CL_{nut} = \frac{b_1 N_{u(crit)} + b_2 N_{i(crit)} + N_{l(crit)}}{a_N} \tag{A5.8}$$

where a_N, b_1 and b_2 are given above and $N_{l(crit)}$ is the critical nitrogen leaching.

As with terrestrial ecosystems, the critical loads of sulphur and nitrogen are limited by the following constraints:

$$CL_{min}(S) = \begin{cases} 0 & \text{if } BC_{l(crit)} < N_{l(crit)} \\ \dfrac{BC_{l(crit)} - N_{l(crit)}}{a_S} & \text{if } BC_{l(crit)} \geq N_{l(crit)} \end{cases} \tag{A5.9}$$

$$CL_{min}(N) = \frac{b_1 N_{u(crit)} + b_2 N_{i(crit)}}{a_N} \tag{A5.10}$$

$$CL_{max}(S) = \frac{BC_{l(crit)}}{a_S} \tag{A5.11}$$

and:

$$CL_{max}(N) = \begin{cases} CL_{min}(N) + \dfrac{BC_{l(crit)}}{a_N} & \text{if } BC_{l(crit)} < N_{l(crit)} \\ CL_{nut}(N) & \text{if } BC_{l(crit)} \geq N_{l(crit)} \end{cases} \tag{A5.12}$$

Figure 4.2 depicts the relationship between deposition and critical loads also in the case of aquatic ecosystems. The slope of the thick line, indicating the possible pairs of critical loads of sulphur and nitrogen, is in this case given by a_N / a_S.

APPENDIX VI. CCE Workshop Reports

Report of the CCE Workshop on Mapping Critical Loads and Levels

14-16 January 1992
Coordination Center for Effects
National Institute of Public Health and Environmental Protection
Bilthoven, The Netherlands

Introduction:

The Coordination Center for Effects (CCE) held a training session on mapping critical levels and loads from 14 to 16 January 1992 at the National Institute of Public Health and Environmental Protection (RIVM) in Bilthoven, The Netherlands.

The meeting was attended by 69 experts from 16 countries (Austria, Commonwealth of Independent States, Czech and Slovak Federal Republic, Denmark, Finland, Germany, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Switzerland, Sweden, United Kingdom, and Yugoslavia). In addition, representatives of the UN ECE Task Force on Mapping (TFM), Task Force on Integrated Assessment Modelling (TFIAM), the International Institute for Applied Systems Analysis (IIASA), and Greenpeace were also present. A list of participants is contained in Annex I.

The purpose of the meeting was: (1) to review data used in critical loads and exceedances for acidity and sulphur, (2) to provide input for the nitrogen critical loads workshop in Sweden in April 1992, and (3) to discuss future mapping activities for critical levels.

Review of critical load maps of acidity and sulphur

The CCE reviewed the status of updated national data for ecosystem coverage (area per grid cell) and input values (base cation deposition, base cation weathering, nitrogen uptake, etc.) for use in future maps, and stressed the importance of this continued data collection. Issues encountered in the development of the critical load maps for acidity and sulphur were addressed. Several points arising from the session's presentations were discussed, including:

The use of steady-state mass balance (SSMB) method for high-elevation and high-precipitation areas: An example of using the Profile model to derive critical loads for high-precipitation areas was presented. The model gives lower critical load values for these areas, since it is not dependent on precipitation amounts. It was agreed that general correction factors could not be recommended without further study, but that each country should use a satisfactory method to calculate national critical loads, as in the past. The Austrian National Focal Center offered to host a workshop (9-10 March 1992) in Vienna to discuss issues relating to the application of the steady-state mass balance method to high-elevation and high-precipitation areas. Further details are available from Helmut Hojesky of the Umweltbundesamt.

The use of low-percentile maps, and how to address negative critical loads: It was noted that the use of low (i.e. 1 or 5) percentile maps ensures that the status of the most sensitive ecosystems are reflected, but may result in critical load values which are unrealistic or unachievable. The selection of critical chemical values designed to protect sensitive fish species results in very low or negative critical loads in large parts of Scandinavia. It was recommended that the use of higher-resolution national data be reviewed to define the use of other percentile(s) on the EMEP grid.

Deposition data: It was noted that while alternative sources of deposition data exist, particularly for nitrogen, but using EMEP data remains the method agreed upon to create exceedance maps. A workshop to review the present approaches used to monitor and calculate deposition used in using the critical loads approach will be held in Sweden in September 1992. The workshop, sponsored by the Nordic Council of Ministers and the Swedish Environmental Protection Board, will address how to proceed with mapping of deposition levels based on these approaches. Further details on the workshop will be available from Gun Lövblad of the Swedish Environmental Research Institute in Göteborg.

Sulphur fractions, and the coupling between critical loads of sulphur and nitrogen: The derivation of the sulphur fraction, which includes nitrogen-related terms, means that the sulphur fraction varies as different base years for sulphur and nitrogen deposition values are chosen; e.g. an increase in the present load of nitrogen could lead to a changing sulphur fraction and thus a decrease of the critical load of sulphur. Deposition data for 1988 are now used; however, the choice of other base years becomes relevant as pollution abatement measures lead to a reduction in sulphur deposition. Using more recent sulphur deposition data to calculate the sulphur fraction leads to changes in the critical loads of sulphur. To reach the sulphur critical load, therefore, even more sulphur abatement is needed. It was noted that this problem could be avoided by treating sulphur and nitrogen simultaneously.

Updating national data: The Coordination Center acknowledged the large amount of data already received from National Focal Centers, and stressed the importance that National Focal Centers for Mapping deliver updates of national input data to the CCE for use in future mapping work.

Mapping critical loads of nitrogen:

Organizers of the workshop on critical loads of nitrogen (Lökeberg, Sweden, 6-10 April 1992) presented details on the issues to be addressed at the workshop. The critical load approach will be developed for four major types of ecosystems: terrestrial, groundwater, surface water, and marine. Many issues were recommended for consideration at the workshop:

General (for all subgroups):

- The link between critical loads of acidification and eutrophication.
- The relative importance of NH_3^+ and NO_3^- in relation to sulphur.
- Relevant regions and areas (within the ECE region).
- The applicability range within Europe for the criteria chosen.
- Importance of denitrification and biological nitrogen fixation.
- Interdependence between criteria (e.g. between diversity and forest growth) and critical loads of similar and different ecosystems or receptors.
- Call for data and results on deposition, criteria, critical load mapping, observed vegetation changes, etc.

Terrestrial/soils subgroup:

- Quantification of input and production of nitrates in relation to leaching and uptake.
- Immobilization and mineralization of nitrogen.
- Combined effects of acidification and eutrophication on vegetation.

Marine subgroup:

- Relevant geographical resolution (main areas or grid net). How to construct a relevant input-output balance.
- How to combine (or separate) effects of nitrogen and phosphorus loadings. Transitions between nitrogen and phosphorus limitations.
- Since estimating critical loads for marine areas is new, establishing relevant criteria becomes very important.
- Assess the importance of indirect deposition.

Lakes subgroup:

- The role of nitrate in connection with episodes.
- Eutrophication of (and other air pollution effects on) streams in mountainous areas, population diversity, and species composition.
- Eutrophication from phosphorus.

Deposition subgroup:

- The link between small-scale and large-scale deposition.
- The importance of wet vs. dry deposition, and filtering.

It was announced that Norway is beginning a project to study the nitrogen cycle, entitled "Nitrogen from Mountain to Fjord". The first part of the project will involve mass balance studies of the nitrogen cycle from deposition through input into the North Sea, and will compare catchments which receive their primary nitrogen input from different sources (i.e. atmospheric deposition vs. agriculture and forest.)

Mapping Critical Loads and Levels (national investigations):

National reports on recent activities in mapping critical loads and/or levels were given by: Austria, Commonwealth of Independent States, Czechoslovakia, Germany, Hungary, Italy, United Kingdom, and Yugoslavia. A number of common points important to critical load mapping were noted, including the availability of input data, the mapping resolution, and the selection of which receptor and chemical criteria are used to define a critical load.

Mapping critical levels:

One of the organizers of the upcoming workshop on critical levels (United Kingdom, 23-26 March 1992) presented an overview of the workshop. Its objectives are to: revise the conceptual basis for calculating critical levels, reassess criteria, assess the need to address pollutants in addition to those covered in the mapping manual, to develop methods for calculating critical levels, and to assess the feasibility of "level II" critical level mapping. It was noted that the workshop will concentrate on reviewing critical levels for vegetation.

A number of issues were recognized as important to be addressed at the workshop, including: the definition of "adverse" effect, choice of receptor, inclusion of climatic factors, modeling needs, and the question of the relative importance of critical levels to critical loads in driving abatement strategies.

Environmental forecasting:

The RIVM's plans in its European environmental forecasting work were discussed. A meeting of environment ministers in Dobris, Czechoslovakia, in June 1991 proposed that a European state of the environment report be developed. This report is designed to provide a basis for decisionmaking about environmental priorities. The European community in Brussels has taken the lead in organizing this work, and the RIVM has made in preliminary forecast of Europe's environment. The importance of this type of forecasting will become increasingly important at the RIVM in the future.

The CCE network of contacts developed through the critical loads exercise, through NFC's and other contacts, could contribute to the production of the European environmental forecast. The CCE will keep NFC's and other interested parties informed about future developments in the project, pending resolution of the scope of RIVM's involvement in the project.

Other examples of regional environmental assessments were presented, including environmental risk assessment models developed at the Technical University of Warsaw and the Institute for Systems Studies in Moscow, and a risk assessment for forest ecosystems done at the University of Munich. Some examples of the use of RIVM's geographic information system (GIS), including a recent report on sustainable use of groundwater in Europe, were also demonstrated.

Concluding discussion/Future activities:

The CCE and NFC's will participate in the upcoming critical loads/levels workshops. On the basis of results from the nitrogen workshop, the CCE will proceed with a mapping methodology to produce first maps of critical loads of nitrogen for the ecosystems currently addressed.

An additional CCE workshop on mapping is tentatively planned for September 1992 (possibly to be hosted by the NFC in Katowice, Poland) to review the progress of work and resolve outstanding issues.

Report of the CCE Workshop on Mapping Critical Loads and Levels

9-11 September 1992
Institute for the Ecology of Industrial Areas
Katowice, Poland

Introduction:

The Coordination Center for Effects (CCE) held a training session on mapping critical loads and levels from 9 to 11 September 1992 in Katowice, Poland at the invitation of the Institute for the Ecology of Industrial Areas.

The meeting was attended by 50 representatives from 15 countries (Austria, Czech and Slovak Federal Republic, Denmark, Finland, France, Germany, Netherlands, Norway, Poland, Russian Federation, Spain, Switzerland, Sweden, Ukraine, and United Kingdom). Representatives of the UN ECE Task Force on Mapping (TFM) and the International Institute for Applied Systems Analysis (IIASA) were also present.

Objectives:

Major objectives of the meeting were:

(1) to agree on a proposed methodology for calculating critical loads of nitrogen. A document entitled "Guidelines for the Computation and Mapping of Nitrogen Critical Loads and Exceedances in Europe" had been prepared by the CCE and co-authors and distributed in advance to participants of the workshop.

(2) to discuss work needed in the near future in updating sulphur critical loads, focusing on the needs of the December 1992 meeting of the Task Force on Integrated Assessment Modelling.

(3) to present available national or regional studies, including preliminary maps, of critical loads of nitrogen.

Lökeberg Workshop on Critical Loads of Nitrogen:

Some findings from the workshop on critical loads of nitrogen, held in Lökeberg, Sweden, in April, 1992 were presented by some of the workshop's session chairmen. Key results from the working sessions on mass balance methods, surface waters, and deposition, include:

Mass balance methods: Using mass balance methods to calculate critical loads of nitrogen should be viewed as a long-term approach, as many of the input variables are uncertain. Gaps in knowledge include data on N accumulation in soil, the effects of N deposition and accumulation, the effects of increased N availability on organisms, N leaching rates at low N loads, biological N fixation rates, inclusion of ammonia volatilization in calcareous areas, and dose-response relationships.

Surface waters: The application of two "Level I" methods: the steady-state water chemistry method and the first order mass balance (FMB) method, were discussed. The FMB (described in detail in the background document prepared for the Lökeberg workshop) can be used for simultaneous calculations of critical loads of potentially acidifying S and N deposition, and their exceedances for surface waters (and forest soils). As a consequence of the inclusion of rate-limited processes in the model formulation, the critical loads computed depend on the deposition to the ecosystem. The workshop group concluded that in general, it is more important to look at total acidity, rather than nitrogen for surface waters.

Deposition: The workshop group found deposition data or estimates good in general, with the exception of deposition estimates for high-elevation areas. Data on the effects of cloud and fog water deposition may be quite important, but are monitored routinely in only a few areas. Similarly, there is little information available on the European scale on gaseous and particulate deposition of nitrogen.

A deposition workshop on to be held in November 1992 (Sweden) will study the feasibility of generating deposition estimates on a grid scale smaller than that of EMEP currently used (150 km x 150 km).

Marine ecosystems: The Katowice workshop supported the proposal for a serious attempt to develop a methodology for assessing and mapping critical loads to (parts of) the marine environment of western Europe. This issues will also be addressed within the framework of the Nordic Council in the near future.

Recommendation: Further attention should be paid to critical nitrogen loads for marine ecosystems, as a follow-up of the Lökeberg effort in this area. The head of the Dutch National Focal Center (NFC), B.J. Heij (Netherlands) and T. Johannessen (Norway) have agreed to take the lead in organizing necessary activities.

Computation and Mapping of Critical Loads of Nitrogen:

The CCE presented a paper developed following the Lökeberg workshop, "Guidelines for the Computation and Mapping of Nitrogen Critical Loads and Exceedances in Europe" (hereafter referred to as "Guidelines") drafted by the CCE and other members of the Lökeberg mapping group. The paper proposes methods for the computation and mapping of nitrogen critical loads and exceedances using an ecosystem-based method, i.e. without a sulphur fraction, and discusses the consequences of this approach on the calculation of sulphur critical loads.

The meeting concluded, as before, that there is no scientific reason for estimating a distinct critical load of sulphur. To accommodate current policy needs, a closer collaboration between the mapping and integrated modeling community is required in addressing proper objective functions. Such objective functions would not so much focus on specific critical loads, but rather on exceedances. Exceedance optimization would focus on the critical load of nitrogen (eutrophication) and the critical load of acidity. In this way combined sulphur and nitrogen objectives can be addressed.

The "Guidelines" paper will be updated by December 1992 and distributed by the CCE to all interested parties.

Recommendations:

- The CCE will begin European-scale mapping for CL(N) using the ecosystem-based method, as described in the "Guidelines".

- The CCE requested all NFC's to review Appendix A of the "Guidelines", which lists the suggested values or ranges for input variables to be used in the CL(N) calculations, and submit any proposed revisions to the CCE.

- The critical load ranges proposed in Appendix B of the "Guidelines" will be used only where mass balance calculations are inappropriate.

- An update of the "Guidelines" will be made with particular emphasis on the definition of objective functions for integrated modelers assessing sulphur and nitrogen reduction scenarios. Regular updates of the "Guidelines" will serve to address methodological, mapping and optimization practicalities.

Computation and Mapping of Critical Loads of Sulphur:

There was a lengthy discussion about the potential misunderstandings among the various groups (scientists, modellers, and policymakers) using the critical loads maps in the UN ECE framework. Much of the difficulty arises from the earlier decision by the mapping community to keep critical loads "clean"; i.e. not to include modifying factors such as base cation deposition and base cation uptake. These factors were included by assessment modelers for the computation of exceedances on an EMEP scale. This approach was felt to have disadvantages, i.e. (1) modifying factors are sometimes available on a much higher than EMEP resolution, leading to loss of information when used on an EMEP scale, and (2) maps of critical loads cannot be directly compared by people who visually investigate EMEP deposition maps which are regularly published by the MSC-W.

Therefore it was decided to include these modifying factors in calculating maps of a new *"critical sulphur deposition"*, which would then be directly comparable to EMEP deposition. Similarly critical acid deposition and critical nitrogen deposition maps can be obtained by also including nitrogen uptake, nitrogen immobilization and nitrogen fixation. Depending on the quality of the available (national) data on modifying factors at CCE, the CCE will proceed in producing a critical sulphur deposition map for the TFIAM using high resolution data on modifying factors. Depending on the timing of the TFIAM modelling exercise, the CCE's current approach of treating modifying factors on an EMEP scale may have to be temporarily continued. In this case, refinements will only be made to avoid contradictions in border grids containing countries where modifying factors are not treated in a comparable way. The critical sulphur deposition will be computed as:

$$CD(S) = CL(S) + S_f\,(BC_d - BC_u)$$

where:
$CD(S)$ = critical sulphur deposition
$CL(S)$ = critical load of sulphur (deposition-based method)
S_f = sulphur fraction
BC_d = base cation deposition
BC_u = base cation uptake

Recommendations:

Critical load of sulphur: The CCE will continue using the deposition-based method (i.e. using the sulphur fraction) for updates of sulphur maps in 1992.

Critical sulphur deposition: National Focal Centers (NFC's) should send critical load calculations using the above equation to the CCE before mid-October 1992 if these data are to be used for the December TFIAM. The CCE will calculate the critical sulphur deposition from the critical load of sulphur and the sulphur fraction if national calculations are not available.

Mapping Critical Loads (national investigations):

National reports on recent activities in mapping critical loads were given by: Germany, Netherlands, Russia, and United Kingdom.

Mapping Issues:

Discussion of ecosystem-based vs. EMEP-area coverage: Expressing critical load percentiles based on ecosystem coverage increases the understanding of decisionmakers of the level of protection afforded at varying reduction levels, but are more difficult to compare directly with EMEP-computed deposition values.

Recommendation: The CCE will continue to produce critical loads maps using both scales (EMEP area and ecosystem coverage). A revised summary explanation of the differences between these two approaches is attached. These data will, as before, be made available to TFIAM modeling groups (ASAM, CASM, RAINS), EMEP, and NFC's.

Mixed receptors: Previous European critical loads maps have been "mixed receptor" maps, showing critical loads for a combination of ecosystems. These ecosystems are weighted by the area they cover either being EMEP-area or ecosystem-area based. When ecosystems overlap (e.g. catchments and forests) choices have to be made about the weighting procedure. The weighting procedure affects the percentiles (see CCE Technical Report No. 1, "Mapping Critical Loads for Europe", section 3.5 and Appendix 5). Data sent to the CCE should be accompanied by a clear description of how weighting was performed. A more general description of a weighting procedure to use is described in the "Guidelines" paper.

Recommendation: The CCE will proceed with weighting data from multiple ecosystems, and grid cells covering more than one country, as previously. The next CCE report documenting the development of European maps of nitrogen critical loads will include a section on the weighting methodology actually used.

Optimization strategies based on critical loads:

Recommendations:

• The distinction between critical loads of sulphur, nitrogen and acidity: TFIAM modelers currently assess sulphur emission reduction by investigating an achieved (e.g. by optimization) sulphur emission vector in terms of its related exceedance of sulphur critical loads. The workshop recommends that the achieved sulphur vector is combined with current nitrogen deposition patterns to investigate the exceedance of the critical loads of acidity as well. This is especially important when assessments for nitrogen emission reductions will be modeled as critical loads of nitrogen become available in 1993. The optimization scheme described in the "Guidelines" paper could serve as a starting point of collaboration between mapping and integrated modeling groups.

- Reflecting optimization results using the ecosystem area or the EMEP area: TFIAM modelers should use ecosystem-based cumulative frequency distributions (CDFs) of critical loads as well as EMEP area-based of critical loads in two ways: (1) the environmental protection to be gained from a scenario should be expressed both in terms of ecosystem and EMEP area protection, and (2) optimization should be driven both by an ecosystem-based percentile and by an EMEP area-based percentile, at least for the scenario considered most relevant.

Issues of the Task Force on Mapping:

A detailed proposal for the long-term mapping program as well as the comments on the proposal of the revised Mapping Manual chapter 3, "Critical Levels" and the new chapter 6, "Critical loads of Nitrogen", will be sent out before the next Task Force meeting planned to take place in Berlin in April 1992.

The paragraph 6.5, "Mapping", can be worked out after the "Guidelines" paper is revised on the basis of the CCE Katowice workshop. The updated versions of the Mapping Manual shall be published as soon as possible.

Future Activities:

Submission/updating national data: The Coordination Center stressed the importance that National Focal Centers for Mapping deliver all available national data on input variables to the CCE for use in future mapping work. The CCE has issued a call for data for calculating critical loads of nitrogen. A list of input data requested by the CCE including their description is attached.

The next CCE mapping workshop is tentatively planned for March 1993. The objectives of this meeting will include (1) first critical load maps for nitrogen, (2) elaborate issues for closer collaboration among ICP's, the EDC, CCE and if appropriate, the International Geosphere-Biosphere Program (IGBP). The workshop will be hosted by the Spanish NFC.

CRITICAL LOADS FOR EMEP GRID SQUARES: PRESENTATION AND USE OF DATA

from the CCE Mapping Workshop
Katowice (Poland), 9-11 September 1992

1.The critical loads mapping exercise involves assigning critical loads to ecosystems in an EMEP grid square. Different countries use different species/ecosystem receptors for mapping and these may occupy different areas, usually less than 100%, of grid squares. While there are a variety of ways that critical loads data can be collated and presented for EMEP grid squares, those based on area avoid value judgement. Critical loads have been computed relative to the ecosystem area in an EMEP grid cell.

2. Using an area approach, there are currently two alternatives for presenting data for EMEP grid squares. In the "grid area" approach, critical loads data relate to receptors which are defined in terms of their percentage area cover of an EMEP square; i.e. the total ecosystem area equals 100%.

3. It should be noted that both approaches have disadvantages associated with their use for presenting critical loads values for EMEP grid squares. These problems result from the lack of data or absence of relevant ecosystems for parts of EMEP squares.

4. These "missing" areas in the "grid area" approach are assigned a critical load value equal to the highest (i.e. least sensitive) critical load estimate in the grid square. In consequence, when considering "protection" offered by or "damage" resulting from particular deposition loads, the grid area percentages will not necessarily reflect protection or damage of the ecosystems for which critical loads estimates have been made. However, they may indicate protection/damage of the grid area itself.

5. To overcome this problem, all area of a grid square may be considered to contain receptors of different types (the SEI"total ecosystem approach") and the grid square assigned gives no immediate indication of which receptors relate to any percentile value, i.e. which are damaged or protected.

6. Using the "ecosystems area" approach, data are only considered for ecosystem areas for which critical loads have been estimated; i.e. areas of non-relevant ecosystems are ignored. Consequently, a small area of receptors in one square may be afforded the same weighting as a large area in another. However, by using this method it may be clearer what the receptor type is and how much of it is protected/damaged.

7. It should be noted that attainment of the lowest critical load affords protection to the entire ecosystem area within the grid square.

8. To avoid confusion when either of the two methods is used, as much information as possible should be presented on the critical loads data. The area cover of the ecosystems for which critical loads have been estimated has already been requested by the TFIAM. Supplementary maps indicating the percentage of relevant ecosystems in an EMEP grid square, the ecosystem(s) being mapped, and the areas where the CCE has "filled gaps"; i.e. where national critical load calculations have not been submitted, should be made. A map indicating whether area-based data or point data have been used for mapping would also be useful.

9. Further comparison of the two approaches (ecosystem-area vs. EMEP-area) is needed. The results of both types of maps produced by the CCE should be used in the TFIAM's optimization exercises.

CRITICAL LOADS DATA REQUESTED BY THE CCE

from the CCE Mapping Workshop
Katowice (Poland), 9-11 September 1992

x, y Longitude and latitude coordinates (southwest corner of grid cell)

CL(S) Critical load of sulphur (units should be in eq ha^{-1} yr^{-1}.

Two possibilities for submission of data:
1. Send CL(S) calculations, including description of methods/formulae used.
2. Send CL(Ac) according to previous method (from CCE Report No. 1). The CCE will then compute and apply a sulphur fraction, on an EMEP-area scale as before. (using 1988 data).

TO BE SUBMITTED BEFORE 16 OCTOBER 1992:

CD(S) Critical deposition of sulphur

Two possibilities for submission of data:
1. Send calculated CD(S), using the formulation given in this report.
2. The CCE uses calculated CL(S) to compute CD(S).

W Weighting factor indicating percentage of grid cell area for which CL(S) and CD(S) calculations are applicable

Weights assigned to critical loads allow the quantification of a cumulative distribution for each EMEP grid cell. The weight should preferably reflect the total area, within **each** country-EMEP grid cross-section, for which the critical load is valid.

For the following input variables, NFC's have two possibilities for submitting data:

1. Submit data on the same scale at which critical load and critical depositions are calculated.
2. Otherwise, the CCE will use the European background data base (as before) to obtain background variables on an EMEP grid scale.

BC_w Base cation weathering

BC_d Base cation deposition

BC_u Base cation uptake

N_u Nitrogen uptake

N_i Nitrogen immobilization (N_{humus} and N_{fix})

N_{fix} Nitrogen fixation

Report of the Fourth CCE Mapping Workshop

16-18 March 1993
Research Center for Energy, Environment and Technology (CIEMAT)
Madrid, Spain

I. Introduction

The Coordination Center for Effects (CCE) held a workshop on mapping critical loads and levels from 16 to 18 March 1993 in Madrid, Spain at the invitation of the Research Center for Energy, Environment and Technology (CIEMAT).

The meeting was attended by over 55 representatives from 18 countries (Austria, Canada, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Netherlands, Norway, Poland, Russian Federation, Spain, Switzerland, Sweden, United Kingdom and United States). Representatives of the UN ECE Task Force on Mapping (TFM) and the International Institute for Applied Systems Analysis (IIASA) were also present.

II. Meeting Objectives

Major objectives of the meeting were:

(1) to agree on proposed methodologies for calculating critical loads and exceedances of nitrogen and sulphur. A document entitled "Guidelines for the Computation and Mapping of Critical Loads and Exceedances in Europe" (Posch *et al.*, 1993) had been distributed in advance to participants of the workshop.

(2) to present recent national results of mapping critical loads of acidity, sulphur and/or nitrogen.

(3) to agree on the outline of a report to document the status of mapping work done by the CCE and National Focal Centers (NFC's).

(4) to agree on a timetable for producing required data and maps to calculate critical loads of nitrogen, and for NFC contributions to the CCE 1993 mapping report.

III. "Guidelines for the Computation and Mapping of Critical Loads and Exceedances in Europe"

Maximilian Posch (Finland) presented a summary of the most recent draft of the "Guidelines" paper, which includes updated methods to calculate critical loads and exceedances of sulphur and nitrogen simultaneously.

The starting point of the proposed method is the ecosystem is indifferent with respect to whether its protection (i.e. achieving critical loads) results from sulphur or from nitrogen deposition reductions. The result is that trade-offs between emissions reductions of these two pollutants can be considered without violating the requirement of meeting the critical load of acidity and eutrophication. These different combinations of required deposition reductions to meet the critical load for an area can be expressed as a function, the so-called *"exceedance indifference curve"*. The "Guidelines" paper contains a detailed discussion of the background and application of the exceedance indifference curve.

Workshop conclusions:

• The methodology proposed in the "Guidelines" is accepted.

• The revised "Guidelines" will include proposed ranges for estimating nitrogen immobilization rates, and two calculation methods to calculate denitrification.

• The CCE will begin European-scale mapping using the ecosystem-based method, as described in the "Guidelines". Results, however, will reviewed bilaterally between the CCE and NFC's. Countries should calculate the values for maximum and minimum values for critical loads of sulphur and nitrogen, as described in the "Guidelines". The CCE will develop European maps of critical loads of nitrogen, from national calculations of CL_{max} and CL_{min} for both nitrogen and sulphur. The factors to be included and format to be followed for submitting national data are attached.

IV. Data Requirements for Critical Load Calculations

The requirements and methods for producing and submitting critical loads data were discussed. The CCE presented European maps of critical deposition for acidity and sulphur, which will be contained in an annex to the sulphur protocol currently being negotiated.

The CCE has also produced preliminary European maps for the CL_{max} and CL_{min} for sulphur and nitrogen using European data bases. These current maps, developed using European data bases, show that $CL_{max}(N)$ is often limited by the critical load of nutrient nitrogen.

Methods of estimating total base cation deposition were discussed. The current method used to calculate critical deposition values interpolates total base cation deposition from the wet deposition values supplied by EMEP.

Some presentations discussed possible methods to estimate the necessary input variables for calculating CL(N), including nitrogen immobilization, denitrification, and nitrogen leaching. These recommendations will be included in the revised mapping guidelines.

Workshop conclusions:

- The importance of accurate estimates of total base cation deposition in calculating exceedances was emphasized. The EMEP program's estimates of base cation deposition should be improved by taking into account an estimate of the dry deposition component.

V. Mapping Critical Loads (National Activities)

National reports on recent activities in mapping critical loads were given by: Austria, Czech Republic, Germany, Poland, Russia, Scandinavia and the United Kingdom.

VI. CCE 1993 Mapping Report

The CCE presented a proposed outline for its report to the UN ECE this year on the status of mapping activities. As with the CCE Technical Report No. 1, a large part of the report will consist of National Focal Center reports and maps. These reports should summarize national mapping activities conducted since the publication of the 1991 report.

After extended discussion, it was decided not to include preliminary maps of the critical load of nitrogen, but to report on the status of methods development and data collection. A revised report outline, guidelines for NFC contributions, and timetable were distributed at the meeting.

Workshop conclusions:

- The CCE will produce a report on the current status of mapping activities, including NFC contributions, for the meeting of the Working Group on Effects in July 1993. The report will summarize the progress made in mapping critical loads since the CCE Technical Report in 1991, but will not include European maps of critical loads of nitrogen.

VII. Future Work

- National Focal Centers should begin work on calculating the maximum and minimum critical loads of sulphur and nitrogen, as outlined in the "Guidelines" paper, and supply this data to the CCE when it becomes available.

DATA REQUIREMENTS FOR CALCULATING AND MAPPING CRITICAL LOADS

from the CCE Mapping Workshop
Madrid (Spain), 16-19 March 1993

I. DATA SUBMISSIONS FROM NATIONAL FOCAL CENTERS

Variables needed to calculate CL(N) and CL(S) according to the methods proposed in the "Guidelines" paper:

Ia. Forest soil ecosystems:

Nitrogen:

$CL_{min}(N)$	Minimum critical load of nitrogen (eq/ha·yr); from equation 3.14.
$CL_{max}(N)$	Maximum critical load of nitrogen (eq/ha·yr); equation 3.18 or 3.19.
$CL_{nut}(N)$	Critical load of nutrient nitrogen (eq/ha·yr); equation 2.17 or 2.18.
$N_{u(crit)}$	Critical nitrogen uptake (eq/ha·yr).
$N_{i(crit)}$	Critical nitrogen immobilization (eq/ha·yr). Set value between 143 - 357 eq/ha·yr [= 2 - 5 kg N/ha·yr], See Section 2.3.2.
$N_{l(crit)}$	Critical nitrogen leaching (eq/ha·yr); See Section 2.3.3.
N_{de}	Denitrification (eq/ha·yr). **It is proposed to base it on the constant denitrification fraction (f_{de}) described in Section 2.3.4.2.**

Sulphur:

$CL_{min}(S)$	Minimum critical load of sulphur (eq/ha.yr); from equation 3.15.
$CL_{max}(S)$	Maximum critical load of sulphur (eq/ha·yr); equation 3.12.
ANC_w	Acid neutralizing capacity produced by weathering (eq/ha·yr). (This term was formerly expressed as BC_w).
$ANC_{l(crit)}$	Critical leaching of acid neutralizing capacity (eq/ha·yr).
BC_{dep}	Total Base Cation deposition **(wet + dry)** (eq/ha·yr); (Refer to the CCE letter of 17 December 1992, Appendix C).
BC_u	Base cation uptake (eq/ha·yr); (If no BC_u data are available, then the CCE proposes to use the data enclosed with the CCE letter of 17 December 1992).

Ib. Aquatic ecosystems (fresh water lake + catchment):
Refer to Appendix C of the "Guidelines" for data requirements.

II. DATA FORMAT:
All data should be submitted to the CCE with a structure (ASCII comma-delimited or in dBase-compatible format) as shown in the following table. If you must use a different format, please contact the CCE **before** submitting data to discuss possible modifications.

Format for data submitted to the CCE.

Field nr.	Field name (= Parameter name)	Field Structure Type, width, decimals **(1)**	Description of parameter
1	Long	N(umeric), free, free **(2)**	Longitude value (degrees) of the point that represents the part of a polygon or a national grid cell (or an area within that grid cell) that is split up by the EMEP grid cells. See Figure A6.1.
2	Lat	N, free, free **(2)**	Latitude value (degrees) of the point that represents the part of a polygon or a national grid cell (or an area within that grid cell) that is split up by the EMEP grid cells. See Figure A6.1.
3	CLmin(N)	N, 8, 1	Minimum critical load of nitrogen (eq/ha·yr); equation 3.14.
4	CLmax(N)	N, 8, 1	Maximum critical load of nitrogen (eq/ha·yr); equation 3.18 or 3.19.
5	Eq_CLmax(N)	N, 5, 0	Equation number used to calculate the CLmax(N); fill out "318" or "319".
6	CLnut(N)	N, 8, 1	Critical load of nutrient nitrogen (eq/ha·yr); equation 2.17 or 2.18.
7	Eq_CLnut(N)	N, 5, 0	Equation number used to calculate the CLmax(N); fill out "217" or "218".
8	CLmin(S)	N, 8, 1	Minimum critical load of sulphur (eq/ha·yr); equation 3.15.
9	CLmax(S)	N, 8, 1	Maximum critical load of sulphur (eq/ha·yr); equation 3.12.
10	Nu,crit	N, 8, 1	Critical nitrogen uptake (eq/ha·yr).
11	Ni,crit	N, 8, 1	Critical nitrogen immobilization (eq/ha·yr); assign a value between 143 - 357 eq/ha·yr [= 2 - 5 kg N/ha·yr] in Section 2.3.2.
12	Nl,crit	N, 8, 1	Critical nitrogen leaching (eq/ha·yr); Section 2.3.3.
13	Nde	N, 8, 1	Denitrification (eq/ha·yr); Section 2.3.4. **It is proposed to base it on the denitrification fraction (f_{de})**
14	ANCw	N, 8, 1	Acid neutralizing capacity produced by weathering (eq/ha·yr).
15	ANCl,crit	N, 8, 1	Critical leaching of acid neutralizing capacity (eq/ha·yr).
16	BC*d	N, 8, 1	Total base cation deposition **(wet & dry)** (eq/ha·yr); (see Appendix C of CCE letter dd. 17 December 1992).
17	BCu	N, 8, 1	Base cation uptake (eq/ha·yr).
18	Ecosyst_type	C(haracter), free / N, free, free **(2)**	Short character or numeric code for type of ecosystem. **(4)**
19	Emepx	N, 3, 0	EMEP x-coordinate of the EMEP cell to which the point is assigned to. **(3)**
20	Emepy	N, 3, 0	EMEP y-coordinate of the EMEP cell to which the point is assigned to. **(3)**
21	Area_emep	N, free, free **(2)**	Area that the point represents in each involved EMEP cell (km^2). **(3)**

Footnotes within table:

1. The total width of the columns includes also the dot and number of decimals.
2. Format of type, width, decimals of the field values depends strongly on the mapping resolution and type of ecosystems mapped on national scale.
3. If the national grid cell area or the polygon area is split up by two or more EMEP cells, all the split areas belonging to that specific national grid cell or polygon have to be represented in the data base as a separate record, as shown in the next data base example for grid cell *q*.

Note that the sum of all values (km^2) in the field "Area_emep" for one EMEP cell always has to be smaller or equal to the total EMEP cell area. If aquatic (catchment) and forest soil ecosystems are both submitted to the CCE be aware that they can overlap in their area coverages. To avoid double counting of the same locations that are shared by both aquatic and forest soil ecosystems you will have to apply a weighting factor for those locations (refer to the Guidelines chapter 4).

4. Some National Focal Centers specify their mapped ecosystem types with short character or numeric codes as in use at national scale of mapping. If so, these short codes need to be explained in the NFC report or as an annex to the submitted data base.

Some examples are given to illustrate how the data bases can be derived from the national maps overlaid with the EMEP grid.

EXAMPLES:

1) National grid cells:

National Focal Center data that are collected or applied on a national grid resolution for national purposes. Within the national grid cell resolution polygons are utilized for the relevant receptor ecosystems.

Nr.	Long	Lat	var.'s...	Ecosyst_type	Ecosyst_ group	Emepx	Emepy	Area_ emep		National grid id.
....	....	....	....	....	....	....	....	....		....
231	3.05	52.25	....	beech-podz	FD	19	15	23		*p*
232	3.83	51.75	....	beech-podz	FD	19	15	22		*q*
233	4.93	53.45	....	dougl-gley	FC	19	16	18		*q*
234	5.04	52.85	....	birch-clay	FD	20	15	11		*q*
235	5.35	52.85	....	birch-clay	FD	20	16	43		*q*
236	6.63	52.25	....	lake	L	20	16	6		*q*
....	....	....	....	....	....	....	....	....		....
....	....	....	....	....	....	....	....	....		....
2543	2.63	52.05	....	lake	L	19	15	3		*x*
2544	5.05	53.95	....	oak-podz	FD	19	16	27		*y*
2545	8.43	52.15	....	oak-podz	FD	20	16	9		*z*

N.B.: The fields "Record number" and "national grid id" in the above example are created by the CCE.

In this example five national grid cells: *p*, *q*, *x*, *y* and *z*. are shown. Assume that the national grid cell resolution is 100 km^2. The cells *x*, *y* and *z* form 'the tail of the data base'.

Grid cell *p* is entirely assigned to Emep cell (19,15). It has only 23 km^2 of relevant ecosystem area; the rest of cell *p* is not registered as relevant receptor area.

- Grid cell *q* is divided over the four Emep cells (19,15), (19,16), (20,15) and (20,16). The total grid cell area of 100 km^2 is covered with relevant receptors, therefore the total of all Area_emep values for grid cell *q* will add to 100 km^2.

The ecosystem type 'birch-clay' (total area is 55 km^2) within the grid cell q is split up by two Emep cells into 2 separate areas. Each area must be registered in the data base as a separate record with a point coordinate assigned to it (see record numbers 234 and 235).

In Emep cell (20,16) the national grid cell q contributes with two types of relevant receptors: ecosystem type 'birch-clay' covers 43 km^2, and ecosystem type 'lake' covers 6 km^2.

- Grid cells x, y and z contain only one type of relevant receptor with areas that do not cover the whole national grid cell.

2) Polygons:
A data base that contains information about polygons will be the same as the example given above. The last column with the grid cell codes will not be used.

3) Points without incorporation of area coverage:
The CCE will use the equal area approach for all points assigned to the a EMEP grid cell when a National Focal Center does not include with the point coordinate the area coverage that each point represents. (Refer to Section 4 of the Guidelines).

The figure below illustrates how a data base is derived from the overlay of the EMEP grid with a national mapping resolution.

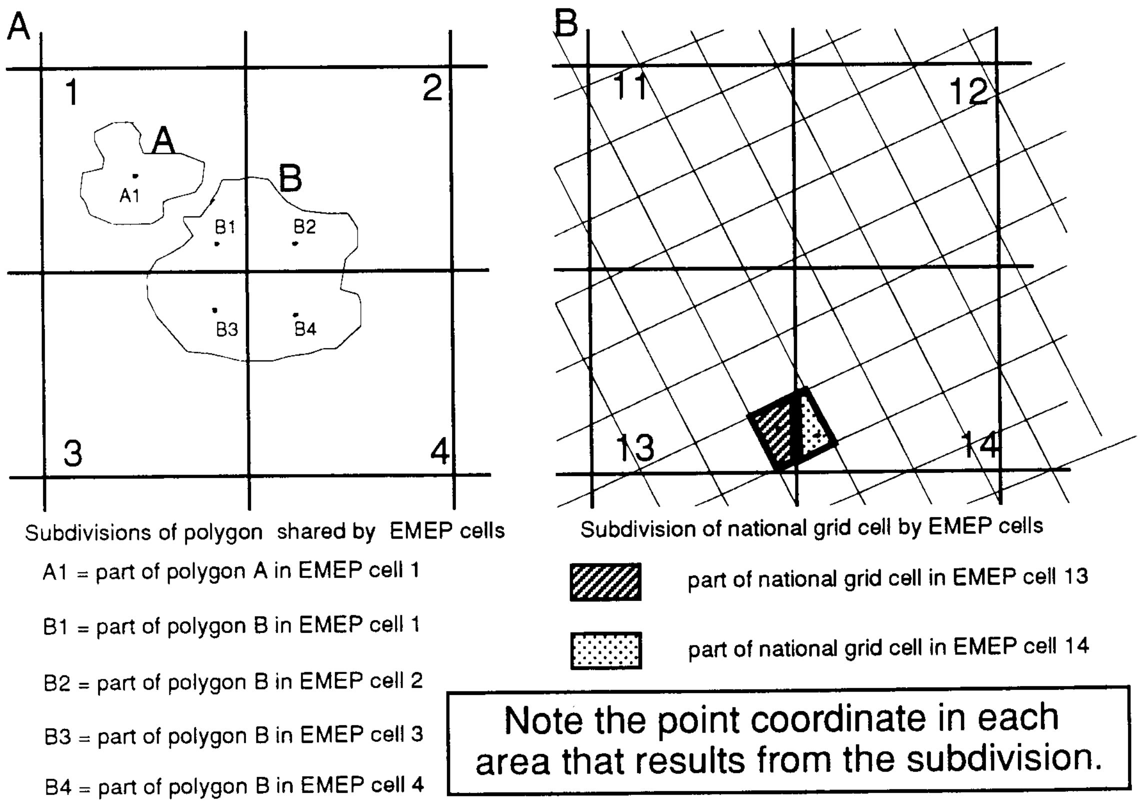


Figure A6.1. *Example of the contribution of (A) a polygon and (B) a national grid cell to the involved EMEP grid cells. Each area is assigned a separate point coordinate (longitude, latitude) as a locational identifier and is stored as a separate record in the data base.*

APPENDIX VII. European Background Data Bases Used in the Steady-State Mass Balance Maps of Critical Loads

This appendix provides an overview of the sources and specifications of the European background data used to produce the European steady-state mass balance maps of critical loads. These data have been used for countries for which no national contribution was provided to the CCE.

The background data have been collected by the Winand Staring Center, and made available to the Coordination Center. These data used are contained in two dBase-compatible data bases: **FOREST.DBF** and **SOIL.DBF**. Data have been produced on a grid of 1° longitude by 0.5° latitude. Paper or disk copies of data for all grid cells for individual countries are available from the Coordination Center.

The CCE produced updated critical loads maps for Europe and for each country, and distributed the maps and input data to all National Focal Centers in December 1992. For countries that submitted data, the critical loads maps in Chapter 2 are based on these national contributions. For other countries, the European background data were used.

NFC's were requested to review and comment on these maps, and to submit any available updated national data. These data have been used to produce the final maps in Chapter 2. (Table 5.1 summarizes the sources of input data used for each country.)

A number of general values are needed to calculate rates of nitrogen and base cation uptake in forests, including wood density, branch-to-stem ratio, and element content on N, Ca, Mg and K in stems and branches of coniferous and deciduous tree species. Data from de Vries *et al.* (1992) was used for countries which did not submit national data.

FOREST.DBF:
This database contains all data that are both grid- and forest-dependent; i.e. data on areal occurrence, uptake, deposition and runoff. Distinctions are made between coniferous (CON) and deciduous (DEC) forests, as well as between basic (B) and derived (D) data. A description of the data base with information on the sources is given in Table A7.1.

SOIL.DBF:
This file contains basic data that are both grid- and soil-dependent; i.e. the percentage of each FAO soil types in each grid, with its inherent characteristics (partly basic and partly derived). Furthermore, it contains derived data on the area of the various forest types on each soil type in each grid, based on an assignment procedure for combining forests and soils as described in de Vries *et al.* (1992). A description of the database with information on the sources is given in Table A7.2.

Table A7.1. *Structure of data base file FOREST.DBF*

Field Name	Description	Units	Type*	Source
Longitude-Latitude		degrees		
LONG	Longitudinal coordinate of south-west corner of grid cell.			
LAT	Latitudinal coordinate of south-west corner of grid cell.			
Areal statistics per grid		km^2	B	IIASA, based on information from aeronautic maps.
AGRID	Total area of the grid cell.			
ACON	Total area of coniferous forests per grid cell.			
ADEC	Total area of coniferous forests per grid cell.			
Growth of coniferous and deciduous forests		$m^3\ ha^{-1}\ yr^{-1}$	B	IIASA, based on information compiled by Nilsson and Sallnäs (1991).
GCON	Annual average growth rate of coniferous forests.			
GDEC	Annual average growth rate of deciduous forests.			
Nitrogen and base cation uptake		$eq\ ha^{-1}\ yr^{-1}$	D	Calculated from growth data and global data.
NUPCON	Rate of nitrogen uptake for coniferous forests.			
NUPDEC	Rate of nitrogen uptake for deciduous forests.			
BCUPCON	Rate of base cation uptake for coniferous forests.			
BCUPDEC	Rate of base cation uptake for deciduous forests.			
Nitrogen immobilization		$eq\ ha^{-1}\ yr^{-1}$	D	Derived from de Vries *et al.* (1992).
NICON	Critical nitrogen immobilization for coniferous forests.			
NIDEC	Critical nitrogen immobilization for deciduous forests.			
Total base cation deposition		$eq\ ha^{-1}\ yr^{-1}$	B	de Vries *et al.* (1992), based on EMEP wet base cation deposition data.
Hydrologic data per grid		$mm\ yr^{-1}$	B	IIASA
PRECIP	Annual average precipitation per grid cell.			
EVAPGRID	Annual average evapotranspiration per grid cell.			
Hydrologic data per forest type		$mm\ yr^{-1}$	D	de Vries *et al.* (1992).
EVAPCON	Annual average evapotranspiration for coniferous forests.			
EVAPDEC	Annual average evapotranspiration for deciduous forests.			
RUNOFFCON	Annual average runoff for coniferous forests.			
RUNOFFDEC	Annual average runoff for deciduous forests.			

* B = Basic data.
D = Derived data.

Table A7.2. *Structure of data base file SOIL.DBF*

Field Name	Description	Units	Type*	Source
Longitude-Latitude		degrees		
LONG	Longitudinal coordinate of south-west corner of grid cell.			
LAT	Latitudinal coordinate of south-west corner of grid cell.			
Soil type, number, slope and texture class		-	B	Description based on FAO soil map.
SOILTYPE SOILNUMBER SLOPECLAS TEXTCLAS	[Explanations on the derivation of these values can be found in the Mapping Vademecum, Appendix III.]			
Parent material and weathering rate class		-	D	Derived from soil type and texture class.
PARMATCLAS WRCLAS	[Explanations on the derivation of these values can be found in the Mapping Vademecum, Appendix III.]			
Weathering rate (for a depth of 0.5 meters)		eq ha^{-1} yr^{-1}	D	Derived according to procedures described in the Mapping Vademecum, Appendix III.
Percentage of each soil type in grid		%	B	IIASA, based on FAO soil map.
Soil slope class		-	-	Assignment procedure described in de Vries *et al.* (1992).
Percentage of forest types on each soil		%	D	Derived according to assignment type in grid procedure.
FPERCON	Percentage of coniferous forest on each soil type per grid cell.			
FPERDEC	Percentage of deciduous forest on each soil type per grid cell.			

* B = Basic data.
D = Derived data.