

# **Life-cycle impact assessment of acidifying and eutrophying air pollutants**

**Calculation of equivalency factors with RAINS-LCA**

**DRAFT VERSION**

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## **Abstract**

Up to now, simple impact models are used to assess the potential impact of acidifying and eutrophying substances released during the life cycle of products. The use of these simple models introduces major model uncertainty in the environmental life cycle assessment of products (LCA), due to the fact that fate of the substance concerned and ecosystem sensitivity are not included. To decrease the above mentioned model uncertainties, the RAINS (Regional Air pollution Information and Simulation) model is adapted for LCA purposes. The adapted model, called RAINS-LCA, is used to calculate acidification and eutrophication potentials of  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{SO}_2$  air emissions for Europe and a number of European regions, taking both fate and effects into account. Substantial differences are found between the new acidification and eutrophication potentials and the ones calculated previously. However, the inclusion of a full fate and effect analysis within the Northern Hemisphere would further improve the calculation of the currently calculated acidification and eutrophication potentials. It is also necessary to calculate acidification and eutrophication potentials for additional substances and additional regions other than in Europe.



# 1. Introduction

Life Cycle Assessment (LCA) is a tool for the assessment of the potential environmental impact of a product system (Heijungs et al., 1992). In this assessment the entire life cycle of a product from resource extraction to waste disposal is considered. According to ISO standardisation guidelines (ISO, 1997a, b, 1998a, b), an LCA study can be divided into four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. In the goal and scope definition, the aim and the subject of an LCA study are determined and a *functional unit* is defined. An example of a functional unit is 'the discharge of rain water falling on the roof of a one-family building during fifty years' with, for instance, the aim to compare the environmental impacts of different types of roof gutters. In the inventory analysis, all extractions of resources and emissions of substances attributable to the studied functional unit are listed. From this list, separate emissions of substances can be identified. In the impact assessment, it is first determined which impact categories have to be considered and which extractions and emissions contribute to which impact categories. Impact categories correspond with types of environmental problems, such as acidification or ozone depletion. Next, the magnitude of the potential impact of individual substances within each impact category is determined. This is done by multiplying for each individual substance the aggregated emission with an equivalency factor (also called 'potentials') for each impact category to which it may potentially contribute (Heijungs et al., 1992). Equivalency factors are substance-specific, quantitative representations of potential impacts per unit emission of a substance. Examples are the Acidification Potential and the Ozone Depletion Potential. Thus, within one impact category, potentials are used as weighting factors to determine the relative contribution of a substance to an impact category, and not to determine environmental risks. The last (optional) step in the impact assessment is the calculation of an environmental index by aggregation the impact categories with each other. Attributing weighting factors to the different impact categories can do this. The final step in an LCA study is the interpretation of the results from the previous three steps, to draw conclusions and to formulate recommendations.

This working paper concentrates on the calculation of acidification and eutrophication potentials of air pollutants which may be used for LCA purposes. Up to now, simple impact models are used to compute equivalency factors to assess the potential impact of acidifying and eutrophying substances released during the life cycle of products (see Heijungs et al., 1992). These simple models introduce major model uncertainty in the environmental life cycle assessment of products (LCA), due to the fact that fate, background concentrations and ecosystem sensitivity are not included in the computation of the impact factors. Recently, to decrease the above mentioned model uncertainties, Potting et al. (1997, 1998) used the RAINS (Regional Air pollution Information and Simulation) model (Alcamo et al., 1991) in the computation of acidification potentials. In contrast to the models used by Heijungs et al. (1992), spatial differentiation, including sensitivity of the receiving environment, fate of the substances and background depositions, are taken into account by Potting et al. (1998). The marginal change in unprotected ecosystems due to a marginal emission change served as an environmental indicator for acidification. However, as this impact indicator is based on step-functions, it is argued to be unsuitable for application in current LCA case studies (Heijungs & Huijbregts, 2000).



Section 2 discusses the nature of this problem and it proposes another impact indicator for acidification as well for eutrophication. Section 3 outlines the adaptations and updates in RAINS needed for the computation of LCA acidification and eutrophication potentials for air pollutants and it describes the selection and recalculation of input data. Using the adapted model, called RAINS-LCA, acidification potentials for NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> air emissions and eutrophication potentials for NH<sub>3</sub> and NO<sub>x</sub> air emissions are calculated for 44 European emission source regions, Western Europe, Eastern Europe and total Europe, respectively (Section 4). Section 5 discusses the validity of the potentials calculated with RAINS-LCA and a comparison is made with previously calculated acidification and eutrophication potentials. Finally, some conclusions are drawn (Section 6).

## 2. Equivalency factors

### 2.1 Impact indicator

In the approach of Potting et al. (1998) the acidification potentials calculated with RAINS relate a change of substance  $x$  in emission source region  $i$  to the change in unprotected ecosystems in its total deposition area. As pointed out by Heijungs & Huijbregts (1999), there may be a difficulty with this approach. In RAINS, a certain area fully contributes when the critical load is exceeded, if only slightly, and the same area is completely disregarded if the critical load is not exceeded, if only slightly. The approach is thus based on step functions. An important consequence of the step-wise way of calculation is that it may lead to a step-wise relationship between the marginal emission change and the change in unprotected ecosystem area. Potting *et al.* (1998) calculate acidification potentials for a 10% emission change in 1990 and one emission scenario for 2010, respectively. When instead of 10% emission change a different emission change is used in the computation, all equivalency factors may change, and if, say, 0.001% is used, they may all become 0, because the emission change may be too small to change any unprotected ecosystem area in protected ecosystem area or the other way around. Thus, the acidification potentials proposed by Potting et al. (1998) may strongly depend on the choice of which marginal emission change is taken. This makes them difficult to apply in current LCA framework (→ Box 1).

Box 1: Simplified example of life cycle impact assessment of acidifying air pollutants.

Potential impacts in LCA are calculated assuming linear relationships between inventory results and the outcome of the impact assessment. The following simplified example may clarify this principle. Lets assume that the production of 1000 kg concrete will lead to 1.5 kg SO<sub>2</sub> emission (1 kg emitted in Germany and 0.5 kg in Poland). If a regionalised LCA impact assessment is performed, the SO<sub>2</sub> emission in Germany will be multiplied with the acidification potential for Germany and the SO<sub>2</sub> emission in Poland will be multiplied with the acidification potential for Poland and the outcomes of the multiplications are summed. If, however, 2000 kg concrete is produced, the SO<sub>2</sub> emissions will be correspondingly two times higher and also the outcome of the LCA impact assessment will be two times higher, because the acidification potentials are considered to be independent of the change in emissions in LCAs. Thus, in LCAs a change in emission will not lead to a change in the acidification potential. However, as have been argued above, acidification potentials, based on marginal change in unprotected ecosystem area, may depend on the chosen marginal emission change which makes the impact indicator difficult to apply in the current LCA framework.

Redefining the impact indicator may overcome the difficulty mentioned above. A candidate for this is one in which we do not measure the marginal change in accumulated square metres of threatened surface, but the marginal change in the hazard index. The hazard index, also known as the PEC/PNEC ratio (Predicted (No) Effect Concentration) is commonly used in defining risks of emissions of toxic substances (EC, 1996) and this concept has already been successfully applied in the calculation of toxicity potentials (Guinée & Heijungs, 1993; Guinée et al., 1996a, Hertwich et al., 1998; Huijbregts, 1999). The new impact indicator is not concerned with the degree to which an environmental standard or critical load is actually exceeded, but with the degree to which it is potentially filled up (Guinée et al., 1996b). This means that marginal changes in the hazard index of all ecosystems are taken into account in the calculation of the impact indicator whether there is an actual exceedance of the critical load or not ( $\rightarrow$  Formula 1). The new indicator may be used in the calculation of acidification potentials as well eutrophication potentials, as there are ecosystem-specific critical loads available for both impact categories in RAINS.

$$\frac{dI_u}{dE_{x,i}} = \frac{\sum_{j=1}^{j=k} \sum_{e=1}^{e=m} A_{e \in j} \times \frac{\sum_{x=1}^{x=n} \sum_{i=1}^{i=q} t_{x,i,j} \times E_{x,i}}{CL_{u,e \in j}}}{dE_{x,i}} = \sum_{j=1}^{j=k} \sum_{e=1}^{e=m} A_{e \in j} \times \frac{t_{x,i,j}}{CL_{u,e \in j}} \quad (1)$$

- $dI_u/dE_{x,i}$  = Marginal change in Accumulated Relative Risk of impact category  $u$  after a marginal emission change of substance  $x$  in region  $i$  ( $\text{km}^2 \cdot \text{year} \cdot \text{kton}^{-1}$ );  
 $A_{e \in j}$  = Area of European ecosystem  $e$  in grid cell  $j$  ( $\text{km}^2$ );  
 $t_{x,i,j}$  = the average transfer coefficient, representing the fraction of emissions of pollutant  $x$  from region  $i$  that deposits on grid element  $j$  ( $\text{eq} \cdot \text{ha}^{-1} \cdot \text{kton}^{-1}$ );  
 $E_{x,i}$  = the emission substance  $x$  in region  $i$  ( $\text{kton} \cdot \text{year}^{-1}$ );  
 $CL_{u,e \in j}$  = Critical load value of European ecosystem  $e$  in grid cell  $j$  related to impact category  $u$  ( $\text{eq} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ )

To stress that the potential is a relative measure, a reference substance is used in the calculation of acidification and eutrophication potentials (Formula 2). The use of a reference substance follows the established use of carbon dioxide ( $\text{CO}_2$ ), ethylene ( $\text{C}_2\text{H}_4$ ), and chlorofluorocarbon (CFC11) as reference substance in the evaluation of global warming, photochemical ozone formation, and stratospheric ozone depletion, respectively (Albritton, et al., 1996; Derwent et al., 1998; Solomon et al. 1995). For the calculation of acidification and eutrophication potentials,  $\text{SO}_2$  and  $\text{NO}_x$  emitted in Switzerland are taken as references, respectively. Acidification and eutrophication potentials are calculated for 44 separate European regions.

$$IP_{u,x,i} = \frac{dI_u/dE_{u,x,i}}{dI_u/dE_{ref}} \quad (2)$$

- $IP_{u,x,i}$  = Potential of impact category  $u$  for substance  $x$  after emission to region  $i$  ( $\text{SO}_2$ - or  $\text{NO}_x$ -equivalents);  
 $dI_u/dE_{x,i}$  = Marginal change in Accumulated Relative Risk of impact category  $u$  after a marginal emission change of substance  $x$  in region  $i$  ( $\text{km}^2 \cdot \text{year} \cdot \text{kton}^{-1}$ )  
 $dI_u/dE_{ref}$  = Marginal change in Accumulated Relative Risk of impact category  $u$  after a marginal emission change of the reference substance, reference region and reference year ( $\text{km}^2 \cdot \text{year} \cdot \text{kton}^{-1}$ )

Furthermore, average potentials are calculated for Europe, Western Europe<sup>1</sup> and Eastern Europe<sup>2</sup>. For every substance, average potentials are calculated by a weighted summation of the region-specific potentials involved. Here, total region-specific emissions per substance are used as weighting factors.

## 2.2 Additional choices

Apart from the choice which type of impact indicator to use, other choices may also influence the model outcomes. This section discusses the possible influence of current and future deposition patterns on the acidification and eutrophication potentials.

### Critical loads

First, deposition profiles may be incorporated in the calculation of critical loads for acidifying N and S deposition. Since the deposition of both S and N contribute to the acidification of an ecosystem, no unique critical loads of sulphur or acidifying nitrogen can be specified. As shown in Posch & Hettelingh (1997) the conditional critical load concept may be used to derive a unique critical load for N and S, respectively. If emission changes deal with nitrogen only, a unique critical load of N for a *fixed* sulphur deposition can be derived from every critical load function. This conditional critical load of N,  $CL(N | S_{\text{dep}})$ , is computed as (Posch & Hettelingh, 1997):

$$CL(N | S_{\text{dep}}) = \begin{cases} CL_{\min}(N) & \text{if } S_{\text{dep}} \geq CL_{\max}(S) \\ CL_{\max}(N) - \alpha \times S_{\text{dep}} & \text{if } S_{\text{dep}} < CL_{\max}(S) \end{cases} \quad (3)$$

with

$$\alpha = \frac{CL_{\max}(N) - CL_{\min}(N)}{CL_{\max}(S)} \quad (4)$$

In an analogous way a conditional critical load for S,  $(CL(S | N_{\text{dep}}))$ , for a fixed nitrogen deposition  $N_{\text{dep}}$  may be calculated:

$$CL(S | N_{\text{dep}}) = \begin{cases} 0 & \text{if } N_{\text{dep}} \geq CL_{\max}(N) \\ \frac{CL_{\max}(N) - N_{\text{dep}}}{a} & \text{if } CL_{\min}(N) < N_{\text{dep}} < CL_{\max}(N) \\ CL_{\max}(S) & \text{if } N_{\text{dep}} \leq CL_{\min}(N) \end{cases} \quad (5)$$

where,

<sup>1</sup> Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, the Baltic Sea, the North Sea, the Mediterranean Sea and the remaining N.E. Atlantic Ocean are considered to be part of Western Europe.

<sup>2</sup> Albania, Belarus, Bosnia-Herzegovina Bulgaria, Croatia, Czech Republic, Estonia, European part of Russia Latvia, Lithuania, Hungary, Macedonia, Moldavia, Poland, Romania, Slovakia, Slovenia, Ukraine, and Yugoslavia are considered to be part of Eastern Europe.

|                   |  |
|-------------------|--|
| $CL(S   N_{dep})$ | = Conditional critical load of sulphur ( $eq.ha^{-1}.yr^{-1}$ )  |
| $CL(N   S_{dep})$ | = Conditional critical load of nitrogen ( $eq.ha^{-1}.yr^{-1}$ ) |
| $CL_{min}(N)$     | = Minimum critical load for nitrogen ( $eq.ha^{-1}.yr^{-1}$ )    |
| $CL_{max}(N)$     | = Maximum critical load for nitrogen ( $eq.ha^{-1}.yr^{-1}$ )    |
| $CL_{max}(S)$     | = Maximum critical load for sulphur ( $eq.ha^{-1}.yr^{-1}$ )     |
| $N_{dep}$         | = Deposition of nitrogen ( $eq.ha^{-1}.yr^{-1}$ )                |
| $S_{dep}$         | = Deposition of sulphur ( $eq.ha^{-1}.yr^{-1}$ )                 |

The use of the conditional critical load concept for LCA purposes is, however, doubtful. An important problem is that the use of conditional critical loads may give counterintuitive outcomes in a relative comparison. As shown in Formula 3, the higher  $SO_2$  emissions (and S deposition), the lower the conditional critical load of N becomes, and, in turn, the higher the acidification potentials of  $NO_x$  and  $NH_3$  will be. This implies that it is 'favourable' for  $SO_2$  to increase its emissions, because in this case the acidification potentials of  $NO_x$  and  $NH_3$  will become relatively higher compared to the  $SO_2$  acidification potentials. As can be derived from Formula 5, the same relation between  $NO_x$  and  $NH_3$  emissions and  $SO_2$  acidification potentials exists. As this is not considered to be valid relationship in a relative comparison, the use of the conditional critical load concept is not a useful option for LCA purposes. Instead of using conditional critical loads, it is also possible to use a point on the critical load function which is independent of current or future N and S deposition. The maximum critical load for nitrogen and sulphur may be used for this purpose. This type of critical loads is deposition independent and represents the maximum allowed nitrogen and sulphur deposition, respectively. In this assessment it is chosen to use the maximum critical loads in the calculation of the acidification potentials only.

### Only above thresholds

In the LCA impact assessment it is standard practice for many impact categories, such as human toxicity and photochemical ozone creation (Guinée et al., 1996b; Derwent et al., 1998), to use 'above and below threshold marginal changes' in the calculation of equivalency factors. One may, however, argue that only marginal changes in the hazard index are important in areas where the critical loads are currently exceeded or will be exceeded in the future. A change in the hazard index in areas where no exceedance occur may not be regarded as important, because no actual risks due to deposition of acidifying and/or eutrophying air pollutants are expected to occur in these areas. Deposition patterns can be used to determine in which part of Europe actual or future exceedances of critical loads are expected. One option is to include only the marginal change in the hazard index of these exceeded areas in the calculation of equivalency factors. An important result of this way of calculation is that the equivalency factors for acidification and eutrophication become dependent on the current or future emission estimates.

One must, however, assume that due to a marginal change in emission no change in the unprotected ecosystem occurs, which may not be the case in reality.<sup>3</sup> Nevertheless, it may be interesting to see how different choices affect the acidification and eutrophication potentials. It is chosen to show the effect on the acidification and eutrophication potentials of the following choices:

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<sup>3</sup> This is exactly the opposite assumption as from Potting et al. (1998) which uses the 'marginal' change in ecosystem area as the environmental indicator as such.

- 1) the use of below and above threshold (critical load) marginal changes in the hazard index versus the use of changes in the hazard index only above the critical load;
- 2) the use of emission data of different years (1990, 1995 and two 2010 emission forecasts) in the calculation of only above marginal change in the hazard index.

To keep the ‘above and below threshold’ and ‘only above threshold’ outcomes comparable, it is chosen to use the same reference situation per impact category in all calculations. Thus, in the calculation of acidification and eutrophication potentials, below and above threshold marginal changes in the hazard index after a marginal change in SO<sub>2</sub> and NO<sub>x</sub> emissions in Switzerland are taken as references, respectively.

### 2.3 Application in LCAs

The use of acidification and eutrophication potentials in current LCAs is relatively straightforward. Scores for the impact categories acidification and eutrophication due to air pollutants can be calculated with the following formulas:

$$I_a = \sum_{i=1}^{i=m} \sum_{x=1}^{x=n} \sum_{y=1}^{y=0} AP_{x,i,y} \times E_{x,i,y} \quad (6)$$

$$I_e = \sum_{i=1}^{i=m} \sum_{x=1}^{x=n} \sum_{y=1}^{y=0} EP_{x,i,y} \times E_{x,i,y} \quad (7)$$

where  $I_a$  and  $I_e$  are the impact scores for acidification and eutrophication (kg), respectively, and  $E_{x,i,y}$  is the emission of substance  $x$  to the air compartment of region  $I$  in year  $y$ , coming from the life cycle inventory (kg), where the summation over different emission years is only relevant in the application of acidification and eutrophication potentials representing the ‘only above marginal change in the hazard index’.

In addition, Formula 6 and 7 can be used for calculating the normalisation scores for acidification and eutrophication, respectively. Normalisation is an optional step in the weighting between impact categories. In normalisation, the potential impact per functional unit is divided by the impact score of a reference situation (Udo de Haes, 1996). Instead of using life cycle inventory emissions, total emissions per region in a certain year are used to calculate normalisation scores for a reference region. It is chosen to calculate normalisation scores for three reference regions (Western Europe, Eastern Europe and total Europe) and three different years (1990, 1995 and two 2010 emission forecasts).

### 3. Input data

#### 3.1 Emissions

Emission estimates for 44 European regions are listed in RAINS. These emission estimates are needed for the ‘only above threshold’ calculations. It is chosen to calculate ‘only above threshold’ eutrophication and acidification potentials for 1990 and 1995 emission estimates and two 2010 emission scenarios. The 1990 emissions were derived from the CORINAIR 1990 emission inventory and national information, while 1995 emission estimates were reported by EMEP/MSC-W (1998).<sup>4</sup> The 2010 emission projections are partly based on a cost optimal allocation of emission reductions to simultaneously achieve the announced policy targets and national emission ceilings for acidification, eutrophication and ozone exposure in the European Union (Amman et al., 1999). The environmental targets are selected by the Working Group on Strategies to guide the forthcoming negotiations on a second NO<sub>x</sub> protocol (→ Table 1).

Table 1: Summary of the environmental targets for the Central scenario (Amman et al., 1999)

| Effect/target  | Value                   |
|--|-------------------------|
| <b>Acidification</b>   |                         |
| - Gap closure on accumulated excess acidity                                    | 95%                     |
| - Gap closure on accumulated excess acidity for Norway                         | 85%                     |
| - Maximum excess deposition for the 2-percent of the most sensitive ecosystems | 850 eq.ha <sup>-1</sup> |
| <b>Health-related ozone</b>  |                         |
| - Gap closure on AOT60 <sup>a</sup>  | 67%                     |
| - Maximum AOT60, to be achieved in 4 out of 5 years                            | 2.9 ppm.h               |
| <b>Vegetation-related ozone</b>  |                         |
| - Gap closure on AOT40 <sup>b</sup>  | 33%                     |
| - Maximum AOT40, mean over 5 years   | 10 ppm.h                |
| <b>Eutrophication</b>  |                         |
| - Gap closure on accumulated excess nitrogen deposition                        | 60%                     |
| - Maximum excess deposition for the 2-percent of the most sensitive ecosystems | not specified           |

<sup>a</sup> AOT60 = the cumulative exposure index over a threshold of 60 ppb over a six-month period; <sup>b</sup> AOT40 = the cumulative exposure index over a threshold of 40 ppb over a three-month period.

In addition, the emission projections build on detailed forecasts of economic activities and application of emission control techniques in various sectors of the economy. Here, two different 2010 forecasts of economic activities are used in the calculations. The first economic activity 2010 forecast scenario, called the BaseLine scenario (BL), represents the ‘business as usual’ energy and agricultural activity projection. The projections in the BL scenario are mainly based on officially reported national energy and agricultural activity projections and on studies performed for the DG-VI and DG-XVII (→ Appendix 1). A comprehensive clarification of the BL projections can be found in the sixth interim report to the European Commission, DG-XI, entitled *Cost-effective control of acidification and ground-level ozone* (Amann et al., 1998). The second economic activity 2010 forecast scenario, called the New Target Policy scenario (NP), represents an ‘optimistic’ energy and agricultural activity projection for 2010 (→ Appendix 1).

<sup>4</sup> the exact numbers were received directly from the emission database of EMEP/MSC-W.

Table 2a: Emission estimates for the West European regions (Amann et al., 1999; EMEP/MSC-W, 1998; C. Hyes, personal communication)

| Region            | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> |
|-------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
|                   | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> |
| Austria           | 77                   | 87                   | 66                   | 61                   | 192                  | 175                  | 90                   | 88                   | 93                   | 60                   | 35                   | 36                   |
| Belgium           | 97                   | 97                   | 60                   | 68                   | 351                  | 339                  | 126                  | 104                  | 336                  | 247                  | 77                   | 64                   |
| Denmark           | 77                   | 114                  | 69                   | 65                   | 274                  | 250                  | 112                  | 137                  | 182                  | 150                  | 60                   | 58                   |
| Finland           | 40                   | 31                   | 31                   | 28                   | 276                  | 259                  | 152                  | 128                  | 226                  | 96                   | 115                  | 116                  |
| France            | 807                  | 668                  | 646                  | 646                  | 1867                 | 1666                 | 710                  | 676                  | 1250                 | 989                  | 225                  | 308                  |
| Germany (new)     | 201                  | 127                  | 132                  | 135                  | 702                  | 391                  | 196                  | 203                  | 4438                 | 1538                 | 146                  | 126                  |
| Germany (old)     | 556                  | 522                  | 278                  | 332                  | 1960                 | 1541                 | 882                  | 806                  | 842                  | 592                  | 320                  | 273                  |
| Greece            | 80                   | 78                   | 72                   | 67                   | 345                  | 357                  | 345                  | 301                  | 504                  | 556                  | 544                  | 378                  |
| Ireland           | 127                  | 124                  | 116                  | 117                  | 113                  | 115                  | 55                   | 53                   | 178                  | 161                  | 36                   | 54                   |
| Italy             | 462                  | 389                  | 356                  | 369                  | 2037                 | 2157                 | 896                  | 885                  | 1679                 | 1437                 | 285                  | 162                  |
| Luxembourg        | 7                    | 8                    | 7                    | 6                    | 22                   | 20                   | 8                    | 6                    | 14                   | 8                    | 3                    | 4                    |
| Netherlands       | 233                  | 152                  | 105                  | 106                  | 542                  | 514                  | 265                  | 192                  | 201                  | 147                  | 50                   | 43                   |
| Norway            | 23                   | 25                   | 21                   | 20                   | 220                  | 222                  | 143                  | 173                  | 52                   | 35                   | 18                   | 32                   |
| Portugal          | 71                   | 92                   | 65                   | 61                   | 208                  | 254                  | 143                  | 127                  | 284                  | 272                  | 142                  | 91                   |
| Spain             | 352                  | 345                  | 352                  | 353                  | 1162                 | 1227                 | 721                  | 695                  | 2189                 | 2061                 | 744                  | 749                  |
| Sweden            | 61                   | 61                   | 48                   | 48                   | 338                  | 362                  | 159                  | 179                  | 119                  | 94                   | 67                   | 57                   |
| Switzerland       | 72                   | 71                   | 63                   | 61                   | 163                  | 136                  | 76                   | 76                   | 43                   | 34                   | 23                   | 26                   |
| United Kingdom    | 329                  | 320                  | 263                  | 252                  | 2839                 | 2227                 | 1192                 | 1088                 | 3805                 | 2352                 | 495                  | 474                  |
| Baltic sea        | 0                    | 0                    | 0                    | 0                    | 80                   | 80                   | 80                   | 80                   | 72                   | 72                   | 72                   | 72                   |
| North sea         | 0                    | 0                    | 0                    | 0                    | 639                  | 639                  | 639                  | 639                  | 439                  | 439                  | 439                  | 439                  |
| Atlantic ocean    | 0                    | 0                    | 0                    | 0                    | 911                  | 909                  | 911                  | 911                  | 641                  | 639                  | 641                  | 641                  |
| Mediterranean sea | 0                    | 0                    | 0                    | 0                    | 13                   | 13                   | 13                   | 13                   | 12                   | 12                   | 12                   | 12                   |

<sup>a</sup> BL = Baseline economic activity scenario; <sup>b</sup> NP = New policy economic scenario

Table 2b: Emission estimates for the East European regions (Amann et al., 1999; EMEP/MSC-W, 1998, C. Hyes, personal communication)

| Region                         | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> | 1990                 | 1995                 | 2010_BL <sup>a</sup> | 2010_NP <sup>b</sup> |
|--------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
|                                | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NH <sub>3</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton NO <sub>x</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> | kton SO <sub>2</sub> |
| Albania                        | 32                   | 31                   | 32                   | 32                   | 24                   | 24                   | 36                   | 33                   | 72                   | 72                   | 55                   | 47                   |
| Belarus                        | 219                  | 219                  | 140                  | 151                  | 402                  | 195                  | 289                  | 249                  | 843                  | 275                  | 498                  | 262                  |
| Bosnia-Herzegovina             | 31                   | 31                   | 22                   | 20                   | 80                   | 80                   | 53                   | 45                   | 487                  | 480                  | 161                  | 277                  |
| Bulgaria                       | 141                  | 99                   | 104                  | 102                  | 355                  | 266                  | 266                  | 217                  | 1842                 | 1497                 | 387                  | 776                  |
| Croatia                        | 40                   | 32                   | 29                   | 27                   | 82                   | 55                   | 87                   | 78                   | 180                  | 63                   | 23                   | 59                   |
| Czech Republic                 | 107                  | 86                   | 100                  | 97                   | 546                  | 412                  | 186                  | 168                  | 1873                 | 1091                 | 281                  | 184                  |
| Estonia                        | 29                   | 29                   | 29                   | 27                   | 84                   | 47                   | 73                   | 56                   | 275                  | 110                  | 176                  | 107                  |
| Hungary                        | 120                  | 116                  | 77                   | 82                   | 219                  | 180                  | 138                  | 148                  | 913                  | 705                  | 292                  | 187                  |
| Latvia                         | 43                   | 17                   | 35                   | 33                   | 117                  | 29                   | 119                  | 78                   | 121                  | 38                   | 104                  | 49                   |
| Lithuania                      | 80                   | 44                   | 72                   | 76                   | 153                  | 67                   | 134                  | 95                   | 213                  | 107                  | 107                  | 51                   |
| Macedonia                      | 17                   | 17                   | 15                   | 14                   | 39                   | 39                   | 29                   | 24                   | 107                  | 106                  | 81                   | 75                   |
| Moldavia                       | 47                   | 47                   | 41                   | 44                   | 87                   | 25                   | 65                   | 54                   | 197                  | 59                   | 37                   | 76                   |
| Poland                         | 505                  | 380                  | 469                  | 465                  | 1217                 | 1120                 | 657                  | 695                  | 3001                 | 2337                 | 720                  | 1392                 |
| Romania                        | 292                  | 221                  | 228                  | 237                  | 518                  | 319                  | 327                  | 326                  | 1331                 | 912                  | 146                  | 365                  |
| Russia (Kalingrad region)      | 11                   | 5                    | 11                   | 11                   | 29                   | 12                   | 24                   | 20                   | 44                   | 25                   | 18                   | 12                   |
| Russia (Kola, Karelia)         | 6                    | 19                   | 4                    | 4                    | 111                  | 35                   | 82                   | 52                   | 739                  | 496                  | 318                  | 335                  |
| Russia (St. Petersburg region) | 44                   | 42                   | 33                   | 30                   | 221                  | 83                   | 161                  | 130                  | 308                  | 190                  | 135                  | 31                   |
| Russia (Remaining)             | 1221                 | 705                  | 843                  | 774                  | 3126                 | 1779                 | 2375                 | 2052                 | 3921                 | 2126                 | 1725                 | 806                  |
| Slovakia                       | 60                   | 45                   | 39                   | 38                   | 219                  | 181                  | 116                  | 88                   | 548                  | 239                  | 93                   | 47                   |
| Slovenia                       | 23                   | 22                   | 16                   | 18                   | 60                   | 67                   | 34                   | 35                   | 200                  | 119                  | 14                   | 71                   |
| Ukraine                        | 729                  | 729                  | 591                  | 541                  | 1888                 | 531                  | 1227                 | 981                  | 3706                 | 1639                 | 1445                 | 621                  |
| Yugoslavia                     | 90                   | 90                   | 64                   | 68                   | 211                  | 59                   | 133                  | 127                  | 585                  | 462                  | 217                  | 250                  |

<sup>a</sup> BL = Baseline economic activity scenario; <sup>b</sup> NP = New policy economic scenario



The energy projection for the countries of the EU-15 meet the reduction targets of the Kyoto agreement, assuming no emission trading (Cofala et al., 1999). For the non-EU countries an ‘Economic and Environmental Convergence’ energy 2010 forecast, developed by Cofala et al. (1997), is used in the NP scenario. The optimistic agricultural activity projection assumes that uniformly for all countries and all animal categories, the total livestock numbers will be 10 percent lower than in the BL forecast (Amann et al., 1999). Tables 2a and 2b show the resulting NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions for 1990, 1995, and the two 2010 forecast scenarios.

### 3.2 Transfer matrices

RAINS calculates total deposition of nitrogen and sulphur compounds on European grid elements (150-km resolution) with substance-specific region-to-grid source-receptor transfer matrices. These transfer matrices indicate which fraction of the emissions from the 44 regions in Europe deposit in which European grid elements. The transfer matrices are based on the results of a Lagrangian model developed by EMEP/MSC-W (co-operative Program for Monitoring and Evaluation of the long-range transmission of air pollutants in Europe) (EMEP/MSC-W, 1996). EMEP/MSC-W model calculations are based on input data of actual meteorological conditions and emissions for the years 1985 through 1995. For each of these years separate calculations are performed and finally averaged over the 11 years.

It appeared, however, that the average transfer matrices in RAINS are not calculated in a correct manner. In RAINS the average transport coefficients are calculated by

$$\bar{t}_{x, i, j} = \frac{\sum_{n=1985}^{n=1995} D_{n, x, i, j}}{\sum_{n=1985}^{n=1995} E_{n, x, i}} \quad (8)$$

- $t_{x, i, j}$  = the average transfer coefficient, representing the fraction of emissions of pollutant x from region I that deposits on grid element j (eq.ha<sup>-1</sup>.kton<sup>-1</sup>);
- $D_{n, x, i, j}$  = the deposition in year n due to emission of substance x from region i on grid element j (eq.ha<sup>-1</sup>.year<sup>-1</sup>);
- $E_{n, x, i}$  = the emission in year n of substance x in region i (kton.year<sup>-1</sup>);

This way of averaging is doubtful, because the causal relationship between yearly emissions and depositions calculated with the EMEP/MSC-W model is neglected in Formula 8. To maintain this causal relationship, the transfer coefficients should be calculated on a yearly basis and afterwards averaged over the 11 years (Formula 9). As the information for a correct way of averaging was not readily available in RAINS, yearly wet and dry deposition data and yearly emissions kindly obtained from EMEP/MSC-W were used to recalculate the average transfer matrices for NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub>.

$$\bar{t}_{x,i,j} = \frac{1}{11} \times \sum_{n=1985}^{n=1995} \frac{D_{n,x,i,j}}{E_{n,x,i}} \quad (9)$$

As 2/3 of the total indetermined deposition of all the three pollutants of the Langrangian model is expected to have its origin in Europe, it is advised by EMEP/MSC-W to re-allocate this fraction to all the European emission sources (Formula 10; EMEP/MSC-W, 1996). Here, it is chosen to separately re-allocate the indetermined fraction of wet and dry deposition on a yearly basis. Thus, the re-allocation procedure (Formula 10) is performed *before* the calculation of the average transfer matrices (Formula 9).

$$t_{n,x,i,j} = \frac{D_{n,x,i,j}}{E_{n,x,i}} \times \left( 1 + \gamma \times \frac{D_{n,x,ind,j}}{D_{n,x,total,j} - D_{n,x,ind,j}} \right) \quad (10)$$

where,

- $t_{n,x,i,j}$  = the transfer coefficient, representing the fraction of emissions of pollutant x from region I that deposits on grid element j in year n (eq.ha<sup>-1</sup>.kton<sup>-1</sup>);
- $\gamma$  = the re-allocation fraction (best estimate is 2/3 for all three pollutants);
- $D_{n,x,ind,j}$  = the indetermined deposition in year n of substance x on grid element j (eq.ha<sup>-1</sup>.year<sup>-1</sup>);
- $D_{n,x,total,j}$  = the total deposition in year n of substance x on grid element j (eq.ha<sup>-1</sup>.year<sup>-1</sup>);

In addition, it appeared that the transfer matrices of the three pollutants in RAINS do not cover complete Europe. Although critical loads are available for some of the edge grid cells, no deposition profiles for these grid cells are given in RAINS. Deposition estimates on border cells of Europe (grid cells covering partly Spain, Portugal and Russia) are not provided by the EMEP/MSC-W, because these estimates may include considerable uncertainty due to boundary transient conditions. As a first approximation, this problem is tackled by using for each edge grid cell the transfer coefficients of the nearest grid cell available.

Finally, the transport matrices cause an LCA-specific problem. The EMEP/MSC-W transport model allows transport across the system domain (Europe). As a consequence of the open character of the system, the fate (behaviour) of an emitted substance can not be taken fully into account. A solution may be to model a larger part of the world. Although models exists to calculate transfer matrices for NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> within the Northern hemisphere (e.g. Galperin et al., 1995; Galperin & Soviev, 1998), critical loads are not available for a substantial part of the Northern hemisphere. Therefore, it is impossible to include the full source-effect relationship of all European source regions in the current calculations of the acidification and eutrophication potentials. In particular, acidification and eutrophication potentials of regions close at the borders of Europe, such as Russia, and pollutants which may travel long distances, such as NO<sub>x</sub>, will be underestimated, since areas outside the EMEP model domain are not accounted for (→ Table 3).

Table 3: Distribution of NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> within the Northern hemisphere for 1991-1994 (derived from Galperin et al., 1995; Galperin & Soviev, 1998)

| Receivers                                  | Emitters   |        |                  |   |        |                  |   |        |                  |
|--|--|--------|------------------|---|--------|------------------|---|--------|------------------|
|  | Oxidised Sulphur<br>(kton S.year <sup>-1</sup> ) |        |                  | Oxidised Nitrogen<br>(kton N.year <sup>-1</sup> ) |        |                  | Remaining Europe <sup>b</sup><br>(kton N.year <sup>-1</sup> ) |        |                  |
|  | N-E <sup>a</sup>                                 | Russia | R-E <sup>b</sup> | N-E <sup>a</sup>                                  | Russia | R-E <sup>b</sup> | N-E <sup>a</sup>  | Russia | R-E <sup>b</sup> |
| North Europe <sup>a</sup>                  | 126  | 80     | 573              | 92  | 14     | 287              | 115   | 17     | 191              |
| Russia                                     | 46   | 2833   | 1283             | 99  | 715    | 543              | 25  | 1217   | 449              |
| Remaining Europe <sup>b</sup>              | 48   | 93     | 7262             | 65  | 50     | 2307             | 43  | 109    | 3208             |
| Ocean and sea                              | 33   | 215    | 3790             | 55  | 72     | 1649             | 40  | 60     | 1213             |
| Remaining Northern hemisphere <sup>c</sup> | 18   | 851    | 639              | 60  | 313    | 377              | 13  | 302    | 188              |
| Export <sup>d</sup>                        | 0  | 17     | 290              | 2   | 13     | 159              | 0   | 7      | 148              |

<sup>a</sup> N-E = Scandinavia and Baltic Sea; <sup>b</sup> R-E = Europe, excluding Scandinavia and Russia; <sup>c</sup> Arctic basin to the North of 70°N and Greenland, USA, Canada, Asian and African countries within the Northern hemisphere; <sup>d</sup> export outside the Northern hemisphere.

### 3.3 Critical loads and ecosystem areas

For about 1.3 million ecosystems acidity critical loads and critical loads of nutrient enrichment (eutrophication) are calculated (De Smet & Posch, 1999). The acidity critical loads refer to both terrestrial and fresh water ecosystems, while critical loads for nutrient enrichment solely refer to terrestrial ecosystems. Unfortunately, the full data set on critical loads was not readily available for the calculation of acidification and eutrophication potentials. Instead a summary of the accumulative critical load distribution function for each EMEP/MSC-W 150x150 km<sup>2</sup> grid cell is used in the calculations. For each grid cell, 29 percentile points of the distribution functions of CL<sub>max</sub>(S), CL<sub>max</sub>(N) and CL<sub>eutro</sub> are available, respectively<sup>5</sup>. These percentiles, however, do not necessarily correspond to the discrete areas for which critical loads are defined. The dashed line in Figure 1 may be, for instance, a true critical load function. The circles are an example of percentages where data are available and the true function should go through these points. Following Kåresen & Hirst (1999), a true critical load function is approximated by taking the average values of the successive known percentile values (→ Figure 1; solid line). This approximation procedure assumes that for every grid cell

$$\sum_{e \in j} \frac{A_{e \in j}}{CL_{e \in j}} \approx \sum_{k=1}^{k=29} \frac{((P_{k+1} - P_k)/100) \times A_{eco, j}}{((CL_{k+1} - CL_k)/2)} \quad (11)$$

in which all variables equal those mentioned above, and

- P<sub>k</sub> = Percentile value of the k<sup>th</sup> point on the cumulative density curve (dimensionless)
- A<sub>eco,j</sub> = Total ecosystem area in grid cell j (km<sup>2</sup>)
- CL<sub>k</sub> = Critical load value of the k<sup>th</sup> point on the cumulative density curve (eq.ha<sup>-1</sup>.yr<sup>-1</sup>)

<sup>5</sup> The 0<sup>th</sup>, 1<sup>th</sup>, 2<sup>th</sup>, 3<sup>th</sup>, 4<sup>th</sup>, 5<sup>th</sup>, 6<sup>th</sup>, 7<sup>th</sup>, 8<sup>th</sup>, 9<sup>th</sup>, 10<sup>th</sup>, 15<sup>th</sup>, 20<sup>th</sup>, 25<sup>th</sup>, 30<sup>th</sup>, 35<sup>th</sup>, 40<sup>th</sup>, 45<sup>th</sup>, 50<sup>th</sup>, 55<sup>th</sup>, 60<sup>th</sup>, 65<sup>th</sup>, 70<sup>th</sup>, 75<sup>th</sup>, 80<sup>th</sup>, 85<sup>th</sup>, 90<sup>th</sup>, 95<sup>th</sup> and 100<sup>th</sup> percentile values of the cumulative critical load function are available.

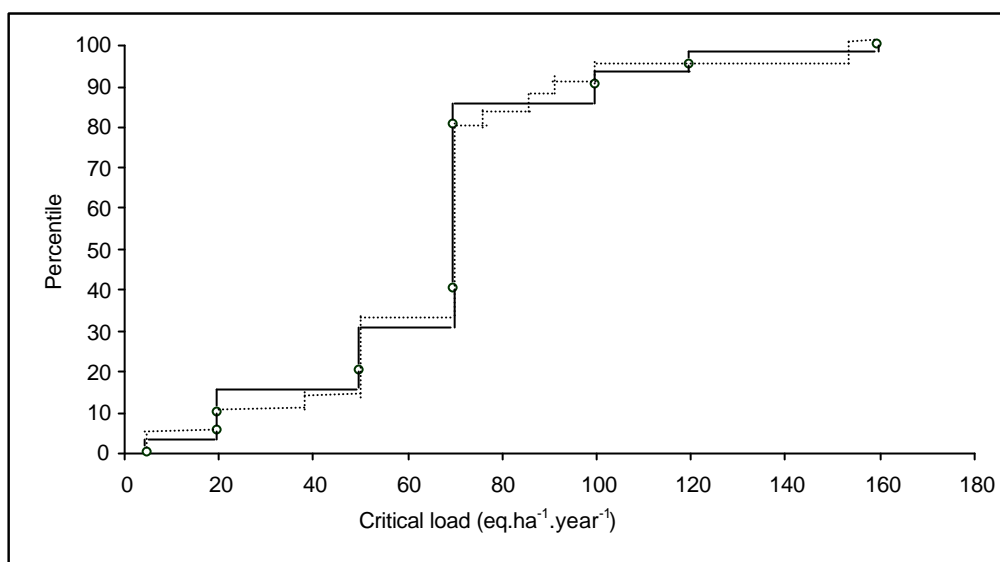


Figure 1: A theoretical example of a true critical load function (dashed line) and the approximation (solid line) of a grid cell. The circles indicate the available points of the cumulative density function (derived from Kåresen & Hirst, 1999).

## 4 Results

Tables 4a and 4b show the region-specific acidification potentials and Table 6 shows the European averages. The following differences between regions and substances can be identified:

- On European average the acidification potential of  $\text{NH}_3$  is about 2.4 to 3.2 times higher than the acidification potential of  $\text{NO}_x$ ; the acidification potential of  $\text{NH}_3$  is about 0.7 to 1.3 times higher than the acidification potential  $\text{SO}_2$ ; and the acidification potential of  $\text{SO}_2$  is about 2.3 to 3.5 times higher than the acidification potential of  $\text{NO}_x$ ;
- Regional differences between the acidification potentials of  $\text{NH}_3$  are the largest, followed by acidification potentials of  $\text{SO}_2$ . Regional differences are the smallest for the acidification potentials of  $\text{NO}_x$ ;
- Maximum regional differences between acidification potentials lie between a factor 80 and 1650, depending on the substance and the chosen scenario. Regions with high acidification potentials are the Kola/Karelia region and the Scandinavian countries, while the southern and south-eastern European regions have relatively low acidification potentials;
- Maximum differences between ‘only above threshold’ acidification potentials of the years 1990, 1995 and 2010 lie between a factor 1.5 and 64, depending on the substance and the emission years/scenarios compared. Differences in acidification potentials related to the year 1990 emissions and the 2010\_NP emission scenario are the highest for  $\text{NH}_3$  emissions in the Russian regions, while the 2010\_BL and 2010\_NP emission scenario does not show large differences for  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{SO}_2$  emissions in all European regions identified (up to a factor 3 for  $\text{SO}_2$  emissions in Belarus).
- Maximum acidification potential differences between substances and regions are between a factor 650 and a factor 3900, dependent on the chosen scenario.  $\text{NO}_x$  acidification potentials for the Mediterranean Sea and  $\text{NH}_3$  acidification potentials for the Kola/Karelia region differ a factor 650 in the A&B scenario, while  $\text{NO}_x$

acidification potentials for the Mediterranean Sea and NH<sub>3</sub> acidification potentials for Norway differ a factor 3900 in the OA\_2010NP scenario.

Tables 5a and 5b show the region-specific eutrophication potentials and Table 6 shows the European averages. The following differences between regions and substances can be identified:

- On European average the eutrophication potential of NH<sub>3</sub> is about 3.4 to 4.8 times higher than the eutrophication potential of NO<sub>x</sub>;
- Regional differences between the eutrophication potentials of NH<sub>3</sub> are found than for NO<sub>x</sub>;
- Maximum regional differences between eutrophication potentials lie between a factor 15 and 33, depending on the substance and the chosen calculation scenario. Regional differences in eutrophication potentials are much lower compared to regional differences in acidification potentials. Regions with high eutrophication potentials are the St Petersburg region, Finland and France, while Ireland and Greece have relatively low eutrophication potentials;
- Maximum differences between 'only above threshold' terrestrial eutrophication potentials of the years 1990, 1995 and 2010 lie between a factor 1.2 and 16, depending on the substance and the emission years/scenarios compared. Differences in terrestrial eutrophication potentials related to the year 1990 emissions and the 2010\_NP emission scenario are the highest for NH<sub>3</sub> emissions in the Russian regions, Finland and Bulgaria, while relatively small differences are found between the 2010\_BL and 2010\_NP emission scenario for NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions in all European regions identified (up to a factor 1.6 for NH<sub>3</sub> emissions in Greece).
- Maximum differences between substances and regions are between a factor 100 and a factor 161, dependent on the chosen scenario. NO<sub>x</sub> eutrophication potentials for the Mediterranean Sea and NH<sub>3</sub> eutrophication potentials for Finland differ a factor 100 in the OA\_1995 scenario, while NO<sub>x</sub> eutrophication potentials for the Mediterranean Sea and NH<sub>3</sub> eutrophication potentials for France differ a factor 161 in the OA\_2010NP scenario.

The squared Pearson correlation coefficient ( $r^2$ ) served as an indicator for differences between acidification potential scenarios (→ Table 8) and differences between eutrophication potential scenarios (→ Table 9). Concerning the acidification potentials, there is a reasonable correlation between the A&B scenario and the OA\_1990 scenario and the other three scenarios, respectively ( $r^2 > 0.6$ ). However, correlations between other combinations are in most cases rather low. Concerning the eutrophication potentials, there is a reasonable correlation between the majority of the scenarios ( $r^2 > 0.6$ ), except between the A&B scenario and some OA scenarios.

Finally, acidifying and eutrophying normalisation figures for Western Europe, Eastern Europe and Total Europe are calculated (→ Table 7). Outcomes are given for different emission years and corresponding acidification and eutrophication potentials are used in the calculations.

Table 4a: Acidification potentials of Ammonia (NH<sub>3</sub>), Nitrogen oxide (NO<sub>x</sub>), and Sulphur dioxide (SO<sub>2</sub>) for 22 West European regions.

| West European Regions | Acidification potentials <sup>a</sup> |                      |                      |                      |                      |                                   |                      |                      |                      |                      |                                    |                      |                      |                      |                      |
|-----------------------|---------------------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|------------------------------------|----------------------|----------------------|----------------------|----------------------|
|                       | Ammonia (NH <sub>3</sub> )            |                      |                      |                      |                      | Nitrogen Oxide (NO <sub>x</sub> ) |                      |                      |                      |                      | Sulphur dioxide (SO <sub>2</sub> ) |                      |                      |                      |                      |
|                       | A&B                                   | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        | A&B                               | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        | A&B                                | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        |
| Austria               | 1.3                                   | 8.4·10 <sup>-1</sup> | 6.0·10 <sup>-1</sup> | 7.2·10 <sup>-2</sup> | 7.4·10 <sup>-2</sup> | 2.7·10 <sup>-1</sup>              | 1.4·10 <sup>-1</sup> | 8.6·10 <sup>-2</sup> | 1.9·10 <sup>-2</sup> | 1.9·10 <sup>-2</sup> | 1.0                                | 6.9·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Belgium               | 1.0                                   | 7.1·10 <sup>-1</sup> | 5.0·10 <sup>-1</sup> | 1.4·10 <sup>-1</sup> | 1.4·10 <sup>-1</sup> | 4.9·10 <sup>-1</sup>              | 2.9·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 5.9·10 <sup>-2</sup> | 5.8·10 <sup>-2</sup> | 1.0                                | 7.1·10 <sup>-1</sup> | 5.0·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> |
| Denmark               | 1.5                                   | 7.8·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> | 8.8·10 <sup>-1</sup>              | 3.9·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.8                                | 1.0                  | 7.2·10 <sup>-1</sup> | 3.5·10 <sup>-1</sup> | 3.5·10 <sup>-1</sup> |
| Finland               | 6.4                                   | 2.2                  | 7.4·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> | 4.1·10 <sup>-1</sup> | 1.9                               | 6.2·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.0·10 <sup>-1</sup> | 5.0                                | 2.0                  | 7.7·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> | 4.7·10 <sup>-1</sup> |
| France                | 2.0                                   | 9.5·10 <sup>-1</sup> | 3.9·10 <sup>-1</sup> | 5.3·10 <sup>-2</sup> | 5.3·10 <sup>-2</sup> | 4.3·10 <sup>-1</sup>              | 2.1·10 <sup>-1</sup> | 1.2·10 <sup>-1</sup> | 2.9·10 <sup>-2</sup> | 2.9·10 <sup>-2</sup> | 1.1                                | 6.3·10 <sup>-1</sup> | 3.7·10 <sup>-1</sup> | 9.2·10 <sup>-2</sup> | 9.2·10 <sup>-2</sup> |
| Germany (new)         | 1.6                                   | 1.1                  | 7.7·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 5.7·10 <sup>-1</sup>              | 3.1·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 5.3·10 <sup>-2</sup> | 5.3·10 <sup>-2</sup> | 1.2                                | 7.6·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> |
| Germany (old)         | 1.4                                   | 1.0                  | 7.6·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup>              | 2.9·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 5.5·10 <sup>-2</sup> | 5.4·10 <sup>-2</sup> | 1.3                                | 9.3·10 <sup>-1</sup> | 6.8·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Greece                | 1.3·10 <sup>-1</sup>                  | 8.7·10 <sup>-3</sup> | 3.9·10 <sup>-3</sup> | 1.2·10 <sup>-3</sup> | 1.1·10 <sup>-3</sup> | 3.7·10 <sup>-2</sup>              | 4.1·10 <sup>-3</sup> | 1.9·10 <sup>-3</sup> | 5.2·10 <sup>-4</sup> | 4.8·10 <sup>-4</sup> | 6.6·10 <sup>-2</sup>               | 1.0·10 <sup>-2</sup> | 6.8·10 <sup>-3</sup> | 3.9·10 <sup>-3</sup> | 3.8·10 <sup>-3</sup> |
| Ireland               | 7.9·10 <sup>-1</sup>                  | 4.0·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup> | 9.7·10 <sup>-2</sup> | 9.4·10 <sup>-2</sup> | 3.4·10 <sup>-1</sup>              | 1.9·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 6.0·10 <sup>-2</sup> | 5.9·10 <sup>-2</sup> | 5.7·10 <sup>-1</sup>               | 3.3·10 <sup>-1</sup> | 2.4·10 <sup>-1</sup> | 1.0·10 <sup>-1</sup> | 1.0·10 <sup>-1</sup> |
| Italy                 | 5.9·10 <sup>-1</sup>                  | 2.7·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> | 2.3·10 <sup>-2</sup> | 2.3·10 <sup>-2</sup> | 1.3·10 <sup>-1</sup>              | 5.5·10 <sup>-2</sup> | 3.3·10 <sup>-2</sup> | 5.8·10 <sup>-3</sup> | 5.7·10 <sup>-3</sup> | 4.6·10 <sup>-1</sup>               | 2.3·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 3.4·10 <sup>-2</sup> | 3.4·10 <sup>-2</sup> |
| Luxembourg            | 1.5                                   | 1.0                  | 5.1·10 <sup>-1</sup> | 9.2·10 <sup>-2</sup> | 9.3·10 <sup>-2</sup> | 5.0·10 <sup>-1</sup>              | 3.1·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 4.5·10 <sup>-2</sup> | 4.5·10 <sup>-2</sup> | 1.3                                | 9.0·10 <sup>-1</sup> | 5.9·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> |
| Netherlands           | 1.0                                   | 7.0·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup>              | 2.9·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 7.3·10 <sup>-2</sup> | 7.2·10 <sup>-2</sup> | 9.2·10 <sup>-1</sup>               | 6.3·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> |
| Norway                | 6.0                                   | 3.2                  | 2.6                  | 1.8                  | 1.8                  | 1.2                               | 5.4·10 <sup>-1</sup> | 3.6·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 3.8                                | 2.2                  | 1.7                  | 1.1                  | 1.1                  |
| Portugal              | 2.8·10 <sup>-1</sup>                  | 2.1·10 <sup>-2</sup> | 1.2·10 <sup>-2</sup> | 3.0·10 <sup>-3</sup> | 3.0·10 <sup>-3</sup> | 8.0·10 <sup>-2</sup>              | 2.0·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> | 2.6·10 <sup>-3</sup> | 2.6·10 <sup>-3</sup> | 1.8·10 <sup>-1</sup>               | 2.3·10 <sup>-2</sup> | 1.4·10 <sup>-2</sup> | 3.4·10 <sup>-3</sup> | 3.3·10 <sup>-3</sup> |
| Spain                 | 2.7·10 <sup>-1</sup>                  | 5.3·10 <sup>-2</sup> | 3.2·10 <sup>-2</sup> | 5.3·10 <sup>-3</sup> | 5.3·10 <sup>-3</sup> | 1.0·10 <sup>-1</sup>              | 3.3·10 <sup>-2</sup> | 1.9·10 <sup>-2</sup> | 3.7·10 <sup>-3</sup> | 3.6·10 <sup>-3</sup> | 2.2·10 <sup>-1</sup>               | 8.0·10 <sup>-2</sup> | 5.0·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> |
| Sweden                | 4.4                                   | 1.9                  | 1.3                  | 5.3·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup> | 1.3                               | 4.9·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> | 1.4·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 3.8                                | 1.8                  | 1.2                  | 7.1·10 <sup>-1</sup> | 6.9·10 <sup>-1</sup> |
| Switzerland           | 1.3                                   | 7.4·10 <sup>-1</sup> | 5.6·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup>              | 1.5·10 <sup>-1</sup> | 9.9·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 1.9·10 <sup>-2</sup> | 1.0                                | 6.1·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> |
| United Kingdom        | 1.5                                   | 1.0                  | 7.9·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 4.3·10 <sup>-1</sup>              | 2.5·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 8.4·10 <sup>-2</sup> | 8.2·10 <sup>-2</sup> | 8.6·10 <sup>-1</sup>               | 5.9·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Baltic sea            | x                                     | x                    | x                    | x                    | x                    | 1.1                               | 4.0·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 8.8·10 <sup>-2</sup> | 8.5·10 <sup>-2</sup> | 2.2                                | 1.0                  | 5.5·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> |
| North sea             | x                                     | x                    | x                    | x                    | x                    | 5.3·10 <sup>-1</sup>              | 2.9·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 8.5·10 <sup>-2</sup> | 8.4·10 <sup>-2</sup> | 9.9·10 <sup>-1</sup>               | 6.5·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Atlantic ocean        | x                                     | x                    | x                    | x                    | x                    | 1.6·10 <sup>-1</sup>              | 7.4·10 <sup>-2</sup> | 4.6·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 2.7·10 <sup>-1</sup>               | 1.3·10 <sup>-1</sup> | 8.3·10 <sup>-2</sup> | 3.4·10 <sup>-2</sup> | 3.3·10 <sup>-2</sup> |
| Mediterranean sea     | x                                     | x                    | x                    | x                    | x                    | 1.5·10 <sup>-2</sup>              | 3.1·10 <sup>-3</sup> | 1.9·10 <sup>-3</sup> | 4.6·10 <sup>-4</sup> | 4.5·10 <sup>-4</sup> | 2.5·10 <sup>-2</sup>               | 5.4·10 <sup>-3</sup> | 3.5·10 <sup>-3</sup> | 7.4·10 <sup>-4</sup> | 7.3·10 <sup>-4</sup> |

x = Potential is not calculated; A&B = Scenario in which 'above and below threshold' marginal changes in the hazard index are summed; OA\_1990 = Scenario in which 'only above threshold' marginal changes in the hazard index are summed, taking 1990 emissions as a starting point; OA\_1995 = Scenario in which 'only above threshold' marginal changes in the hazard index are summed, taking 1995 emissions as a starting point; OA\_2010-BL = Scenario in which 'only above threshold' marginal changes in the hazard index are summed, taking 2010 Baseline forecast emissions as a starting point; OA\_2010-NP = Scenario in which 'only above threshold' marginal changes in the hazard index are summed, taking 2010 New Policy forecast emissions as a starting point;

Table 4b: Acidification potentials of Ammonia (NH<sub>3</sub>), Nitrogen oxide (NO<sub>x</sub>), and Sulphur dioxide (SO<sub>2</sub>) for 22 East European regions.

| Region                         | Acidification potentials   |                      |                      |                      |                      |                                   |                      |                      |                      |                      |                                    |                      |                      |                      |                      |
|--------------------------------|----------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|------------------------------------|----------------------|----------------------|----------------------|----------------------|
|                                | Ammonia (NH <sub>3</sub> ) |                      |                      |                      |                      | Nitrogen Oxide (NO <sub>x</sub> ) |                      |                      |                      |                      | Sulphur dioxide (SO <sub>2</sub> ) |                      |                      |                      |                      |
|                                | A&B                        | OA                   | OA                   | OA                   | OA                   | A&B                               | OA                   | OA                   | OA                   | OA                   | A&B                                | OA                   | OA                   | OA                   | OA                   |
|                                | 1990                       | 1995                 | 2010_BL              | 2010_NP              |                      | 1990                              | 1995                 | 2010_BL              | 2010_NP              |                      | 1990                               | 1995                 | 2010_BL              | 2010_NP              |                      |
| Albania                        | 1.6·10 <sup>-1</sup>       | 1.1·10 <sup>-2</sup> | 5.6·10 <sup>-3</sup> | 1.7·10 <sup>-3</sup> | 1.6·10 <sup>-3</sup> | 4.9·10 <sup>-2</sup>              | 7.2·10 <sup>-3</sup> | 3.7·10 <sup>-3</sup> | 1.0·10 <sup>-3</sup> | 9.3·10 <sup>-4</sup> | 1.3·10 <sup>-1</sup>               | 2.5·10 <sup>-2</sup> | 1.7·10 <sup>-2</sup> | 9.9·10 <sup>-3</sup> | 9.6·10 <sup>-3</sup> |
| Belarus                        | 2.0                        | 7.6·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 7.4·10 <sup>-2</sup> | 9.2·10 <sup>-1</sup>              | 2.3·10 <sup>-1</sup> | 6.5·10 <sup>-2</sup> | 3.2·10 <sup>-2</sup> | 2.2·10 <sup>-2</sup> | 2.2                                | 6.7·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 6.3·10 <sup>-2</sup> |
| Bosnia-Herzegovina             | 2.3·10 <sup>-1</sup>       | 5.0·10 <sup>-2</sup> | 2.5·10 <sup>-2</sup> | 8.3·10 <sup>-3</sup> | 7.8·10 <sup>-3</sup> | 1.0·10 <sup>-1</sup>              | 3.0·10 <sup>-2</sup> | 1.5·10 <sup>-2</sup> | 4.6·10 <sup>-3</sup> | 4.3·10 <sup>-3</sup> | 2.5·10 <sup>-1</sup>               | 8.5·10 <sup>-2</sup> | 5.8·10 <sup>-2</sup> | 3.6·10 <sup>-2</sup> | 3.5·10 <sup>-2</sup> |
| Bulgaria                       | 3.9·10 <sup>-1</sup>       | 2.6·10 <sup>-2</sup> | 1.0·10 <sup>-2</sup> | 3.5·10 <sup>-3</sup> | 3.0·10 <sup>-3</sup> | 1.1·10 <sup>-1</sup>              | 1.5·10 <sup>-2</sup> | 5.6·10 <sup>-3</sup> | 1.9·10 <sup>-3</sup> | 1.6·10 <sup>-3</sup> | 2.0·10 <sup>-1</sup>               | 3.4·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> | 9.8·10 <sup>-3</sup> |
| Croatia                        | 3.1·10 <sup>-1</sup>       | 9.5·10 <sup>-2</sup> | 5.0·10 <sup>-2</sup> | 1.5·10 <sup>-2</sup> | 1.4·10 <sup>-2</sup> | 1.6·10 <sup>-1</sup>              | 5.9·10 <sup>-2</sup> | 3.1·10 <sup>-2</sup> | 8.9·10 <sup>-3</sup> | 8.4·10 <sup>-3</sup> | 3.9·10 <sup>-1</sup>               | 1.9·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 7.4·10 <sup>-2</sup> | 7.3·10 <sup>-2</sup> |
| Czech Republic                 | 1.4                        | 1.1                  | 8.3·10 <sup>-1</sup> | 8.5·10 <sup>-2</sup> | 8.5·10 <sup>-2</sup> | 4.5·10 <sup>-1</sup>              | 2.4·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 3.5·10 <sup>-2</sup> | 3.4·10 <sup>-2</sup> | 1.2                                | 8.3·10 <sup>-1</sup> | 6.1·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> |
| Estonia                        | 3.0                        | 1.2                  | 2.2·10 <sup>-1</sup> | 1.2·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 1.5                               | 4.9·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 5.9·10 <sup>-2</sup> | 5.4·10 <sup>-2</sup> | 4.1                                | 1.7                  | 3.1·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> |
| Hungary                        | 6.2·10 <sup>-1</sup>       | 3.0·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 8.0·10 <sup>-2</sup> | 7.6·10 <sup>-2</sup> | 3.1·10 <sup>-1</sup>              | 1.2·10 <sup>-1</sup> | 6.1·10 <sup>-2</sup> | 2.2·10 <sup>-2</sup> | 2.0·10 <sup>-2</sup> | 1.0                                | 6.6·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> | 4.2·10 <sup>-1</sup> | 4.2·10 <sup>-1</sup> |
| Latvia                         | 2.5                        | 6.9·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 7.9·10 <sup>-2</sup> | 6.8·10 <sup>-2</sup> | 1.2                               | 3.4·10 <sup>-1</sup> | 9.1·10 <sup>-2</sup> | 4.7·10 <sup>-2</sup> | 4.2·10 <sup>-2</sup> | 2.4                                | 7.5·10 <sup>-1</sup> | 2.5·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> |
| Lithuania                      | 1.7                        | 5.0·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 7.3·10 <sup>-2</sup> | 6.1·10 <sup>-2</sup> | 9.8·10 <sup>-1</sup>              | 2.8·10 <sup>-1</sup> | 8.6·10 <sup>-2</sup> | 4.2·10 <sup>-2</sup> | 3.7·10 <sup>-2</sup> | 1.9                                | 6.2·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> | 1.4·10 <sup>-1</sup> | 1.2·10 <sup>-1</sup> |
| Macedonia                      | 1.8·10 <sup>-1</sup>       | 1.1·10 <sup>-2</sup> | 5.8·10 <sup>-3</sup> | 2.0·10 <sup>-3</sup> | 1.9·10 <sup>-3</sup> | 5.2·10 <sup>-2</sup>              | 7.6·10 <sup>-3</sup> | 4.0·10 <sup>-3</sup> | 1.3·10 <sup>-3</sup> | 1.2·10 <sup>-3</sup> | 1.5·10 <sup>-1</sup>               | 2.5·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> |
| Moldavia                       | 5.9·10 <sup>-1</sup>       | 1.2·10 <sup>-1</sup> | 3.7·10 <sup>-2</sup> | 1.3·10 <sup>-2</sup> | 1.0·10 <sup>-2</sup> | 3.4·10 <sup>-1</sup>              | 6.9·10 <sup>-2</sup> | 2.0·10 <sup>-2</sup> | 8.1·10 <sup>-3</sup> | 6.6·10 <sup>-3</sup> | 6.8·10 <sup>-1</sup>               | 1.6·10 <sup>-1</sup> | 7.1·10 <sup>-2</sup> | 4.1·10 <sup>-2</sup> | 3.5·10 <sup>-2</sup> |
| Poland                         | 1.7                        | 1.0                  | 5.0·10 <sup>-1</sup> | 8.2·10 <sup>-2</sup> | 9.1·10 <sup>-2</sup> | 5.9·10 <sup>-1</sup>              | 2.4·10 <sup>-1</sup> | 1.1·10 <sup>-1</sup> | 3.4·10 <sup>-2</sup> | 3.3·10 <sup>-2</sup> | 1.3                                | 7.4·10 <sup>-1</sup> | 4.3·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> |
| Romania                        | 4.5·10 <sup>-1</sup>       | 8.6·10 <sup>-2</sup> | 3.4·10 <sup>-2</sup> | 1.3·10 <sup>-2</sup> | 1.1·10 <sup>-2</sup> | 2.0·10 <sup>-1</sup>              | 4.6·10 <sup>-2</sup> | 1.9·10 <sup>-2</sup> | 6.8·10 <sup>-3</sup> | 6.1·10 <sup>-3</sup> | 4.6·10 <sup>-1</sup>               | 1.4·10 <sup>-1</sup> | 8.2·10 <sup>-2</sup> | 5.0·10 <sup>-2</sup> | 4.7·10 <sup>-2</sup> |
| Russia (Kaliningrad region)    | 2.3                        | 5.9·10 <sup>-1</sup> | 2.0·10 <sup>-1</sup> | 7.9·10 <sup>-2</sup> | 7.4·10 <sup>-2</sup> | 8.9·10 <sup>-1</sup>              | 2.8·10 <sup>-1</sup> | 1.0·10 <sup>-1</sup> | 4.6·10 <sup>-2</sup> | 4.2·10 <sup>-2</sup> | 1.9                                | 6.6·10 <sup>-1</sup> | 3.0·10 <sup>-1</sup> | 1.5·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> |
| Russia (Kola, Karelia)         | 1.0·10 <sup>1</sup>        | 4.2                  | 7.5·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 2.0                               | 7.6·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> | 7.2·10 <sup>-2</sup> | 7.4·10 <sup>-2</sup> | 7.2                                | 4.3                  | 2.3                  | 4.2·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> |
| Russia (St. Petersburg region) | 6.0                        | 1.7                  | 1.6·10 <sup>-1</sup> | 7.4·10 <sup>-2</sup> | 6.1·10 <sup>-2</sup> | 1.9                               | 5.2·10 <sup>-1</sup> | 8.1·10 <sup>-2</sup> | 4.0·10 <sup>-2</sup> | 3.6·10 <sup>-2</sup> | 5.2                                | 1.6                  | 2.5·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 1.2·10 <sup>-1</sup> |
| Russia (Remaining)             | 3.7                        | 4.3·10 <sup>-1</sup> | 2.3·10 <sup>-2</sup> | 1.0·10 <sup>-2</sup> | 6.8·10 <sup>-3</sup> | 1.1                               | 1.6·10 <sup>-1</sup> | 1.2·10 <sup>-2</sup> | 5.5·10 <sup>-3</sup> | 4.4·10 <sup>-3</sup> | 3.0                                | 4.2·10 <sup>-1</sup> | 3.4·10 <sup>-2</sup> | 1.7·10 <sup>-2</sup> | 1.3·10 <sup>-2</sup> |
| Slovakia                       | 1.1                        | 6.8·10 <sup>-1</sup> | 4.4·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> | 3.5·10 <sup>-1</sup>              | 1.4·10 <sup>-1</sup> | 7.7·10 <sup>-2</sup> | 2.6·10 <sup>-2</sup> | 2.4·10 <sup>-2</sup> | 1.5                                | 1.0                  | 8.6·10 <sup>-1</sup> | 6.6·10 <sup>-1</sup> | 6.6·10 <sup>-1</sup> |
| Slovenia                       | 6.8·10 <sup>-1</sup>       | 3.7·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 2.8·10 <sup>-2</sup> | 2.8·10 <sup>-2</sup> | 1.7·10 <sup>-1</sup>              | 8.4·10 <sup>-2</sup> | 4.4·10 <sup>-2</sup> | 9.4·10 <sup>-3</sup> | 9.3·10 <sup>-3</sup> | 5.7·10 <sup>-1</sup>               | 3.4·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 7.7·10 <sup>-2</sup> | 7.7·10 <sup>-2</sup> |
| Ukraine                        | 9.4·10 <sup>-1</sup>       | 1.9·10 <sup>-1</sup> | 5.5·10 <sup>-2</sup> | 2.2·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 5.6·10 <sup>-1</sup>              | 8.7·10 <sup>-2</sup> | 1.8·10 <sup>-2</sup> | 7.9·10 <sup>-3</sup> | 6.2·10 <sup>-3</sup> | 1.1                                | 1.8·10 <sup>-1</sup> | 5.4·10 <sup>-2</sup> | 2.9·10 <sup>-2</sup> | 2.3·10 <sup>-2</sup> |
| Yugoslavia                     | 2.8·10 <sup>-1</sup>       | 4.9·10 <sup>-2</sup> | 2.3·10 <sup>-2</sup> | 8.0·10 <sup>-3</sup> | 7.5·10 <sup>-3</sup> | 1.3·10 <sup>-1</sup>              | 3.3·10 <sup>-2</sup> | 1.5·10 <sup>-2</sup> | 4.9·10 <sup>-3</sup> | 4.6·10 <sup>-3</sup> | 3.4·10 <sup>-1</sup>               | 1.3·10 <sup>-1</sup> | 8.7·10 <sup>-2</sup> | 5.7·10 <sup>-2</sup> | 5.5·10 <sup>-2</sup> |

See Table 4a for abbreviations

Table 5a: Eutrophication potentials of Ammonia (NH<sub>3</sub>) and Nitrogen oxide (NO<sub>x</sub>) for 22 West European regions.

| West European Regions | Eutrophication potentials  |                      |                      |                      |                      |                                   |                      |                      |                      |                      |
|-----------------------|----------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|
|                       | Ammonia (NH <sub>3</sub> ) |                      |                      |                      |                      | Nitrogen oxide (NO <sub>x</sub> ) |                      |                      |                      |                      |
|                       | A&B                        | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        | A&B                               | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        |
| Austria               | 4.2                        | 3.9                  | 3.6                  | 2.4                  | 2.3                  | 8.9·10 <sup>-1</sup>              | 7.1·10 <sup>-1</sup> | 6.3·10 <sup>-1</sup> | 4.8·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> |
| Belgium               | 2.9                        | 2.6                  | 2.5                  | 2.2                  | 2.2                  | 1.2                               | 1.0                  | 9.3·10 <sup>-1</sup> | 7.8·10 <sup>-1</sup> | 7.8·10 <sup>-1</sup> |
| Denmark               | 2.5                        | 1.6                  | 1.3                  | 9.3·10 <sup>-1</sup> | 8.7·10 <sup>-1</sup> | 1.6                               | 9.1·10 <sup>-1</sup> | 6.9·10 <sup>-1</sup> | 5.5·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> |
| Finland               | 1.5·10 <sup>1</sup>        | 9.2                  | 6.4                  | 3.6                  | 2.8                  | 3.5                               | 1.6                  | 9.9·10 <sup>-1</sup> | 7.5·10 <sup>-1</sup> | 6.2·10 <sup>-1</sup> |
| France                | 6.4                        | 6.2                  | 6.0                  | 5.3                  | 5.3                  | 1.3                               | 1.2                  | 1.1                  | 8.9·10 <sup>-1</sup> | 8.9·10 <sup>-1</sup> |
| Germany (new)         | 4.6                        | 4.0                  | 3.8                  | 3.5                  | 3.4                  | 1.5                               | 1.2                  | 1.0                  | 9.2·10 <sup>-1</sup> | 9.0·10 <sup>-1</sup> |
| Germany (old)         | 3.7                        | 3.3                  | 3.1                  | 2.6                  | 2.6                  | 1.3                               | 1.0                  | 9.4·10 <sup>-1</sup> | 7.9·10 <sup>-1</sup> | 7.7·10 <sup>-1</sup> |
| Greece                | 1.5                        | 6.6·10 <sup>-1</sup> | 4.3·10 <sup>-1</sup> | 3.9·10 <sup>-1</sup> | 2.4·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup>              | 1.4·10 <sup>-1</sup> | 9.1·10 <sup>-2</sup> | 8.2·10 <sup>-2</sup> | 6.6·10 <sup>-2</sup> |
| Ireland               | 1.0                        | 4.7·10 <sup>-1</sup> | 4.2·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup>              | 3.1·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> |
| Italy                 | 2.8                        | 2.2                  | 2.1                  | 1.4                  | 1.4                  | 6.0·10 <sup>-1</sup>              | 4.5·10 <sup>-1</sup> | 4.1·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup> |
| Luxembourg            | 4.4                        | 4.1                  | 4.0                  | 3.4                  | 3.3                  | 1.4                               | 1.2                  | 1.1                  | 9.5·10 <sup>-1</sup> | 9.5·10 <sup>-1</sup> |
| Netherlands           | 2.3                        | 2.0                  | 1.8                  | 1.6                  | 1.6                  | 1.1                               | 8.4·10 <sup>-1</sup> | 7.5·10 <sup>-1</sup> | 6.3·10 <sup>-1</sup> | 6.2·10 <sup>-1</sup> |
| Norway                | 6.2                        | 1.6                  | 1.2                  | 3.4·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 1.6                               | 5.7·10 <sup>-1</sup> | 3.8·10 <sup>-1</sup> | 2.5·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Portugal              | 2.4                        | 1.5                  | 1.6                  | 1.2                  | 1.1                  | 4.9·10 <sup>-1</sup>              | 3.1·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> |
| Spain                 | 2.0                        | 1.2                  | 1.1                  | 6.7·10 <sup>-1</sup> | 6.5·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup>              | 3.5·10 <sup>-1</sup> | 3.3·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Sweden                | 5.7                        | 2.7                  | 2.0                  | 1.3                  | 1.2                  | 2.1                               | 1.0                  | 6.8·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> |
| Switzerland           | 5.0                        | 4.8                  | 4.7                  | 3.8                  | 3.8                  | 1.0                               | 8.9·10 <sup>-1</sup> | 8.4·10 <sup>-1</sup> | 6.6·10 <sup>-1</sup> | 6.6·10 <sup>-1</sup> |
| United Kingdom        | 1.7                        | 9.1·10 <sup>-1</sup> | 7.9·10 <sup>-1</sup> | 4.9·10 <sup>-1</sup> | 4.8·10 <sup>-1</sup> | 7.6·10 <sup>-1</sup>              | 5.0·10 <sup>-1</sup> | 4.4·10 <sup>-1</sup> | 3.5·10 <sup>-1</sup> | 3.4·10 <sup>-1</sup> |
| Baltic sea            | X                          | x                    | x                    | x                    | x                    | 2.1                               | 1.2                  | 8.4·10 <sup>-1</sup> | 6.9·10 <sup>-1</sup> | 6.2·10 <sup>-1</sup> |
| North sea             | X                          | x                    | x                    | x                    | x                    | 1.1                               | 7.4·10 <sup>-1</sup> | 6.5·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> | 5.2·10 <sup>-1</sup> |
| N.E. Atlantic ocean   | X                          | x                    | x                    | x                    | x                    | 4.0·10 <sup>-1</sup>              | 2.8·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> |
| Mediterranean sea     | X                          | x                    | x                    | x                    | x                    | 1.2·10 <sup>-1</sup>              | 6.5·10 <sup>-2</sup> | 6.4·10 <sup>-2</sup> | 3.5·10 <sup>-2</sup> | 3.3·10 <sup>-2</sup> |

See Table 4a for abbreviations



Table 5b: Eutrophication potentials of Ammonia (NH<sub>3</sub>) and Nitrogen oxide (NO<sub>x</sub>) for 22 East European regions.

| East European Regions          | Eutrophication potentials  |                      |                      |                      |                      |                                   |                      |                      |                      |                      |
|--------------------------------|----------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|
|                                | Ammonia (NH <sub>3</sub> ) |                      |                      |                      |                      | Nitrogen oxide (NO <sub>x</sub> ) |                      |                      |                      |                      |
|                                | A&B                        | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        | A&B                               | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        |
| Albania                        | 2.8                        | 1.4                  | 1.1                  | 9.3·10 <sup>-1</sup> | 8.7·10 <sup>-1</sup> | 5.0·10 <sup>-1</sup>              | 2.9·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> | 1.6·10 <sup>-1</sup> |
| Belarus                        | 4.5                        | 2.4                  | 1.8                  | 1.6                  | 1.5                  | 2.0                               | 9.7·10 <sup>-1</sup> | 6.3·10 <sup>-1</sup> | 6.0·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> |
| Bosnia-Herzegovina             | 2.9                        | 2.5                  | 2.3                  | 1.4                  | 1.4                  | 6.1·10 <sup>-1</sup>              | 4.5·10 <sup>-1</sup> | 3.8·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> |
| Bulgaria                       | 2.8                        | 2.5                  | 1.3                  | 1.3                  | 9.6·10 <sup>-1</sup> | 5.6·10 <sup>-1</sup>              | 3.9·10 <sup>-1</sup> | 2.3·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> |
| Croatia                        | 1.5                        | 1.1                  | 9.8·10 <sup>-1</sup> | 6.7·10 <sup>-1</sup> | 6.4·10 <sup>-1</sup> | 6.7·10 <sup>-1</sup>              | 4.9·10 <sup>-1</sup> | 4.1·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 3.0·10 <sup>-1</sup> |
| Czech Republic                 | 4.2                        | 3.7                  | 3.5                  | 3.0                  | 3.0                  | 1.3                               | 1.0                  | 9.1·10 <sup>-1</sup> | 8.0·10 <sup>-1</sup> | 7.7·10 <sup>-1</sup> |
| Estonia                        | 8.7                        | 5.9                  | 4.2                  | 3.7                  | 3.3                  | 3.3                               | 1.7                  | 1.1                  | 9.9·10 <sup>-1</sup> | 8.6·10 <sup>-1</sup> |
| Hungary                        | 2.2                        | 1.7                  | 1.4                  | 1.1                  | 1.0                  | 1.0                               | 7.3·10 <sup>-1</sup> | 5.8·10 <sup>-1</sup> | 4.9·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> |
| Latvia                         | 7.3                        | 5.0                  | 3.9                  | 3.8                  | 3.5                  | 2.6                               | 1.4                  | 9.1·10 <sup>-1</sup> | 8.3·10 <sup>-1</sup> | 7.3·10 <sup>-1</sup> |
| Lithuania                      | 4.9                        | 3.3                  | 2.6                  | 2.5                  | 2.4                  | 2.2                               | 1.1                  | 7.8·10 <sup>-1</sup> | 7.2·10 <sup>-1</sup> | 6.5·10 <sup>-1</sup> |
| Macedonia                      | 2.3                        | 1.6                  | 1.0                  | 8.5·10 <sup>-1</sup> | 7.8·10 <sup>-1</sup> | 4.7·10 <sup>-1</sup>              | 3.4·10 <sup>-1</sup> | 2.4·10 <sup>-1</sup> | 2.0·10 <sup>-1</sup> | 1.8·10 <sup>-1</sup> |
| Moldavia                       | 1.6                        | 7.8·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> | 9.1·10 <sup>-1</sup>              | 4.6·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 3.0·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> |
| Poland                         | 6.1                        | 5.2                  | 4.8                  | 4.6                  | 4.5                  | 1.6                               | 1.1                  | 9.0·10 <sup>-1</sup> | 8.3·10 <sup>-1</sup> | 7.9·10 <sup>-1</sup> |
| Romania                        | 2.3                        | 1.6                  | 9.4·10 <sup>-1</sup> | 8.8·10 <sup>-1</sup> | 8.2·10 <sup>-1</sup> | 7.5·10 <sup>-1</sup>              | 4.8·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 2.9·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> |
| Russia (Kalingrad region)      | 6.7                        | 4.7                  | 2.4                  | 2.2                  | 2.1                  | 2.0                               | 1.1                  | 7.8·10 <sup>-1</sup> | 7.1·10 <sup>-1</sup> | 6.5·10 <sup>-1</sup> |
| Russia (Kola, Karelia)         | 1.6·10 <sup>1</sup>        | 3.4                  | 1.9                  | 1.6                  | 1.4                  | 3.2                               | 8.3·10 <sup>-1</sup> | 2.8·10 <sup>-1</sup> | 2.6·10 <sup>-1</sup> | 2.2·10 <sup>-1</sup> |
| Russia (St. Petersburg region) | 1.4·10 <sup>1</sup>        | 8.5                  | 6.0                  | 5.7                  | 4.9                  | 3.8                               | 1.8                  | 1.1                  | 9.9·10 <sup>-1</sup> | 8.6·10 <sup>-1</sup> |
| Russia (Remaining)             | 8.4                        | 3.2                  | 1.6                  | 2.0                  | 1.7                  | 2.3                               | 9.1·10 <sup>-1</sup> | 4.1·10 <sup>-1</sup> | 5.1·10 <sup>-1</sup> | 4.2·10 <sup>-1</sup> |
| Slovakia                       | 4.0                        | 3.4                  | 3.0                  | 2.3                  | 2.2                  | 1.1                               | 8.1·10 <sup>-1</sup> | 6.7·10 <sup>-1</sup> | 5.7·10 <sup>-1</sup> | 5.4·10 <sup>-1</sup> |
| Slovenia                       | 2.8                        | 2.3                  | 2.0                  | 9.8·10 <sup>-1</sup> | 9.6·10 <sup>-1</sup> | 6.4·10 <sup>-1</sup>              | 5.1·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> | 3.1·10 <sup>-1</sup> |
| Ukraine                        | 3.0                        | 1.8                  | 1.3                  | 1.3                  | 1.1                  | 1.5                               | 6.7·10 <sup>-1</sup> | 3.7·10 <sup>-1</sup> | 4.3·10 <sup>-1</sup> | 3.6·10 <sup>-1</sup> |
| Yugoslavia                     | 2.8                        | 2.2                  | 1.8                  | 1.3                  | 1.2                  | 7.0·10 <sup>-1</sup>              | 5.0·10 <sup>-1</sup> | 3.8·10 <sup>-1</sup> | 3.0·10 <sup>-1</sup> | 2.7·10 <sup>-1</sup> |

See Table 4a for abbreviations

Table 6: Average acidification and eutrophication potentials for West Europe, East Europe and total Europe.

|                       | A&B<br>1990          | OA<br>1990           | A&B<br>1995          | OA<br>1995           | A&B<br>2010_BL       | OA<br>2010_BL        | A&B<br>2010_NP       | OA<br>2010_NP        |
|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| <b>Acidification</b>  |                      |                      |                      |                      |                      |                      |                      |                      |
| <b>NH<sub>3</sub></b> |                      |                      |                      |                      |                      |                      |                      |                      |
| West Europe           | 1.4                  | 7.6·10 <sup>-1</sup> | 1.3                  | 4.8·10 <sup>-1</sup> | 1.3                  | 1.3·10 <sup>-1</sup> | 1.3                  | 1.2·10 <sup>-1</sup> |
| East Europe           | 2.0                  | 4.6·10 <sup>-1</sup> | 1.8                  | 1.6·10 <sup>-1</sup> | 1.9                  | 4.2·10 <sup>-2</sup> | 1.9                  | 3.7·10 <sup>-2</sup> |
| Total Europe          | 1.7                  | 6.1·10 <sup>-1</sup> | 1.6                  | 3.2·10 <sup>-1</sup> | 1.6                  | 8.2·10 <sup>-2</sup> | 1.6                  | 8.0·10 <sup>-2</sup> |
| <b>NO<sub>x</sub></b> |                      |                      |                      |                      |                      |                      |                      |                      |
| West Europe           | 4.2·10 <sup>-1</sup> | 2.1·10 <sup>-1</sup> | 4.1·10 <sup>-1</sup> | 1.2·10 <sup>-1</sup> | 4.0·10 <sup>-1</sup> | 4.8·10 <sup>-2</sup> | 4.1·10 <sup>-1</sup> | 4.8·10 <sup>-2</sup> |
| East Europe           | 7.4·10 <sup>-1</sup> | 1.7·10 <sup>-1</sup> | 7.0·10 <sup>-1</sup> | 5.4·10 <sup>-2</sup> | 7.8·10 <sup>-1</sup> | 1.5·10 <sup>-2</sup> | 7.6·10 <sup>-1</sup> | 1.4·10 <sup>-2</sup> |
| Total Europe          | 5.5·10 <sup>-1</sup> | 1.9·10 <sup>-1</sup> | 5.0·10 <sup>-1</sup> | 1.0·10 <sup>-1</sup> | 5.7·10 <sup>-1</sup> | 3.3·10 <sup>-2</sup> | 5.6·10 <sup>-1</sup> | 3.3·10 <sup>-2</sup> |
| <b>SO<sub>2</sub></b> |                      |                      |                      |                      |                      |                      |                      |                      |
| West Europe           | 9.1·10 <sup>-1</sup> | 5.5·10 <sup>-1</sup> | 7.9·10 <sup>-1</sup> | 3.3·10 <sup>-1</sup> | 8.0·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> | 8.4·10 <sup>-1</sup> | 1.3·10 <sup>-1</sup> |
| East Europe           | 1.7                  | 5.9·10 <sup>-1</sup> | 1.6                  | 3.0·10 <sup>-1</sup> | 2.0                  | 1.1·10 <sup>-1</sup> | 1.6                  | 1.1·10 <sup>-1</sup> |
| Total Europe          | 1.3                  | 5.7·10 <sup>-1</sup> | 1.2                  | 3.1·10 <sup>-1</sup> | 1.5                  | 1.2·10 <sup>-1</sup> | 1.3                  | 1.2·10 <sup>-1</sup> |
| <b>Eutrophication</b> |                      |                      |                      |                      |                      |                      |                      |                      |
| <b>NH<sub>3</sub></b> |                      |                      |                      |                      |                      |                      |                      |                      |
| West Europe           | 3.8                  | 3.2                  | 3.7                  | 2.9                  | 3.8                  | 2.4                  | 3.8                  | 2.4                  |
| East Europe           | 5.4                  | 3.0                  | 5.0                  | 2.0                  | 5.3                  | 2.2                  | 5.2                  | 2.0                  |
| Total Europe          | 4.6                  | 3.1                  | 4.3                  | 2.5                  | 4.6                  | 2.3                  | 4.5                  | 2.2                  |
| <b>NO<sub>x</sub></b> |                      |                      |                      |                      |                      |                      |                      |                      |
| West Europe           | 1.0                  | 7.2·10 <sup>-1</sup> | 9.9·10 <sup>-1</sup> | 6.2·10 <sup>-1</sup> | 9.5·10 <sup>-1</sup> | 4.6·10 <sup>-1</sup> | 9.5·10 <sup>-1</sup> | 4.5·10 <sup>-1</sup> |
| East Europe           | 1.8                  | 8.6·10 <sup>-1</sup> | 1.7                  | 5.7·10 <sup>-1</sup> | 1.8                  | 5.3·10 <sup>-1</sup> | 1.8                  | 4.6·10 <sup>-1</sup> |
| Total Europe          | 1.3                  | 7.7·10 <sup>-1</sup> | 1.2                  | 6.0·10 <sup>-1</sup> | 1.3                  | 4.9·10 <sup>-1</sup> | 1.3                  | 4.5·10 <sup>-1</sup> |

See Table 4a for abbreviations

Table 7: West European, East European and total European normalisation levels for acidification (kg SO<sub>2</sub>-equivalents) and eutrophication (kg NO<sub>x</sub>-equivalents).

| Region                | A&B<br>1990          | A&B<br>1995          | A&B<br>2010_BL       | A&B<br>2010_NP       | OA<br>1990           | OA<br>1995           | OA<br>2010_BL        | OA<br>2010_NP        |
|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| <b>Acidification</b>  |                      |                      |                      |                      |                      |                      |                      |                      |
| Western Europe        | $2.75 \cdot 10^{10}$ | $1.97 \cdot 10^{10}$ | $1.05 \cdot 10^{10}$ | $1.03 \cdot 10^{10}$ | $1.58 \cdot 10^{10}$ | $7.21 \cdot 10^9$    | $1.30 \cdot 10^9$    | $1.26 \cdot 10^9$    |
| Eastern Europe        | $5.11 \cdot 10^{10}$ | $3.02 \cdot 10^{10}$ | $2.50 \cdot 10^{10}$ | $1.98 \cdot 10^{10}$ | $1.61 \cdot 10^{10}$ | $4.74 \cdot 10^9$    | $9.97 \cdot 10^8$    | $8.29 \cdot 10^8$    |
| Total Europe          | $7.86 \cdot 10^{10}$ | $4.99 \cdot 10^{10}$ | $3.55 \cdot 10^{10}$ | $3.01 \cdot 10^{10}$ | $3.19 \cdot 10^{10}$ | $1.20 \cdot 10^{10}$ | $2.29 \cdot 10^9$    | $2.09 \cdot 10^9$    |
| <b>Eutrophication</b> |                      |                      |                      |                      |                      |                      |                      |                      |
| Western Europe        | $2.93 \cdot 10^{10}$ | $2.59 \cdot 10^{10}$ | $1.79 \cdot 10^{10}$ | $1.77 \cdot 10^{10}$ | $2.27 \cdot 10^{10}$ | $1.81 \cdot 10^{10}$ | $1.02 \cdot 10^{10}$ | $1.00 \cdot 10^{10}$ |
| Eastern Europe        | $3.81 \cdot 10^{10}$ | $2.46 \cdot 10^{10}$ | $2.78 \cdot 10^{10}$ | $2.54 \cdot 10^{10}$ | $1.99 \cdot 10^{10}$ | $9.36 \cdot 10^9$    | $9.95 \cdot 10^9$    | $8.40 \cdot 10^9$    |
| Total Europe          | $6.74 \cdot 10^{10}$ | $5.05 \cdot 10^{10}$ | $4.57 \cdot 10^{10}$ | $4.31 \cdot 10^{10}$ | $4.26 \cdot 10^{10}$ | $2.74 \cdot 10^{10}$ | $2.02 \cdot 10^{10}$ | $1.84 \cdot 10^{10}$ |

See Table 4a for abbreviations

Table 8: Squared Pearson correlation coefficient ( $r^2$ ) between different acidification potential scenarios

| <b>Acidification</b>  | A&B  | OA<br>1990 | OA<br>1995 | OA<br>2010_BL | OA<br>2010_NP |
|-----------------------|------|------------|------------|---------------|---------------|
| <b>NH<sub>3</sub></b> |      |            |            |               |               |
| A&B                   | 1    |            |            |               |               |
| OA_1990               | 0.85 | 1          |            |               |               |
| OA_1995               | 0.27 | 0.56       | 1          |               |               |
| OA_2010BL             | 0.26 | 0.44       | 0.84       | 1             |               |
| OA_2010NP             | 0.25 | 0.43       | 0.84       | 1.00          | 1             |
| <b>NO<sub>x</sub></b> |      |            |            |               |               |
| A&B                   | 1    |            |            |               |               |
| OA_1990               | 0.84 | 1          |            |               |               |
| OA_1995               | 0.33 | 0.69       | 1          |               |               |
| OA_2010BL             | 0.36 | 0.61       | 0.84       | 1             |               |
| OA_2010NP             | 0.34 | 0.60       | 0.86       | 1.00          | 1             |
| <b>SO<sub>2</sub></b> |      |            |            |               |               |
| A&B                   | 1    |            |            |               |               |
| OA_1990               | 0.84 | 1          |            |               |               |
| OA_1995               | 0.50 | 0.83       | 1          |               |               |
| OA_2010BL             | 0.32 | 0.47       | 0.67       | 1             |               |
| OA_2010NP             | 0.31 | 0.48       | 0.70       | 0.99          | 1             |

Table 9: Squared Pearson correlation coefficient ( $r^2$ ) between different eutrophication potential scenarios

| <b>Eutrophication</b> | A&B  | OA<br>1990 | OA<br>1995 | OA<br>2010_BL | OA<br>2010_NP |
|-----------------------|------|------------|------------|---------------|---------------|
| <b>NH<sub>3</sub></b> |      |            |            |               |               |
| A&B                   | 1    |            |            |               |               |
| OA_1990               | 0.64 | 1          |            |               |               |
| OA_1995               | 0.40 | 0.89       | 1          |               |               |
| OA_2010BL             | 0.36 | 0.81       | 0.91       | 1             |               |
| OA_2010NP             | 0.27 | 0.72       | 0.87       | 0.98          | 1             |
| <b>NO<sub>x</sub></b> |      |            |            |               |               |
| A&B                   | 1    |            |            |               |               |
| OA_1990               | 0.76 | 1          |            |               |               |
| OA_1995               | 0.37 | 0.83       | 1          |               |               |
| OA_2010BL             | 0.43 | 0.87       | 0.96       | 1             |               |
| OA_2010NP             | 0.33 | 0.79       | 0.97       | 0.99          | 1             |

## 5. Discussion

### 5.1 Comparison with previous acidification and eutrophication potentials

First, a comparison is made between acidification potentials given by Heijungs et al. (1992), Potting et al. (1998) and this report. To increase the comparability of the potentials, some additional modifications are necessary. First, total European averages are calculated from region-specific potentials in Potting et al. (1998), in the same way as done in this report ( $\rightarrow$  Section 2.3). Furthermore, in the calculation of European averages (this report and Potting et al., 1998) the complete system area (Europe) is

taken as the reference region instead of Switzerland. Finally, acidification potentials are recalculated by using the same reference substance for all three literature sources. As can be seen in Table 8, European averaged acidification potentials hardly differ between Potting et al. (1998) and this report. However, the inclusion of fate and effects in the calculation of acidification potentials may cause a different priority setting between substances and in turn in different LCA outcomes. Heijungs et al. (1992) regard the acidification potential of NH<sub>3</sub> and NO<sub>x</sub> 1.5-2.8 and 1.7-2.4 times more important than this report. The main reason for the above-mentioned differences in acidification potentials is that for every ecosystem the maximum critical load for N is higher than the maximum critical load for S (see Posch et al., 1999).<sup>6</sup> Another reason for the differences found may be that there is a systematic difference in deposition on sensitive areas between the three pollutants. Finally, as shown in Table 3, a larger portion of NO<sub>x</sub> flows across the system boundaries compared to NH<sub>3</sub> and SO<sub>2</sub>, which may partially cause the relatively lower acidification potentials of this substance.

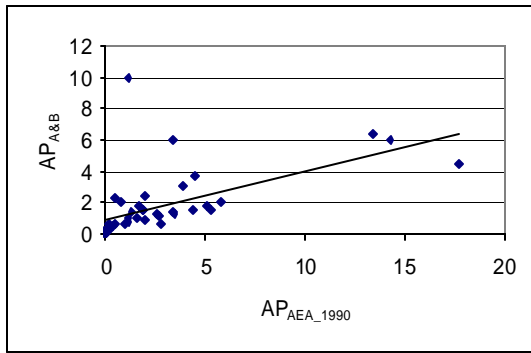
Table 10: Recalculated acidification potentials (SO<sub>2</sub>-equivalents) and eutrophication potentials (NO<sub>x</sub>-equivalents), derived from Heijungs et al. (1992), Potting et al. (1998), and this report.

|                      | Heijungs | AEA<br>1990 | AEA<br>2010 | A&B<br>1990 | OA<br>1990 | A&B<br>1995 | OA<br>1995 | A&B<br>2010BL | OA<br>2010BL | A&B<br>2010NP | OA<br>2010NP |
|----------------------|----------|-------------|-------------|-------------|------------|-------------|------------|---------------|--------------|---------------|--------------|
| <b>Acidification</b> |          |             |             |             |            |             |            |               |              |               |              |
| NH <sub>3</sub>      | 1.9      | 1.1         | 0.94        | 1.3         | 1.1        | 1.3         | 1.0        | 1.1           | 0.71         | 1.2           | 0.69         |
| NO <sub>x</sub>      | 0.70     | 0.36        | 0.27        | 0.41        | 0.34       | 0.41        | 0.33       | 0.38          | 0.29         | 0.43          | 0.29         |
| SO <sub>2</sub>      | 1        | 1           | 1           | 1           | 1          | 1           | 1          | 1             | 1            | 1             | 1            |

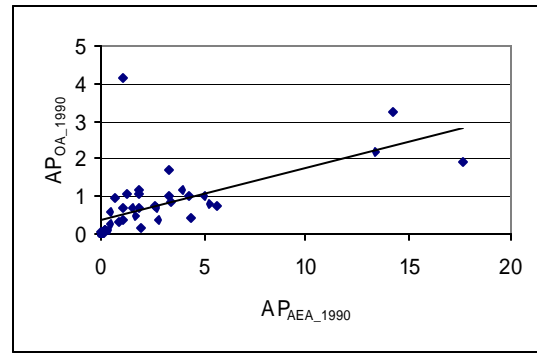
See Table 4a for abbreviations

Secondly, region-specific acidification potentials calculated by Potting et al. (1998) are compared with the region-specific acidification potentials of 3 scenarios, given in Section 4. As can be seen in the Figures 2 and 3, the correlation between the acidification potentials given by Potting et al. (1998) and this report is in most cases low ( $r^2 < 0.5$ ). This indicates that the choice for an LCA-compatible impact indicator in the calculation of region-specific acidification potentials may be an important one. The correlations between SO<sub>2</sub> acidification potentials for the year 1990 of Potting et al. (1998) and comparable acidification potentials presented in this report are, however, surprisingly high (explained variance  $\approx 76-90\%$ ; Figure 2e and 2f). Apparently, the relative ranking between SO<sub>2</sub> emissions in different European regions using the marginal change in affected ecosystem area as an impact indicator and using a marginal SO<sub>2</sub> emission change of 10%, gives similar results as the relative ranking by the marginal change in the hazard index (both for the ‘above and below critical loads’ scenario and ‘year 1990 only above’ scenario).

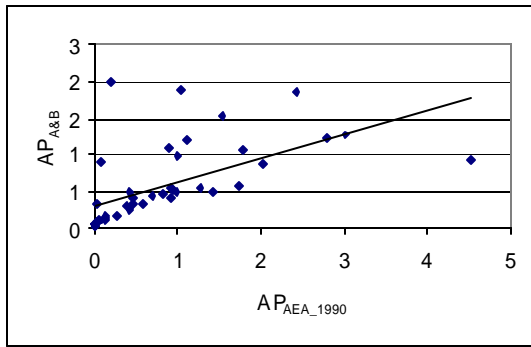
<sup>6</sup> Only if the minimum critical load for N and the denitrification fraction are both zero in an ecosystem, the CL<sub>max</sub>(N) equals the CL<sub>max</sub>(S). In all other cases the CL<sub>max</sub>(N) is higher than the CL<sub>max</sub>(S).



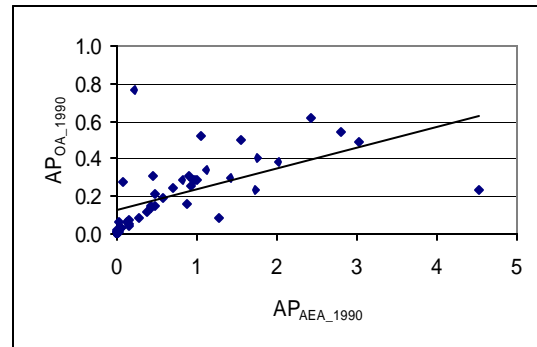
2a: NH<sub>3</sub> acidification potentials ( $r^2 = 0.32$ )



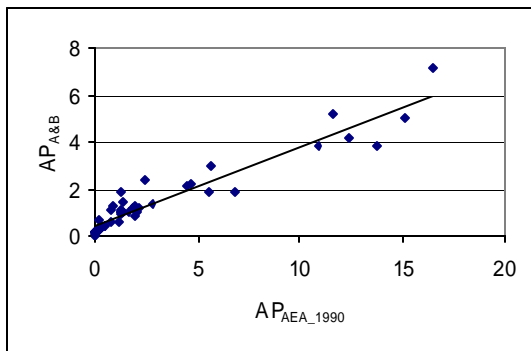
2b: NH<sub>3</sub> acidification potentials ( $r^2 = 0.36$ )



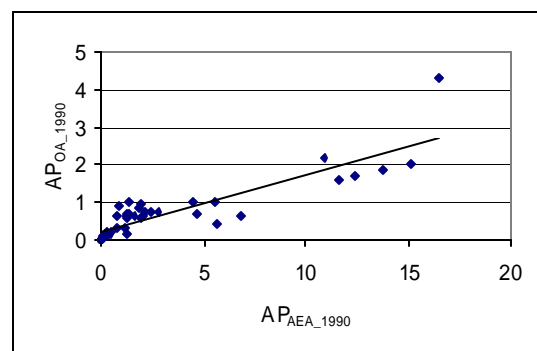
2c: NO<sub>x</sub> acidification potentials ( $r^2 = 0.34$ )



2d: NO<sub>x</sub> acidification potentials ( $r^2 = 0.33$ )

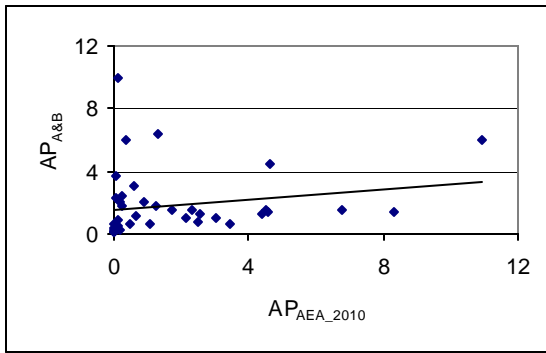


2e: SO<sub>2</sub> acidification potentials ( $r^2 = 0.90$ )

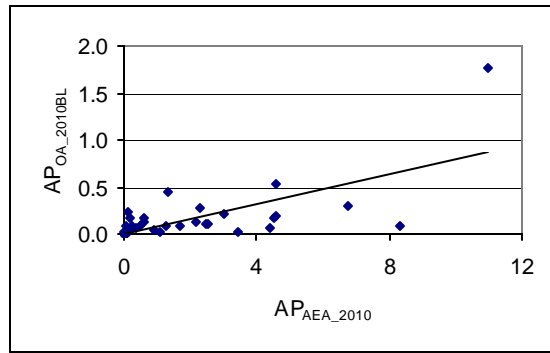


2f: SO<sub>2</sub> acidification potentials ( $r^2 = 0.76$ )

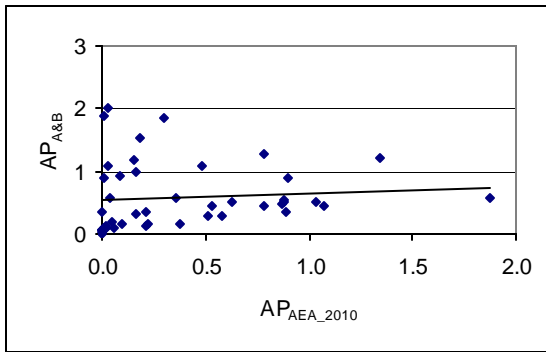
Fig. 2a-f: Relationship between region-specific acidification potentials of NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> for the year 1990 ( $AP_{AEA}$  in  $ha \cdot ton^{-1}$ ) derived from Potting et al. (1998) and region-specific acidification potentials for the 'above and below threshold' scenario ( $AP_{A\&B}$  in  $SO_2$ -eq.) and the 'only above threshold' scenario for 1990 emissions ( $AP_{OA-1990}$  in  $SO_2$ -eq.). For every comparison the Pearson correlation coefficient  $r$  is calculated.



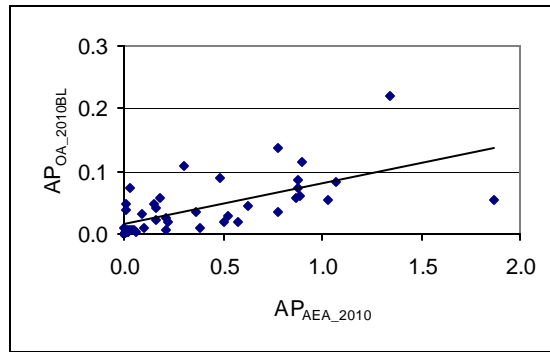
3a: NH<sub>3</sub> acidification potentials ( $r^2 = 0.04$ )



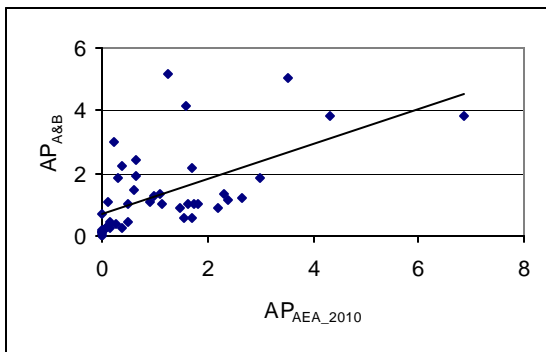
3b: NH<sub>3</sub> acidification potentials ( $r^2 = 0.48$ )



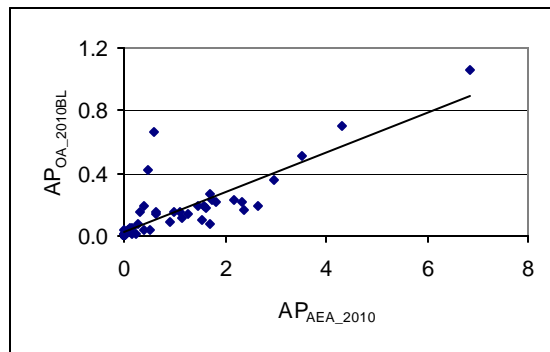
3c: NO<sub>x</sub> acidification potentials ( $r^2 = 0.01$ )



3d: NO<sub>x</sub> acidification potentials ( $r^2 = 0.41$ )



3e: SO<sub>2</sub> acidification potentials ( $r^2 = 0.33$ )



3f: SO<sub>2</sub> acidification potentials ( $r^2 = 0.67$ )

Fig. 3a-f: Relationship between region-specific acidification potentials of NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> for the year 2010 ( $AP_{AEA}$  in  $ha \cdot ton^{-1}$ ) derived from Potting et al. (1998) and region-specific acidification potentials for the ‘above and below threshold’ scenario ( $AP_{A\&B}$  in  $SO_2$ -eq.) and the ‘only above threshold’ scenario for 2010 Baseline scenario emissions ( $AP_{OA-2010BL}$  in  $SO_2$ -eq.). For every comparison the fraction of the explained variance (Pearson correlation coefficient  $r^2$ ) is calculated.<sup>7</sup>

<sup>7</sup> The acidification potentials of the Kola/Karelia region are left out the calculation of the Pearson correlation coefficients between  $AP_{A\&B}$  and  $AP_{AEA-2010}$  (Fig. 3e) and  $AP_{OA-2010BL}$  and  $AP_{AEA-2010}$  (Fig. 3f), because the potential derived from Potting et al. (1998) appeared to be an extreme outlier (25.2  $SO_2$ -eq.).

## 5.2 RAINS-LCA

The significance of the acidification and eutrophication potentials calculated with RAINS-LCA is dependent on the validity of the assumptions concerning the model structure, input data, and use in LCA case studies. The validity of the acidification and eutrophication potentials is assessed by a critical discussion of these assumptions.

RAINS-LCA is primarily concerned with the LCA-consistent implementation of a fate and effects analysis in the calculation of acidification and eutrophication potentials. However, several limitations may be identified. The first limitation of RAINS-LCA is that it may not cover all LCA-relevant regions and pollutants. For instance, only acidification and eutrophication potentials for European regions are calculated. Other models, such as the RAINS-ASIA model (Foell et al., 1995), may be used to calculate equivalency factors for regions outside Europe. Furthermore, acidification potentials for other acidifying air pollutants than  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{SO}_2$  are not included in RAINS-LCA, because transfer matrices for these pollutants are lacking on a European scale. Air pollutants, such as hydrogen chloride (HCl) and hydrogen fluoride (HF), may, however, be dominant in some life cycle inventories. Eutrophication potentials of water emissions, such as N and P, are also lacking in RAINS-LCA.

Another limitation of RAINS-LCA is that it allows flows across its system boundary. The consequence is that the fate of an emitted substance in Europe can not be taken fully into account, most likely causing an underestimation of acidification and eutrophication potentials of  $\text{NO}_x$  and potentials for Russian regions ( $\rightarrow$  Section 3.2). The fate part of RAINS-LCA may be improved by including transfer matrices for  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{SO}_2$  within the Northern hemisphere (Galperin et al., 1995; Galperin & Soviev, 1998). However, this inclusion will only improve the model calculations, if corresponding critical load values will become available. Moreover, the current transfer coefficients in RAINS-LCA may be further improved, if Eulerian 50-50 km grid cell transfer matrices become available. Advantages of the Eulerian model are that local dry deposition of  $\text{NO}_x$  and  $\text{NH}_3$  can be integrally taken into account in the transport model calculations, the source-receptor matrices can be calculated more precisely (lower indetermined fraction), and the spatial resolution of the transfer matrices will become closer to the spatial resolution of the ecosystem critical loads database.

Improvements may also be possible in the effect part of RAINS-LCA. Because, individual critical load data are not readily available due to confidentiality restrictions, a summary of the accumulative critical load distribution function for each EMEP/MSW-W 150x150 km<sup>2</sup> grid cell had to be used in the calculations ( $\rightarrow$  Formula 11). The validity of the Formula 11 is checked by comparing the outcomes of the exact and the approximated  $\sum A/CL$  for grid cells situated in Sweden, Great Britain and Germany. These countries kindly submitted their detailed data set on critical loads and ecosystem areas. As can be seen in Table 9, the approximation procedure gives in general satisfactory results for the analysed grid cells (Ratio < 1.05). However, the comparison of the approximated and detailed  $\sum A/CL$  for S was for some grid cells problematic. It appeared in the detailed database that some grid cells



contain  $CL_{\max}(S)$  value(s) of  $0 \text{ eq.ha}^{-1}.\text{yr}^{-1}$ .<sup>8</sup> Now, the mathematical problem arises that the outcome of  $\sum A/CL$  for  $S$  will become infinity in all the grid cells containing ecosystems with a  $CL_{\max}(S)$  of  $0 \text{ eq.ha}^{-1}.\text{yr}^{-1}$ . In turn, the acidification potential of every emitting region which deposits in that grid cell becomes infinity. Here, it is chosen to exclude all zeros from the detailed calculation procedure. It is expected that these zero critical loads do not have any empirical justification, because small natural  $S$  depositions (e.g. from volcanoes) did not cause any demonstrable effect within these ecosystems. Table 11 shows that for these grid cells the approximation procedure generally produce larger outcomes compared to the exact calculations. However, deviations are not larger than 20%. It is not expected that the approximation procedure causes a large error in the current acidification and eutrophication potential calculations.

Table 11: Ratio of the exact and approximated  $\sum A/CL$  for acidifying  $S$  and  $N$  ( $S_{\text{acid}}$  and  $N_{\text{acid}}$ ) and eutrophying  $N$  ( $N_{\text{eutro}}$ ). Grid cells are situated in Germany, Sweden and United Kingdom.

| x150 | Y150 | Ratio $S_{\text{acid}}$ | Ratio $N_{\text{acid}}$ | Ratio $N_{\text{eutro}}$ | x150 | y150 | Ratio $S_{\text{acid}}$ | Ratio $N_{\text{acid}}$ | Ratio $N_{\text{eutro}}$ |
|------|------|-------------------------|-------------------------|--------------------------|------|------|-------------------------|-------------------------|--------------------------|
| 13   | 16   | 1.01                    | 1.02                    | 1.02                     | 17   | 26   | 1.06                    | 1.00                    | 1.00                     |
| 13   | 17   | 1.01                    | 1.02                    | 1.00                     | 17   | 27   | 1.02                    | 1.00                    | 1.01                     |
| 14   | 16   | 1.00                    | 1.01                    | 1.01                     | 18   | 13   | 1.00                    | 1.00                    | 1.00                     |
| 14   | 17   | 1.06                    | 1.01                    | 1.01                     | 18   | 14   | 1.00                    | 1.00                    | 1.00                     |
| 14   | 18   | 1.00                    | 1.00                    | 1.00                     | 18   | 15   | 1.00                    | 1.00                    | 1.00                     |
| 14   | 19   | 1.00                    | 1.00                    | 1.10                     | 18   | 23   | 1.08                    | 1.02                    | 1.01                     |
| 15   | 14   | 1.00                    | 1.00                    | 1.00                     | 18   | 24   | 0.88 <sup>a</sup>       | 1.01                    | 1.00                     |
| 15   | 15   | 1.00                    | 1.01                    | 1.02                     | 19   | 21   | 1.01                    | 1.01                    | 1.00                     |
| 15   | 16   | 0.97                    | 1.00                    | 1.00                     | 19   | 22   | 0.91 <sup>a</sup>       | 1.00                    | 1.00                     |
| 15   | 17   | 1.00                    | 1.00                    | 1.00                     | 19   | 23   | 1.00                    | 1.00                    | 1.00                     |
| 16   | 11   | 1.00                    | 1.00                    | 1.00                     | 20   | 21   | 1.01                    | 1.01                    | 1.00                     |
| 16   | 12   | 1.00                    | 1.00                    | 1.00                     | 20   | 22   | 1.00                    | 1.01                    | 0.99                     |
| 16   | 13   | 0.99                    | 1.02                    | 1.02                     | 20   | 23   | 1.00                    | 1.00                    | 1.00                     |
| 16   | 14   | 1.00                    | 1.00                    | 1.00                     | 21   | 21   | 1.00                    | 1.00                    | 1.02                     |
| 16   | 15   | 1.10 <sup>a</sup>       | 1.00                    | 1.02                     | 21   | 16   | 1.00                    | 1.00                    | 1.00                     |
| 16   | 16   | 1.00                    | 1.00                    | 1.00                     | 21   | 17   | 0.99                    | 1.00                    | 1.00                     |
| 16   | 26   | 1.10                    | 1.04                    | 1.00                     | 21   | 18   | 1.00                    | 1.00                    | 1.00                     |
| 16   | 27   | 0.81 <sup>a</sup>       | 1.00                    | 1.01                     | 21   | 19   | 1.00                    | 1.00                    | 1.00                     |
| 17   | 12   | 1.00                    | 1.00                    | 1.00                     | 22   | 15   | 1.00                    | 1.00                    | 1.00                     |
| 17   | 13   | 0.97 <sup>a</sup>       | 1.00                    | 1.03                     | 22   | 16   | 1.00                    | 1.00                    | 1.00                     |
| 17   | 14   | 1.00                    | 1.00                    | 1.00                     | 22   | 17   | 1.00                    | 1.00                    | 1.00                     |
| 17   | 15   | 1.00                    | 1.00                    | 1.00                     | 22   | 18   | 1.00                    | 1.00                    | 0.99                     |
| 17   | 24   | 1.13                    | 1.00                    | 1.00                     | 23   | 15   | 1.00                    | 1.00                    | 1.00                     |
| 17   | 25   | 1.08                    | 1.01                    | 1.00                     |      |      |                         |                         |                          |

<sup>a</sup> Ecosystem(s) with  $CL_{\max}(S)$  of  $0 \text{ eq.ha}^{-1}.\text{year}^{-1}$  are left out in the detailed calculation procedure; <sup>b</sup> Additional information from the RIVM is required.

Finally, a considerable amount of uncertainty may be attached to the input data, needed in the calculation of emissions, receptor matrices and critical loads (e.g. Alcamo & Bartnicki, 1987, 1990; Barkman, 1997; Hettelingh & Janssen, 1993; Hettelingh & Posch, 1997; Hoekstra & Heuberger, 1995;). The combined effect of these input uncertainties on the uncertainty of acidification and eutrophication potentials can be assessed with help of Monte Carlo simulation. With help of the

<sup>8</sup> This was not recognised in the approximation procedure, because percentile values are used instead of individual numbers. It turned out that for none of the grid cells 0<sup>th</sup> and 1<sup>th</sup> percentile values are both  $0 \text{ eq.ha}^{-1}.\text{yr}^{-1}$ .

uncertainty outcomes it may be possible to judge if the regional differences between the potentials are significant in view of the uncertainties in the input data. This information may also be used to assess the significance of environmental product comparisons. The assessment of acidification and eutrophication potential uncertainties will be part of forthcoming research.

### **5.3 Application of acidification and eutrophication potentials**

As shown in Section 2.5 the use of the acidification and eutrophication potentials in LCA is in principle relatively straightforward. However, several problems may occur. First, different types of acidification and eutrophication potentials may be used in the calculations. The results in this report show that the correlation between the scenario outcomes for both acidification and eutrophication may be rather low, indicating that it may be a significant choice which scenario should be used in the application of acidification and eutrophication potentials. As the ultimate goal of environmental policy is to minimize current and future environmental risks, one may argue that the use of one of the 'only above critical load' scenarios in the LCA impact assessment of acidifying and eutrophying air pollutants is preferable. In this case, the choice for one of the 'only above critical load' scenarios should depend on the time horizon of the LCA case study. However, from a precautionary point of view the 'above and below critical load' scenario may be preferred, as every acidifying and eutrophying air pollutant is judged potentially harmful in this type of impact indicator.

Secondly, a difficulty of the implementation of the region-specific acidification and eutrophication potentials in LCAs may be that already more spatial information is required than is currently available in most cases. Emissions, used in the calculations of life cycle inventories, must be reported separately for distinguished regions in Europe. If this spatial information is not available, average European acidification potentials may be used instead. One should, however, keep the following limitations in mind. The averaged acidification and eutrophication potentials for Western Europe, Eastern Europe and whole Europe given in this report assume that  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{SO}_2$  emissions coming from life cycle inventories have the same regional distribution as the over-all emissions of these substances ( $\rightarrow$  Table 2). This may, however, may not be the case in reality. Furthermore, emissions in many product life cycles take partly place outside Europe which cannot be characterised in a valid way with European averaged acidification and eutrophication potentials.

Finally, in the previous section it was mentioned that RAINS-LCA does not calculate eutrophication potentials for water emissions. For the LCA impact assessment of eutrophication it may, however, be a solution to judge eutrophication of soils and surface water bodies as separate impact categories in LCA case studies. Eutrophication potentials calculated in this study may be used to assess the potential impact on terrestrial ecosystems, because the current calculations are solely based on critical loads for terrestrial ecosystems ( $\rightarrow$  Section 3.3). As the calculation of eutrophication potentials by Heijungs et al. (1992) is based on the average C:N:P ratio of aquatic algae (Redfield ratio), these potentials may be used in the impact assessment of eutrophying emissions to water.

## 6. Conclusions

RAINS-LCA calculates acidification and eutrophication potentials which are compatible with the current LCA framework. Both fate and effects of NH<sub>3</sub>, NO<sub>x</sub> and SO<sub>2</sub> air emissions are taken into account in these calculations. Substantial differences are found between the new acidification and eutrophication potentials and the ones calculated previously. However, particularly the inclusion of a full fate and effect analysis within the Northern hemisphere would further improve the calculation of the current acidification and eutrophication potentials. It is also necessary to calculate acidification and eutrophication potentials for additional substances and additional regions other than in Europe. Finally, an uncertainty (importance) analysis should be applied to operationalise data uncertainty in the computation of acidification and eutrophication potentials and to be able to focus further research on parameters which contributes dominantly to the uncertainty in these potentials.

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## Appendix A: Economic activity data

Table A1: Projections of total primary energy consumption for the European countries (Amann et al., 1998, J. Cofala, personal communication)

| Region                | 1990<br>[PJ] | 2010_BL<br>[PJ] | 2010_NTP<br>[PJ] |
|-----------------------|--------------|-----------------|------------------|
| Albania               | 128          | 143             | 212              |
| Austria               | 1242         | 1421            | 1361             |
| Belgium               | 1907         | 2436            | 2183             |
| Bulgaria              | 1296         | 1262            | 1003             |
| Denmark               | 731          | 783             | 826              |
| Finland               | 1233         | 1604            | 1423             |
| France                | 9141         | 11143           | 10765            |
| Germany (new)         | 3194         | 2276            | 2733             |
| Germany (old)         | 11340        | 11900           | 10892            |
| Greece                | 911          | 1785            | 1325             |
| Hungary               | 1109         | 1350            | 1190             |
| Ireland               | 409          | 698             | 623              |
| Italy                 | 6676         | 8455            | 7118             |
| Luxembourg            | 122          | 129             | 129              |
| Netherlands           | 2737         | 3715            | 2855             |
| Norway                | 1591         | 1904            | 1904             |
| Poland                | 4202         | 4951            | 4752             |
| Portugal              | 699          | 1113            | 1083             |
| Romania               | 2425         | 2525            | 2246             |
| Spain                 | 3612         | 5227            | 4984             |
| Sweden                | 2430         | 2581            | 2417             |
| Switzerland           | 1119         | 1184            | 1184             |
| Great Britain         | 8544         | 9875            | 9301             |
| Kola, Karelia         | 606          | 527             | 387              |
| St. Petersburg region | 1357         | 1197            | 950              |
| Kalingrad region      | 137          | 122             | 104              |
| Belarus               | 1762         | 1553            | 1184             |
| Ukraine               | 9970         | 8559            | 6194             |
| Moldavia              | 392          | 324             | 317              |
| Remaining Russia      | 16137        | 14772           | 11475            |
| Estonia               | 423          | 366             | 250              |
| Latvia                | 399          | 359             | 266              |
| Lithuania             | 677          | 565             | 415              |
| Czech Republic        | 1956         | 1765            | 1460             |
| Slovakia              | 987          | 982             | 757              |
| Slovenia              | 231          | 234             | 229              |
| Croatia               | 413          | 447             | 411              |
| Bosnia-Herzegovina    | 311          | 297             | 261              |
| Yugoslavia            | 790          | 725             | 688              |
| Macedonia             | 151          | 138             | 180              |

Table A2: Live stock estimates and nitrogen fertilizer use up to the year 2010 (Amann et al., 1998)

| Region                | Cattle          |         | Pigs            |         | Poultry         |         | Nitrogen fertilizer use        |      |
|-----------------------|-----------------|---------|-----------------|---------|-----------------|---------|--------------------------------|------|
|                       | million animals |         | million animals |         | million animals |         | 1000 tons N.year <sup>-1</sup> |      |
|                       | 1990            | 2010_BL | 1990            | 2010_BL | 1990            | 2010_BL | 1990                           | 2010 |
| Albania               | 0.6             | 0.8     | 0.2             | 0.3     | 5.0             | 8.4     | 73                             | 60   |
| Austria               | 2.6             | 2.2     | 3.7             | 3.4     | 13.8            | 12.0    | 137                            | 109  |
| Belgium               | 3.1             | 2.8     | 6.4             | 7.2     | 23.6            | 40.3    | 166                            | 137  |
| Bulgaria              | 1.6             | 0.9     | 4.4             | 4.3     | 36.3            | 43.6    | 453                            | 530  |
| Denmark               | 2.2             | 1.7     | 9.3             | 11.7    | 16.2            | 17.4    | 395                            | 261  |
| Finland               | 1.4             | 0.9     | 1.4             | 1.4     | 9.5             | 8.1     | 228                            | 180  |
| France                | 21.4            | 20.9    | 12.3            | 17.4    | 271.7           | 317.3   | 228                            | 180  |
| Germany (new)         | 5.3             | 4.5     | 8.5             | 7.5     | 29.8            | 21.2    | 640                            | 505  |
| Germany (old)         | 14.2            | 11.2    | 22.4            | 13.7    | 84.1            | 57.3    | 1560                           | 1296 |
| Greece                | 0.7             | 0.6     | 1.0             | 1.2     | 27.7            | 33.0    | 428                            | 294  |
| Hungary               | 1.6             | 1.6     | 9.7             | 7.9     | 58.6            | 63.5    | 359                            | 639  |
| Ireland               | 7.0             | 7.4     | 1.0             | 2.2     | 9.0             | 13.2    | 370                            | 357  |
| Italy                 | 7.8             | 7.0     | 6.9             | 6.5     | 173.3           | 184.0   | 879                            | 919  |
| Luxembourg            | 0.2             | 0.4     | 0.1             | 0.1     | 0.1             | 0.1     | 20                             | 16   |
| Netherlands           | 4.9             | 4.8     | 13.9            | 11.2    | 93.8            | 79.5    | 404                            | 291  |
| Norway                | 1.0             | 0.7     | 0.7             | 0.8     | 5.4             | 5.3     | 111                            | 92   |
| Poland                | 10.0            | 12.9    | 19.5            | 23.8    | 70.0            | 97.8    | 671                            | 855  |
| Portugal              | 1.3             | 1.3     | 2.7             | 2.2     | 31.2            | 33.6    | 150                            | 144  |
| Romania               | 6.3             | 6.2     | 11.7            | 10.3    | 119.3           | 146.8   | 765                            | 780  |
| Spain                 | 5.1             | 6.0     | 16.0            | 20.3    | 44.9            | 83.1    | 1064                           | 1052 |
| Sweden                | 1.7             | 1.8     | 2.3             | 2.4     | 12.6            | 12.6    | 212                            | 199  |
| Switzerland           | 1.9             | 1.7     | 1.8             | 1.4     | 6.5             | 6.5     | 63                             | 30   |
| Great Britain         | 12.1            | 10.4    | 7.5             | 7.8     | 136.4           | 141.0   | 1516                           | 1298 |
| Kola, Karelia         | 0.2             | 0.1     | 0.2             | 0.2     | 5.6             | 3.9     | 4                              | 3    |
| St. Petersburg region | 1.5             | 1.0     | 1.3             | 1.3     | 32.0            | 22.0    | 74                             | 63   |
| Kalingrad region      | 0.5             | 0.3     | 0.3             | 0.3     | 4.0             | 2.7     | 17                             | 60   |
| Belarus               | 7.2             | 4.3     | 5.2             | 4.0     | 49.8            | 43.3    | 780                            | 676  |
| Ukraine               | 25.2            | 20.5    | 19.9            | 23.0    | 255.1           | 260.0   | 1885                           | 1599 |
| Moldavia              | 1.1             | 1.0     | 2.0             | 1.5     | 25.0            | 19.0    | 123                            | 228  |
| Remaining Russia      | 40.1            | 25.9    | 28.8            | 18.0    | 432.8           | 297.9   | 3323                           | 1868 |
| Estonia               | 0.8             | 0.6     | 1.1             | 1.2     | 7.0             | 7.8     | 110                            | 151  |
| Latvia                | 1.5             | 0.7     | 1.6             | 1.5     | 11.0            | 7.6     | 143                            | 221  |
| Lithuania             | 2.4             | 2.2     | 2.7             | 2.8     | 18.0            | 19.2    | 256                            | 309  |
| Czech Republic        | 3.4             | 3.4     | 4.6             | 5.8     | 33.3            | 49.1    | 370                            | 350  |
| Slovakia              | 1.5             | 0.8     | 2.5             | 2.6     | 16.5            | 22.0    | 217                            | 180  |
| Slovenia              | 0.5             | 0.4     | 0.6             | 0.7     | 13.5            | 12.9    | 88                             | 103  |
| Croatia               | 0.8             | 0.6     | 1.6             | 1.3     | 15.0            | 8.4     | 114                            | 190  |
| Bosnia-Herzegovina    | 0.9             | 0.7     | 0.6             | 0.6     | 9.0             | 8.0     | 19                             | 10   |
| Yugoslavia            | 2.2             | 2.0     | 4.3             | 4.1     | 28.0            | 21.0    | 146                            | 145  |
| Macedonia             | 0.3             | 0.3     | 0.2             | 0.2     | 22.0            | 22.0    | 6                              | 3    |