EC4MACS

Uncertainty Treatment

The CCE-EIA Ecosystems Impact Model

European Consortium for Modelling of Air Pollution and Climate Strategies - EC4MACS

Editors:
Jean-Paul Hettelingh, Maximilian Posch, Jaap Slootweg

Coordination Centre for Effects
at The Netherlands Environmental Assessment Agency
Bilthoven, The Netherlands.

March 2012

EC4MACS Report on Uncertainties

Uncertainties of critical loads and their exceedances

Coordination Centre for Effects

30 June 2010

Jean-Paul Hettelingh, Maximilian Posch, Jaap Slootweg
max.posch@pbl.nl

"… . But there are also unknown unknowns – the ones we don't know we don't know …"
(former Defense Secretary Donald Rumsfeld, 2002)

Introduction

This report summarises the work carried out by the Coordination Centre for Effects (CCE), often in collaboration with other (EC4MACS) partners, with respect to uncertainty assessments in the context of critical loads. This context consists of uncertainties inherent to the methods and data used to compute critical loads as well as uncertainties related to the calculation of critical load exceedances. Uncertainties of the latter are especially relevant for the analysis and comparison of environmental effects, on a European scale, of emission abatement scenarios in integrated assessment. The uncertainty of exceedances includes the variability of depositions and their source-emissions. More recently, the issue of uncertainty of effects of air pollution has been broadened to include also interactions with climate change.

Studies by – or with involvement of – the CCE on uncertainties

Inevitably, from the beginning of the use of critical loads in the support of emission reduction policies the question of uncertainties in critical load and their exceedance calculation has been raised; and almost as far back reaches the list of investigations in this field. In the following only work is described that was carried out by the CCE or work in which the CCE was involved as a partner. Beside that, there are numerous studies on a national or site-specific level that investigated different aspects of uncertainties in critical load assessments. For a literature review see Skeffington (2006).

In the 2nd Status Report of the CCE (Hettelingh et al. 1993) the first time uncertainties in critical loads of acidity have been addressed (Hettelingh and Jansen 1993). In the 4th CCE Status Report (Posch et al. 1997) a more extensive investigation into the values of critical loads as a function of the variability in input data, especially between different national submissions, has been reported. One of the conclusions is that base cation weathering (or rather the net base cation input) was responsible for explaining a large part of the variability in critical loads. In the 5th CCE Status Report (Posch et al. 1999) UK 'help-in-kind' with the aim, *inter alia*, 'to improve confidence in critical loads and exceedance maps' was reported by Hall et al. (1999). In the same Status Report a study on the issue of the influence of local variability in deposition on critical load exceedances was reported (Kåresen and Hirst 1999), which was further elaborated and published in Hirst et al. (2000). A short summary on data reliability in the context of European critical loads can be found in Hettelingh et al. (2001).

The most intensive work on uncertainties in critical loads, especially their use in integrated assessment modelling was carried out in the period 2000/2001, both at the CCE and IIASA. In the 6th CCE Status Report (Posch et al. 2001) an extensive investigation into the uncertainty of ecosystem protection (quantified by critical loads and their exceedances) in the framework of integrated assessment modelling is documented (Suutari et al. 2001a). A minor – but relevant – example of the findings is that the uncertainty in the distribution (CDF) of critical loads in a grid cell (or any other region) is generally (much) smaller than the uncertainties in the individual critical loads in that cell. As a price, the information on the exact locations of those critical loads is lost, but this does not matter in the IAM context, since a single deposition is used for the entire grid cell (see Appendix A). The same methodology was applied in a case study for Finland (Syri et al. 2000)

The influence of climate change on critical loads has also been investigated since more than 10 years. The CCE was a partner in the EU AIR-CLIM project, carried out during the period 1998–2001, probably the first project linking in an integrated way the interactions between air pollution and climate change (Alcamo et al. 2002). During that project also the influence of a changing climate on critical loads has been investigated (Posch 2002). More recently, the influence of climate change on the recovery of forests on a European scale has been investigated with the aid of dynamic models (Reinds et al. 2009).

The work by Suutari et al. (2001a) was extended and incorporated into a comprehensive study carried out at IIASA, looking at the uncertainties in the whole chain from economic activities to ecosystem protection (Suutari et al. 2001b). The methodology developed during that study allows ascribing numerical uncertainties in ecosystem protection, if all individual uncertainties in activity factors, emission calculations, deposition and critical loads can be specified.

In a UNECE workshop on uncertainty management in integrated assessment modelling held in 2002 the practicalities/problems of using uncertainty information in policy advice were discussed. One of the (many) conclusions was that "*policy makers, in contrast to scientists, are not interested in the detailed statistics about uncertainties. They are interested in robust strategies. Robustness implies that strategies (control needs and priorities between countries, sectors, pollutants) do not significantly change due to changes in the uncertain model elements. Robust strategies should avoid regret investments (no-regret approach) and/or the risk of serious damage (precautionary approach).*" For details see the Annex of UNECE (2002).

Assessing robustness of baseline scenarios

In the following we assess the robustness on critical load exceedances due to depositions calculated from recently made available emission baseline scenarios listed in Table 1. Also listed are the total European emissions converted to Geq a^{-1}, since this are the units which ecosystems 'experience'. As can be seen, total nitrogen (N) emissions exceed total sulphur (S) emissions already in 2000, whereas in 2030 and under the MFR scenario ammonia emissions alone are comparable to or greater than total S emissions.

Table 1: Baseline emission scenarios made available by CIAM/IIASA in June 2010. The last 3 columns give the total European **emissions in Geq a^{-1}** of the respective scenario and pollutant.

Scenario	Short name	Year	SO2	NOx	NH3
NAT09_Cur_Pol_v2_2000[a]	NAT09-2000	2000	700.77	468.08	374.05
NAT09_Cur_Pol_v2_2020[a]	NAT09-2020	2020	446.28	327.88	362.79
PRIMES_BL2009_current_2020[b]	PRI09-2020	2020	437.57	319.52	358.17
PRIMES_BL2009_current_2030[b]	PRI09-2030	2030	368.10	307.70	362.64
CENTRAL_MFR[c]	MFR-2020	2020	207.56	170.42	220.80

[a]Based on national emission estimates; [b]Based on PRIMES model results; [c]Maximum technically feasible reductions (not really a baseline scenario).

1. Influence of 2020 baseline scenarios on CL exceedances

From the emission scenarios given in Table 1 deposition fields have been calculated with the linearised EMEP/MSC-W eulerian dispersion model, using transfer matrices for a 5-year average meteorology. These deposition fields, which comprise grid-average deposition as well as deposition onto forests and (semi-)natural ecosystems for every EMEP50 grid cell, have been used for exceedances calculations. Since there are 2 baseline scenarios given for the year 2020, it is of interest to evaluate how much their differences influence the exceedances of critical loads for that year. A summary of the area exceeded and the magnitude of the exceedance (calculated as average accumulated exceedance or AAE) in the EU27 is given in Table 2.

Table 2: Ecosystem area exceeded and CL exceedance (AAE) in the EU27 in the year 2020 for the 2 baseline scenarios (see Table 1). The last row gives the sensitivity-index (SI) calculated with eq.1.

Scenario	Nutrient N Critical Loads		Acidity Critical Loads	
	Ecoarea (%)	AAE (eq ha^{-1} a^{-1})	Ecoarea (%)	AAE (eq ha^{-1} a^{-1})
NAT09-2020	61.12	179.05	6.74	23.07
PRI09-2020	58.87	170.40	6.14	20.25
SI	1.96	2.57	4.67	6.41

Table 2 shows that the percentages of the areas where the critical loads are exceeded (columns 2 and 4) under NAT09-2020 are not much higher than under PRI09-2020, i.e. by about 2 and 0.6 % for nutrient and acidifying effects, respectively. The magnitude of the exceedances (columns 3 and 5), confirms the slightly higher risk of effects under the NAT09-2020. Obviously, relative differences of the magnitudes of exceedances of the critical loads of acidity are greater since the values are closer to zero than those of the critical loads of nutrient-N. It is likely, that differences for individual countries will vary within a wider range of exceedance magnitudes than for the whole of Europe. One (additional) reason is that low (or zero) exceedances occur in large part of European natural areas (Russia, northern and southern European countries), thus drowning the differences in high deposition areas.

The small differences in these results hide the *sensitivity* of the model chain to obtain them. This sensitivity can be assessed with the aid of the following ***sensitivity index*** (SI):

$$(1) \qquad SI = \frac{|E_1 - E_2|}{E_1} \Big/ \frac{|f(E_1) - f(E_2)|}{f(E_1)}$$

where E_i is the driving variable(s) (here: European emissions) and f is the model (here the dispersion-critical load-exceedance model chain). The sensitivity index simple relates the relative change in the driver to the relative change in the outcome; $SI = 1$ means that a relative change in the drivers of, say, p results in the same relative change in the output (Note: the SI is independent of units used). If $SI < 1$, the sensitivity is small; and for $SI > 1$ the relative change in the result will be greater than the relative change in the drivers.

The sensitivity index for the 2 competing 2020 baseline scenarios was computed with the total N emissions (see Table 1) as a driver for the nutrient N CL-exceedances, and with the total S+N emissions for acidity CL-exceedances (that's why emissions in Table 1 are given in eq). The resulting *SI*'s are shown in Table 2 – and the result is surprising: in all 4 cases is the exceedance (very) sensitive to changes in emissions, the AAE more so than the ecosystem area exceeded. Of course, several caveats apply; e.g. when approaching zero (is in the case of acidification), relative changes become large. Nevertheless, these results indicate that effort should be put into narrowing the differences in emission estimates for the same year, especially since the sensitivities might be (much) greater in individual countries.

The spatial distribution of the two scenario exceedances is illustrated in Figure 1. These 2 pairs of maps don't show much difference. Maps, however, can be deceiving (see, e.g., Monmonier 1996) since the choice of intervals for the displayed data ranges will hide (some) differences.

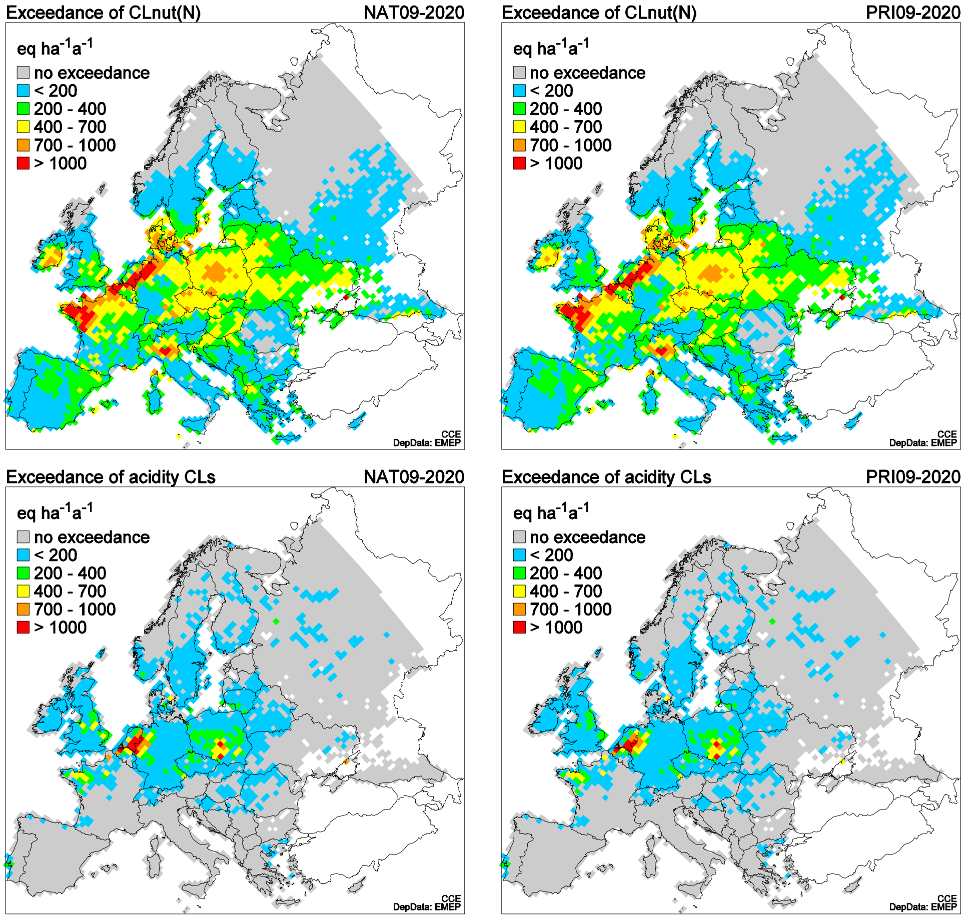

Figure 1: Exceedance of the critical loads of nutrient N (top) and acidity (bottom) in 2020 for the two baseline scenarios (left: NAT09, right: PRIMES09).

2. Likelihood of exceedance (ensemble assessment)

In Hettelingh et al. (2007) an approach to assess the likelihood of exceedances has been introduced, based on the methodology of the IPCC (2005). Using this approach, the areas exceeded by the modelled (*CLnutN*) and empirical (*CLempN*) critical loads for nutrient nitrogen (N) in every EMEP grid cell are combined. For the baseline scenarios (see Table 1) this yields the maps in Fig. 2. The maps show the likelihoods of exceedances of critical loads of nitrogen for the year 2000 (top left; *NAT09*), for maximum of feasible reductions (MFR) in 2020 (top right; *MFR*). These are the extremes currently available: the historic situation for 2000 and the maximum technically feasible reductions in 2020. The centre maps show results for the two baseline scenarios for 2020: using national data (left; *NAT09*) and using PRIMES output (right; *PRI09*). These maps confirm the conclusions from Table 2 that the likelihood of exceedance of nutrient N critical loads for the two different baseline scenarios for 2020 do not give very different results (centre maps), and that this likelihood is decreasing (i.e. less red shaded areas) in many regions in comparison to 2000 (top left). The bottom map shows results with PRIMES output for the year 2030 (*PRI09*); they do not differ much from those for 2020.

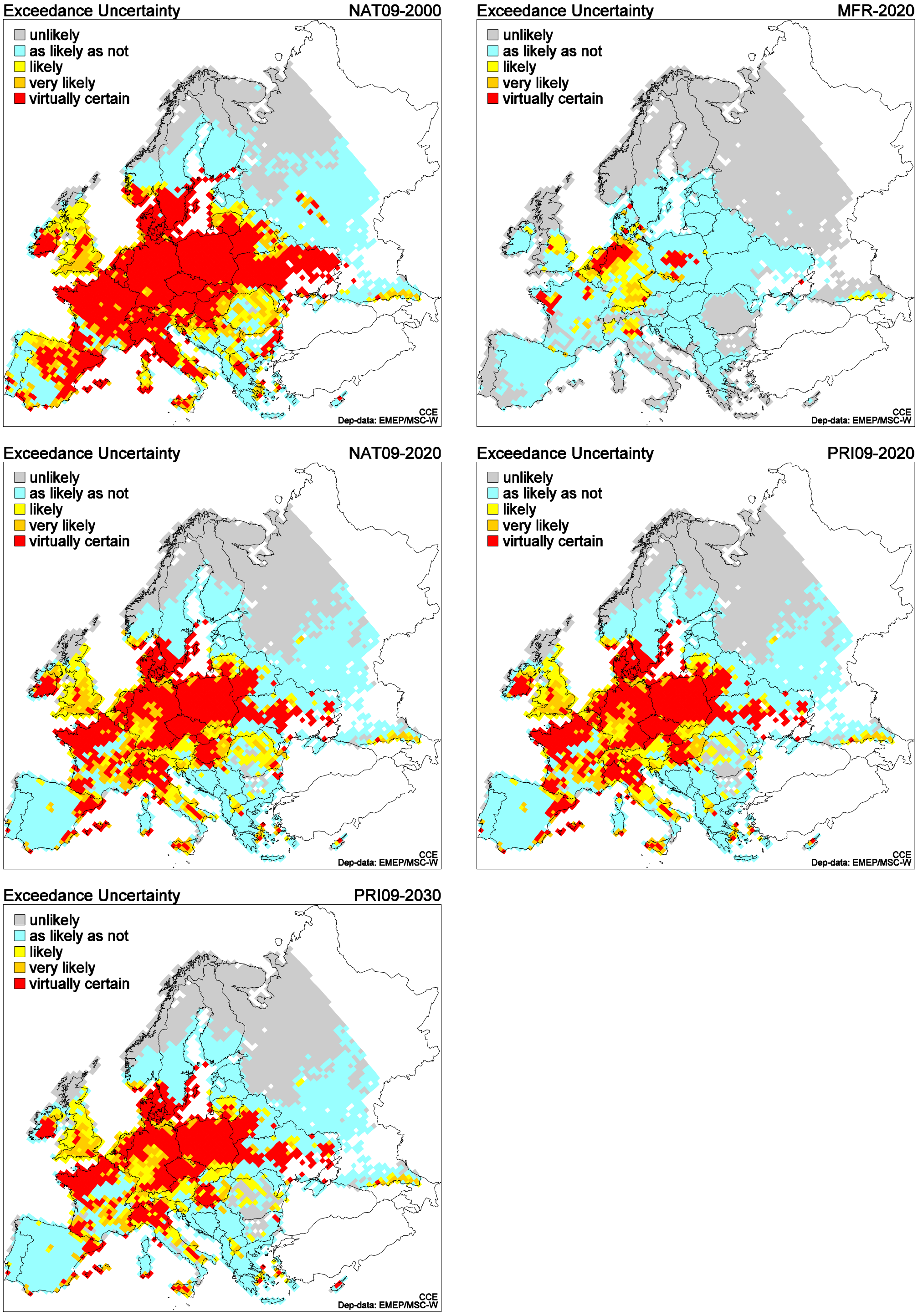

Figure 2: Likelihood of exceedances of critical loads of nitrogen for the year 2000 (top left), for maximum technically feasible reductions (MFR) in 2020 (top right); the two baseline scenarios for 2020 (centre): using national data (left) and using PRIMES output (right); and with PRIMES output for the year 2030 (bottom).

3. Influence of deposition correlations on CL exceedances

Deposition calculations are carried out with the unified eulerian dispersion model of EMEP/MSC-W only for a few selected scenarios. Routine calculations of critical load exceedances (and other impact indicators within the GAINS model) are performed with depositions generated with a linearised version of the unified model, so-called transfer matrices (see, e.g., Posch et al. 2005). In contrast to the transfer matrices from the 1990s (lagrangian EMEP model), from the unified model also transfer matrices for the correlation between pollutants are available, i.e. the interaction between, e.g., ammonium and sulphate in the atmosphere, can be taken into account. And in routine exceedance calculations at the CCE the correlations between pollutants are always included. Since this is not the case everywhere – neglecting the correlative matrices saves matrix storage and multiplications – we investigate here in the influence of neglecting the correlations on critical load exceedances. Mapping the exceedances for the NAT09-2020 scenario indicates that the differences are not big (Fig. 3).

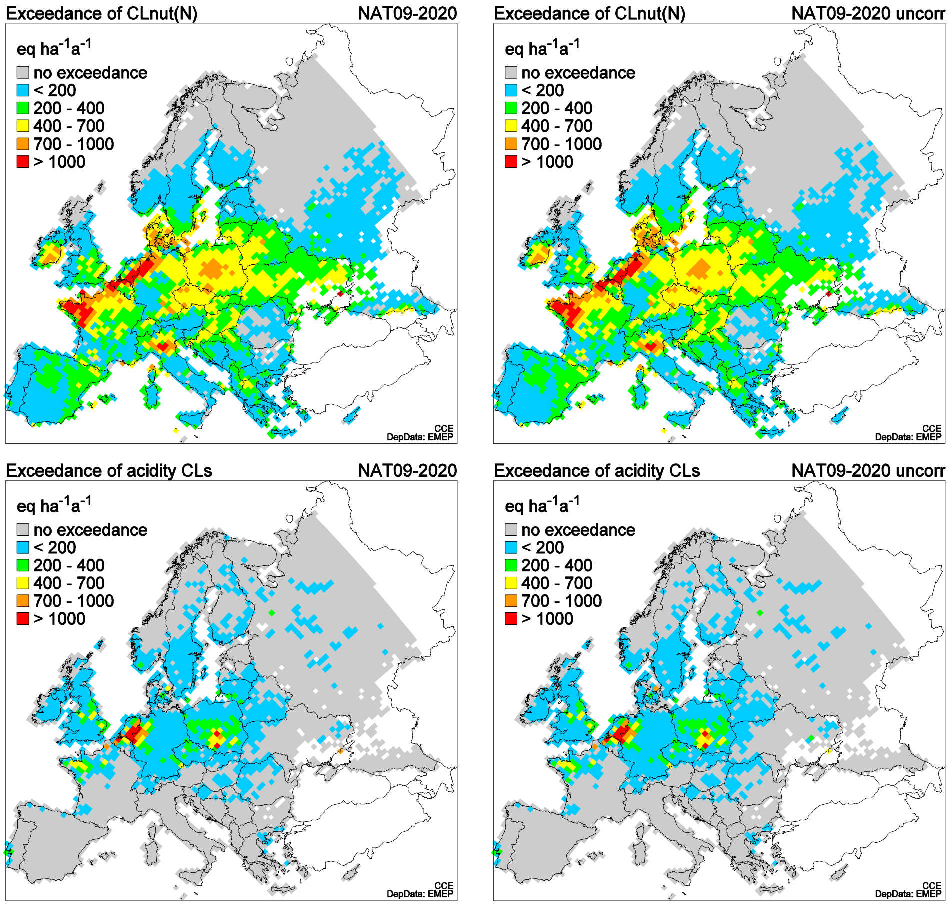

Figure 3: Exceedance of the critical loads of nutrient N (top) and acidity CLs (bottom) for the NAT09-2020 scenario using correlated depositions (standard case; left) and uncorrelated depositions (right).

Since it is difficult to infer quantitative results from maps, we show in Table 3 the percent exceeded area and average accumulated exceedance (AAE) in the EU27 for the five baseline scenarios for correlated and uncorrelated depositions.

Table 3: Ecosystem area exceeded and AAE of nutrient N and acidity CLs in the EU27 for the 5 scenarios (see Table 1) computed with depositions including the correlations between the pollutants (standard case) and using uncorrelated depositions.

Scenario	Exarea (%)		AAE (eq ha^{-1} a^{-1})	
	correlated dep.	uncorrelated dep.	correlated dep.	uncorrelated dep.
	Critical Loads of nutrient N			
NAT09-2000	74.22	74.00	333.38	333.51
NAT09-2020	61.12	60.84	179.05	177.57
PRI09-2020	58.87	58.79	170.40	169.86
PRI09-2030	55.41	55.85	149.82	151.13
MFR-2020	23.86	24.31	34.61	36.33
	Critical Loads of acidity			
NAT09-2000	18.72	19.69	107.87	127.91
NAT09-2020	6.74	6.69	23.07	23.02
PRI09-2020	6.14	6.12	20.25	19.78
PRI09-2030	5.27	5.26	16.12	15.87
MFR-2020	1.98	2.03	4.05	4.20

The Table shows that, indeed, differences are not big, at least when looking at the large area of the EU27. For individual countries the differences will be larger in many cases; and this should be investigated further, e.g., by calculating the sensitivity index (eq.1), using total depositions to ecosystem areas as 'driver'. Although not a real bias – using the uncorrelated deposition gives both higher and lower values, depending on the scenario – the interaction between pollutants should be considered in any assessment, since it is a reality and a simple description is available.

Concluding remarks

Over the last decade the emphasis in police-related uncertainty analysis has shifted from the detailed mathematical modelling and reporting of sensitivities and uncertainties to the assessment of biases and robustness. No biases in the calculation of critical loads are known at the present; if they were known for longer time they would have been already remedied. A distinction has also to be made between the numbers (ecosystem properties) entering a critical load calculation and the critical limit chosen: critical loads for very similar sites may differ, since the choice of the target to be protected (e.g., damage to tree fine roots versus ground vegetation species loss) determines the critical load. Investigations have shown that the most uncertain parameters are the net base cation input (weathering) and the long-term immobilisation of N (which is not measurable, and difficult to assess). Also the determination of both computed and empirical critical loads for the same sites allows assessing the robustness of exceedance estimates, a procedure recommended for routine use.

For policy advice it is the exceedance of critical loads which is of importance. And this is also determined by the uncertainties in the emission estimates and those in the atmospheric dispersion modelling. While the uncertainties of the whole chain has been investigated earlier (Suutari et al. 2001b), we here looked at the influence of (a) the existence of two different emission estimates (baseline scenarios) for 2020 and (b) the exclusion of correlation in the dispersion of pollutants. In both cases the influence is not big, but discernible; and most likely (much) larger when examining it for individual (small) countries. Also, restricting the assessment to comparing scenarios (as opposed to looking at absolute values) will reduce uncertainties.

The issue of climate change has not only re-focussed and delayed policy making in the field pollution abatement, but also has influences emissions, atmospheric dispersions and (the exceedance of) critical loads. Over the last decade the influence of climate change on critical loads has been studied different levels of sophistication, and it remains an issue that will stay centre stage – but this should not be used as an excuse for inaction.

References

Alcamo J, Mayerhofer P, Guardans R, Van Harmelen T, Van Minnen J, Onigkeit J, Posch M, De Vries B, 2002. An integrated assessment of regional air pollution and climate change in Europe: Findings of the AIR-CLIM project. *Environmental Science & Policy* 5(4): 257-272

Barkman A, 1998. Critical loads – Assessment of uncertainty. Reports in Ecology and Environmental Engineering 1:1998, Department of Chemical Engineering II, Lund University, Lund, Sweden

Downing RJ, Hettelingh J-P, De Smet PAM (eds), 1993. Calculation and Mapping of Critical Loads in Europe: Status Report 1993. RIVM Report 259101003, Coordination Centre for Effects, Bilthoven, Netherlands, www.rivm.nl/cce

Hall J, Cooper J, Hornung M, Morton D, Reynolds B, Ullyett J, Warr T, 1999. UK help-in-kind to the Mapping Programme. In: M Posch et al., *op. cit.*, pp 35-44

Hettelingh J-P, Janssen P, 1993. Preliminary uncertainty and sensitivity analysis of computed critical deposition of acidity in Europe. In: RJ Downing et al., *op. cit.*, pp 51-55

Hettelingh J-P, Posch M, 1997. An analysis of critical load and input data variability. In: M Posch et al., *op. cit.*, pp 29-39

Hettelingh J-P, Posch M, De Smet PAM, 2001. Multi-effect critical loads used in multi-pollutant reduction agreements in Europe. *Water, Air and Soil Pollution* 130: 1133-1138

Hettelingh J-P, Posch M, Slootweg J, 2007. Tentatively exploring the likelihood of exceedances: Ensemble Assessment of Impacts (EAI). In: J Slootweg et al., *op. cit.*, pp 53-58

Hirst D, Kåresen K, Høst G, Posch M, 2000. Estimating the exceedance of critical loads in Europe by considering local variability in deposition. *Atmospheric Environment* 34: 3789-3800

IPCC, 2005. Guidance Notes for lead authors of the IPCC fourth assessment report on addressing uncertainties, http://ipcc-wg1.ucar.edu/wg1/Report/AR4_UncertaintyGuidanceNote.pdf

Kåresen K, Hirst D, 1999. Estimating the exceedance of critical loads by accounting for local variability in deposition. In: M Posch et al., *op. cit.*, pp 45-51

Monmonier M, 1996. *How to Lie with Maps.* 2nd edition, University of Chicago Press, 207 pp

Posch M, Hettelingh J-P, De Smet PAM, Downing RJ (eds), 1997. Calculation and mapping of critical thresholds in Europe: Status Report 1997. RIVM Report 259101007, Coordination Centre for Effects, Bilthoven, Netherlands, iv+163 pp www.rivm.nl/cce

Posch M, De Smet PAM, Hettelingh J-P, Downing RJ (eds), 1999. Calculation and mapping of critical thresholds in Europe: Status Report 1999. RIVM Report 259101009, Coordination Centre for Effects, Bilthoven, Netherlands, iv+165 pp www.rivm.nl/cce

Posch M, De Smet PAM, Hettelingh J-P, Downing RJ (eds), 2001. Modelling and mapping of critical thresholds in Europe: Status Report 2001. RIVM Report 259101010, Coordination Centre for Effects, Bilthoven, Netherlands, iv+188 pp www.rivm.nl/cce

Posch M, 2002. Impacts of climate change on critical loads and their exceedances in Europe. *Environmental Science & Policy* 5(4): 307-317

Posch M, Slootweg J, Hettelingh J-P (eds), 2005. European critical loads and dynamic modelling: CCE Status Report 2005. MNP Report 259101016, Coordination Centre for Effects, Bilthoven, Netherlands, 171 pp www.rivm.nl/cce

Posch M, Hettelingh J-P, Heyes C, 2005. Use of critical loads in integrated assessment modelling. In: M Posch et al., *op. cit.*, pp 71-76

Reinds GJ, Posch M, Leemans R, 2009. Modelling recovery from soil acidification in European forests under climate change. *Science of the Total Environment* 407: 5663-5673

Skeffington RA, 2006. Quantifying uncertainty in critical loads: (A) Literature review. *Water, Air and Soil Pollution* 169: 3-24

Slootweg J, Posch M, Hettelingh J-P (eds), 2007. Critical loads of nitrogen and dynamic modelling: CCE Progress Report 2007. MNP Report 500090001, Coordination Centre for Effects, Bilthoven, Netherlands, 201 pp www.rivm.nl/cce

Suutari R, Schöpp W, Posch M, 2001a. Uncertainty analysis of ecosystem protection in the framework of integrated assessment. In: M Posch et al., *op. cit.*, pp 55-62

Suutari R, Amann M, Cofala J, Klimont Z, Posch M, Schöpp W, 2001b. From economic activities to ecosystem protection in Europe – An uncertainty analysis of two scenarios of the RAINS integrated assessment model. CIAM/CCE Report 1/2001, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, iv+57 pp www.iiasa.ac.at/~rains

Syri S, Suutari R, Posch M, 2000. From emissions in Europe to critical load exceedances in Finland - Uncertainty analysis of acidification integrated assessment. *Environmental Science & Policy* 3: 263-276

UNECE 2002. Integrated Assessment Modelling. Document EB.AIR/GE.1/2002/5 & EB.AIR/WG.5/2002/1, UN Economic Commission for Europe, Geneva

Appendix A: Uncertainty reduction when aggregating to a CDF

It is often assumed that the uncertainty in the protection percentage in a grid cell is identical to the uncertainty in the critical load function. This is a gross oversimplification, and in the following we shall demonstrate why the properly derived uncertainty in the protection level will in general be smaller.

In Fig.Aa an example of a cumulative distribution (CDF) of critical loads (CLs) within a grid cell is shown. Also shown are their *individual uncertainty ranges* (e.g., ± one standard deviation). For Fig.Ab, we obtain the *uncertainty range of the CDF* by randomly drawing a value from every individual CL range, sorting them and thus create a new CDF. This is repeated many (several thousand) times. From the many random CDFs the mean and range (standard deviation) is calculated for every value (smallest, second smallest, …, largest) and these define the uncertainty range of the CDF. Fig.Ab was created in that way from the data in Fig.Aa, assuming that the values are independently and uniformly distributed around their respective mean (± 25%). As can be seen, for most parts of the CDF the uncertainties are reduced considerably by this aggregation process, a phenomenon also observed in Barkman (1998).

One has to bear in mind that the data in Fig.Ab do *not* represent individual CLs, but rather the means and uncertainty ranges of the different percentiles of the CDF in Fig.Aa. Any intra-grid spatial information is lost, but this does not matter for our applications, since we compare the CDF to a single (average) deposition value for the grid. In the example shown in Fig.A we assumed statistical independence between the different CLs. With an increasing correlation, the uncertainty bands would become wider, and complete correlation would leave the uncertainty ranges unchanged (i.e. Fig.Ab would be identical to Fig.Aa). The reduction of the uncertainty ranges depends also on the degree of overlap between the individual uncertainty ranges. If there were no overlap, there would be no narrowing of the uncertainty band, since the order of the randomly varied CLs would never change (as is the case for some points of the CDF in Fig.Aa).

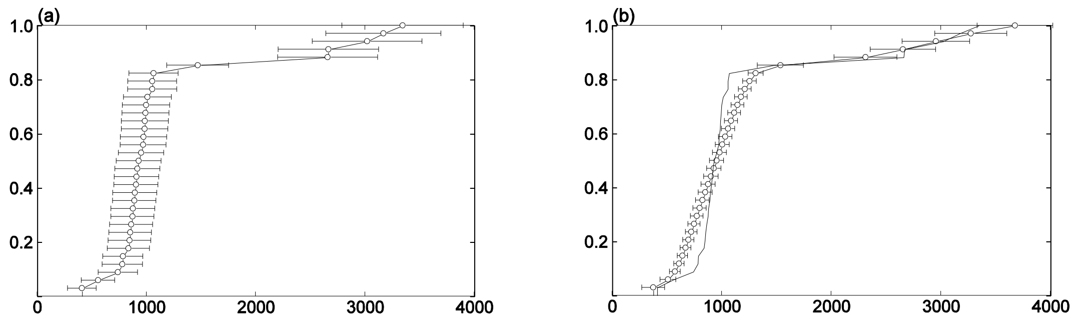

Figure A. (a) Examples of critical load (CL) values (white circles) displayed as cumulative distribution function (CDF). The horizontal interval at every CL value indicates its uncertainty range. The thin line connecting the CL values is a guide for the eye (and the usual way to plot a CDF). (b) CDF of the mean values of the smallest, 2nd smallest, …, largest values of every realisation of randomly and independently selected values from (a), together with their (generally smaller) uncertainty ranges (the thin line shows the CDF from (a)).