Economic Evaluation of Proposals for Emission Ceilings for Atmospheric Pollutants

January 1999

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AEA Technology

Interim report for DGXI of the European Commission.

Analysis of Scenarios from IIASA's Seventh Interim Report

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AEA Technology
D5 Culham
Oxfordshire
OX14 3DB
UK
Telephone +44-1235-463687
Facsimile +44-1235-463574

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	Name	**Signature**	**Date**
Authors	Mike Holland, Dan Forster, Katie King, Ann Haworth, Paul Watkiss		
Reviewed by	Mike Holland		
Approved by	George Marsh		

Executive Summary

1. AEA Technology, under sub-contract to IIASA, have conducted an economic evaluation of scenarios being explored in the development of further controls on acidification and ground-level ozone. The derivation of these scenarios is described in IIASA's Seventh Interim Report on Cost-effective Control of Acidification and Ground-level Ozone, released in January 1999. The analysis presented here includes quantification of benefits and their comparison with the estimated costs of attaining these scenarios.

2. The benefits analysis uses the ALPHA (Atmospheric Long-range Pollution Health-environment Assessment) model, used previously in assessment of scenarios relevant to the ozone directive. Experts throughout Europe have now had the opportunity to review ALPHA, and a number of comments have been received. To the extent appropriate and possible these comments have been accounted for.

3. In view of the rapid progress being made in environmental economic assessments, and continuing dispute in some parts of the methodology, the authors have taken a flexible approach to the analysis. Where different opinions exist, options are discussed and sensitivity analysis has been employed. In these cases the authors have sought not to unduly bias the analysis towards either their own views, the views of the study sponsors, or other bodies consulted during the course of the work. Reasons for preferring one set of assumptions over any other are given where appropriate.

Scenarios

4. The following scenarios were investigated;

- REFERENCE (REF) - the stricter of current legislation/current reduction plans for each country.
- H1: central scenario for reducing acidification, eutrophication and ground level ozone
- H2: 'low' ambition scenario for reducing acidification, eutrophication and ground level ozone
- H3: 'high' ambition scenario for reducing acidification, eutrophication and ground level ozone
- H5/1: 'low' ambition scenario for reducing ground level ozone only
- H5/2: central scenario for reducing ground level ozone only
- H5/3: 'high' ambition scenario for reducing ground level ozone only

Precise targets for each effect for scenarios H1, H2 and H3 are shown in Table 1. The H5 series of scenarios are based only on the ozone-related targets.

Table 1. Targets for the six scenarios assessed.

	Low ambition (H2)	Central scenario (H1)	High ambition (H3)
Acidification			
Gap closure on accumulated excess acidity	90 %	95 %	95 %
Maximum excess deposition for the 2-percent of the most sensitive ecosystems	(900 eq/ha)	(850 eq/ha)	800 eq/ha
Health-related ozone			
Gap closure on AOT60	60 %	67 %	70 %
Maximum AOT60, to be achieved in 4 out of 5 years	3.0 ppm.h	2.9 ppm.h	2.8 ppm.h
Vegetation-related ozone			
Gap closure on AOT40	30 %	33 %	35 %
Maximum excess AOT40, mean over five years	10.5 ppm.h	10 ppm.h	9.5 ppm.h
Eutrophication			
Gap closure on accumulated excess nitrogen deposition		(50 %)	(50%)
Maximum excess deposition for the 2-percent of the most sensitive ecosystems	(1400 eq/ha)	(1300 eq/ha)	(1000 eq/ha)

Methods

5. The methodology adopted largely follows that of the European Commission DGXII ExternE Project. It is based on a logical stepwise progression through emission, change in exposure, quantification of impacts using exposure-response functions, to valuation based on willingness-to-pay.

6. The ALPHA model is based on the EMEP 150x150 km grid, and permits analysis of the effects of sulphur/nitrogenous pollutants and ozone on public health, materials, crops, forests, ecosystems and visibility. Air quality data are calculated from emissions estimates generated for each scenario by RAINS, combined with country to grid-cell factors calculated from EMEP model runs for all pollutants except ozone. Ozone data are generated externally using the EMEP model run by DNMI.

   A key feature of the model is the ease with which the major sensitivities can be assessed. This is reflected in the extensive sensitivity analysis presented in this report.

7. Table 2 lists the effects that would be influenced by the emission changes defined by the IIASA scenarios. It also shows which have been included in the analysis and which excluded.

Table 2. Effects quantified and not quantified in the course of this study.

Effect	Quantified?	Comments
Health		
NO_3 and SO_4 aerosols		
acute - mortality	✓	
chronic - mortality	✓	Limited availability of data
acute - morbidity	✓	
chronic - morbidity	✓	
Ozone		
acute - mortality	✓	Less clear linkage between O_3 and mortality than for PM_{10}
acute - morbidity	✓	
chronic - morbidity	✗	No information on possible chronic effects
SO_2		
acute - mortality	✓	
acute - morbidity	✓	
chronic - morbidity	✗	No information on possible chronic effects
Direct effects of VOCs	✗	Lack of data on speciation, etc.
Direct effects of NO_2	✗	Lack of reasonable evidence for effects at current ambient levels
Altruistic effects	✗	Reliable valuation data not available
Materials		
SO_2 / Acid effects on utilitarian buildings	✓	
Effects on cultural assets, steel in re-inforced concrete	✗	Of limited importance in scenarios that do not consider SO_2 reduction
Effects of O_3 on paint, rubber	✗	EU-wide stock at risk unavailable
Macroeconomic effects	✗	Lack of models at the EU level
Crops		
Direct effects of SO_2 and O_3 on crop yield	✓	
Indirect SO_2 and O_3 effects on livestock	✓	
N deposition as fertiliser	✓	
Interactions between pollutants, with pests and pathogens, climate...	✗	Exposure-response data unavailable
Acidification/liming	✓	Effect of atmospheric deposition likely to be negligible
Macroeconomic effects	✗	Lack of models at the EU level
Forests		
O_3 effects on timber production	✓	
Non-O_3 effects	✗	No data available
Non-timber benefits of forests	✗	No data available
Exceedence of critical load for eutrophication	✗/✓	Critical loads exceedence reported, but no data available for valuation
Exceedence of critical load for acidification	✗/✓	Critical loads exceedence reported, but very limited data available for valuation
Other ecosystems		
Exceedence of O_3 critical level	✗	No data available for valuation
Exceedence of critical load for eutrophication	✗/✓	Critical loads exceedence reported, but no data available for valuation
Exceedence of critical load for acidification	✗/✓	Critical loads exceedence reported, but very limited data available for valuation
Visibility		
Change in amenity	✓	Extremely uncertain against background of little concern in Europe. Valuation based on US data

8. Coverage of health issues appears to be reasonably comprehensive in relation to the effects of short-term exposures, though perhaps not for long-term exposures through a lack of data. There is debate about the inclusion of functions linking mortality with acute exposure to ozone, and chronic exposure to fine particles. In the absence of definitive guidance these issues have been assessed using sensitivity analysis. The authors' current preference is for inclusion of both functions. Acknowledging the potential significance of uncertainty in this area the effect of excluding mortality altogether is also shown in the results.

9. Debate also concerns the correct approach to apply to valuation of cases of premature mortality. Problems arise because many, perhaps most, of those at increased risk of premature mortality linked to short term exposure to air pollution may only have a very limited life expectancy even in the absence of air pollution. Also, ambient air pollution will rarely be the most important determinant of age at death. Two approaches are investigated, one where valuation is based on the value of statistical life (VOSL) approach, and another based on the value of life years (VOLY) concept. Our preference here is for the more conservative approach based on VOLY. A recent review in the UK, yet to be published, has suggested that the correct approach for valuation of acute effects of air pollution on mortality is to use an adjusted VOSL that is much smaller than the typical figure of 2 MEuro. We suggest that this approach would give a result almost identical to our application of the VOLY, so a separate sensitivity analysis has not been undertaken.

10. Similarly, coverage of pollution effects on agriculture is reasonably comprehensive, though again subject to uncertainty. Possible sources of error are discussed in the report. Some seem likely to lead to overestimation of damage, others to underestimation.

11. Assessment of materials damage concentrates on the effects of acidic deposition. Associated damages are small compared to those on health and agriculture. Effects on buildings of cultural merit, and of ozone on polymers have not been included in this study because of a lack of data on effect and valuation.

12. Forest damage from ozone is included, though the approach used is far from satisfactory. Particular criticism could be applied to exposure-response functions used, and a necessarily simplistic valuation function. Ideally evaluation would be scenario based to account for differences in future demand for forest products and developments in Europe-wide forest management over the next 50 or so years. Although results are subject to high uncertainty, results suggest that reduced forest output caused by ozone exposure is likely to be much less important than ozone effects on agriculture.

13. Loss of amenity through effects of emissions on visibility was quantified using valuation data from the US literature, suggesting that significant benefits could be attained. These results have high uncertainty. The reliability of benefits transfer from the USA to Europe is particularly questionable in this case. However, this and other uncertainties are accounted for in the cost-benefit analysis.

14. The report does not consider a number of effects of the pollutants of interest here because of a lack of data at some point in the analytical chain. These effects include those on ecosystems, secondary economic implications of changed agricultural yield and materials damage, possible chronic effects of ozone on health, etc. (see Table 1).

15. As noted already, there are important uncertainties in the analysis. From review of the potential for error in the analysis, the key sensitivities were found to be;
    - Issues relating to the assessment of mortality generally
    - Prediction of changes in ozone exposure using the EMEP model
    - Influence of meteorological and other factors on estimates of changes in crop yield
    - Omission of effects on ecosystems, possible chronic effects of ozone exposure on morbidity, indirect economic effects arising from reduced agricultural yield, etc.

    A variety of techniques have been used in this report to resolve the problems caused by uncertainty in a transparent manner:
    - Statistical assessment of uncertainties
    - Clear identification of effects included and excluded from the analysis
    - Stratified sensitivity analysis covering all quantified effects
    - Further sensitivity analysis of specific uncertainties

Results

16. Based on the principal set of assumptions followed in the study, the most important impacts in the benefits analysis were those on human health and crops. Effects on forest productivity and materials were negligible in comparison, whilst those on ecosystems were unquantified, beyond re-iterating data on exceedence of critical loads and levels given in the IIASA report. Unlike some previous studies, it was found that the benefits from reduced impacts on agriculture offset a significant proportion of total costs.

17. Effects on the agricultural sector are complicated, as sulphur and nitrogen depositions have the capacity to improve crop growth, whilst ozone will reduce it. Overall, the negative ozone effect substantially outweighs the benefits of S and N fertilisation.

18. Comparison of costs and benefits is made in Tables 3a and 3b. Data presented are for total benefits across the EU15; additional benefits arising outside the EU are not included. Table 3a shows the results where mortality valuation is based on value of life years (VOLY) whilst Table 3b shows results for mortality valuation based on value of statistical life (VOSL). The tables summarise the stratified sensitivity analysis. Benefits are expressed cumulatively, sequentially adding together results for groups of impact types, based on the results of a confidence ranking exercise conducted in the course of our work. Group I contains those effects for which respondents to a questionnaire had most confidence in the results, Group V those that respondents had least confidence in. The groupings were as follows;
    Group I: materials damage (excluding paint); N fertilisation on crops; acute effects on mortality (VOLY approach); morbidity (excluding restricted activity days and chronic bronchitis)
    Group II: restricted activity days; paint damage; ozone and SO_2 effects on crops
    Group III: acute effects on mortality (VOSL approach); chronic effects on bronchitis;
    Group IV: ozone effects on forests; chronic effects on mortality (VOLY approach)
    Group V: chronic effects on mortality (VOSL approach); changes in visibility

Table 3a: Comparison of costs and benefits for each scenario, for the case where mortality valuation uses the VOLY approach. For explanation see text.

	Cumulative benefits (MEuro/year)					Costs
Scenario	Group I	+ Group II	+ Group III	+ Group IV	+ Group V	(MEuro)
Joint Acidification, Eutrophication, Ozone						
H2	460	2400	3400	11000	12000	4200
H1	640	3000	4500	17000	17000	7500
H3	920	4100	6700	27000	29000	16000
Ozone Directive						
H5/1	280	2200	2800	8200	8600	3500
H5/2	320	2500	3300	9500	9900	4300
H5/3	380	3100	3900	11000	12000	5800

Table 3b: Comparison of costs and benefits for each scenario, for the case where mortality valuation uses the VOSL approach. For explanation see text.

	Cumulative benefits (MEuro/year)					Costs
Scenario	Group I	+ Group II	+ Group III	+ Group IV	+ Group V	(MEuro)
Joint Acidification, Eutrophication, Ozone						
H2	270	2200	11000	11000	22000	4200
H1	370	2800	15000	15000	32000	7500
H3	530	3800	22000	22000	51000	16000
Ozone Directive						
H5/1	120	2000	9000	9100	15000	3500
H5/2	140	2400	10000	11000	18000	4300
H5/3	170	2900	12000	13000	21000	5800

In each table the shading denotes the number of these groups required for benefits to exceed costs in each scenario. It is seen that the least certain of the quantified effects are not needed for benefits to exceed costs, provided that the main assumptions followed in the study are correct.

In all cases results show the difference in the annual costs and benefits between the scenario selected and the REF scenario for 2010.

19. At this point it is important to refer back to Table 2 for a review of the effects that have not been included in this assessment. In most cases these effects are additive to those shown in Table 3. The effect of other uncertainties, for example possible exaggeration of mortality benefits (lack of an ozone threshold in the core analysis, assumptions on the harmfulness of different particulate fractions, etc.) should also be considered (noting, of course, that not all uncertainties affecting the quantified estimates would tend towards over-estimation).

20. We need to ask whether any of the effects that have been omitted may be significant in economic terms. Most of the concern over transboundary air pollution in Europe has in the past concentrated on damage to ecosystems and cultural heritage, particularly, though not exclusively, stonework. The IIASA results for critical loads exceedence for acidification and eutrophication for scenarios REF, H1, H2 and H3 are reproduced in this report. It is noted that substantial reductions in ecosystem exceedence will be achieved with respect to acidification under REF, with the % of ecosystems at risk falling to about 4.3% across the Union. However, this still leaves significant levels of overall exceedence in several countries, particularly Belgium, Germany, the Netherlands and the UK (in all cases exceedence will affect more than 10% of ecosystems). Also, uneven distribution of exceedence within countries will mean that some types of ecosystem are likely to remain at significant risk, even

when the overall rate of exceedence within a country appears to be low. The H1 scenario reduces exceedence in all of these countries except the Netherlands to below 10%. In the Netherlands exceedence falls from 60% under REF to 24% under H1. The situation with respect to eutrophication appears more severe, with several countries showing more than 90% exceedence by ecosystem area under the REF scenario. Under the H1 scenario all but four member states still show exceedence across more than 10% of ecosystems in 2010 and five are predicted to still experience exceedence across more than 50% of their ecosystems.

21. For the scenarios considered, the contribution made by each pollutant to the overall balance of costs and benefits is highest for NO_x followed by SO_2/O_3, and finally NH_3.

22. Combining different assumptions on the individual elements in the list of uncertainties given at point [15] above, it is possible to generate total benefit estimates that are smaller than the costs for the scenarios considered. Our analysis does not therefore '*prove beyond all reasonable doubt*' that benefits to European Union Member States from reduction of emissions in those states would exceed costs. As an example, Figure 1 shows the comparison of cost and quantified benefit for each scenario with mortality effects (about which there is so much debate) and effects on visibility excluded: in all cases cost exceeds quantified benefits. Of course the group of effects such as ozone damage to ecological resources which are not quantified in money terms in this assessment still remain outside the analysis, and should be considered on top of the results shown. Remember also that the cost estimates are subject to their own uncertainties. There is a common view that the IIASA cost estimates are too high, though this is not apparently shared by industry.

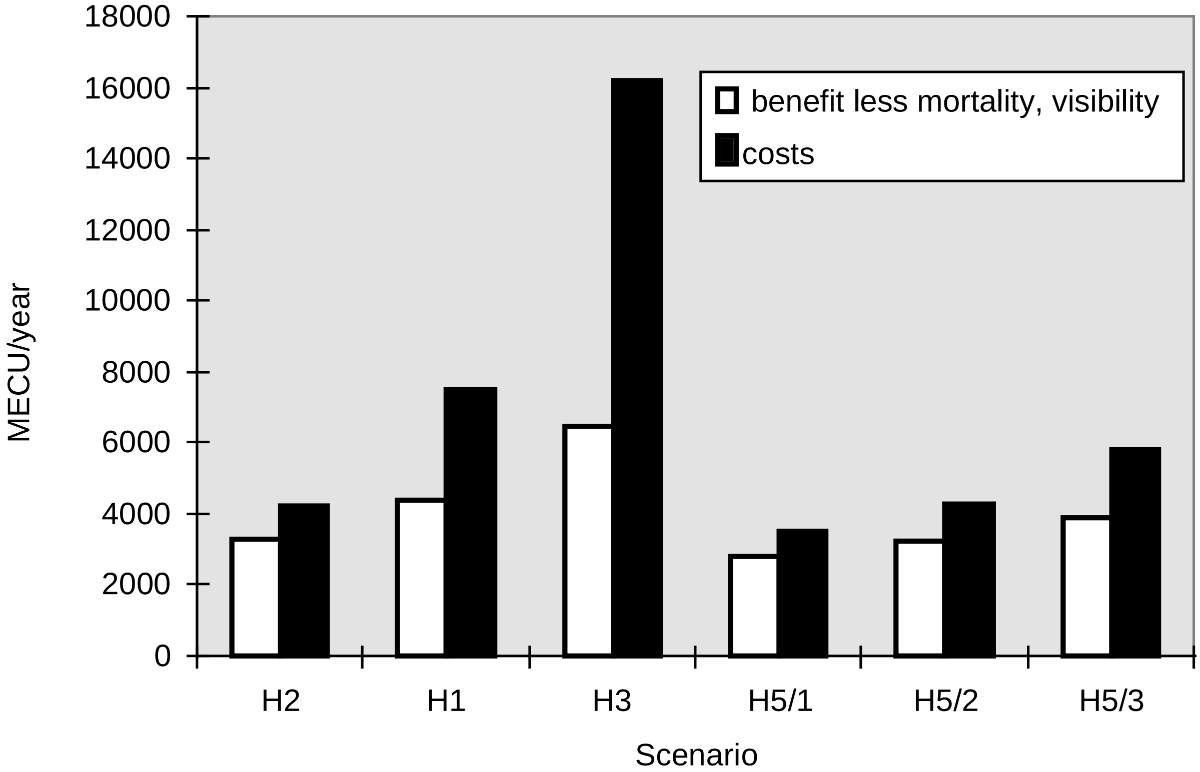


Figure 1. Comparison of costs with quantified benefits without accounting for pollution-related mortality and effects on visibility.

23. We conclude that, according to our central case and associated assumptions, benefits are likely to exceed the costs of implementing the scenarios considered in this study. This conclusion needs to be considered against other information presented in the report. Most notable are the level of confidence associated with estimated benefits, and the weighting that should be given to effects that remain unquantified. The limitations of other inputs to the work, notably the cost estimates made at IIASA and the results of the EMEP ozone model also need to be considered.

24. The findings presented here are only one of several inputs to the political process of determining air quality limits that provide an appropriate level of protection for human health and the environment. The decision on limit values needs to take into account variation in the benefit:cost ratio, and aversion to risks of error on both sides of the cost-benefit equation.

Contents

Appendices

1. Introduction

1.1 OBJECTIVES OF THE STUDY

The purpose of this report is to estimate the benefits of certain scenarios (see Section 2) developed in the Seventh Report on Cost-effective Control of Acidification and Ground-level Ozone by IIASA (Amann *et al*, 1999). To avoid unnecessary repetition, readers should refer to the series of reports produced at IIASA (Amann *et al*, 1996; 1997;1998a, b, c) for further background information.

This report follows two earlier studies. The first was funded by the UK Department of the Environment, Transport and the Regions on behalf of the UNECE Task Force on Economic Assessment of Abatement Strategies (Holland *et al*, 1998a), and addressed the benefits of some preliminary scenarios considered in the context of the Multi-pollutant, Multi-effect Protocol. The second was funded by DGXI of the European Commission and was mainly concerned with the development of a directive on ozone limits (Holland *et al*, 1998b). Particular attention was given in these studies to two problems;

- making the analysis more comprehensive than earlier assessments of economic benefits which have largely been limited to consideration of effects on human health, materials and crops
- the reporting of uncertainty

We have sought to ensure that the framework adopted is consistent with the IIASA study, the position papers of working groups advising DGXI of the European Commission, and work being carried out in support of the development of the UNECE's Multi-pollutant, Multi-effect Protocol. This covers not just the scenarios considered, but also the pollution transport models used, databases of stock at risk, exposure-response functions and other matters.

1.2 THE USE OF ALTERNATIVE FORMS OF RISK ASSESSMENT

There is some disparity in the list of exposure-response functions used in this report and the position papers of some of the Commission's working groups dealing with ambient air quality directives. Traditionally, environmental quality objectives have been set from consideration of those effects that can be described in terms of exposure-response with most confidence. The question faced is of the form "At what concentration is a given pollutant harmful?". In contrast, the question asked here is "How do benefits compare with costs?". In this context it is appropriate to be more inclusive, whilst being transparent on uncertainty and applying sensitivity analysis to show the effect of using different assumptions where valid alternatives exist.

1.3 SCOPE OF THE STUDY

This report is concerned with the effects of emissions of SO_2, NO_x, NH_3 and VOCs (insofar as the latter affect ozone levels). Chemical processes in the atmosphere link these primary pollutants to a number of secondary pollutants, the most important of which are aerosols, ozone, acidic deposition and N deposition. These pollutants cause, or have been claimed to cause, various types of damage (Table 1).

Table 1. Pollutants relevant to the development of Directives on acidification and ground-level ozone, and their potential effects.

Pollutant	**Effect**
NO_x	Human health - mortality Human health - morbidity Effects on crops, possibly beneficial from fertilisation effects, possibly negative through interaction with insect pests Reduced visual range
SO_2	Human health - mortality Human health - morbidity Effect on crop yield, Damage to building materials Damage to forests Ecological damage
NH3	Effects of NH3 are covered under other pollutants (aerosols, N deposition, acidic deposition...)
VOCs	Human health - mortality (dependent on VOC speciation) Human health - morbidity (dependent on VOC speciation)
Nitrate aerosols	Human health - mortality Human health - morbidity Reduced visual range
Sulphate aerosols	Human health - mortality Human health - morbidity Reduced visual range
Acidic deposition	Acidification of ecosystems and associated effects (change in species diversity, loss of fish, etc.) Damage to building materials Damage to historic buildings and objects of cultural worth
N deposition	Eutrophication of ecosystems and associated effects (change in species diversity, productivity, etc.)
Ozone	Human health - mortality Human health - morbidity Crop yield effects Damage to materials (e.g. paint, rubber, textiles...) Forest damage Other ecological damage

No attempt is made in the table to identify which effects are real at ambient European levels, and which are not: it is simply presented to identify the range of impacts that have been considered here. Effects of some of these pollutants on climate change are beyond the scope of the study. As will become apparent, there remain several types of damage that cannot be quantified at the present time.

1.4 STRUCTURE OF THIS REPORT

Section 2 contains details of the scenarios used in this analysis. Section 3 provides brief details of the methods used in the study. Details of exposure-response functions etc. are briefly listed in Appendix II. For a more thorough overview of the methodology see Holland *et al* (1998a, b; 1999). Section 4 reviews the results obtained, and is followed in Section 5 by the cost benefit and uncertainty analysis. Section 6 provides the conclusions of the study.

Appendix I contains a list of the abbreviations used in the report. Appendix II contains details of the stock at risk databases, exposure-response functions, valuation data etc. used in the study. Appendix III contains details of the manner in which the stratified sensitivity analysis that forms the basis of our CBA was developed. The report is completed by the listing of references cited, in Appendix IV.

2. Scenarios for Assessment

Benefits have been quantified for the following scenarios, taking data from Amann *et al* (1999):

- REFERENCE (REF - against which all other scenarios are compared)
- H2: 'low' ambition scenario for reducing acidification, eutrophication and ground level ozone
- H1: central scenario for reducing acidification, eutrophication and ground level ozone
- H3: 'high' ambition scenario for reducing acidification, eutrophication and ground level ozone
- H5/1: central scenario for reducing ground level ozone only
- H5/2: 'low' ambition scenario for reducing ground level ozone only
- H5/3: 'high' ambition scenario for reducing ground level ozone only

Table 2. Summary of the environmental targets for each scenario.

	Low ambition (H2)	Central scenario (H1)	High ambition (H3)
Acidification			
Gap closure on accumulated excess acidity	90 %	95 %	95 %
Maximum excess deposition for the 2-percent of the most sensitive ecosystems	(900 eq/ha)	(850 eq/ha)	800 eq/ha
Health-related ozone			
Gap closure on AOT60	60 %	67 %	70 %
Maximum AOT60, to be achieved in 4 out of 5 years	3.0 ppm.h	2.9 ppm.h	2.8 ppm.h
Vegetation-related ozone			
Gap closure on AOT40	30 %	33 %	35 %
Maximum excess AOT40, mean over five years	10.5 ppm.h	10 ppm.h	9.5 ppm.h
Eutrophication			
Gap closure on accumulated excess nitrogen deposition		(50 %)	(50%)
Maximum excess deposition for the 2-percent of the most sensitive ecosystems	(1400 eq/ha)	(1300 eq/ha)	(1000 eq/ha)

The targets for scenarios H5/1, H5/2 and H5/3 are the same as those for H2, H1 and H3 respectively, but for ozone only. Emission and cost data for each scenario are shown in the following tables.

Table 3. NO_x emissions in 2010 (kt).

Country	REF	H1	H2	H3	H5/1	H5/2	H5/3
Austria	103	91	92	89	91	91	89
Belgium	191	127	127	127	127	127	127
Denmark	128	127	128	96	128	128	128
Finland	152	152	152	151	152	152	152
France	858	679	706	633	706	682	648
Germany	1184	1051	1081	930	1086	1086	1071
Greece	344	264	253	317	253	261	291
Ireland	70	59	63	46	70	70	66
Italy	1130	869	900	842	900	863	839
Luxembourg	10	8	7	6	7	6	6
Netherlands	280	238	280	213	280	280	280
Portugal	177	144	177	144	160	144	129
Spain	847	781	847	587	847	803	726
Sweden	190	152	158	147	158	158	152
UK	1186	1181	1181	859	1181	1181	1181
EU-15	6849	5922	6152	5185	6148	6032	5886
Albania	36	36	36	36	36	36	36
Belarus	316	316	316	316	316	316	316
Bosnia-H	60	60	60	60	60	60	60
Bulgaria	297	297	297	297	297	297	297
Croatia	91	91	91	91	91	91	91
Czech_R.	296	296	296	296	296	296	296
Estonia	73	73	73	73	73	73	73
Hungary	198	198	198	198	198	198	198
Latvia	118	118	118	118	118	118	118
Lithuania	138	138	138	138	138	138	138
Norway	178	178	178	178	178	178	178
Poland	879	879	879	879	879	879	879
Moldova	66	66	66	66	66	66	66
Romania	458	458	458	458	458	458	458
Russia	2653	2653	2653	2653	2653	2653	2653
Slovakia	132	132	132	132	132	132	132
Slovenia	36	36	36	36	36	36	36
Switzerland	79	79	79	79	79	79	79
Macedonia	29	29	29	29	29	29	29
Ukraine	1433	1433	1433	1433	1433	1433	1433
Yugoslavia	152	152	152	152	152	152	152
Non-EU	7718	7718	7718	7718	7718	7718	7718
Atlantic	911	911	911	911	911	911	911
Baltic	80	80	80	80	80	80	80
North Sea	639	639	639	639	639	639	639
SEA	1629	1629	1629	1629	1629	1629	1629
TOTAL	16196	15269	15499	14532	15494	15379	15233
total w/o ships	14567	13640	13870	12903	13866	13750	13604

Table 4. VOC emissions in 2010 (kt).

Country	REF	H1	H2	H3	H5/1	H5/2	H5/3
Austria	205	129	129	129	129	129	123
Belgium	193	102	103	101	103	102	101
Denmark	85	85	85	84	85	85	83
Finland	110	110	110	110	110	110	110
France	1223	932	1015	771	1015	932	849
Germany	1137	924	925	912	925	924	916
Greece	267	173	169	188	168	173	179
Ireland	55	55	55	54	55	55	55
Italy	1159	962	962	893	962	962	811
Luxembourg	7	6	5	5	5	5	5
Netherlands	233	156	157	152	157	153	153
Portugal	144	102	113	102	113	102	102
Spain	669	662	669	642	669	657	645
Sweden	290	219	219	215	219	219	216
UK	1351	964	1023	953	1023	974	957
EU-15	7128	5581	5739	5310	5738	5581	5303
Albania	41	41	41	41	41	41	41
Belarus	309	309	309	309	309	309	309
Bosnia-H	48	48	48	48	48	48	48
Bulgaria	190	190	190	190	190	190	190
Croatia	111	111	111	111	111	111	111
Czech_R.	305	304	304	304	304	304	304
Estonia	49	49	49	49	49	49	49
Hungary	160	160	160	160	160	160	160
Latvia	56	56	56	56	56	56	56
Lithuania	105	105	105	105	105	105	105
Norway	195	195	195	195	195	195	195
Poland	807	807	807	807	807	807	807
Moldova	42	42	42	42	42	42	42
Romania	504	504	504	504	504	504	504
Russia	2787	2786	2786	2786	2786	2786	2786
Slovakia	140	140	140	140	140	140	140
Slovenia	40	40	40	40	40	40	40
Switzerland	144	144	144	144	144	144	144
Macedonia	19	19	19	19	19	19	19
Ukraine	851	851	851	851	851	851	851
Yugoslavia	139	139	139	139	139	139	139
Non-EU	7041	7041	7041	7041	7041	7041	7041
Atlantic	0	0	0	0	0	0	0
Baltic	0	0	0	0	0	0	0
North Sea	0	0	0	0	0	0	0
SEA	0	0	0	0	0	0	0
TOTAL	14168	12621	12779	12351	12778	12621	12344
	14169	12622	12780	12351	12779	12622	12344

Table 5. NH_3 emissions in 2010 (kt).

Country	REF	H1	H2	H3	H5/1	H5/2	H5/3
Austria	67	67	67	66	67	67	67
Belgium	96	57	80	57	96	96	96
Denmark	72	71	71	65	72	72	72
Finland	31	31	31	31	31	31	31
France	777	718	771	530	777	777	777
Germany	571	413	513	366	571	571	571
Greece	74	74	74	74	74	74	74
Ireland	126	123	126	123	126	126	126
Italy	432	430	432	430	432	432	432
Luxembourg	7	7	7	7	7	7	7
Netherlands	136	104	119	104	136	136	136
Portugal	67	67	67	67	67	67	67
Spain	353	353	353	346	353	353	353
Sweden	48	48	48	48	48	48	48
UK	297	264	293	224	297	297	297
EU-15	3154	2826	3051	2537	3154	3154	3154
Albania	35	35	35	35	35	35	35
Belarus	163	163	163	163	163	163	163
Bosnia-H	23	23	23	23	23	23	23
Bulgaria	126	126	126	126	126	126	126
Croatia	37	37	37	37	37	37	37
Czech_R.	108	108	108	108	108	108	108
Estonia	29	29	29	29	29	29	29
Hungary	137	137	137	137	137	137	137
Latvia	35	35	35	35	35	35	35
Lithuania	81	81	81	81	81	81	81
Norway	21	21	21	21	21	21	21
Poland	541	541	541	541	541	541	541
Moldova	48	48	48	48	48	48	48
Romania	304	304	304	304	304	304	304
Russia	894	894	894	894	894	894	894
Slovakia	47	47	47	47	47	47	47
Slovenia	21	21	21	21	21	21	21
Switzerland	66	66	66	66	66	66	66
Macedonia	16	16	16	16	16	16	16
Ukraine	649	649	649	649	649	649	649
Yugoslavia	82	82	82	82	82	82	82
Non-EU	3462	3462	3462	3462	3462	3462	3462
TOTAL	6616	6288	6513	5998	6616	6616	6616

Table 6. SO_2 emissions in 2010 (kt).

Country	REF	H1	H2	H3	H5/1	H5/2	H5/3
Austria	40	40	40	33	40	40	40
Belgium	193	76	82	75	193	193	193
Denmark	90	77	90	25	90	90	90
Finland	116	116	116	116	116	116	116
France	448	218	318	163	448	448	448
Germany	581	463	514	444	581	581	581
Greece	546	546	546	546	546	546	546
Ireland	66	28	28	23	66	66	66
Italy	567	566	566	295	566	566	566
Luxembourg	4	3	4	2	4	4	4
Netherlands	73	50	50	50	73	73	73
Portugal	141	141	141	141	141	141	141
Spain	774	746	744	197	774	774	774
Sweden	67	67	67	66	67	67	67
UK	980	497	718	422	980	980	980
EU-15	4687	3637	4026	2600	4687	4687	4687
Albania	55	55	55	55	55	55	55
Belarus	494	494	494	494	494	494	494
Bosnia-H	415	415	415	415	415	415	415
Bulgaria	846	846	846	846	846	846	846
Croatia	70	70	70	70	70	70	70
Czech_R.	366	366	366	366	366	366	366
Estonia	175	175	175	175	175	175	175
Hungary	546	546	546	546	546	546	546
Latvia	104	104	104	104	104	104	104
Lithuania	107	107	107	107	107	107	107
Norway	32	32	32	32	32	32	32
Poland	1397	1397	1397	1397	1397	1397	1397
Moldova	117	117	117	117	117	117	117
Romania	594	594	594	594	594	594	594
Russia	2344	2344	2344	2344	2344	2344	2344
Slovakia	137	137	137	137	137	137	137
Slovenia	71	71	71	71	71	71	71
Switzerland	26	26	26	26	26	26	26
Macedonia	81	81	81	81	81	81	81
Ukraine	1488	1488	1488	1488	1488	1488	1488
Yugoslavia	269	269	269	269	269	269	269
Non-EU	9732	9732	9732	9732	9732	9732	9732
Atlantic	641	641	641	641	641	641	641
Baltic	72	72	72	72	72	72	72
North Sea	439	439	439	439	439	439	439
SEA	1152	1152	1152	1152	1152	1152	1152
TOTAL	15571	14521	14910	13484	15571	15571	15571
Total less seas	14419	13369	13758	12332	14419	14419	14419

Table 7. Costs of meeting the emission scenarios in 2010 (MEuro/year)

Country	REF	H1	H2	H3	H5/1	H5/2	H5/3
Austria	1093	119	117	136	118	120	169
Belgium	1704	1053	591	1120	455	459	499
Denmark	623	6	0	123	0	0	1
Finland	889	0	0	0	0	0	0
France	8659	916	421	4270	373	719	1366
Germany	13813	2147	1100	4376	918	933	1140
Greece	1482	338	449	119	455	363	202
Ireland	618	44	24	96	0	0	0
Italy	9644	403	313	731	313	420	971
Luxembourg	98	4	11	33	12	30	30
Netherlands	2588	971	354	1255	89	140	140
Portugal	1530	57	21	57	22	57	98
Spain	6495	22	10	605	0	10	44
Sweden	1554	87	73	117	73	73	92
UK	7964	1348	741	3163	648	957	1071
EU-15	58754	7514	4227	16202	3476	4280	5823
Albania	0	0	0	0	0	0	0
Belarus	0	0	0	0	0	0	0
Bosnia-H	1	0	0	0	0	0	0
Bulgaria	157	0	0	0	0	0	0
Croatia	52	0	0	0	0	0	0
Czech_R.	979	0	0	0	0	0	0
Estonia	0	0	0	0	0	0	0
Hungary	586	0	0	0	0	0	0
Latvia	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0
Norway	623	0	0	0	0	0	0
Poland	3342	0	0	0	0	0	0
Moldova	0	0	0	0	0	0	0
Romania	157	0	0	0	0	0	0
Russia	715	0	0	0	0	0	0
Slovakia	423	0	0	0	0	0	0
Slovenia	128	0	0	0	0	0	0
Switzerland	949	0	0	0	0	0	0
Macedonia	1	0	0	0	0	0	0
Ukraine	328	0	0	0	0	0	0
Yugoslavia	92	0	0	0	0	0	0
Non-EU	8534	0	0	0	0	0	0
Atlantic	0	0	0	0	0	0	0
Baltic	0	0	0	0	0	0	0
North Sea	0	0	0	0	0	0	0
SEA	0	0	0	0	0	0	0
TOTAL	67288	7514	4227	16202	3476	4280	5823

3. The Benefit Assessment

3.1 OUTLINE OF METHODOLOGY

The study has three main activities, the first of which has been carried out by Markus Amann and his colleagues at IIASA and is reported separately (Amann *et al*, 1999):

1. The cost-effectiveness analysis, i.e., the analysis of strategies aimed at the achievement of environmental targets for ground-level ozone and acidification at least cost;
2. The benefit analysis, determining the monetary value of environmental improvements achieved by alternative strategies;
3. Comparison of the costs of strategies with monetised environmental benefits, including exploration of the effects of uncertainties (particularly those affecting benefits estimates) on net costs/benefits.

This Chapter provides an outline of the methodology followed in the study. Specific details are provided in Appendix II though for a more complete report on the methods used readers should refer to our other reports (Holland *et al*, 1998a, b; 1999).

3.1.1 The Cost-Effectiveness Analysis

The cost-effectiveness optimization is carried out at IIASA using the 'Regional Air Pollution Information and Simulation' model (RAINS). This determines the least-cost combinations of measures for achieving lower emissions for the pollutants under consideration for each country/region under study for different target levels, with each set of targets defining a scenario.

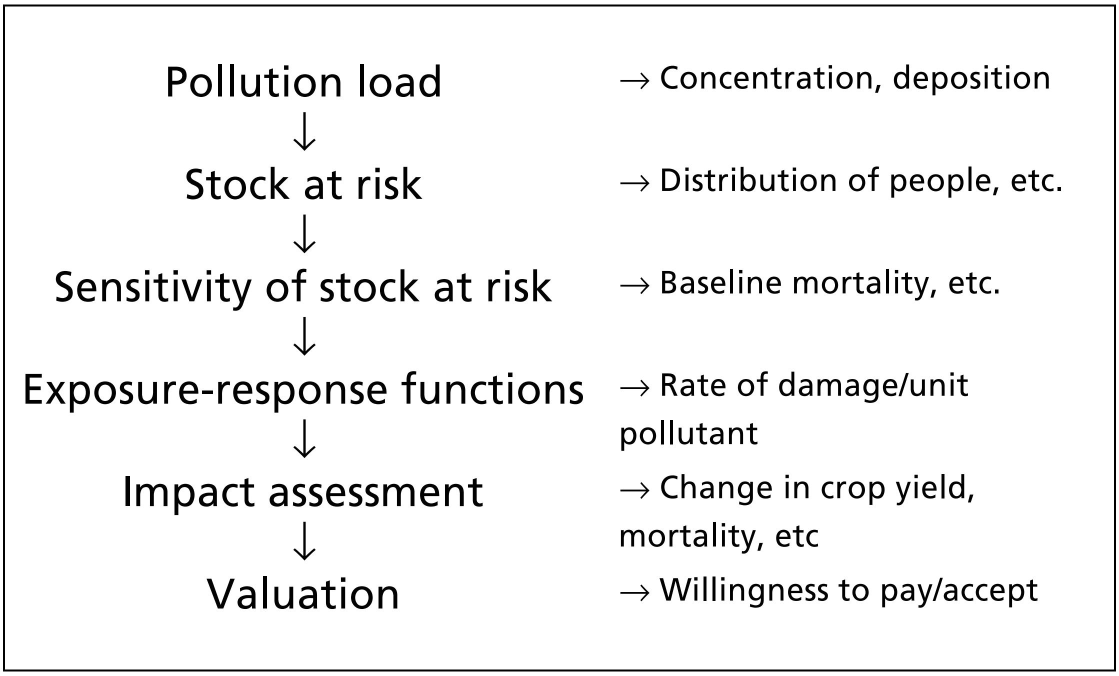
The optimization module within RAINS uses information on emission control costs together with a description of pollutant chemistry and transport based on EMEP to determine the least-cost allocation of emission control measures for achieving exogenously determined environmental targets. Such targets can be grid-specific, and may take into account current exposure levels and the environmental sensitivities of the receptors to be protected, as well as the limits imposed by available emission control measures. As a result, the optimization module can identify the (country-specific) cost-effective abatement level for the pollutants under consideration (SO_2, NO_x, VOC, NH_3), and the costs of the implied measures.

The response of regional ozone exposure to changes in precursor emissions is based on the EMEP Photochemical Oxidants Model developed by the Norwegian Meteorological Institute (DNMI). The optimisation of RAINS uses the mapping of critical loads reflecting thresholds of regional environmental sensitivity carried out by each European country, led by the Coordination Centre for Effects (CCE) at the National Institute of Public Health and the Environment (RIVM) in the Netherlands (Hettelingh *et al*, 1995; Posch *et al*, 1997).

A limitation of the RAINS model results from the fact that it mainly considers end-of-pipe technologies for emission abatement. Potentially cheaper options for pollution control, such as fuel switching and energy conservation are not considered. Clearly this should lead to an upward bias in the costings. However, commentators from industry (e.g. Cocks and Rodgers, 1997) have said that the costs to industry could be higher than those generated by RAINS, resulting from alternative assumptions on plant availability, efficiency of scrubbers, etc..

3.1.2 The Benefits Analysis

The monetary evaluation of benefits within this study relies to a large extent on the ExternE framework for externalities assessment developed through the collaboration of a number of scientific institutions, supported by DGXII under the JOULE Programme. The ExternE methodology has advanced considerably since the series of reports published at the end of 1995 (European Commission, 1995a-f). The present study also takes into account some other new work (see Appendix II). The overall framework adopted is a logical stepwise progression from quantification of pollutant loads to valuation.



Data on the stock at risk have been taken from various sources. The main source is the land use database held by RIVM (Veldkamp and van der Velde, 1995). The categories contained within the database are, however, typically too coarsely aggregated for direct application within this study and additional data were necessary (see Table 8).

Further details on stock at risk data for each of the impacts assessed within the study are given in Appendix II.

The main source of exposure-response functions is the ExternE project (European Commission, 1998). Data on exceedence of critical loads and levels is taken from the work of the modeling team at IIASA. Some information has been taken from unpublished sources which were reviewed extensively in our previous reports (Holland *et al,* 1998a, b). Exposure-response functions and valuation data are summarised in Appendix II. For a more complete discussion about the way in which functions were selected see European Commission (1998) or one of our earlier reports (Holland *et al*, 1998a, b; 1999).

Table 8. Overview of data on stock at risk.

RIVM dataset	Used for:	Additional data
Population	Health effects	Population of Bosnia Herzogovina Age structure of population Frequency of asthma Death rates
	Materials damage	Inventories of buildings and material use
	Changes in visibility	None needed
Land use	Crop damage	Crop production data by species
	Forest damage	Forest production data for coniferous and deciduous woods
	Ecosystem damage	None needed

Valuation data in most cases reflect European Union average prices. The only exceptions relate to crops and timber and pulp prices for which world market levels are used.

3.1.3 Comparison of costs and benefits

Costs and benefits need to be expressed relative to the baseline for each scenario of reduced emissions. We regard the main part of this activity to be the sensitivity analysis. Key sensitivities relate to the treatment of potential effects on mortality, the exclusion of a number of types of damage, assumptions regarding human behaviour in buildings maintenance and transferability of experimental data on crop yield in relation to air pollution. A stratified sensitivity analysis was developed for addressing uncertainty in a transparent manner in or earlier work (see Appendix III and Chapter 5). This is again followed here, together with additional analysis of individual uncertainties as appropriate.

4. Results of the Benefits Assessment

4.1 INTRODUCTION

The results of the benefits assessment are provided in this chapter, receptor by receptor in the following order;

Health
Materials
Crops
Natural Ecosystems
Forests
Visibility

This structure allows sensitivity analysis to be explored for each set of impacts, and discussion of the main sensitivities involved.

The results for each scenario are expressed relative to the baseline of the REF scenario. All of the results given refer to annual benefits in the year 2010. Prices are given in 1990Euro for consistency with the output of the RAINS model. **Benefits of emission reductions within the EU to non-EU countries have not been included in our assessment, though they can be quantified using the ALPHA model. They would clearly increase overall benefits.**

Results in terms of the magnitude of avoided impact achieved by moving to a more restrictive emissions scenario, rather than the economic benefit achieved, are presented only for impacts on mortality. We regard this as unnecessary for other types of impact for the following reasons;

- **Morbidity:** Inclusion of these data would add substantially to the number of tables presented in the report. Given that quantified morbidity effects are small in economic terms the inclusion of these data seems unnecessary.
- **Materials:** Open markets exist for repair to materials, so data on impacts seems unnecessary. In any case, it would be difficult to derive a metric for materials damage that would be immediately meaningful (e.g. change in erosion rates in um or g/m^2).
- **Agriculture, forestry:** Goods in these receptor classes are commonly traded. The benefit of including yield loss information separately on more than 40 classes of agricultural produce seems very small.
- **Visibility:** The physical metric of reduced visibility is not well known, and thus would have little meaning to most readers. This point is exacerbated by the experimental nature of our analysis on visibility, and the very low level of confidence with which we view the results.

4.2 HEALTH EFFECTS

4.2.1 Results by country, and sensitivity analysis

The results of the health benefits assessment are presented for morbidity and mortality by country in Table 9 and Table 10a to f, respectively.

Table 9. Annual morbidity benefits for 2010 for the scenarios studied compared to the REF scenario. All figures in million Euro (MEuro), base year 1990.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	42	59	92	33	36	41
Belgium	84	120	180	46	50	56
Denmark	8	13	25	4	5	5
Finland	2	3	5	1	1	2
France	290	420	690	200	240	280
Germany	400	610	940	240	260	290
Greece	23	22	16	23	22	16
Ireland	4	7	14	1	2	2
Italy	270	330	510	250	290	330
Luxembourg	17	24	36	11	12	13
Netherlands	140	210	310	73	78	87
Portugal	4	22	59	8	18	29
Spain	38	94	320	28	58	110
Sweden	12	18	34	8	8	9
United Kingdom	190	330	630	71	78	89
Total	1500	2300	3900	1000	1200	1400

The following were identified as key sensitivities in this analysis, starting with those affecting the morbidity results;

1. Chronic effects of air pollution on the incidence of bronchitis in adults.
2. Acute effects of air pollution on restricted activity days (RADs).

These two effects dominate the other effects on morbidity (see Appendix II for a full list of the effects considered). Both are probably less certain than other morbidity effects: RADs because the broad range of symptoms involved makes valuation of an average case extremely difficult, and some concern over the quality of the study from which the exposure response function was taken: chronic effects on the incidence of bronchitis in adults because of the high valuation linked to new incidence of chronic disease. The results are not necessarily wrong, but further substantiation of the input data is desirable.

Table 10a. Reduction in the number of cases of premature mortality related to ozone and secondary particulate exposure. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	100	140	210	83	91	110
Belgium	240	310	400	130	140	160
Denmark	20	30	50	14	15	17
Finland	7	9	13	6	6	7
France	790	1100	1600	570	670	790
Germany	1000	1400	2000	640	690	780
Greece	72	70	54	72	69	59
Ireland	14	19	29	7	8	9
Italy	660	780	1200	620	710	860
Luxembourg	45	61	84	29	33	37
Netherlands	390	510	640	210	230	250
Portugal	26	61	130	31	54	76
Spain	110	240	800	95	170	290
Sweden	31	44	72	24	25	28
United Kingdom	690	1000	1300	370	420	450
Total	4200	5800	8600	2900	3300	3900

Table 10b: Annual benefits for 2010 from reduction in the number of cases of mortality from short-term (acute) exposures, calculated using the VOSL approach for valuation. All figures in million Euro (MEuro), base year 1990. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	210	270	390	180	200	230
Belgium	380	510	680	280	310	340
Denmark	42	61	100	31	34	38
Finland	14	18	27	13	13	15
France	1500	2000	3000	1300	1500	1700
Germany	1900	2600	3600	1400	1500	1700
Greece	160	150	120	160	150	130
Ireland	24	34	56	15	17	19
Italy	1400	1700	2400	1400	1600	1900
Luxembourg	81	110	150	64	72	81
Netherlands	640	840	1100	450	500	550
Portugal	55	130	260	69	120	170
Spain	230	510	1400	210	380	630
Sweden	65	90	140	52	55	62
United Kingdom	1200	1700	2200	810	910	1000
Total	7800	11000	16000	6400	7300	8600

Table 10c: Annual benefits for 2010 from reduction in the number of cases of mortality from short-term (acute) exposures, calculated using the VOLY approach for valuation. All figures in million Euro (MEuro), base year 1990. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	5	7	10	5	5	6
Belgium	10	13	17	7	8	9
Denmark	1	2	3	1	1	1
Finland	0	0	1	0	0	0
France	38	50	76	32	37	44
Germany	46	64	90	35	38	43
Greece	4	4	3	4	4	3
Ireland	1	1	1	0	0	0
Italy	35	42	59	34	39	47
Luxembourg	2	3	4	2	2	2
Netherlands	16	21	28	11	12	14
Portugal	1	3	7	2	3	4
Spain	6	13	36	5	9	16
Sweden	2	2	4	1	1	2
United Kingdom	29	42	54	20	23	25
Total	200	270	390	160	180	220

Table 10d. Life years lost to chronic effects of exposure to fine particles. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	3400	4800	7400	2700	2900	3300
Belgium	6400	9500	14000	3700	3900	4400
Denmark	620	1100	2100	330	350	400
Finland	140	220	390	97	99	120
France	22000	33000	55000	16000	19000	22000
Germany	31000	49000	76000	19000	21000	24000
Greece	1800	1700	1200	1800	1700	1200
Ireland	330	540	1100	100	110	140
Italy	22000	27000	41000	21000	24000	26000
Luxembourg	1300	1900	2900	860	950	1100
Netherlands	11000	16000	25000	5800	6200	6900
Portugal	270	1800	4700	630	1400	2300
Spain	2900	7500	25000	2200	4600	8500
Sweden	920	1500	2800	580	600	700
United Kingdom	14000	24000	51000	4900	5300	6100
Total	120000	180000	310000	80000	91000	110000

Table 10e: Benefits from reduction in the number of cases of mortality from long-term (chronic) exposures to secondary particles, calculated using the VOLY approach for valuation. All figures in million Euro (MEuro), base year 1990. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	230	320	490	180	200	220
Belgium	430	630	960	250	260	300
Denmark	41	71	140	22	23	27
Finland	10	15	26	7	7	8
France	1500	2200	3700	1100	1300	1500
Germany	2100	3300	5100	1300	1400	1600
Greece	120	120	80	120	110	83
Ireland	22	36	75	7	7	9
Italy	1500	1800	2700	1400	1600	1800
Luxembourg	86	130	190	58	63	72
Netherlands	710	1100	1700	390	410	460
Portugal	18	120	320	42	94	160
Spain	200	500	1700	150	310	570
Sweden	62	98	180	39	40	47
United Kingdom	920	1600	3400	330	350	410
Total	7900	12000	21000	5400	6100	7200

Table 10f**.** Benefits from reduction in the number of cases of mortality from long-term (chronic) exposures to secondary particles, calculated using the VOSL approach for valuation. All figures in million Euro (MEuro), base year 1990. Assuming that the chronic effect is real, results are subsequently generated based on very conservative assumptions with respect to the average number of life years lost per case affected. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	370	520	810	290	320	370
Belgium	700	1000	1600	400	430	490
Denmark	68	120	230	36	38	44
Finland	16	24	42	11	11	13
France	2500	3600	6000	1800	2100	2400
Germany	3400	5300	8300	2100	2300	2600
Greece	200	190	130	190	180	140
Ireland	36	59	120	11	12	15
Italy	2400	3000	4500	2300	2600	2900
Luxembourg	140	210	320	95	100	120
Netherlands	1200	1800	2800	640	680	760
Portugal	30	190	520	70	150	260
Spain	320	830	2800	240	510	930
Sweden	100	160	300	64	66	76
United Kingdom	1500	2700	5600	530	580	670
Total	13000	20000	34000	8800	10000	12000

Key sensitivities (continued)…

3. Approach to valuation of mortality.

Table 10b and

Table 10c show wide differences in valuation through the application of VOLY and VOSL approaches. There has been much debate around this part of the methodology over the last two years. NERA (1997) expressed a preference for a value of the VOSL in the context of mortality related to air-pollution very much closer to zero than the 2.2 MEuro per premature death adopted here. As noted in a previous report (Holland *et al*, 1998b), the effect of adopting the VOLY approach could be to provide almost the same result as a VOSL closer to zero. Although the debate about terminology may continue it may thus have little effect on the results. It is necessary to note that there remain a large number of economists, including the UNECE TFEAAS group, who recommend use of a VOSL of the order of 2 MEuro.

4. Discount rate applied in derivation of the value of a life year.

Holland *et al* (1998b) demonstrated that varying the discount rate between 0 and 10% would affect estimates of acute effects on mortality made using the VOLY by a factor of about 2, and chronic effects by between 25% and 46%. The USEPA analysis (Post *et al*, 1997) used a rate of 5%, compared to the 4% used here as best estimate. There is general consensus that the correct figure is around the 4% used here, so the overall sensitivity to discount rate appears to be minor.

5. Thresholds.

The Steering Group on ambient air quality requested that account be taken of the effect of the possible existence of a threshold for ozone effects on mortality. No threshold was suggested by the Group, however, reflecting the lack of data in this area. Further problems arise because of the format and resolution of the EMEP ozone output. Given these problems, Holland *et al* (1998b) illustrated the possible effect of a threshold by extrapolation from the analysis of ozone effects in Great Britain (COMEAP, 1997). The assumed threshold in that study was 50 ppb, which led to a factor 18 reduction in the number of cases of premature mortality each year (from 12,500 to 700). This almost eradicates the mortality effects of ozone.

6. Inclusion of effects of chronic mortality.

We accept that available assessments of chronic mortality effects, particularly that by Pope *et al* (1995) are valid, though some would disagree. There is also a problem arising from a lack of information about the lifetime exposures of the subjects of the Pope study. This area of the work requires further basic research to validate the findings of the US studies by Pope *et al* (1995) and others. The sensitivity to inclusion and exclusion of chronic effects on mortality is shown in the next section.

7. Use of EMEP ozone data for analysis of impacts in urban areas.

The problem that arises here is the need for sub-grid scale modelling of ozone concentrations in the urban centres where much of the European population lives. It could be assumed that the modelling applied here is not relevant to urban areas, in which case the health benefits linked to ozone reduction would be approximately halved. The problem is clearly most significant for the H3 ozone scenarios, rather than the joint acidification, eutrophication, ozone scenarios (H1, H2 and H3).

8. Lack of consideration of impacts occurring outside the EU.

The range of pollutant transport linked to emissions from the EU extends over great distances. Rabl and Eyre (1997) reported that non-European impacts could be of the order of 50% of the regional effects quantified within Europe. Also, effects in European countries that are not part of the EU should be considered. This provides a tendency to underestimation of benefits in this study. Although these benefits are not of chief concern for EU Member States, they are relevant to the broader debate at the UNECE level.

9. Omission of:
    - a) Effects listed in Table AII.2 in Appendix II (acute effects of NO_2 on mortality, etc.)
    - b) Valuation of altruism
    - c) Effects of changes in emission of pollutants not considered in this study, arising from the measures forecast to be implemented under each scenario.

The omission of these effects will bias the analysis towards underestimation, countering effects listed above that might lead to overestimation of benefits, though to an unknown extent.

10. Sensitivity to slope of the exposure-response functions for acute effects on mortality

The available literature implies a range of slope factors for the change in mortality rate per ug/m^3 PM_{10} from 0.04% to 0.11%. The rate used here is 0.074%, roughly central between these two limits. Assuming that other assumptions are correct this leads to potential variation of about 50% around the estimates shown here, with a factor 3 variation from low to high.

11. Sensitivity to assumptions on the period of life lost to acute effects on mortality when applying the VOLY approach to valuation

There is no firm evidence as to the period of life that is lost on average to the acute effects of air pollution on mortality. Some speculate that it could be a matter of a few days, others that the true figure is in the order of months, perhaps as long as a year. In this study we have adopted a mean of 6 months, roughly in the middle of other estimates that have been made. We would expect the median to be significantly less than the mean. Variation of this figure leads to a simple linear variation in the estimate of benefits based on the VOLY approach.

12. Sensitivity to assumptions on the period of life lost to chronic effects on mortality when applying the VOSL approach to valuation

For chronic effects on mortality there is uncertainty as to the average period of life lost by those affected. Here we assume an average of 10 years per case which appears conservative, biasing the results of a VOSL based analysis downwards. Results are further biased downwards by the use of the lower estimate of the VOSL from NERA (1997).

4.3 IMPACTS ON MATERIALS

4.3.1 Results

Results for benefits in terms of reduced damage to building materials are shown in Table 11. The difference between scenarios H1/2/3 and the H5 scenarios demonstrates the dominant role of SO_2.

Table 11. Annual benefits for 2010 of reduced damage to materials from moving to the scenarios examined from REF. All figures in million Euro (1990).

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	1	2	3	1	1	1
Belgium	7	9	10	1	1	1
Denmark	0	0	1	0	0	0
Finland	0	0	0	0	0	0
France	9	14	21	2	3	3
Germany	15	22	29	4	4	5
Greece	0	0	0	0	0	0
Ireland	0	1	1	0	0	0
Italy	4	5	17	3	4	5
Luxembourg	1	1	2	0	0	0
Netherlands	11	14	17	1	1	2
Portugal	0	0	1	0	0	0
Spain	1	2	11	0	1	1
Sweden	0	1	2	0	0	0
United Kingdom	24	41	54	1	1	2
Total	75	110	170	15	17	20

4.3.2 Key sensitivities

Key sensitivities in assessment of materials damage are:

1. Assumptions of behaviour with respect to maintenance.
2. Lack of country specific inventory data.
3. Definition of service lifetimes.
4. Assumptions relating to the exposure of material used in buildings, compared to the exposure of experimental samples.
5. Assumptions regarding the mechanism of paint damage from air pollution.
6. Omission of;
    a) Effects on historic buildings
    b) Effects on steel in re-inforced concrete

c) Ozone effects on paint and polymers
d) Indirect economic effects.

For the first three of these sensitivities it is possible the direction of error introduced by the assumptions made in this study is not identifiable. Sensitivities 4 and 5 are likely to tend to overestimation of damage, though paint effects seem so small that sensitivity can be ignored in the context of the wider analysis conducted here. In the broader context of this analysis the omissions listed are probably unimportant, given the comparatively low level of benefit quantified for the materials that are included.

4.4 IMPACTS ON AGRICULTURE

4.4.1 Results

Estimated benefits attributable to the scenarios studied over those of the move to the REF scenario are given in Table 12.

Table 12. Estimated annual benefits to agriculture in 2010 of reducing emissions. All figures in million Euro (MEuro), base year 1990. All results show difference to REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	19	21	24	20	22	25
Belgium	44	43	35	50	56	62
Denmark	13	14	18	13	14	16
Finland	1	1	1	1	1	1
France	510	590	740	520	620	730
Germany	200	200	240	220	240	260
Greece	81	78	58	82	79	71
Ireland	7	8	8	7	8	8
Italy	450	500	610	450	500	660
Luxembourg	0	0	-1	0	0	0
Netherlands	82	74	49	90	99	110
Portugal	13	25	34	15	24	32
Spain	59	160	380	72	140	250
Sweden	2	3	3	3	3	3
United Kingdom	100	110	48	110	120	130
Total	1600	1800	2200	1600	1900	2300

4.4.2 Key sensitivities

The following key sensitivities have been identified regarding effects on agriculture;

1. Extrapolation of exposure-response functions to different cultivars and crops from those tested experimentally.
2. Assumptions regarding relationship between forage and livestock/milk production.
3. Effect of water stress on sensitivity to ozone.

4. Omission of interactions between;
    a) different pollutants
    b) pests
    c) pathogens
    d) frost
    e) other environmental stresses
5. Omission of indirect economic effects

The overall direction of error in the estimates made is, as for most other receptors, not clear. Of the sensitivities listed we can be confident that 3 would bias to overestimation of damage if left uncorrected and that 4 is likely to bias towards underestimation.

Water stressed plants are less susceptible to ozone damage than plants growing in an ideal environment because their stomata shut, greatly reducing gas transfer between the ambient air and sensitive sites within leaves. This effect is of much concern because of the strong correlation between water stress and periods when ozone levels are high. Experimentally grown plants are typically not water stressed, and so available data would appear likely to over-estimate ozone damages.

Holland *et al* (1998a, b) reviewed data on irrigation across Europe. More than 15% of arable and permanent crops in Albania, Bulgaria, Cyprus, Denmark, Greece, Italy, Moldova, the Netherlands, Portugal and Spain are irrigated at rates typically in excess of 200 mm per year. Most attention is presumably given to high value crops, so these should be at less risk of drought effects than lower value crops (hence the % of crop *value* under irrigation may be much greater than the % of crop *area* under irrigation). Permanent crops with deep root systems may not be seriously affected by drought in all but the most adverse situations within Europe. Taking this information into account, the effect of drought on crop yield/ozone relations may not be substantial.

4.5 EFFECTS ON FOREST PRODUCTIVITY

4.5.1 Results

Results are presented in Table 13. Both the functions derived for Norway spruce and for beech have been used and an average taken. It would be possible to apply them separately to soft- and hard-wood production respectively. However, given the uncertainties associated with the derivation of the exposure-response functions such refinement seems unnecessary.

4.5.2 Key sensitivities

1. Extrapolation of exposure-response functions;
    a) to mature forests
    b) to forests across Europe
    c) to species other than beech and Norway spruce
2. Assumptions on costing - response of the forestry sector to long term changes in forest productivity.
3. The need for discounting damages to the time when forests are harvested.

4. Exclusion of impacts;
   a) use values not linked to timber production
   b) effects of acidification and eutrophication (only ozone is considered by the functions used here).

Table 13. Estimated annual benefits for 2010 in terms of timber and pulp production of reducing ozone levels in Europe. All results show difference to REF scenario. No account is taken of the effects of acidification and nitrogen deposition.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	11	12	15	11	12	14
Belgium	6	6	6	6	6	7
Denmark	0	0	0	0	0	0
Finland	2	2	3	2	2	3
France	43	51	67	43	51	61
Germany	35	38	44	35	39	43
Greece	1	1	1	1	1	1
Ireland	0	0	0	0	0	0
Italy	8	9	12	8	9	12
Luxembourg	0	0	0	0	0	0
Netherlands	1	1	1	1	1	1
Portugal	3	6	8	4	6	7
Spain	3	7	17	4	7	11
Sweden	5	5	7	5	5	6
United Kingdom	2	3	2	2	3	3
Total	120	140	180	120	140	170

The problems with exposure-response functions are certainly not insignificant, but they are likely to be of secondary importance to issues surrounding forest economics. It is possible that there is sufficient timber grown in Europe for any losses linked to ozone to be absorbed by a slight, but sustainable increase in the area of forest harvested each year. Another possibility is that conversion of agricultural land to forest is needed to maintain supplies. Given the extended life cycle of forests compared to agriculture these changes could be planned and costs minimised. Yet another possibility is that failure to act fast enough to counteract the threat of future shortages could have serious repercussions in years to come. Again, given the extended life cycle of forests and the discounting of future forest revenues it is possible that even severe problems in the forest sector in the future could count for little now in economic terms (though this does not necessarily mean that nothing should be done about them). The analysis conducted here implies that damages will be small, compared to other things considered in this study, though effects could become much more significant of course were the effects of acidification and eutrophication brought in.

It must be noted that the analysis presented here values forests only in terms of timber production. Amenity and existence values associated with forests are large, and if these were taken into account results could increase substantially.

4.6 EFFECTS ON ECOSYSTEMS

Damage to ecosystems has not been quantified in monetary terms in this report due to a lack of good valuation data, and concern over the application of existing economic methods to issues of sustainability. However, we do report the results of Amann *et al* (1999) which describe exceedence of critical loads and levels, in order that these measures of risk can be set alongside the other effects quantified.

In 1990 critical loads for acidification and eutrophication were exceeded across 25% and 55% of ecosystems in the EU respectively. Substantial improvements with respect to acidification are anticipated under the REF scenario, with only the Netherlands predicted to have more than 25% of ecosystems subject to exceedence in 2010 (Table 14). Elsewhere, Belgium, Germany and the UK would have more than 10% of ecosystems with exceedence. Eutrophication appears a more difficult problem with only six EU Member States with less than 25% of ecosystems in exceedence by 2010 (Table 15). Four countries, Belgium, Germany, Luxembourg and the Netherlands are predicted to have exceedence across more than 90% of ecosystems in 2010.

Given the concern that acidification has raised within Europe it appears certain that the major improvements predicted in moving from 1990 emissions to the REF scenario would be valued highly when the results of the economic studies by Navrud (1988), Johansson and Kristrom (1988), Ecotec (1994) and MacMillan (1996) are considered. However, future reduction in the risk of acidification may not be valued so highly in many countries, with 10 of the 15 having exceedence over less than 5% of ecosystems (Table 14: accepting the definition of exceedence adopted for the IIASA study which excludes the 2% most sensitive ecosystems). Set against this is the prediction that in five countries there is predicted to be a halving in ecosystems at risk from acidification under the H1 scenario (Table 14). Also, exceedence will not be uniform but concentrated in areas of high deposition, so that some types of ecosystem will remain at high risk, possibly even in countries with apparently low exceedeence rates. The general high level of exceedence for eutrophication could imply that reductions in exceedence of this critical load could be highly valued.

Further research is clearly needed in this area. At the moment we can only infer that significant benefits could arise from further reduction of critical loads exceedence from a very limited stock of data, and this in itself does not allow quantification of damages. To achieve a successful valuation it will be necessary to consider not just the area of ecosystem at risk, but also the extent to which different types of ecosystem are at risk.

Table 14. Ecosystems with acid deposition above their critical loads for acidification for the REF, H1, H2 and H3 scenarios.

	1000 ha				Percent of ecosystems			
	REF	H2	H1	H3	REF	H2	H1	H3
Ambition		Low	Central	High		Low	Central	High
Austria	162	122	99	78	3.3	2.5	2.0	1.6
Belgium	155	99	52	24	22.1	14.0	7.4	3.4
Denmark	9	7	6	4	2.3	1.8	1.5	1.1
Finland	1183	1164	1150	1130	4.3	4.3	4.2	4.1
France	218	111	88	38	0.7	0.4	0.3	0.1
Germany	1617	1110	727	515	15.8	10.8	7.1	5.0
Greece	0	0	0	0	0.0	0.0	0.0	0.0
Ireland	12	9	9	8	1.3	1.0	1.0	0.9
Italy	74	62	58	52	0.7	0.6	0.6	0.5
Luxembourg	5	4	1	0	5.9	4.3	0.9	0.5
Netherlands	193	134	76	63	60.4	41.8	23.7	19.8
Portugal	1	1	1	1	0.0	0.0	0.0	0.0
Spain	17	17	17	0	0.2	0.2	0.2	0.0
Sweden	1605	1494	1420	1236	4.1	3.9	3.7	3.2
UK	1182	926	649	288	12.3	9.7	6.8	3.0
EU-15	6433	5259	4351	3437	4.3	3.5	2.9	2.3

Table 15. Ecosystems with nitrogen deposition above their critical loads for eutrophication for the REF, H1, H2 and H3 scenarios.

	1000 ha				Percent of ecosystems			
	REF	H2	H1	H3	REF	H2	H1	H3
Ambition		Low	Central	High		Low	Central	High
Austria	3441	3172	2773	2583	58	53	46	43
Belgium	677	644	586	471	96	92	83	67
Denmark	119	99	91	57	38	32	29	18
Finland	2538	2291	2163	1858	15	14	13	11
France	25160	23936	22524	17884	79	75	71	56
Germany	9184	8489	7474	6283	90	83	73	61
Greece	236	206	211	219	10	8	9	9
Ireland	58	57	54	47	6	6	6	5
Italy	3795	3557	3452	3338	32	30	29	28
Luxembourg	80	75	66	54	91	86	75	62
Netherlands	291	284	278	271	91	89	87	85
Portugal	709	708	683	578	25	25	24	20
Spain	1158	1097	964	487	14	13	11	6
Sweden	891	813	737	589	5	4	4	3
UK	126	98	64	0	1	1	1	0
EU-15	48461	45527	42117	34720	40	38	35	29

Table 16. Ozone population exposure for the REF, H1, H2 and H3 scenarios.

	Cumulative population exposure index (million.persons.ppm.h)				Average population exposure index (ppm.h)			
	REF	H2	H1	H3	REF	H2	H1	H3
Ambition		Low	Central	High		Low	Central	High
Austria	3	2	2	2	0.5	0.3	0.3	0.3
Belgium	34	24	23	21	3.1	2.2	2.1	1.9
Denmark	3	2	1	1	0.5	0.3	0.3	0.2
Finland	0	0	0	0	0.0	0.0	0.0	0.0
France	89	56	53	45	1.6	1.0	0.9	0.8
Germany	140	102	99	88	1.8	1.3	1.3	1.1
Greece	4	2	2	2	0.4	0.2	0.2	0.2
Ireland	1	0	0	0	0.3	0.1	0.1	0.1
Italy	63	40	38	33	1.1	0.7	0.7	0.6
Luxembourg	1	1	1	1	3.0	2.2	2.1	1.8
Netherlands	38	28	27	25	2.6	1.9	1.8	1.7
Portugal	8	6	6	5	0.8	0.6	0.6	0.5
Spain	7	4	4	1	0.2	0.1	0.1	0.0
Sweden	0	0	0	0	0.0	0.0	0.0	0.0
UK	77	49	45	42	1.3	0.9	0.8	0.7
EU-15	466	317	300	267	1.3	0.9	0.8	0.7

Table 17. Ozone vegetation exposure indices for the REF, H1, H2 and H3 scenarios.

	Cumulative vegetation exposure index (1000 km^{2}.ppm.h)				Average vegetation exposure index (ppm.h)			
	REF	H2	H1	H3	REF	H2	H1	H3
Ambition		Low	Central	High		Low	Central	High
Austria	257	217	213	201	5.0	4.2	4.1	3.9
Belgium	141	117	115	113	9.1	7.5	7.4	7.3
Denmark	53	38	36	29	1.8	1.3	1.2	1.0
Finland	0	0	0	0	0.0	0.0	0.0	0.0
France	2345	1897	1816	1658	7.3	5.9	5.6	5.1
Germany	1204	966	943	883	5.7	4.6	4.4	4.2
Greece	170	136	137	145	3.1	2.5	2.5	2.7
Ireland	8	4	3	2	0.3	0.2	0.1	0.1
Italy	1186	1017	996	945	7.5	6.5	6.3	6.0
Luxembourg	14	11	11	10	9.3	7.4	7.3	6.8
Netherlands	79	63	63	63	6.1	4.9	4.8	4.9
Portugal	274	254	233	215	4.7	4.4	4.0	3.7
Spain	1281	1197	1093	865	4.2	3.9	3.6	2.8
Sweden	18	10	9	7	0.1	0.0	0.0	0.0
UK	153	102	96	101	1.9	1.2	1.2	1.2
EU-15	7183	6029	5765	5237	3.8	3.2	3.1	2.8

4.7 EFFECT ON VISIBILITY

4.7.1 Results

The estimated annual benefits in terms of willingness to pay for improvements in visibility arising from reducing emissions to the levels of the scenarios investigated are given in Table 18. The benefits quantified here are subject to considerable uncertainty. The results seem too high to be credible against an impact that causes so little concern in Europe at the present time.

Table 18. Annual benefits in 2010 through improvements in visibility by scenario, compared to the REF scenario.

Country	H2	H1	H3	H5/1	H5/2	H5/3
Austria	17	24	38	13	15	17
Belgium	29	44	68	16	18	20
Denmark	4	7	14	2	2	3
Finland	1	2	3	1	1	1
France	110	170	280	81	94	110
Germany	140	220	350	86	92	100
Greece	7	7	5	7	7	5
Ireland	3	6	12	1	1	1
Italy	97	120	180	91	100	120
Luxembourg	5	8	12	4	4	5
Netherlands	47	74	120	25	27	30
Portugal	1	9	24	3	7	12
Spain	15	39	130	11	24	44
Sweden	6	10	18	4	4	5
United Kingdom	83	150	330	28	31	36
Total	570	880	1600	370	430	510

4.7.2 Uncertainties

It is easy to say that analysis of effects on visibility is applicable only in the USA, because no-one voices concern over reduced visual range in Europe. However, given the size of the results it is important to dwell on them, and ask how unreasonable they are. First we need to put the analysis into context. Imagine, for example arriving at the top of the Eiffel Tower to discover that you can hardly see anything of Paris. It seems nonsense to say that this would not affect the enjoyment of anyone who has gone to the expense and effort of making the trip. It is reasonable to conclude, therefore, that some WTP for improvement in visibility is likely to exist in Europe. Unfortunately we do not appear able to postulate with confidence what might be a reasonable figure of damages, or even a reasonable range.

Within this report we cannot resolve the problems associated with this issue. The plain fact is that our estimates of visibility benefits look truly excessive compared to perception of reduced visibility as a problem in Europe. However, the results from the use of US data, and consideration of issues surrounding the problem suggest that there are grounds for believing that people *could* be willing to pay significant amounts of money for improvements in visual range, though it is doubtful that the true figure is as high as those calculated here.

4.8 ESTIMATES OF STATISTICAL UNCERTAINTY

Table 19 provides estimates of error for different damage categories as reported by Holland *et al* (1998a).

Table 19. Estimated geometric standard deviations for different impact categories considered in this analysis.

Damage category	σ_g	$(\sigma_g)^2$	**Rating**
Health - morbidity	3.7	13.7	A
Health - mortality	4.3	18.5	B
Materials damage	3.9	15.2	A
Crops - N and acidity deposition	3.5	12.2	A
Crops - ozone damage	3.8	14.4	A
Forests	4.4	19.4	B
Visibility	5.2	27.0	B

The 95% confidence interval is calculated by dividing/multiplying the median estimate by the square of the geometric standard deviation, shown in the third column of the table. The ranges generated are thus extremely broad (a consequence of multiplicative analysis). The ranges are however heavily skewed, which is apparent from consideration that dividing/multiplying our median estimates by the geometric standard deviation (as opposed to its square) yields the 68% confidence interval. This is illustrated in the following example:

Median estimate for impact *X*: 10 MEuro, Geometric standard deviation: 4

68% confidence interval:	2.5 to 40 MEuro
95% confidence interval:	0.63 to 160 Euro

Note that to some extent at least the confidence bands are misleading. Taking the example of visibility, most would say that the median estimate made in this report is excessive, let alone a 95% confidence interval that would bring in an estimate 27 times as high (though an estimate 27 times lower may seem more reasonable on current evidence). In some other cases the net direction of the biases contained within the analysis is unclear.

Overall this part of the analysis succeeds in providing quantitative data on uncertainty, but on its own fails to clarify issues. [That is, beyond stating that the benefits analysis is subject to large uncertainty, which is already widely appreciated]. Some commentators will no doubt say that the existence of large uncertainties undermines the credibility of benefits analysis as a tool for policy makers. In fact we regard the converse as true: the fact that possible errors are large makes it all the more essential that benefits analysis is carried out so that policy makers develop an appreciation of the potential risks of their actions.

4.9 BENEFITS AGGREGATED BY POLLUTANT

The following series of tables show damages aggregated across impacts by pollutant for each scenario. The order of importance is NO_x, SO_2/O_3, and then lastly NH_3 in scenarios H1/2/3, and NO_x then O_3 for the H5 suite of scenarios. To highlight the fact that not all effects of these pollutants are quantifiable we express totals within the Tables as 'sub-totals': true totals covering all types of damage are not quantified ('nq' in the Tables). Visibility effects are omitted from the Tables because of the complex nature of the function for visual range estimation and the high level of uncertainty in the output.

Table 20. Benefits by pollutant for the H2 scenario (MEuro/year).

	NO_x	**NH_3**	**SO_2**	**O_3**	**Sub-Total**
Health-Morbidity	930	120	400	77	1500
Health-Mortality(VOSL)	8800	1100	4200	3300	17000
Health-Mortality(VOLY)	5300	660	1900	82	8000
Materials	25	-	50	nq	75
Agriculture	-8	-8	-43	1600	1600
Forestry	nq	nq	nq	120	120
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	9700	1200	4600	5100	21000
Sub Total (VOLY)	6300	770	2300	1900	11000
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 21. Benefits by pollutant for the H1 scenario (MEuro/year).

	NO_x	**NH_3**	**SO_2**	**O_3**	**Sub-Total**
Health-Morbidity	1200	360	620	86	2300
Health-Mortality(VOSL)	12000	3400	6600	3700	25000
Health-Mortality(VOLY)	7000	2100	3000	92	12000
Materials	25	-	87	nq	110
Agriculture	-18	-18	-66	1900	1800
Forestry	nq	nq	nq	140	140
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	13000	3700	7200	5800	30000
Sub Total (VOLY)	8300	2400	3600	2300	17000
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 22. Benefits by pollutant for the H3 scenario (MEuro/year).

	NO_x	**NH_3**	**SO_2**	**O_3**	**Sub-Total**
Health-Morbidity	2100	610	1000	86	3900
Health-Mortality(VOSL)	20000	5700	11000	3600	41000
Health-Mortality(VOLY)	12000	3500	5000	91	21000
Materials	25	-	140	nq	170
Agriculture	-35	-35	-103	2400	2200
Forestry	nq	nq	nq	180	180
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	22000	6300	12000	6300	47000
Sub Total (VOLY)	14000	4100	6000	2800	27000
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 23. Benefits by pollutant for the H5/1 scenario (MEuro/year).

	NO_x	**O_3**	**Sub-Total**
Health-Morbidity	930	77	1000
Health-Mortality(VOSL)	8800	3300	12000
Health-Mortality(VOLY)	5400	82	5400
Materials	15	nq	15
Agriculture	-4	1700	1600
Forestry	nq	120	120
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	9700	5100	15000
Sub Total (VOLY)	6300	1900	8200
Effects not quantifiable	nq	nq	nq
Total	nq	nq	nq

Table 24. Benefits by pollutant for the H5/2 scenario (MEuro/year).

	NO_x	**O_3**	**Sub-Total**
Health-Morbidity	1100	89	1200
Health-Mortality(VOSL)	10000	3800	14000
Health-Mortality(VOLY)	6100	95	6200
Materials	17	nq	17
Agriculture	-5	1900	1900
Forestry	nq	140	140
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	11000	6000	17000
Sub Total (VOLY)	7200	2300	9500
Effects not quantifiable	nq	nq	nq
Total	nq	nq	nq

Table 25. Benefits by pollutant for the H5/3 scenario (MEuro/year).

	NO_x	**O_3**	**Sub-Total**
Health-Morbidity	1200	110	1400
Health-Mortality(VOSL)	12000	4500	16000
Health-Mortality(VOLY)	7200	110	7300
Materials	20	nq	20
Agriculture	-6	2400	2300
Forestry	nq	170	170
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	13000	7100	20000
Sub Total (VOLY)	8500	2700	11000
Effects not quantifiable	nq	nq	nq
Total	nq	nq	nq

5. Cost-Benefit Analysis

5.1 COST DATA

Cost data for the scenarios studied here, net of the costs of attaining the REF scenario were given in Section 2. They were calculated at IIASA using the RAINS model; for further details see Amann *et al* (1999).

5.2 COLLATING THE BENEFITS DATA

An uncertainty ranking exercise was conducted as part of an earlier study (Holland *et al*, 1998a) by researchers and government officials in the UK (Appendix III). This provided a means of conducting a stratified sensitivity analysis within the framework of cost-benefit. Once the ranking was complete data were grouped as follows, partly to make data easier to handle, and partly because the ranking exercise is somewhat subjective.

Group I:
    Materials damage (excluding paint)
    Crops - N fertilisation effects
    Effects of acute exposure to air pollutants on mortality (VOLY)
    Morbidity (excluding restricted activity days and chronic effects on bronchitis)
Group II:
    Restricted activity days
    Paint damage from acidic deposition
    Crops - ozone and SO_2 effects
Group III:
    Effects of acute exposure to air pollutants on mortality (VOSL)
    Chronic effects on bronchitis
Group IV:
    Ozone damage to forests
    Effects of chronic exposure to air pollutants on mortality (VOLY)
Group V:
    Effects of chronic exposure to air pollutants on mortality (VOSL)
    Visibility effects

The ranking of course omits a number of impacts or possible impacts which have not been quantified in the study, in particular;

- Health effects for which data are currently unavailable, such as possible chronic effects of ozone on morbidity, or for which we conclude that reported effects are most likely to be artefacts of experimental design (we include direct effects of NO_2 in this category)
- Effects on ecosystems
- Effects on structures and artefacts of cultural merit (it would appear that these are likely to be of little importance in this context, as indicated by the low benefits for reduced damage to those materials that are included)

- Indirect economic effects of pollution damage to agriculture and buildings
- Effects on non-timber attributes of forests
- Altruistic effects related to health impacts

Double counting is possible as effects are added into each group. For example it would be wrong to add VOSL estimates of acute effects on mortality to VOLY estimates. This has been avoided. Chronic and acute estimates of mortality from fine particles are also not combined.

At various meetings the authors have invited those present to follow the instructions given in Appendix III to derive listings that could show a different perspective to that of the UK group that originally carried out the ranking exercise. No further response has been received during subsequent studies, and so the listing derived in the original study are retained.

5.3 COMPARISON OF COSTS AND BENEFITS

Results for the median estimate of each of these impacts have been brought together by group for each country. Overall the results are dominated by effects on health, particularly mortality, though benefits from crop protection are significant when compared with costs, as will be shown below. The categories are now added together sequentially in the following tables, starting with the group to which most confidence is attached (Group I), and compared with the costs of each scenario. Two tables are presented for each scenario, one for each of the two methods for valuation of mortality. The tables are highlighted to identify the number of effect groupings required for benefits to exceed costs. In countries where the sum of all benefits do not exceed costs, the costs column is also highlighted.

Table 26a. Comparison of costs and benefits of moving to the H2 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	10	40	68	300	320	120
Belgium	29	93	140	570	600	590
Denmark	2	17	22	63	67	0
Finland	1	2	3	15	16	0
France	82	660	840	2400	2500	420
Germany	110	410	660	2800	2900	1100
Greece	7	94	110	230	240	450
Ireland	2	9	12	34	37	24
Italy	64	580	760	2200	2300	310
Luxembourg	5	9	19	100	110	11
Netherlands	47	160	250	950	1000	350
Portugal	3	16	18	40	41	21
Spain	12	80	100	300	320	10
Sweden	3	9	16	82	88	73
United Kingdom	90	230	340	1300	1300	740
Total	460	2400	3400	11000	12000	4200

Table 26b. Comparison of costs and benefits of moving to the H2 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	5	35	270	280	570	120
Belgium	19	83	520	530	1100	590
Denmark	1	16	63	63	120	0
Finland	0	2	17	19	33	0
France	44	620	2300	2400	4300	420
Germany	61	360	2500	2500	5300	1100
Greece	3	90	260	260	400	450
Ireland	1	9	36	36	70	24
Italy	29	540	2100	2100	3900	310
Luxembourg	3	7	98	98	210	11
Netherlands	31	150	870	870	1900	350
Portugal	1	15	72	76	100	21
Spain	6	75	330	330	600	10
Sweden	2	7	80	85	170	73
United Kingdom	61	200	1500	1500	2900	740
Total	270	2200	11000	11000	22000	4200

Table 27a. Comparison of costs and benefits of moving to the H1 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	13	49	88	420	440	120
Belgium	37	110	190	820	860	1100
Denmark	2	20	29	99	110	6
Finland	1	3	4	21	23	0
France	110	810	1100	3300	3500	920
Germany	140	500	900	4200	4400	2100
Greece	7	90	100	220	230	340
Ireland	2	12	16	52	57	44
Italy	76	660	880	2700	2800	400
Luxembourg	7	12	27	150	160	4
Netherlands	60	190	320	1400	1500	970
Portugal	6	36	50	170	180	57
Spain	24	210	270	780	820	22
Sweden	5	12	24	130	140	87
United Kingdom	140	320	520	2200	2300	1300
Total	630	3000	4500	17000	17000	7500

Table 27b. Comparison of costs and benefits of moving to the H1 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	7	42	350	360	790	120
Belgium	24	97	680	690	1600	1100
Denmark	1	19	88	88	190	6
Finland	0	2	22	25	46	0
France	60	760	3000	3100	6100	920
Germany	81	440	3400	3400	8000	2100
Greece	3	86	250	250	390	340
Ireland	1	11	49	49	110	44
Italy	34	620	2500	2500	4700	400
Luxembourg	4	10	130	130	300	4
Netherlands	39	160	1100	1100	2700	970
Portugal	3	33	180	180	330	57
Spain	11	200	760	770	1400	22
Sweden	2	10	110	120	260	87
United Kingdom	99	280	2100	2100	4700	1300
Total	370	2800	15000	15000	32000	7500

Table 28a. Comparison of costs and benefits of moving to the H3 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	21	69	130	630	670	140
Belgium	45	130	240	1200	1300	1100
Denmark	3	29	46	180	200	120
Finland	1	4	7	36	39	0
France	150	1100	1500	5200	5500	4300
Germany	200	680	1300	6400	6700	4400
Greece	5	66	76	160	160	120
Ireland	3	14	24	98	110	96
Italy	130	860	1200	3900	4100	730
Luxembourg	9	17	41	230	240	33
Netherlands	74	200	410	2100	2200	1300
Portugal	13	61	100	420	450	57
Spain	84	540	750	2400	2600	600
Sweden	8	20	42	230	250	120
United Kingdom	170	380	790	4200	4500	3200
Total	920	4100	6600	27000	29000	16000

Table 28b. Comparison of costs and benefits of moving to the H3 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	11	59	510	520	1200	140
Belgium	28	110	900	910	2200	1100
Denmark	1	26	140	140	340	120
Finland	1	3	33	36	72	0
France	79	1000	4500	4500	9600	4300
Germany	110	590	4800	4800	12000	4400
Greece	2	64	190	190	290	120
Ireland	2	13	78	78	190	96
Italy	69	800	3500	3500	7100	730
Luxembourg	5	14	190	190	450	33
Netherlands	47	170	1500	1500	3800	1300
Portugal	6	55	360	360	800	57
Spain	48	510	2100	2200	4500	600
Sweden	4	16	180	190	440	120
United Kingdom	120	320	2900	2900	7800	3200
Total	530	3800	22000	22000	51000	16000

Table 29a. Comparison of costs and benefits of moving to the H5/1 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	8	36	58	240	260	120
Belgium	13	74	100	350	370	460
Denmark	1	16	18	40	43	0
Finland	1	2	3	11	12	0
France	55	630	760	1900	2000	370
Germany	62	340	500	1800	1900	920
Greece	7	94	110	230	230	460
Ireland	1	8	9	15	16	0
Italy	60	570	740	2100	2200	310
Luxembourg	3	6	12	69	73	12
Netherlands	21	130	180	560	580	89
Portugal	3	20	25	71	74	22
Spain	9	88	110	250	270	0
Sweden	2	7	11	55	58	73
United Kingdom	37	160	200	520	550	650
Total	280	2200	2800	8200	8600	3500

Table 29b. Comparison of costs and benefits of moving to the H5/1 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	3	32	240	250	450	120
Belgium	6	67	370	380	660	460
Denmark	0	15	48	49	75	0
Finland	0	2	15	17	25	0
France	24	600	2000	2000	3300	370
Germany	27	310	1900	1900	3400	920
Greece	3	90	260	260	400	460
Ireland	0	7	23	23	31	0
Italy	26	540	2100	2100	3600	310
Luxembourg	1	4	75	75	140	12
Netherlands	9	120	620	620	1100	89
Portugal	1	19	93	97	140	22
Spain	4	83	310	310	480	0
Sweden	1	5	62	67	110	73
United Kingdom	16	140	990	990	1400	650
Total	120	2000	9000	9100	15000	3500

Table 30a. Comparison of costs and benefits of moving to the H5/2 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	9	40	63	270	280	120
Belgium	14	82	110	380	400	460
Denmark	1	17	20	43	45	0
Finland	1	2	3	11	12	0
France	64	740	890	2200	2300	720
Germany	68	370	540	1900	2000	930
Greece	7	91	100	220	220	360
Ireland	1	9	10	17	18	0
Italy	68	650	840	2400	2500	420
Luxembourg	3	6	14	76	80	30
Netherlands	23	140	190	600	620	140
Portugal	5	34	45	140	150	57
Spain	16	170	210	520	550	10
Sweden	2	7	12	57	61	73
United Kingdom	41	180	220	570	600	960
Total	320	2500	3300	9500	9900	4300

Table 30b. Comparison of costs and benefits of moving to the H5/2 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	4	35	260	270	500	120
Belgium	6	75	420	420	720	460
Denmark	0	16	53	53	80	0
Finland	0	2	16	18	26	0
France	28	700	2300	2400	3800	720
Germany	30	330	2000	2100	3600	930
Greece	3	87	250	250	380	360
Ireland	0	8	26	26	35	0
Italy	29	610	2300	2400	4200	420
Luxembourg	1	4	84	84	160	30
Netherlands	10	130	680	680	1100	140
Portugal	2	31	160	170	270	57
Spain	7	160	580	580	940	10
Sweden	1	6	66	71	120	73
United Kingdom	19	160	1100	1100	1500	960
Total	140	2400	10000	11000	18000	4300

Table 31a. Comparison of costs and benefits of moving to the H5/3 scenario from the REF scenario with mortality valuation based on VOLY with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	10	46	73	310	320	170
Belgium	16	91	130	430	450	500
Denmark	1	19	22	49	51	1
Finland	1	2	3	13	14	0
France	76	880	1100	2600	2700	1400
Germany	76	410	600	2200	2300	1100
Greece	6	80	90	170	180	200
Ireland	1	10	11	20	22	0
Italy	84	820	1000	2800	2900	970
Luxembourg	4	7	16	87	91	30
Netherlands	25	150	210	660	690	140
Portugal	7	46	65	230	240	98
Spain	27	300	370	940	980	44
Sweden	3	8	14	65	70	92
United Kingdom	45	190	240	650	690	1100
Total	380	3100	3900	11000	12000	5800

Table 31b. Comparison of costs and benefits of moving to the H5/3 scenario from the REF scenario with mortality valuation based on VOSL with values in MEuro/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	+II	+III	+IV	+V	Costs
Austria	4	40	300	320	570	170
Belgium	7	82	460	470	810	500
Denmark	1	18	59	59	90	1
Finland	0	2	18	20	29	0
France	33	840	2800	2800	4500	1400
Germany	33	370	2300	2300	4100	1100
Greece	2	77	220	220	310	200
Ireland	0	9	30	30	41	0
Italy	36	780	2900	2900	4900	970
Luxembourg	2	5	95	95	180	30
Netherlands	11	140	740	750	1300	140
Portugal	3	42	230	240	410	98
Spain	11	280	980	990	1600	44
Sweden	1	7	75	80	130	92
United Kingdom	20	170	1200	1200	1700	1100
Total	170	2900	12000	13000	21000	5800

5.3.1 Trends in the Results

5.3.1.1 Variation in the benefit:cost ratio

Variation in the ratio of benefits to costs is shown in Table 32. The higher the figure, the more cost-effective the measures applied, in terms of the impacts quantified here. The table shows that the patterns observed agree with the expectation that benefit per unit cost should fall as emission standards are tightened.

Table 32. Benefit:cost ratios for each scenario; benefits based on VOLY valuation of mortality, with all quantified benefits included.

Scenario	Benefit	Cost	Ratio
H2	12000	4200	2.81
H1	17000	7500	2.32
H3	29000	16000	1.79
H5/1	8600	3500	2.47
H5/2	9900	4300	2.31
H5/3	12000	5800	2.01

5.3.1.2 Scenario H1, H2, H3: Joint targets, mortality valuation using VOLY

Taking the whole of the EU into account it was found necessary for benefits to exceed costs to include all impact categories up to category IV (including chronic effects of fine particles on mortality) when following valuation in terms of life years lost. This was true for all 3 scenarios. However, having added in category IV effects, total benefits exceeded costs by significant factors in all cases.

Costs exceed total estimated benefits in Belgium and Greece for H1, Greece only for H2, but for no countries in H3.

5.3.1.3 Scenario H1, H2, H3: Joint targets, mortality valuation using VOSL

Taking the whole of the EU into account it was found necessary for benefits to exceed costs to include all impact categories up to category III (including effects of acute exposure on mortality) when basing mortality valuation on the value of statistical life. This was true for all 3 scenarios. Having added in category III effects, total benefits again exceeded costs by a significant factor in each case.

Overall, bringing in all 5 categories in the confidence ranking, only Greece experienced cost in excess of benefit (scenario H2).

5.3.1.4 H5 Scenarios: Ozone targets only, mortality valuation using VOLY

Similar patterns are observed for this suite of scenarios as for H1/2/3; with mortality valuation based on VOLY, all categories up to category IV (including effects of chronic exposure to fine particles on mortality) are required. Costs exceed benefits for Belgium, Greece, Sweden and the UK in all three scenarios.

5.3.1.5 H5 Scenarios: Ozone targets only, mortality valuation using VOSL

Only Greece in scenario H5/1 is predicted to experience a net cost for these conditions.

5.3.2 Effects of main sensitivities

The main sensitivities identified in the course of this study are as follows;

1. Alternative approaches to valuation of mortality
2. Inclusion of function for assessment of the chronic effects of fine particles on mortality
3. Assumption that all fractions of PM_{10} are equally aggressive to human health
4. Inclusion of function linking ozone to mortality and the effect of possible thresholds for ozone effects on mortality
5. Prediction of changes in ozone exposure using the EMEP model
6. Influence of meteorological and other factors on estimates of changes in crop yield
7. Inclusion of effects on livestock production
8. Inclusion of effects arising from changes in visibility
9. Omission of effects on ecosystems, possible chronic effects of ozone exposure on morbidity, indirect economic effects arising from reduced agricultural yield, altruistic effects of health impacts, etc.
10. Error in RAINS estimates of costs
11. Starting point bias (use of the REF scenario, rather than 1990 emissions data).

Each of these is now considered in turn. For the most part they are considered individually, though some interpretation of their possible combined effect is also provided.

5.3.2.1 Alternative approaches to valuation of mortality

The effect of this sensitivity is explicitly demonstrated in the tables. Adopting the VOLY approach leads to net benefits provided that it is also accepted that chronic exposure to fine particles is causally associated with premature mortality (note: this, nor any other statement made in this report should be thought to imply that air quality is here regarded as the only or indeed the main factor that influences the timing of death). Observing that total quantified benefits exceed costs by a factor of about 2 for all scenarios it is clear that the VOLY could be reduced below the 67,000 Euro applied to these chronic effects for costs and quantified benefits to balance.

5.3.2.2 Inclusion of function for assessment of the chronic effects of fine particles on mortality

There is much debate about the validity of the association observed by Pope et al, and (accepting that it is valid) the correct interpretation of Pope's results for quantification purposes. On this latter point note that the results of Pope have already been scaled down by a factor 2 here to account for previous exposure to levels of PM that are higher than those found in urban areas of the USA and EU today. The valuation wen using the VOSL is also (intentionally) biased towards conservatism. If this function were not included the conclusion that benefits exceed costs would only apply when mortality valuation was based on the VOSL.

5.3.2.3 Assumption that all fractions of PM_{10} are equally aggressive to human health

In the absence of substantive information to the contrary this assumption is followed here with respect to nitrates. Further work to clarify this issue is extremely important as it will enable better targeting of measures to reduce the health impacts of exposure to particles in the ambient air. An alternative assumption that nitrates are not harmful (because of their solubility, chemical characteristics, or whatever) would clearly lead to zero benefits from nitrate particle-related mortality in this study. The effect of this assumption is illustrated in the next section (5.3.2.4).

5.3.2.4 Inclusion of function linking ozone to mortality, and the effect of possible thresholds for ozone effects on mortality

The use of ozone thresholds would have little effect on the overall results on its own. Adopting the VOLY approach to valuation there would be almost no effect at all, as associated results for acute effects of air pollution on mortality are insignificant. Even when the VOSL approach is used it is apparent from results presented in this that the use of an ozone threshold would not make much difference: benefits at the EU level would still exceed costs once category IV impacts (VOLY valuation case) or category III impacts (VOSL valuation case) were added in. Given that this is the case when ozone effects on mortality are reduced by a factor 18 to account for a threshold (assuming the UK COMEAP analysis to be correct), the inclusion or exclusion of the ozone mortality function is itself of little account in most respects. As several of the main sensitivities identified here are associated with mortality it is instructive to see how total benefits summed across morbidity, agriculture, forests and materials compare with costs (Figure 1). Effects on visibility are also excluded from this comparison, because of their low confidence ranking.

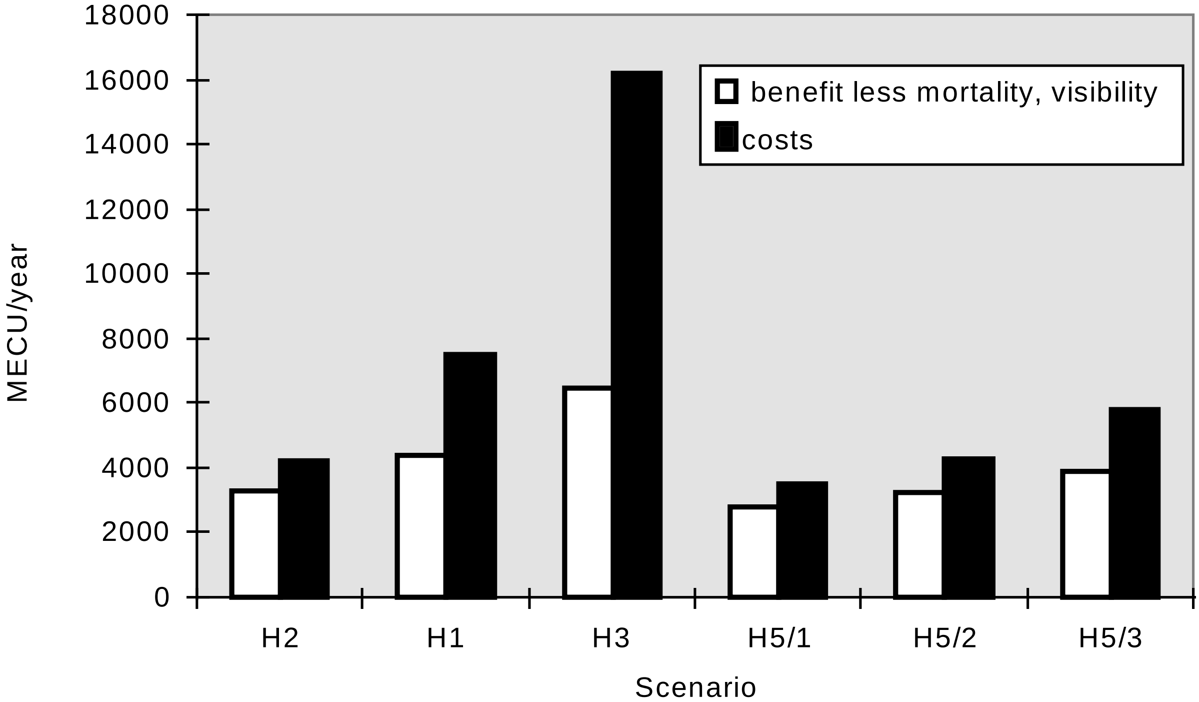


Figure 1. Comparison of costs with benefits without accounting for pollution-related mortality and effects on visibility, and other effects not quantified in this study (e.g. those listed in section 5.3.2.9).

The figure shows that costs (assuming the RAINS estimates are correct) would exceed benefits for all scenarios, if benefits were restricted to the aspects of morbidity, agriculture, forests and materials that it has been possible to value here. The addition of known effects other than on mortality and visibility that are unquantified (on ecosystems, non-timber attributes of forests, some types of material such as rubber, etc.) could well drive benefits beyond costs for some or all of the scenarios considered. Given the closeness of some of the results shown in Figure 1 the accuracy of the estimates of costs made by RAINS is extremely important if mortality effects are entirely or partially eliminated from the analysis. There is a widely held view that RAINS tends to overestimate costs because the abatement techniques considered are restricted to technological solutions. Allowing flexibility in the way that countries can meet their emissions target would bring in a broader range of options, some of which could well be less expensive than those considered by RAINS. An argument against this made by representatives of industry seems to be based on the view that the cost-effectiveness of at least some of the measures included in RAINS is over-estimated, though this view may not have considered the availability of potentially cheaper options excluded from RAINS in coming to its conclusions.

5.3.2.5 Prediction of changes in ozone exposure using the EMEP model

The problems of modelling the benefits of emissions abatement using the EMEP model with its 150 by 150 km resolution have already been discussed in this report. The implicit assumption in our analysis is that the EMEP model correctly predicts changes in ozone exposure. (Note that this becomes complicated for the benefits assessment because of thresholds for effects on vegetation and possibly on health). Ideally modelling at a much finer resolution would be done in order to gauge the reliability of the assessment carried out here. However, this type of modelling was beyond the scope of this study.

5.3.2.6 Influence of meteorological and other factors on estimates of changes in crop yield

There is much resistance to the quantification of effects of ozone on agriculture, arising from an inability to account for a number of environmental factors. Water stress is perhaps the most important of these, and a failure to consider it could lead to a significant overestimation of benefits. Set against this is the fact that large parts of the driest areas of the EU are irrigated, presumably in those areas where high value crops are grown. Also set against this is the omission of other influences that could be related to ozone exposure that would further reduce yield, such as interactions of air pollution with some pests and pathogens.

5.3.2.7 Inclusion of effects on livestock production

The approach used for inclusion of effects on livestock and milk production, scaling production against changes in pasture grass productivity, is in itself prone to significant uncertainty. However, the maximum error set against other quantified effects on agriculture is only around 20%, so is unlikely to have a significant effect on the overall assessment.

5.3.2.8 Inclusion of effects arising from changes in visibility

There is little confidence in the quantification of welfare benefit associated with changes in visibility. This is reflected by the fact that this impact was ranked last in the confidence ranking exercise. It is noted however that the inclusion or exclusion of effects on visibility had little effect on the balance of the cost benefit equation for any scenario: inclusion of visibility was not needed for overall benefits to exceed costs in any scenario, taking the base case assumptions as correct.

5.3.2.9 Omission of effects on ecosystems, possible chronic effects of ozone exposure on morbidity, indirect economic effects arising from reduced agricultural yield, altruistic effects of health impacts, etc.

Omission of these effects will clearly provide some bias towards underestimation of damages. Accepting that the assumptions followed in the analysis are correct, and that the ratio of benefit to cost is sufficiently high to warrant reduction of ozone levels, the omission of these impacts would not be important. If it is felt that our analysis greatly overestimates benefits, the need to reduce ozone levels is a question of the weighting to be given to the effects that we have not been able to quantify. It was noted in Chapter 4 that there are reasonable grounds for expecting that the benefits from reduction in critical loads exceedence for ecosystems may well provide substantial benefits additional to those quantified here.

5.3.2.10 Error in RAINS estimates of costs

The level of error in the estimated costs of the different scenarios is likely to be markedly less than the error in the benefits assessment. However, as noted above in Section 5.3.2.4, there are circumstances under which error in estimates made by RAINS become important, the example used being the case where estimated mortality benefits are assumed to be too uncertain for inclusion in the cost-benefit analysis, even when valuation is based on the more conservative VOLY approach.

6. Conclusions

1. The starting point for our conclusions is that total estimates of benefits appear likely to exceed costs for all of the scenarios considered.

2. We are careful to say that this is only the starting point. This conclusion needs to be considered against other information presented in the study. Most notable are the level of confidence associated with estimated benefits, and the weighting that should be given to effects that remain unquantified. The limitations of other inputs to the work, notably the cost estimates made at IIASA and the results of the EMEP ozone model also need to be considered.

3. There are two general approaches to assessment of benefits that are subject to significant uncertainty. The first is conservative, quantifying only those effects for which it is felt that associated uncertainty will be small. The second, which was followed here, is to quantify more widely, and then to consider the potential errors involved (a theme that is explored throughout the report). Adopting the first approach is most useful in considering what level of pollutant concentration or deposition may be considered 'safe', or pose an 'acceptable risk'. Beyond establishing whether or not a pollutant is known to be harmful to one or more receptor types, it may provide rather poor guidance on the range of possible effects of a pollutant, and on the balance of costs and benefits. For cost-benefit analysis we prefer the alternative, to quantify as far as possible and then to consider the uncertainties. Backed up by an appropriate level of uncertainty and sensitivity analysis a reasonably robust and complete perspective can be obtained.

4. Based on extensive review of the potential for error in the analysis, the key sensitivities in this analysis were found to be;
   a) Issues relating to the assessment of mortality generally
   b) Prediction of changes in ozone exposure using the EMEP model
   c) Influence of meteorological and other factors on estimates of changes in crop yield
   d) Omission of effects on ecosystems, possible chronic effects of ozone exposure on morbidity, indirect economic effects arising from reduced agricultural yield, altruistic effects related to health impacts, etc.

5. Other sensitivities were explored, but found to be less significant. The inclusion of a function for quantifying the effects of acute exposure to ozone on mortality, for example, was found to have very limited impact on the results. When valued using the value of life years (VOLY) approach, ozone related mortality was insignificant compared to costs. When the value of statistical life was applied instead, the benefits relating to reductions in secondary particle concentrations (through lower SO_2 NH_3 and NO_x emissions) were found to be sufficient to drive benefits higher than costs, though the benefit:cost ratio would clearly be affected. Note that there are in turn questions over the role of nitrates in the association between particulate matter and mortality.

6. The most important impacts in the benefits analysis were those on human health and crops. Effects on forest productivity and materials were negligible in comparison, whilst those on

ecosystems were unquantified. Unlike some previous studies, it was found that the benefits from reduced impacts on agriculture offset a significant proportion of total costs. The extent to which the analysis is dominated by health effects is thus reduced.

7. Valuation of changes in visibility, based on US data, suggest that this effect could be significant. However, it is not perceived to be an important issue in Europe at the present time. Many reasons can be proposed for the difference in perception between Europe and the USA, but without original data from Europe the issue must remain one of speculation. Results of this part of the analysis are thus regarded as being of very low reliability, and most commentators, including the authors suspect that they are seriously over-estimated. Visibility damages were found to be of very little importance in the comparison of costs and benefits because of their low position in the confidence ranking exercise.

8. Effects on the agricultural sector are complicated, as both sulphur and nitrogen depositions have the capacity to improve crop growth, whilst ozone will reduce it. Overall, the negative ozone effect substantially outweighs the benefits of S and N fertilisation.

9. Combining different assumptions on the individual elements in the list of uncertainties given at point [6] above, it is possible to generate total benefits estimates that are smaller than the costs for the scenarios considered. Our analysis does not therefore ‘prove beyond all reasonable doubt’ that benefits would exceed costs. We do however believe that the assumptions that go into our core analysis form a reasonable interpretation of available data. Section 5 demonstrated rather limited sensitivity to variation in most of the key uncertainties identified so far as to the question of whether benefits would exceed costs. We therefore feel justified in saying that our starting point conclusion [point 1], that benefits are likely to exceed costs for all scenarios, is reasonably robust.

10. The findings presented here are only one of several inputs to the political process of determining air quality limits that provide an appropriate level of protection for human health and the environment. The decision on limit values needs to take into account variation in the benefit:cost ratio, and aversion to risks of error on both sides of the cost-benefit equation.

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The views and methodologies adopted in this report do not necessarily reflect those of the study sponsors, DGXI of the European Commission, other contributors to work on air quality legislation for the European Commission and UNECE activities under the Convention on Long Range Transboundary Air Pollution, nor of other members of the ExternE project team.

Appendix I

Abbreviations and Terminology

AOT40	Accumulated concentration of ozone over a threshold of 40 ppb
AOT60	Accumulated concentration of ozone over a threshold of 60 ppb
CBA	Cost-benefit analysis
CLE	Current legislation scenario
CO	Carbon monoxide
CO_2	Carbon dioxide
CRP	Current reduction plan scenario
CV	Contingent valuation
DETR	UK Department of the Environment, Transport and the Regions
DNMI	Norwegian Meteorological Institute
DTI	UK Department of Trade and Industry
EC	European Commission
EU	European Union
IIASA	International Institute for Applied Systems Analysis
IOM	Institute of Occupational Medicine
ITE	Institute of Terrestrial Ecology
LRTAP	Convention on Long Range Transboundary Air Pollution
MFR	Maximum feasible reduction scenario
NH_3	Ammonia
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
O_3	Ozone
PM_{10}	Fine particles less than 10 μm in diameter
$PM_{2.5}$	Fine particles less than 2.5 μm in diameter
REF	Reference scenario
SO_2	Sulphur dioxide
TFEAAS	Task Force on Economic Aspects of Abatement Strategies
UNECE	United Nations Economic Commission for Europe
VOCs	Volatile organic compounds
VOLY	Value of life year
VOSL	Value of statistical life
WTA	Willingness to accept
WTP	Willingness to pay
YOLL	Years of life lost

MATHEMATICAL NOTATION

The following prefixes and suffixes are used in this work;

E*x*, E-*x* as a suffix to a number, denotes that the number in question should be multiplied by 10 to the power *x* or -*x*. Hence 6.4E-3 is equal to 0.0064.

The following prefixes to units are also used;
n = nano = 10^{-9}
μ or u = micro = 10^{-6}
m = milli = 10^{-3}
k = kilo = 10^{3} = thousands
M = mega = 10^{6} = millions
G = giga = 10^{9} = billions

This system is standard notation in the sciences. Note that m and M are not equivalent (by a factor of 10^{9}) and hence should not be interchanged.

Appendix II

Data Used in the Analysis

AII.1 Modelling Pollution Concentrations and Deposition

The analysis is based on the EMEP 150 x 150 km grid. Model runs have been carried out at the Norwegian Meteorological Institute, relating emissions in a number of years to air concentrations and deposition of all of the pollutants relevant to this study. Average transfer coefficients for each country to grid cell combination were calculated for a six year period (covering 1989 to 1994), in order to account for meteorological variation. Data on ozone were supplied specifically for the scenarios assessed (Simpson, Heyes, personal communication, January 1999), based on average meteorology over a five year period.

AII.2 Health Effects Assessment

AII.2.1 Stock at risk data and atmospheric modelling

The main source of population data used here is the RIVM land use database (Veldkamp and van der Velde, 1995). These data have been transferred to the EMEP 150 x 150 grid, and disaggregated to urban and rural populations. The Bosnian population, absent from the original inventory, was taken from UN sources.

Additional data to those provided by RIVM are required to define the fraction of the population in various groups considered to be at special risk - the elderly, children, and asthmatics. In addition, death rate data are required for the whole of Europe. Data on age structure and death rates were obtained from Rayner *et al* (1994), drawing on relevant UN reports (Demographic Yearbook, Population and Vital Statistics Report and World Population Prospects). Over Europe these provide average factors as follows;

Fraction of children in European population: 0.2
Fraction of adults in European population: 0.8
Fraction of people > 65 years in European population: 0.14
Annual death rate per thousand people: 10.2

The following estimates are made for asthmatics (R. Anderson, personal communication, October 1997);

Child asthmatics as a fraction of the UK population: 0.02
Adult asthmatics as a fraction of the UK population: 0.04

AII.2.2 Exposure-response functions

The available literature on the health effects of air pollution has been reviewed by Hurley, Donnan and their colleagues at the Institute of Occupational Medicine, providing the exposure-response functions listed in Table AII.1. The protocol followed was to review the literature to identify effects for which the evidence seemed reasonably strong. The reported functions for these effects are taken from individual studies that appear representative of the broader literature. The uncertainty rating (also developed under the ExternE Project) provides an assessment of uncertainty throughout the chain of analysis - in other words from quantification of emissions through to valuation of damage. Table AII.1 contains a 'core' set of exposure-response functions and AII.2 functions recommended only for use in sensitivity analysis within the ExternE Project. Many different sensitivity analyses could be performed for the present study. The functions listed in Table AII.2 have not been included here; the Table is retained here to show that there are possible areas of under-estimation for the health impacts assessment.

AII.2.3 Valuation data

Valuation of mortality related to air pollution exposure has been conducted using both the value of statistical life (VOSL) and value of life year (VOLY) approaches. Debate on this issue is continuing. Values used are shown in Tables AII.3 to 5.

Table AII.1. Quantification of human health impacts. The exposure response slope, f_{er}, has units of [cases/(yr-person-ug/m^3)] for morbidity, [% change in annual mortality rate/(ug/m^3)] for acute effects on mortality, and years of life lost for chronic effects on mortality.

Receptor	Impact Category	Reference	Pollutant	f_{er} [1]	Uncertainty rating [2]
ASTHMATICS					
adults	Bronchodilator usage	Dusseldorp *et al*, 1995	PM_{10}	0.163	B
	Cough	Dusseldorp *et al*, 1995	PM_{10}	0.168	A
	Lower respiratory symptoms (wheeze)	Dusseldorp *et al*, 1995	PM_{10}	0.061	A
children	Bronchodilator usage	Roemer *et al*, 1993	PM_{10}	0.078	B
	Cough	Pope, Dockery, 1992	PM_{10}	0.133	A
	Lower respiratory symptoms (wheeze)	Roemer *et al*, 1993	PM_{10}	0.103	A
all	Asthma attacks (AA)	Whittemore, Korn, 1980	O_3	4.29E-3	B?
ELDERLY 65 years +					
	Congestive heart failure (CHF)	Schwartz, Morris, 1995	PM_{10}	1.85E-5	B
CHILDREN					
	Chronic bronchitis	Dockery *et al*, 1989	PM_{10}	1.61E-3	B
	Chronic cough	Dockery *et al*, 1989	PM_{10}	2.07E-3	B
ADULTS					
	Restricted activity days (RAD)[3]	Ostro, 1987	PM_{10}	0.025	B
	Minor restricted activity day(MRAD)[4]	Ostro, Rothschild, 1989	O_3	9.76E-3	B
	Chronic bronchitis	Abbey *et al*, 1995	PM_{10}	4.9E-5	A
ENTIRE POPULATION					
	Respiratory hospital admissions (RHA)	Dab *et al*, 1996	PM_{10}	2.07E-6	A
		Ponce de Leon, 1996	SO_2	2.04E-6	A
			O_3	7.09E-6	A
	Cerebrovascular hospital admissions (CVA)	Wordley *et al*, 1997	PM_{10}	5.04E-6	B
	Symptom days	Krupnick *et al*, 1990	O_3	0.033	A
DEATH RATES					
	Acute Mortality	WHO, 1997	PM_{10}	0.074%	B
	Acute Mortality	Anderson *et al*, 1996, Touloumi *et al*, 1996	SO_2	0.072%	B
		Sunyer *et al*, 1996	O_3	0.059%	B
	Chronic Mortality	Pope *et al*, 1995	PM_{10}	0.00036	B

[1] Sources: [ExternE, European Commission, 1995b; 1998] and [Hurley and Donnan, 1997].

[2] Uncertainty ratings are discussed in more detail in Section 3.8. A rating of 'A' is equivalent to a geometrical standard deviation of 2.5 to 4; one of 'B' to between 4 and 6.

[3] Assume that all days in hospital for RHA, CHF and CVA are also restricted activity days (RAD). Also assume that the average stay for each is 10, 7 and 45 days respectively.

Thus, **net RAD = RAD - (RHA*10) - (CHF*7) - (CVA*45)**.

[4] Assume asthma attacks are also MRAD, and hence should deducted from the MRAD total.

Table AII.2. Human health functions not applied in this study, but illustrating a potential for underestimation in the benefits assessment. The exposure response slope, f_{er} , is primarily from data for Western Europe and has units of [cases/(yr-person-ug/m^3)] for morbidity, and [%change in annual mortality rate/(ug/m^3)] for mortality.

Receptor	Impact Category	Reference	Pollutant	f_{er}[1]	Uncertainty rating[1]
ELDERLY, 65 years +					
	Ischaemic heart disease	Schwartz and Morris, 1995	PM_{10}	1.75E-5	B
ENTIRE POPULATION					
	Respiratory hospital admissions (RHA)	Ponce de Leon, 1996	NO_2	2.34E-6	A?
	ERV for COPD	Sunyer *et al*, 1993	PM_{10}	7.20E-6	B?
	ERV for asthma	Schwartz, 1993 and Bates *et al*, 1990	PM_{10}	6.45E-6	B?
		Cody *et al*, 1992 and Bates *et al*, 1990	O_3	1.32E-5	B?
	ERV for croup in pre school children	Schwartz *et al*, 1991	PM_{10}	2.91E-5	B?
	Acute Mortality	Sunyer *et al*, 1996, Anderson *et al*, 1996	NO_2	0.034%	B?

[1] See footnotes to Table AII.1.

Table AII.3. Estimated VOLY for acute and chronic effects of air pollution at different discount rates. The 4% discount rate is selected as a median estimate.

Type of effect/discount rate	VOLY (1990Euro)
Acute effects on mortality	
0%	61,000
4%	110,000
10%	195,000
Chronic effects on mortality	
0%	98,000
4%	67,000
10%	50,000

Table AII.4 Estimated VOSL for acute and chronic effects of air pollution on mortality from NERA (1997).

Type of effect	VOSL (1990Euro)
Acute effects on mortality	
Low bound	0
High bound	2,200,000
Chronic effects on mortality	
Low bound	1,100,000
High bound	2,200,000

Table AII.5. Values in Euro for morbidity impacts (Markandya, to be published in European Commission, 1998).

Endpoint	Value	Estimation Method and Comments
Acute Morbidity		
Restricted Activity Day (RAD)	63	CVM in US estimating WTP.
Symptom Day (SD) and Minor Restricted Activity Day	6.3	CVM in US estimating WTP. Account has been taken of Navrud's study.
Chest Discomfort Day or Acute Effect in Asthmatics (Wheeze)	6.3	CVM in US estimating WTP. Same value applies to children and adults.
Emergency Room Visits (ERV)	186	CVM in US estimating WTP.
Respiratory Hospital Admissions (RHA)	6,560	CVM in US estimating WTP.
Cardiovascular Hospital Admissions	6,560	As above.
Acute Asthma Attack	31	COI (adjusted to allow for difference between COI and WTP). Applies to both children and adults.
Chronic Morbidity		
Chronic Illness (VSC)	1,000,000	CVM in US estimating WTP.
Chronic Bronchitis in Adults	88,000	Rowe et al (1995).
Non fatal Cancer	375,000	US study.
Malignant Neoplasms	375,000	Valued as non-fatal cancer.
Chronic Case of Asthma	88,000	Based on treating chronic asthma as new cases of chronic bronchitis.
Cases of change in prevalence of bronchitis in children	225	Treated as cases of acute bronchitis.
Cases of change in prevalence of cough in children	188	As above.

AII.3 Damage to Materials

AII.3.1 Stock at risk data

The stock at risk is derived from data on building numbers and construction materials taken from building survey information. Such studies are generally performed for individual cities; these can then be extrapolated to provide inventories at the national level. For countries for which data are not available, values must be extrapolated from elsewhere, though this inevitably results in lower accuracy. In general it is assumed that the distribution of building materials follows the distribution of population. Sources of data are as follows;

Eastern Europe (including the former East Germany):
Kucera *et al* (1993b), Tolstoy *et al* (1990) - data for Prague
Scandinavia:
Kucera *et al* (1993b), Tolstoy *et al* (1990) - data for Stockholm and Sarpsborg
UK, Ireland:
Ecotec (1996), data for UK extrapolated to Ireland
Former West Germany:
Hoos *et al* (1987) - data for Dortmund and Köln
Other western Europe:
Average of material use per person from Hoos *et al*, Kucera *et al* and Tolstoy *et al* (excluding Prague), and Ecotec.

For galvanised steel in structural (non-building) applications an average of material data was derived from European Commission (1995b) and Kucera *et al* (1993b).

AII.3.2 Meteorological, atmospheric and background pollution data

The exposure-response functions require data on meteorological conditions. Of these, the most important are precipitation and humidity. Data have been taken from Kucera (1994).

AII.3.3 Dose-response functions

The main source of data for exposure response functions used here is the work conducted under the UN ECE Programme (Kucera, 1993a, 1993b, 1994). This section lists the dose-response functions used, which should be assumed to originate from the work of Kucera unless otherwise referenced. The following key applies to all equations given:

ER = erosion rate (um/year)
P = precipitation rate (m/year)
SO_2 = sulphur dioxide concentration (ug/m^3)
O_3 = ozone concentration (ug/m^3)
H^+ = acidity (meq/m^2/year)
R_H = average relative humidity, %
f_1 = $1-\exp[-0.121.R_H/(100-R_H)]$
TOW = fraction of time relative humidity > 80% and temperature >0°C
ML = mass loss (g/m^2) after 4 years

In all the ICP functions, the original H^+ concentration term (in mg/l) has been replaced by an acidity term using the conversion:

$P \cdot H^+$ (mg/l) = $0.001 \cdot H^+$ (acidity in meq/m^2/year)

To convert mass loss for stone and zinc into an erosion rate in terms of material thickness, we have assumed respective densities of 2.0 and 7.14 tonnes/m^3. The functions used are as follows;

Unsheltered limestone (4 years): $ML = 8.6 + 1.49.TOW.SO_2 + 0.097.H^+$
Unsheltered sandstone (4 years) (also mortar): $ML = 7.3 + 1.56.TOW.SO_2 + 0.12.H^+$
Brickwork: no effect
Concrete; assumed no effect, though air pollution may affect steel reinforcement
Carbonate paint: $\Delta ER/tc = 0.01[P]8.7(10^{-pH} - 10^{-5.2})+0.006.SO_2.f_1$ (Haynie, 1986)
Silicate paint: $\Delta ER/tc = 0.01[P]1.35(10^{-pH} - 10^{-5.2})+0.00097.SO_2.f_1$ (Haynie, 1986)
Steel: assumed either painted or galvanised, not assessed independently
Unsheltered zinc (4 years): $ML = 14.5 + 0.043.TOW.SO_2.O_3 + 0.08.H^+$
Sheltered zinc (4 years): $ML = 5.5 + 0.013.TOW.SO_2.O_3$
Aluminium: assumed too corrosion resistant to be affected significantly.

AII.3.4 Calculation of repair frequency

We assume that maintenance is ideally carried out after a given thickness of material has been lost. This parameter is set to a level beyond which basic or routine repair schemes may be insufficient, and more expensive remedial action would be needed. A summary of the critical thickness loss for maintenance and repair are shown in Table AII.6.

Table AII.6. Assumed critical thickness for maintenance or repair measures for building materials.

Material	Critical thickness loss
Natural stone	5 mm
Rendering	5 mm
Mortar	5 mm
Zinc:	
Construction - sheet and strip	25 um
Other construction, agriculture and street furniture	50 um
Pylons, other transport	100 um
Galvanised steel	50 um
Paint	20 um

AII.3.5 Repair costs

Table AII.7. Repair and maintenance costs [Euro/m^2] applied in this analysis.

Material	**Euro/m^2**
Zinc	21
Galvanised steel	25
Natural stone	235
Rendering, mortar	25
Paint	11

AII.4 Effects of Air Pollution on Agricultural Systems

AII.4.1 Acidification of agricultural soils

UK TERG (1988) concluded that the threat of acid deposition to soils of managed agricultural systems should be minimal, since management practices (liming) counteract acidification and often override many functions normally performed by soil organisms. They suggested that the only agricultural systems in the UK that are currently under threat from soil acidification are semi-natural grasslands used for grazing, especially in upland areas. Particular concern has been expressed since the 1970s when traditional liming practices were cut back or ceased altogether, even in some sensitive areas, following the withdrawal of government subsidies. Concern has also been expressed in other countries. Agricultural liming applications decreased by about 40% in Sweden between 1982 and 1988 (Swedish EPA, 1990). Although liming may eliminate the possibility of soil degradation by acidic deposition in well-managed land, the efficacy of applied lime may be reduced by acidic deposition, and application rates may need to be increased.

The basis of the method is to calculate:

- The total amount of acidifying pollutant deposited to the land surface in a given area;
- The amount which falls on soils which require lime (excluding, for example, urban areas, water and soils on calcareous drifts);
- The cost of neutralising this amount of acidic deposition with lime;
- The increased acidic deposition in this area resulting from the change from one scenario to another;
- The additional cost of neutralising the difference in inputs to soils which require lime (priced at 16.8 Euro per tonne of lime).

AII.4.2 Fertilisational effects of nitrogen deposition

Nitrogen is of course an essential plant nutrient, applied by farmers in large quantity to their crops. The deposition of additional nitrogen to agricultural soils may thus be beneficial (assuming that N saturation is not reached). The analysis quantifies total deposition of nitrogen to arable land and permanent pastures. The benefit is calculated directly from the cost of nitrate fertiliser, Euro 430/tonne of nitrogen (Nix, 1990). Given that additional inputs will still be needed under current conditions to meet crop N requirements for intensive agricultural systems there is a negligible saving in the time required for fertiliser application (if any), so it seems reasonable to cost benefits purely in terms of the (perhaps theoretical) reduction in N required as fertiliser.

Similar analysis has not been performed for afforested areas. There is concern that prolonged deposition of N to these areas can lead to nutrient imbalance (Schulze *et al*, 1989), and hence that observed benefits in terms of enhanced productivity are not sustainable.

AII.4.3 Ozone effects

For both scenarios, ozone crop damages have been calculated using EMEP's accumulated ozone above a threshold of 40 ppb (AOT40) metric, where AOT40 is defined by:

$$AOT40 = \int \max(O_3 - 40, 0).dt$$

The time integral is over the growing season, which, for crops, is taken to be daylight hours in the months May-July. The metric has the units ppb.hours, or ppm.hours.

Functions are listed in tables AII.8 and AII.9.

Table AII.8. Estimated sensitivity of different crops to ozone. Species written in normal type are discussed in the review by Jones *et al* (1997). Species written in italics are not specifically discussed by Jones *et al*, but do feature in European crop production statistics. Sensitivity in these cases is estimated by analogy with similar crops.

Tolerant crops	maize	barley	leaf crops	sugar beet
	raspberries	olives	olive oil	strawberries
	cabbages			
Slightly sensitive crops	pasture grass	sorghum	oats	rye
	rice	*millet*		
Sensitive crops	wheat	clover	soybeans	beans
	potato	tomato	sunflower	grapes
	apples	*oranges*	*plums*	*watermelons*
	lemons	*peaches*	*grapefruit*	*carrots*
	limes	*pears*	*tangerine*	*cucumbers*
	flax	*hops*	*onion*	*dates*
	hemp	*linseed*	*rapeseed*	*sesame seed*
Very sensitive crops	tobacco			

Table AII.9. **Ozone exposure-response functions.**

Crop type	**Exposure Response Function** % loss per ppm.hour AOT40
Tolerant crops	0
Slightly sensitive crops	1.0
Sensitive crops	1.75
Very sensitive crops	3.57
Meat and milk products	0.5

AII.4.4 SO_2 effects

The following functions were used to quantify % yield change (y) from SO_2 effects on agriculture, derived from the work of Baker *et al* (1986), accounting for the fertilisational effect of sulphur at low concentration (European Commission, 1995);:

$y = 0.74(SO_2) - 0.055(SO_2)^2$ (from 0 to 13.6 ppb SO_2)
$y = -0.69(SO_2) + 9.35$ (above 13.6 ppb SO_2)

These functions have been applied to the following crops:

maize
oats
leaf crops
soybeans
sunflower
hops
tobacco
barley
rye
sugar beet
beans
carrots
hemp
wheat
millet
raspberries
potato
cucumber
linseed
sorghum
rice
strawberries
tomato
flax
sesame seed

For pasture the following function has been used, based on a review by Roberts (1984). All data used to derive the functions was taken from studies on *Lolium perenne*, the most common pasture grass in Europe. Again, the functions have been adapted to account for fertilisation of crops below the lowest exposure adopted experimentally.

$y = 0.20(SO_2) - 0.013(SO_2)^2$ (from 0 to 15.3 ppb)
$y = -0.18(SO_2) + 2.75$ (above 15.3 ppb)

Meat and milk production are assumed to be 50% as sensitive as pasture grass, on which livestock are primarily dependent for food.

AII.4.5 Valuation of crop losses

Valuation of crop losses has been undertaken using prices from United Nations Food and Agriculture Organisation (FAO, 1994).

AII.5 Ecosystem Damage

Data on ecosystem impacts are taken directly from Amann *et al* (1999). They provide estimated exceedence of critical loads for acidification and eutrophication in each country in the European Union.

AII.6 Forest Damage

In the economic assessment of effects of air pollution on forests we focus on the effects of ozone. At the Kuopio workshop on critical levels (Karenlampi and Skarby, 1996) two functions were proposed for ozone effects on forest productivity;

Species: beech; % productivity change = $-0.27x$
Species: Norway spruce; % productivity change = $-0.18x$
where x = ozone expressed as AOT40, (the ozone concentration accumulated over a threshold of 40 ppb in daylight hours over the growing season), expressed in ppm.hours.

In this study no economic assessment is made of the effects on forestry of acidification, N deposition and exposure to SO_2 due to a lack of data. Impacts are quantified only to the extent of identifying areas in which ecosystems (including forests) experience exceedence of critical loads and critical levels.

AII.7 Visibility

The core reference used here is the review by Landrieu (1997), prepared for the meeting of the UNECE TFEAAS of June 1997. Virtually all published data in this area are from the USA.

Light extinction results from two phenomena, scattering and absorption. The function proposed for the analysis adds together extinction from various fractions of ambient air;

$$b = b_{air} + e_S\left(SO_4^{--}\right) f\left(RH\right) + e_N\left(NO_3^{-}\right) f\left(RH\right) + e_O\left(organics\right) g\left(RH\right)$$
$$+ e_C\left(elementalcarbon\right) + e_D\left(otherfineparticles\right) + e_G\left(NO_2\right)$$

b = light extinction coefficient of the atmosphere (km^{-1})
b_{air} = scattering of light by molecules in unpolluted air = 0.011 km^{-1} (average value)
SO_4^{--}, NO_3^{-}, etc. are air concentrations of the pollutants of concern
$e_{subscript}$ defines the scattering efficiencies of each fraction. The units given in the Landrieu paper are $m^2\ mg^{-1}$, except for NO_2, for which e_G is expressed in $km^{-1}ppm^{-1}$). Values for each are as follows, noting in most cases that there is an absence of specific field data;

e_S = 0.003 e_N = 0.003
e_O = 0.003 e_C = 0.012
e_D = 0.001 e_G = 0.33

f(RH) and g(RH) are ratios of the scattering due to hygroscopic aerosols at a given relative humidity RH to the scattering at 0% RH

Ammonium is not specifically accounted for in the function proposed by Landrieu. We assume that all ammonium is present as either sulphate or nitrate.

Landrieu describes the complex interaction between humidity and scattering efficiency. Following Sisler *et al* (1994) the following is adopted for the average annual scattering effect of humidity on nitrates and sulphates;

$$f(RH) = 4.6 - 15(RH) + 19(RH)^2$$

and for the average annual scattering effect of humidity on organics;

$$g(RH) = 2.5 - 6(RH) + 5(RH)^2$$

Expanding the equation and expressing NO_2 in ug m^{-3} for consistency with the other pollutants, leaves the function;

$$\begin{aligned}
b = \quad & 0.011 \\
& +0.003\left(SO_4^{--}\right)(4.6 - 15[RH] + 19[RH]^2) \\
& +0.003\left(NO_3^{-}\right)(4.6 - 15[RH] + 19[RH]^2) \\
& +0.003\left(NH_4^{+}\right)(4.6 - 15[RH] + 19[RH]^2) \\
& +0.003(organics)(2.5 - 6[RH] + 5[RH]^2) \\
& +0.012(elemental\ carbon) \\
& +0.001(other\ \ fine\ particles) \\
& +0.00017\left(NO_2\right)
\end{aligned}$$

The ‘haziness index’ (dv) suggested by Pitchford (1994), can be combined with a value of 8 Euro/dv to quantify value (in Euro) per person;

$$value\ per\ person = 8 \cdot dv = 80 \cdot \ln\left(\frac{b}{0.01}\right)$$

Maddison (1997) has reviewed a number of different studies to produce an alternative estimate of WTP. One of the purposes of the analysis was to test whether the results of certain studies were statistically different from the rest of the literature. The function derived by Maddison, converted to give WTP in Euro, and omitting terms that covered studies that Maddison found to be flawed, was:

$$WTP = 125 \cdot \ln(V_2 / V_1)$$

V_1 = initial visual range
V_2 = final visual range

Appendix III

Development of the Stratified Sensitivity Analysis for CBA

AIII.1 Introduction

Formal statistical methods can be used in benefits analysis, but fail to account for some important aspects of uncertainty. In earlier studies of this type we have pioneered what we term as a 'Stratified Sensitivity Analysis for CBA' to communicate uncertainty in a transparent and we hope easily understood manner. The work started by asking numerous experts and interested parties in the UK to rank impact types by order of perceived uncertainty (note the use of the word perceived - the ranking is subjective, and the exercise is inevitably biased by the viewpoint of the person developing the questionnaire). The purpose of this approach is to focus attention on the impact categories that are regarded as most certain, to some extent taking attention away from extremely uncertain impacts that may have little effect on the outcome of the cost-benefit analysis.

Once impacts have been ranked, calculated damages can be added sequentially, starting with those with perceived lowest uncertainty, until they exceed the abatement costs (should they reach this point at all). This can be repeated using alternative estimates based on additional uncertainty analysis.

Possible outcomes are as follows;

1. **Only a few benefit categories are needed to exceed costs, excluding some that are perceived to be relatively well characterised.** In this case the conclusion that benefits will exceed costs looks robust.

2. **All relatively well characterised impacts (however identified) are needed for benefits to exceed costs.** Confidence in the conclusions is reduced, but the conclusion that benefits exceed costs is still likely to look justified because several types of impact remain to be added in, counteracting (albeit to an extent unknown) possible over-estimates amongst the effects that have been included.

3. **Many impact categories are needed, including some that are thought to be quite poorly characterised.** Further loss of confidence in the robustness of the conclusion that benefits exceed costs.

4. **The total of all quantified benefits added together is not sufficient to exceed costs.** This outcome would suggest that the scenario under consideration is too extreme. However,

consideration would still need to be given to the question of whether overall damages are underestimated (e.g. from the exclusion of some impact types such as damage to cultural assets, or from any downward biases present in the modelling framework). Consideration would also have to be given to the question of whether estimated costs were excessive, for example through exclusion of options such as fuel switching.

Of course, it is not enough to simply demonstrate that benefits will exceed costs to justify a given course of action. Ideally one should consider the ratio of benefit to cost for a variety of actions, selecting those where the ratio is highest to gain the most benefit from scarce resources. This is extremely difficult to do, particularly when dealing with issues of contrasting uncertainty. The methods that we are suggesting for uncertainty and sensitivity analysis (in this appendix and in the main text of the report) head in the right direction, but certainly leave scope for further improvement.

AIII.2 Method

The full questionnaire on sensitivity was distributed to some UK analysts, and policy makers in several UK government departments. Full responses were obtained from the authors of the earlier report (Holland *et al*, 1998) and four environmental policy makers. Additional responses were obtained from policy makers in health and transport, who felt unable to complete the ranking exercise because of a lack of familiarity with some areas of the analysis. The full questionnaire is reproduced below.

Sensitivity Analysis Questionnaire

Given that a full and reliable assessment of uncertainty is not possible at the present time it is necessary for individuals to use their experience to generate a ranking. Because this is judgmental it is useful for rankings to be made by people from different areas of expertise, and this has been done under the present study. Steering group members were asked to produce their own rankings for the impacts listed in the following table. The table is followed by guidance notes for its completion.

	Paint damage from acidic deposition
	Crops - N fertilisation effects
	Visibility
	Macroeconomic effects of crop yield change on agriculture
	Acute morbidity (excluding restricted activity days)
	Restricted activity days
	Crops - ozone damage (low estimate taken as 50% of total calculated to account for ozone x drought interaction)
	Crops - ozone damage (high estimate - no account taken of possible interaction with water stress)
	Damage to natural ecosystems
	Acute mortality (low valuation based on value of life years)
	Acute mortality (high valuation based on value of statistical life)
	Crops - need for additional liming to counteract acidification
	Materials damage (excluding paint)
	Forest damage
	Materials damage (macroeconomic effects)
	Chronic effects on mortality (low estimate - VOLY approach)
	Chronic effects on mortality (high estimate - VOSL approach)
	Chronic morbidity (excluding bronchitis)
	Chronic bronchitis

Rules

1. In the left hand column write down the order in which you want to rank effects, 1 being given to the damage estimate that you have most confidence in, through to 19 for the estimate that you regard as being most uncertain.
2. 'Low' estimates for ozone effects on crops and acute mortality have to come in before 'high' estimates. Note, this does not necessarily imply that, for example, the VOLY approach is preferable to the VOSL approach for mortality valuation: if you prefer the VOSL approach you would probably agree that damages would have to be at least those generated using VOLYs.
3. It may be helpful to start by grouping effects according to the broad level of confidence that you have in them.
4. Pay no attention to the listings presented elsewhere in this report. We need an independent ranking from each contributor.
5. Don't assume that anyone knows the 'right' answer - this is not a test of what people know, it is supposed to be an honest survey of perceptions about the uncertainty of different types of impact. Conventional wisdom can be very wide of the mark!
6. Tied rankings, even multiple tied rankings (within reason - a 19 way tie will be assumed to indicate that people did not try hard enough) are preferred where you cannot distinguish between impacts.

[end of questionnaire]

AIII.3 Results

Full results from the survey, and the development of the final ranking were described in our earlier reports to the UNECE (Holland *et al*, 1998a) and the European Commission (Holland *et al*, 1998b). Here we simply reproduce the final ranking. Recognising that the ranking is itself subject to uncertainty, and for ease of subsequent handling of results within the CBA, effects for which confidence was broadly similar were grouped together. A total of 5 groups were used, Group I representing the effects that it was felt could be quantified with the highest confidence, and Group V with the least. This version of the ranking is slightly updated from the original. SO_2 effects on crops have been introduced, whilst secondary economic impacts arising from effects on materials and agriculture, and economic evaluation of impacts on ecosystems have been taken out.

Rank	Effect	Group
1	Materials damage (excluding paint)	I
2	Crops - N fertilisation effects	I
3	Acute mortality (low valuation based on value of life years)	I
4	Acute morbidity (excluding restricted activity days)	I
5	Crops - need for additional liming to counteract acidification	II
6	Restricted activity days	II
7	Paint damage from acidic deposition	II
8	Crops - direct ozone effects on yield	II
9	Crops - direct SO_2 effects on yield	II
10	Chronic morbidity (excluding bronchitis)	II
11	Acute mortality (high valuation based on value of statistical life)	III
12	Chronic bronchitis	III
13	Ozone damage to forests	IV
14	Chronic effects on mortality (low estimate - VOLY approach)	IV
15	Chronic effects on mortality (high estimate - VOSL approach)	V
16	Visibility	V

Appendix IV

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