The role of secondary particulates in European emission abatement strategies

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Economic assessments have indicated that the greatest benefits of reducing atmospheric emissions of sulphur and nitrogen compounds in Europe come from the resulting reductions in secondary particulate concentrations. For comparison with abatement strategies devised to reduce exceedance of critical loads for acidification, this paper, therefore, considers optimisation of emission abatement strategies to reduce secondary particulate concentrations and minimise human exposure. It is seen that this changes the relative emphasis between some countries in reducing their emissions, and also places less importance on emissions of ammonia from agriculture relative to those of SO_2 and NO_x. The effect of placing emphasis on improvement in the more highly polluted areas of Europe is also examined by imposing a threshold. The benefits of the strategies in terms of ecosystem protection and human exposure to particulates are presented for all scenarios studied. The scenarios are also interpreted in terms of a " blame matrix" for human exposure to secondary particulates.

1. Introduction

It is well established that the emission of ammonia and of oxides of sulphur and nitrogen into the atmosphere can result in the long range transport of these pollutants, thus causing acidification and eutrophication, and contributing to ozone formation, in areas far removed from the points of origin of the pollutants. The deleterious effects of acidification, eutrophication, and tropospheric ozone are well known. Recently the damaging effects of particulates upon human health have become a matter of common concern. Attention has focused mainly on primary particulates which occur at high concentrations close to local sources. However, what is less well known is that away from these local sources of primary particulates, a very large fraction of the ambient particulate background consists of secondary aerosols. These result from conversion of the primary pollutants SO_2, NO_x and NH_3 to secondary compounds such as NH_4NO_3 and $(NH_4)_2SO_4$. SO_2 is oxidised to SO_4, whereupon it can react quickly with ammonia molecules to form $(NH_4)_2SO_4$, and any remaining ammonia can then form NH_4NO_3.

European abatement strategies for acidifying pollutants include the UN ECE Oslo Protocol [1], and the proposed UN ECE multi-pollutant, multi-effect protocol [2], and are designed to cost-effectively reduce the levels of acidification, eutrophication and ozone formation within the region. During development of the second sulphur protocol the use of critical loads was introduced, based on levels of deposition which were deemed sustainable without causing adverse effects on natural ecosystems. Similarly, critical levels have been adopted to define acceptable exposure levels of crops and forests to ozone. The UN ECE agreements are based upon optimised strategies devised to cost-effectively reduce exceedance of critical loads for acidification and/or eutrophication, and/or exceedance of critical levels for exposure of forests and crops to ozone, and/or population exposure to ozone using a surrogate indicator for health-related excess ozone above the WHO guideline [3]. Simultaneously these concepts have also been used by the European Union in developing strategies to combat acidification and tropospheric ozone in EU countries.

Economic assessments of the benefits of these air pollution amelioration policies have identified the reduction in damage to human health as the benefit providing the greatest reward. These benefits result not only from the reduction in tropospheric ozone but also from the reduction in secondary particulates, which the strategies are not actually designed to *cost-effectively* reduce. This is so both for the strategies being drawn up by the UN ECE for new protocols, and for those being considered by the EU as a basis for new directives; and in spite of the fact that some studies have shown that in economic terms the benefits to human health that result from reducing emissions of acidifying compounds greatly exceed those to ecosystems [4]. Although there were significant uncertainties in these estimates, it is therefore important to examine the nature of abatement strategies directly designed to cost-effectively reduce human exposure to secondary particulates in the UN ECE region.

Epidemiological studies have shown no clear evidence of a threshold for effects of particulates on human health [5] and current economic assessments are based on statistically significant relationships between annual average particulate burdens ($\mu g\, m^{-3}$) and health effects [4]. At the present level of understanding no distinction is made between different types of particle; and both chronic health effects and changes in mortality are assumed to be directly proportional to the mass of particulate material present. The implied effects of sulphate, nitrate and ammonium components are therefore directly additive to each other and to those of other particulate components such as carbonaceous compounds. We have therefore explored abatement strategies aimed at minimising the total exposure of the European population to the sum of the sulphate, nitrate and ammonium particulate components.

Particulate standards for protection of human health are based on 24 h average concentrations [5]. Recently, the European Commission has proposed a standard of 50 $\mu g\,m^{-3}$ for PM10 averaged over a 24 h period and $\mu g\,m^{-3}$ for an annual average [6]. The modelling tools used in this study provide information about concentrations of secondary particulates. Primary particulates are clearly a major contributor to human health problems associated with PM10, and these are not included in the UN ECE multi-pollutant, multi-effect protocol. At the time of writing modelling studies of long-range transport of primary particulates are in their infancy owing to the lack of reliable data on emissions and meteorological transport. More detailed work is currently under way to model the long-range transport of primary particulates and to compare the relative concentrations of primary and secondary particulates in Europe [7] and indicates that in 1990, secondary particulate concentrations over Europe were considerably higher than primary. Possible reductions in primary PM10 as a result of measures to reduce emissions of sulphur and nitrogen oxides may occur, but at the time of writing these have not been quantified. Therefore, this paper focuses on the contribution made by abatement strategies to the reduction of secondary particulates in the UN ECE region. Abatement strategies to reduce PM10 as a whole would need to consider emissions from a wider range of emission sources than have been considered so far in the UN ECE process, such as the cement industry. Future work will include a study of the nature of these potential strategies. Although beyond the scope of this paper, such strategies would need to incorporate the approach described here to cost-effectively reduce secondary particulates. It should be emphasised that, unlike primary particulates, secondary particulates accumulate in areas far removed from the emission sources to which they can be traced. Thus the highest concentrations of secondary particulates are not to be found in cities or other large emission sources, but rather substantially downwind of such sources. Sub-grid effects are much less important, as far as human exposure is concerned, than for primary particulates, which are found in high concentrations close to major emission sources in cities.

The modelling studies produce annual average concentrations of secondary particulates. However, much of the damage to human health will occur during episodes in which the long-range transport of sulphate, nitrate and ammonium contribute significantly to violation of air quality standards. These are likely to occur in the more polluted areas of Europe, where the annual average concentrations are also highest. Additional calculations have therefore been undertaken setting a threshold of 8 $\mu g\,m^{-3}$ for the annual average combined sulphate, nitrate and ammonium components, equivalent to approximately 15% of the daily air quality standard.

In addition, a reduction in secondary particulates also cause a reduction in visibility, and the economic benefit of this has also been assessed as potentially very high [8]. In this case the response is not directly linear with the particulate mass, but depends on an extinction curve. Nevertheless improved visibility is an additional reason for considering strategies aimed at reducing particulate burdens.

2. Concentration of secondary particulates in Europe

The EMEP meteorological synthesising centre West has provided matrices linking country sources of SO_2, NO_x, and NH_3 to air concentration patterns of SO_4, NO_3 and NH_4, expressed as annual averages, for each of the 11 years 1985–1995 inclusive. These data have been combined to produce an 11-year average source–receptor matrix for unit emission in each country, and then scaled up by the country emissions in 1990, which are provided by the UN Economic Commission for Europe. Figures 1–4 show the resulting concentration of total secondary particulate, and those of the component SO_4, NH_4 and NO_3 modelled for 1990, based on an 11-year average of meteorological conditions. The EMEP model used is the 150 × 150 km resolution Lagrangian version [9].

There is reason to believe that the assumptions made in the EMEP model concerning the fraction of sulphur emitted as sulphate may cause an overestimation of the SO_4 concentrations; and further that the NO_3 concentrations may also be overestimated by a factor of 2. This may be partly due to loss of volatile NO_3 components with some measurement techniques. Extensive studies of the role of such uncertainties in abatement strategies is published elsewhere [10]. It is anticipated that EMEP will produce new results based on an Eulerian model (as opposed to the current Lagrangian model). This approach is likely to produce a significant advance in the accuracy of the long-range transport modelling and future work will include the use of these results and a comparison of how strategies may change as a result of the incorporation of these matrices.

3. Optimisation techniques for abatement strategies: the ASAM model

The Abatement Strategies Assessment Model, ASAM, has been described previously [11]. It is one of several models which played a role in the UN ECEs preparations for international protocols through the Task Force on Integrated Assessment Modelling. The model draws together information detailing (1) the costs of abatement or each pollutant in each European country, provided by IIASA [12,13], (2) the EMEP source–receptor matrices which indicate the concentrations or depositions of a pollutant at any of some 600 receptors which result from unit

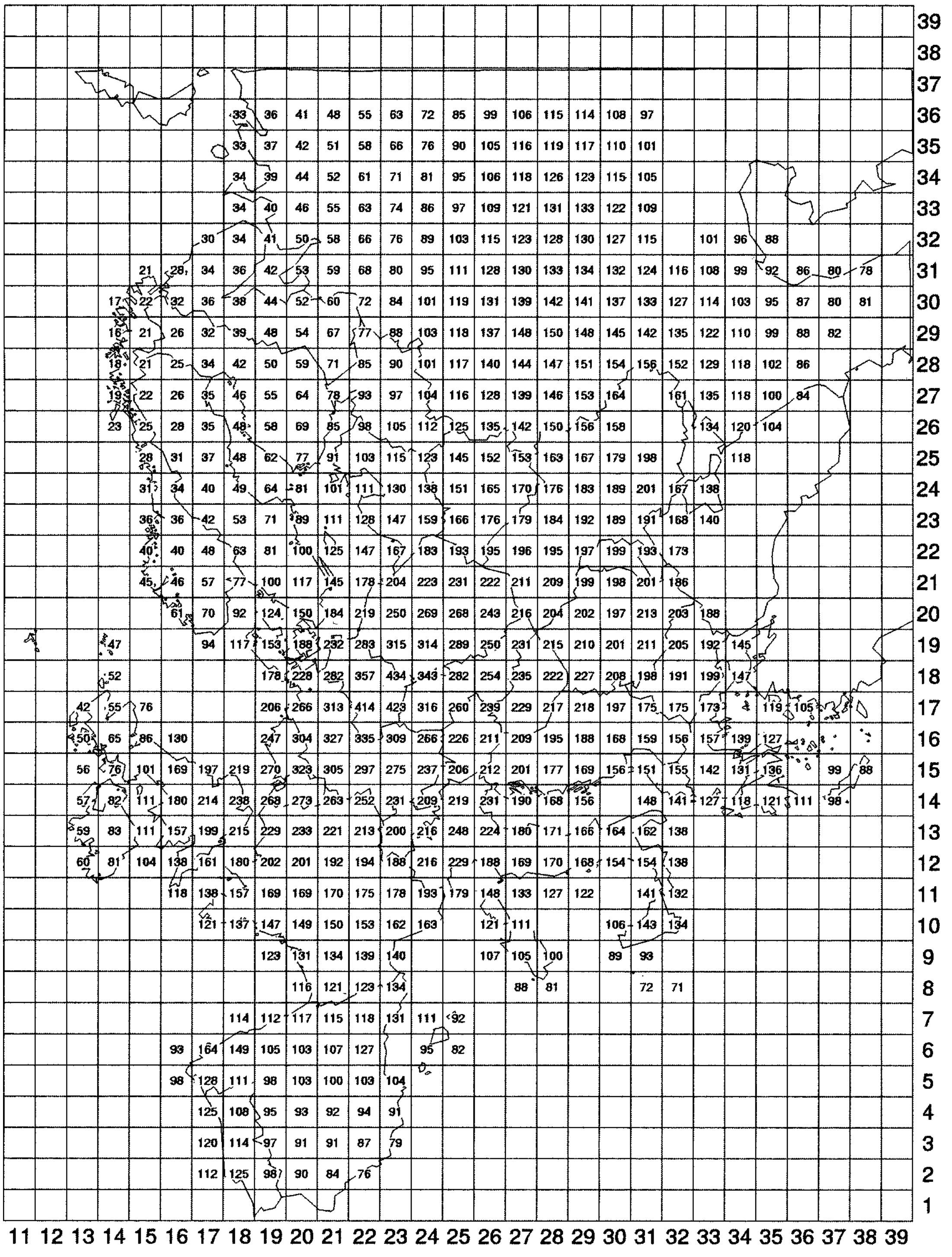

Figure 1. Total secondary particulate concentrations in 1990. Units: 100 ng$(SO_4 + NO_3 + NH_4)\,m^{-3}$.

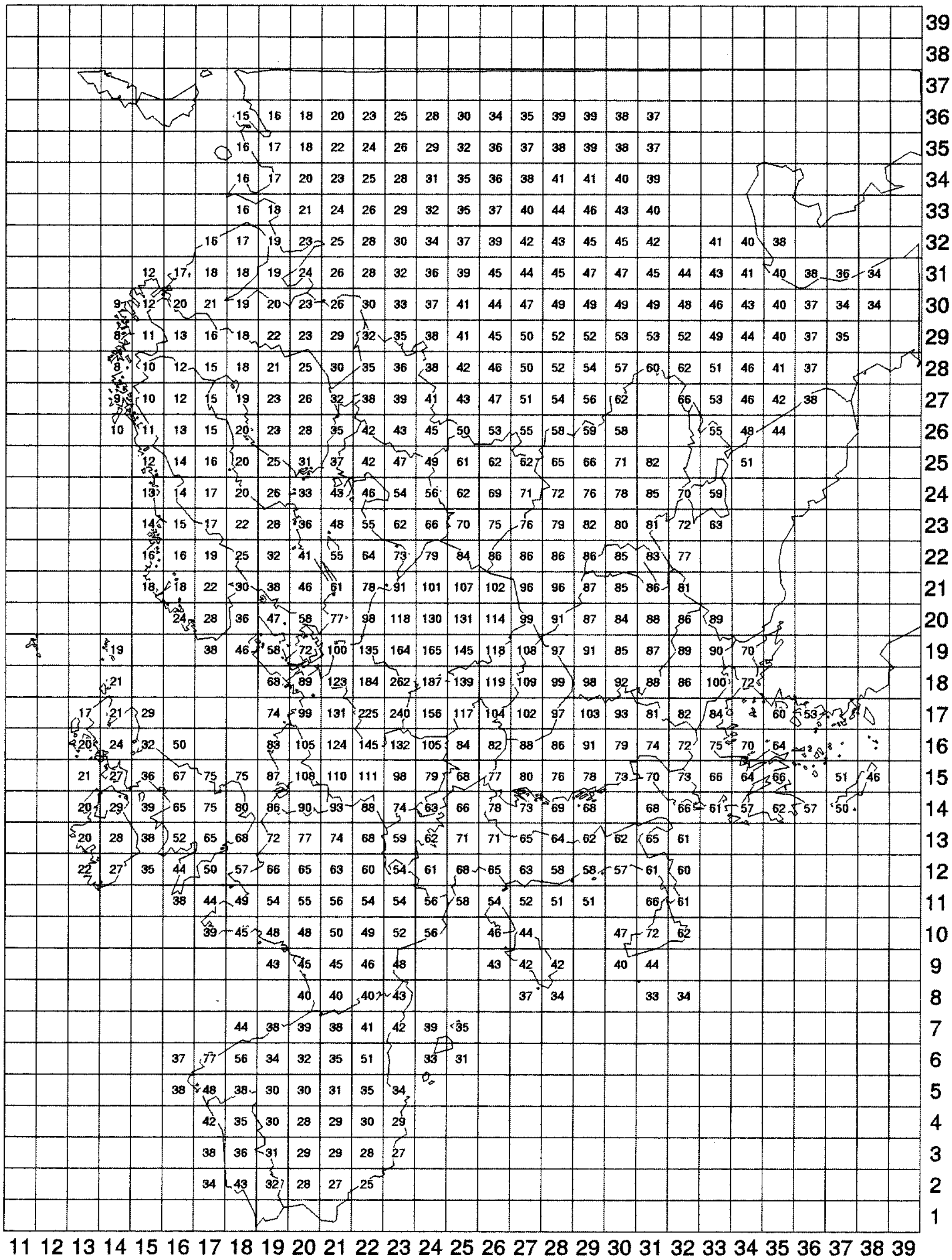

Figure 2. Total sulphate concentration in 1990. Units: 100 ng $SO_4\,m^{-3}$.

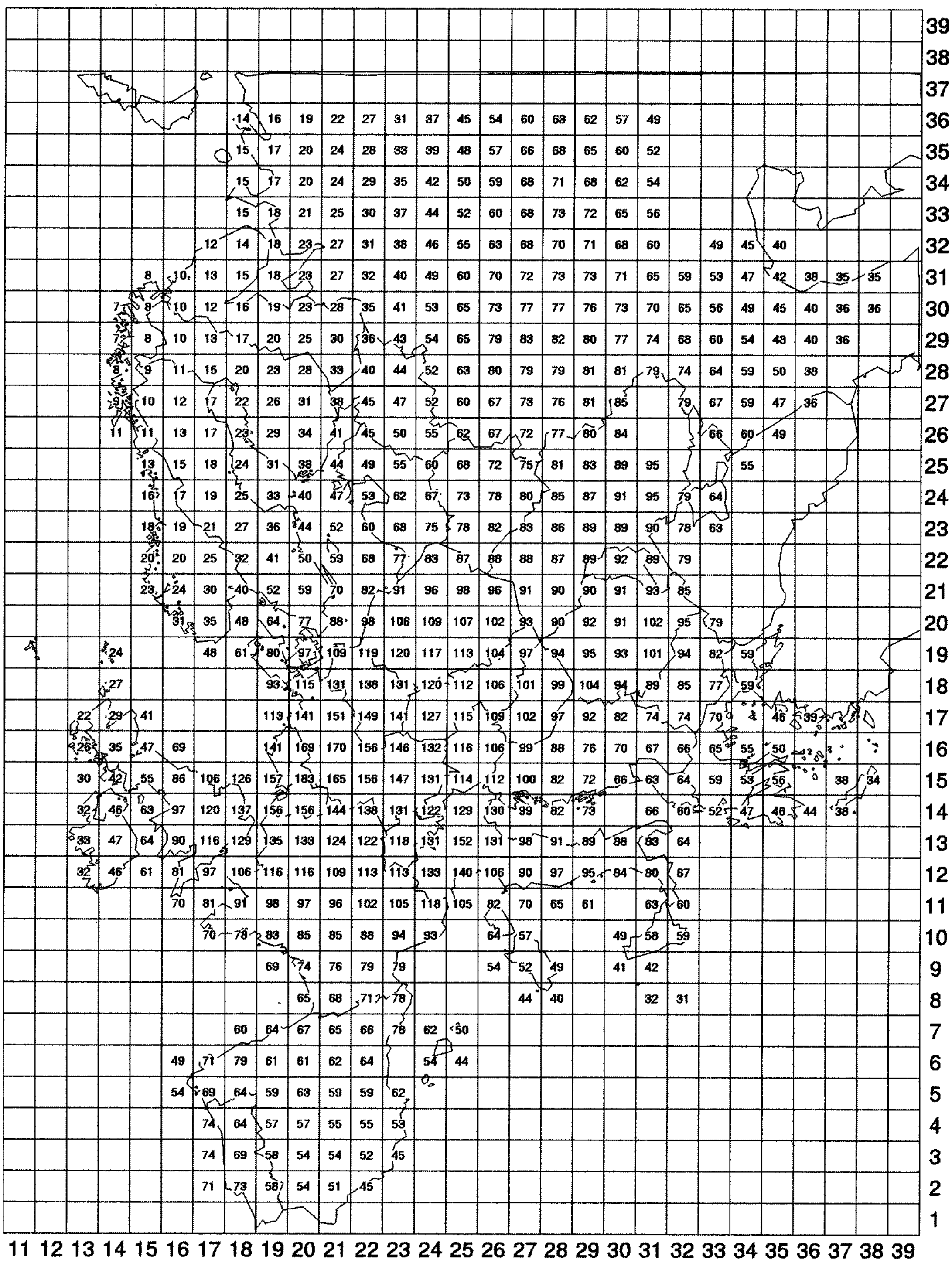

Figure 3. Total nitrate concentration in 1990. Units: 100 ng $NO_3\ m^{-3}$.

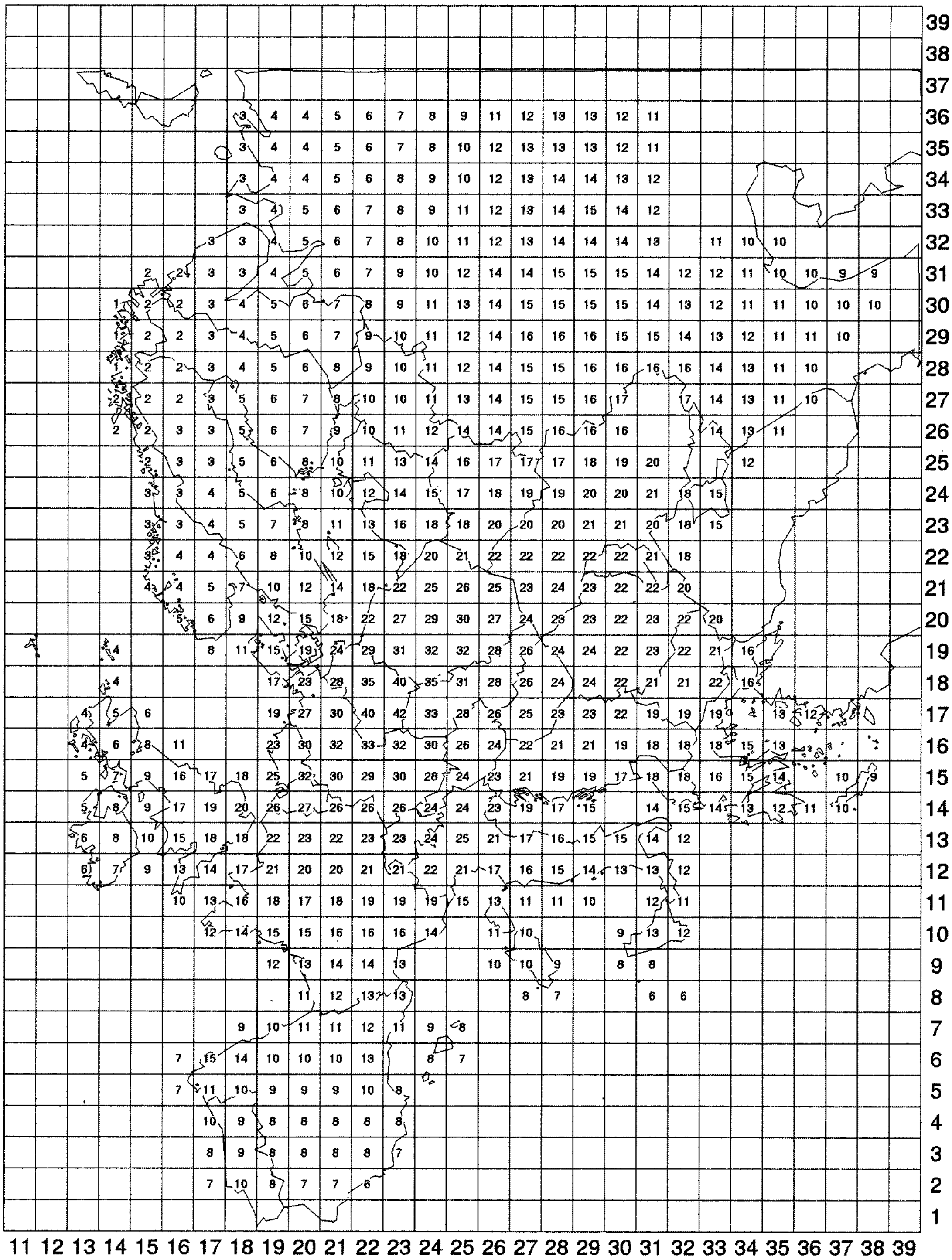

Figure 4. Total ammonium concentration in 1990. Units: 100 ng $NH_4\,m^{-3}$.

Table 1
Emissions at the REFERENCE and MFR scenarios (kT/yr).

Country	REF			MFR		
	SO_2	NO_x	NH_3	SO_2	NO_x	NH_3
Albania	56	36	34	6	15	26
Austria	45	87	77	36	78	53
Belgium	195	204	82	58	111	50
Bulgaria	846	290	126	135	115	100
Denmark	73	133	72	21	86	39
Finland	116	170	33	65	90	23
France	532	822	670	213	512	441
Germany	740	1226	557	365	776	336
Greece	375	339	72	59	193	52
Hungary	547	196	137	290	114	92
Eire	95	73	126	30	33	107
Italy	603	1195	366	206	718	294
Luxembourg	4	11	6	3	5	6
The Netherlands	89	291	136	45	180	95
Norway	34	153	21	20	107	17
Poland	1397	831	508	417	441	348
Portugal	151	199	73	37	102	53
Romania	599	458	300	107	173	206
Spain	802	892	353	187	549	237
Sweden	87	198	53	61	132	44
Switzerland	30	89	53	15	61	42
Turkey	354	175	415	354	175	415
United Kingdom	980	1186	298	254	654	220
Kola/Karelia	474	61	4	86	34	2
St. Petersburg	138	121	34	29	60	20
Belarus	480	180	163	43	111	113
Ukraine	1492	1094	649	397	568	402
Moldavia	117	34	48	19	24	33
R.F. USSR[a]	1759	1813	857	491	930	533
Estonia	175	73	29	15	26	19
Latvia	57	90	29	18	56	19
Lithuania	107	110	81	21	58	54
Czech Republic	178	231	105	97	128	82
Slovakia	119	113	51	70	75	40
Slovenia	37	31	20	14	22	15
Croatia	71	83	37	19	37	28
BosniaHerzegovina	415	60	23	24	22	16
FedRepYugoslavia	269	152	83	28	56	54
Macedonia	81	29	16	6	11	10
Total	14718	13526	6795	4362	7635	4735

[a] Remaining former USSR.

emission in any country, and (3) the sensitivity of the receptors to the pollutant.

In the case of deposition this latter sensitivity is expressed in terms of critical loads [14] provided by the Coordinating Centre for Effects at RIVM in the Netherlands, and in the case of concentration it can be expessed in terms of critical levels which are constant across Europe. (These levels may be set to zero if no critical level can be defined, or to a selected standard such as a WHO guideline although none currently exists for particulates.) ASAM uses an iterative approach to identify the most cost-effective way to approach critical loads or levels, or alternatively intermediate target loads selected carefully as interim goals useful for policy makers. It may be set up either to reduce the deposition to the European region or to reduce the concentration of secondary particulates.

The method of optimisation used is to define benefit functions which indicate the advantages of reducing pollutant burdens at receptors. These functions are normally defined as the reduction in exceedance of critical/target loads at receptors. The model then derives a prioritised sequence of abatement steps by comparing the costs and benefits (in terms of reduced exceedance) of abatement options not yet implemented in each country. At each stage in the sequence ASAM selects that abatement step for implementation which gives the highest ratio of benefit to cost.

The benefit functions may be manipulated to reflect different opinions concerning where exceedance of critical loads/levels is the most damaging. For example, in this paper where the model is used to examine reduction of secondary particulates, it is possible to either take

Table 2

Optimised emissions (kT/yr) and costs (M e.c.u./yr) in an ASAM derived abatement strategy to reduce secondary particulate concentrations in the UN ECE region (strategy 1).

Country	SO_2		NO_x		NH_3	
	Cost	Emissions	Cost	Emissions	Cost	Emissions
Albania	11.4	23	14.3	26.6	1.1	32.5
Austria	0	44.7	0.6	86.9	0	77
Belgium	29.4	164.3	112.8	149.4	1.6	78.4
Bulgaria	166	165.9	32.2	243.7	2.8	121.2
Denmark	6.5	60.3	53.7	96.8	0.8	69.8
Finland	0	116	75.6	116.9	1.2	31.3
France	119.8	278.2	331.6	609.9	11.7	647.6
Germany	321.4	525.6	611.3	1006.9	21.1	544
Greece	0	374.9	6.4	320.5	0.6	70.8
Hungary	87.3	306.6	101.4	144	8.5	129
Eire	10.4	73.3	9.9	51	0	126
Italy	125.8	335.5	528.2	849	4.1	359.2
Luxembourg	0	4	4.3	8.4	0	6
The Netherlands	14.2	64.2	122.9	232.8	0	136
Norway	0	34	13.2	130.4	0.2	21.1
Poland	600.6	434.4	413.2	588.3	64	472.2
Portugal	89.9	39.1	104.9	136	0.9	71.2
Romania	165.4	135.3	334.3	245.9	7.4	288.3
Spain	312.3	237.9	317.2	635.1	0	353
Sweden	0	87	57.2	160.1	0	53
Switzerland	0	30	32.4	77.7	1.4	52.1
Turkey	0	354	0	175	0	415
United Kingdom	317.8	423.7	117.5	1050.7	12.7	278.1
Kola/Karelia	138.7	126.4	14.5	54	0.5	3.6
St. Petersburg	50.1	36.6	78.9	90.9	2.8	30.5
Belarus	201.2	63.9	38.9	167.1	3.1	157.2
Ukraine	503.9	402.5	515.1	869.5	17.2	616.5
Moldavia	49	22.3	0	34.1	1	45.6
R.F. USSR	475.9	589.5	1020.3	1451.5	21.1	817.8
Estonia	71.8	25.1	27.4	48.3	1.1	27.4
Latvia	30.6	24.7	18.6	82.2	0.5	28.4
Lithuania	48.4	30.2	49	90	1.8	77.2
Czech Republic	43.8	119.1	73.9	186.5	0	105
Slovakia	30.7	72.8	26.2	100.4	2.1	49.6
Slovenia	8.8	15.4	2.4	29.6	1.2	18.8
Croatia	21.5	24.2	41.6	64.6	0.9	36.1
BosniaHerzegovina	110.1	34.3	40.2	36.4	0.9	21.9
FedRepYugoslavia	179.9	45.8	120.1	87.9	2.3	80
Macedonia	17.2	42.6	1.4	24.6	1.2	13.3
Total	4359.8	5987.4	5463.6	10559.6	197.8	6562

the view that a reduction in particulate levels anywhere is equally beneficial, or to argue that the benefits should reflect the population present in each receptor grid square. In the latter case the human exposure across the whole grid area is taken into account since there is an integration of particulate concentrations weighted by population distribution.

The model produces the resulting emissions ceilings and abatement costs ascribed to each country after specified levels of total expenditure, or on attainment of the environmental targets set. If the latter are not achievable ASAM still indicates how fast and how closely it is possible to converge towards them with increasing expenditure until all abatement options have been implemented.

ASAM has been extensively compared with another optimisation model, RAINS [3,15] and shown to give almost identical results for strategies when exactly the same assumptions are made about target loads for acidification and abatement measures.

4. Abatement strategies designed to cost-effectively reduce human exposure to particulates

Table 1 shows the emissions at the so-called REFERENCE scenario, which is the starting point for the modelling of abatement strategies adopted by the TFIAM at the time of writing. This scenario takes into account the Business-As-Usual Energy Projections for 2010, and then

Table 3
Optimised emissions (kT/yr) and costs (M e.c.u./yr) in an ASAM derived abatement strategy to reduce human exposure to secondary particulates in the UN ECE region (strategy 2).

Country	SO_2		NO_x		NH_3	
	Cost	Emissions	Cost	Emissions	Cost	Emissions
Albania	11.4	23	1.9	32.5	0.5	32.8
Austria	0	44.7	0.6	86.9	0	77
Belgium	125.1	98.2	152.7	140.1	48.5	64
Bulgaria	166	165.9	24.3	249.8	2.8	121.2
Denmark	6.5	60.3	41.6	101.8	0.3	70.2
Finland	0	116	3.5	160.1	0.2	32.2
France	167.1	246.7	354.5	603.2	11.7	647.6
Germany	794.8	416.1	814.3	955.9	402.9	436
Greece	0	374.9	5.1	322.5	0.4	71.1
Hungary	87.3	306.6	107.1	142.2	8.5	129
Eire	10.4	73.3	9.9	51	0	126
Italy	200.1	276.4	538.9	845.9	4.1	359.2
Luxembourg	0.7	3.5	6.9	7.9	0	6
The Netherlands	31	51.2	161.1	222.9	0	136
Norway	0	34	9	134.6	0	21.4
Poland	554.2	471.8	413.2	588.3	64	472.2
Portugal	74.9	50.4	55.7	148.8	0.6	71.5
Romania	139.7	156.5	331.9	246.5	7.4	288.3
Spain	286.8	260	215.6	678	0	353
Sweden	0	87	11.7	183.1	0	53
Switzerland	0	30	47.9	73.7	3.5	51.2
Turkey	0	354	0	175	0	415
United Kingdom	317.8	423.7	807.1	792.9	14	277.3
Kola/Karelia	0	474	0	61.3	0.1	4
St. Petersburg	28.5	68.2	0	120.8	1.3	31.3
Belarus	141.9	104.8	0	179.8	3.1	157.2
Ukraine	501.8	403.7	223.4	982.1	17.2	616.5
Moldavia	49	22.3	0	34.1	1	45.6
R.F. USSR	473.5	593	0	1812.8	21.1	817.8
Estonia	71.5	25.4	5	60.3	0.6	27.6
Latvia	6.4	42.1	0	89.6	0.5	28.4
Lithuania	26.5	45.6	0.4	109.3	1.8	77.2
Czech Republic	51	113.4	126.4	168.6	0	105
Slovakia	30.7	72.8	26.7	100.2	2.2	49.6
Slovenia	8.8	15.4	14.5	25.8	1.2	18.8
Croatia	21.5	24.2	41.6	64.6	0.9	36.1
BosniaHerzegovina	110.1	34.3	40.2	36.4	0.9	21.9
FedRepYugoslavia	179.9	45.8	119.6	88.1	2.3	80
Macedonia	17.2	42.6	1.4	24.6	1.2	13.3
Total	4692	6251.8	4713.5	10902.1	624.8	6441.9

assumes that countries will comply with both Current Reduction Plans and Current Legislation (e.g., EC directives). Figure 5 shows the total concentration of secondary particulates in Europe at the REFERENCE scenario. It is clear that the situation is much improved compared with 1990 (figure 1). Table 1 also shows the emissions at the Maximum Feasible Reductions (MFR) considered possible at the time of writing (according to the cost information provided by IIASA).

ASAM has been set up to reduce particulate concentrations in terms of mass of SO_4, NO_3 and NH_4, since as explained previously the deleterious effects of human exposure to particulates appear to depend upon the mass of the material rather than its nature.

The first model experiment (strategy 1) is simply to reduce the concentration of particulates everywhere as far as possible at minimum cost. Table 2 shows the resulting abatement strategy at a total UN ECE expenditure level of 10 billion e.c.u./yr.

The second model experiment (strategy 2) involves weighting the concentrations by the population distribution, as explained previously, so that the model is aiming to reduce a more precise measure of human exposure to particulates. Table 3 shows the resulting emission pattern, also at a total UN ECE expenditure level of 10 billion e.c.u./yr. Figure 7 shows the resulting concentration of secondary particulates in Europe. It is clear that this represents a considerable improvement over the REFERENCE scenario

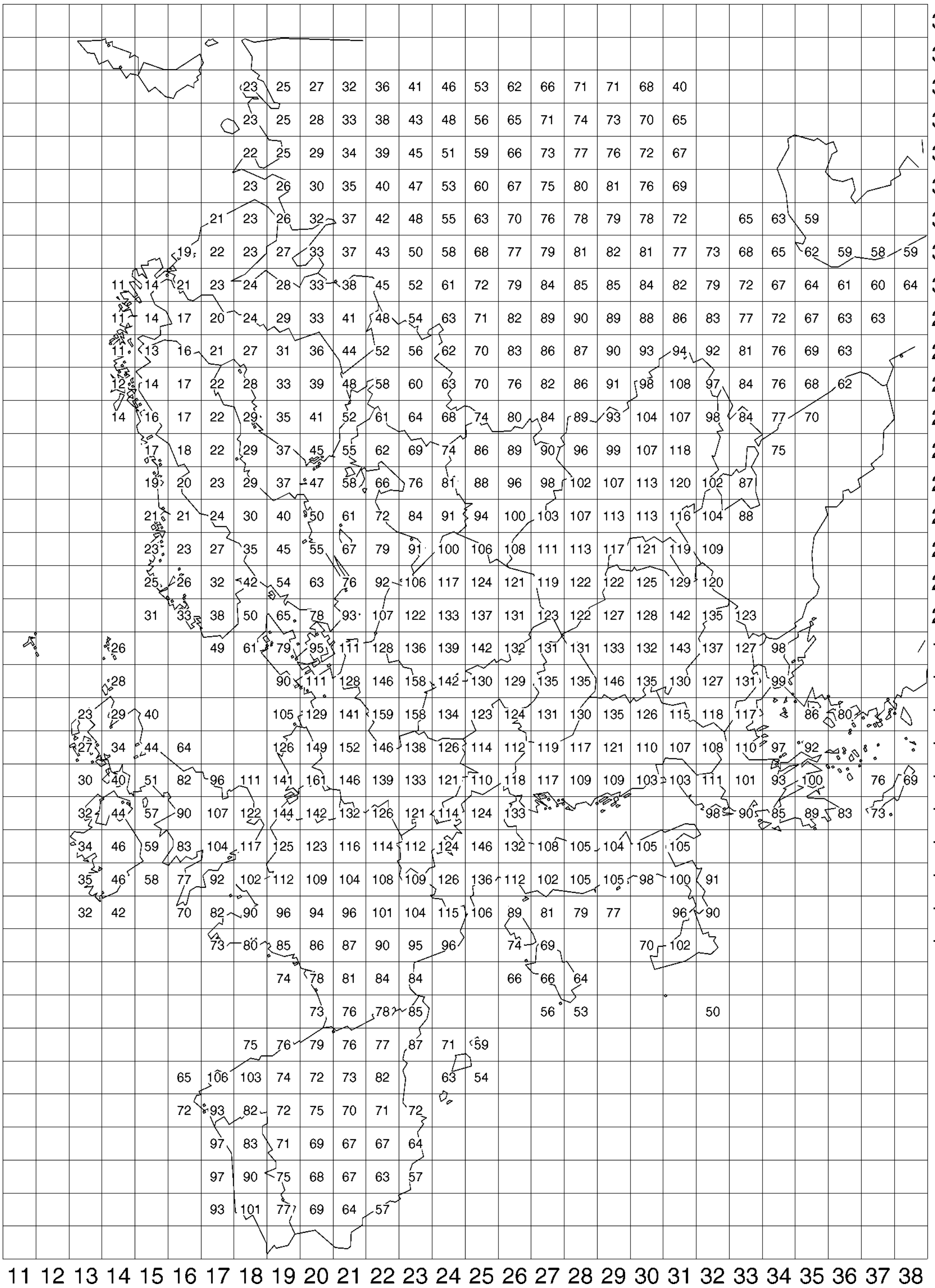

Figure 5. REFERENCE scenario total secondary particulate concentration. Units: 100 $ng(SO_4 + NO_3 + NH_4)\,m^{-3}$.

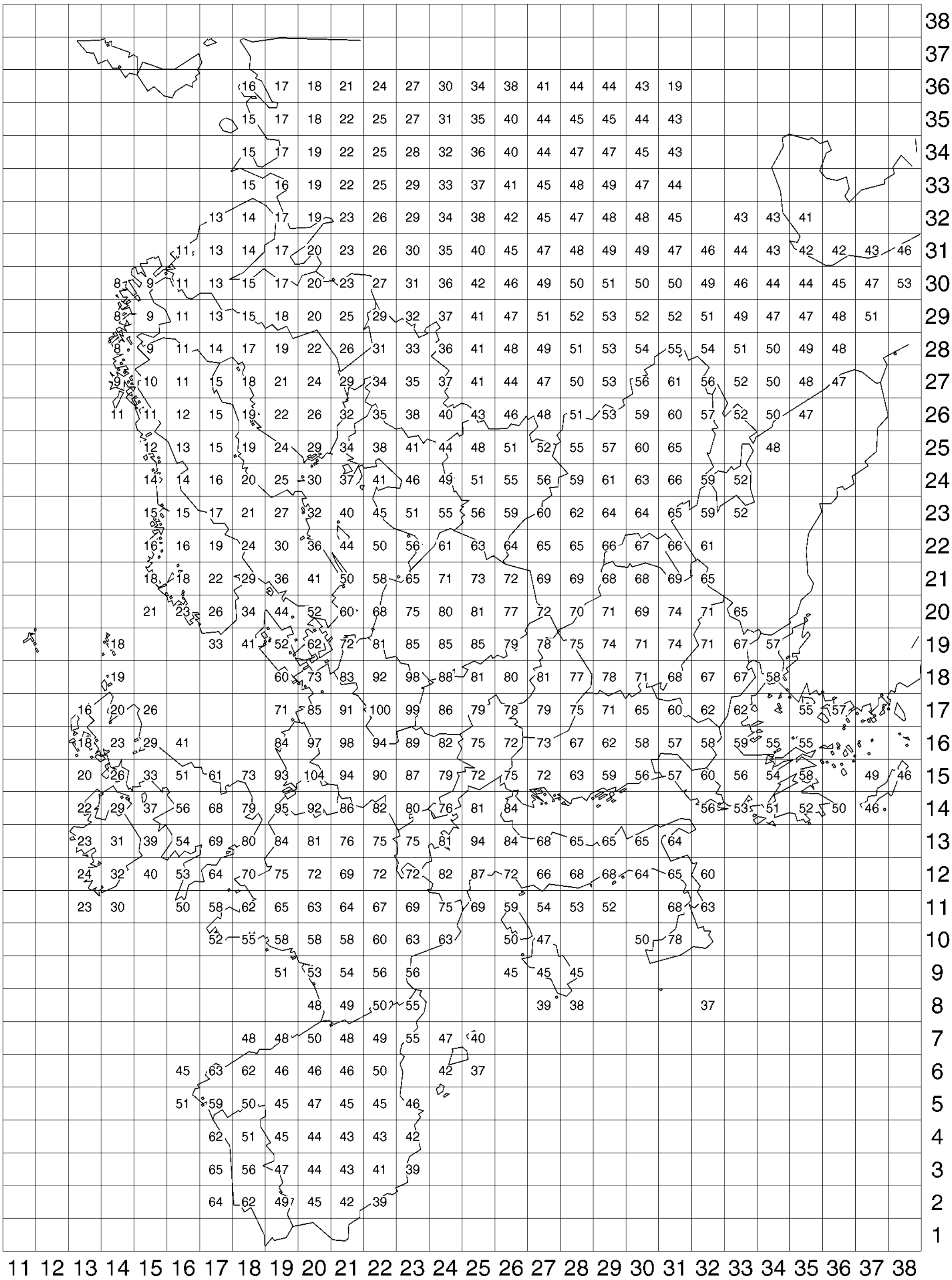

Figure 6. MFR scenario total secondary particulate concentration. Units: 100 $ng(SO_4 + NO_3 + NH_4)\,m^{-3}$.

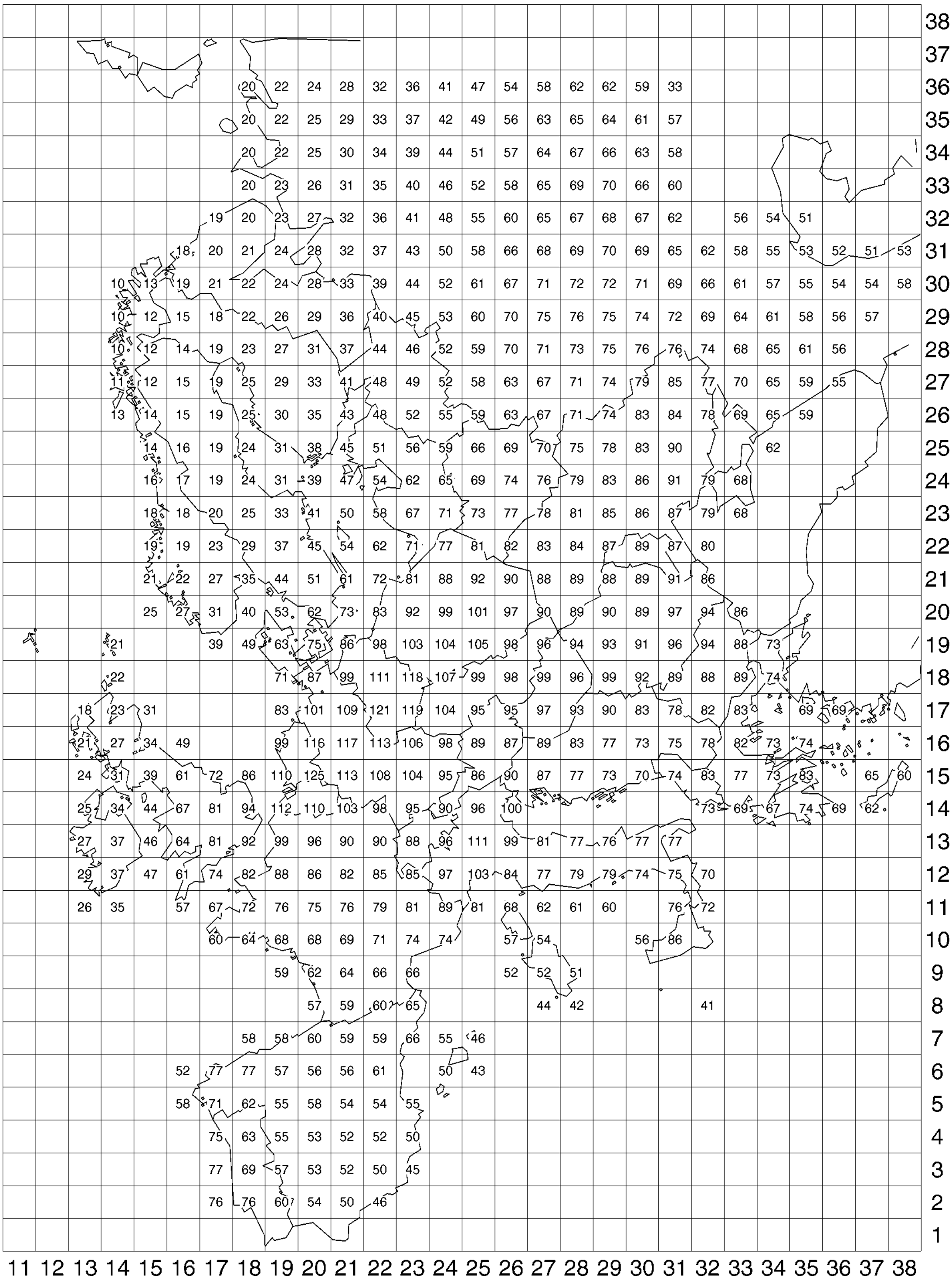

Figure 7. Total secondary particulate concentration under strategy 2, designed to reduce human exposure to particulates, at an overall cost of 10 billion e.c.u./yr. Units: 100 $ng(SO_4 + NO_3 + NH_4)\,m^{-3}$.

Table 4
Optimised emissions (kT/yr) and costs (M e.c.u./yr) in an ASAM derived abatement strategy to reduce human exposure to secondary particulates in the parts of the UN ECE region where concentrations exceed 8 $\mu g\,m^{-3}$ (strategy 3).

Country	SO_2		NO_x		NH_3	
	Cost	Emissions	Cost	Emissions	Cost	Emissions
Albania	11.4	23	14.3	26.6	1.1	32.5
Austria	0	44.7	0.6	86.9	4.4	75.5
Belgium	148.9	85.1	161.4	138.8	54.5	62.7
Bulgaria	166	165.9	32.2	243.7	2.8	121.2
Denmark	6.5	60.3	34.5	105.2	0.3	70.2
Finland	0	116	3.2	160.5	0	32.5
France	167.1	246.7	379.8	597.8	11.7	647.6
Germany	814.8	411.5	916.4	939.9	494.9	415.6
Greece	0	374.9	6.4	320.5	0.6	70.8
Hungary	99.6	298.7	142.5	132.7	8.8	129
Eire	10.1	73.8	9.9	51	0	126
Italy	212.4	267.8	538.9	845.9	14.6	354.3
Luxembourg	0.7	3.5	6.9	7.9	0	6
The Netherlands	31	51.2	190.8	216.9	0	136
Norway	0	34	7.9	136.4	0	21.4
Poland	600.6	434.4	426	583.9	64	472.2
Portugal	30.1	88	46.7	151.9	0.6	71.5
Romania	165.4	135.3	507.8	211.3	19.8	281.7
Spain	135.5	477.5	88.8	743.1	0	353
Sweden	0	87	3	191.6	0	53
Switzerland	0	30	51	73.1	12.1	48.3
Turkey	0	354	0	175	0	415
United Kingdom	378.7	370.7	812.6	791.1	14	277.3
Kola/Karelia	0	474	0	61.3	0	4.2
St. Petersburg	0	138.3	0	120.8	0.4	32.5
Belarus	141.9	104.8	0	179.8	3.1	157.2
Ukraine	447.8	445.1	331	934.7	17.2	616.5
Moldavia	49	22.3	0	34.1	1	45.6
R.F. USSR	0	1758.6	0	1812.8	4.9	840.1
Estonia	0	175.1	2.8	63.1	0.1	28.3
Latvia	6.4	42.1	0	89.6	0.2	28.8
Lithuania	25.3	46.9	0.4	109.3	1.8	77.2
Czech Republic	51	113.4	156.9	159.7	0	105
Slovakia	32.9	71.3	39.9	96.5	2.2	49.6
Slovenia	10.5	14	14.7	25.7	1.2	18.8
Croatia	25.7	21.5	61.4	58.9	0.9	36.1
BosniaHerzegovina	110.1	34.3	52.7	32.7	0.9	21.9
FedRepYugoslavia	189.3	41.5	120.1	87.9	2.3	80
Macedonia	39.4	14.8	1.4	24.6	1.2	13.3
Total	4108.1	7752.2	5162.7	10823.2	741.5	6428.7

(figure 5). Indeed, although MFR, at a total overall cost of 52 billion e.c.u./yr, produces further reductions (figure 6), it is clear that much of the benefit is obtained at a 10 billion e.c.u./yr expenditure level.

Finally, in addition to population weighting, a threshold level of 8 $\mu g\,m^{-3}$ is set implying that the only areas that the model need to attempt to reduce particulates are those areas where the concentration of particulates exceeds 8 $\mu g\,m^{-3}$ at the REFERENCE scenario (i.e., the initial emissions prior to optimisation) (strategy 3). This reflects a need to concentrate on the areas where the secondary particulate contributes a significant proportion of the limits set for total particulate exposure. (In this context future work may need to take more specific account of episodes in excess of a threshold rather than total annual exposure – more analogous to the approach taken with ozone.) Table 4 shows the results.

5. An abatement strategy designed to cost-effectively reduce acidification of ecosystems

The ASAM model has traditionally been used for the purposes of reducing acidification and/or eutrophication in a cost-effective manner. Table 5 shows the emissions resulting from an optimisation (strategy 4), beginning again at the REFERENCE scenario, in which acidifcation is reduced to a specially defined target load. The target load selected is one of those currently (i.e., at the time of writing) under investigation in the UN ECE task force on

Table 5
Optimised emissions (kT/yr) and costs (M e.c.u./yr) in an ASAM derived abatement strategy to reduce acidification of ecosystems to a target load defined as the 90% gap closure in accumulated exceedance: total cost 10 billion e.c.u./yr (strategy 4).

Country	SO_2		NO_x		NH_3	
	Cost	Emissions	Cost	Emissions	Cost	Emissions
Albania	0.6	52.4	0	36.3	0	33.7
Austria	0	44.7	0	87.2	0	77
Belgium	164.8	79.3	129.6	144.9	60.2	61.6
Bulgaria	56.5	448.4	0	290.3	0	125.4
Denmark	98	21.6	81.3	91.8	362.7	46.4
Finland	84.4	73.4	111.4	104.4	22	27.6
France	194.2	230.7	64	734.3	28.6	640.2
Germany	304.3	530.8	465.9	1047.2	1169.2	350.1
Greece	0	374.9	0	338.6	0	72.3
Hungary	99.6	298.7	2.9	190.6	8.8	129
Eire	56.4	37.1	45.7	39.1	195.1	107.3
Italy	298.4	226.8	204.8	989.3	420.7	297.6
Luxembourg	0.7	3.5	1.4	9.3	0	6
The Netherlands	55.8	45.3	190.8	216.9	190.3	117
Norway	38	20.2	134.3	108.8	61.9	17.3
Poland	563.4	464.3	187.3	681.8	65.5	471.7
Portugal	0	150.9	1.4	186.6	0	72.5
Romania	133.6	165.9	5.1	425.8	0	300
Spain	0	801.6	3.5	871.4	0	353
Sweden	124.5	61.4	101.7	146.7	46.1	49
Switzerland	67.3	14.7	41.7	75.1	104	42.3
Turkey	0	354	0	175	0	415
United Kingdom	541.2	300.2	935.8	764	227.2	237.5
Kola/Karelia	185.3	89.2	17.5	52.7	0.5	3.6
St. Petersburg	50.1	36.6	0	120.8	1.3	31.3
Belarus	136.2	115	0	179.8	0	162.8
Ukraine	309.8	670.8	0	1094.5	0	649
Moldavia	62	19.3	0	34.1	0	47.6
R.F. USSR	0	1758.6	0	1812.8	0	855.6
Estonia	81	18.7	28.6	47.8	6.5	25.6
Latvia	6.4	42.1	0	89.6	7.9	26
Lithuania	25.3	46.9	0	109.7	3.1	76.6
Czech Republic	51	113.4	53.2	194.9	0	105
Slovakia	32.9	71.3	0	112.7	29.4	44.7
Slovenia	8.8	15.4	0	30.6	0.6	19.1
Croatia	19.7	25.7	0	83.2	0.2	36.7
BosniaHerzegovina	34.5	228.5	0	59.6	0.2	22.5
FedRepYugoslavia	0	268.7	0	152.1	0	82.7
Macedonia	0	81.2	0	28.6	0	15.4
Total	3884.6	8402.1	2807.6	11959.1	3012	6253.8

integrated assessment modelling. These targets are commonly defined by calculating a particular measure of acidification for the 1990 situation, and seeking to reduce this quantity by a certain percentage. The targets thus derived are known as "gap-closure" targets. The measure used to quantify the level of acidification in this case is the "accumulated exceedance" [16]. (The selection of such gap closure targets and their implications is being published elsewhere [17].)

The 90% accumulated exceedance gap closure target is achieved at a total cost to the UN ECE of 10 billion e.c.u./yr and the results of the optimisation are therefore directly comparable with tables 2 to 4, which correspond to the same total UN ECE expenditure of 10 billion e.c.u./yr.

6. Comparison of strategies to reduce acidification or particulate exposure

A comparison of the distribution of emission and reductions and costs for two strategies with different aims (either (a) to reduce acidification or (b) to reduce human exposure to secondary particulates) but with the same overall cost to Europe, is now possible since both strategies 2 and 4 require the same total investment of 10 billion e.c.u./yr.

There is a 26% decrease in S emissions in the particulate strategy relative to the acidification strategy; and a 9% decrease in NO_x emissions; whilst there is a 3% increase in NH_3 emissions. The reason for this is that the human exposure to particulates is measured in terms of persons exposure to unit mass of pollutant, and thus SO_4, being the

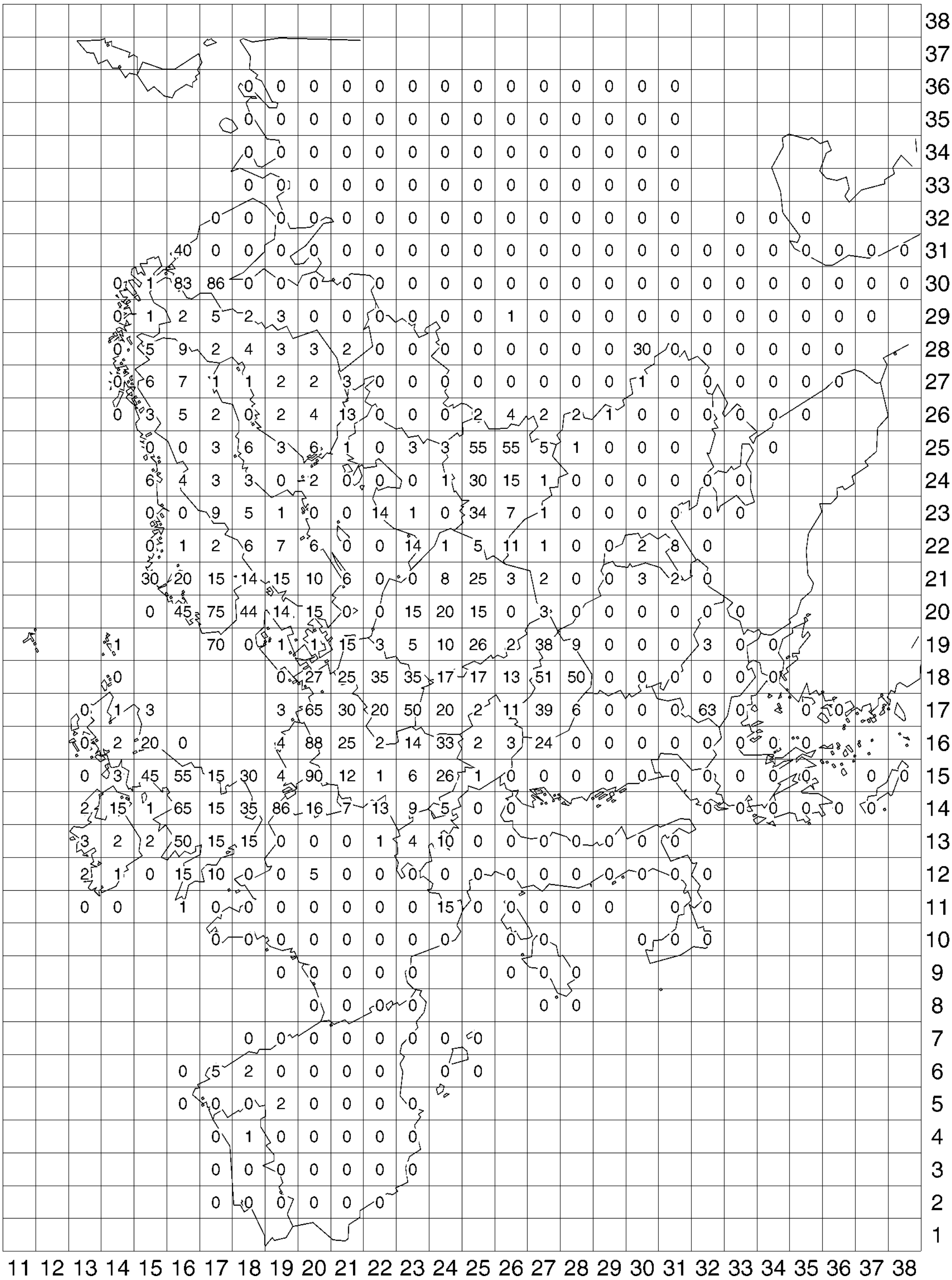

Figure 8. % ecosystem areas unprotected from acidification at the REFERENCE scenario.

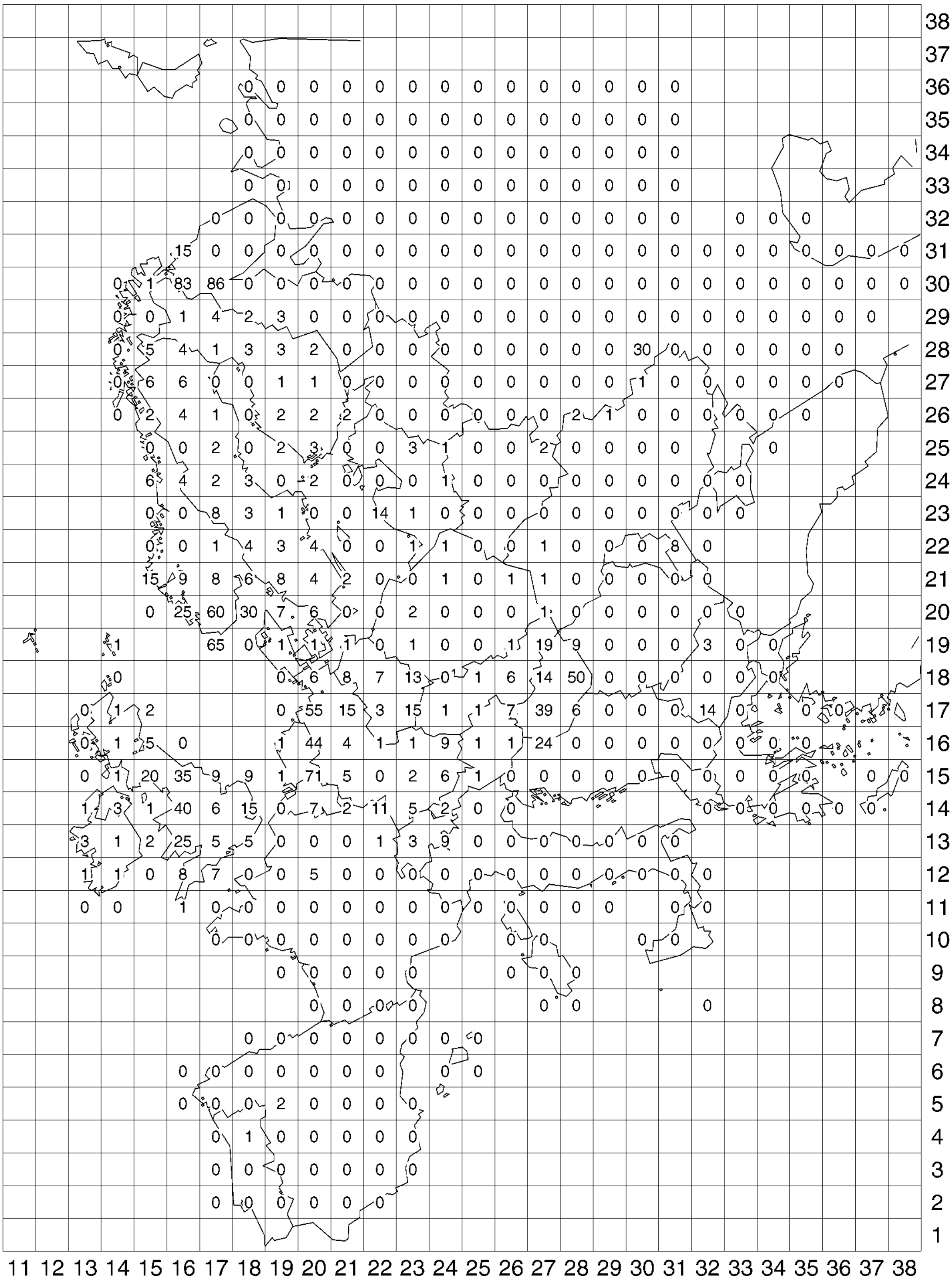

Figure 9. % ecosystem areas unprotected from acidification under strategy 2, designed to reduce human exposure to particulates, at an overall cost of 10 billion e.c.u./yr.

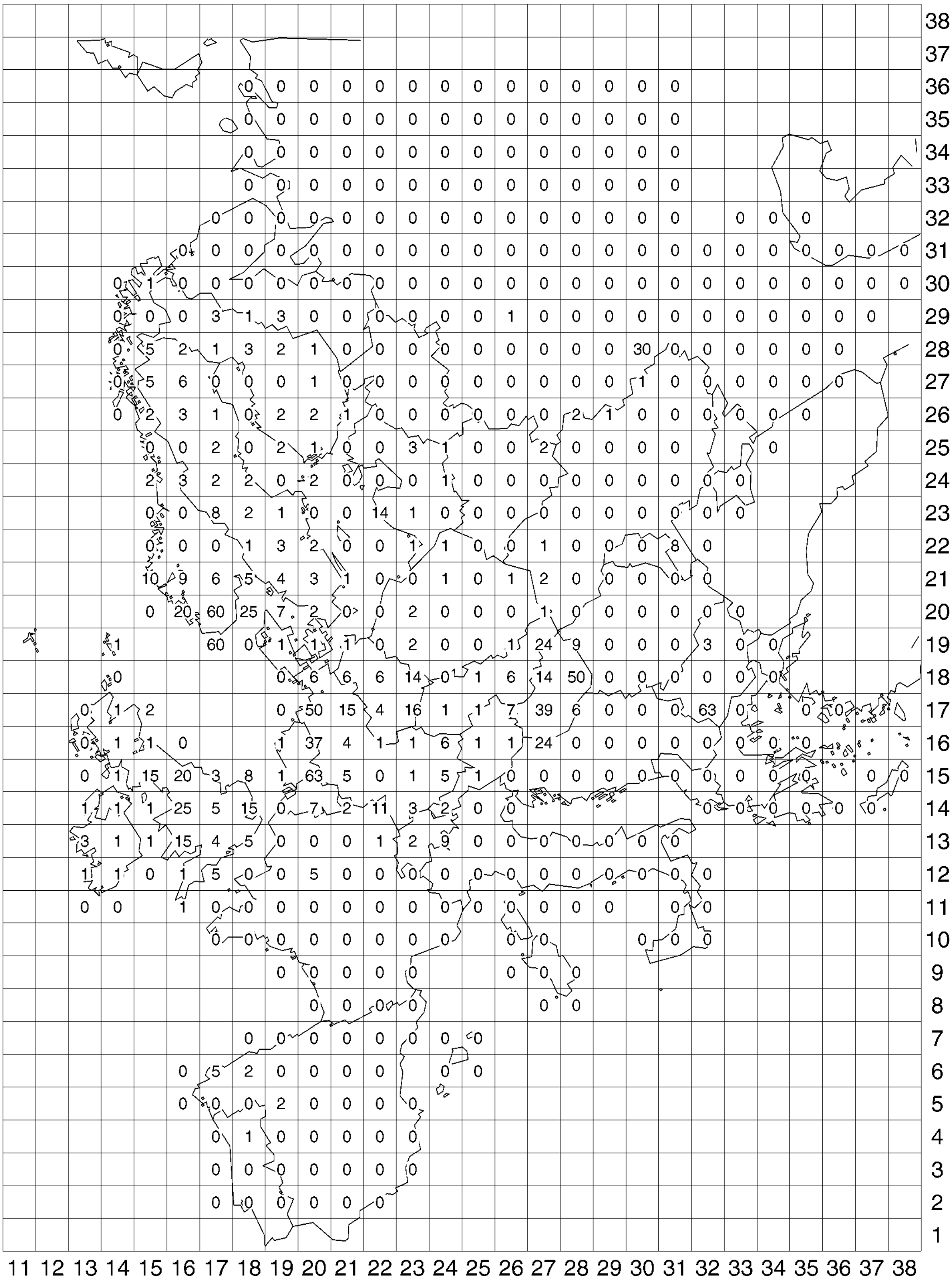

Figure 10. % ecosystem areas unprotected from acidification under strategy 4, designed to reduce acidification, at an overall cost of 10 billion e.c.u./yr.

Table 6
Differences between country emissions in optimised abatement strategies designed to reduce acidification of ecosystems or exposure to secondary particulates. [a]

Country	Strategy								
	2 (KT/yr)			2 (%)			1 (%)		
	SO_2	NO_x	NH_3	SO_2	NO_x	NH_3	SO_2	NO_x	NH_3
Albania	−29	−4	−1	−56	−10	−3	−56	−27	−4
Austria	0	0	0	0	0	0	0	0	0
Belgium	19	−5	2	24	−3	4	107	3	27
Bulgaria	−283	−41	−4	−63	−14	−3	−63	−16	−3
Denmark	39	10	24	179	11	51	179	5	50
Finland	43	56	5	58	53	17	58	12	13
France	16	−131	7	7	−18	1	21	−17	1
Germany	−115	−91	86	−22	−9	25	−1	−4	55
Greece	0	−16	−1	0	−5	−2	0	−5	−2
Hungary	8	−48	0	3	−25	0	3	−24	0
Eire	36	12	19	98	30	17	98	30	17
Italy	50	−143	62	22	−14	21	48	−14	21
Luxembourg	0	−1	0	0	−15	0	14	−10	0
The Netherlands	6	6	19	13	3	16	42	7	16
Norway	14	26	4	68	24	24	68	20	22
Poland	8	−94	1	2	−14	0	−6	−14	0
Portugal	−101	−38	−1	−67	−20	−1	−74	−27	−2
Romania	−9	−179	−12	−6	−42	−4	−18	−42	−4
Spain	−542	−193	0	−68	−22	0	−70	−27	0
Sweden	26	36	4	42	25	8	42	9	8
Switzerland	15	−1	9	104	−2	21	104	3	23
Turkey	0	0	0	0	0	0	0	0	0
United Kingdom	124	29	40	41	4	17	41	38	17
Kola/Karelia	385	9	0	431	16	11	42	2	0
St. Petersburg	32	0	0	86	0	0	0	−25	−3
Belarus	−10	0	−6	−9	0	−3	−44	−7	−3
Ukraine	−267	−112	−33	−40	−10	−5	−40	−21	−5
Moldavia	3	0	−2	16	0	−4	16	0	−4
R.F. USSR	−1166	0	−38	−66	0	−4	−66	−20	−4
Estonia	7	13	2	36	26	8	34	1	7
Latvia	0	0	2	0	0	9	−41	−8	9
Lithuania	−1	0	1	−3	0	1	−36	−18	1
Czech Republic	0	−26	0	0	−13	0	5	−4	0
Slovakia	2	−13	5	2	−11	11	2	−11	11
Slovenia	0	−5	0	0	−16	−2	0	−3	−2
Croatia	−2	−19	−1	−6	−22	−2	−6	−22	−2
BosniaHerzegovina	−194	−23	−1	−85	−39	−3	−85	−39	−3
FedRepYugoslavia	−223	−64	−3	−83	−42	−3	−83	−42	−3
Macedonia	−39	−4	−2	−48	−14	−14	−48	−14	−14
Total	−2150	−1057	188	−26	−9	3	−29	−12	5

[a] Note: percentages are expressed relative to the emission levels present in the optimised acidification abatement strategy. Thus a positive figure indicates that country emissions are reduced less in strategy 2, particulate exposure, than in strategy 4, acidification.

most massive secondary aerosol component, is the most damaging, closely followed by NO_3, whilst NH_4 is less significant.

The change in the distribution of emissions between countries is dramatic (table 6). Within countries the large and significant changes in terms of emission levels are seen. In Bulgaria, Germany, Portugal, Spain, and Ukraine, larger emission reductions of both NO_x and SO_2 are required for the particulates strategy than for the acidification strategy; whilst the United Kingdom and Scandinavian countries require a smaller emission cut. In percentage terms the largest differences are in Scandinavia, Eire, Switzerland, and the former USSR, though the emission levels in some of these countries are rather small. In countries such as France, Italy, Poland, and Romania, the picture is more mixed, with increasing emphasis on particulate reduction implying greater reduction in NO_x and a smaller reduction in SO_2. The additional commitments on NO_x and SO_2 are a trade-off against the relaxed commitments for NH_3 reduction, especially in Scandinavia, Eire, Italy, Germany, the Netherlands, and the UK.

Table 6 also includes the % changes in emissions for strategy 1 which reduces particulate levels everywhere rather than taking human population distribution into account. This results in a similar shift of emission ceilings to strategy 2, except that the shifts of emphasis when com-

Table 7
Levels of human exposure to particulates in three strategies aiming to reduce particulates, and one acidification strategy compared with the situation at the REFERENCE scenario. [a]

Region	Particulate			Acidification	Reference
	Strategy 1	Strategy 2	Strategy 3	strategy 4	scenario
Total particulate					
Total EU	3314	3156	3151	3349	4082
Total UNECE	5578	5480	5495	5935	7108
Sulphate					
Total EU	649	612	616	668	939
Total UNECE	1188	1150	1202	1317	1883
Nitrate					
Total EU	2032	1947	1947	2136	2493
Total UNECE	3271	3257	3229	3601	4069
Ammonium					
Total EU	633	597	589	544	650
Total UNECE	1119	1150	1064	1016	1155

[a] Units: person g.

Table 8
Percentages of ecosystems remaining unprotected from acidification in three strategies aiming to reduce particulates, and one acidification strategy compared with the situation at the REFERENCE scenario.

Country	Particulate			Acidification	Reference
	Strategy 1	Strategy 2	Strategy 3	strategy 4	scenario
Austria	1.7	1.6	1.6	1.6	3.3
Belgium	19.8	19.8	19.8	19.8	21.5
Denmark	0.7	0.7	0.7	0.7	0.9
Finland	1.9	3.2	3.8	1.8	4.8
France	0.6	0.5	0.5	0.5	1.6
Germany	11.9	7.2	6.7	6.7	19.8
Greece	0	0	0	0	0
Eire	1.5	1.5	1.5	1.5	2.3
Italy	0	0	0	0	0.1
Luxembourg	15	15	15	15	15
The Netherlands	47.7	29.7	27.6	18.1	62.7
Portugal	0.3	0.3	0.3	0.3	0.3
Spain	0	0	0.1	0.3	0.3
Sweden	3.6	3.6	3.7	2.8	5.8
United Kingdom	10.4	9.4	8.9	6.2	18.7
Albania	0	0	0	0	0
Bulgaria	4.2	4.2	4.2	18.5	18.5
Hungary	34.2	34.2	34.2	34.2	59.7
Norway	8.3	8.2	8.2	6.7	11.9
Poland	0.5	0.4	0.4	0.5	8.4
Romania	0	0	0	0	0
Switzerland	9.7	9.7	9.7	9.2	9.8
Belarus	0.1	0.1	0.1	0.1	23.9
Ukraine	0.1	0.1	0.1	0.2	0.7
Moldova	1	1	1	1	3.2
R.F. USSR	0.2	1.4	1.5	0.2	1.6
Estonia	0	0	0	0	0
Latvia	3.3	3.3	3.3	3.3	3.3
Lithuania	0	0	0	0	0
Czech Republic	7.5	3.4	3.2	3.4	31.3
Slovakia	0	0	0	0	0
BosniaHerzegovina	0	0	0	0	0
FedRepYgoslavia	0	0	0	0	0
Macedonia	0	0	0	0	0
Total EU	1.4	2.1	2.1	1.2	3.7
Total UNECE	3.2	3.0	3.1	2.3	5.7

Table 9
Country contributions to human exposure to secondary particulates at the REFERENCE scenario. [a]

Country	ECE				EU			
	All	SO_4	NO_3	NH_4	All	SO_4	NO_3	NH_3
Albania	12.2	3.1	5.1	4	5.5	1.4	2.3	1.8
Austria	47.1	3.3	26.4	17.4	29.8	2.1	16.4	11.4
Belgium	166.1	29.7	105.9	30.4	149.2	26.5	94.5	28.2
Bulgaria	81.9	37.9	33.3	10.7	24	12.3	8.7	3
Denmark	34.1	3.6	24.8	5.8	20.7	2.2	14.7	3.8
Finland	19.2	2.9	14.4	1.9	5.8	0.9	4.1	0.7
France	493	67.1	313.1	112.8	441.8	60	278.8	102.9
Germany	1077.2	264.1	605.7	207.3	810.3	177.1	472.5	160.7
Greece	45.8	12.9	27.5	5.4	30.7	8.9	18.1	3.7
Hungary	148.2	57.5	57.4	33.2	39.3	16	14.9	8.4
Eire	22.8	4.8	10.8	7.2	21.4	4.5	10.2	6.8
Italy	511.8	58.5	386.6	66.7	419.9	47.5	316	56.4
Luxembourg	8.4	0.6	5.5	2.2	7.5	0.6	4.9	2
The Netherlands	169.8	11.3	122.7	35.8	149.1	10	107.1	32
Norway	12.1	0.5	10.8	0.7	7	0.3	6.2	0.4
Poland	424	131.3	199.2	93.6	112.3	37.4	52.2	22.7
Portugal	73.9	11.1	57.5	5.3	73.3	11.1	57	5.3
Romania	270.3	45.2	182.7	42.5	35.8	6.2	24.5	5
Spain	253.6	46.6	175.3	31.7	245	44.9	169.2	30.9
Sweden	28.1	2.5	21.8	3.9	13.9	1.2	10.4	2.2
Switzerland	55	3.3	38.4	13.2	45.2	2.7	31.6	10.9
Turkey	15.9	5.9	4.9	5.1	3.2	1.2	1.1	0.9
United Kingdom	476.8	95.7	316.8	64.3	439.2	87.6	290.3	61.3
Kola/Karelia	8.1	5.7	2.1	0.2	1.7	1.3	0.4	0
St. Petersburg	25.4	5.7	16.6	3.1	2.3	0.6	1.4	0.3
Belarus	86.7	36	35.5	15.3	9.3	3.6	3.9	1.7
Ukraine	369.4	104.3	195.9	69.2	22	6.3	11	4.7
Moldavia	21.3	9.9	6.9	4.5	1.4	0.7	0.3	0.3
R.F. USSR	402.1	70.4	270.5	61.3	9.7	2	6.5	1.2
Estonia	17.8	8.4	7	2.4	2.8	1.3	1.1	0.5
Latvia	18.6	3.5	12.8	2.4	2.7	0.5	1.8	0.3
Lithuania	33.8	8	18.6	7.2	5.7	1.4	3.1	1.2
Czech Republic	122.2	21.6	68.9	31.7	61.5	11.7	34.9	14.8
Slovakia	60.4	12.5	34.7	13.2	16.5	3.6	9.4	3.5
Slovenia	16.7	3.3	9.1	4.2	10.8	2.2	5.9	2.7
Croatia	37.6	7.9	22.1	7.7	17	3.9	9.9	3.2
BosniaHerzegovina	61.4	42.5	14.1	4.8	20.9	14.4	5.1	1.5
FedRepYugoslavia	89.7	33.3	40.4	15.9	20	8	8.7	3.3
Macedonia	6.7	3.3	2.3	1.1	2.4	1.3	0.6	0.5
Background [b]	1284	608	565.8	110.3	746.1	313.6	383.1	49.4
Total	7109.2	1883.7	4069.9	1155.6	4082.7	939	2492.8	650.5

[a] Units: person g/yr.
[b] The background emissions include natural emissions from the sea, emissions from shipping, emissions from outside the EMEP grid such as North America, and emission from the EMEP Remaining Unallocated Land Areas, which are defined as Georgia, Kasakhstan, and the part of N. Africa within the EMEP grid [8].

pared with strategy 4 are rather more significant, with the exception of Germany. Interestingly the UK NO_x ceiling is highest in this scenario than in any of the others investigated.

Finally, strategy 3 which reduces human exposure only in areas where the REFERENCE scenario concentration of secondary particulates exceeds 8 $\mu g\,m^{-3}$, results in a similar pattern of NO_x and NH_3 emission ceilings to strategy 2, but there are some significant differences for SO_2. This is to be expected since SO_4 is the most massive secondary particulate component. For example, there is a more stringent emission limit on the UK and Polish SO_2 emissions, whilst the limits in the former USSR and Spain are much less stringent. This is fairly obvious because those countries are far from the central European region, where the particulate concentrations are high, whilst the UK and Poland are close to/upwind of such areas.

7. Benefits of the abatement strategies in terms of ecosystem protection and reduction in human exposure to particulates

The country emissions resulting from the different types of abatement strategies have been examined in detail. It is now of primary importance to assess the benefits of the

Table 10
Country contributions to acid deposition at the REFERENCE scenario. [a]

Country	ECE				EU			
	All	S	N(ox)	N(r)	All	S	N(ox)	N(r)
Albania	1.3	0.4	0.1	0.8	0.5	0.1	0.1	0.2
Austria	2.8	0.4	0.5	1.9	2.1	0.3	0.2	1.6
Belgium	6	2.3	1.5	2.2	5.2	2	1.1	2
Bulgaria	9.7	5.9	1.2	2.7	2.9	2.1	0.3	0.5
Denmark	3.6	0.8	0.9	1.8	2.6	0.6	0.5	1.6
Finland	3	1.2	1	0.8	1.9	0.8	0.5	0.7
France	27.8	5.8	5.5	16.5	25.3	5.1	4.5	15.7
Germany	31.9	8.6	8.7	14.6	23.2	5.3	5.4	12.5
Greece	4.5	2	1	1.5	3.5	1.5	0.6	1.3
Hungary	10.9	6.1	1.4	3.4	1.7	1	0.3	0.5
Eire	4.3	0.8	0.4	3.1	4	0.7	0.3	2.9
Italy	19.2	5.2	5.7	8.4	16	4.2	4.1	7.8
Luxembourg	0.3	0.1	0.1	0.1	0.2	0	0.1	0.1
The Netherlands	6.6	1	2.1	3.5	5.5	0.9	1.5	3.1
Norway	1.5	0.3	0.7	0.5	0.7	0.2	0.4	0.2
Poland	33.8	14.9	5.8	13	5.8	2.8	1.3	1.7
Portugal	3.4	0.9	0.8	1.7	3.3	0.9	0.8	1.7
Romania	14.8	5.4	2.5	6.8	1.1	0.5	0.4	0.3
Spain	16.8	5.8	3.9	7.1	16	5.4	3.6	7
Sweden	3.7	0.9	1.2	1.6	2.7	0.7	0.7	1.3
Switzerland	2.3	0.4	0.5	1.4	1.5	0.3	0.4	0.9
Turkey	2.2	0.8	0.3	1.1	0.6	0.3	0.1	0.3
United Kingdom	24.9	9.3	7.1	8.5	21.2	8	5.3	7.9
Kola/Karelia	4	3.6	0.3	0.1	1.7	1.6	0.1	0
St. Petersburg	3.3	1.6	0.9	0.8	0.5	0.3	0.2	0.1
Belarus	6.4	5.1	1.2	0.1	0.5	0.4	0.1	0
Ukraine	26.1	18.1	7.7	0.4	1.1	0.7	0.5	0
Moldavia	2.4	1.1	0.2	1.1	0.1	0.1	0	0
R.F. USSR	37.5	12.9	8	16.6	0.8	0.3	0.3	0.2
Estonia	3.2	1.9	0.5	0.8	0.9	0.5	0.2	0.2
Latvia	2	0.4	0.4	1.2	0.3	0.1	0.1	0.1
Lithuania	3.2	0.7	0.3	2.2	0.3	0.1	0.1	0.2
Czech Republic	6	1.9	1.7	2.4	2.2	0.8	0.6	0.8
Slovakia	3.3	1.3	0.8	1.3	0.7	0.2	0.2	0.3
Slovenia	0.9	0.3	0.1	0.5	0.6	0.2	0.1	0.3
Croatia	2.1	0.8	0.6	0.7	0.6	0.2	0.2	0.1
BosniaHerzegovina	4.3	3.5	0.3	0.5	0.8	0.7	0.1	0
FedRepYugoslavia	5.3	2.6	0.9	1.9	0.7	0.4	0.2	0.1
Macedonia	0.9	0.5	0.1	0.3	0.4	0.2	0	0.2
Background [b]	47.4	26.8	14.3	6.3	24.8	14.2	8.4	2.3
Total	393.6	162.4	91.2	137.5	184.5	64.7	43.9	76.7

[a] Units: keq H^+/ha/yr N(ox) = as oxidised N, N(r)= as reduced N.
[b] The background emissions include natural emissions from the sea, emissions from shipping, emissions from outside the EMEP grid such as North America, and emission from the EMEP Remaining Unallocated Land Areas, which are defined as Georgia, Kasakhstan, and the part of N. Africa within the EMEP grid [8].

proposed strategies in terms of their impact on both the levels of human exposure to secondary particulates (table 7) and also to what extent the acidification of ecosystems is ameliorated (table 8).

Strategies aimed at reducing particulate levels do so more efficiently than the acidification strategy, by about 500 person g pollutant per year. An acidification strategy provides about 72% of the benefit that a straight particulate strategy would provide in terms of human exposure reduction. Not surprisingly, amongst the particulate strategies the population-weighted run is most efficient in terms of reduction of human exposure.

Correspondingly, strategies aimed at reducing acidification to ecosystems do so more effectively than the particulate strategies. The population weighted particulate strategy reduced ecosystems unprotected from acidification from 5.7 to 3.0%, compared to 2.3% for the acidification run. Thus the population weighted particulate strategy supplies between 70 and 80% of the benefit to acidifying ecosystems, and vice versa. The ecosystem areas which are protected less by the particulate strategy are in the UK, the Netherlands, Scandinavia, and Switzerland. Figures 8–10 show in detail the % ecosystems protected on a grid square basis at the REFERENCE scenario, for the popula-

Table 11
(a) "Blame" matrix for human exposure to particulate as a function of abatement strategy type, showing only the 12 countries with the highest UN ECE contribution (figures show human exposure to secondary particulate in person g/yr).

Scenario	Reference		Strategy 1		Strategy 4
UN ECE expenditure	0		10 billion DM/yr		10 billion DM/yr
Germany	1077	Germany	783	Germany	837
Italy	512	France	370	France	417
France	493	Italy	366	R.F. USSR	402
UK	477	R.F. USSR	353	Italy	396
Poland	424	UK	313	Ukraine	312
R.F. USSR	402	Poland	272	Poland	294
Ukraine	369	Ukraine	270	UK	285
Romania	270	Spain	180	Spain	250
Spain	254	Romania	151	Romania	225
The Netherlands	170	The Netherlands	136	The Netherlands	128
Belgium	166	Belgium	111	Hungary	119
Hungary	148	Hungary	105	Belgium	110

(b) "Blame" matrix for acid deposition as a function of abatement strategy type, showing only the 12 countries with the highest UN ECE contribution (figures show acid deposition in keq $H+/ha/yr$).

Scenario	Reference		Strategy 1		Strategy 4
UN ECE expenditure	0		10 billion DM/yr		10 billion DM/yr
R.F. USSR	37	R.F. USSR	28	R.F. USSR	37
Poland	34	Germany	23	France	23
Germany	32	France	23	Germany	23
France	28	Poland	21	Poland	22
Ukraine	26	UK	17	Spain	17
UK	25	Italy	15	Ukraine	16
Italy	19	Ukraine	12	UK	14
Spain	17	Spain	12	Italy	13
Romania	15	Romania	9	Romania	11
Hungary	11	Hungary	8	Hungary	8
Bulgaria	10	The Netherlands	6	Bulgaria	7
The Netherlands	7	Czech Republic	5	FedRepYugoslavia	5

tion weighted particulate strategy and for the acidification strategy.

8. Country contributions to the levels of particulate exposure and acid deposition

In an attempt to understand how source apportionment changes as a result of the abatement strategies, the contribution made by each country to human exposure to particulates, and to the total amount of acid deposition, were calculated, for the REFERENCE scenario and for each strategy. The figures shown in tables 9 and 10 apply to the REFERENCE scenario, i.e., the point from which all optimisations begin. Table 11 (a) and (b) (first two columns) show, for the REFERENCE scenario, the 12 countries to which the highest contributions can be attributed.

It is clear that some countries are responsible for large amounts of pollution both in terms of secondary particulates and acid deposition (Germany, France, UK, Poland) whilst other countries play a less significant role (Estonia, Sweden, Slovakia, etc.). However, there are also significant differences in source apportionment for acid deposition and for secondary particulate exposure; for example the remaining former USSR (i.e., that part of the former USSR not included in other listed countries) plays a much stronger role in particulate exposure than in acid deposition.

The last four columns of table 11 (a) and (b) show how the situation changes upon application of optimised abatement strategies. In general the major "players" are still the same even after an expenditure of 10 billion e.c.u./yr, although there are some significant shifts in source apportionment.

9. Summary and conclusions

This modelling study has compared a number of abatement strategies to reduce two different adverse effects, human exposure to secondary particulates, and acidification of ecosystems. Until now the latter have been the main driving force behind the modelling of suitable abatement strategies for Europe. Since the economic benefits of reducing human exposure to secondary particulates are very high, it is important to examine the nature of a strategy designed specifically to do so. The modelling results have been derived using the Abatement Strategies Assessment Model, ASAM. The scenarios to reduce exposure are based on the assumption that the adverse effects to human health relate to the concentration to which a person is exposed in g m^{-3}, regardless of the type of aerosol concerned. Thus the total exposure at a receptor is obtained by summing the atmospheric concentrations of SO_4, NO_3 and NH_4 at the receptor.

Five scenarios are presented:

(1) the REFERENCE scenario;

(2) scenario designed to reduce particulate concentrations;

(3) a scenario to reduce human exposure to particulates;

(4) a scenario to reduce human exposure to particulates in areas where concentrations are especially high;

(5) a scenario to reduce acidification of ecosystems using the accumulated exceedance approach.

Table 6 illustrates that scenarios aimed at reducing particulate burdens and human exposure (the most beneficial consequences of emission reductions according to studies undertaken for UN ECE Task Force on Economic Aspects of Abatement Strategies (TFEAAS)), give some significantly different emphasis to specific countries and pollutants as compared with scenarios derived for protection of ecosystems from acidification. On a European scale, there is less emphasis on reductions in ammonia emissions when considering particulates, whilst there is more emphasis on reducing SO_2 and NO_x. The situation for individual countries, however, is more complex than this. In particular, less emission reductions are implied in the UK when considering particulates, especially for SO_2; whilst more emission reductions are implied for SO_2 and NO_x in Germany. At the same time, less emission reductions are implied for NH_3 in Germany. Southern Europe (Spain, Portugal) are required to reduce emissions further in a particulate strategy; whilst Scandinavian countries are required to do less. In Central and Eastern Europe (e.g., Poland, Czech Republic) and also Italy, NO_x reductions become more important.

The summary of the scenarios (table 7) shows that strategies aimed at reducing population exposure to secondary particulates also provide considerable benefits to acidifying ecosystems, and vice versa. In particular, some 3% ecosystems remain unprotected in the UN ECE region, as compared with 2.3% for the scenario aimed at reducing acidification; whilst a further 500 person g human exposure to particulates are removed.

Table 9 is actually a "blame matrix" for human exposure to secondary particulates in Europe at the REFERENCE scenario. It highlights Germany as the major contributor to human exposure to secondary particulates in Europe, with Italy, the UK, Poland, and the former USSR also being large contributors. In all cases nitrate is the largest component, in spite of the fact that SO_4 is more massive. This highlights the increasingly important role played by N emissions in Europe. The nature of the abatement strategy to reduce human exposure can be seen to relate well to this table, since those countries with the highest levels of "blame" are the same countries which are implicated in the abatement strategy. In actual fact, an important component of the damage to human health will occur during episodes. Blame matrices for episodes might look rather different, although currently such information is not readily available.

Table 10 shows the corresponding "blame matrix" for acid deposition at the REFERENCE scenario. It also highlights the countries most strongly implicated in strategies to reduce acidification of ecosystems.

The general conclusion is that strategies to reduce human exposure to particulates are significantly different from strategies to reduce acidification of ecosystems. Therefore, it is important to examine the effectiveness of proposed abatement strategies in reducing human exposure to particulates, since these proposed strategies are likely to be derived on the basis of ecosystem protection.

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