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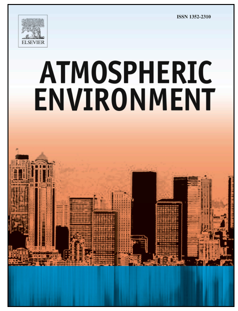

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Critical load exceedances under equitable nitrogen emission reductions in the EU28

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Abstract

The ecosystem area in the 28 states of the European Union (EU28) for which eutrophication critical loads are exceeded is investigated under the revised National Emission Ceiling Directive (NECD) and under alternative scenarios whereby reduction efforts are shared equitably among Member States. The focus is on nitrogen oxide (NO_x) and ammonia (NH_3) emission reduction policies that ensure that the total EU28 emission reduction target for 2030 under the NECD is achieved, but by equity-based emission reductions for each Member State. A gradual reduction of emissions of nitrogen in the EU28 is assessed by imposing ever lower common maximum densities for emissions (a) per unit area of a country (areal-equity) (b) per capita of a country's population (per capita-equity), and (c) per euro (€) of a country's GDP (GDP-equity). The NECD aims at a reduction of EU28 emissions of NO_x and NH_3 of 63% and 19%, respectively in 2030, compared to base year 2005. Under these reductions, about 67% of EU28 ecosystem area remains at risk of adverse effects of nitrogen deposition. We demonstrate that reducing N emissions subject to GDP-equity among EU28 Member States could have reduced that area at risk to about 61%. The application of areal and per capita-equity does not lead to significantly different ecosystem areas at risk when compared to NECD.

Keywords: Air pollution; Critical loads; EU28 Ecosystems; Eutrophication; NEC Directive; Nitrogen deposition.

1. Introduction

The search for mechanisms to share the cost of measures to abate emissions of air pollutants has a long history in the development of mitigation policies. Cap-and-trade policies were instrumental in the Acid Rain Program following the 1990 amendment to the USA Clean Air Act (see US-EPA, 1990). It allowed for the selling and trading of sulphur dioxide emission allowances of power plants nationwide, subject to a regionally set emission cap. Following its relative success, cap-and-trade policies are also being put in place in support of greenhouse gas emission mitigation, such as the European Union (EU) Emission Trading Scheme (EC, 2003). In cap-and-trade policies, emission regulation addresses the allocation of (best) available technology, related emission reduction costs and emission permits. Mejean *et al.* (2015) elaborate – in the context of climate change – how allocation rules can be derived from equity principles pointing out that these are a matter of distributing costs (Ringius *et al*., 2002 cited in Mejean *et al.*,2015) and commonly referred to as burden sharing. An example of applying equity in the early days of air pollution control was the 1985 protocol to the 1979 Convention on Long-range Transboundary Air Pollution (LRTAP Convention) on the reduction of sulphur emissions (UNECE, 1985) that was based on the concept of a flat 30% reduction of sulphur dioxide emissions by the Parties to the LRTAP Convention.

A common characteristic of applying burden sharing concepts, irrespective of whether they address climate change or air pollution, is that the risks to environmental and health impacts are not a target for, but rather a consequence of emission reductions. Burden sharing turns out to imply "the right to emit" as Averchenkova *et al.* (2014) put it with respect to the 2030 mitigation pledges for the 2015 Climate Conference (UNFCCC, 2015). Therefore, the result of sharing the burden of the mitigation of air pollution sources between countries is that it does not necessarily also lead to sharing the impacts. Successive air pollution abatement policies under the LRTAP Convention (UNECE, 1994; UNECE, 1999; UNECE, 2012) were focused on setting emission ceilings taking risks for the environment and public health into account (Reiss *et al.,* 2012). Burden sharing in these agreements was embodied by model assessments aiming at the minimization of total European mitigation costs subject to protection targets for environmental and public health.

Based on this concept under the LRTAP Convention, a similar approach was conducted in the European Union (EC, 2001). The environmental and health targets of the 2001 National Emission Ceiling Directive (NECD) referred to 6th Environmental Action Programme of the EU, aiming at compliance with the critical loads for acidification and eutrophication and with critical levels for ground-level ozone (see Hettelingh *et al.*, 2013). However, the political agreement on emission ceilings implied an unequal distribution of emission reductions and ecosystems protection over EU28 Member States.

Finally, the latest revision of the NECD (EU, 2016) establishes for each Member State emission reduction requirements for five air pollutants (SO_2, NO_x, VOC, NH_3 and PM2.5) for 2030 relative to the base year 2005, with the aim to reduce harmful impacts of air pollution on human health and vegetation. "Member States should implement this Directive in a way that contributes effectively to achieving the Union's long-term objective on air quality, as supported by the guidelines of the World Health Organisation, and the Union's biodiversity and ecosystem protection objectives by reducing the levels and deposition of acidifying, eutrophying and ozone air pollution below critical loads and levels as set out by the LRTAP Convention" (EU, 2016, pp. L344-2, para. 8). This reference is interesting because critical load exceedances within a country are caused by both national as well as transboundary emission sources. As a consequence, the answer to questions addressing equity of burden sharing becomes particularly complex.

With the focus on eutrophication, we investigate in this paper the effect on the protection of EU28 ecosystems by applying (ever stricter) equity of NO_x and NH_3 emissions in Member States. This affects the distribution of emissions reductions of these pollutants, leading to (ever lower) ecosystem areas in the EU28 for which eutrophication critical loads (CLeutN) are exceeded. We also compare these emission reductions to those under the NEC Directive. In particular, the paper examines equity of emissions (a) per unit area of a country, (b) per capita of a country's population, and (c) per € of a country's GDP. We also compare the resulting areas at risk against those resulting from the NEC Directive, and conclude with an assessment of the efficiency of applying equity principles in terms of the risk of eutrophication in the EU28 Member States.

2. Method for assessing exceedances under equitable emissions

Here we describe the emissions of NO_x and NH_3 (section 2.1), their atmospheric dispersion (section 2.2), critical loads for eutrophication and their exceedances (section 2.3) and, finally, the application of NO_x and NH_3 emission densities to establish alternative risks of eutrophication compared to those under the NECD (section 2.4).

2.1. Emission and density data

Emission data for NO_x and NH_3 of EU28 Member States for 2005 and their NECD projections for 2030 are obtained from Amann et al. (2018) as a basis to compute emission densities whereby emissions for each EU28 Member State are normalized using its geographical area, population and gross domestic product (GDP). More specifically, emission densities (a) per unit area of a country (areal-equity), (b) per capita of a country's population (per capita-equity), and (c) per € of a country's GDP (GDP-equity) are based on capita and GDP data for the NECD base year 2005 (EU, 2016b, Annex 1), while the areas of Member States have been obtained from the Fischer Weltalmanach (2018). Emission densities for 2005 are summarized here (Table 1), whereas isolines of total nitrogen emissions as function of these densities can be found in the Supplementary Material (Figure S1).

Table I: Areal (in tN/km^2), per capita (in kgN/cap) and per GDP-€ (in gN/€) emission densities for NO_x-N and NH_3-N emissions in 2005 in the EU28 countries.

	tN/km^2		kgN/cap		gN/€	
	NO_x-N	NH_3-N	NO_x-N	NH_3-N	NO_x-N	NH_3-N
Austria	0.83	0.65	8.5	6.63	0.28	0.22
Belgium	3.03	1.87	8.87	5.47	0.29	0.18
Bulgaria	0.49	0.3	6.97	4.26	1.82	1.11
Croatia	0.43	0.56	5.61	7.35	0.59	0.77
Cyprus	1.22	0.95	8.95	6.95	0.45	0.35
Czech Republic	1.07	0.88	8.3	6.78	0.68	0.56
Denmark	1.27	1.47	10.1	11.69	0.24	0.28
Estonia	0.27	0.18	9.07	5.92	0.9	0.59
Finland	0.16	0.09	10.63	6.07	0.34	0.2
France	0.77	1.14	7.04	10.38	0.24	0.35
Germany	1.22	1.55	5.28	6.7	0.2	0.25
Greece	0.93	0.36	11.08	4.32	0.59	0.23
Hungary	0.51	0.7	4.69	6.46	0.52	0.71
Ireland	0.61	1.22	10.32	20.69	0.29	0.57
Italy	1.2	1.18	6.27	6.17	0.24	0.24
Latvia	0.19	0.22	5.52	6.19	0.7	0.79
Lithuania	0.23	0.42	4.57	8.11	0.62	1.1
Luxembourg	6.59	1.86	36.95	10.4	0.5	0.14
Malta	8.53	4.46	6.7	3.5	0.5	0.26
Netherlands	2.63	3.02	6.7	7.68	0.21	0.24
Poland	0.76	0.83	6.25	6.77	0.9	0.97
Portugal	0.81	0.47	7.11	4.15	0.47	0.27
Romania	0.43	0.67	4.74	7.47	0.98	1.55
Slovakia	0.55	0.54	5	4.96	0.54	0.54
Slovenia	0.75	0.82	7.62	8.32	0.5	0.54
Spain	0.88	0.81	10.32	9.51	0.47	0.44
Sweden	0.13	0.12	6.59	5.8	0.19	0.17
United Kingdom	1.89	1.04	7.79	4.29	0.29	0.16
EU28	0.79	0.79	7.07	7.08	0.31	0.31

Countries that have already applied stringent emission reductions before the base year 2005 can be expected to have relatively low emission densities in 2005 depending on the size of the area, population or GDP. Minimum areal, per capita and GDP equities for NO_x emissions in 2005 are obtained in Sweden (0.13 tN/km^2), Lithuania (4.57 kgN/cap) and Sweden (0.19 gN/€) (see Table 1), respectively. Maximum values for these three densities are computed for Malta (8.53 tN/km^2), Luxemburg (36.95 kgN/cap) and Bulgaria (1.82 gN/€), respectively. For NH_3, minimum densities are computed for Finland (0.09 tN/km^2), Malta (3.50 kgN/cap) and United Kingdom (0.16 gN/€), respectively, and maximum NH_3 emission densities are obtained for Malta (4.46 tN/km^2), Ireland (20.69 kgN/cap) and Romania (1.55 gN/€). Weighing these emission densities with their corresponding 2005 country emissions and scaling to 100% gives the cumulative distribution functions (CDFs) shown in Figure 1. The CDFs of the three densities illustrate that the median for each of the NO_x emission densities are 0.93 tN/km^2, 7.04 kgN/cap and 0.29 gN/€, and for NH_3 1.14 tN/km^2, 6.77 kgN/cap and 0.35 gN/€, respectively.

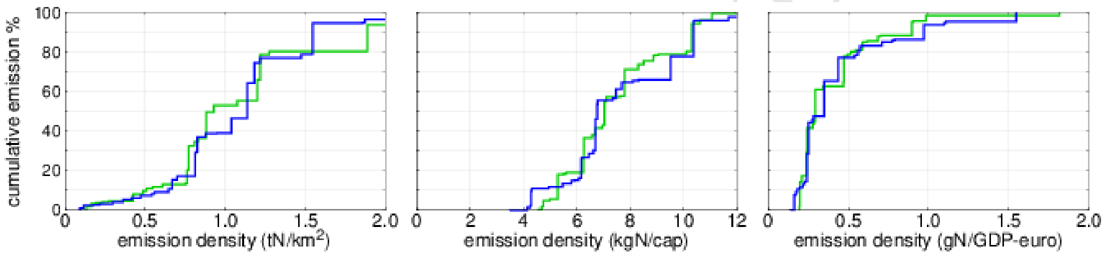

Fig. 1. Cumulative distributions of EU28 countries' 2005 emission densities per area (left), per capita (centre), and per GDP-€ (right) weighed by their respective 2005 emission (see Table I; green=NO_x-N, blue=NH_3-N; 100%=total EU28 2005 emissions).

2.2 Dispersion modelling

The Meteorological Synthesizing Centre West (MSC-W) of the Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (EMEP) models, *inter alia*, the depositions of NO_x and NH_3 on a 0.50°×0.25° longitude-latitude grid from European national emissions (Simpson et al., 2012). Note that also sulphur emissions are needed to compute nitrogen deposition due to their chemical interactions. In this paper, we assume sulphur emissions for all Member States equal to those agreed under NECD-2030. EMEP also derives so-called source-receptor matrices (SRMs) by conducting a series of model runs for five 'typical' meteorological years and three aggregated land use classes (forests, semi-natural vegetation and open land/surface waters). The derived SRMs can then be used to quickly compute depositions for any given set of emissions by matrix multiplications (Amann et al., 2011). In this paper the SRMs generated in 2012 are used to compute depositions from any set of NO_x and NH_3 country emissions for assessing areas where eutrophication critical loads are exceeded.

2.3 Critical loads for eutrophication and exceedances

The concept of a critical load is defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson and Grennfelt, 1988). Details on the critical load concept and its applications can be found in De Vries et al. (2015). The concept has been applied to support effect-based European air pollution abatement agreements (see, e.g., Hettelingh et al., 2013; 2015; Reiss et al., 2012). The most recent estimates of critical loads (see Hettelingh et al., 2017) for eutrophication were used for the assessment described in this paper. These include data from twelve EU28 Member States for different European ecosystems (Table S1). Critical loads for the remaining Member States were taken from the so-called European background database, held at the Coordination Centre for Effects under the LRTAP Convention (see Posch and Reinds, 2017).

Exceedances of critical loads are calculated for deposition patterns that result from the emissions in 2005 and 2030, the target year of the 2016 NECD (EU, 2016). The exceedance in each deposition grid cell is computed as the so-called Average Accumulated Exceedances (AAE: see Posch et al., 2001; 2015) in each grid cell, computed as the ecosystem area-weighted sum of the differences, in each grid cell, between ecosystem-specific nitrogen deposition and critical load for eutrophication, expressed in equivalents, or moles of charge, per area and year (note that in the case of nitrate and ammonium, equivalents are the same as moles, and that, e.g., kg of N can be obtained by multiplying with 0.014). The AAE can also be computed for any geographical area, e.g., the Member States individually and for the EU28 as a whole; and results for 2005 and 2030 are given in Table 2. Figure 2 shows the gridded AAE for eutrophication in Europe in 2005 and 2030.

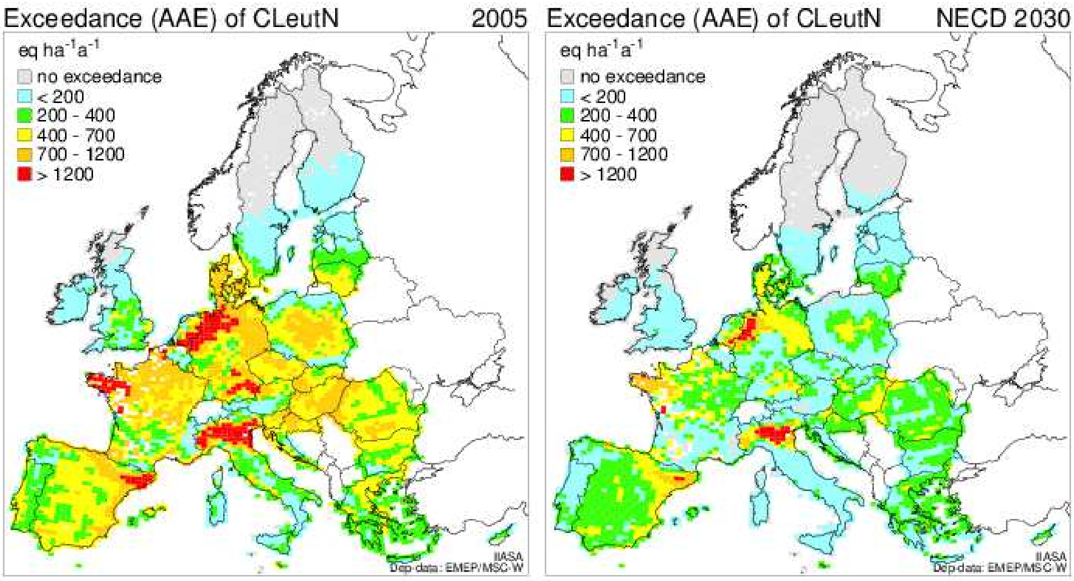

Fig. 2. Average Accumulated Exceedances (AAE) of the critical loads for eutrophication in the EU28 countries in 2005 (left) and under the NECD 2030 emissions (EU, 2016) (right).

The computed area at risk of eutrophication, i.e. where the AAE exceeds zero, both in 2005 and 2030 turns out to cover large shares of the EU28 ecosystem area (all non-grey areas in Figure 2). High AAE, i.e. higher than 700 eq $ha^{-1}a^{-1}$, in 2005 (orange and red shadings in Figure 2, left) occur in the border area of the Netherlands, Germany and Belgium and in France, Spain, southern Germany and northern Italy. In 2030, the magnitude and coverage of the area at risk is reduced (Figure 2, right) compared to 2005, but eutrophication continues to be a risk in the whole of the EU28 including areas with very high critical load exceedances on the border between the Netherlands and Germany and the north of Italy in particular.

The three highest national AAEs in 2005 (Table 2) are in The Netherlands (958 eq ha^{-1} a^{-1}), Luxemburg (887 eq ha^{-1} a^{-1}), and Germany (769 eq ha^{-1} a^{-1}), which values are relatively high compared to 413 eq $ha^{-1}a^{-1}$, the average for the EU28. The area at risk of eutrophication in 2005 is computed to cover 81% in the ecosystem area of the EU28. Under NECD emissions for 2030 (NECD-2030), that percentage is reduced to 67 %, implying that, compared to 2005, an additional 14 % of the EU ecosystem area is protected under NECD-2030.

Table 2: Ecosystem area (in 1000 km^2) at risk (%) in the EU28 in 2005 and 2030 under NECD, i.e. ecosystem area where the critical loads for eutrophication (CLeutN) have a positive exceedance (computed as AAE in eq ha^{-1}a^{-1})

Country	Ecosystem area	Risk of eutrophication in: 2005		NECD-2030	
	1000 km^2	%	AAE	%	AAE
Austria	51	75	285	32	61
Belgium	6	11	22	1	2
Bulgaria	51	100	355	93	166
Croatia	34	97	528	83	233
Cyprus	2	100	280	100	228
Czech Republic	6	100	648	96	162
Denmark	6	100	761	99	388
Estonia	27	83	112	30	17
Finland	41	10	5	1	0
France	177	89	493	73	201
Germany	107	82	769	65	319
Greece	67	100	339	95	207
Hungary	28	100	653	79	289
Ireland	18	8	12	3	3
Italy	106	77	391	42	147
Latvia	37	97	243	84	102
Lithuania	22	100	428	97	241
Luxembourg	1	100	887	100	442
Malta	<1	100	436	99	270
Netherlands	5	76	958	69	442
Poland	97	77	401	51	121
Portugal	35	100	329	99	147
Romania	105	100	488	93	248
Slovakia	24	100	549	89	231
Slovenia	13	100	663	87	270
Spain	231	100	520	97	317
Sweden	59	14	29	11	9
United Kingdom	73	22	59	6	7
EU28	**1,431**	**81**	**413**	**67**	**188**

2.4 Modelling areas at risk under equal emission densities

The ecosystem area in the EU28 for which eutrophication critical loads are exceeded is investigated under simulated emission reductions that gradually reduce emissions of NO_x and NH_3 in the EU28 by imposing ever lower common (i.e. EU28-wide) maxima for areal, per capita and GDP densities, starting from 2005 emissions.

We assume that a country is not allowed to increase its emissions compared to the 2005 level, i.e. in this procedure, the emission density of a country is only reduced when the value is lower than the 2005 density shown in Table 1. This implies that in no Member State emissions in 2030 can be higher than those in 2005 (Table S2), irrespective of whether emission reductions are established under NECD-2030, areal-, per capita or GDP-equity. However, compared to emission reductions committed under NECD-2030, a rich country can have higher emissions under GDP-equity in 2030 than relatively poor countries, while a country with a small area may have to reduce more under areal-equity.

3. Results

EU28 emissions are shown in Figure 3 as function of the respective maximal emission density, i.e. as function of $\sum_k \min\{x, x_{2005,k}\}$, where x is the prescribed maximum emission density and $x_{2005,k}$ the 2005 emission density of country k (100%=total EU28 2005 emissions).

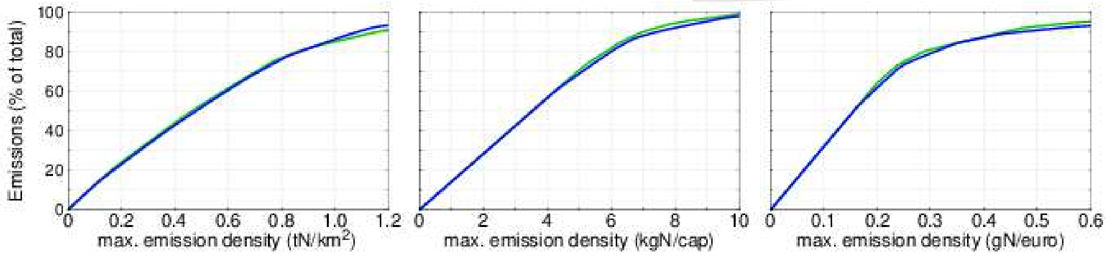

Fig. 3. EU28 2005 emissions as function of the maximal areal (left), per capita (centre), and per GDP-€ (right) emission density (100%=total EU28 2005 emissions; green=NO_x-N, blue=NH_3-N).

Figure 3 illustrates that the percentage share in EU28 totals of NO_x and NH_3 emissions, is similar for each of the three equities. For example, 50% of the NO_x emissions (i.e. an equitable reduction in EU28 Member States of 2005 NO_x emissions by 50%) can be obtained by applying a maximum emission density of approximately 0.47 tN/km^2, 3.54 kgN/cap or 0.16 gN/€. Very similar maximum emission densities also hold when applied to obtain 50% of 2005 EU28 NH_3 emissions. However, if the lowest NO_x emission densities (see section 2.1 and Table 1) were applied to all EU28 countries, Figure 3 reveals that about 16% (at 0.13 tN/km^2, in Sweden), 65% (at 4.57 kgN/cap, in Lithuania) and 61% (at 0.19 gN/€, in Sweden) can be obtained by applying the three equities, respectively, on total 2005 NO_x emissions of the EU28; implying respective reductions of 2005 NO_x emissions by about 84%, 35% and 39%. Similarly, applying the lowest NH_3 emission densities would lead to approximately

89%, 51% and 55% ammonia emission reductions in the EU28, respectively. These reductions, in turn, lead to a decreasing area at risk of eutrophication and lower AAEs compared to area at risk and AAE for 2005. This is illustrated in Figures 4 and 5 showing isolines of the percentage of the ecosystem area for which the critical loads for eutrophication are exceeded within the EU28 Member States as function of applying to all Member States maximum emission densities (Figure 4) and of percentage emission reductions induced by maximum emission densities (Figure 5).

Also shown in Figure 4 as horizontal (blue lines) and vertical lines (green lines) are the maximum emission densities for an equitable 10, 25, 50, 75 and 90 % overall emission reduction in NO_x and NH_3, respectively.

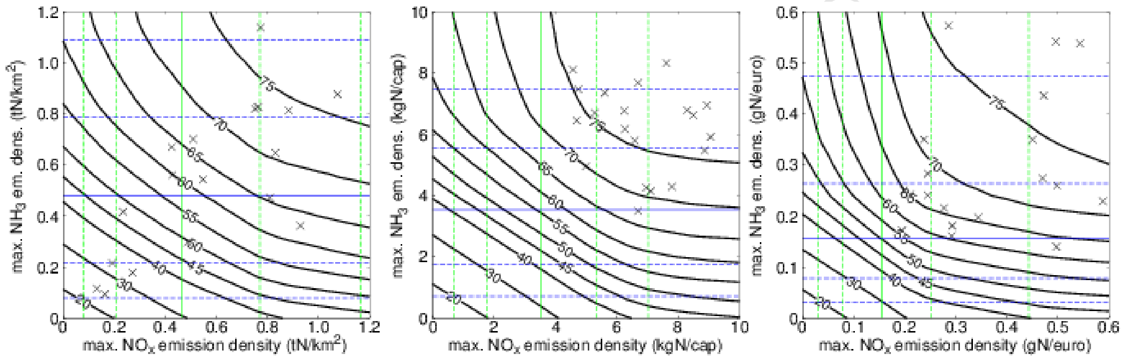

Fig. 4. Isolines of EU28 ecosystem area exceedance percentages of eutrophication critical loads, CLeutN, as a function of the maximum areal (left), the maximum per capita (centre), and the maximum per GDP-€ (right) emission densities of NO_x and NH_3. The vertical green and horizontal blue lines show the maximum emission densities for an equitable 10, 25, 50 (solid line), 75 and 90 % overall emission reduction in the EU28 for NO_x (right-to-left) and NH3 (top-to-bottom), resp. The crosses show the densities of the EU28 countries (those within the frame of the plot; see Table I).

As can be seen from Figure 4 that by reducing both NOx and NH3 2005 emissions in 2030 equitably by 50% (solid blue and green line, respectively) leaves about 57% of the ecosystem area unprotected when areal (Figure 4, left) is pursued, 55% for per capita-equity (Figure 4, centre), and about 50% of the area remain unprotected for per GDP-equity (Figure 4, right).

The axes of Figure 4 and Figure 5 are non-linearly connected via the graphs in Figure 3. Hence Figure 5 shows eco-risk isolines that are derived from the application of maximum emission densities to emissions of NO_x and NH_3 for each EU28 Member State to achieve the percent emission reduction (assuming NECD-2030 emissions for sulphur in all countries). The blue dots in Figure 5 show the percentage area exceeded if total emission reductions (compared to 2005) for the EU28 under NECD-2030 were achieved by respective equitable maximum emission densities in the EU Member States. Emissions of each Member State in 2005 and in 2030 under NECD and the application of maximum emission densities to achieve the same overall reductions are given in Table S2.

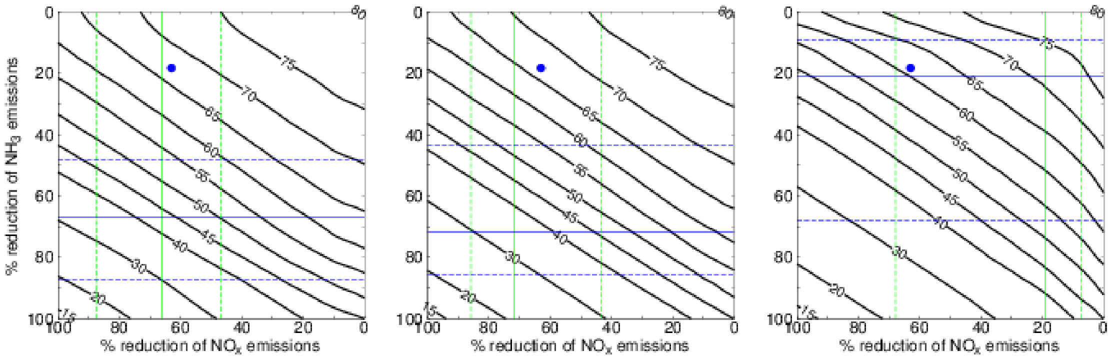

Fig. 5. Isolines of European ecosystem area exceedance percentages of eutrophication critical loads, CLeutN, as a function of the European total emission reductions of NO_x and NH_3 induced by maximum areal (left), maximum per capita (centre), and maximum per GDP-€ (right) emission densities. The vertical green and horizontal blue lines show the emission reductions corresponding to (maximum) densities of 0.1, 0.3 (solid line) and 0.5 tN/km^2 (left), 1, 2 (solid line) and 4 kgN/cap (centre), and 0.1, 0.3 (solid line) and 0.5 gN/€ (right). For the blue dots, see text.

However, Figures 4 and 5 underpin that the area at risk of CLeutN exceedance can be reduced to, or below, the percentage area exceeded under NECD-2030, i.e. 67% (Table 2). This is achieved by applying maximum emission densities without violating the NECD-2030 emission reduction objectives for NO_x and NH_3 of 63% and 19% respectively, shown in Figure 5 by blue dots. This is the case in particular with the application of GDP-equity leading to a smaller area at risk, i.e. 61% (Table 3) for the EU28 and also to a lower AAE, i.e. 181 eq ha^{-1}a^{-1} as compared to 188 eq ha^{-1}a^{-1} (Table 2). Table 3 also shows that the ecosystem area at risk under areal- and per capita equity is not different from that under NECD-2030, i.e. 67%. However, the AAE under areal-equity is higher (201 eq ha^{-1}a^{-1}) and equal under per-capita equity (188 eq ha^{-1}a^{-1}).

Table 3: Ecosystem area at risk (%) and AAE (eq ha^{-1} a^{-1}) in 2030 caused by EU28 Member State reductions of NO_x-N and NH_3-N emissions derived from applying areal, per capita and GDP-equity such that the overall reduction of NO_x and NH_3 emissions meet the objective under NECD, i.e. 63% and 19%, respectively.

EU Member State	Eco area	Exceedance in 2030 under					
		areal-equity		per capita-equity		GDP-equity	
	1000 km^2	% area	AAE	% area	AAE	% area	AAE
Austria	51	36	66	40	94	42	107
Belgium	6	0	0	1	2	3	5
Bulgaria	51	98	218	94	181	54	65
Croatia	34	85	290	85	278	81	184
Cyprus	2	100	235	100	229	100	228
Czech Republic	6	95	194	100	260	79	149
Denmark	6	98	297	99	339	100	546
Estonia	27	39	21	30	16	11	10
Finland	41	1	1	1	0	1	0
France	177	70	173	58	112	79	262
Germany	107	58	221	70	439	74	516
Greece	67	97	219	95	201	92	177
Hungary	28	95	399	94	381	70	207
Ireland	18	1	1	0	0	0	0
Italy	106	37	120	51	208	54	221
Latvia	37	87	112	83	102	50	52
Lithuania	22	97	267	96	231	82	111
Luxembourg	1	98	260	100	380	100	594
Malta	<1	97	240	100	298	100	300
Netherlands	5	27	45	70	509	74	749
Poland	97	52	138	54	142	23	22
Portugal	35	100	185	98	144	99	141
Romania	105	98	360	95	292	52	87
Slovakia	24	93	302	92	298	81	138
Slovenia	13	93	322	95	301	83	244
Spain	231	98	369	95	232	96	269
Sweden	59	12	9	12	11	12	13
United Kingdom	73	5	6	10	14	13	20
EU28	**1,431**	**67**	**201**	**67**	**188**	**61**	**181**

The geographical pattern of exceedances (AAE) over the EU28 Member States is shown in Figure 6.

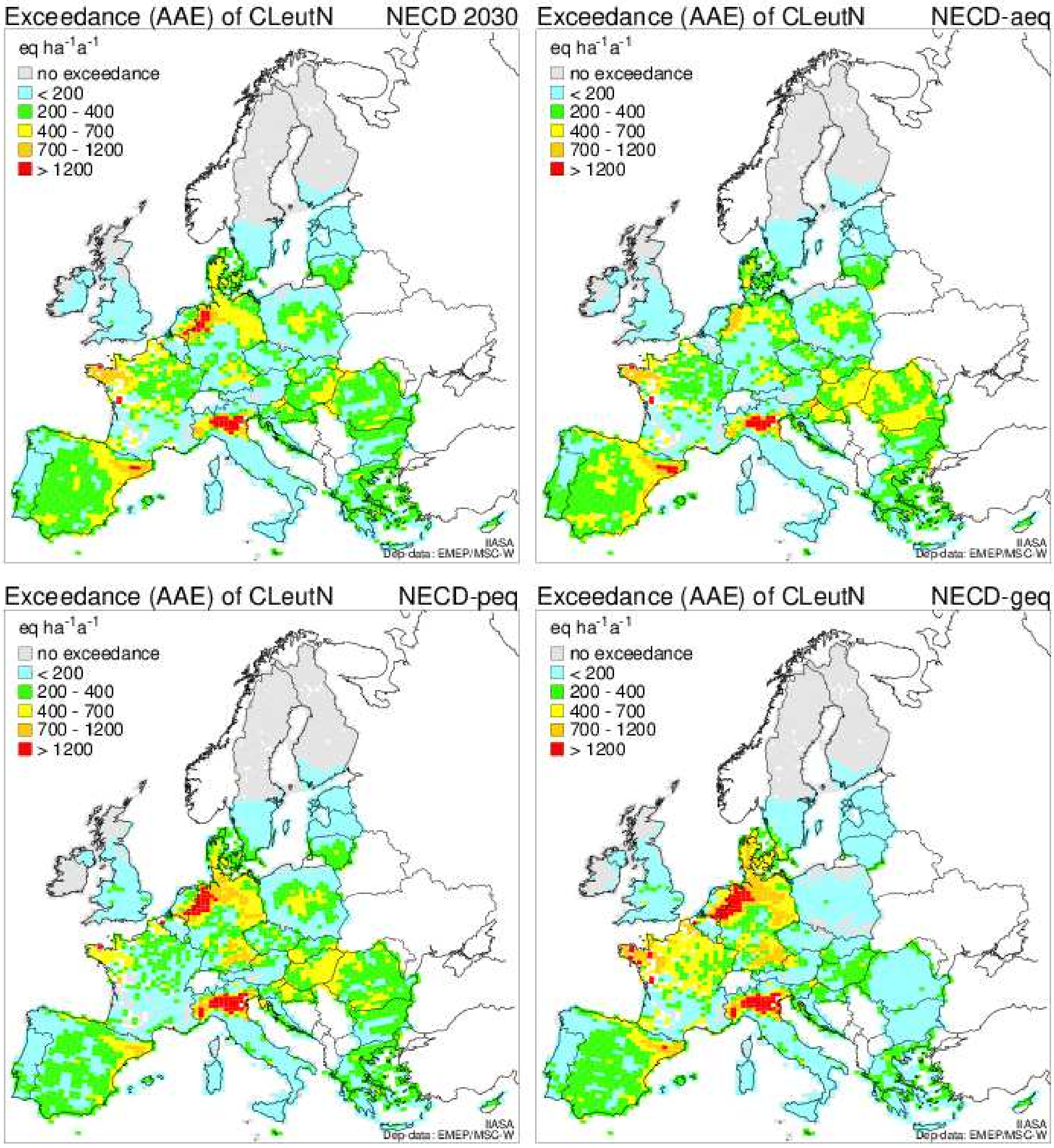

Fig. 6. Exceedance (AAE) of eutrophication critical loads for depositions due to NECD-2030 emissions (top left); and the AAE for depositions due to the same EU28 total emissions based on maximum emission densities of NO_x and NH_3 on a per area (top right), per capita (bottom left) and per GDP-€ (bottom right) basis.

The application of GDP-equity results in exceedances (Figure 6, bottom right) in, e.g., the Baltic states, Poland, Romania and Bulgaria that are lower than 200 eq ha^{-1}a^{-1} (blue shading), i.e. markedly lower than under NECD-2030 (Figure 6, top left), where maximum exceedances in these countries range between 400-700 eq ha^{-1}a^{-1} (yellow shading). From Table S2 it can be seen that NO_2 and NH_3 emissions for these countries is markedly lower under GDP-equity than their commitments under NECD-2030. The fact that these countries would have to reduce their emissions more than under NECD-2030 is because their GDP is relatively low within the EU28. However, other countries have higher exceedances under GDP-equity than under NECD-2030. This is especially apparent in Germany and the Netherlands, where larger areas have exceedances higher than 1200 eq $ha^{-1}a^{-1}$ under GDP-equity than under NECD-2030. Indeed, when inspecting the AAE for the entire country, under NECD-2030 the AAE in the Netherlands and in Germany is 442 and 319 eq $ha^{-1}a^{-1}$, respectively (Table 2), while under GDP-equity the AAEs are 749 and 516 eq $ha^{-1}a^{-1}$, respectively (Table 3). This is (largely) a consequence that the emissions of the Netherlands and Germany are higher under GDP-equity than under NECD-2030 (Table S2).

The pattern of exceedances under per capita-equity is broadly similar to that under NECD-2030. However, under areal-equity the exceedance in the Netherlands is significantly reduced to a level of about 45 eq $ha^{-1}a^{-1}$ (Table 3) compared to 442 eq $ha^{-1}a^{-1}$ (Table 2) under NECD-2030. To reach this ecosystem protection under areal-equity the Dutch would have to reduce emissions of NO_x and NH_3 more than under NECD-2030, i.e. from 140 kt and 120 kt, respectively, to 45 and 46 kt (Table S2). The reason is that areal emission densities are relatively high for countries with small geographical coverage, such as the Netherlands. In general, it should be noted that imposing ever lower common maximum densities for areal-, per capita- and GDP-equities to 2005 emissions, imply that quite stringent emission reductions are computed for Member States with high emission densities.

Finally, it can be noted from comparing the area at risk between Table 3 and Table 2 that emission reductions under the application of per capita-equity leads to less area at risk than under NECD-2030 in France (58% versus 73%), Ireland (0% versus 3%), Latvia (83% versus 84%) and Spain (95% versus 97%). A spatial view of the distribution of areas at risk of exceedances of CLeutN, as percentage of the total ecosystem area in each grid cell, is provided in Figure S2. The increased protection of ecosystem area shown in Figure 6 is confirmed in Figure S2. The grid cells in the Baltic states, Poland, Romania and Bulgaria with more than 99% areal exceedance under NECD-2030 (Figure S2, top left) are reduced to less than 80% of the ecosystem area at risk under emission reductions following GDP-equity (Figure S2, bottom right).

4. Summary and concluding remarks

Burden sharing concepts tend to address risks for environmental and health impacts implicitly, i.e. as a consequence of, rather than a target for, emission reductions, irrespective of the environmental issue at stake. In this paper the risk of impacts of excessive nitrogen deposition in 2030 to the ecosystems in the EU28 is investigated for the 2016 National Emission Ceiling Directive, and three alternative emission reduction schemes. These alternatives are established by imposing ever lower maximum densities for emissions of NO_x and NH_3 on the basis of areal-equity, per capita-equity and GDP-equity. These equity-based emission reductions are formulated such that the reduction of total NO_x and NH_3 of the EU28 for 2030 does not violate the objectives set under NECD-2030, i.e. a 63% and 19% reduction, respectively.

The emission reduction objectives under NECD-2030 lead to 67% of the European ecosystem area having an exceedance of eutrophication critical loads. In this paper it is demonstrated that the EU28 ecosystem area at risk can be reduced to 61% when applying GDP-equity. The distribution over the EU28 of areas where critical loads are exceeded also changes compared to NECD-2030, leading to less areas at risk and lower exceedances in Member States including the Baltic States, Poland, Romania and Bulgaria. An increased coverage of areas at risk and higher exceedances are identified under GDP-equity in Member States such as the Netherlands and Germany. The application of areal and per-capita equity does lead to a change of the EU28 area at risk compared to NECD-2030.

It turns out that 10, 4 and 14 Member States have a diminished percentage of the area at risk under areal-, per capita- and GDP equity, respectively, when compared to the ecosystem protection in these countries under NECD-2030. The Member States with the highest benefits under each of the three equities in terms of an increased percentage ecosystem protection compared to NECD-2030 are the Netherlands (42%), France (14%) and Romania (41%), respectively. Similarly, the countries with the highest percentage loss of ecosystem protection are Hungary, both under areal (-16%), and per capita (-14%) equity, and Italy under GDP equity (-12%). It turns out that decreased areas at risk in Member States come with higher emission reduction requirements compared to NECD-2030, while the opposite holds for Member States with an increased percentage of area at risk. For Europe as a whole, the restriction is met that emission reductions under the equity approach is equal to that agreed under NECD 2030.

In this paper the benefit of applying GDP-equity to emission reductions set under NECD-2030 for the EU28, is clearly established in terms of the protection of ecosystems against eutrophication critical load exceedances in most Member States and in the EU28 as a whole, both in terms of area protection as well as AAE magnitude. However, it is noted that the magnitude and distribution over Member States of the emission reductions agreed under NECD 2030, and computed under our equity approach, are not sufficient to protect all European ecosystems from nitrogen deposition. It would be challenging to explore whether human health impacts, that constituted an important target of emission reductions under the NEC Directive, can be included in equity-oriented assessments presented in this paper. For this, more work is needed to establish the distribution of the costs of emission reductions over Member States to complete the knowledge on impacts of burden sharing as addressed in this paper.

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Critical load exceedances under equitable nitrogen emission reductions in the EU28

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Highlights:

- 67% of EU28 ecosystems risk impacts of N emissions under the 2016 NEC Directive.
- Imposing common N emissions/GDP€ reduce impacts to 61% of EU28 ecosystems.
- Under this GDP-equity CL exceedances diminish particularly in the east of the EU28.
- Imposing common N-emission/area or /capita densities has similar impacts as NEC.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: