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Global assessment of acidification and eutrophication of natural ecosystems

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Abstract

In this study a global assessment has been made of the present and possible future acidification and eutrophication risks of natural and semi-natural terrestrial ecosystems, and riverine nitrogen transport to estuaries, coastal seas and continental shelves. The major objectives were to delineate areas potentially affected by deposition of nitrogen and sulphur compounds, to estimate the severity of acidification and eutrophication problems, and to identify research and data gaps. The results indicate that the critical loads for acidification and eutrophication are exceeded in 6-15% and 7-18% of the global area of natural and semi-natural ecosystems, respectively. Currently, most serious risks are found in the heavily industrialised regions of eastern USA, Europe and the Former Soviet Union, but risks were also found for parts of South America, large parts of Asia and parts of Western, Eastern and Southern Africa. Scenario analysis shows that both acidification and eutrophication risks could significantly increase in the second group of regions.

Preface

This study, carried out in the framework of UNEP's Second Global Environment Assessment as part of RIVM project 402001 has a twofold objective: the first is to assess the present and possible future risks of acidification and eutrophication of terrestrial natural and semi-natural ecosystems, as well as nitrogen loading of rivers and estuaries; the second is to identify research gaps and data and to give recommendations for future research.

The results of this assessment should be regarded as indicative in view of the global scale of the assessment and the existing knowledge gaps on the potential effects of S and N inputs on ecosystems.

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The designations employed for countries and global regions and their presentations are based on the classification used in RIVM's global assessment models, and do not imply the expressions of any opinion concerning the legal status of any country, territory, city or area or its authority, or concerning the delimitation of its frontiers or boundaries. Similarly, the designations "developed" and "developing" countries are intended for statistical convenience, and do not express an opinion about the stage reached by a particular country, territory or area in the development process.

Contents

Abbreviations

CRP	Current Reduction Plans Scenario
DIN	Dissolved Inorganic Nitrogen
DMS	Dimethyl sulphide
GEO	Global Environment Outlook
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (= NO + NO_2)
NO_3^-	Nitrate
pH	Measure of acidity
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
RIVM	National Institute of Public Health and the Environment
S	Sulphur
SO_2	Sulphur dioxide
Tg	teragram; 1 Tg = 10^{12}g
UNEP	United Nations Environment Programme

Summary

Assessment method and scenario employed
Large-scale acidification and eutrophication caused by human activities increasing the inputs of nitrogen (N) and sulphur (S) compounds into the earth's atmosphere and hydrosphere have been identified as important environmental problems in North America and Europe about 30 years ago. Recently, acidification and eutrophication caused by sharply increasing emissions of S and N compounds have also been recognised as potential threats to ecosystems in other parts of the world.

This study assessed the present and possible future acidification, and eutrophication, of natural and semi-natural terrestrial ecosystems, and riverine nitrogen transport to estuaries, coastal seas and continental shelves. The major aims were to delineate areas potentially affected by S and N deposition, to estimate the severity of acidification and eutrophication problems, and to identify research and data gaps.

In this assessment, global deposition fields were combined with sensitivity maps on the basis of soil, ecosystem and climate data, and soil dust deposition. Considering the existing uncertainties, results should be regarded as indicative. We assessed the uncertainty by using three sets of sensitivity classes for both acidification and eutrophication. This gives some indication of the uncertainties involved, but does not represent a full uncertainty analysis. Uncertainties in critical loads and those in deposition estimates are likely to be of the same magnitude.

The most important antropogenic sources of S emissions are fossil fuel burning and industrial sources. The most important antropogenic sources of N emissions are industry, fossil fuel burning, transport and agriculture. The "Current Reduction Plans" emissions scenario (CRP) used in this study assumes that *global* anthropogenic emissions of sulphur dioxide (+3%), nitrogen oxides (+13%) and ammonia (+19%) will increase in the 1990-2015 period. The CRP scenario can be considered as a moderate-growth scenario. In Europe and North America, however, emissions are assumed to decline, following existing reduction plans in these regions.

Current and future acidification and eutrophication risks
The results of this study indicate that the regions where acidification is most severe, currently occur in Europe and North America. However, the results also indicate that critical loads for acidification are currently exceeded in South America, Asia and Africa. In total, about 6-15% of the world's terrestrial (semi-)natural ecosystems may be negatively affected by acid deposition. Compared to previous studies considering S deposition only, the current studies finds acidification risks to occur also in some areas further away from highly industrialised areas.

Analysis of risks using the CRP scenario shows that acidification risks will increase significantly outside Europe and North America, both with respect to the area affected and the severity of exceedance of critical loads, particularly in China. In the relative short time period covered (15-20 years) the problem of acidifcation could become more wide-spread and in some regions more intense.

(Semi-)natural Ecosystems exposed to acidification and eutrophication risks

Region	% of (semi-)natural ecosystems area with exceedance ratio[a] >1.0				Ecosystem most affected
	Acidification		Eutrophication		
Canada	14	(10-20)	5	(2-17)	Temperate forest
USA	24	(23-26)	21	(18-25)	Temperate forest
South America	12	(5-29)	12	(7-21)	Tropical seasonal and dry forest, savannahs
Western Africa	12	(7-20)	16	(13-27)	Savannahs
Eastern Africa	3	(2-5)	8	(6-15)	Savannahs
Southern Africa	5	(2-14)	4	(2-11)	Savannahs
OECD Europe	35	(25-45)	32	(20-45)	Temperate forests
Eastern Europe	47	(39-63)	61	(44-77)	Temperate forests
Former USSR	5	(2-8)	9	(3-21)	Tundra and taiga ecosystems
South Asia	6	(3-8)	32	(24-38)	Tropical forests
East Asia	15	(13-17)	19	(15-25)	Tropical forests
South East Asia	21	(9-36)	12	(6-22)	Tropical rainforests
Japan	11	(4-15)	6	(3-9)	Temperate forests
World	10	(6-15)	11	(7-18)	

[a] Exceedance ratio = deposition : critical load. The results for acidification and eutrophication are presented as the percentage of the area of (semi-)natural ecosystems where the exceedance ratio > 1.0. The first number is the percentage for the medium estimate of the critical load; the results for the low and high critical load estimates are in parentheses.

For eutrophication, in 7-18% of the area of natural and semi-natural ecosystems the deposition exceeds the critical load for eutrophication. The results suggest that, apart from the heavily industrialised regions, a number of regions with low population densities, such as in South America and Africa, and remote regions in Canada and the former USSR, may already be or become affected by N eutrophication.

For aquatic ecosystems we assessed the most important sources of riverine dissolved inorganic nitrogen (DIN), which include fertiliser use (56%), human sewage (24%) and deposition (18%). Highest riverine nitrogen transport rates are found in OECD Europe, Eastern Europe and South and East Asia, largely reflecting the distribution of agricultural production intensity and human population.

In many regions eutrophication and acidification occur simultaneously. However, regionally, there are important differences. Generally, acidification is concentrated in industrialised areas, while eutrophication occurs close to regions with intensive agricultural production causing large emissions and deposition of N. Where acidification and eutrophication occur simultaneously, their combined effect may create significant stress in (semi-)natural ecosystems.

Uncertainties and research recommendations

Uncertainties in our assessment and recommendations for future research related to emission and deposition estimates, and critical loads, are summarised in the table below. All these uncertainties aside, the global critical loads map and the exceedance of critical loads for acidification of terrestrial ecosystems show patterns similar to those of regional (more detailed) maps.

The current results can be interpreted as an indication of the geographic distribution of regions where acidification and eutrophication of ecosystems are potential problems.

Major uncertainties and recommendations for future global assessments of acidification and eutrophication

	Major uncertainties	*Potential issues for future global studies*
Emissions of NH_3 and NO_x	Lack of measurement data; scarcity of data on agricultural management; scarcity of information on spatial and temporal distribution of fluxes within countries	As in the near future, no data will be available to improve currently available emission inventories; one approach is to validate emission fields where possible,using forward and inverse atmospheric chemistry transport models
Deposition fluxes	Low resolution of deposition fields,which are used in combination with a high resolution vegetation database; errors in emission fields (see above) and chemistry transport models; major uncertainties regarding base cation deposition.	Three alternatives approaches may be used: (i) use of source receptor matrices on a 1^0 grid for (sub)-continental calculations; (ii) refine the chemistry transport model to 1^0x1^0 resolution by accounting for sub-grid effects; (iii) Simple source-receptor matrix to be used in combination with country data on emissions.
Critical loads for acidifi-cation	Soil buffering capacity is based on properties of representative soil profile data; in some regions the soils data is limited, so that global mean data were used.	Field research with different realistic doses of acidity added to different soil types and vegetation types should be developed, including direct effects of atmospheric pollution on plants.
Soil and vegetation processes	Growth of plants affects proton release through cation and anion exchange and leaching. This process, which may account for a considerable portion of acidification, has not been taken into account	Models describing acidity release in ecosystems through plant growth and decomposition.
Cricical loads for eutro-phication	Eutrophication effects of enhanced N deposition in permafrost, arctic, tundra and taiga systems, high-altitude forests, calcareous soils, Mediterranean ecosystems, tropical ecosystems, mainly tropical forests, savannas and deserts, coastal (shallow) seas and alpine lakes.	Field research, and consultation of experts world-wide.
Riverine N transport	Use of country averaged data (see emissions) and non-robust regression equations for extrapolation; no data on run-off to calculate concentrations of total N (not only DIN as in this study), needed to assess eutrophication.	Concentrations of total N in riverine systems should be determined by calculating river total N loading and river discharge on the basis of precipitation surplus, runoff and flow to the groundwater. To allow for a complete assessment of eutrophication, P concentrations should also be considered.
General	Uncertainty resulting from omission of acidifying effects of N and S, which may interact with eutrophication and climate change in certain regions.	Eutrophication coupled with acidification, rising atmospheric CO_2 concentration and climate change should be considered.

Regional studies could be considered for those areas identified as potential risk areas, such as parts of South America, Western and Southern Africa and parts of Siberia. Such studies might, in particular, look into the issues identified in the table below – and can be used to check the more course results presented here. It should be noted that potential responses also need to be identified at a regional level.

Finally, the current study indicates that acidification and eutrophication risks are more wide-spread than the well-known areas of Western and Eastern Europe, Eastern USA and South-East Asia. These risks could even increase, following expected increases in emissions from agriculture (growing volume and use of fertilisers), transport and fossil fuel combustion. Including assessments of these risks within the context of (global) integrated assessment could provide useful information for environmental management, certainly when considering the combined impacts of acidification, eutrophication and climate change.

1. Introduction

1.1. Scope of the study

Industrial, agricultural and other anthropogenic activities have greatly modified the global biogeochemical cycles of nitrogen (N) and sulphur (S). Vitousek *et al.* (1997) indicated that humans have doubled the natural rate of N fixation, and atmospheric N deposition rates have increased between three to more than ten times, compared to pre-industrial times (Galloway *et al.*, 1995). Also, emissions of S into the atmosphere have more than doubled. Under natural conditions, both the S and N cycles play an important role in transporting (micro-)nutrients to ecosystems. The current human disruption of both cycles, however, leads to deposition rates far in excess of natural rates. Several environmental problems are directly related to disturbance of the S and N cycles; these include acidification and eutrophication of soils and water. A recent study into current and future threats to global biodiversity ranked nitrogen deposition among the most important threats (Leemans, 1999).

Large-scale acidification was identified as an important environmental problem in North America and Europe about 30 years ago. More recently, acidification has also been recognised as a potential threat to ecosystems in other parts of the world (e.g. Rodhe *et al.*, 1988; RIVM/UNEP, 1997). Most assessments of acidification focus on the effects of S deposition (e.g. Foell *et al.*, 1995; Kuylenstierna *et al.*, 1998). However, N deposition, either as ammonium or nitrate, also contributes to acidification (Van Breemen *et al.*, 1982) and eutrophication.

So far, assessments of eutrophication risks have focused on the scale of continents. In view of sharply increasing emissions of S and N compounds outside regions which currently experience acidification and eutrophication problems (Europe and North America), it is important to assess current and future risks in other parts of the world. Early recognition of risks might allow for formulating responses before structural ecosystem damage occurs. Because N is involved in both acidification and eutrophication, both problems may occur simultaneously.

This study, which aims to identify areas with potential acidification and eutrophication risks on the global scale, has two objectives:

1. To inventory the geographic distribution of current and potential future acidification of natural and semi-natural terrestrial ecosystems, resulting from the combined effect of S and N, and N loading of both terrestrial and aquatic ecosystems (rivers, estuaries and coastal seas).
2. To identify current knowledge and data gaps – and provide recommendations for future research.

We will first briefly discuss the mechanisms of acidification and eutrophication, and the assessment procedure used in this study.

1.2. Mechanisms of acidification and eutrophication

Emissions of sulphur and nitrogen compounds

Anthropogenic S emissions consist mainly of SO_2 from combustion of fossil fuels (primarily coal and oil). Natural sources of atmospheric SO_2 include volcanoes and algae in the oceans (oceanic S emissions are mainly in the form of dimethyl sulphide, DMS).

The most important N substances emitted by human activities are nitric oxide and nitrogen dioxide (NO and NO_2, respectively, together denoted as NO_x) and ammonia (NH_3). Many different sources are responsible for the emission of N gases. Fossil fuel combustion, biomass burning, lightning and microbiological emissions from soils are the major processes involved in the production of NO_x. NH_3 originates from many sources, including volatilisation from animal waste, synthetic fertilisers and soils, and emissions from biomass burning, human population, fuel combustion and industrial processes (Lee *et al.*, 1997; Bouwman *et al.*, 1997).

Tropospheric chemistry and transport

In the troposphere, S and N gases are involved in several chemical reactions and transported over hundreds of kilometres and deposited elsewhere. Disruption of both the S and N cycles also contributes to other environmental problems than acidification and eutrophication.

Nitrogen oxides (NO_x) contribute to the generation of ozone (O_3) in the troposphere, thus affecting the oxidant balance of the troposphere. In the lower troposphere, NO_x is of concern because it is one of the precursors of summer-smog, causing effects on human health, vegetation and materials.

Ammonia (NH_3) is the primary acid-neutralising agent in the atmosphere, where it reacts with sulphuric acid (H_2SO_4) to produce ammonium sulphate, thereby influencing the pH of aerosols, cloud water and rainfall. The reaction of O_3 with SO_2 is pH limited, thus the presence of NH_3, neutralising H_2SO_4 in the droplets, may allow further SO_2 oxidation to take place. The presence of H_2SO_4 may result in an increased transport distance of NH_x, as NH_3 gas dry deposits faster by a factor of 5-10 than NH_4^+ particles (see Bouwman *et al.*, 1997 and references included here).

Sulphate particles have an important negative effect on radiative forcing of the sun, either directly by back scattering of radiation or indirectly by increasing cloud lifetimes through the formation of cloud condensation nuclei (resulting in increased cloud albedo) (Charlson *et al.*, 1990; 1991).

Acidification

The proportion of the soil cation exchange capacity that is occupied by base cations is called the base saturation. Weathering of soil minerals by hydrogen ions forms a natural supply of bases. The total number of exchangeable base cations represents the soil's acid buffering capacity. Generally, soils with low base saturation are dominated by slowly weathering minerals.

Hydrogen ions resulting from SO_2 deposition or transformation of N in soil ecosystems replace base cations at the soil's cation exchange complex (CEC). Base cations may leach to the subsoil and groundwater, causing a relative increase in the proportion of hydrogen ions in

the soil. When base saturation decreases by the substitution of bases by hydrogen ions, soil acidity increases (or pH decreases), while the increase of hydrogen ion concentration is increasingly buffered by dissolution of minerals containing aluminium (Van Breemen *et al.*, 1983). Below pH 5 aluminium concentrations in the soil solution increase exponentially with acidifying inputs.

The process of soil acidification, as described above, has multiple effects:

1. Aluminium ions are toxic to plant roots;
2. Hydrogen ions may cause direct injury to plant roots;
3. Indirect effects may occur by decreasing nutrient availability at low pH (e.g. solubility of various phosphates and trace elements decreases with pH);
4. Several microbiological processes such as nitrogen fixation and mycorrhizal activity are disrupted at low pH, and plants may become more susceptible to attack by soil pathogens.

Sulphur (deposited as SO_2 or SO_4^{2-} containing aerosols) contributes directly to acidification. Acidification by nitrate and ammonium deposition depends on the transformations of N compounds in the soil. For example, plant uptake of ammonium (NH_4^+) produces acidity, while uptake of nitrate (NO_3^-) consumes acidity.

In systems where NO_3^- leaching is negligible, acid production and consumption are in balance. In natural ecosystems with no harvesting of biomass, increased deposition of N, either as ammonium or nitrate, could cause soil acidification when N leaches as nitrate (Reuss and Johnson, 1986). Nitrate ions are mobile in the soil solution because the anion exchange capacity of most soils is small. Therefore inputs of N that are not balanced by increased plant uptake lead to nitrate leaching, as is commonly observed (Vitousek *et al.*, 1997).

Nitrification may also contribute to soil acidification, releasing an equivalent amount of acidity in the oxidation of ammonia or ammonium to nitrate (Van Breemen *et al.*, 1982).

Eutrophication
Plant species in many habitats are adapted to nutrient-poor conditions, and can only compete successfully on soils with low N levels. Because N is the primary nutrient limiting plant, algae and microbial production in many terrestrial, freshwater and marine environments, increases in N inputs (in any form) can alter these ecosystems. Increased N inputs can result in shifts in plant and algae species composition, increased productivity, decreased species diversity, alteration of tolerance towards several natural stress conditions such as frost, drought and herbivory (Pitcairn, 1994), as well as development of hypoxic (low oxygen) and anoxic (no oxygen) conditions in aquatic systems (Vitousek *et al.*, 1997; Seitzinger and Kroeze, 1998).

An indirect effect of N enrichment of ecosystems is an increase in microbiological production of nitrous oxide (N_2O) and NO_x (Mosier *et al.*, 1998). Apart from effects on the ecosystems scale, there are also global scale consequences of increased N inputs to terrestrial (Holland *et al.*, 1997) and aquatic ecosystems. Carbon storage may be stimulated in terrestrial ecosystems, which may balance the global carbon losses from deforestation.

1.3. Methodology

The procedure used in this report to assess the acidification and eutrophication in natural and semi-natural terrestrial ecosystems is presented schematically in **Figure 1.1**. The overall procedure is similar to that of Kuylenstierna *et al.* (1998). However, in this study we also included the contribution of N deposition to acidification and eutrophication.

In this analysis recent simulation results for S and N deposition from the STOCHEM model (Collins *et al.*, 1997; Stevenson *et al.*, 1998) are used. The STOCHEM model is driven by emissions of S and N, based on scenarios of economy, population and emission factors. The STOCHEM atmospheric chemistry-transport model produces deposition fields at a $5^{o} \times 5^{o}$ resolution.

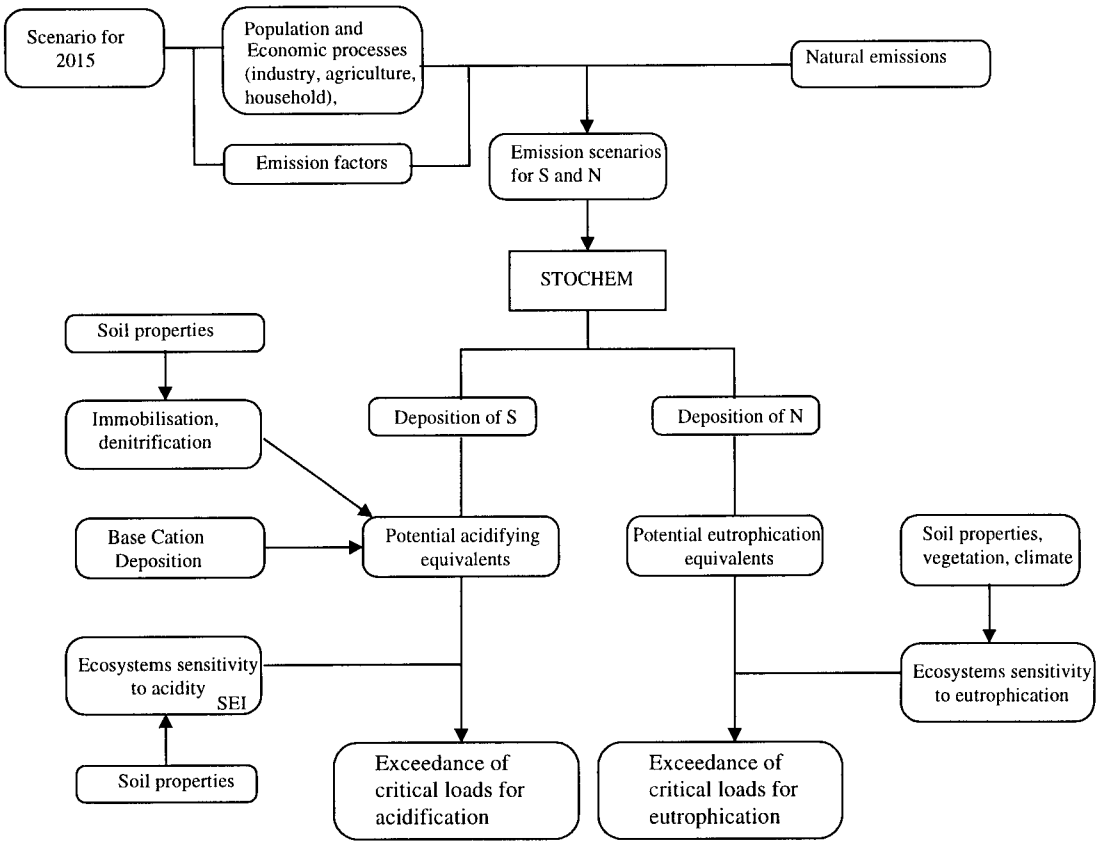

Figure 1.1: Methodology of the acidification and eutrophication risk assessment for terrestrial ecosystems

In the assessment of acidification risks, soil processes affecting N cycling and deposition of base cations need to be taken into account. The potentially acidifying effect of N is reduced by soil N immobilisation and denitrification, while base cations neutralise acidity. In the assessment, uptake of N by plants has been ignored. In many managed and semi-natural ecosystems there is uptake of N, while N inputs coupled to increasing atmospheric CO_2 may lead to enhanced growth. It is assumed that where there is net N uptake of N by plants, this is balanced by net uptake of base cations. Hence, the error caused by ignoring net N uptake is (partly) balanced by ignoring base cation uptake. In systems where no net uptake of N occurs, the anthropogenic inputs of N from deposition leach from the soil as nitrate, causing acidification.

Nitrogen deposition can be used directly to assess eutrophication risks. This study focuses on the eutrophication effects of N on global terrestrial and aquatic ecosystems. For aquatic ecosystems, the results of an available assessment of riverine N transport to estuaries, coastal seas and continental shelves were used.

In this study we compare the net acid deposition and total nitrogen deposition with so-called "critical loads". Critical loads refer to "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson and Grennfelt, 1988). This approach has been successfully applied in Europe in the framework of negotiations for the Convention on Long-Range Transboundary Air Pollution (see e.g. Hettelingh *et al.*, 1995 and Posch *et al.*, 1997). In this study critical loads for acidification are based on soil properties, while those for eutrophication are based on vegetation, soil and climate. The results are presented as the "exceedance ratio", i.e. the ratio deposition : critical load.

Agricultural areas are assumed not to be affected by acid deposition and eutrophication, as farmers can use calcium carbonate to correct decreasing soil pH, and under most circumstances crops benefit from the extra N inputs. We also assumed that the distribution and extent of agricultural areas will not change in the coming 2-3 decades.

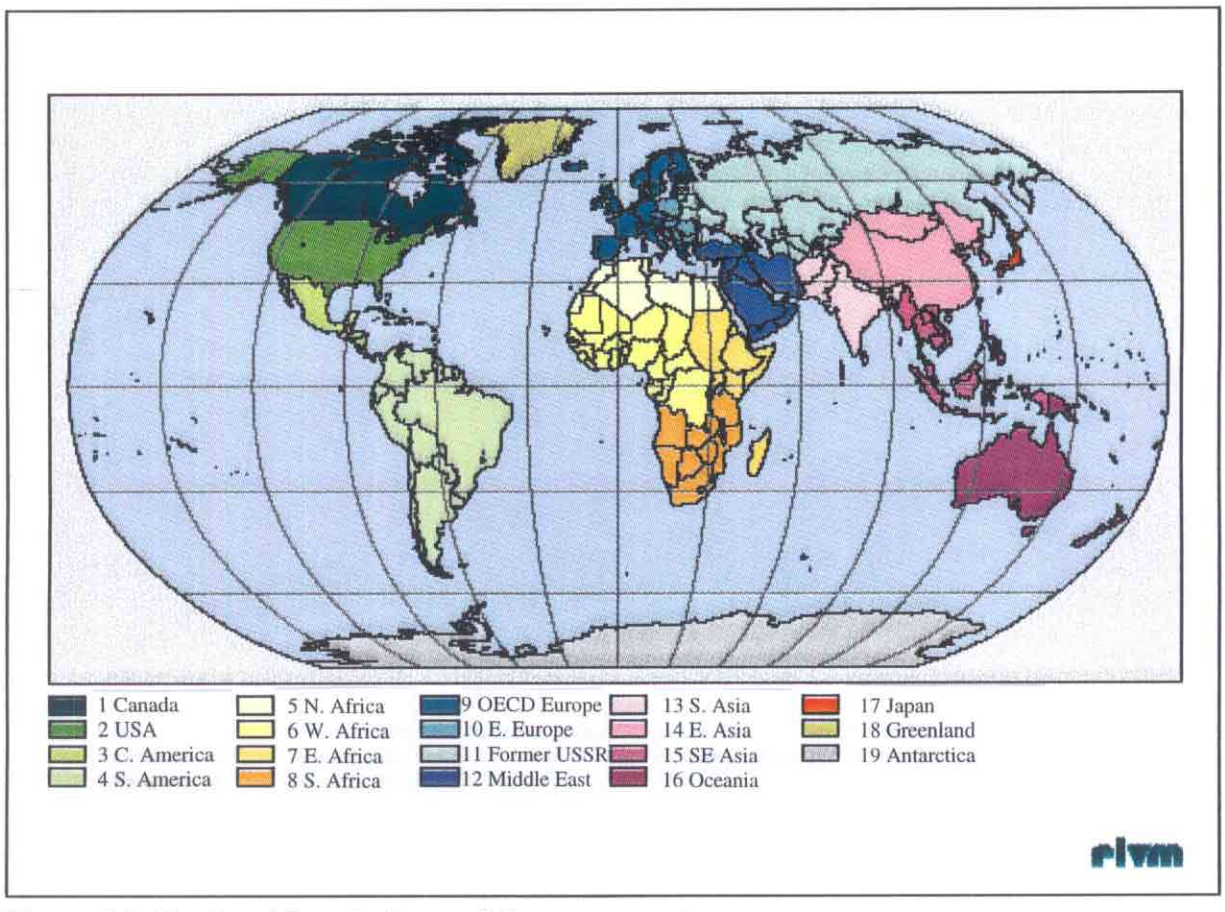

Figure 1.2: Regional break-down of the assessment
Source: Kreileman *et al.* (1998).

The emissions of S and N, and riverine N transport and N loading of estuaries and coastal seas are expressed in units of mass (g, kg, Tg), while deposition fluxes are expressed in (potential) acid equivalents (1 mol S = 2 acid equivalents, 1 mol N = 1 acid equivalent).

The results are presented for 19 world regions, as in **Figure 1.2**. These regions, defined for use in the RIVM-IMAGE model, are almost identical to those used in UNEP's Second Environment Assessment (Kreileman *et al.*, 1998).

As the coverage of this assessment is global, and because there are important gaps of knowledge on the potential effects of S and N inputs on ecosystems, the results have to be considered as preliminary, aimed at identifying potentially affected regions and identifying data and knowledge gaps, and research needs.

1.4. Outline of this report

Chapter 2 discusses atmospheric S and N emissions and deposition, and future scenarios. Chapter 3 presents the assessment of acidification risks for terrestrial systems based on critical loads (section 3.1), processes in soils (3.2), base cation deposition (3.3) and the acidification hazard (3.4). Chapter 4 discusses the critical N-eutrophication loads for terrestrial ecosystems (4.1) and the eutrophication risks (4.2). Chapter 5 includes a discussion on N inputs to world rivers and transport to estuaries and coastal seas. Major uncertainties of the analysis and recommendations for future research are presented in Chapter 6. Conclusions are summarised in Chapter 7.

2. Emission and deposition of sulphur and nitrogen compounds

2.1. Current emissions

Considerable uncertainties are involved in compiling global emission inventories for SO_2, NH_3 and NO_x. Inventories of these species at $1^o x 1^o$ resolution (**Figure 2.1**) and their uncertainties are discussed in detail in Olivier *et al.* (1996 and 1998). Here, we will briefly discuss the major sources of emissions.

Sulphur is mainly emitted as SO_2 by fossil fuel combustion, accounting for almost 60 Tg SO_2-S yr^{-1} on the global scale (**Table 2.1**). Other important sources of atmospheric SO_2 are industrial processes (11 Tg S yr^{-1}), and land use and waste treatment (~2 Tg S yr^{-1}, in particular from biomass burning). About 25 Tg SO_2-S yr^{-1} is emitted by natural sources, including volcanoes and algea in the oceans, where S is emitted in the form of dimethyl sulphide. An important part of the anthropogenic SO_2 originates in East Asia (~19%), USA (~15%), Western Europe (~15%) and the Former Soviet Union (~12%) (**Table 2.1**).

The main N substances emitted by human activities are nitrogen monoxide (NO) and nitrogen dioxide (NO_2) (together denoted as NO_x) and ammonia (NH_3). Global emissions of NO_x and NH_3 amount to 44 (including 13 Tg N yr^{-1} from soils based on Davidson and Kingerlee, 1997) and 54 Tg N yr^{-1}, respectively (**Tables 2.2** and **2.3**).

Table 2.1: Emissions of sulphur dioxide, 1990

Region	Biofuels	Biomass burning	Fossil	Industry	Total Tg S yr^{-1}
1 Canada	14%	1%	77%	8%	1.4
2 USA	0%	0%	95%	5%	10.9
3 Central America	0%	3%	77%	19%	1.5
4 South America	0%	13%	35%	51%	2.9
5 Northern Africa	2%	1%	80%	17%	0.7
6 Western Africa	4%	56%	18%	23%	0.7
7 Eastern Africa	7%	73%	19%	1%	0.3
8 Southern Africa	1%	16%	55%	28%	1.8
9 OECD Europe	2%	0%	76%	21%	11.2
10 Eastern Europe	0%	0%	85%	15%	5.4
11 Former USSR	0%	1%	77%	22%	11.5
12 Middle East	1%	2%	91%	7%	2.3
13 South Asia	4%	7%	83%	6%	2.4
14 East Asia	1%	1%	87%	12%	15.3
15 South East Asia	3%	9%	76%	13%	1.4
16 Oceania	3%	1%	63%	33%	0.8
17 Japan	0%	0%	78%	22%	0.9
18 Greenland	0%	0%	0%	0%	0.0
Total terrestrial	0.8	1.9	57.1	11.7	71.5
Oceans					15

Source: Calculated from EDGAR Version 2.0 (Olivier et al., 1996).
Note: Excluding 2.5 Tg SO_2-S yr^{-1} from international shipping and 10 Tg S yr^{-1} from volcanoes.

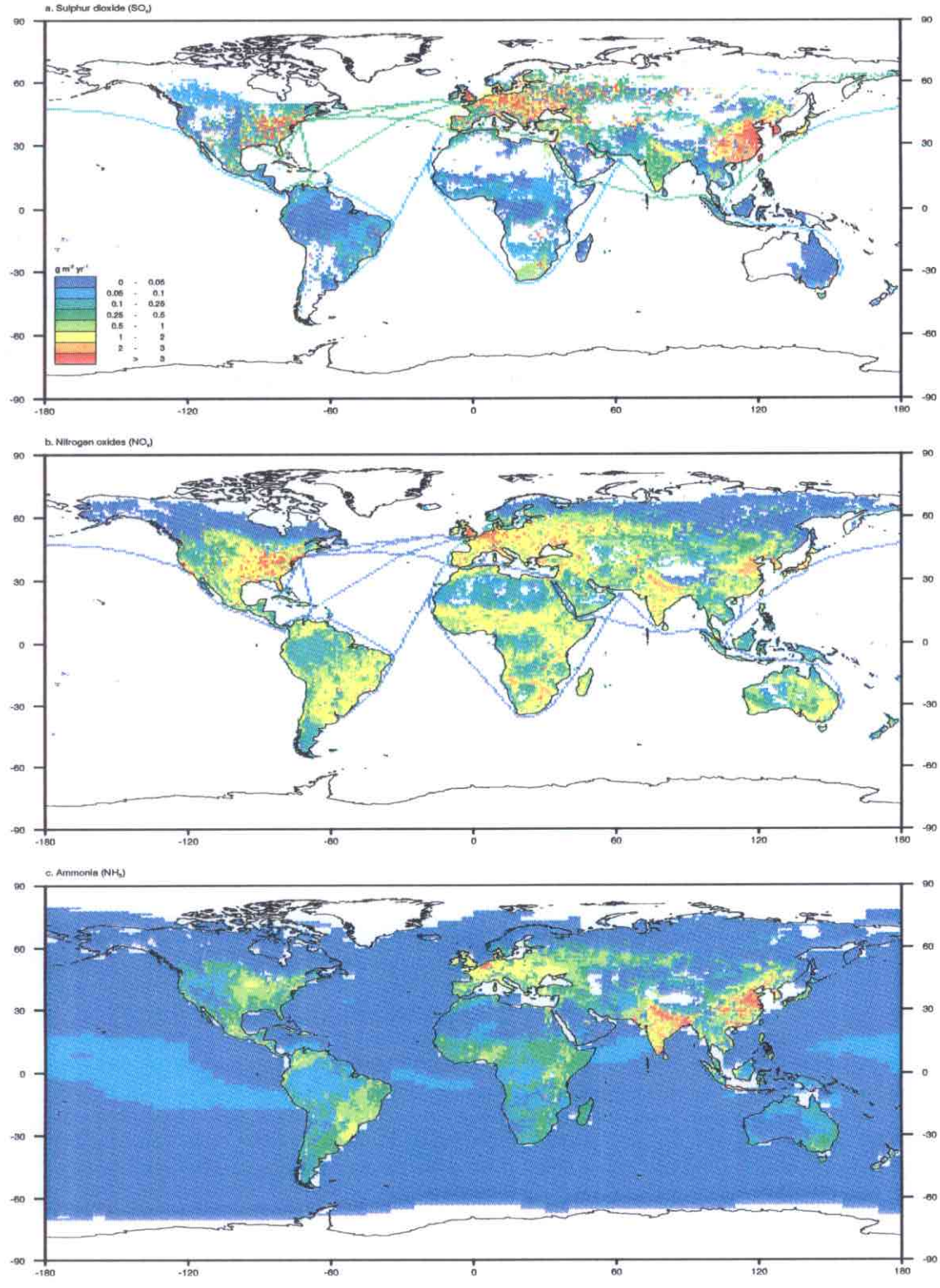

Figure 2.1: Global distribution of emissions of (a) sulphur dioxide (anthropogenic sources), (b) nitrogen oxides and (c) ammonia (all sources).

Sulphur dioxide emissions data exclude oceans (DMS) and volcanoes; nitrogen oxides and ammonia include antropogenic and natural sources, including oceans. Units are g SO_2 m^{-2} yr^{-1}, and g N $m^{-2}yr^{-1}$ for NO_x and NH_3. Source: RIVM-EDGAR (Olivier *et al.* [1996] for SO_2 and NO_x and Bouwman *et al.* [1997] for NH_3). For NO_x the emissions from soils were derived from Davidson and Kingerlee (1997). This is an update of the current Global Emissions Inventory Activity inventory of Yienger and Levy (1995) on the basis of recent measurements and a detailed stratification scheme.

Table 2.2: Emissions of nitrogen oxides, 1990

Region	Agriculture	Biomass Burning[a]	Natural[b]	Industry/ energy	Total Tg N yr^{-1}
1 Canada	17%	8%	8%	67%	0.8
2 USA	7%	4%	6%	83%	8.2
3 Central America	12%	18%	21%	50%	1.0
4 South America	8%	30%	44%	17%	4.3
5 Northern Africa	13%	10%	41%	36%	0.7
6 Western Africa	8%	47%	41%	3%	2.7
7 Eastern Africa	8%	38%	52%	2%	1.7
8 Southern Africa	5%	41%	37%	18%	2.4
9 OECD Europe	6%	5%	5%	84%	4.4
10 Eastern Europe	14%	5%	8%	72%	0.9
11 Former USSR	15%	5%	14%	66%	4.5
12 Middle East	11%	11%	34%	43%	1.7
13 South Asia	21%	34%	13%	32%	2.6
14 East Asia	5%	17%	13%	65%	4.1
15 South East Asia	7%	47%	9%	36%	1.2
16 Oceania	11%	3%	60%	26%	1.4
17 Japan	1%	1%	4%	93%	0.9
18 Greenland	-	-	-	-	0
Total terrestrial	9%	18%	21%	52%	43.5

Source: Calculated from EDGAR Version 2.0 (Olivier et al., 1996).
Note: Estimates exclude emissions from international shipping.
[a] Including biofuels.
[b] Based on Davidson and Kingerlee (1997).

Table 2.3: Emissions of ammonia, 1990

Region	Agriculture	Humans	Biomass Burning[a]	Natural	Industry/ energy	Total Tg N yr^{-1}
1 Canada	70%	2%	8%	17%	2%	0.6
2 USA	81%	4%	9%	3%	3%	3.0
3 Central America	79%	5%	11%	4%	0%	1.4
4 South America	64%	3%	19%	14%	0%	5.8
5 Northern Africa	80%	11%	5%	3%	1%	0.5
6 Western Africa	39%	6%	40%	15%	0%	2.3
7 Eastern Africa	65%	4%	21%	10%	0%	2.0
8 Southern Africa	43%	4%	40%	12%	0%	1.5
9 OECD Europe	87%	7%	4%	1%	1%	2.9
10 Eastern Europe	90%	5%	3%	0%	1%	1.2
11 Former USSR	87%	4%	2%	6%	1%	3.6
12 Middle East	83%	8%	4%	4%	1%	1.1
13 South Asia	83%	8%	9%	1%	0%	7.5
14 East Asia	84%	7%	6%	2%	1%	8.3
15 South East Asia	66%	9%	21%	4%	0%	2.5
16 Oceania	64%	1%	23%	12%	0%	1.0
17 Japan	72%	22%	2%	1%	4%	0.3
18 Greenland	8%	15%	0%	78%	0%	0
Total terrestrial	75%	6%	13%	6%	1%	45.4
Oceans						8.2

Source: Calculated from Bouwman *et al.* (1997).
[a] Including biofuels.

Table 2.4: Regional anthropogenic emissions in 2015 according to the Current Reduction Plan Scenario (CRP) used in this study

	SO_2	NO_x	NH_3
	(Index compared to 1990)		
U.S.A + Europe	0.79	0.90	-
Rest of the world	1.31	1.37	-
Total world	1.03	1.13	1.19

Source: Stevenson *et al.*, 1998.
-, information not available.

On the global scale, agriculture (principally livestock production) is by far the dominant source of NH_3, while industrial sources and fossil fuel combustion are the most important sources for NO_x, with major contributions from natural sources (soils) and biomass burning. Regionally, this pattern is different. In regions with extensive natural areas, such as Canada, South America, western and southern Africa and Oceania, the contribution of natural ecosystems (12-17% for NH_3 and 30-47% for NO_x) to emissions is more important than it is globally. In areas with large scale biomass burning (deforestation, savannah burning), such as South America, Sub-Saharan Africa, and South and South East Asia; this source contributes to 19 to 40% to the regional NH_3 emissions and 37 to 47% to NO_x emissions.

2.2. Emission scenarios

Emission scenario used in this study

There are various scenarios for future emissions of S and N compounds. Most of them project global emissions of acidifying pollutants to increase as a result of continued growth of human activities and fossil fuel consumption. However, regional trends differ markedly in the various projections. Internationally agreed abatement plans for sulphur dioxide and nitrogen oxides in Europe, and national plans in North America and Japan, will probably lead to reduction in emissions of acidifying pollutants in these regions. For other regions a strong growth of emissions is expected.

The scenario for the period 1992-2015 used in this study is presented in **Table 2.4.** Emissions from fuel combustion, biomass burning and agriculture in 2015 were assumed to increase in most world regions, based on the IPCC-IS92a scenario (Pepper *et al.*, 1992; Houghton *et al.*, 1992). In contrast to IS92a for North America and Europe, the emissions of sulphur dioxide and nitrogen dioxide were assumed to decrease by about 30-40% and 5-20% in the period 1992-2015, respectively, corresponding to current policies within these regions (Current Reduction Plans scenario, CRP) (Stevenson *et al.*, 1998).

The CRP scenario of this study and alternative scenarios

Below we discuss the potential developments for SO_2, NO_x and NH_3 in more detail, presenting alternative scenarios as a reference. Among the different scenarios, the CRP scenario can be considered as a moderate-growth scenario.

Sulphur dioxide

In the CRP scenario, sulphur dioxide emissions decrease by about 20% in Europe and North America in the 1990-2015 period, reflecting existing policy commitments in these regions.

Table 2.5: Regional emission of S compounds in 2015 according to alternative scenarios

	IS92a	Conventional development	
		No control	Partial control
	(Index compared to 1990)		
North America	1.03	1.75	0.75
Europe + FSU	0.92	1.40	0.76
Asia and Pacific	1.65	2.26	2.21
Latin America +Africa	1.49	1.50	1.50
World	1.21	1.70	1.25

Source: IS92a: Pepper *et al.* (1992) and Houghton *et al.* (1992); Conventional Development Scenario: Posch *et al.* (1996).

Outside these regions, however, emissions increase by more than 30%. The CRP scenario is loosely based on the IPCC IS92a scenario (Pepper *et al.*, 1992). Two more detailed scenario has been constructed by Posch *et al.* (1996), taking into account the existing abatement plans for some regions (**Table 2.5**).

The "no control" scenario of Posch *et al.* (1996) represents an extreme scenario because it is unlikely that industrialised countries will abandon their current laws for controlling emissions. Emissions of this scenario are considerably higher than the CRP scenario.

In the case of the "partial control" scenario, the emissions in Asia, particularly China, are still expected to increase rapidly, even though some controls were assumed. Emissions in Europe and North America decrease according to the "partial control" scenario by 24% and 25%, respectively, which is slightly lower than the CRP scenario. Full implementation of regional and national emissions policies within these regions might even result in even lower emissions – up to 70% reduction in OECD Europe and 45% in Eastern Europe (Amann *et al.*, 1997). In total, global emissions in the "partial control" scenario increase by 25%; under the CRP scenario, in contrast, they are assumed to increase by only 3%.

Nitrogen oxide

For anthropogenic NO_x emissions, the IPCC IS92a scenario projects an increase in emissions by about 30% between 1990 and 2015 (Pepper *et al.*, 1992). This scenario has been presented on a grid-basis by Lee *et al.* (1997). In the IPCC IS92a scenario, almost no increase of emissions is projected for North America and Europe. Major increases are predicted for South, East and South East Asia, Middle East, Africa and Latin America. Emissions according to the CRP scenario are lower than those of the IS92a scenario, in particular, in Europe and North America, but also in other regions. Global emissions are assumed to increase by 13%.

Ammonia

A scenario has been constructed by FAO (1997) and Bouwman and Van der Hoek (1997) for NH_3 emissions from agriculture in developing countries. This scenario indicates a sharp increase in N fertiliser use in developing countries from 50 Tg N yr^{-1} in 1995 to close to 100 Tg N yr^{-1} in 2025. Emissions from fertilisers, however, are expected to decrease by about a third as result of assumed changes in the type of fertilisers used. At the same time, N in animal waste may increase from the current 64 to 104 Tg N yr^{-1} in 2025, causing a 60% increase in emissions. According to the CRP scenario the global NH_3 emission will increase by 19% between 1992 and 2015 (**Table 2.4**).

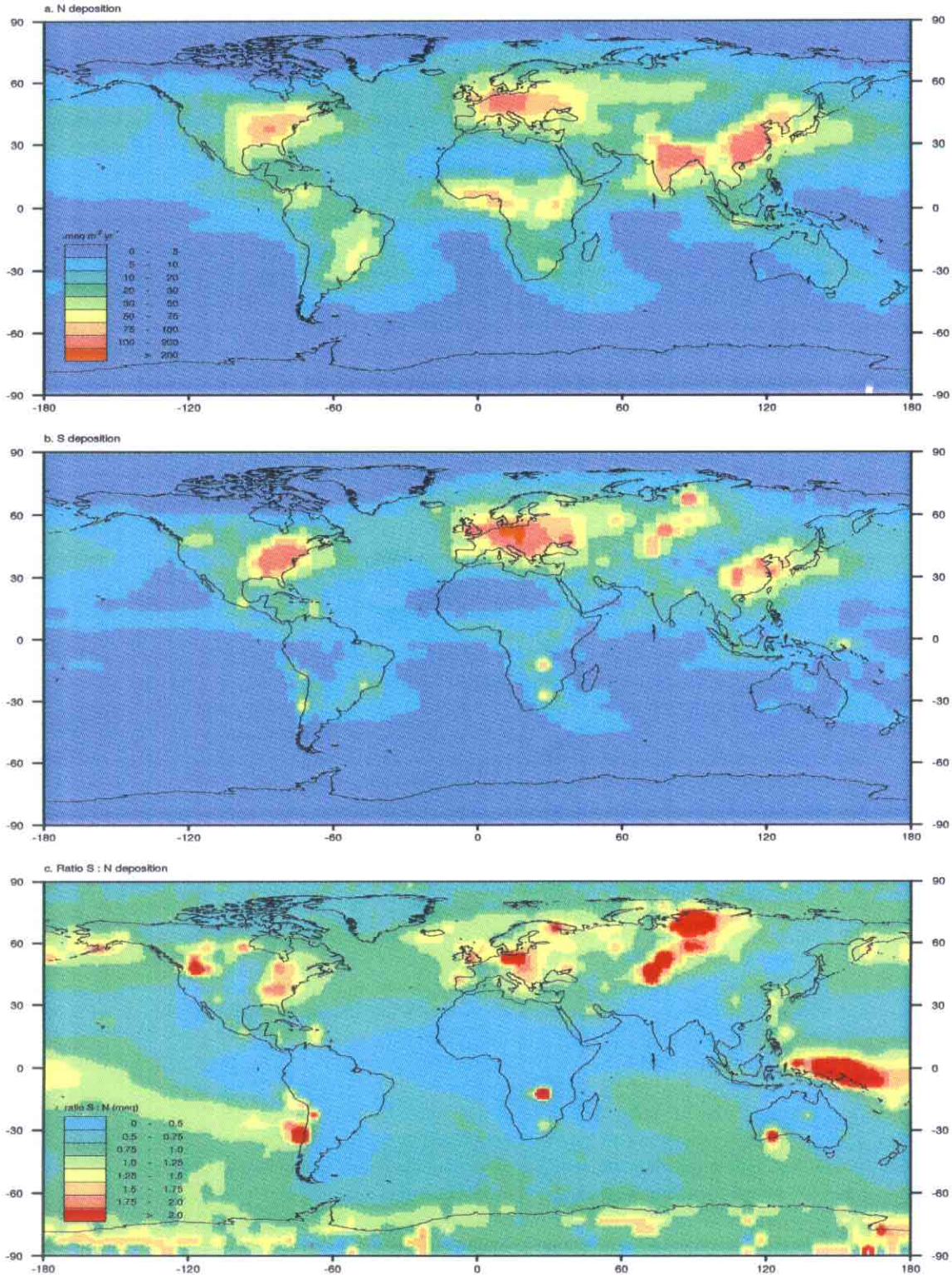

Figure 2.2: Annual total (wet plus dry) deposition of (a) sulphur, (b) nitrogen and (c) the ratio of sulphur and nitrogen deposition for the year 1992.

Source: Deposition is simulated with the STOCHEM model (Stevenson *et al.*, 1998). The original model output is presented as 5°x5° grid boxes. For this study the data were converted to a 1°x1° grid using a smoothing filter.

2.3. Deposition

The STOCHEM model has been used to assess S and N deposition fluxes on a $5^{o}\times5^{o}$ resolution on the basis of the 1992 and 2015 emissions of SO_2, NO_x and NH_3 as described in the previous sections (Collins *et al.*, 1997; Stevenson *et al.,* 1998)[1]. With this resolution long-range transport of S and N compounds can be represented reasonably well. The deposition data for both S and N were redrawn from the original $5^{o}x5^{o}$ to a $1^{o}x1^{o}$ resolution using a filter smoothing the spatial patterns (see **Figure 2.2** for 1992 and **Figure 2.3** for 2015).

Using the STOCHEM model, it is not possible to describe the short-range local dry deposition of gases, in particular ammonia. For sulphur and nitrogen oxides, this process is much less important. To account for more short range processes, $1^{o}x1^{o}$ resolution emission fields for NH_3 were used to estimate the dry deposition of NH_3 close to the sources. The fraction of the total emission that is dry-deposited within a few km from the source depends on many factors, including the height of the source and the surface roughness (Asman, 1998), and the compensation concentration (Conrad and Dentener, 1999). Most terrestrial sources are close to the surface, giving a fraction of 0.4-0.6 of re-deposition of the emitted NH_3 within 2 km of the source for a neutral atmosphere (Asman, 1998). Re-deposition may amount to about 0.4 for a roughness length of 0.25 m (coniferous forest) and 0.6 for roughness lengths in the order of 1.0 m (deciduous forest). As the ecosystems considered are natural with more pronounced roughness variation than agricultural fields, the overall fraction of re-deposition of the emissions is assumed to be 0.5. This fraction was used to modify the $1^{o}\times1^{o}$ deposition fields with the $1^{o}x1^{o}$ emission inventory of Bouwman *et al.* (1997). For certain vegetation types this may underestimate dry-deposition fluxes, while for ecosystems with low roughness lengths this fraction may be an overestimate.

Another way to add more spatial variation in deposition fluxes may be by presenting differences in vegetation types to estimate differences in compensation points of canopies for describing deposition fluxes. Since describing this effect for the spatial resolution of 0.5^{o} of the vegetation/land cover database would introduce many uncertainties, for example, by not describing meteorological variability and other sub-grid effects, the deposition fluxes in this study were not corrected for differences in vegetation.

Comparison of the STOCHEM deposition fields for 1992 with (regional) assessments showed a good correspondence with EMEP estimates of N and sulphur deposition in Europe (Tuovinen, 1994), MOGUNTIA model results for N deposition at the global scale (Dentener and Crutzen, 1994; Holland *et al.*, 1997; Lelieveld *et al.*, 1998), and RAINS Asia information on S deposition (Foell *et al.*, 1995). In **Figures 2.2 and 2.3** S and N deposition rates are presented for 1992 and for the CRP scenario for 2015, respectively.

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[1] The STOCHEM model has been developed by the Meteorological Office (UK) (Stevenson et al., 1997). The model calculates the deposition and surface concentration of several tropospheric air pollutants on a 5° x 5° grid basis for the world as a whole. The driving forces of calculations with this model are emissions from fuel combustion, biomasss burning and emissions from agriculture. Other model estimates are available, such as $10^{o}x10^{o}$ resolution deposition fields simulated with the MOGUNTIA model for NH_x in Dentener and Crutzen (1994), Holland *et al.* (1997) and Lelieveld *et al.* (1998) for NO_x. In view of the uncertainties involved in chemistry-transport modelling, and to reduce errors caused by aggregation, we decided to use the more detailed $5^{o}\times5^{o}$ deposition fields.

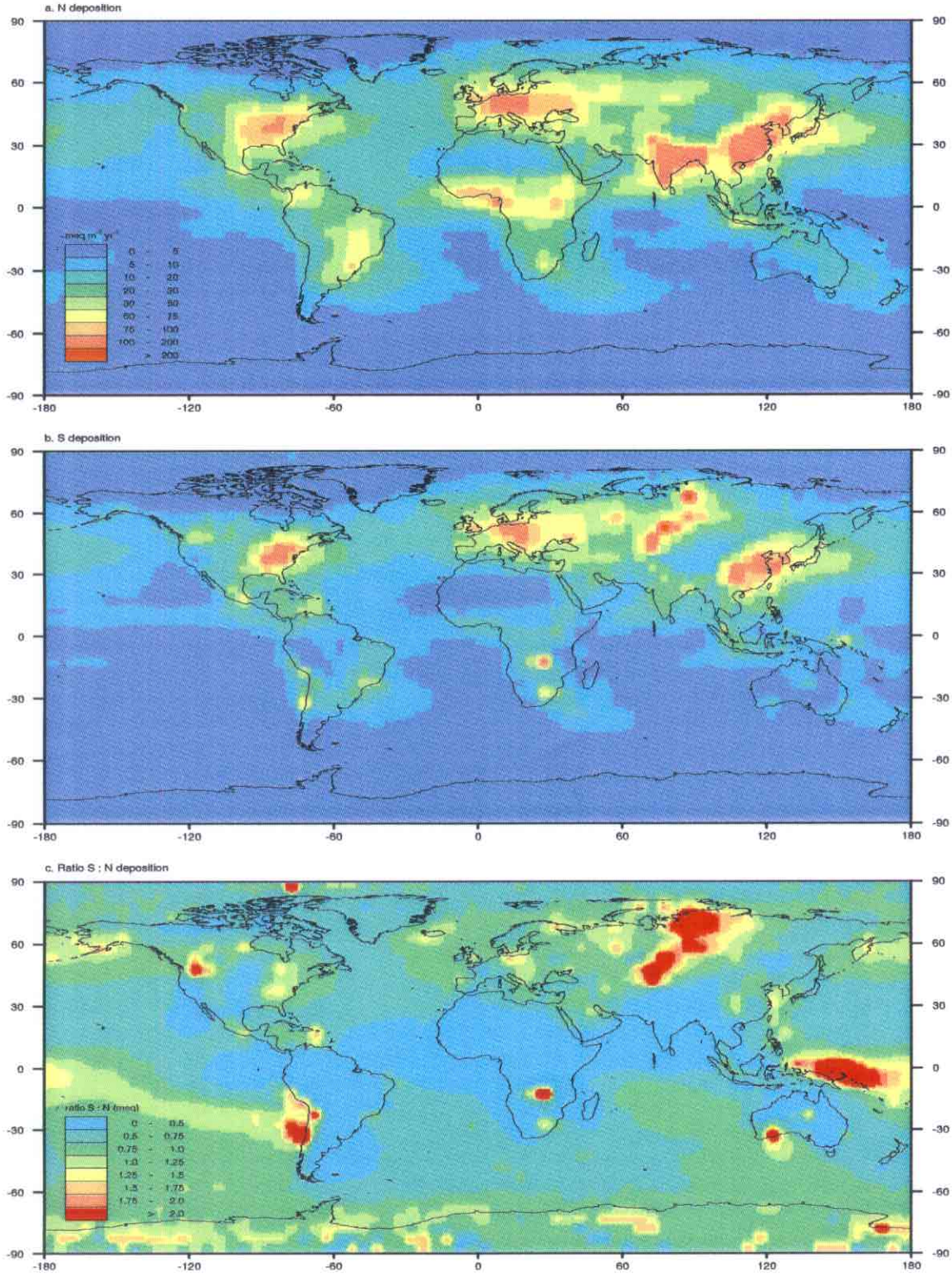

Figure 2.3: Annual total (wet plus dry) deposition of (a) sulphur, (b) nitrogen and (c) the ratio of sulphur and nitrogen deposition for the year 2015 (CRP-scenario).
Source: Deposition is simulated with the STOCHEM model (Stevenson *et al.*, 1998). The original model output is presented as 5°x5° grid boxes. For this study the data were converted to a 1°x1° grid using a smoothing filter.

The calculated 1992 deposition onto global land areas amounts to $3.2x10^{12}$ eq S yr^{-1} and $4.4x10^{12}$ eq N yr^{-1} (**Table 2.6**). The highest mean S deposition rates occur in Eastern Europe (158 meq S $m^{-2}yr^{-1}$), followed by OECD Europe (74 meq S $m^{-2}yr^{-1}$) and USA (45 meq S $m^{-2}yr^{-1}$) (**Annex 1**). Highest maximum S deposition rates occur in Eastern Europe and OECD Europe (>250 meq S $m^{-2}yr^{-1}$), and somewhat smaller fluxes in North America and the former USSR (~200 meq S $m^{-2}yr^{-1}$). The highest mean regional N deposition rates of 1200 mg N m^{-2} per year occur in Eastern Europe (**Annex 1**). South Asia and OECD Europe have mean deposition rates of 80 and 90 meq N m^{-2} per year, respectively. Other regions with somewhat lower deposition rates are Japan and East Asia. The highest maximum deposition rates (about 150 meq N $m^{-2}yr^{-1}$) occur in East and South Asia and somewhat lower deposition rates occur in Western and Eastern Europe, North America, South East Asia, Western and Eastern Africa and Japan (**Annex 1**).

Figures 2.2 and 2.3 also show the S:N deposition ratio expressed as acid equivalents. Nitrogen dominates the acid deposition in most parts of the world. However, sulphur dominates the acid inputs in regions close the industrialised regions with high sulphur emissions.

According to the CRP scenario, the total global S deposition onto terrestrial surfaces does not change between 1990 and 2015. However, there are considerable regional differences, following the differences in emissions discussed in Section 2.2. Between 1990 and 2015, deposition rates in Canada, USA, Western and Eastern Europe and the Middle East are projected to decrease. Deposition rates in other global regions are projected to increase. The global terrestrial deposition for N increases from 60 to 70 Tg yr^{-1} as a result of increases in all world regions. These N deposition estimates exclude short-range dry deposition of ammonia.

Table 2.6: Results for N and S deposition for 1992 and 2015 (CRP scenario)[b]

Region[a]		1992		CRP scenario (2015)	
	Area	N	S	N	S
	Mha	/10^{12} eq yr^{-1}			
Oceans	35863	3.6	2.6	4.0	2.7
1 Canada	975	0.1	0.2	0.2	0.1
2 USA	951	0.4	0.4	0.4	0.3
3 Central America	321	0.1	0.1	0.1	0.1
4 South America	1815	0.5	0.2	0.6	0.2
5 Northern Africa	594	0.1	0.0	0.1	0.0
6 Western Africa	1152	0.4	0.1	0.5	0.1
7 Eastern Africa	602	0.2	0.0	0.2	0.1
8 Southern Africa	699	0.2	0.1	0.2	0.1
9 OECD Europe	433	0.2	0.3	0.2	0.2
10 Eastern Europe	116	0.1	0.2	0.1	0.1
11 Former USSR	2203	0.6	0.8	0.7	0.8
12 Middle East	624	0.2	0.1	0.2	0.1
13 South Asia	533	0.4	0.1	0.5	0.1
14 East Asia	1150	0.6	0.4	0.8	0.5
15 South East Asia	505	0.2	0.1	0.2	0.1
16 Oceania	882	0.1	0.0	0.1	0.0
17 Japan	57	0.0	0.0	0.0	0.0
18 Greenland	220	0.0	0.0	0.0	0.0
Total	51011	8.0	5.8	9.1	5.8
Total terrestrial	15149	4.4	3.2	5.0	3.1

Source: Stevenson *et al.* (1998).

[a] See Figure 1.2.

[b] N deposition excludes short-range transport..

3. Global acidification of terrestrial ecosystems

For the assessment of the acidification hazard on the basis of the deposition estimates described in Chapter 2, N deposition rates have to be corrected for uptake of N and base cations, N immobilisation and denitrification in soils. Finally, acid inputs have to be corrected for the neutralising effect of base cation deposition. The resulting "net" potential acidity is then compared with the sensitivity of (semi-)natural terrestrial ecosystems to acidifying deposition.

3.1. Nitrogen uptake, immobilisation and denitrification

In natural unmanaged ecosystems increased deposition of N, either as ammonium or nitrate, causes soil acidification when N leaches as nitrate (Reuss and Johnson, 1986). Nitrate ions are mobile in the soil solution because the anion exchange capacity of most soils is only limited. Hence, inputs of N that are not balanced by increased plant uptake cause increasing nitrate leaching, and thus acidification, as is commonly observed (Vitousek *et al.*, 1997).

Not all N deposition contributes to acidification, as part of the N is lost from the soil system due to plant uptake, immobilisation and denitrification. To determine the net acidifying effect of N inputs, we accounted for these processes on the basis of a number of assumptions:

1. Uptake of N and base cations by plants is ignored. In many semi-natural (managed) ecosystems uptake of N occurs, while N inputs coupled to increasing atmospheric CO_2 may lead to enhanced growth. It is assumed that a net N uptake by plants, where present, is balanced by a net uptake of base cations. Hence, the error caused by ignoring net N uptake is (partly) balanced by ignoring base cation uptake. In systems where no net uptake of N occurs, the anthropogenic inputs of N from deposition leach from the soil as nitrate, causing acidification.
2. Soil N immobilisation (N_i in Eq. 3.1; Section 3.4) amounts to 75 meq N m^{-2} in all ecosystems. This assumption is based on deposition fluxes of between 50 and 100 meq N $ha^{-1}yr^{-1}$ for long-term equilibrium calculations at critical load recommended by Umweltbundesamt (1996);
3. Soil denitrification amounts to a fraction (f_{de} in Eq. 3.1; Section 3.4) of the N that is not immobilised. This fraction is a function of soil texture and soil drainage (**Table 3.1**).

Table 3.1: Fraction of denitrification (f_{de}) as a function of soil texture and soil drainage class

	Drainage class	Soil texture class			
		Coarse	Medium	Fine	Organic
1	Well drained	0.1	0.3	0.7	0.8
2	Moderately well drained	0.2	0.4	0.8	0.8
3	Moderately well drained	0.3	0.5	0.8	0.8
4	Poorly drained	0.4	0.6	0.8	0.8
5	Very poorly drained	0.6	0.8	0.8	0.8

Source: Modified from De Vries *et al.* (1993). Texture classes for FAO/Unesco soil types are taken from Bouwman *et al.* (1993).

3.2. Base cation deposition

For assessing acidification risks, it is necessary to account for the deposition of base cations which neutralise acidity in deposition. The most important base cations are potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) compounds. Their deposition is due to emissions from various sources, including soil dust, fossil fuel combustion, forest fires and biomass burning, industrial sources and sea salts.

Except for some regional assessments and scattered measurements, no data on global base cation deposition are available.

In the absence of a direct estimate of base cation deposition, Kuylenstierna *et al.* (1998) used the distribution of soil dust deposition from Tegen and Fung (1994; 1995) as a surrogate for total cation deposition. Kuylenstierna *et al.* (1998) assumed soil dust to contain 20% calcium so as to arrive at cation deposition rates consistent with measurements in Europe, Thailand and Japan.

As an alternative method, we used unpublished simulation results (I. Tegen, personal communication, 1999) using the model of Tegen and Fung (1994; 1995), with actual Ca contents of soil particles from Lee *et al.* (1999). This yielded a 4 % global Ca content of soil particles..

Hence, the 20% calcium content of soil dust used by Kuylensierna *et al.* (1998) is considerably higher than the actual Ca contents of soil dust (**Figure 3.1**). This is to account for the non-soil-dust sources of base cations mentioned above.

Table 3.2: Comparison of measured base cation deposition fluxes with modelled Ca deposition from soil dust

Country / region	Reference	Measurement	Method A[a]	Method B[a]
			meq m^{-2} yr^{-1}	
South Carolina, USA	Markewitz *et al.* (1998)	24 (Ca + Mg)	20-40/10-20	0-5
Japan	Hara (1993)	35 (Ca)	40-60/60-80	5-10
Japan	Hara *et al.* (1995)	21.7 (Ca) 22.9 (Mg)	40-60/60-80	5-10
Thailand	Granat *et al.* (1996)	7-8 (Ca) 1.5-2 (Mg)	5-10	0-5
Southern Europe	Draaijers *et al.* (1995)	50-100/100-200	60-80	10-20
Central Europe	Draaijers *et al.* (1995)	20-50	20-60	5-10
Northern Europe	Draaijers *et al.* (1995)	0-20	0-5/5-10	0-5
Sardinia	Guerzoni *et al.* (1995)	52 (nss[b] Ca) 58 (nss[b] Ca + Mg)	60-80	10-20
	Le Bolloch & Guerzoni (1995)	20 (nss[b] Ca)		
Finland	Soveri and Peltonen (1995)	8 (Ca + Mg) winter only	0-5/5-10	0-5
Sweden	Hultberg and Ferm (1995)	23 (Ca; 24% of this is non marine) 66 (Mg; primarily marine)	10-20	0-5

[a] Method A, simulated soil clay + silt deposition from Tegen and Fung (1994; 1995), assuming a 20% Ca content; Method B, the model of Tegen and Fung (1994) driven by a 1°x1° inventory of soil Ca content taken from Lee *et al.* (1999).
b nss = non-sea salt.

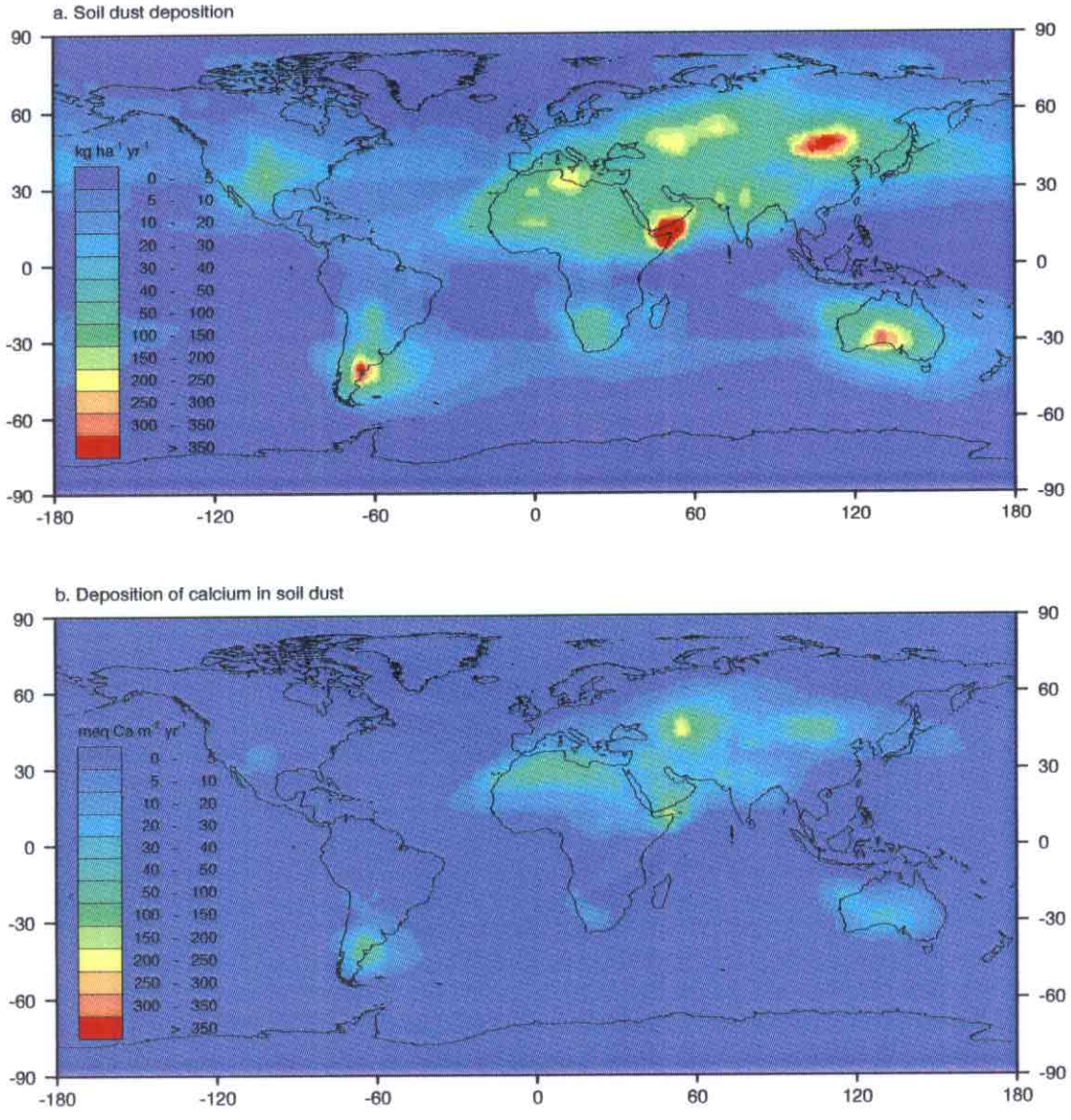

Figure 3.1: (a) Global distribution of deposition of soil dust from Tegen and Fung (1995) and of (b) Ca in soil dust.

The soil dust deposition in panel (a) was used to estimate Ca deposition, assuming 20% Ca content for all soils and texture classes. For 20% Ca content, the unit kg $ha^{-1}yr^{-1}$ approximately equals meq Ca $m^{-2}yr^{-1}$. The data of figure b has been derived by using data on soil Ca content (Lee et al., 1999) as input for the model of Tegen and Fung (1994) (I. Tegen, 1999, personal communication).

We compared the two above described methods with measured deposition fluxes (**Table 3.2**). Most data are from industrialised regions, where industrial and combustion sources may contribute significantly to base cation deposition. In addition, in some locations contributions from sea-salt were significant or dominant. The method based on 20% soil dust shows a surprisingly good agreement with measurements. The second method, based on actual calcium content, results in much lower deposition rates. Therefore, we decided to adopt the method of Kuylenstierna *et al.* (1998) in our acidification assessment, recognising it as a surrogate for actual deposition and, furthermore, the actual Ca deposition in remote areas, where soil dust is the predominant source of base cations, as probably overestimated. An improvement in this method can be achieved by using emission inventories for Ca, Mg, K and Na for all sources to drive an atmospheric model.

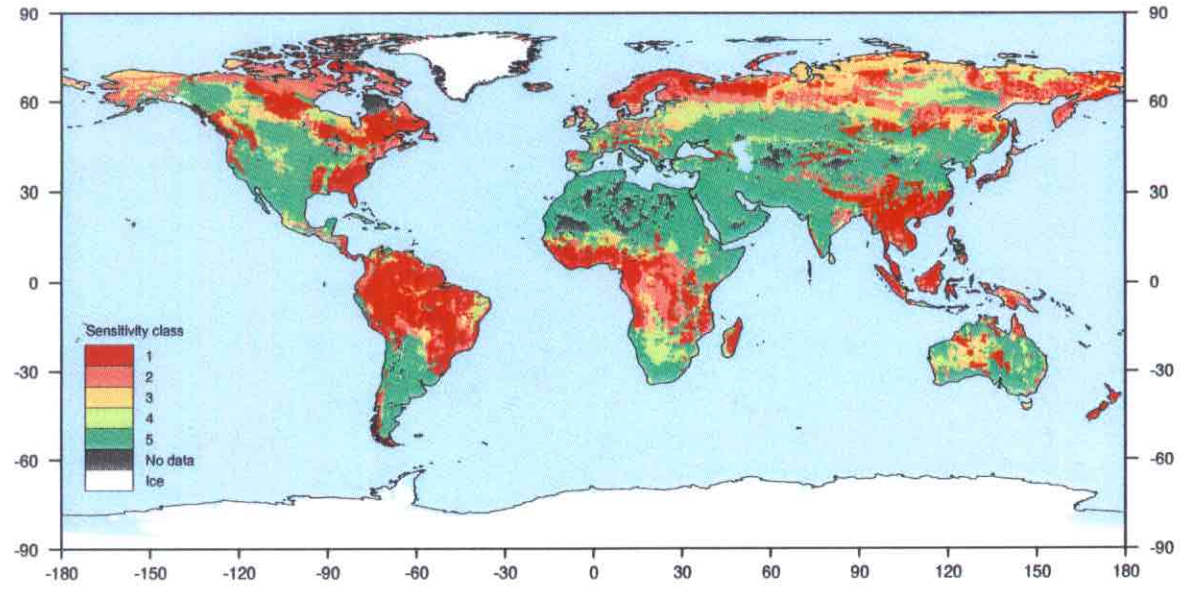

Figure 3.2: The global distribution of five classes of sensitivity to acid deposition
Source: Cinderby *et al.* (1998).

3.3. Critical loads for acidification in ecosystems

In this assessment the ecosystem sensitivity ranking of Cinderby *et al.* (1998) was used (see also Kuylenstierna et al., 1998). The ranking of ecosystem sensitivity of Cinderby *et al.* (1998) was made in consultation with experts from various countries, including ecologists and soil scientists. The sensitivity of ecosystems was derived on the basis of soil buffering ability, which is determined from the soil's cation exchange capacity (CEC) and base saturation (i.e. the proportion of the cation exchange complex occupied by base cations).

The combination of CEC and base saturation represents the capacity of the soil to buffer acidity by means of cation exchange. The data on CEC and base saturation used by Cinderby *et al.* (1998) were taken from Batjes and Bridges (1994) and Batjes (1997). Based on this, five sensitivity classes were formulated and the approach has been applied to the digital version of the FAO/Unesco Soil Map of the World (FAO, 1995). A sixth class is used for all the areas where data on soil CEC and base saturation were not available. **Figure 3.2** shows the global distribution of the six classes.

Critical loads for acid deposition were assigned to each of the sensitivity classes. In this study, we employed a range of critical loads expressing the uncertainty in the method used to determine the soil sensitivity. The medium estimate is the one proposed by Cinderby *et al.* (1998). The high and low classes represent +50% and –50%, respectively, of the value for the medium class (**Table 3.3**).

Soils with sensitivity class 5 were assumed to be insensitive to acid deposition according to Cinderby *et al.* (1998). In our class 5 of the medium and high estimates for critical loads, we also assumed insensitivity to acid deposition, while in the low estimate we assumed a soil sensitivity to deposition rates of > 200 meq m^{-2} yr^{-1} (**Table 3.3**).

Table 3.3: Critical loads for the sensitivity classes presented in Figure 3.2

Sensitivity class	Critical load		
	Low	Medium	High
		(meq m^{-2} yr^{-1})	
1	12.5	25	37.5
2	25	50	75
3	50	100	150
4	100	200	300
5	200	> 200[a]	> 300[a]

Source: Based on Cinderby *et al.* (1998).

[a] Class 5 for the medium and high estimates of the critical load is assumed to be insensitive to acid deposition.

3.4. Acidification hazard

The acidification risk is expressed as the exceedance ratio, i.e. the ratio of acid deposition:critical load, whereby acid deposition is corrected for base cation deposition, N immobilisation and denitrification:

$$\text{Exceedance ratio} = \frac{\left(S_{dep} + (N_{dep} - N_i) * (1 - f_{de}) - BC_{dep}\right)}{CL} \qquad (3.1)$$

where S_{dep} = S deposition (meq $m^{-2}yr^{-1}$), N_{dep} = N deposition (meq $m^{-2}yr^{-1}$), N_i = N immobilisation (meq $m^{-2}yr^{-1}$), f_{de} = fraction of N that is denitrified (no dimension), BC_{dep} = deposition of base cations (meq $m^{-2}yr^{-1}$) and CL = critical load (meq $m^{-2}yr^{-1}$).

Figure 3.3 shows the exceedance of critical loads for the world for 1992. The results are summarised in **Table 3.4** for high, medium and low sensitivity (i.e. high, medium and low critical loads). In addition, for the medium sensitivity case, the table also shows the exceedance of twice the critical load. Areas in the various classes of the exceedance ratio are presented in **Annex 2** for the current situation, and in **Annex 3** for the CRP scenario for 2015. The location and extent of (agro-) ecosystems is assumed to show no change between 1992 and 2015.

According to our results based on the medium estimates of critical loads, current acidification is most prominent in the industrialised countries of Western Europe (35% of the area of [semi-]natural ecosystems affected), Eastern Europe (47%) and the eastern part of North America (USA and Canada). In addition, acid deposition exceeds critical loads in extensive areas in East Asia (15%) and South East Asia (21%). In most regions, a considerable share of the affected areas experience severe acidification risks (exceedance ratio > 2.0).

A much smaller fraction of the area of (semi-)natural ecosystems experiences acidification in the Former Soviet Union, Western and Central Africa and South America. Where exceedance ratios are greater than 1.0 in these regions, this is a result of high soil sensitivity, despite the relatively low acid deposition rates.

Contrary to the results of Cinderby *et al.* (1998), who only accounted for S deposition, the combined assessment of S and N indicates that areas away from the highly industrialised areas may also be affected by acid deposition.

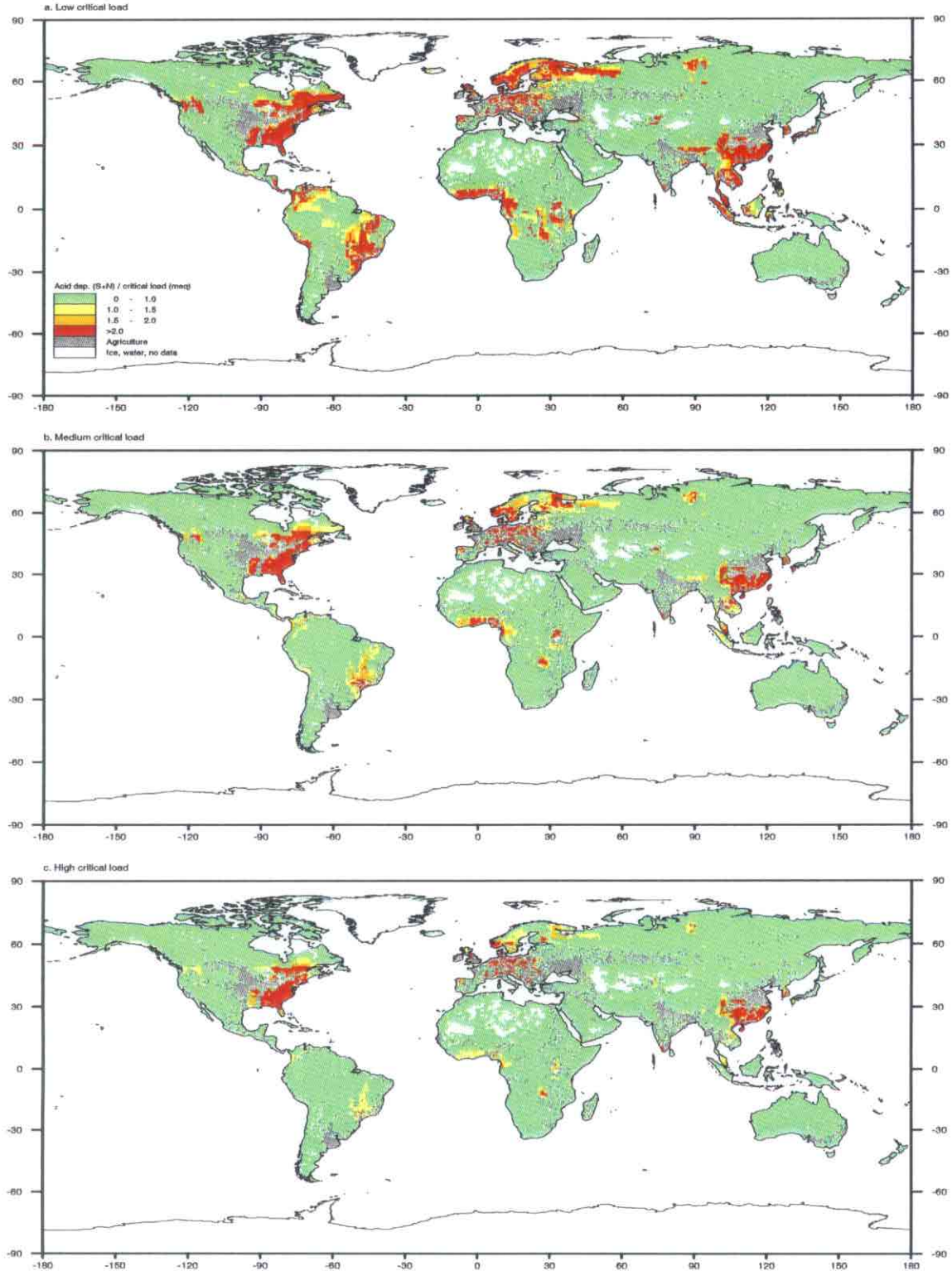

Figure 3.3: Global distribution of the acidification exceedance ratio for terrestrial (semi-) natural ecosystems for 1992, using (a) low estimates of critical loads (upper panel); (b) medium estimates (middle panel) and (c) high estimates (bottom panel).

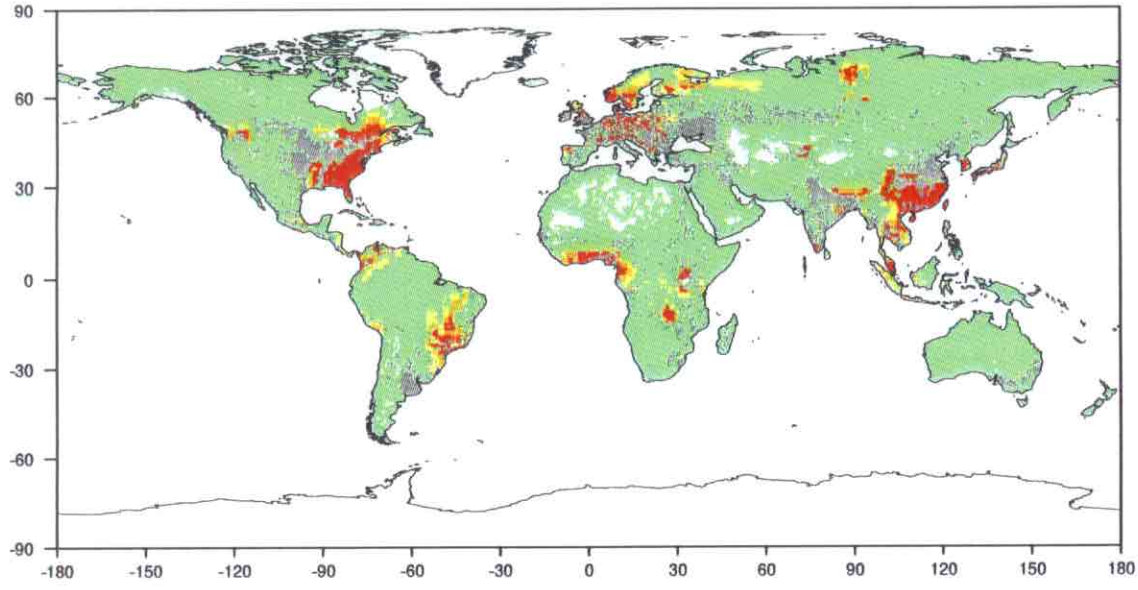

Figure 3.4: Global distribution of the acidification exceedance ratio for terrestrial (semi-) natural ecosystems for 2015 according to the CRPscenario
Note: medium estimates for critical loads have been used.

Table 3.4: Exceedance of critical loads for acidification

	1992				CRP 2015[d]
Sensitivity assumed:	High[b]	Medium[b]	Low[b]	Medium[b]	Medium[b]
Exceedance classes[c]:	>1	>1	>1	>2	> 1
	(% of natural areas)				
Canada	20%	14%	8%	5%	10%
USA	26%	24%	22%	20%	23%
Central America	7%	5%	1%	0%	6%
South America	29%	12%	5%	1%	17%
Northern Africa	0%	0%	0%	0%	0%
Western Africa	20%	12%	7%	3%	14%
Eastern Africa	5%	3%	2%	2%	4%
Southern Africa	14%	5%	2%	0%	6%
OECD Europe	45%	35%	25%	18%	29%
Eastern Europe	63%	47%	39%	34%	41%
Former USSR	8%	5%	2%	1%	5%
Middle East	1%	1%	0%	0%	0%
South Asia	8%	6%	3%	1%	9%
East Asia	17%	15%	13%	12%	17%
South East Asia	36%	21%	9%	4%	29%
Oceania	0%	0%	0%	0%	0%
Japan	13%	11%	4%	3%	15%
Greenland	0%	0%	0%	0%	0%
Global land area	15%	10%	6%	4%	11%

[a] Exceedance ratio = ratio deposition : critical load
[b] Sensitivity : High = Low range of critical loads; Medium = Medium range of critical loads; Low = High range of critical loads.
[c] Exceedance class: > 1.0 indicates the percentage of the area (semi-)natural ecosystems with an exceedance ratio > 1.0; > 2.0 indicates the percentage of (semi-)natural ecosystems with exceedance ratio > 2.0 (severe risk).
[d] CRP 2015 indicates the results under the CRP scenario for 2015 (using medium critical loads).

Figure 3.4 and **Table 3.4** present the potential global acidification in 2015 based on the CRP scenario described in Chapter 2. According to this scenario, the situation will slightly improve in OECD Europe, Eastern Europe, the USA and Canada between 1992 and 2015 – although still large areas of these regions will be exposed to high rates of acid deposition. In the other regions, the area with exceedance ratios > 1.0 will generally increase, in particular in South East Asia and South America. In Asia, relatively large areas with exceedance ratios > 1.0 are found in parts of the Russian Federation (in particular near large industrial areas in Siberia) and in major parts of China. This suggests that in the relatively short time period covered (15-20 years), the problem of acidification could become more widespread on the global scale.

4. Global eutrophication risk of terrestrial ecosystems

This chapter discusses the potential global eutrophication risks for terrestrial ecosystems, using the deposition scenarios described in **Chapter 2**. First, critical loads for N for different ecosystems were derived. Next, the eutrophication risks were estimated by comparing N deposition with these critical loads.

4.1. Critical nitrogen loads for terrestrial ecosystems

It is essential to understand the effects of N on the biological ecosystem processes regulating the N cycling to establish reliable critical loads for ecosystems. The most important effects of increased atmospheric deposition on biological systems are:

1. Short-term effects of N gases and aerosols on individual species,
2. Soil mediated effects of acidification,
3. Soil-mediated effects of N enrichment and
4. Changes in competitive relationships between species, resulting in loss of diversity.

A review of available literature on effects of N deposition on natural and semi-natural vegetation in Europe is presented in Bobbink *et al.* (1996). Critical loads were established on the basis of various expert meetings. A range of 50-145 meq m^{-2} yr^{-1} was proposed for the critical load for species diversity and leaching of nitrate for both coniferous and deciduous forests. For acidic forests (50-105 meq m^{-2} yr^{-1}) and for forests in humid climates (35-70 meq m^{-2} yr^{-1}) somewhat lower ranges were assumed to describe the sensitivity of ground flora, decline of lichens and increase of free-living algae. A similar range of 70-145 meq m^{-2} yr^{-1} was proposed for heathlands, with somewhat lower values for arctic and alpine heath lands (35-105 meq m^{-2} yr^{-1}).

Effects on grasslands are known to occur at higher deposition rates of 105-250 meq m^{-2} yr^{-1}, with lower values (70-105 meq m^{-2} yr^{-1}) for montane and subalpine grasslands (Bobbink *et al.*, 1996). Effects on grasslands include an increase in tall grasses, change in diversity and disruption of N cycling with increasing leaching rates. On the basis of experiments where effects of N inputs occur at high N levels in mesotrophic wetlands, these wetlands (145-250 meq m^{-2} yr^{-1}) are considered less susceptible to N deposition than ombrotrophic bogs and shallow soft-water bodies (35-70 meq m^{-2} yr^{-1}). The main effects on wetlands are an increase in tall grasses, decline of diversity and disruption of the N cycle.

Bobbink *et al.* (1996) also suggested how to use the ranges on the basis of abiotic factors (**Table 4.1**). In general, low temperatures, dry soil conditions, long frost periods and low base-cation saturation cause higher sensitivities than high temperatures, soil wetness, absence of frost and fertile soils (high base-cation saturation). As soil pH and soil fertility are indicators for the availability of base cations, we used these two properties to represent base cations saturation.

On the basis of these rules, we have extrapolated the critical load methodology to ecosystems outside of Europe. On the basis of the land-cover/vegetation database from Olson *et al.* (1983) at a 0.5^{o}x0.5^{o} grid groupings were made, based on the expected sensitivity.

Table 4.1: Ranges for critical loads for N for terrestrial ecosystems

Range (sensitivity)	Temperature	Soil wetness	Frost period	Base cation availability
Lower part of range (high sensitivity)	cold	dry	long	low
Middle part of range (medium sensitivity)	moderate	normal	short	medium
Higher part of range (low sensitivity)	hot	wet	none	high

Source: Bobbink *et al.* (1996).

Different classes were distinguished on the basis of soil and climate. Class 2 represents ecosystems with intermediate susceptibility, generally in moderate climates, and for soils with intermediate pH, base saturation and drainage. Class 1 includes ecosystems with high susceptibility to N inputs, generally caused by low soil pH, low base saturation, dry soil conditions, or permafrost. Class 3, for ecosystems with low susceptibility to enhanced N deposition, includes warm climates, soils with poor drainage (wet conditions), high base saturation and high pH. To assess the susceptibility of the analysis to variations in critical loads, ranges of critical loads were established by using high, medium and low values within each class on the basis of the range quoted in the literature (**Table 4.2**).

The highest critical load values were assumed for tropical rain forest, tropical seasonal forest and mangroves (**Table 4.2**). Rain forests are known to be limited by phosphorous (P) (Bouwman *et al.*, 1993; Vitousek *et al.*, 1997), and not by N. Hence, addition of minor amounts of N are expected to affect leaching rates much more than species diversity or biological processes, with a range for class 2 for this group of 145-215 meq m^{-2} yr^{-1}.

Table 4.2: Ranges of critical loads for N deposition for groups of vegetation types and three soil classes[a]

Type	Soil class 1[b] High susceptibility			Soil class 2[b] Medium susceptibility			Soil class 3[b] Low susceptibility		
	L	M	H	L	M	H	L	M	H
	in meq m^{-2} yr^{-1}								
Tropical ecosystems									
Tropical rain forest, seasonal forest, mangroves	70	105	145	145	180	215	215	250	285
Tropical dry forests	35	55	70	70	105	145	145	180	215
Savannahs, semi-arid woods, thorns, low scrub, tropical montane forest	20	30	35	35	55	70	70	90	105
Mediterranean grasslands, warm grass / shrub	55	65	70	70	90	105	105	125	145
Temperate ecosystems									
Temperate forests, woods in agricultural areas, cool grass/shrub	35	55	70	70	90	105	105	125	145
Tundra, taiga, Siberian parks	20	25	35	35	55	70	70	90	105
Bogs, heaths/moors	20	25	35	35	45	55	55	65	70
Marsh/swamp	55	65	70	70	90	105	105	125	145
Deserts	35	55	70	70	90	105	105	125	145

Source: Vegetation types are based on Olson *et al.* (1983). Values are based on Bobbink *et al.* (1996) and the suggested use of ranges as presented in **Table 4.1**.

[a] Soil properties determine the column from which critical loads are selected. In this study three different ranges are used to assess the uncertainties in critical loads and deposition fluxes. For the *low range* of critical loads, all lower values (L) from the soil classes 1-3 are used. For the *high range,* the highest number (H) from soil class 1-3 is taken, while for the *medium range* of critical loads, the medium values (M) are used.

[a] Soil Class 2 includes all soils with intermediate climatic conditions, pH, base saturation and drainage. Class 3 includes soils with high base saturation, high pH, soils in warm climates and wet soils with impeded drainage. Class 1 includes susceptible soil regions with cold climates, low pH, low base saturation and soils with permafrost.

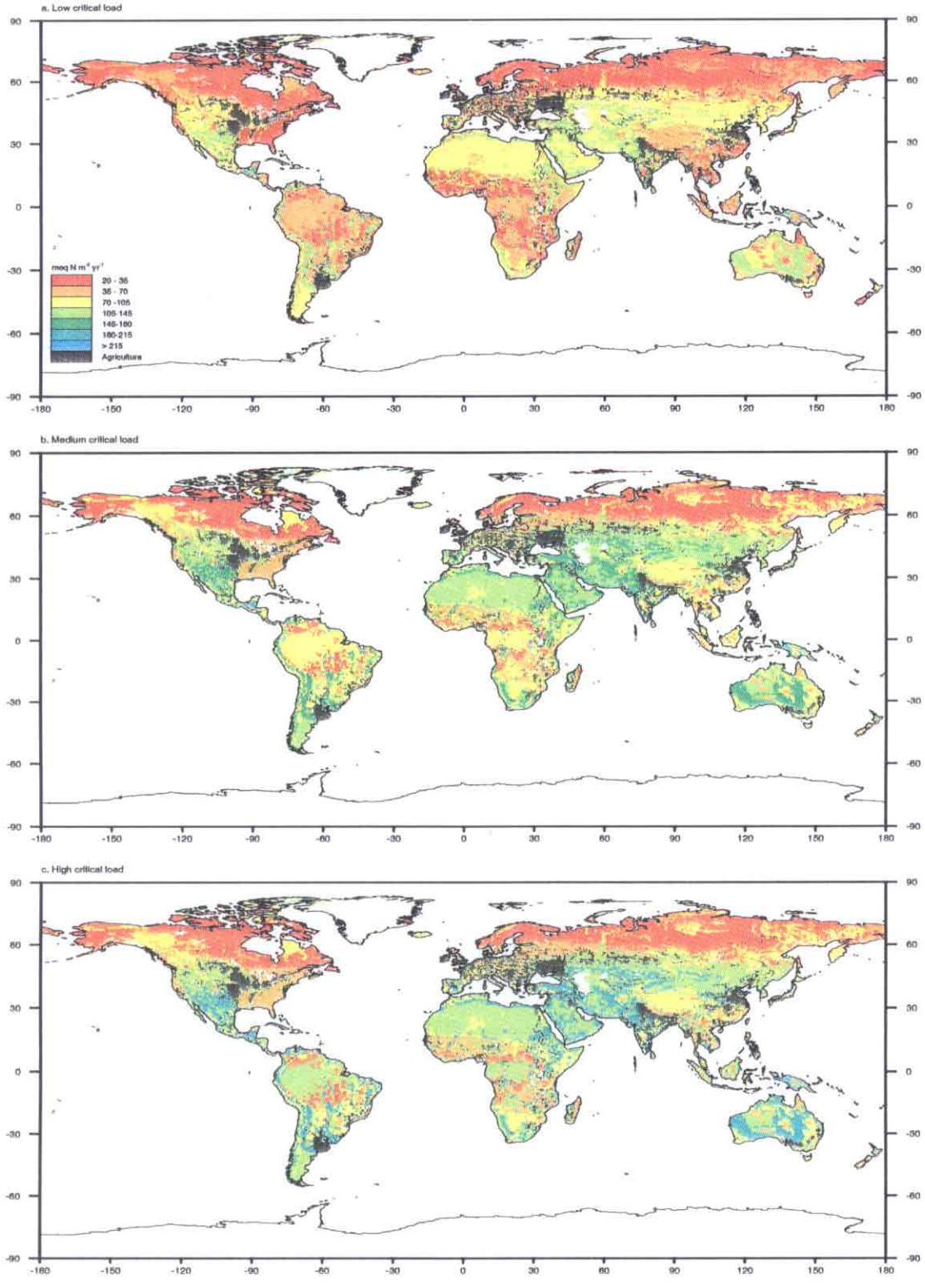

Figure 4.1: Global distribution of critical loads for N-eutrophication for (a) low range; (b) medium range; (c) high range estimates (see Table 4.2)

Similar to the European montane forests, we assumed tropical montane forests to have a low range for class 2 soils (35-70 meq m^{-2} yr^{-1}). Tropical dry forests, savannah ecosystems, semi-arid woods, and scrub-rich and thorny vegetation types have lower citical loads than tropical ecosystems with higher annual precipitation. In these systems N is concentrated under natural conditions in tree spots, while in the intermediate tree-free spaces, N is more limited. Particularly in these open spaces, addition of N may affect species diversity. For tropical dry forests the range for class 2 soils of 70-145 meq m^{-2} yr^{-1} is assumed to be somewhat higher than for savannah systems (35-70 meq m^{-2} yr^{-1}).

As for European grasslands and eutrophic wetlands, susceptibility to N of Mediterranean and tropical grassland and marshes is assumed to be lower than for some forest ecosystems. However, on the basis of higher temperatures the critical loads are higher (105-145 meq m^{-2} yr^{-1} for grasslands in the range for class 2 soils and 105-180 meq m^{-2} yr^{-1} for marshes) than for their temperate counterparts, which have a range of 70-105 meq m^{-2} yr^{-1} for class 2 soils.

Similar to the European values, critical loads in the class 2 soil range for temperate forests are 70-105 meq m^{-2} yr^{-1}. In colder regions with tundra, taiga and Siberian parks lower critical loads (35-70 meq m^{-2} yr^{-1}) are used for class 2 soils. Finally, desert ecosystems are assumed to have values comparable to those of temperate grasslands, as in these systems addition of N may affect diversity of the sparse vegetation.

In the assessment of eutrophication risks, the three ranges of critical loads are used as alternative sets to evaluate sensitivity versus N deposition. This gives some indication of the uncertainties involved. The distribution of critical loads (**Table 4.2**) presented in **Figure 4.1** shows that for all three ranges of critical loads, the regions with the highest susceptibility to N deposition are in northern Canada, Scandinavia and northern Russia. However, the extent of these regions is much smaller for the high range of critical loads than for the low range. Scattered regions of high susceptibility occur in South America and Africa. In tropical forests the low soil pH is the major cause of low critical loads, while in other regions the ecosystem itself (savannah and other dry and semi-arid vegetation types) has a high susceptibility, locally amplified by low soil pH. Intermediate susceptibility occurs in the western USA, Europe and Russia.

4.2. Eutrophication hazard

By comparing the three ranges of critical loads (low, medium and high) with the total N deposition, potentially affected regions can be identified. In **Figure 4.2** the affected regions were grouped on the basis of the eutrophication risk expressed as the exceedance ratio (N deposition divided by the critical load). It should be noted that vegetation types with a high surface roughness may actually experience higher deposition fluxes than those calculated for $5^{o}x5^{o}$ grids. Hence, for a ratio of 0.75, the critical loads may, under certain conditions, already be exceeded.

Areas in the various classes of the exceedance ratio are presented in **Annex 4** for the current situation, and in **Annex 5** for the CRP scenario for 2015. Location and extent of (agro-) ecosystems are assumed not to change between 1992 and 2015. Summarised results in **Table 4.3** indicate that in 7-18% of the global area of (semi-)natural ecosystems the exceedance ratio is greater than 1.0 for the medium estimates of the critical load. In particular, N deposition in OECD Europe exceeds critical loads (~30% of the area of (semi-)natural eco-

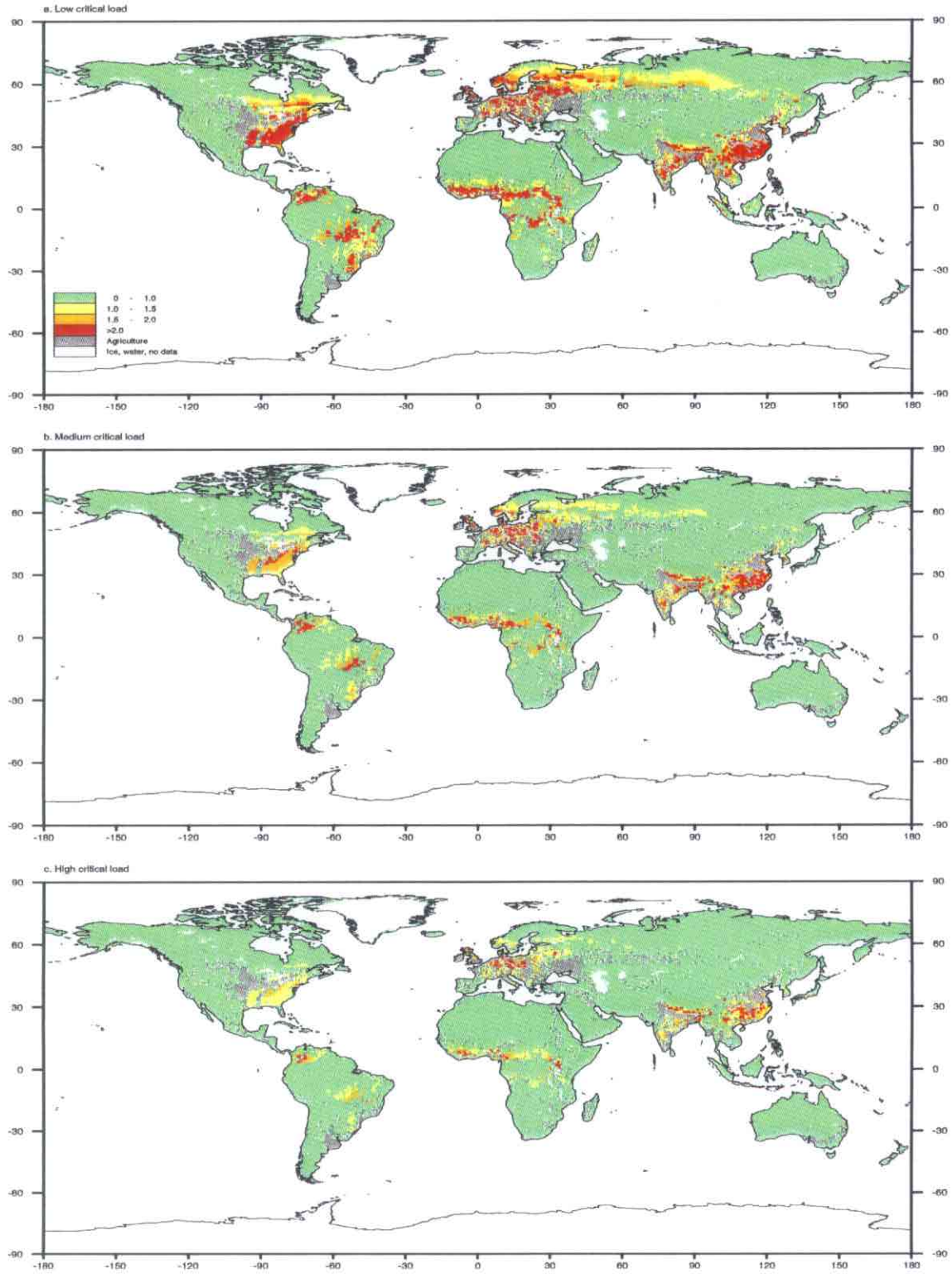

Figure 4.2. Global distribution of the eutrophication exceedance ratio for terrestrial (semi-) natural ecosystems for 1992, using (a) low estimates of critical loads; (b) medium estimates and (c) high estimates

Table 4.3: Exceedance of critical loads for eutrophication for 18 world regions

	1992				CRP 2015[d]
Sensitivity assumed:	High[b]	Medium[b]	Low[b]	Medium[b]	Medium[b]
Exceedance classes[c]:	>1	>1	>1	>2	> 1
	(% of natural areas)				
Canada	17	5	2	0	6
USA	25	21	18	2	22
Central America	3	1	0	0	1
South America	21	12	7	3	14
Northern Africa	0	0	0	0	0
Western Africa	27	16	13	4	17
Eastern Africa	15	8	6	2	9
Southern Africa	11	4	2	0	4
OECD Europe	45	32	20	8	32
Eastern Europe	77	61	44	28	65
Former USSR	21	9	3	0	12
Middle East	1	0	0	0	1
South Asia	38	32	24	9	36
East Asia	25	19	15	8	23
South East Asia	22	12	6	2	14
Oceania	0	0	0	0	0
Japan	9	6	3	0	9
Greenland	0	0	0	0	0
Global land area	18	11	7	2	12

[a] Exceedance ratio = ratio deposition : critical load

[b] Sensitivity : High = Low range of critical loads; Medium = Medium range of critical loads; Low = High range of critical loads.

[c] Exceedance class: > 1.0 indicates the percentage of the area (semi-)natural ecosystems with an exceedance ratio > 1.0; > 2.0 indicates the percentage of (semi-)natural ecosystems with exceedance ratio > 2.0 (severe risk).

[d] CRP 2015 indicates the results under the CRP scenario for 2015 (using medium critical loads).

systems), Eastern Europe (~60%) and North America (~20% of the USA and 5% of Canada) for the medium critical load. In the former USSR the affected area of (semi-)natural ecosystems is 9% for the medium critical load, mainly in remote tundra and taiga ecosystems.

Within the group of developing countries, Asian and African countries have extensive areas of (semi-)natural ecosystems where critical loads are exceeded by N deposition (South Asia, 32%, East Asia, 19%, and South East Asia, 12%, Western Africa, 16% and Eastern Africa, 8%). According to our results for the medium critical load in Central and South America in 1% and 12% of the natural and semi-natural ecosystems, respectively, the exceedance ratio is greater than 1.0.

The results suggest that a number of regions with low population densities, such as South America and Africa, and remote regions such as Canada and the former USSR, may be affected by N eutrophication. This result is consistent in all three ranges of critical loads.

Following the CRP scenario, in the coming decades the areas with exceedance ratios > 1.0 will not change significantly in most developed countries; they will increase slightly in most tropical regions, including South America, Africa, South, East and South East Asia and Japan (**Table 4.3 and Figure 4.3**). The projected eutrophication risk differs from that for acidification, as in the CRP scenario no reduction plans were assumed for NH_3 gas emissions in Europe and North America and the emissions of NO_x stabilise.

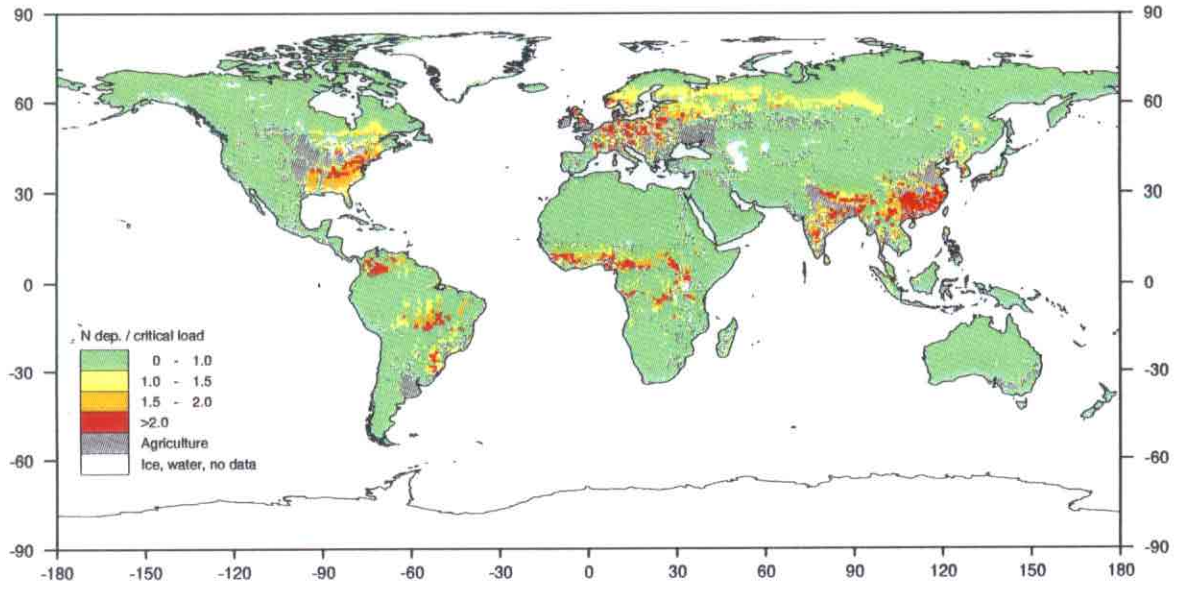

Figure 4.3 Global distribution of the eutrophication exceedance ratio for terrestrial (semi-) natural ecosystems for 2015 according to the CRP-scenario

5. Global nitrogen loading of aquatic systems

5.1. Nitrogen inputs to world rivers and transport to estuaries and coastal seas

Nitrogen concentrations in surface waters have increased over time. Historical data indicate that nitrate fluxes and concentrations in the large rivers of the world are correlated with human population densities in watersheds (Cole *et al.*, 1993).

Nitrogen in streams and rivers draining relatively undisturbed forests is largely organic (references in Vitousek *et al.*, 1997). With increasing human disturbance, the total N fluxes will increase, with a higher proportion composed of nitrate (Howarth *et al.*, 1996). Using relatively undisturbed areas as references, Howarth *et al.* (1996) estimated that riverine total N fluxes from most of the temperate regions surrounding the North Atlantic Ocean have increased from pre-industrial times by 2 to 20-fold. For the North Sea regions the N increase may have been 6- to 20-fold. Increased N concentrations of nitrate have also been observed in groundwater in many agricultural regions, although the magnitude of this storage is difficult to determine outside a few well characterised aquifers.

Nitrogen inputs to rivers originate from natural and anthropogenic sources throughout the terrestrial environment. These sources of riverine N include diffuse sources (groundwater, storm runoff and atmospheric deposition) and point sources (mainly human population concentrations in cities). The rivers draining the continents eventually empty into the coastal seas, continental shelves and oceans at estuaries, thus forming the major conduit for N transport to estuaries.

The results of a recent analysis by Seitzinger and Kroeze (1998) can be used to illustrate the magnitude of global N inputs to rivers and aquifers. In this study, a simple model, developed by Caraco and Cole (1998), was adopted to estimate the dissolved inorganic nitrogen (DIN) transport by rivers on the basis of a relationship developed for 35 major world rivers. DIN transport was described as a function of N inputs from human sewage, fertiliser use and atmospheric N deposition. The relationship was applied to a modified version of the database of watersheds developed by Cogley (1994). Results were calculated for all rivers within a watershed, and presented for the 177 watersheds in the data base and 303 estuarine grid cells mapped by Seitzinger and Kroeze (1998).

Fertiliser use represents both the use of synthetic fertilisers and animal manure, for which global inventories were developed by Bouwman *et al.* (1995). The global estimates of atmospheric N deposition used by Seitzinger and Kroeze were those for NO_x presented by Holland *et al.* (1997) and Lelieveld *et al.* (1998) for NO_x. Human sewage production is based on the inventory of human population densities used by Olivier *et al.* (1996) in the IGAC-GEIA project.

The results presented in **Figure 5.1** indicate that largest riverine DIN transport and N inputs to estuaries are found in OECD Europe and Eastern Europe, north-eastern United States, South Asia, East Asia and South East Asia. There is over a 1000-fold range in DIN transport rates by rivers to estuaries in the 177 watersheds considered (**Figure 5.1**). The highest DIN yield was calculated for the Rhine watershed. Watersheds in South East Asia, the South

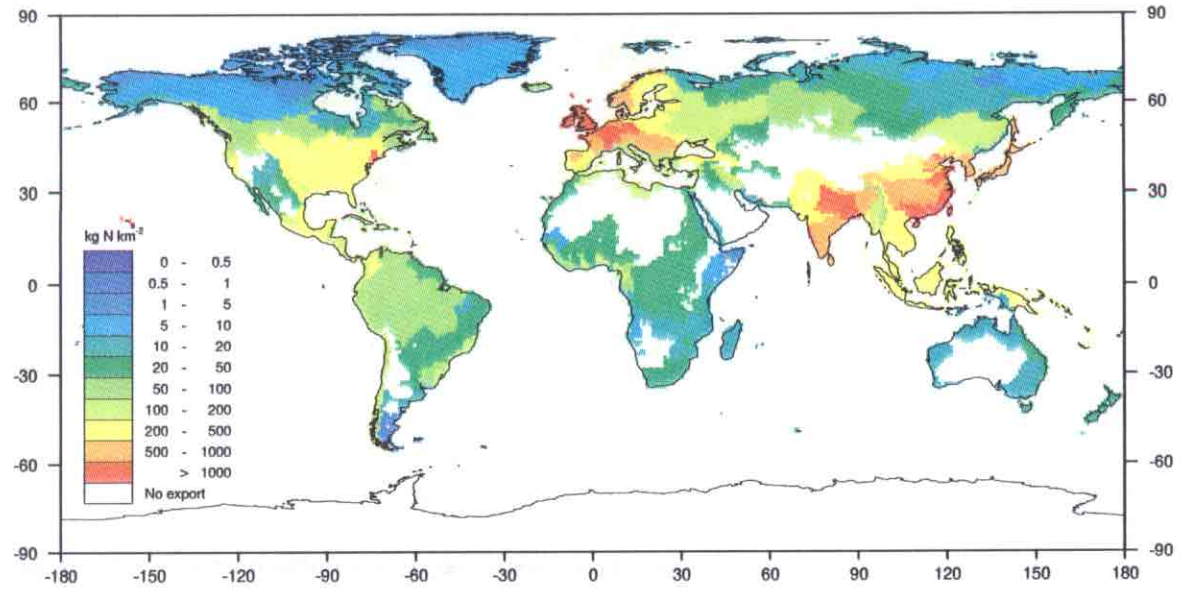

Figure 5.1: Riverine transport of dissolved inorganic nitrogen (DIN) to estuaries due to all sources.
Source: Seitzinger and Kroeze (1998).
Units are kg N km^{-2} per year. Highest rates of riverine nitrogen transport occur in Europe, and South and East Asia.

Pacific islands, the USA east of the Rocky Mountains, parts of western Central America, northwest India, and the Baltic, Caspian and Black Seas also had relatively high DIN yields varying between 200-500 kg N km^{-2}. Intermediate DIN rates of 20 to 200 kg N km^{-2} can be seen in Africa, Russia south of 60°N, South America, western North America and Canada below 50°N. The owest rates were estimated for northern regions (Canada north of 50°N, Asia north of 60°N) and arid regions in Argentina, USA, Eastern Africa, the Middle East and Australia.

Seitzinger and Kroeze (1998) have estimated the contributions to total DIN transport from fertiliser use, atmospheric N deposition and human sewage on the basis of the model discussed above. Worldwide about 58% of the total DIN transport of 20.8 Tg N yr^{-1} stems from fertilisers, while human sewage and deposition account for 24 and 18%, respectively. The contributions of the three sources of N inputs presented in **Figure 5.2** show the contributions to N transport from fertiliser use, deposition and human population to have very similar patterns, with the highest N transport in OECD Europe, Eastern Europe and South and East Asia.

On a regional scale similar calculations have been carried out for Europe using the CARMEN model (Klepper *et al.*, 1995) on a 10°x10° resolution. The transport to European coastal seas was calculated from the total N load of surface waters in watersheds, retention within watersheds and atmospheric deposition (**Figure 5.3**). Results indicate that concentrations also strongly depend on the hydrological conditions of coastal waters, with high concentrations in the Baltic and Black Seas, where less exchange occurs with oceanic waters, and lower concentrations in the North Sea, where water is constantly refreshed with oceanic water.

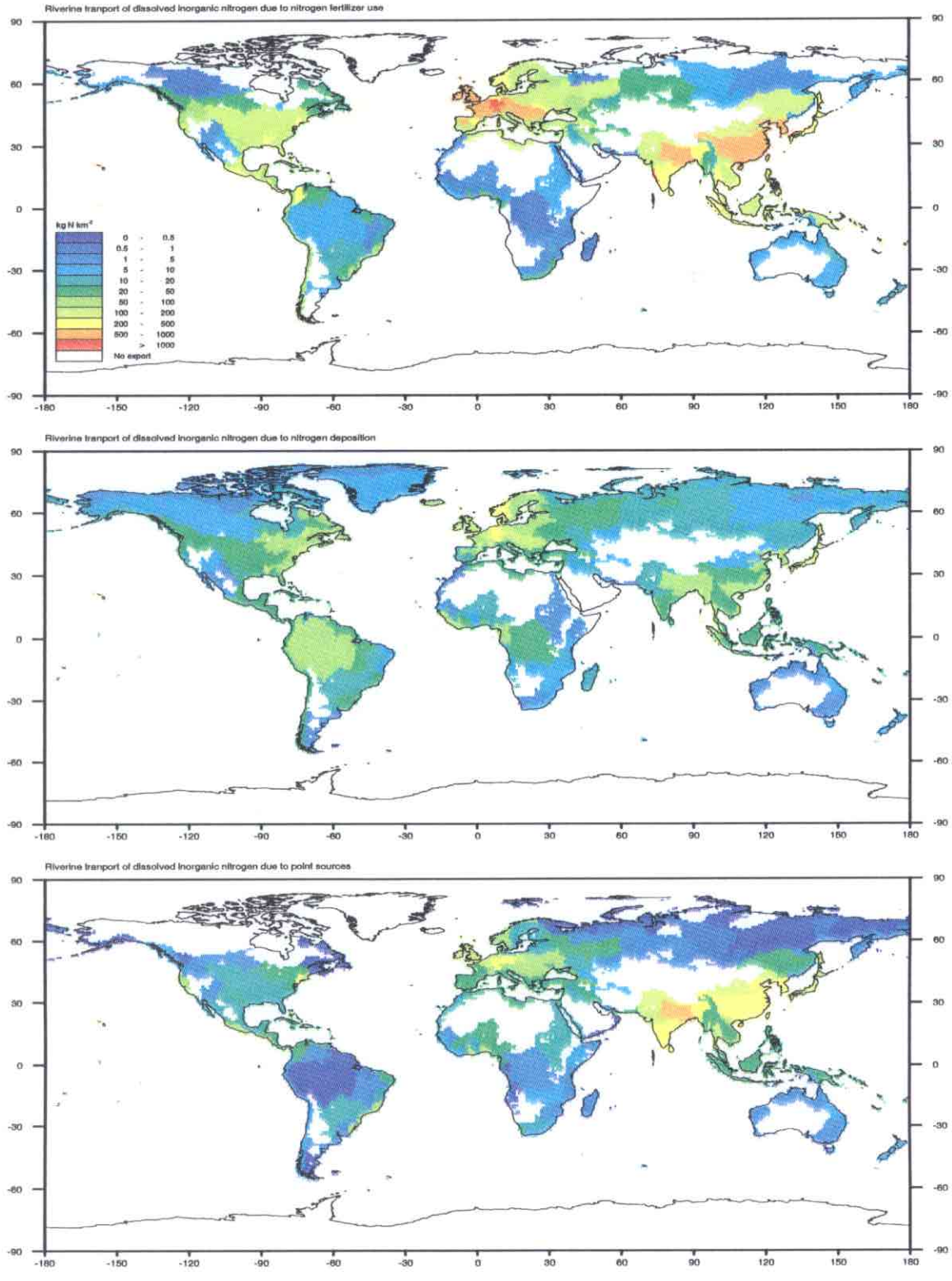

Figure 5.2: Predicted export of dissolved inorganic nitrogen (DIN) attributed to (a) fertilizer use; (b) N deposition; (c) human sewage
Source: Seitzinger and Kroeze (1998).
Units are kg N km^{-2} year.

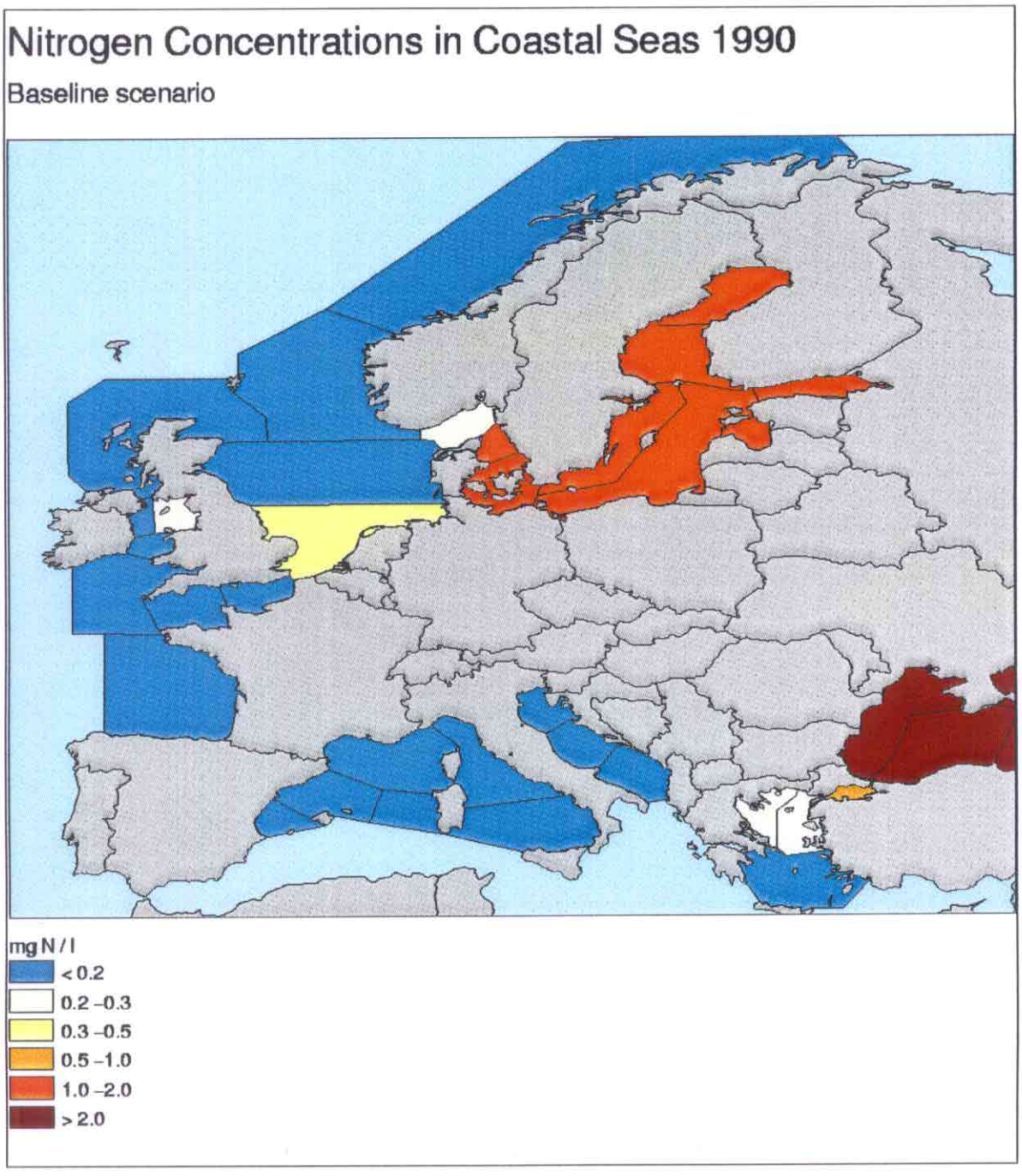

Figure 5.3: Potential N concentrations in coastal seas
Source: Klepper *et al.* 1995.

5.2. Effects of nitrogen

In freshwater systems with sufficient P, addition of inorganic N can cause eutrophication. This can occur either independently or coupled to acidification (Schindler *et al.*, 1985). Decreased diversity of both plant and animal species generally accompanies both eutrophication and acidification.

Most often, eutrophication in estuaries and coastal seas is caused by anthropogenic N loading, in sharp contrast with freshwater systems where P limits net primary production and controlling eutrophication (Schindler, 1977). Eutrophication can cause hypoxia and anoxia,

both of which appear to have become more prevalent in many estuaries and coastal seas. Low oxygen conditions have resulted in significant losses of fish and shellfish sources. Increasing anoxia has been observed in the Baltic Sea, Black Sea and Chesapeake Bay, while hypoxic events have increased in the North Sea, the Kattegat and Long Island Sound. Eutrophication is also associated with a loss of diversity both in the benthic community and among planktonic organisms, as manifested by incidence of nuisance algae blooms in many estuaries and coastal seas (Vitousek *et al.*, 1997, including references).

For freshwater ecosystems, estuaries and coastal seas it is difficult to establish a system of critical loads for N. This is caused by the complexity of the interactions between N and P in eutrophication in these systems, and the high seasonal and interannual variability of weather conditions causing runoff and associated N inputs and water discharge. Therefore, the anthropogenic N transport, here assumed to be represented by DIN, is used as an indication of the potential for eutrophication.

6. Uncertainties and knowledge gaps

6.1. Uncertainties

There are considerable uncertainties involved in the assessments presented in this study, as will be discussed in this chapter. In view of them, the results must be interpreted as broadly indicative of the geographic distribution of acidification and eutrophication of (semi-)natural ecosystems. In fact, the study intends to be above all, a scoping study to identify high risk areas and the current understanding of acidification and eutrophication risks at a global scale. All these uncertainties aside, the global critical loads map and the exceedance of critical loads for acidification of terrestrial ecosystems show patterns similar to those of regional (more detailed) maps.

In this study ranges of critical loads have been presented for acidification and eutrophication. For the deposition fluxes we have no expression of uncertainty. The available deposition fields are model results and it is not within the scope of this study to compare model results with measured deposition fluxes of S and N, nor to perform a model intercomparison as proposed by Sofiev (1999) to assess the uncertainties in deposition fluxes. Because the exceedance ratio is calculated as the ratio deposition / critical load, the range in critical loads can be interpreted as a result of the uncertainty in both deposition and ecosystem sensitivity.

Below we will discuss main uncertainties related to emissions, deposition, critical loads and riverine N transport to estuaries and coastal seas, and give recommendations for future research.

Emissions and deposition

Major uncertainties are found in the deposition fluxes, stemming from the underlying emission estimates and the atmospheric chemistry transport models used. Uncertainties in emissions are discussed in Olivier *et al.* (1998), Lee *et al.* (1997) and Bouwman *et al.* (1997). These articles indicate that uncertainties vary strongly from one region to another, and that uncertainties are associated with scarcity of data, particularly on agricultural management, flux measurements for diffuse sources such as soils and aquatic systems, and re-absorption of N gases by canopies in terrestrial ecosystems.

The uncertainty in atmospheric models can be expressed by the important disagreement between different models, as was discussed by Holland *et al.* (1997). Differences in atmospheric sources of N gas emissions, transport, and resolution and representation of chemical reactions contributed to distinct spatial and temporal patterns of N deposition simulated by different models.

Apart from the uncertainties in the emission and deposition fields, there may be errors resulting from the scale used and from differences between the resolution of the various spatial databases. The 0.5^{o}x0.5^{o} resolution for vegetation data, for example, does not have sufficient detail to include certain ecosystems such as wetlands. An evident example of a scaling error is the overlaying of low resolution deposition fields (5^{o}x5^{o}) with high resolution critical load values for terrestrial ecosystems (0.5^{o}x0.5^{o}), as done in this study. In reality, considerable variability occurs within the 5^{o}x5^{o} deposition fields. It is this variability on small-temporal and temporal scales which may strongly influence the exceedance of critical

loads. This variability has not been taken into account here.

A further uncertainty is the deposition of base cations. Here, an assessment of soil dust deposition was used. By assuming a Ca content of 20% for all soil dust particles irrespective of their origin, the estimates are consistent with a number of point measurements in Europe and Asia. However, soil dust is not the only source of Ca deposition, and soil dust also contains other base cations and weatherable minerals. In addition, maximum soil Ca content in soils are less than 10%, indicating that in remote regions the assumption of a 20% Ca content may be an overestimate. Using a soil-Ca content presented in Lee *et al.* (1999) as an input for the model of Tegen and Fung (1994) yielded much lower Ca deposition rates from soil dust than the above described approximation.

Critical loads for acidification in terrestrial ecosystems
The uncertainty in deposition estimates and sensitivity on the global scale is high, with the effects of N deposition in tropical ecosystems particularly poorly known. For Europe and South East Asia the global map shows a good correspondence with results of regional acidification assessments (e.g. Posch et al., 1997; Foell et al., 1995), despite the differences in the scale of calculations. Rates of immobilisation and denitrification (in particular in tropical ecosystems) are rather uncertain. In addition, acidification of soils is not only influenced by external inputs of acidity. In the long term, ecosystem acidification also results from the cation and anion balance during growth of vegetation, affecting proton release (Markewitz *et al.*, 1998).

Critical loads for eutrophication in terrestrial ecosystems
Bobbink *et al.* (1996) identified a number of major gaps in knowledge on effects of enhanced N inputs through deposition on temperate terrestrial and aquatic ecosystems. These gaps follow: (i) quantified effects of enhanced N deposition on fauna are extremely scarce; (ii) critical loads for N deposition to arctic and alpine ecosystems are highly speculative, and those for steppe grasslands, Mediterranean vegetation types, high altitude forests, and ecosystems on neutral and calcareous soils require further research; (iii) most research carried out so far has focused on effects of enhanced deposition on trees only, and more research is needed to quantify effects on ground vegetation and (ground) fauna.

For temperate ecosystems outside Western Europe, major uncertainties are in the permafrost regions and cold northern taiga and tundra ecosystems. On the basis of Bobbink *et al.* (1996), low critical load values were assumed for these systems. Critical N loads for the tropical ecosystems are completely based on assumptions. Most uncertain are the susceptibilities of dry tropical ecosystems, including savannahs, dry tropical forests, semi-arid systems and tropical grasslands.

Another uncertainty is how the ecosystems' sensitivity will change under the influence of climate change and anthropogenic N inputs. This may be most important in temperate and cold climates, such as the above-mentioned arctic, alpine, steppe and high altitude ecosystems.

Riverine N transport
The analysis for the aquatic systems is based on a simple model developed by Caraco and Cole (1998) to estimate the dissolved inorganic nitrogen (DIN) transport by rivers as a function of point source N inputs from human sewage and diffuse N inputs from fertiliser use

and atmospheric N deposition. Measured values were compared with modelled results, resulting in a regression coefficient (r^2) of 0.84. Regressions based on a least squares fitting are known to be non-robust methods, where results may highly depend on a few observations in the data set used. The regression equation is applied globally to watersheds on the basis of country average use of fertiliser and animal manure, and the above low-resolution deposition flux fields. This may cause a problem if the amount of N exported by rivers depends on the level of the N loading from fertilisers, or if a certain threshold value exists below which export may be negligible. This may be important in agricultural regions, where often only a fraction of the area of a specific crop is fertilised, and where important differences exist in fertiliser application rates between crops (Bouwman, 1998). Hence the model used only gives an indication of the magnitude of riverine DIN transports.

Overall
For the identification of acidification and eutrophication risks for terrestrial ecosystems, the most important causes of uncertainty seem to be the assumed sensitivity of tropical ecosystems to deposition of N and S. In those regions where other sources were available, i.e.. the temperate zones of North America and Europe, the results of our assessment seem to comply to more detailed, regional assessments. Also the deposition of base cations is currently highly uncertain outside the well-studied areas of Europe, North America, and to some lesser degree East Asia. As the sensitivity of some tropical ecosystems to N and S deposition is very high, small deposition flows of N and S can lead to exceedances. For these regions, the assessment is, consequently, also very sensitive to uncertainties in deposition. Comparison of the CRP scenario applied in this study to those used in other studies suggests that the scenario used, in general, can be regarded as a medium-growth scenario.

6.2. Recommendations regarding gaps in knowledge

On the basis of this analysis a number of recommendations related to improvements in the geographic distributions of land use and associated emission estimates, deposition calculations, and determination of susceptibility of terrestrial and aquatic ecosystems to N enrichment can be given..

N and S emissions and deposition
Uncertainties in emission estimates are associated with scarcity of data on agricultural management, flux estimates for diffuse sources such as soils and aquatic systems, and re-absorption of N gases by canopies in terrestrial ecosystems. Uncertainties can be reduced by applying various scaling approaches. Examples of such approaches include the delineation of functional types in ecosystems and the use of flux models, as discussed by Bouwman *et al.* (1999). For most gases, flux measurements are required according to measurement strategies based on the functional types.

The emission scenarios used in this study have been most elaborately worked out for Europe and the United States, where currently existing policies have been integrated into the emission scenarios. For other regions, the emission scenarios are simple extrapolations, not based on existing plans and policies.

Deposition fluxes are derived from the 5^{o}x5^{o} grid calculations of the STOCHEM model. Important improvements can be achieved by:

1. Performing calculations on a $1^{o}x1^{o}$ grid using a source receptor matrix derived from other atmospheric models. Such an approach could be used for regions such as Europe. On the global scale the matrices will become too large to handle with current computer resources.
2. As an alternative, the global STOCHEM calculations can be refined to a $1^{o}x1^{o}$ grid by accounting for the local contribution as a function of local/regional meteorology and land cover/land use. Such a method is similar to approximations used for calculations of small-scale N deposition in Europe (EDACS, EUTREND), for example.
3. A third alternative approach can be used if only country-scale emissions are available. This approach consists of establishing source-receptor matrices for NO_x and NH_x that summarise the various chemical and transport processes of the two species in the atmosphere. Whether or not this matrix can be assumed to be linear needs to be investigated in relation to the scale of the calculations (time scale of one year, spatial scale of hundreds on km). This approach is contained in the IMAGE2 models for computation of sulphur deposition (Alcamo *et al.*, 1995) and is also appropriate for scenario analysis.

Base cation deposition
As an improvement for obtaining a better spatial distribution of base cation deposition, the approach for soil dust with actual soil Ca contents should be complemented with base cation deposition modelled from inventories of base cation emissions from industrial and combustion sources.

Soil N cycle
For N deposition, however, processes such as leaching, immobilisation and denitrification, as indicated in this report, play an important role. Here, relatively simple equations have been used to incorporate these processes into our analysis. In addition, the net uptake of N by plants was assumed to be negligible. A simple model describing these processes would form a major improvement.

Critical loads for terrestrial ecosystems
The global critical loads map for acidification of terrestrial ecosystems has been attuned relatively well to regional (more detailed) maps relatively well. However, quantified effects of enhanced S and N deposition on fauna are extremely scarce. In particular, critical loads for eutrophication for arctic and alpine heath lands, steppe grasslands, Mediterranean vegetation types, high altitude forests, ecosystems on neutral and calcareous soils, permafrost regions, taiga and tundra ecosystems, and basically all tropical ecosystems are highly uncertain. In particular, quantified effects of N enrichment on ground vegetation and (ground) fauna are required.

One way to improve these estimates is by stimulating manipulation of S and N inputs with realistic treatments in long-term ecosystem studies in unaffected and affected areas. Results from such experiments are essential to verifying dynamic ecosystem models which integrate the major vegetation and soil processes. However, it cannot be expected that experimental data will be available within the next decade. Therefore an alternative would be to consult experts world-wide to assess the available research data so as to arrive at a system of default values in the meantime. Regional studies, based on more detailed maps which better present the mozaic of ecosystems that could not be included with the 0.5^{o} resolution database used in this study are also required.

Interactions with other environmental stresses
The impacts of acidification and eutrophication are in reality strongly coupled with other environmental stresses, including climate change. Hence, in future studies not only should S and N deposition be addressed, but also climate change and rising atmospheric CO_2 concentrations. Eutrophication studies could then also consider effects of increasing N inputs, changing climate and the CO_2 fertilisation effect on ecosystem net primary production, and emissions of N gases such as nitrous oxide and nitrogen oxides.

Riverine N transport
The global analysis of riverine DIN transport to estuaries is a good illustration of the distribution of estuaries and coastal seas affected by potential eutrophication. However, the method can only be used to estimate total river transport at the river mouth. To calculate concentrations of *total* N in freshwater systems, in combination with P, a similar but more advanced approach could be used. For this, river discharge at any point needs to be calculated on the basis of precipitation surplus, runoff and flow to groundwater. Together with N and P in the runoff, concentrations in the water can be calculated. The model used to calculate river discharge also calculates the water percolation through the soils into aquifers. Hence, the same method could be used to calculate N and P leaching to groundwater.

7. Conclusions

The objective of this study was to make a global inventory of the geographic distribution of acidification and eutrophication. Moreover, the study aimed to contribute to the identification of data and knowledge gaps in this area.

Acidification of terrestrial ecosystems
According to our results based on the medium estimates of critical loads, current acidification is most prominent in the industrialised countries of Europe and the western part of the United States and Canada (**Table 7.1**). However, the study indicates that currently critical loads are exceeded in the south-eastern part of part of Brazil and the La Plata region, some parts of Siberia, the southern part of Western Africa, central Africa, the eastern part of China and parts of South East Asia. In some parts (in particular, tropical ecosystems) the high sensitivity of ecosystems causes exceedance, even at low N and S deposition rates. In total, net acid deposition exceeds the medium critical loads in about 10% of the world's (semi-)natural terrestrial ecosystems.

The Current Reduction Plans (CRP) scenario assumes moderately increasing emissions in most regions between 1992 and 2015, loosely following the IPCC IS92a scenario. In Europe and the U.S.A., however, the scenario assumes decreasing emissions, thus incorparing existing policy targets and planned policy efforts within these regions. According to the CRP emissions scenario, acidification risks will decrease in Europe and North America. In other world regions (in particular, Siberia, China, South East Asia, Southern Africa) acidification will increase significantly, both with respect to the area affected and the severity of exceedance of critical loads. For the world as a whole, in 2015 net acid deposition exceeds the medium critical loads in 11% of the area of terrestrial (semi-) natural ecosystems. This means that in the relatively short time period covered (15-20 years) the global problem of acidification could become more wide-spread and in some regions more intense.

Table 7.1: (Semi-)natural Ecosystems exposed to acidification and eutrophication risks

Region	% of (semi-)natural ecosystems area with exceedance ratio[a] >1.0				Ecosystem most affected
	Acidification		Eutrophication		
Canada	14	(10-20)	5	(2-17)	Temperate forest
USA	24	(23-26)	21	(18-25)	Temperate forest
South America	12	(5-29)	12	(7-21)	Tropical seasonal and dry forest,
Western Africa	12	(7-20)	16	(13-27)	Savannahs
Eastern Africa	3	(2-5)	8	(6-15)	Savannahs
Southern Africa	5	(2-14)	4	(2-11)	Savannahs
OECD Europe	35	(25-45)	32	(20-45)	Temperate forests
Eastern Europe	47	(39-63)	61	(44-77)	Temperate forests
Former USSR	5	(2-8)	9	(3-21)	Tundra and taiga ecosystems
South Asia	6	(3-8)	32	(24-38)	Tropical forests
East Asia	15	(13-17)	19	(15-25)	Tropical forests
South East Asia	21	(9-36)	12	(6-22)	Tropical rainforests
Japan	11	(4-15)	6	(3-9)	Temperate forests
World	10	(6-15)	11	(7-18)	

[a] Exceedance ratio = deposition : critical load. The results for acidification and eutrophication are presented as the percentage of the area of (semi-)natural ecosystems where the exceedance ratio > 1.0. The first number is the percentage for the medium estimate of the critical load; the results for the low and high critical load estimates are in parentheses.

Despite all the uncertainties discussed, the results show good agreement with assessments made on the regional scale for Europe and Asia (Foell *et al.,* 1995; Posch *et al.*, 1997). In general, the results of this assessment agree with other global studies such as Rodhe *et al.* (1988) and Kuylenstierna *et al.* (1998). However, most of them only considered S deposition. Including N inputs as a cause of acidification, as done in this study, shows that the potentially affected areas is significantly larger and further away from the highly industrialised areas, when compared to previous global studies considering S deposition alone. Hence, N deposition may form an important contribution to acidification.

Eutrophication of terrestrial ecosystems
For assessment of eutrophication risks, we first derived critical loads for terrestrial ecosystems. The regions with the highest sensitivity to N deposition are in northern Canada, Scandinavia and northern Russia. Scattered regions of high sensitivity occur in South America and Africa. In tropical forests the low soil pH is the major cause of low critical load values, while in other parts the ecosystem itself (savannah, and other dry and semi-arid vegetation types) is highly susceptible, locally amplified by low soil pH. Intermediate sensitivity occurs in western USA, Europe and Russia. It should be emphasised that many ecosystems showing high sensitivity (e.g. moorlands, pools, etc.) are not distinguished due to the low resolution of the land-cover database used.

Deposition exceeds critical loads for eutrophication in 7-18% of the global area of (semi-) natural ecosystems (**Table 7.1**). Large parts are affected by N deposition, particularly in OECD Europe (exceedance ratio >1.0 in ~30% of the area of (semi-)natural ecosystems), Eastern Europe (~60%), and North America (~20% in the USA and 5% in Canada) for the medium critical load. In the former USSR 9% of the (semi-)natural ecosystems is affected with reference to medium critical load, mainly remote tundra and taiga ecosystems.

Within the group of developing countries, Asian and African countries have extensive natural and semi-natural areas that are affected by eutrophication (South Asia, 32%, East Asia, 19%, and South East Asia, 12%, Western Africa (16%) and Eastern Africa (8%). According to our results for the medium critical load, deposition exceeds critical loads for eutrophication in Central (1% of the area of (semi-)natural ecosystems) and South America (12%).

The results suggest that, apart from the heavily industrialised regions, a number of regions with low population densities, such as South America and Africa, and remote regions in Canada and the former USSR, may become or already be affected by N eutrophication.

Eutrophication of aquatic ecosystems
Turning to the aquatic ecosystems, about 58% of the total world-wide DIN transport of 20.8 Tg N yr^{-1} comes from fertilisers, while human sewage and deposition account for 24 and 18%, respectively. The contributions to N transport from fertiliser use, deposition and human population show very similar patterns, with the highest N transport in OECD Europe, Eastern Europe and South and East Asia, largely reflecting the distribution of agricultural production intensity and human population.

Acidification and eutrophication
Available emission scenarios suggest that in many tropical regions S and N emissions may strongly increase in the near future, and that problems of acidification and N eutrophication may aggravate and expand over larger areas in these regions. In many cases the two problems

occur simultaneously as result of high deposition of N. However, significant differences between the two risk areas also exist. In general, acidification is more localised in industrialised areas than eutrophication (as result of the fact that a major source of N deposition is agriculture). As a result, in South America, for instance, considerable areas experience eutrophication riks, while acidification risks are low. The most striking differences occur in Japan and Canada (where the area with exceedance of critical loads for acidification is larger than that for eutrophication) and South Asia (where there is very little acidification but a high eutrophication hazard). There may be three reasons for the differences:

1. Deposition of S (which contributes to acidification but not to eutrophication);
2. Differences in soil and ecosystem susceptibility (including the processes of leaching, immobilisation and denitrification);
3. Deposition of base cations.

In the case of India, both 2) and 3) play an important role, causing the low acidification risk. In Canada and Japan differences are caused by the relatively high sensitivity to acidification and high S deposition. In cases where acidification and eutrophication risks occur simultaneously, their combined effect may create significant stress on existing ecosystems.

Uncertainties and research recommendations
There are considerable uncertainties in this study related to emission and deposition estimates, base cation deposition, critical loads and effects of acidification and eutrophication. The results, therefore, must be interpreted as broadly indicative of the geographic distribution of acidification and eutrophication of ecosystems. All the uncertainties aside, the global critical loads map and the exceedance of critical loads for acidification of terrestrial ecosystems show patterns similar to those of regional (more detailed) maps.

It could be worthwile to look in more detail to the potential risk areas identified in this study. Detailed field research to investigate dose–effect relationships, and regional studies of this type, could provide better insights into those areas identified as potential risk areas, such as parts of South America, Western and Southern Africa and parts of Siberia.

The study suggests that both eutrophication and acidification could be classified as universal problems at the global scale (simultaniously occuring at many different places in different regions – but with largely regional dynamics). The areas involved seem to be increasing. The imporantance of global studies, as this one, is to identify potential risk areas, and to give a general overview of the situation.

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Annex 1: Deposition of S and N in 1992 and 2015

Deposition of S and N for 19 world regions and the oceans for the 1992 situation and the situation in 2015, according to the CRP scenario, expressed as total annual deposition, and average deposition rates and standard deviation; minimum and maximum values of deposition rates occurring within each region are given.

	Area	N deposition					S deposition				
		Total	Avg.	Stdv.	Max.	Min.	Total	Avg.	Stdv.	Max.	Min.
	Mha	10^{12}eq N yr^{-1}		meq N m^{-2} yr^{-1}			10^{12}eq S yr^{-1}		meq S m^{-2} yr^{-1}		
1992 Situation											
Canada	975	0.1	15	14	100	2	0.2	17	68	163	3
USA	951	0.4	42	49	106	3	0.4	45	62	199	3
Central America	321	0.1	28	15	49	13	0.1	20	9	50	32
South America	1815	0.5	27	30	68	3	0.2	9	11	49	3
Northern Africa	594	0.1	12	31	36	5	0.0	8	16	36	9
Western Africa	1152	0.4	37	42	91	5	0.1	8	11	77	25
Eastern Africa	602	0.2	32	18	84	5	0.0	8	63	24	12
Southern Africa	699	0.2	24	25	67	8	0.1	13	18	85	9
OECD Europe	433	0.2	57	41	122	6	0.3	74	58	301	7
Eastern Europe	116	0.1	90	92	115	60	0.2	158	169	278	57
Former USSR	2203	0.6	27	22	92	3	0.8	35	30	188	9
Middle East	624	0.2	26	29	60	11	0.1	20	25	72	21
South Asia	533	0.4	81	56	157	17	0.1	18	11	34	15
East Asia	1150	0.6	54	64	148	10	0.4	35	45	118	57
South East Asia	505	0.2	33	20	101	4	0.1	15	32	37	7
Oceania	882	0.1	9	10	19	2	0.0	4	5	30	4
Japan	57	0.0	53	30	65	32	0.0	41	37	57	28
Greenland	220	0.0	5	5	13	1	0.0	3	3	10	6
Antarctica	1316	0.0	0	57	1	0	0.0	0	0	1	0
Global land area	13832	4.4	32				3.2	26			
Oceans	35863	3.6	10	14	146	0	2.6	7	12	222	0
CRP scenario (2015)											
Canada	975	0.2	16	14	103	2	0.1	14	71	119	10
USA	951	0.4	45	52	110	4	0.3	35	46	146	4
Central America	321	0.1	32	18	55	15	0.1	21	13	64	37
South America	1815	0.6	31	34	81	3	0.2	12	14	64	3
Northern Africa	594	0.1	13	33	42	6	0.0	7	20	38	10
Western Africa	1152	0.5	40	47	100	6	0.1	9	13	104	31
Eastern Africa	602	0.2	36	20	94	5	0.1	9	76	25	14
Southern Africa	699	0.2	27	28	76	9	0.1	16	23	115	10
OECD Europe	433	0.2	57	39	126	6	0.2	47	35	184	8
Eastern Europe	116	0.1	92	94	115	61	0.1	99	105	166	57
Former USSR	2203	0.7	31	25	95	4	0.8	36	31	257	10
Middle East	624	0.2	30	33	64	14	0.1	21	24	46	24
South Asia	533	0.5	97	70	188	20	0.1	22	15	44	18
East Asia	1150	0.8	66	78	185	11	0.5	46	59	158	70
South East Asia	505	0.2	39	25	121	4	0.1	18	41	47	7
Oceania	882	0.1	10	11	20	2	0.0	5	6	30	2
Japan	57	0.0	67	41	84	40	0.0	50	47	72	46
Greenland	220	0.0	5	5	13	2	0.0	3	3	9	11
Antarctica	1316	0.0	0	57	2	0	0.0	0	0	1	0
Global land area	13832	5.0	36				3.1	26			
Oceans	35863	4.0	11	15	175	0	2.7	7	11	153	0

Avg., average; Stdv., standard deviation for region; Max., maximum value within region; Min, minimum value within region.

Annex 2: Acidification risk for 1992

Risk of acidification in (semi-)natural ecosystems for 18 world regions for 1992.

Region	Exceedance ratio				Area natural ecosystems	Total area	Total excee-dance
	<1	1-1.5	1.5-2	>2	Mha	Mha	%
Low range of critical loads							
Canada	7558	393	230	1213	9394	9778	20%
USA	5679	165	110	1704	7658	9586	26%
Central America	2599	47	44	112	2802	3264	7%
South America	11788	1795	1005	1958	16545	18064	29%
Northern Africa	5645	0	0	0	5645	5974	0%
Western Africa	8728	565	350	1247	10890	11542	20%
Eastern Africa	5210	71	22	161	5464	6054	5%
Southern Africa	5460	299	319	254	6332	6942	14%
OECD Europe	1697	257	273	858	3084	4317	45%
Eastern Europe	214	89	55	228	586	1172	63%
Former USSR	18402	504	367	711	19984	22150	8%
Middle East	5628	5	0	26	5658	6246	1%
South Asia	3399	69	48	176	3691	5340	8%
East Asia	8170	99	95	1511	9875	11514	17%
South East Asia	2697	369	334	827	4227	5047	36%
Oceania	8446	9	0	0	8455	8901	0%
Japan	435	2	5	56	499	581	13%
Greenland	2249	0	0	0	2249	2249	0%
Global land area	104005	4738	3256	11040	123039	138719	15%
Medium range of critical loads							
Canada	8108	582	226	479	9394	9778	14%
USA	5824	154	142	1539	7658	9586	24%
Central America	2656	120	24	3	2802	3264	5%
South America	14495	1229	703	118	16545	18064	12%
Northern Africa	5645	0	0	0	5645	5974	0%
Western Africa	9567	532	417	374	10890	11542	12%
Eastern Africa	5291	68	15	90	5464	6054	3%
Southern Africa	5997	225	79	30	6332	6942	5%
OECD Europe	2000	311	215	557	3084	4317	35%
Eastern Europe	312	46	29	199	586	1172	47%
Former USSR	18885	626	246	227	19984	22150	5%
Middle East	5628	26	5	0	5658	6246	1%
South Asia	3481	114	72	24	3691	5340	6%
East Asia	8362	186	170	1158	9875	11514	15%
South East Asia	3328	511	218	170	4227	5047	21%
Oceania	8455	0	0	0	8455	8901	0%
Japan	443	38	3	16	499	581	11%
Greenland	2249	0	0	0	2249	2249	0%
Global land area	110723	4768	2565	4982	123039	138719	10%
High range of critical loads							
Canada	8690	253	112	340	9394	9778	8%
USA	5978	234	221	1225	7658	9586	22%
Central America	2775	24	0	3	2802	3264	1%
South America	15724	752	69	0	16545	18064	5%
Northern Africa	5645	0	0	0	5645	5974	0%
Western Africa	10099	592	166	33	10890	11542	7%
Eastern Africa	5359	37	68	0	5464	6054	2%
Southern Africa	6223	85	6	18	6332	6942	2%
OECD Europe	2311	266	154	353	3084	4317	25%
Eastern Europe	358	39	18	170	586	1172	39%
Former USSR	19511	318	131	24	19984	22150	2%
Middle East	5653	5	0	0	5658	6246	0%
South Asia	3595	72	3	21	3691	5340	3%
East Asia	8547	214	211	903	9875	11514	13%
South East Asia	3839	260	119	9	4227	5047	9%
Oceania	8455	0	0	0	8455	8901	0%
Japan	481	5	13	0	499	581	4%
Greenland	2249	0	0	0	2249	2249	0%
Global land area	115492	3158	1291	3098	123039	138719	6%

The risk is indicated by the areas in different exceedance classes and by the percentage of the total area where critical loads are exceeded. Exceedance is given as the ratio of acid deposition : critical load. In the assessment, three alternative sets of critical loads are used (Low, Medium and High range of critical loads) as to deal with the uncertainties involved (see Table 3.3).

Annex 3: Acidification risk for 2015

Risk of acidification in (semi-)natural ecosystems for 18 world regions for the CRP scenario based on the medium estimate of critical loads (Table 3.3).

Region	Exceedance ratio[a]				Area natural ecosystems	Total area	Total excee-dance
	<1	1-1.5	1.5-2	>2	Mha	Mha	%
Canada	8461	316	203	414	9394	9778	10%
USA	5923	95	192	1448	7658	9586	23%
Central America	2626	116	39	21	2802	3264	6%
South America	13794	1365	874	512	16545	18064	17%
Northern Africa	5645	0	0	0	5645	5974	0%
Western Africa	9349	557	448	536	10890	11542	14%
Eastern Africa	5272	77	19	96	5464	6054	4%
Southern Africa	5955	146	140	91	6332	6942	6%
OECD Europe	2196	282	169	437	3084	4317	29%
Eastern Europe	348	43	22	172	586	1172	41%
Former USSR	18951	616	242	175	19984	22150	5%
Middle East	5642	9	7	0	5658	6246	0%
South Asia	3363	105	89	135	3691	5340	9%
East Asia	8218	103	224	1330	9875	11514	17%
South East Asia	3013	593	355	267	4227	5047	29%
Oceania	8455	0	0	0	8455	8901	0%
Japan	423	12	7	56	499	581	15%
Greenland	2249	0	0	0	2249	2249	0%
Global land area	109882	4435	3030	5690	123038	138719	11%

[a] Exceedance is given as the ratio acid deposition : critical load.

The risk is indicated by the areas in different exceedance classes and by the percentage of the total area where critical loads are exceeded. Location and extent of (agro-) ecosystems is assumed not to change between 1992 and 2015.

Annex 4: Eutrophication risk for 1992

Risk of eutrophication in (semi-)natural ecosystems for 18 world regions for 1992 based on three critical load estimates as presented in Table 4.2.

Region	Exceedance ratio				Area natural ecosystems	Total area	Total excee-dance
	<1	1-1.5	1.5-2	>2	Mha	Mha	%
Low range of critical loads							
Canada	7768	1084	379	164	9394	9778	17
USA	5718	345	260	1336	7658	9586	25
Central America	2728	54	12	9	2802	3264	3
South America	13055	1409	817	1265	16545	18064	21
Northern Africa	5645	0	0	0	5645	5974	0
Western Africa	7967	1194	325	1404	10890	11542	27
Eastern Africa	4639	380	129	316	5464	6054	15
Southern Africa	5661	409	148	114	6332	6942	11
OECD Europe	1708	535	360	481	3084	4317	45
Eastern Europe	133	223	24	206	586	1172	77
Former USSR	15879	2380	1119	606	19984	22150	21
Middle East	5616	21	19	2	5658	6246	1
South Asia	2297	476	341	577	3691	5340	38
East Asia	7376	935	313	1251	9875	11514	25
South East Asia	3277	434	240	277	4227	5047	22
Oceania	8445	10	0	0	8455	8901	0
Japan	456	15	8	20	499	581	9
Greenland	2249	0	0	0	2249	2249	0
Global land area	100618	9902	4491	8027	123038	138719	18
Medium range of critical loads							
Canada	8885	453	56	0	9394	9778	5
USA	6047	492	948	171	7658	9586	21
Central America	2782	21	0	0	2802	3264	1
South America	14535	1044	468	498	16545	18064	12
Northern Africa	5645	0	0	0	5645	5974	0
Western Africa	9146	511	773	460	10890	11542	16
Eastern Africa	5021	163	175	105	5464	6054	8
Southern Africa	6076	179	61	15	6332	6942	4
OECD Europe	2106	569	169	240	3084	4317	32
Eastern Europe	230	148	44	164	586	1172	61
Former USSR	18283	1376	256	69	19984	22150	9
Middle East	5637	19	0	2	5658	6246	0
South Asia	2520	513	342	317	3691	5340	32
East Asia	7998	630	432	815	9875	11514	19
South East Asia	3732	333	61	100	4227	5047	12
Oceania	8455	0	0	0	8455	8901	0
Japan	471	28	0	0	499	581	6
Greenland	2249	0	0	0	2249	2249	0
Global land area	109819	6479	3784	2957	123038	138719	11
High range of critical loads							
Canada	9244	150	0	0	9394	9778	2
USA	6296	1200	162	0	7658	9586	18
Central America	2794	9	0	0	2802	3264	0
South America	15352	699	403	91	16545	18064	7
Northern Africa	5645	0	0	0	5645	5974	0
Western Africa	9526	929	279	156	10890	11542	13
Eastern Africa	5162	196	46	59	5464	6054	6
Southern Africa	6228	98	6	0	6332	6942	2
OECD Europe	2479	359	123	123	3084	4317	20
Eastern Europe	326	98	100	61	586	1172	44
Former USSR	19414	504	55	10	19984	22150	3
Middle East	5656	0	2	0	5658	6246	0
South Asia	2805	513	224	149	3691	5340	24
East Asia	8436	575	496	368	9875	11514	15
South East Asia	3977	152	84	14	4227	5047	6
Oceania	8455	0	0	0	8455	8901	0
Japan	484	15	0	0	499	581	3
Greenland	2249	0	0	0	2249	2249	0
Global land area	114527	5499	1981	1032	123038	138719	7

The risk is indicated by the areas in different exceedance classes and by the percentage of the total area where critical loads are exceeded. Exceedance is given as the ratio N deposition : critical load. In the assessment, three alternative sets of critical loads are used (Low, Medium and High range of critical loads) as to deal with the uncertainties involved (see Table 4.2).

Annex 5: Eutrophication risk for 2015

Risk of eutrophication in (semi-)natural ecosystems for 18 world regions for the CRP scenario based on the medium estimate of critical loads (Table 4.2).

Region	Exceedance ratio[a]				Area natural ecosystems	Total area	Total exceedance
	<1	1-1.5	1.5-2	>2	Mha	Mha	%
Canada	8813	498	79	4	9394	9778	6
USA	5938	518	888	313	7658	9586	22
Central America	2767	30	3	3	2802	3264	1
South America	14233	1094	571	647	16545	18064	14
Northern Africa	5645	0	0	0	5645	5974	0
Western Africa	8990	563	702	635	10890	11542	17
Eastern Africa	4971	180	147	166	5464	6054	9
Southern Africa	6055	191	46	40	6332	6942	4
OECD Europe	2089	607	131	258	3084	4317	32
Eastern Europe	207	176	77	125	586	1172	65
Former USSR	17682	1844	344	114	19984	22150	12
Middle East	5628	28	0	2	5658	6246	1
South Asia	2381	497	398	416	3691	5340	36
East Asia	7640	850	411	974	9875	11514	23
South East Asia	3632	321	165	109	4227	5047	14
Oceania	8453	2	0	0	8455	8901	0
Japan	453	17	20	8	499	581	9
Greenland	2249	0	0	0	2249	2249	0
Global land area	107825	7417	3982	3815	123038	138719	12

[a] Exceedance is given as the ratio acid deposition : critical load.

The risk is indicated by the areas in different exceedance classes and by the percentage of the total area where critical loads are exceeded. Location and extent of (agro-) ecosystems is assumed not to change between 1992 and 2015.

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