The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA

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Abstract

Background, aim and scope The methodological choices and framework to assess environmental impacts in life cycle assessment are still under discussion. Despite intensive developments worldwide, few attempts have been made hitherto to systematically present the role of different factors of characterisation models in life cycle impact assessment (LCIA). The aim of this study is to show how European average and country-dependent characterisation factors for acidifying and eutrophying emissions differ when using (a) acidifying and eutrophying potentials alone, (b) depositions from an atmospheric dispersion model or (c) critical loads in conjunction with those depositions. Furthermore, in the latter case, the contributions of emissions, an atmospheric transport model and critical loads to changes in characterisation factors of NO_2 are studied. In addition, the new characterisation factors based on the accumulated exceedance (AE) method are presented using updated emissions, a new atmospheric transport model and the latest critical loads.

Materials and methods In this study, characterisation factors for acidifying and eutrophying emissions are calculated by three different methods. In the 'no fate' (NF) methods, acidifying and eutrophying potentials alone are considered as characterisation factors. In the 'only above terrestrial environment' (OT) approach, characterisation factors are based on the deposition of the acidifying or eutrophying substances to terrestrial land surfaces. The third method is the so-called AE method in which critical loads are used in conjunction with depositions. The results of the methods are compared both at the European and the country level using weighted mean, weighted standard deviation, minimum and maximum values. To illustrate the sensitivity of the AE method, changes in European emissions, employed atmospheric dispersion model and the critical loads database are conducted step-by-step, and the differences between the results are analysed.

Results and discussion For European average characterisation factors, the three characterisation methods of acidification produce results in which the contributions of NH_3, NO_2 and SO_2 to the acidification indicator do not differ much within each method when 1 kg of each acidifying substance is emitted. However, the NF methods cannot describe any spatial aspects of environmental

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problems. Both OT and AE methods show that the spatial aspects play an important role in the characterisation factors. The AE method results in greater differentiations between country-dependent characterisation factors than does the OT method. In addition, the results of the AE and OT methods differ from each other for individual countries. A major shortcoming of the OT approach is that it does not consider the sensitivity of the ecosystems onto which the pollutants are deposited, whereas the AE approach does. In the case of the AE method, a new atmospheric dispersion model, new information on emissions and critical loads have a different influence on the characterisation factors, depending on the country. The results of statistics show that the change in the atmospheric dispersion model has a greatest influence on the results, since ecosystem-specific depositions are taken into account for the first time.

Conclusions and recommendations The simple NF methods can be used in a first approximation to assess the impacts of acidification and terrestrial eutrophication in cases where we do not know where the emissions occur. The OT approach is a more advanced method compared with the NF method, but its capability to describe spatial aspects is limited. The AE factors are truly impact-oriented characterisation factors and the information used here represents the current best knowledge about the assessment practice of acidification and terrestrial eutrophication in Europe. The key message of this study is that there is no shortcut to achieving advanced characterisation of acidification and terrestrial eutrophication: an advanced methodology cannot develop without atmospheric dispersion models and information on ecosystem sensitivity.

1 Background, aim and scope

Characterisation is a core phase in life cycle impact assessment (LCIA). According to the International Organization for Standardization (ISO 2006a, 2006b), the aim of characterisation is to aggregate environmental interventions (emissions, resource extractions and land use) to impact category indicator results using characterisation factors. In order to achieve reliable impact category indicator results, it is recommended that scientifically based characterisation factors be used. Thus, the critical point is how characterisation factors are determined.

Acidification is one of the most common impact categories used in LCIA. In the beginning of the 1990s, there existed only one characterisation method for acidification, the so-called CML 92 method (Heijungs et al.

1992). At the end of the 1990s, Potting et al. (1998) developed a country-dependent characterisation methodology of acidification to produce more realistic category indicator results. They used the RAINS model (Amann et al. 1999) developed at the International Institute for Applied Systems Analysis (IIASA) together with a European critical load database (Hettelingh et al. 1995a). A critical load or—in the case of acidification—a critical load function is used to characterise the sensitivity of an ecosystem. Every combination of nitrogen and sulphur deposition lying on or below that function does not cause harmful effects related to acidification. Later, several authors have produced country-dependent characterisation factors for acidification and terrestrial eutrophication by using the results of atmospheric dispersion models and critical loads for Europe (Huijbregts et al. 2001; Krewitt et al. 2001; Potting and Hauschild 2004; Hettelingh et al. 2005; Seppälä et al. 2006).

In the United States, nation-wide critical loads for acidification and terrestrial eutrophication are not available. Therefore, Norris (2003) has used depositions obtained with the atmospheric dispersion model TRACI for the determination of state-dependent characterisation factors for acidifying emissions.

In the life cycle assessment community, there is a need to develop a global LCIA methodology for regional environmental problems such as acidification and terrestrial eutrophication. The key question concerns the appropriate methodology for characterisation. The European methods seem to be more scientifically based, but they require more input data which are mostly missing from other continents. At present, (politically) accepted critical loads for acidification and terrestrial eutrophication on a continental scale are only available in Europe, although there have been efforts on a global scale (Bouwman et al. 2002), in south–east Asia (Hettelingh et al. 1995b) and in eastern Canada (Ouimet et al. 2006). Dispersion models capable of modelling the fate of acidifying and eutrophying emissions are available in Europe, North America and Asia.

The aim of this paper is threefold: First, to show how European average and country-dependent characterisation factors for acidifying and eutrophying emissions differ when using (a) acidifying and eutrophying potentials alone, (b) depositions from an atmospheric dispersion model or (c) critical loads in conjunction with those depositions. Secondly, to illustrate, for the last case, the sensitivity of the characterization factors on changes in emissions, the atmospheric transport model and the critical loads. And thirdly, to update the characterisation factors presented in Seppälä et al. (2006) using updated emissions, a new atmospheric transport model and the latest critical loads. With this, we hope to create material for the discussion about global best practices in characterisation.

2 Materials and methods

In this study, characterisation factors for acidifying and eutrophying emissions are calculated by three different methods described below. The results are compared both at the European and the country level. European average characterisation factors for each method are calculated by multiplying the emissions of each country by their corresponding country-dependent characterisation factors and dividing by the total European emissions. Thus, the European average characterisation factor equals the weighted mean of country-specific characterisation factors. In addition, the weighted standard deviations of the country-specific characterisation factors are presented to express the uncertainty of the weighted means. The uncertainty calculation was conducted according to an equation presented by Hauschild and Potting (2005).

The results of the three different characterisation methods cannot be directly compared with each other, although the methods produce the characterisation results in the same units. The bases of calculations differ, and only relative differences of characterisation factors have a meaning in the comparison of different methods. For this reason, the results of different compounds were converted to shares in total impacts and European average X equivalents. Results presented in European average X equivalent describe the characterisation factors of substance X divided by the corresponding European average characterisation factor (see above) of substance X.

Emission-based, 'no fate' approach In this approach, the additional emissions of sulphur dioxides (SO_2), nitrogen oxides (expressed as NO_2) and ammonia (NH_3) into the atmosphere (or any other medium, not dealt with in this paper) are used to characterise the impact of a (new) product. This is the oldest method and is described in Heijungs et al. (1992).

To make the different emission types comparable and to characterise their (maximum) acidifying and eutrophying potential, they are converted to moles of H^+ or 'moles of charge' (mol_c, the official SI unit) or 'equivalents' (eq). This conversion is effected by multiplying the mass of the emission with z/M where M is the molecular weight of the molecule (ion) released and z its electrical charge. If sulphur emissions are measured in g of SO_2 ($M=64$) and since sulphate ions have a charge of $z=2$, one obtains $2/64 = 0.03125$ eq/g as a conversion factor. For nitrogen oxides (given as NO_2, $M=46$) and ammonia (NH_3, $M=17$), the (rounded) conversion factors are 0.0217 and 0.0588 eq/g, respectively (since $z=1$ for nitrate and ammonium).

Since the fate of the emissions is not taken into account in these simple characterisation approaches, we call them 'no fate' (NF) methods.

Deposition-based, 'only above terrestrial environment' approach The second characterisation method is based on the deposition of the acidifying or eutrophying substances. This method is used in the USA and known as the TRACI method (Bare et al. 2003, Norris 2003). In this method, the fate of emissions is taken into account by computing their contribution to their deposition at every location. This means that the characterisation factors depend on the location (country) where the pollutants are released; however, their actual impact on the environment is not considered; thus, we call this method 'only above terrestrial environment' (OT) method and the derived characterisation factors are known as OT factors.

The country-dependent characterisation factors for OT as indicator are defined for every pollutant P ($=SO_2$, NO_2, NH_3) as:

$$COT_{P,j} = \frac{\Delta OT^{X\_P,j}_{\text{Europe}}}{\Delta E_{X\_P,j}} \tag{1}$$

with

$$\Delta OT^{X\_P,j}_{\text{Europe}} = OT_{\text{Europe}} - OT^{X\_P,j}_{\text{Europe}} \tag{2}$$

and

$$\Delta E_{X\_P,j} = E_{P,j} - E_{X\_P,j} \tag{3}$$

where $COT_{P,j}$ is the OT characterisation factor for emissions of pollutant P in country or sea area j, OT_{Europe} is the total deposition to the terrestrial environment in Europe due to the emissions in a chosen reference year, $OT^{X\_P,j}_{\text{Europe}}$ is the total OT factor in Europe after reducing emissions of pollutant P by a percentage or a fixed absolute amount X in country j (with emissions in all other regions unchanged), $E_{P,j}$ the emissions of pollutant P in country j in the reference year and $E_{X\_P,j}$ the emissions of P in country j after reduction X.

The deposition of S and N is obtained from the EMEP Eulerian atmospheric dispersion (Tarrason et al. 2006). This model is routinely used for assessments performed under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) and provides, inter alia, annual average deposition of sulphur and nitrogen species on a 50×50-km^2 grid covering Europe extending to the Urals and including Turkey and Cyprus. In the context of the OT methods, only depositions onto the land area shown in Fig. 1 are used.

It is assumed that European emissions have only a small effect on acidification and terrestrial eutrophication outside Europe, and the deposition outside Europe is thus neglected. In this paper, we use depositions calculated from the expected emissions in 2010 ('current legislation scenario') and, to minimise the effects of inter-annual variability, averages over five meteorological years (1996–1998, 2000 and 2003) are used. The EMEP model is

Fig. 1 Depositions onto the *grey-shaded area* are used in the OT characterisation factor calculations

inherently non-linear, but for estimates not too far from the reference model run, linear approximations, making use of so-called source–receptor relationships (Tarrason et al. 2003), give reliable results.

We compute the OT factors for reductions by 1 kt per country, certainly a small quantity compared to the overall emissions, thus justifying the use of the linearised model. Since the depositions of sulphur and nitrogen species are given in mass of S and N, the conversion factors to make them comparable from the viewpoint of their (maximum) acidifying and eutrophying potential (see above) are 2/32 = 0.0625 and 1/14 = 0.0714 eq/g, respectively.

Critical load exceedance-based, accumulated exceedance approach The third characterisation method does not only take into account the dispersion of an emission in the atmosphere, but also the sensitivity of the ecosystem receiving the (additional) deposition due to the emission (increase). Ecosystem sensitivity is characterised by the so-called critical load (functions) for acidification and eutrophication, which are routinely used in the assessment of emission reduction options under the LRTAP Convention (Hettelingh et al. 1995a, 2001, 2007). The currently used critical load database (Hettelingh et al. 2007) consists of about 1.2 million different ecosystems such as forests, surface waters and semi-natural vegetation, covering about half of the European land area.

In the long run, the risk of ecosystem damage for a country is quantified by the so-called accumulated exceedance (AE). This is defined as the area-weighted sum of all of the critical load exceedances within the region (country)

of interest (Posch et al. 2001). This AE method has been presented by Seppälä et al. (2006) where also further details can be found. In the AE method, country-dependent characterisation factors CAE_{Pj} are calculated according to Eqs. 1, 2 and 3 with 'OT' replaced by 'AE'. Seppälä et al. (2006) showed that the AE indicator is not sensitive to the choice of reduction X, and here we use 1 kt reductions per country, as for the OT indicator. The units of results are the same as in the cases of the NF and OT methods (eq/g). For the method comparison, the newest AE version described above was used.

Since the publication of the AE indicators by Seppälä et al. (2006), there was a change in (a) emissions (Table 3 of the Appendix), (b) the employed atmospheric dispersion model (see above) and (c) the critical loads database (Hettelingh et al. 2007). Therefore, updated AE indicators are calculated and presented here. For NO_2, the calculations are step-by-step to illustrate the sensitivity of the model to the different changes. The starting point for the calculations is the model results produced by Seppälä et al. (2006). First, the emissions of 2002 in the old model are replaced by the emissions based on 'current legislation scenario' in 2010. In the second step, the emissions of 2010 are used and the old atmospheric dispersion model (EMEP 1998) is changed to the new Eulerian model (Tarrason et al. 2006). This model not only provides grid-average depositions, but also depositions onto different land cover categories, such as forests and semi-natural vegetation. In the final calculation, the emissions of 2010, the new atmospheric model and the recent critical loads database (Hettelingh et al. 2007) are used.

3 Results and discussion

For European average characterisation factors in 2010, the three characterisation methods of acidification produce results in which the contributions of NH_3, NO_2 and SO_2 to the acidification indicator results do not differ much within each method when 1 kg of each acidifying substance is emitted (Fig. 2). The results of the simple NF method
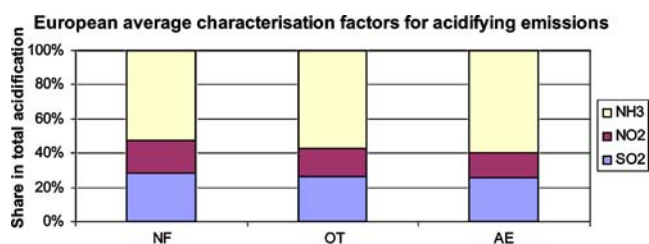

Fig. 2 Contributions of NH_3, NO_2 and SO_2 to the acidification indicator results when 1 kg of each acidifying substance is emitted as derived from European average characterisation factors of the NF, OT and AE methods

European average characterisation factors for eutrophying emissions

Fig. 3 Contributions of NH$_3$ and NO$_2$ to the terrestrial eutrophication indicator results when 1 kg of each acidifying substance is emitted as derived from European average characterisation factors of the NF, OT and AE methods
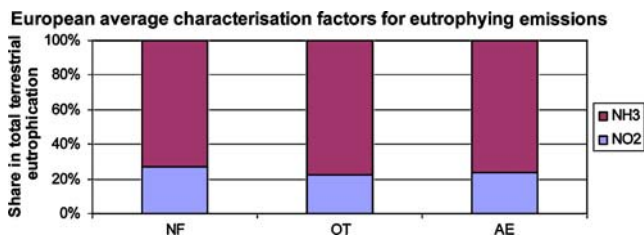
differ from the results of the AE and OT methods mostly with respect to ammonia. The reason for this difference is partly due to the fact that ammonia is not as widely transported in air as NO$_2$ and SO$_2$. For this reason, the share of emissions of NO$_2$ and SO$_2$ deposited onto the sea and outside Europe is greater than the share of ammonia deposited. Since virtually all ammonium is nitrified after deposition onto land areas, it acts as an acidifying agent. The NF method cannot describe this feature, but the AE and OT methods do.

In the case of terrestrial eutrophication, the average European characterisation factors differ only little between the methods (Fig. 3). Similar to the case of acidification, the OT and AE methods produce characterisation factors more similar to each other than to the NF method.

In the OT method, the values of country-dependent characterisation factors vary between −73% and +35% around the weighted mean values for acidification and terrestrial eutrophication. The AE method results in even greater differentiations between country-dependent characterisation factors. The weighted standard deviations for the

AE method are much greater than the values of the OT method (Table 1). In addition, the results of the AE and OT methods differ from each other for individual countries (Figs. 4 and 5). For example, the OT approach in acidification produces a different picture for the characterisation factor of NO$_2$ emissions of Sweden (SE) compared with the characterisation factor derived from the AE approach. In general, the AE method produces the greater variation of characterisation factors between different countries than the OT method. Critical loads, i.e. the ecosystem sensitivity, have a large influence on the final results.

The question arises: Which method produces the best results? NF methods are very simple, but do not describe the spatial aspects of environmental problems. However, it provides a good starting point for a first approximation in cases in which we do not know where the emissions occur in Europe. The OT approach adds a spatial aspect to the characterisation factors by taking into account the atmospheric dispersion characteristics from the place of release. The limited area for which depositions are calculated, especially the exclusion of the sea areas (see Fig. 1), distorts the relative magnitude of the OT factors, especially in coastal areas. A major shortcoming of the OT approach is that it does not consider the sensitivity of the ecosystems onto which the pollutants are deposited, i.e. a built-up area is treated equally to a nature conservation area. This is overcome by the AE approach, which takes into account the sensitivity of ecosystem characterised by critical loads. Critical loads are a simple way of describing ecosystem sensitivity using a steady-state approach. More sophisticated approaches, such as the use of dynamic bio-geochemical

Table 1 Statistics (eq/kg) for the characterisation factors of the NF, OT and AE methods

| Method	Emission	Weighted mean	Weighted standard deviation (%)	Minimum (%)	Maximum (%)
Acidification					
NF	SO$_2$	31.60	0 (0)	31.60 (0)	31.60 (0)
	NO$_2$	21.73	0 (0)	21.73 (0)	21.73 (0)
	NH$_3$	58.80	0 (0)	58.80 (0)	58.80 (0)
OT	SO$_2$	20.11	8.72 (43)	5.49 (−73)	25.56 (27)
	NO$_2$	12.76	5.81 (46)	3.23 (−75)	17.20 (35)
	NH$_3$	44.27	16.41 (37)	10.94 (−75)	53.33 (20)
AE	SO$_2$	1.31	1.40 (107)	0.01 (−99)	5.91 (352)
	NO$_2$	0.74	0.59 (79)	0.01 (−99)	2.11 (186)
	NH$_3$	3.02	3.12 (104)	0.01 (−99)	13.90 (361)
Terrestrial eutrophication					
NF	NO$_2$	21.73	0 (0)	21.73 (0)	21.73 (0)
	NH$_3$	58.80	0 (0)	58.80 (0)	58.80 (0)
OT	NO$_2$	12.76	5.81 (46)	3.23 (−75)	17.20 (35)
	NH$_3$	44.27	16.41 (37)	10.94 (−75)	53.33 (20)
AE	NO$_2$	4.26	1.46 (34)	0.65 (−85)	6.79 (59)
	NH$_3$	13.47	5.07 (38)	1.55 (−88)	24.74 (84)
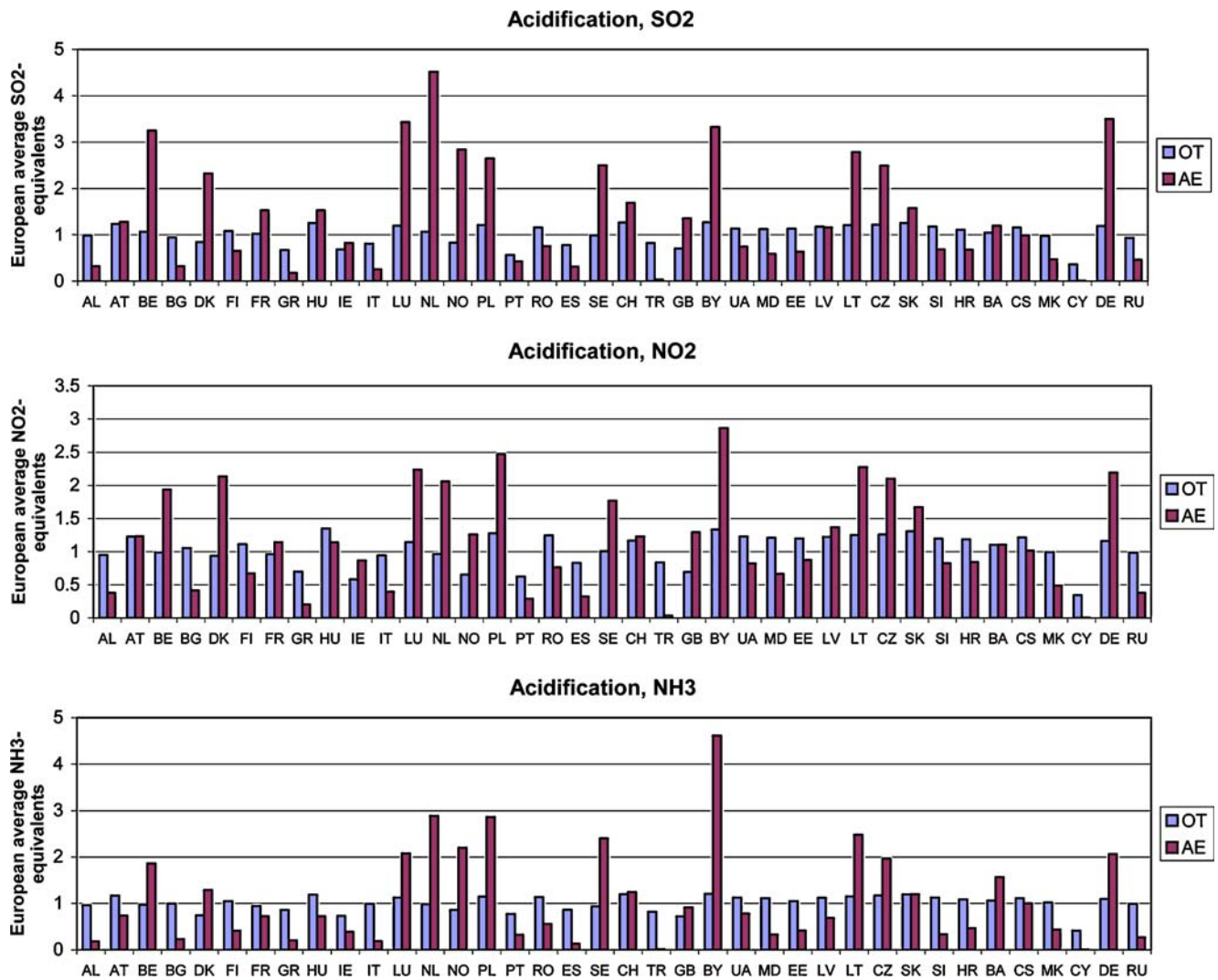
Fig. 4 Country-dependent characterisation factors for acidifying emissions calculated by the OT and the AE methods. For the NF method, characterisation factors are all one in these figures. Country codes are: *AL* Albania, *AT* Austria, *BE* Belgium, *BG* Bulgaria, *DK* Denmark, *FI* Finland, *FR* France, *GR* Greece, *HU* Hungary, *IE* Ireland, *IT* Italy, *LU* Luxemburg, *NL* Netherlands, *NO* Norway, *PL* Poland, *PT* Portugal, *RO* Romania, *ES* Spain, *SE* Sweden, *CH* Switzerland, *GB* United Kingdom, *BY* Belarus, *UA* Ukraine, *MD* Moldova, *EE* Estonia, *LV* Latvia, *LT* Lithuania, *CZ* Czech Republic, *SK* Slovakia, *SI* Slovenia, *HR* Croatia, *BA* Bosnia and Herzegovina, *CS* Serbia and Montenegro, *CY* Cyprus, *MK* Macedonia, *DE* Germany, *RU* Russia (European part)

models, have been suggested (e.g. Van Zelm et al. 2007), but critical loads have the advantage of being also widely used in policies on S and N emission reductions (see, e.g. Hettelingh et al. 1995a, 2001, 2007).

As mentioned above, compared to the AE factors presented in Seppälä et al. (2006), a new atmospheric dispersion model and new information on emissions and critical loads has become available. These changes, when analysed step-by-step, have a different influence on the AE characterisation factors, depending on the country (Fig. 6). In addition, looking at the results of statistics shows that the change in the atmospheric dispersion model has the greatest influence on the results (Table 2). This is not surprising,

since the new model provides ecosystem-specific depositions, and the consistently higher depositions were not included in the old model. The new AE factors are tabulated in Table 4 of the Appendix.

4 Conclusions and recommendations

In the context of acidification and terrestrial eutrophication, the NF methods, by their very formulation, do not take into account any spatial aspects of environmental problems. But it provides a good first approximation in cases where we do not know that the emissions occur. Due to its simplicity, it is also
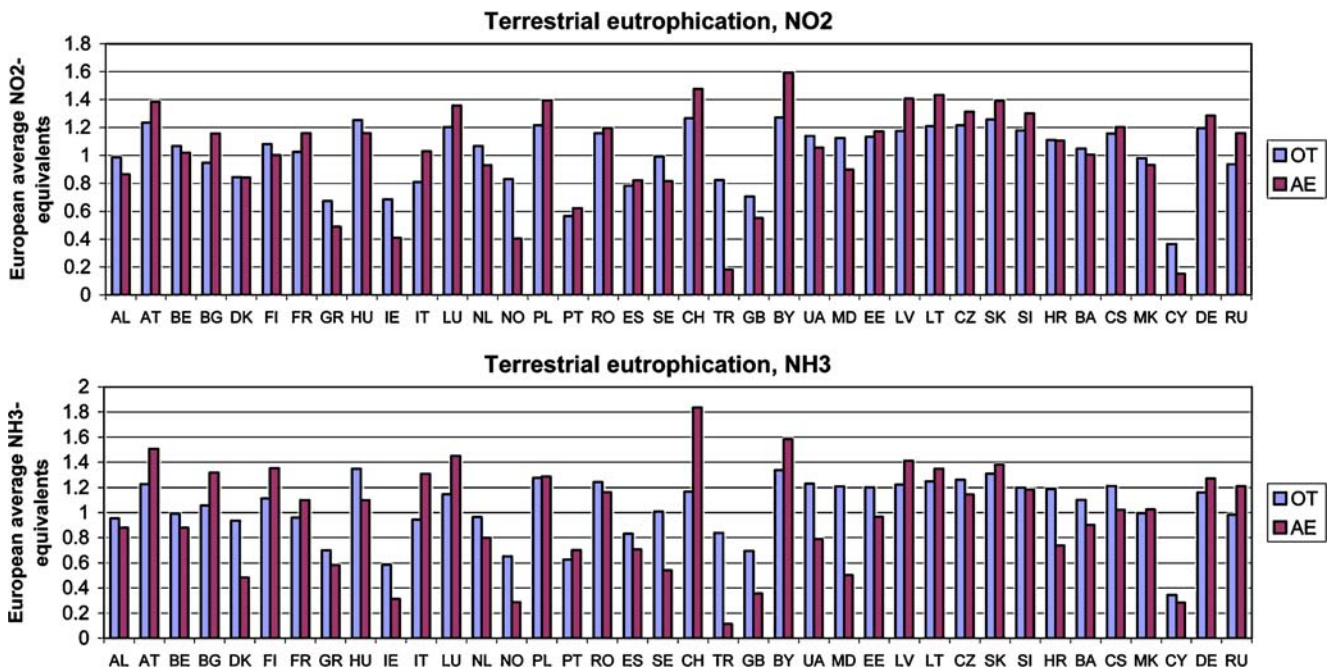
Fig. 5 Country-dependent characterisation factors for eutrophying emissions calculated by the OT and AE approaches. For the NF method, characterisation factors are all one in these figures (see Fig. 4 and/or Tables 3 and 4 of the Appendix for country codes)

suitable for global applications, especially since atmospheric dispersion model results or data about ecosystem sensitivity are not available for many areas of the world.

The OT methods with the atmospheric dispersion models introduce a spatial aspect into characterisation factors. The

exclusion of deposition to sea areas and areas beyond the modelling domain causes biases in these country-dependent characterisation factors. However, their main drawback is that they do not take into account the sensitivity of the area onto which the deposition falls.
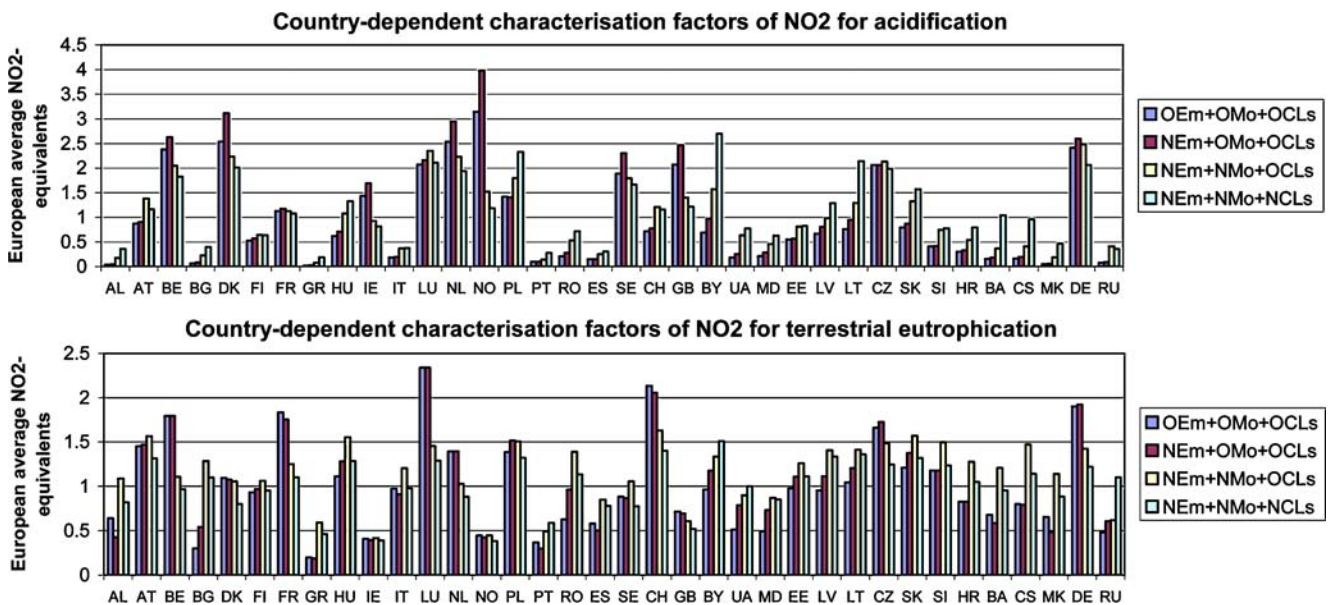
Fig. 6 Country-dependent characterisation factors of NO_2 for acidification and terrestrial eutrophication calculated by the AE approach when emissions, atmospheric dispersion model and critical loads are changed step-by-step. *OEm* old 2002 emissions, *OMo* old atmospheric dispersion model, *OCLs* old critical loads, *NEm* new

2010 emissions based on 'current legislation scenario', *NMo* new atmospheric dispersion model (Tarrason et al. 2006), *NCLs* new critical loads (Hettelingh et al. 2007). Old model and old data refer to the ones used in Seppälä et al. (2006)

Table 2 Statistics (eq/kg) for the characterisation factors of NO_2 for acidification and eutrophication calculated by the AE approach with different assumptions concerning European emissions, employed atmospheric dispersion model and the critical loads database (see legend of Fig. 6)

Model combination	Weighted mean	Weighted standard deviation (%)	Minimum (%)	Maximum (%)
Acidification				
OEm+OMo+OCLs	0.35	0.35 (100)	0.01 (−98)	1.11 (215)
NEm+OMo+OCLs	0.22	0.25 (112)	0.01 (−95)	0.89 (298)
NEm+NMo+OCLs	0.86	0.67 (78)	0.15 (−82)	2.14 (149)
NEm+NMo+NCLs	0.78	0.58 (73)	0.01 (−81)	2.11 (170)
Terrestrial eutrophication				
OEm+OMo+OCLs	1.51	0.87 (57)	0.30 (−80)	3.55 (134)
NEm+OMo+OCLs	1.49	0.80 (54)	0.26 (−83)	3.48 (134)
NEm+NMo+OCLs	4.15	1.50 (36)	1.73 (−58)	6.78 (63)
NEm+NMo+NCLs	4.49	1.46 (34)	1.71 (−62)	6.79 (51)

Note that the data do not include Turkey and Cyprus

The AE method adds critical loads as indicators for ecosystem sensitivity to the OT method and, thus, AE factors are truly impact-oriented characterisation factors. Obviously, the more data and models that are added, the greater the uncertainty will be. However, the information used here represents the current best knowledge about the assessment practice of acidification and terrestrial eutrophication in Europe. For this reason, it is recommended to replace the earlier European country-dependent characterisation factors with the factors generated in this study. In addition, it is recommended to update characterisation factors if significant changes in any those three aspects will be made in the future.

This study showed that only sophisticated assessment approaches for acidification and terrestrial eutrophication can take into account variations in the states of the environmental problems in different parts of the world. However, the current situation does not allow one to use these advanced characterisation methods, such as the AE method, outside of Europe due to a lack of suitable atmospheric dispersion models and/or measures of ecosystem sensitivity. For this reason, there is a need to improve and develop methodological bases with information on ecological sensitivity in the areas outside Europe, especially in those regions where acidification and terrestrial eutrophication play an important role. This is essential for developing an advanced global impact assessment methodology that is more and more important due to the increasing world trade. The core message of this study is that there is no shortcut to success in the advanced characterisation of acidification and terrestrial eutrophication.

Appendix

Table 3 Country emissions (in kt/a) of sulphur and nitrogen compounds for 2010 according to the 'Current Legislation' scenario

Country	SO_x (as SO_2)	NO_x (as NO_2)	NH_3
Albania (AL)	30	28	26
Austria (AT)	30	160	56
Belarus (BY)	349	271	147
Belgium (BE)	99	232	79
Bosnia and Herzegovina (BA)	411	54	17
Bulgaria (BG)	979	147	124
Croatia (HR)	69	94	33
Cyprus (CY)	17	21	6
Czech Republic (CZ)	121	187	68
Denmark (DK)	18	147	81
Estonia (EE)	44	28	11
Finland (FI)	61	151	34
France (FR)	414	1,089	733
Germany (DE)	450	1,176	624
Greece (GR)	168	266	54
Hungary (HU)	266	135	83
Ireland (IE)	33	99	129
Italy (IT)	376	1,006	421
Latvia (LV)	11	29	14
Lithuania (LT)	33	41	55
Luxemburg (LU)	3	28	6
Macedonia (MK)	82	41	15
Moldova (MD)	117	64	45
Netherlands (NL)	60	315	144
Norway (NO)	21	193	23
Poland (PL)	1,046	616	328
Romania (RO)	668	283	285
Portugal (PT)	103	214	69
Russia (European part) (RU)	2,464	2,758	835
Serbia and Montenegro (CS)	277	168	69

Table 3 (continued)

Country	SO$_x$ (as SO$_2$)	NO$_x$ (as NO$_2$)	NH$_3$
Slovakia (SK)	54	72	32
Slovenia (SI)	22	39	20
Spain (ES)	416	970	382
Sweden (SE)	59	201	51
Switzerland (CH)	16	71	63
Turkey (TR)	1,708	852	241
Ukraine (UA)	1,145	1,184	619
United Kingdom (GB)	366	1,085	323
Sea area			
Atlantic—remaining N–E	901	1,266	0
Baltic Sea	228	352	0
Black Sea	57	86	0
Mediterranean Sea	1,189	1,639	0
North Sea	454	648	0
Background country/area			
Armenia	4	13	25
Azerbaijan	15	43	25
Georgia	9	30	97
Iceland	29	30	3
Kazakhstan	237	50	18
Remaining Asian area	830	122	303
North Africa	413	96	235
Natural marine emissions	743	0	0
Volcanic emissions	2,000	0	0

Table 4 Country-dependent characterisation factors (eq/kg) for acidification and terrestrial eutrophication based on the AE indicator, using the Eulerian atmospheric model, the 2006 critical load database and the predicted emissions for Europe in 2010

Country	Acidification			Terrestrial eutrophication	
	SO$_2$	NO$_2$	NH$_3$	NO$_2$	NH$_3$
Albania (AL)	0.4	0.3	0.6	3.7	11.9
Austria (AT)	1.7	0.9	2.2	5.9	20.3
Belarus (BY)	4.4	2.1	13.9	6.8	21.3
Belgium (BE)	4.2	1.4	5.6	4.3	11.9
Bosnia and Herzegovina (BA)	1.6	0.8	4.7	4.3	12.2
Bulgaria (BG)	0.4	0.3	0.7	4.9	17.8
Croatia (HR)	0.9	0.6	1.4	4.7	10.0
Cyprus (CY)	0.0	0.0	0.0	0.6	3.8
Czech Republic (CZ)	3.3	1.6	5.9	5.6	15.4
Denmark (DK)	3.0	1.6	3.9	3.6	6.5
Estonia (EE)	0.8	0.6	1.3	5.0	13.0
Finland (FI)	0.9	0.5	1.2	4.3	18.2
France (FR)	2.0	0.8	2.2	5.0	14.8
Germany (DE)	4.6	1.6	6.2	5.5	17.1
Greece (GR)	0.2	0.1	0.6	2.1	7.8
Hungary (HU)	1.7	1.0	2.1	5.8	12.9
Ireland (IE)	1.1	0.6	1.2	1.7	4.2
Italy (IT)	0.3	0.3	0.6	4.4	17.6
Latvia (LV)	1.5	1.0	2.1	6.0	19.0

Table 4 (continued)

Country	Acidification			Terrestrial eutrophication	
	SO$_2$	NO$_2$	NH$_3$	NO$_2$	NH$_3$
Lithuania (LT)	3.6	1.7	7.5	6.1	18.2
Luxemburg (LU)	4.5	1.7	6.3	5.8	19.5
Macedonia (MK)	0.6	0.4	1.3	4.0	13.8
Moldova (MD)	0.8	0.5	1.0	3.8	6.8
Netherlands (NL)	5.9	1.5	8.7	4.0	10.8
Norway (NO)	3.7	0.9	6.6	1.7	3.9
Poland (PL)	3.5	1.8	8.6	5.9	17.4
Romania (RO)	1.0	0.6	1.7	5.1	15.7
Portugal (PT)	0.6	0.2	1.0	2.6	9.4
Russia (European part) (RU)	0.6	0.3	0.8	4.9	16.3
Serbia and Montenegro (CS)	1.3	0.8	3.0	5.1	13.8
Slovakia (SK)	2.1	1.2	3.6	5.9	18.6
Slovenia (SI)	0.9	0.6	1.0	5.5	15.9
Spain (ES)	0.4	0.2	0.4	3.5	7.3
Sweden (SE)	3.3	1.3	7.2	3.5	7.3
Switzerland (CH)	2.2	0.9	3.8	6.3	24.7
Turkey (TR)	0.1	0.0	0.0	0.8	1.6
Ukraine (UA)	1.0	0.6	2.3	4.5	10.6
United Kingdom (GB)	1.8	1.0	2.8	2.3	4.8

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