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Comparison of the acidifying impact from emissions with different regional origin in life-cycle assessment [1]

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Abstract

In current life-cycle impact assessment, little attention is paid to the spatial aspects of emissions: the place where an emission is released and the area and or target system on which the emission has its impact. This lack of differentiation affects the relevance of the assessed impact. This paper presents factors for Europe that relate the region of emission to the acidifying impact on its deposition area.

Keywords: Emissions; Life-cycle; Assessment

1. Introduction

Life-cycle assessment studies generally pay no attention to the site where an emission is released. This lack of differentiation may affect the relevance of the assessed impact. It is expected that the accuracy of prediction can be enhanced considerably by the introduction of a few site factors to the assessment process [1–3]. This article presents such factors for impact assessment of acidification. The acidification factors are

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established with help of the Regional Air Pollution INformation and Simulation (RAINS) model [4]. Section 2 outlines some main principles and limitations of life-cycle inventory analysis and subsequent life-cycle impact assessment. Methods and means are drawn in Section 3. Section 4 presents the calculated site factors. Section 5 provides a discussion, while Section 6 gives some main conclusions.

2. Life-cycle inventory analysis and life-cycle impact assessment

Life-cycle inventory quantifies the emissions per functional unit for each process in the life-cycle of a product. A regular life-cycle inventory will mainly use emission factors (quantities per unit of process output) to establish emission quantities. These emission factors can in general not be traced back to emission flow, and other time and location parameters of the process which is the source of that emission. Consequently, also the emission quantities in life-cycle inventory cannot be traced back to these parameters [2]. Only the geographical location or region of processes is in general known, because these data are required to calculate the emission quantity from transport.

In life-cycle impact assessment, all emission quantities of a given substance are summed up along the whole life-cycle and next aggregated with the summed emissions of other substances contributing to the same impact. Aggregation is based on equivalency assessment [5], in which the emitted quantity of a substance is multiplied with an equivalency factor that relates the emission to the equivalent emission quantity of a reference substance. Several sets of equivalency factors for acidification exist [6–8]. The equivalency factors from Refs. [6] and [8] distinguish to some extent between different types of receiving areas, but disregard emission dispersion and subsequent deposition.

The lack of spatial (and temporal) source information puts limitations on life-cycle impact assessment, since no environmental concentrations can be calculated, and seemingly no surpassing of thresholds can be evaluated. A feasible solution for the spotted problem was proposed by Potting and Blok [1] in a site-dependent approach: after an acidifying substance is emitted, it is dispersed and deposited. Deposition together with background deposition may result in exceedance of critical loads. Each link in this cause/effect chain can be characterized by descriptors that for acidification are specified by the geographical site where the emission takes place. This geographical site can be linked to an acidification factor that relates the emission to the impact on its deposition area. The only required additional data from inventory analysis, that in most cases already is provided by current life-cycle inventory, is the geographical site of emission. The problems of the lack of differentiation in life-cycle assessment is, in the meanwhile, widely recognized, and the need for a site-dependent impact assessment is recommended by the SETAC-workgroup on life-cycle impact assessment [2] and others [8,3].

3. Method and means

Relating the site of emissions to the impact on its deposition area is one of the key elements in the RAINS model, and this model (version 7_2), has therefore been used to

establish acidification factors. The RAINS model is developed by the International Institute for Applied System Analysis (IIASA) in Vienna (Austria). RAINS is an integrated assessment model that combines information on emission levels from 44 regions with information on long range atmospheric transport in order to estimate patterns of depositions and concentrations for comparison with critical loads and thresholds for acidification, eutrophication and tropospheric ozone creation [4].

Acidification factors have been established by reducing one by one the emission levels of each distinguished region with 10%, and next relating the result to the reference situation [9] (the initial emission level and surface of unprotected ecosystems; see Table 1):

$$\mathrm{AF}_{s,i} = \left(\mathrm{UES}(E(\mathrm{ref})) - \sum_{j=1}^{m} \mathrm{UES}_j\left((1-\Delta)E(\mathrm{ref})\right) \right) / \Delta E_{s,i}(\mathrm{ref})$$

Where: $\mathrm{AF}_{s,i}$ = the acidification factor expressing the area of ecosystem that gets unprotected by an emission quantity of compound (s) in region (i);

UES(E(ref)) = The amount of unprotected ecosystems in the reference situation;

$\mathrm{UES}_{s,j}$ = The amount of unprotected ecosystem in grid element (j);

E(ref) = The emission levels in the reference situation;

$E_{s,i}$(ref) = The emission level of substance (s) in region (i) in the reference situation;

$\Delta = 0.1$ (the 10% change in emission level of the region in question).

Calculations have been done for the years 1990 and 2010, and for sulfur dioxide, nitrogen oxide and ammonia. Only the reference situation and results for 1990 are presented here (see Table 1). The 2010 results and a more thorough report on methodology, results and discussion can be found in Ref. [10].

4. Acidification factors

As can be seen from Table 1, there are large differences among regions in the acidification factors for sulfur dioxide. The acidification factors for the Southern and South-Eastern European regions are in general low. This is the combined effect of the insensitivity of the receiving (calcareous) ecosystems for (changes in) acidifying depositions, and the relatively low emission and related deposition levels in these regions. The acidification factors for the Scandinavian and Baltic regions, and in the European part of the former USSR are rather high, as a result of deposition on the rather sensitive areas in these regions. The Western and Mid European regions have moderate acidification factors due to the rather high emission and related deposition levels in these regions.

The acidification factors for nitrogen oxide show less pronounced differences among regions, and are in all cases lower than the acidification factors for sulfur dioxide. As long as nitrogen functions as a fertilizer, it does not contribute to acidification. Besides, nitrogen oxide transport travels, on average, longer distances than sulfur dioxide transport. This has a ‘smoothing’ effect on the acidification factors. Since transport distances of ammonia are relatively short, the acidification factors for this substance show sharper differences than those of nitrogen dioxide.

Table 1
The total emissions/substance and region, the total area/region, the total area of ecosystem/region, the total area of unprotected ecosystem in that region, the total area of ecosytem that gets unprotected by the total emission from that region, and the acidification factors/substance/region for the year 1990

Region	Emissions			Total area of:		Unprotected ecosystem			Acidification factors			
	SO_x (kton)	NO_x (kton)	NH_3 (kton)	Region (1000 ha)	Ecosystem (1000 ha)	In region (1000 ha)	(%)	By region (1000 ha)	SO_2 (ha/ton)	NO_x (ha/ton)	NH_3 (ha/ton)	H^+ eq. (ha/1E6-eq.)
Albania	119.98	29.99	30.00	2881	1062	0	0	3	0.02	0.00	0.01	0.00
Austria	89.97	221.97	91.00	8373	4872	2895	59	930	1.31	0.42	3.44	216.74
Belarus	709.96	284.95	257.00	20706	1901	364	19	8650	4.65	4.54	5.72	15.39
Belgium	316.99	352.00	95.00	3054	621	477	77	1314	1.28	0.82	1.10	604.63
Bosnia-Herzogovina	479.99	79.76	36.00	5151	1449	0	0	77	0.15	0.04	0.06	0.00
Bulgaria	2019.96	375.97	140.63	11 102	3782	0	0	261	0.07	0.02	0.05	0.00
Croatia	179.98	82.95	37.00	5640	1638	13	1	69	0.30	0.12	0.17	6.13
CRZF	1875.98	741.98	105.00	7904	2656	2532	95	4263	1.91	0.69	1.26	12.33
Denmark	179.98	268.98	140.00	4217	974	174	18	2080	5.56	2.02	5.28	83.82
Estonia	274.99	71.98	29.00	4549	1891	389	21	3347	12.43	1.54	3.92	37.36
Finland	259.94	299.92	41.00	33 449	32 208	5017	16	4613	15.14	2.42	13.40	733.26
France	1298.00	1585.00	700.00	54 783	14 483	618	4	3438	0.79	0.47	0.74	50.15
Germany new	4520.98	693.97	205.00	35 642	8693	6971	80	11 824	2.17	0.90	1.89	33.38
Germany old	809.93	2376.93	554.00	35 642	8693	6971	80	7276	1.94	1.42	3.31	33.38
Greece	509.91	305.91	78.00	12 582	2455	0	0	9	0.01	0.00	0.01	0.00
Hungary	1009.98	237.98	176.00	9297	1620	142	9	1560	2.08	0.37	0.90	13.24
Ireland	177.98	114.97	126.00	6900	489	23	5	382	0.78	0.57	1.11	3.72
Italy	1678.00	2047.00	416.00	30 174	6627	1159	17	2538	0.56	0.14	0.47	55.75
Latvia	114.99	92.98	38.00	6441	2716	374	14	1358	2.39	1.12	1.90	22.12
Lithuania	221.97	157.98	84.00	6498	1896	82	4	1369	6.85	1.00	1.67	42.78
Luxembourg	14.00	23.00	7.00	260	88	15	17	36	0.86	0.43	1.89	31.62
Netherlands	204.98	574.98	236.00	3610	320	282	88	1645	1.24	0.97	1.55	3.51

Norway	53.93	229.90	39.00	31,752	32 065	8060	25	1824	10.90	2.80	14.25	633.56
Poland	3209.92	1279.00	508.00	31,119	6372	5904	93	14 537	2.79	1.73	5.08	43.69
Portugal	282.97	215.00	93.00	8884	2829	1	0	8	0.02	0.01	0.01	0.82
Moldova	90.99	34.98	50.00	2917	8	0	3	134	0.17	0.02	0.14	17.22
Romania	1311.00	546.00	300.00	23 713	6234	578	9	1378	0.43	0.14	0.35	0.04
Kalingrad region	35.99	16.00	11.23	373 489	345 607	27 475	8	107	1.23	0.07	0.45	342.49
Kola, Karelia	739.94	47.94	5.64	373 489	345 607	27 475	8	11 846	16.45	0.21	1.12	342.49
St. Petersburg reg.	284.94	109.96	44.97	373 489	345 607	27 475	8	4165	11.60	1.04	3.35	342.49
Remaining Russia	3398.27	2500.80	1129.16	373 489	345 607	27 475	8	15 657	5.68	0.89	4.42	342.49
SKRE	542.98	226.98	62.00	4836	1992	1340	67	1288	1.36	0.47	2.68	170.40
Slovenian	195.00	57.00	27.00	2029	906	430	48	651	1.16	0.27	2.78	406.82
Spain	2265.86	1178.00	353.00	49 525	8523	74	1	472	0.13	0.04	0.04	7.81
Sweden	135.92	410.91	61.00	44 469	43 650	10 108	23	3932	13.82	3.03	17.68	1189.36
Switzerland	43.00	165.00	62.00	4126	1189	353	30	265	1.28	0.42	2.63	96.39
Macedonia	106.00	38.84	16.78	2537	1066	0	0	0	0.00	0.00	0.00	0.00
Ukraine	2781.84	1096.83	926.00	57 977	8253	1082	13	8237	1.27	1.27	1.98	31.57
United Kingdom	3751.91	2701.92	320.00	23 103	7890	4741	60	11 739	1.94	0.92	4.32	101.40
Yugoslavia	581.00	210.84	99.00	10 215	3413	0	0	365	0.24	0.04	0.10	0.00
Atlantic ocean	317.00	348.57						113	0.19	0.14		
Baltic sea	73.00	81.00						664	4.48	1.77		
Mediterranean sea	12.00	13.00						0	0.00	0.00		
North sea	173.00	191.91						446	1.58	0.94		

The acidifying impact from an emission can be estimated by multiplication of the emission with the acidification factor for that region and that substance.

Acidification factors for acidifying substances other than sulphur dioxide, nitrogen oxide and ammonia may conditionally be calculated from the ones for H^+ equivalents (multiply the acidification factor for H^+ equivalents with the number of H^+ potentially deliverable by, and divided with the molecular mass of the substance in question).

Approximation of acidification factors for these other substances is only acceptable under the conditions that a substance fully deposits in the same region as where the source is located (like hydrogen chloride), and that the deposed substance is fully leached (like sulfur, unlike phosphor) and not retained in the soil or taken up by the vegetation (like nitrogen).

The acidification factors for H^+ equivalents are derived by dividing the change in area of unprotected ecosystems in regions with the change in sulfur depositions in that region.

The change in unprotected ecosystem by reducing the total emission from each region has also been determined with the RAINS model (see Table 1). This change is compared with the estimated change by regions on the basis of the acidification factors (factor × total emission). The accordance between both appears to be fairly good. The differences remain within 90 to 110% for 21 regions, and within 50 to 200% for 16 regions. These results suggest a reasonable good stability of the estimated acidification factors for moderate changes in the reference situation.

5. Discussion

The acidification factors are based on calculations with the RAINS model. The credibility of, and uncertainties in these acidification factors are therefore strongly related to the credibility of, and uncertainties in the model. One of the principal motives for developing the RAINS model was to provide scientific support for negotiations in Europe under the Geneva Convention on Transboundary Air Pollution in Europe. In this role, the RAINS model and the constituting sub-modules (like the EMEP atmospheric transfer matrices, and the critical loads compiled by CCE) have gained broad scientific and political acceptance in Europe.

The RAINS model is like all models, a simplification of reality. Quantification of combined uncertainties in the assessed impact is one of the next steps in the continuing development of the model, and recommended for future update of acidification factors presented here. While the uncertainties in the RAINS model are expected to remain within a factor two, however, they are canceled out to a large extent in the acidification factors due to the large number of ecosystems they cover. The information gained by the use of these factors thus compensates fully for the additional uncertainties they introduce.

One of the basic assumptions underlying the presented acidification factors is the marginal contribution that total emissions from separate processes in the product's life-cycle make to the total deposition on receiving grid elements. This assumption follows a second assumption that, separate processes make only a marginal contribution to the total emission from a region. This second assumption is in general true, though not for some exceptional cases. For these cases, however, the deposition on receiving grid elements, the net result of import and export of emissions, still reasonably applies to the first assumption.

The term deposition in this article refers to annual average deposition. The marginality of total emissions from separate processes justifies another assumption that implicitly underlies the presented framework: also for a given moment in time, the contribution from separate processes may be regarded as marginal.

The geographical range on which the analysis needs to be done in order to capture about most of the acidifying impact from emissions has shown to be several hundreds of kilometers (see also above). In the nearby future, the RAINS model will implement the transfer matrices of 50×50 km grid resolution that will soon be released by EMEP. Update of the acidification factors presented here for this smaller scale resolution is recommended.

6. Conclusions and recommendations

Acidification and normalization factors have been established for 44 regions in Europe to facilitate site-dependent life-cycle impact assessment of acidification. The acidification factors relate the region of emission to the impact on its deposition area. The application of the acidification factors in life-cycle impact assessment is very simple.

An emission have to be multiplied with the acidification factor for that region and substance to derive the estimated acidifying impact of that emission. The only additional data required, the geographical site or region where an emission takes place, is in general, already provided by current life-cycle inventory analysis.

The acidification factors show a reasonable good stability of the estimated acidification factors for changes in the reference situation, and the gain of information by using these factors fully compensates for the introduction of additional uncertainties. It is recommended for future update to quantify these uncertainties.

The presented framework has shown to be able to establish feasible acidification factors for use in life-cycle impact assessment. It is desirable to extend the existing Europe set with factors for the other continents. The same framework can also be used to achieve similar factors for other environmental impacts. The RAINS version 7.2 provides the possibility to do so for tropospheric ozone creation and eutrophication-via-air in Europe.

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