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Economic Evaluation of Proposals for Emission Ceilings for Atmospheric Pollutants

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AEA Technology

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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 Sixth Interim Report on Cost-effective Control of Acidification and Ground-level Ozone, released in October 1998. 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.

Scenarios

4. The following scenarios from IIASA's Sixth Interim Report were investigated;

- REFERENCE (REF) - the stricter of current legislation/current reduction plans for each country.
- 1990 emissions
- F1: central scenario for reducing acidification, eutrophication and ground level ozone
- F4:'low' ambition scenario for reducing acidification, eutrophication and ground level ozone
- F5: 'high' ambition scenario for reducing acidification, eutrophication and ground level ozone
- F3: central scenario for reducing ground level ozone only
- F3/1: 'low' ambition scenario for reducing ground level ozone only
- F3/3: 'high' ambition scenario for reducing ground level ozone only

Methods

5. 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.

6. 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.

7. 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. For 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.

8. Table 1 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.

9. 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.

10. Debate also concerns the correct approach to apply to valuation of cases of premature mortality, given the fact that 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 in any case, and that 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 MECU. Our analysis finds that this approach would give a result almost identical to our application of the VOLY, so a separate sensitivity analysis has not been undertaken.

11. 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.

12. 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.

13. 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. A more sophisticated assessment is not currently possible given

the lack of appropriate forest growth models. In view of the deficiencies in impact assessment a scenario based approach to valuation is not warranted. Overall results suggest that reduced forest output is likely to be much less important than effects on agriculture.

Table 1. 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 work in the research literature
acute - morbidity	✓	
chronic - morbidity	✓	
Ozone		
acute - mortality	✓	Less clear linkage between O_3 and mortality than for PM_{10}
acute - morbidity	✓	
chronic - morbidity	✗	No data for assessment of chronic effects
SO_2		
acute - mortality	✓	
acute - morbidity	✓	
chronic - morbidity	✗	No data for assessment of 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	✗	Likely to be of limited importance in scenarios that do not consider SO_2 effects
Effects of O_3 on paint, rubber	✗	No exposure-response data yet available
Macroeconomic effects	✗	Analysis based on limited data
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, etc.	✗	Exposure-response data unavailable
Acidification/liming	✓	Effect of atmospheric deposition likely to be negligible
Macroeconomic effects	✗	Analysis based on limited data
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

14. 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. However, given a high degree of uncertainty regarding the transferability of the US data, the inclusion of these results to justify emissions abatement in Europe is not felt to be appropriate.

15. 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).

16. There are clearly numerous uncertainties in the analysis. From review of the potential for error in the analysis, the key sensitivities were;
    - 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.

    The existence of significant uncertainty poses difficulties in interpretation of the results of the study. A variety of techniques have been used to try to resolve the issue in a transparent manner. An alternative to the approach adopted here would be to quantify only those benefits for which it is felt that associated uncertainty would be small. This involves taking a necessarily subjective position on how good the evidence must be on a given effect for analysis to be considered robust. Beyond establishing whether or not a pollutant is known to be harmful, it would provide rather poor guidance on the range of possible effects of the pollutants considered in this study, and on the balance of costs and benefits. Instead we prefer a more holistic approach, quantifying a wide range of impacts and then undertaking a comprehensive analysis of the potential effects of the errors contained in them.

Results

17. 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 (see figures 1 to 4, below). Effects on forest productivity and materials were negligible in comparison, whilst those on ecosystems were unquantified, beyond re-iterating results given in the IIASA Sixth Report. Unlike some previous studies, it was found that the benefits from reduced impacts on agriculture offset a significant proportion of total costs.

18. 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.

19. Statistical uncertainties in the results were quantified and shown to be significant, partly because of the error in each element of the analysis and partly because of the multiplicative nature of the analysis. To these must be added discontinuous uncertainties, for example concerning the use or not of a threshold for ozone effects on mortality, the approach taken to valuation of mortality, the fact that some impacts are not assessed, that some factors, such as those that influence ozone effects on crop yield, are not integrated to the analysis, etc.

These uncertainties are assessed here as far as possible using extensive sensitivity analysis following the initial comparison of costs and benefits.

20. Comparison of costs and benefits is made in Tables 2a and 2b. Data presented are for total benefits across the EU15; additional benefits arising outside the EU are not included. Table 2a shows the results where mortality valuation is based on value of life years (VOLY) whilst Table 2b shows results for mortality valuation based on value of statistical life (VOSL). 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 2a: Comparison of costs and benefits for each scenario, for the case where mortality valuation uses the VOLY approach. For explanation see text.

	Cumulative benefits (MECU/year)					Costs
Scenario	Group I	+ Group II	+ Group III	+ Group IV	+ Group V	(MECU)
1990	4700	14000	25000	110000	120000	49141
Joint Acidification, Eutrophication, Ozone						
F4	590	2800	4200	16000	17000	5754
F1	720	3500	5300	20000	21000	9138
F5	980	4500	7400	31000	33000	17977
Ozone Directive						
F3/1	320	2400	3200	10000	10000	3962
F3	390	2900	4000	13000	14000	5497
F3/3	480	3500	4900	17000	17000	8945

Table 2b: Comparison of costs and benefits for each scenario, for the case where mortality valuation uses the VOSL approach. For explanation see text.

	Cumulative benefits (MECU/year)					Costs
Scenario	Group I	+ Group II	+ Group III	+ Group IV	+ Group V	(MECU)
1990	3200	12000	82000	82000	180000	49141
Joint Acidification, Eutrophication, Ozone						
F4	340	2600	14000	14000	27000	5754
F1	410	3200	17000	18000	35000	9138
F5	550	4100	24000	24000	51000	17977
Ozone Directive						
F3/1	140	2200	10000	10000	18000	3962
F3	170	2700	13000	13000	23000	5497
F3/3	210	3200	16000	16000	29000	8945

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 cost-benefit analysis is based on the difference between the scenario selected and IIASA's REF scenario for 2010.

21. At this point it is important to refer back to Table 1 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 2. 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).

22. 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 1990, REF, F4, F1 and F5 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 from about 25% to 4.4% 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 F1 scenario reduces exceedence in three of these countries to below 10%. The exception is the Netherlands, where exceedence falls from 62% under REF to 24% under F1. 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 F1 scenario all but four member states still show exceedence across more than 10% of ecosystems and five are predicted to still experience exceedence across more than 50% of their ecosystems.

23. The contribution made by each pollutant to the overall balance of costs and benefits is shown in Table 3. The order of pollutants by benefit is in all cases NO_x (highest), SO_2, O_3, NH_3 (lowest).

24. Combining different assumptions on the individual elements in the list of uncertainties given at point [16] 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 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.

Table 3: Damages by pollutant for each scenario: estimates based on value of life years (VOLY) approach and value of statistical life (VOSL) approach are separated. Totals are referred to as 'sub-totals' to indicate that numerous effects have not been quantified in this study.

VOLY	NO_x	NH_3	SO_2	O_3	Sub-Total
1990	59760	2949	43967	6452	113128
F4	9250	1345	3157	2034	15786
F1	11538	2534	3795	2477	20344
F5	18422	4008	5317	2999	30745
F3/1	7796	-	-	2065	9862
F3	10512	-	-	2443	12955
F3/3	13733	-	-	2856	16589

VOSL	NO_x	NH_3	SO_2	O_3	Sub-Total
1990	92309	4589	66932	13343	177173
F4	14291	2085	4810	5136	26323
F1	17827	3927	5784	6092	33632
F5	28463	6213	8112	6641	49430
F3/1	12042	-	-	5315	17357
F3	16237	-	-	6117	22354
F3/3	21214	-	-	7023	28237

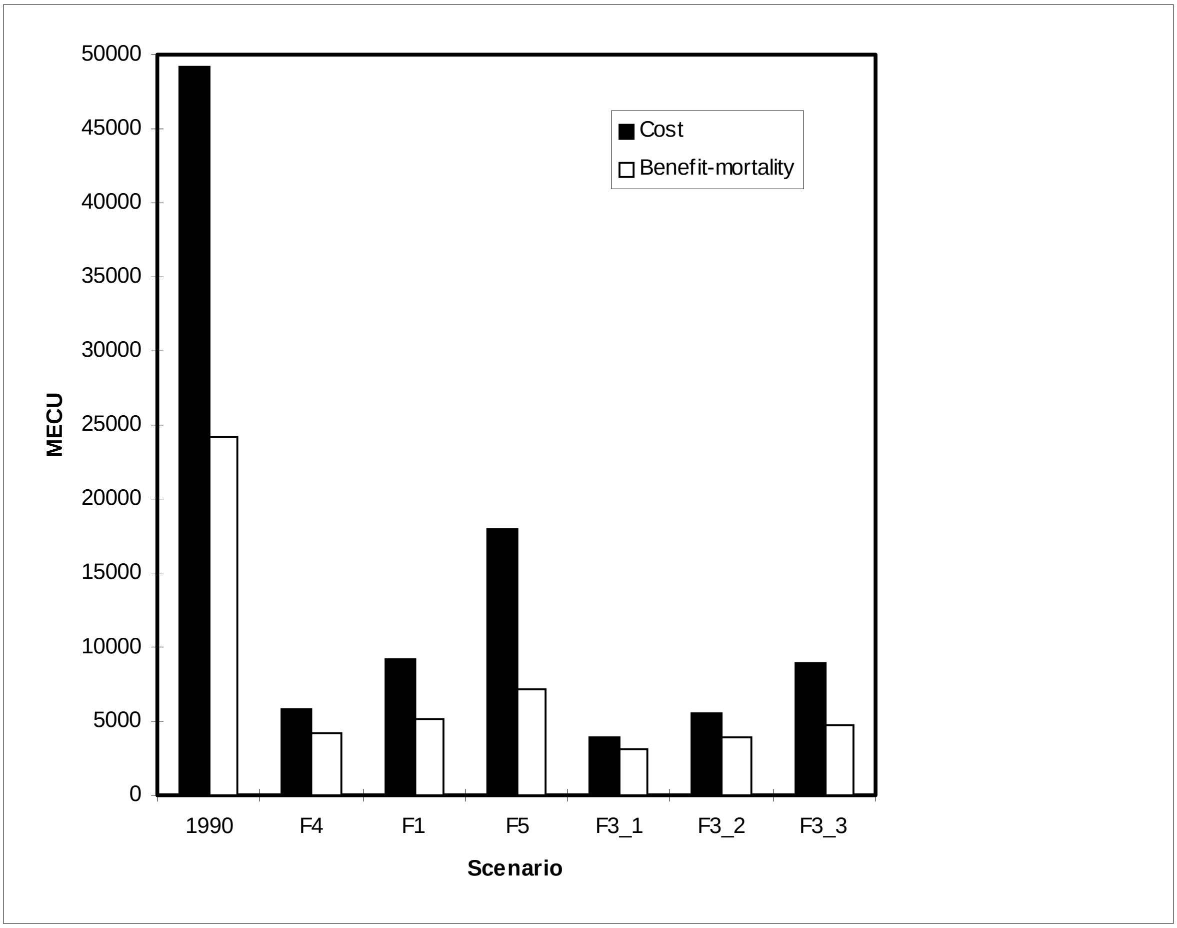

Figure 1. Comparison of costs with quantified benefits without accounting for pollution-related mortality and effects on visibility.

25. 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.

26. 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 provide estimates of the benefits of certain scenarios (see Section 2) developed in the Sixth Interim Report on Cost-effective Control of Acidification and Ground-level Ozone by IIASA (Amann *et al*, 1998). To avoid unnecessary repetition, readers should refer to the series of reports produced at IIASA (Amann *et al*, 1996; 1997;1998a, b) 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. 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. This reflects differences in response to uncertainty. The working groups have tended to restrict their papers to those effects that can be described with most confidence. In the context of cost-benefit analysis 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 to those adopted in the 'core' analysis exist.

1.2 INTERPRETATION OF RESULTS AND UNCERTAINTY

Environmental cost-benefit analysis is frequently subject to a much higher level of uncertainty than other types of analysis (for example, assessment of the costs of abatement of pollution). This level of uncertainty arises through several factors. Firstly, there is the innate variability of ecological systems and human society. Secondly the analysis is essentially multiplicative, which tends to magnify uncertainties. Thirdly some areas of the work require further research before any estimate of damages can be made. Fourthly, much of the analysis currently relies upon the use of assumptions that it has not always been possible to test as thoroughly as desired (for example in transfer of valuation data from one area to another). Despite these problems we contend that the simple fact that analysis of environmental benefits is prone to significant uncertainty is of little relevance, because all analysis is subject to uncertainty, and policy makers routinely have to account for it when making decisions.

We must clearly be explicit about uncertainties in order that policy makers can take account of them. In this study we have sought both to identify and quantify uncertainties to the extent possible. We then provide a highly structured comparison of costs and benefits to allow good understanding of the potential risks of different actions.

Given the problem of high uncertainty, a number of commentators have questioned the desirability of quantifying impacts and of assigning monetary values to them. After all, environmental policy has been made successfully for many years without recourse to cost-benefit analysis, so why start now? The following examples illustrate why it is essential that benefits are quantified, and why it is appropriate to take this analysis beyond impact assessment to monetary valuation.

Consider first the case of the assessment of crop losses induced by exposure to ozone. It is well known that experimental conditions may differ significantly to the average for crops in the field, and that this may alter plant uptake of, and hence response to, ozone. It has been argued that these uncertainties are too significant to permit quantification of effects for use in support of the development of policy. We reject this argument on the grounds that quantification is essential in order to establish whether or not an effect is likely to be significant when compared to the costs that will be incurred in abating pollution. Having made an initial quantification it is of course possible to consider whether an estimate is likely to be too large or too small, and to investigate the problem using sensitivity analysis. Without quantification we can only say whether or not an effect is likely. It is not possible to say whether or not additional pollution abatement is desirable in the interests of providing a solution that best serves society. Nor is it possible to say how far one should go in abating emissions if it is agreed that additional action is needed.

Accepting that impacts should be quantified, it is then logical to ask why they should be monetised. In the case of damage to openly traded goods (crops, timber, materials, etc.) monetisation allows a large number of different impacts to be drawn together into a unified index in a non-controversial manner. Without monetisation this study would need to report results for about 40 different crops; given that a tonne of grain is not directly comparable with a tonne of tomatoes it would be nonsense to simply add together predicted changes in agricultural yield. Also, a unit such as a tonne of grain has limited meaning to most people, whereas everyone understands money.

Clearly the issue is more problematic in relation to human health for example, because it is not traded in the same way as other goods. Some aspects of health can be costed easily and without controversy, such as expenditure on drugs and medical care. However, to quantify other aspects, pain and suffering, death, etc., which tend to dominate the ‘total economic value’ of health damages, we typically rely on willingness-to-pay estimates derived using techniques such as contingent valuation. All that the economics seeks to do here is to establish a monetised index that allows inspection of the preference for the allocation of resources (i.e. money). Hence the question we address is: do people value the effects of pollution damage highly enough that they are willing to spend their money on reducing pollution? We accept that there are important issues that still need to be resolved, regarding for example the valuation of pollution-induced mortality. However, such issues can be explicitly addressed (as is done in this report) using sensitivity analysis. Once this is done, valuations across different receptor types (health, crops, etc.) can be aggregated for comparison against costs.

The next question is why should we need cost-benefit analysis now if we have managed well enough without it in the past? As is shown in this report, the implementation of measures to reduce pollution leads to a gradual reduction in the ratio of benefits to cost. At some point it will be very hard to justify further improvement in air quality ahead of other issues (remembering that money is a limited resource and that air pollution is only one of many problems that we would like to resolve). By routinely weighing costs and benefits against a common index (money) we can create a framework that will in time reduce the possibility of serious inconsistency in decision making processes. Given the amount of legislation that has already been agreed that affects air quality and will lead to continuing improvements in air quality over the coming years, we need to know whether we are still in a position to get a good return on investments made.

This establishes a rationale for quantifying effects in the face of uncertainty, and of expressing them in monetary terms. The next issue concerns interpretation of the overall results of a CBA subject to significant uncertainty. Take three unrelated cases, Options A, B and C, for which costs are quantified with low uncertainty, and benefits quantified, but with a high level of uncertainty. In Option A benefits substantially exceed costs, even at the lower end of the benefit error bar. In Option B costs greatly exceed benefits, even at the upper end of the error bar for benefits. In Option C the comparison does not provide a clear-cut answer with costs within the error bar for benefit. Considering each issue in isolation the political response could well be to accept Option A, reject Option B and either accept Option C or defer a decision until better information is available.

However, in the real world policies are rarely considered in isolation and other factors could influence decisions. For example, Option A could be rejected on the grounds that although it is worthwhile there are other options available that are likely to give higher benefits per unit cost. Option B could be accepted if it was known, for example, that some effects that were perceived to be important had been excluded from the analysis. Accordingly, the cost-benefit analysis presented in this report, and other materials presented to the policy makers, provide information, but do not alone define policy. Our role is therefore to improve understanding of the likely magnitude of effects and the uncertainties on both sides of the cost-benefit equation is essential in order to allow policy-makers the opportunity to balance the risk of error against their own views on risk aversion. This should allow the rationale behind any decision made to be well founded and explicit.

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
NH_3	Effects of NH_3 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 of this report contains details of the REF and MFR scenarios that define the extremes for the 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). 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* (1998):

- REFERENCE (REF - against which all other scenarios, including 1990 emissions, are compared)
- 1990 emissions
- F1: central scenario for reducing acidification, eutrophication and ground level ozone
- F4:'low' ambition scenario for reducing acidification, eutrophication and ground level ozone
- F5: 'high' ambition scenario for reducing acidification, eutrophication and ground level ozone
- F3: central scenario for reducing ground level ozone only
- F3/1: 'low' ambition scenario for reducing ground level ozone only
- F3/3: 'high' ambition scenario for reducing ground level ozone only

Targets for the different scenarios are given in Table 2 for scenarios F1, F4 and F5, and Table 3 for the F3 scenarios.

Table 2. Summary of the environmental targets for the scenarios F1, F4, F5.

	Low ambition (F4)	Central scenario (F1)	High ambition (F5)
Acidification			
Gap closure on accumulated excess acidity	90%	95%	95%
Maximum excess deposition for the 2% most sensitive ecosystems	(900 eq/ha)	(850 eq/ha)	800 eq/ha
Ozone - health			
Gap closure on AOT60	60%	66%	70%
Maximum AOT60 for 4 out of 5 years	3.0 ppm.h	2.9 ppm.h	2.7 ppm.h
Ozone - vegetation			
Gap closure on AOT40	30%	33%	35%
Maximum AOT40 for 4 out of 5 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% most sensitive ecosystems	(1400 eq/ha)	(1300 eq/ha)	1000 eq/ha

Table 3. Summary of the environmental targets for the F3 scenarios.

Table to be completed.

	Low ambition (F3/1)	Central scenario (F3)	High ambition (F3/3)
Ozone - health			
Gap closure on AOT60	60%	66.7%	70%
Maximum AOT60 for 4 out of 5 years	3.0	2.9	2.7
Ozone - vegetation			
Gap closure on AOT40	30%	33.3%	35%
Maximum AOT40 for 4 out of 5 years	13.5	13.0	12.5

Emission and cost data for each scenario are shown in the following tables.

Table 4. Emissions and control costs for NO_x and VOC for 1990 and the REF scenario (emissions in kilotons, costs in million ECU/year). From Amann *et al*, 1998c.

		NO_x			VOC		Costs
	1990	REF	Change	1990	REF	*Change*	of REF
Austria	192	113	-41%	352	208	-41%	784
Belgium	351	207	-41%	398	212	-47%	1000
Denmark	274	136	-50%	162	86	-47%	383
Finland	276	162	-41%	213	112	-47%	525
France	1867	1044	-44%	2399	1242	-48%	6180
Germany	2662	1263	-53%	3066	1137	-63%	8704
Greece	345	344	0%	336	205	-39%	933
Ireland	113	81	-28%	111	46	-59%	410
Italy	2037	1186	-42%	2053	1176	-43%	6881
Luxembourg	22	10	-55%	19	8	-58%	60
Netherlands	542	312	-42%	490	241	-51%	1486
Portugal	208	197	-5%	217	144	-34%	1092
Spain	1162	892	-23%	1048	669	-36%	4793
Sweden	338	200	-41%	492	287	-42%	976
UK	2839	1186	-58%	2663	1351	-49%	5934
EU-15	13226	7333	-45%	14017	7123	-49%	40140
Albania	24	36	50%	30	37	23%	0
Belarus	402	180	-55%	279	231	-17%	210
Bosnia-H.	80	60	-25%	46	43	-7%	1
Bulgaria	354	290	-18%	198	192	-3%	4
Croatia	83	83	0%	79	87	10%	6
Czech Rep.	522	231	-56%	322	224	-30%	492
Estonia	84	73	-13%	44	44	0%	1
Hungary	214	196	-8%	206	144	-30%	424
Latvia	117	90	-23%	51	40	-22%	31
Lithuania	152	110	-28%	104	84	-19%	29
Norway	220	151	-31%	308	196	-36%	495
Poland	1209	810	-33%	709	754	6%	1217
Moldova	87	34	-61%	52	41	-21%	46
Romania	518	458	-12%	483	505	5%	0
Russia	3485	2675	-23%	3332	2696	-19%	16
Slovakia	207	112	-46%	143	141	-1%	325
Slovenia	60	31	-48%	60	25	-58%	125
Switzerland	163	89	-45%	291	173	-41%	715
FYR Macedonia	39	29	-26%	20	20	0%	1
Ukraine	1888	1094	-42%	1074	836	-22%	139
Yugoslavia	211	152	-28%	124	121	-2%	3
Non-EU	10118	6983	-31%	7954	6635	-17%	2301
Total[1]	24973	15945	-39%	21971	13758	-37%	42441

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[1] Including ship emissions

Table 5. Emissions and control costs for SO_2 and NH_3 for 1990 and the REF scenario (emissions in kilotons, costs in million ECU/year). From Amann *et al*, 1998c.

		SO_2		Costs		NH_3		Costs
	1990	REF	Change	of REF	1990	REF	*Change*	of REF
Austria	93	42	-55%	174	77	67	-13%	0
Belgium	336	208	-38%	341	97	96	-1%	0
Denmark	185	90	-51%	115	77	72	-6%	0
Finland	232	116	-50%	204	40	31	-23%	0
France	1250	489	-61%	1004	805	798	-1%	0
Germany	5280	608	-88%	2146	757	571	-25%	0
Greece	504	562	12%	331	80	74	-8%	0
Ireland	178	70	-61%	108	127	126	-1%	9
Italy	1679	593	-65%	1577	462	416	-10%	12
Luxembourg	14	4	-71%	9	7	7	0%	15
Netherlands	201	74	-63%	306	233	136	-42%	237
Portugal	284	146	-49%	152	71	67	-6%	0
Spain	2189	793	-64%	678	352	353	0%	28
Sweden	119	67	-44%	293	61	48	-21%	113
UK	3805	980	-74%	1148	329	297	-10%	0
EU-15	16348	4842	-70%	8586	3576	3159	-12%	413
Albania	72	55	-24%	0	32	35	9%	0
Belarus	843	480	-43%	4	219	163	-26%	0
Bosnia-H.	487	415	-15%	0	31	23	-26%	0
Bulgaria	1841	846	-54%	126	141	126	-11%	0
Croatia	180	70	-61%	52	40	30	-25%	3
Czech Rep.	1873	368	-80%	293	107	108	1%	0
Estonia	275	175	-36%	0	29	29	0%	0
Hungary	913	546	-40%	144	120	137	14%	0
Latvia	121	57	-53%	15	43	35	-19%	0
Lithuania	213	107	-50%	0	80	81	1%	0
Norway	50	27	-46%	62	23	21	-9%	0
Poland	2999	1397	-53%	739	505	508	1%	16
Moldova	197	117	-41%	0	47	48	2%	0
Romania	1331	594	-55%	132	292	300	3%	1
Russia	5012	2344	-53%	691	1282	894	-30%	0
Slovakia	548	137	-75%	80	60	47	-22%	0
Slovenia	200	37	-82%	41	23	21	-9%	0
Switzerland	43	30	-30%	72	72	66	-8%	0
FYR Macedonia	107	81	-24%	0	17	16	-6%	0
Ukraine	3706	1488	-60%	325	729	649	-11%	0
Yugoslavia	585	269	-54%	47	90	82	-9%	0
Non-EU	21595	9638	-55%	2822	3980	3418	-14%	20
Total[2]	39096	14480	-62%	11408	7556	6577	-13%	433

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[2] Including ship emissions

Table 6. NO_x and VOC emissions for the variations in the ambition levels of the joint scenarios: F4 - low ambition level, F1 - central scenario, F5 - high ambition level. Percentage changes relate to the year 1990. From Amann *et al*, 1998c.

	NO_x								VOC							
	REF		F4 low ambition		F1 central		F5 high ambition		REF		F4 low ambition		F1 central		F5 high ambition	
	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*
Austria	113	-41%	100	-48%	94	-51%	93	-52%	208	-41%	131	-63%	133	-62%	143	-59%
Belgium	207	-41%	111	-68%	111	-68%	111	-68%	212	-47%	103	-74%	103	-74%	103	-74%
Denmark	136	-50%	136	-50%	136	-50%	116	-58%	86	-47%	86	-47%	86	-47%	86	-47%
Finland	162	-41%	162	-41%	162	-41%	162	-41%	112	-47%	112	-47%	112	-47%	112	-47%
France	1044	-44%	788	-58%	757	-59%	686	-63%	1242	-48%	948	-60%	866	-64%	792	-67%
Germany	1263	-53%	1088	-59%	1062	-60%	879	-67%	1137	-63%	953	-69%	947	-69%	883	-71%
Greece	344	0%	303	-12%	338	-2%	344	0%	205	-39%	175	-48%	202	-40%	205	-39%
Ireland	81	-28%	74	-35%	66	-42%	57	-50%	46	-59%	46	-59%	46	-59%	46	-59%
Italy	1186	-42%	1003	-51%	879	-57%	830	-59%	1176	-43%	981	-52%	935	-54%	885	-57%
Luxembourg	10	-55%	5	-77%	5	-77%	5	-77%	8	-58%	5	-74%	5	-74%	5	-74%
Netherlands	312	-42%	275	-49%	261	-52%	211	-61%	241	-51%	160	-67%	154	-69%	150	-69%
Portugal	197	-5%	129	-38%	112	-46%	108	-48%	144	-34%	130	-40%	127	-41%	127	-41%
Spain	892	-23%	877	-25%	822	-29%	712	-39%	669	-36%	669	-36%	669	-36%	665	-37%
Sweden	200	-41%	193	-43%	181	-46%	181	-46%	287	-42%	256	-48%	235	-52%	244	-50%
UK	1186	-58%	1186	-58%	1186	-58%	914	-68%	1351	-49%	1044	-61%	1032	-61%	958	-64%
EU-15	7333	-45%	6429	-51%	6171	-53%	5409	-59%	7123	-49%	5799	-59%	5651	-60%	5404	-61%

Table 7. SO_2 and NH_3 emissions for the variations in the ambition levels of the joint scenarios: F4 - low ambition level, F1 - central scenario, F5 - high ambition level. Percentage changes relate to the year 1990. From Amann *et al*, 1998c.

	SO_2								NH_3							
	REF		F4 low ambition		F1 central		F5 high ambition		REF		F4 low ambition		F1 central		F5 high ambition	
	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*
Austria	42	-55%	42	-55%	42	-55%	42	-55%	67	-13%	67	-13%	67	-13%	66	-14%
Belgium	208	-38%	109	-68%	64	-81%	64	-81%	96	-1%	85	-12%	60	-38%	57	-41%
Denmark	90	-51%	90	-51%	48	-74%	31	-83%	72	-6%	71	-8%	70	-9%	68	-12%
Finland	116	-50%	116	-50%	116	-50%	116	-50%	31	-23%	31	-23%	31	-23%	31	-23%
France	489	-61%	258	-79%	256	-80%	171	-86%	798	-1%	792	-2%	727	-10%	619	-23%
Germany	608	-88%	526	-90%	453	-91%	419	-92%	571	-25%	437	-42%	396	-48%	388	-49%
Greece	562	12%	562	12%	562	12%	562	12%	74	-8%	74	-8%	74	-8%	74	-8%
Ireland	70	-61%	32	-82%	32	-82%	32	-82%	126	-1%	125	-2%	122	-4%	126	-1%
Italy	593	-65%	593	-65%	593	-65%	593	-65%	416	-10%	416	-10%	416	-10%	316	-32%
Luxembourg	4	-71%	4	-71%	4	-71%	2	-86%	7	0%	7	0%	7	0%	7	0%
Netherlands	74	-63%	53	-74%	53	-74%	53	-74%	136	-42%	129	-45%	106	-55%	105	-55%
Portugal	146	-49%	146	-49%	146	-49%	146	-49%	67	-6%	67	-6%	67	-6%	67	-6%
Spain	793	-64%	769	-65%	759	-65%	376	-83%	353	0%	353	0%	353	0%	353	0%
Sweden	67	-44%	67	-44%	67	-44%	67	-44%	48	-21%	48	-21%	48	-21%	48	-21%
UK	980	-74%	564	-85%	537	-86%	430	-89%	297	-10%	274	-17%	264	-20%	238	-28%
EU-15	4842	-70%	3930	-76%	3731	-77%	3104	-81%	3159	-12%	2974	-17%	2807	-22%	2563	-28%

Table 8. Emission control costs for the variations in the ambition levels of the joint scenarios: F4 - low ambition level, F1 - central scenario, F5 - high ambition level, in million ECU/year. From Amman *et al*, 1998c.

	SO_2				NO_x/VOC				NH_3				Total			
	REF	F4	F1	F5	REF	F4	F1	F5	REF	F4	F1	F5	REF	F4	F1	F5
		low	central	high		low	central	high		low	central	high		low	central	high
Costs	total	on top of REF			total	on top of REF			total	on top of REF			total	on top of REF		
Austria	174	0	0	0	784	124	137	98	0	0	0	0	958	124	137	98
Belgium	341	52	193	193	1000	856	856	856	0	21	312	467	1341	929	1361	1516
Denmark	115	0	21	46	383	0	0	22	0	0	1	6	498	0	22	74
Finland	204	0	0	0	525	0	0	0	0	0	0	0	729	0	0	0
France	1004	120	123	500	6180	756	1265	3015	0	0	65	669	7184	876	1453	4185
Germany	2146	162	554	727	8704	1179	1369	4004	0	670	1258	1289	10850	2011	3181	6021
Greece	331	0	0	0	933	172	19	0	0	0	0	0	1264	172	19	0
Ireland	108	18	19	19	410	1	10	30	9	5	49	0	527	25	77	48
Italy	1577	0	0	0	6881	325	640	963	12	0	0	259	8470	325	640	1222
Luxembourg	9	0	0	6	60	45	45	41	15	0	0	0	84	45	46	47
Netherlands	306	17	17	17	1486	160	246	588	237	82	680	836	2029	259	944	1441
Portugal	152	0	0	0	1092	186	284	311	0	0	0	0	1244	186	284	311
Spain	678	9	13	165	4793	1	17	138	28	0	0	0	5499	10	30	303
Sweden	293	0	0	0	976	12	40	33	113	0	0	0	1382	12	40	33
UK	1148	176	238	590	5934	590	643	1893	0	12	23	195	7082	779	904	2678
EU-15	8586	555	1178	2263	40140	4408	5572	11993	413	791	2389	3721	49139	5754	9139	17977

Table 9. NO$_x$ and VOC emissions for variations in ambition levels for ground-level ozone (Scenarios F3/1, F3 and F3/3). Percentage changes relate to the year 1990. From Amann *et al*, 1998c.

	NO$_x$								VOC							
	REF		F3/1 Low ambition		F3 Central		F3/3 High ambition		REF		F3/1 Low ambition		F3 Central		F3/3 High ambition	
	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*	kt	*Change*
Austria	113	*-41%*	100	*-48%*	98	*-49%*	87	*-55%*	208	*-41%*	131	*-63%*	125	*-64%*	124	*-65%*
Belgium	207	*-41%*	111	*-68%*	111	*-68%*	111	*-68%*	212	*-47%*	103	*-74%*	103	*-74%*	103	*-74%*
Denmark	136	*-50%*	136	*-50%*	136	*-50%*	136	*-50%*	86	*-47%*	86	*-47%*	86	*-47%*	86	*-47%*
Finland	162	*-41%*	162	*-41%*	162	*-41%*	162	*-41%*	112	*-47%*	112	*-47%*	112	*-47%*	112	*-47%*
France	1044	*-44%*	765	*-59%*	754	*-60%*	711	*-62%*	1242	*-48%*	946	*-61%*	866	*-64%*	853	*-64%*
Germany	1263	*-53%*	1183	*-56%*	1064	*-60%*	958	*-64%*	1137	*-63%*	963	*-69%*	943	*-69%*	888	*-71%*
Greece	344	*0%*	292	*-15%*	339	*-2%*	344	*0%*	205	*-39%*	172	*-49%*	203	*-40%*	205	*-39%*
Ireland	81	*-28%*	81	*-28%*	81	*-28%*	79	*-30%*	46	*-59%*	46	*-59%*	46	*-59%*	46	*-59%*
Italy	1186	*-42%*	1008	*-51%*	880	*-57%*	829	*-59%*	1176	*-43%*	982	*-52%*	933	*-55%*	821	*-60%*
Luxembourg	10	*-55%*	5	*-77%*	5	*-77%*	5	*-77%*	8	*-58%*	5	*-74%*	5	*-74%*	5	*-74%*
Netherlands	312	*-42%*	312	*-42%*	312	*-42%*	266	*-51%*	241	*-51%*	161	*-67%*	161	*-67%*	154	*-69%*
Portugal	197	*-5%*	128	*-38%*	112	*-46%*	104	*-50%*	144	*-34%*	130	*-40%*	127	*-41%*	127	*-41%*
Spain	892	*-23%*	892	*-23%*	877	*-25%*	822	*-29%*	669	*-36%*	669	*-36%*	669	*-36%*	669	*-36%*
Sweden	200	*-41%*	200	*-41%*	199	*-41%*	181	*-46%*	287	*-42%*	287	*-42%*	282	*-43%*	235	*-52%*
UK	1186	*-58%*	1186	*-58%*	1186	*-58%*	1186	*-58%*	1351	*-49%*	1071	*-60%*	1033	*-61%*	973	*-63%*
EU-15	7333	*-45%*	6560	*-50%*	6314	*-52%*	5982	*-55%*	7123	*-49%*	5863	*-58%*	5692	*-59%*	5399	*-61%*

Table 10. Emission control costs for variations in ambition levels for ground-level ozone (Scenarios F3/1, F3 and F3/3), in million ECU/year. From Amann *et al*, 1998c.

	SO_2				NO_x/VOC				NH_3				Total			
	REF	F3/1 low ambition	F3 central	F3/3 high ambition	REF	F3/1 low ambition	F3 central	F3/3 high ambition	REF	F3/1 low ambition	F3 central	F3/3 high ambition	REF	F3/1 low ambition	F3 central	F3/3 high ambition
Costs	total	on top of REF			total	on top of REF			total	on top of REF			total	on top of REF		
Austria	174	0	0	0	784	125	169	238	0	0	0	0	958	125	169	238
Belgium	341	0	0	0	1050	856	856	856	0	0	0	0	1391	856	856	856
Denmark	115	0	0	0	383	0	0	0	0	0	0	0	498	0	0	0
Finland	204	0	0	0	525	0	0	0	0	0	0	0	729	0	0	0
France	1004	0	0	0	6180	935	1290	2023	0	0	0	0	7184	935	1290	2023
Germany	2146	0	0	0	9890	956	1410	2910	0	0	0	0	12036	956	1410	2910
Greece	331	0	0	0	933	215	16	0	0	0	0	0	1264	215	16	0
Ireland	108	0	0	0	410	0	0	0	9	0	0	0	527	0	0	0
Italy	1577	0	0	0	6881	318	645	1202	12	0	0	0	8470	318	645	1202
Luxembourg	9	0	0	0	60	45	45	45	15	0	0	0	84	45	45	45
Netherlands	306	0	0	0	1486	136	136	234	237	0	0	0	2029	136	136	234
Portugal	152	0	0	0	1092	189	288	349	0	0	0	0	1244	189	288	349
Spain	678	0	0	0	4793	0	1	17	28	0	0	0	5499	0	1	17
Sweden	293	0	0	0	976	0	2	39	113	0	0	0	1382	0	2	39
UK	1148	0	0	0	5934	487	639	1032	0	0	0	0	7082	487	639	1032
EU-15	8586	0	0	0	41376	4263	5498	8946	413	0	0	0	50375	4263	5498	8946

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*, 1998c):

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 followed readers should refer to our earlier reports (Holland *et al*, 1998a, b).

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.

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.

Pollution load → Concentration, deposition
↓
Stock at risk → Distribution of people, etc.
↓
Sensitivity of stock at risk → Baseline mortality, etc.
↓
Exposure-response functions → Rate of damage/unit pollutant
↓
Impact assessment → Change in crop yield, mortality, etc
↓
Valuation → Willingness to pay/accept

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 11).

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).

Table 11. 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 the 1990 emission scenario represent the benefits of the increment to the REF scenario. For the other scenarios considered the baseline is the REF scenario. All of the results given refer to annual benefits in the year 2010. Prices are given in 1990ECU for consistency with the output of the RAINS model. **Benefits of emission reductions within the EU to countries outside it 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 12 and Table 17a to f, respectively.

Table 12. Annual morbidity benefits for 2010 for the scenarios studied compared to the REF scenario. All figures in million ECU (MECU), base year 1990.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	640	58	76	110	35	52	69
Belgium	650	120	150	210	65	77	97
Denmark	130	12	16	27	4.7	6.7	9.8
Finland	55	2.1	2.9	4.6	0.75	1.1	1.9
France	2500	430	540	800	290	350	440
Germany	5600	620	780	1100	290	420	570
Greece	150	13	8.6	10	14	7.1	7.4
Ireland	55	6.3	7.7	14	1.9	2.3	3.1
Italy	2200	270	400	570	230	360	430
Luxembourg	150	26	31	44	15	19	24
Netherlands	1300	200	260	380	98	120	170
Portugal	120	30	42	67	27	35	42
Spain	670	80	130	280	54	73	110
Sweden	210	15	21	34	5.7	8.2	13
UK	2700	300	360	640	92	110	150
Total EU	17000	2200	2800	4300	1200	1600	2100

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 13a. Reduction in the number of cases of premature mortality related to ozone and secondary nitrate exposure. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	1000	120	150	210	87	120	150
Belgium	1000	220	270	350	150	170	210
Denmark	220	25	32	48	14	18	24
Finland	110	5.7	7.6	11	3.3	4.1	6.5
France	4400	930	1100	1600	760	890	1100
Germany	8200	1100	1400	1900	720	920	1200
Greece	290	37	24	28	40	22	24
Ireland	89	14	16	25	7.1	8.2	10
Italy	4000	640	910	1200	580	840	1000
Luxembourg	240	50	60	81	38	44	53
Netherlands	1900	360	440	570	240	270	330
Portugal	250	61	85	130	57	75	89
Spain	1300	190	290	560	150	200	280
Sweden	350	32	42	63	17	22	33
UK	3400	660	770	1000	380	440	520
Total EU	27000	4500	5600	7900	3200	4000	5000

Table 13b: 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 ECU (MECU), base year 1990. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	2300	260	340	460	190	260	330
Belgium	2200	490	590	770	340	380	460
Denmark	480	55	70	110	31	39	52
Finland	230	13	17	24	7.3	9.1	14
France	9700	2100	2500	3500	1700	2000	2300
Germany	18000	2500	3100	4300	1600	2000	2600
Greece	650	81	54	62	88	48	53
Ireland	200	30	36	55	16	18	22
Italy	8800	1400	2000	2700	1300	1800	2200
Luxembourg	530	110	130	180	83	97	120
Netherlands	4100	780	960	1200	530	600	730
Portugal	540	130	190	280	120	160	200
Spain	2900	420	650	1200	330	430	610
Sweden	780	70	93	140	38	48	72
UK	7500	1500	1700	2200	840	960	1200
Total EU	59000	9900	12000	17000	7100	8900	11000

Table 13c: 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 ECU (MECU), base year 1990. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	56	6.6	8.4	12	4.8	6.5	8.4
Belgium	55	12	15	19	8.4	9.6	11
Denmark	12	1.4	1.7	2.6	0.78	0.98	1.3
Finland	6	0.31	0.42	0.59	0.18	0.23	0.36
France	240	51	63	87	42	49	59
Germany	450	63	77	110	40	51	65
Greece	16	2	1.3	1.6	2.2	1.2	1.3
Ireland	5	0.74	0.89	1.4	0.39	0.45	0.55
Italy	220	35	50	68	32	46	56
Luxembourg	13	2.8	3.3	4.5	2.1	2.4	2.9
Netherlands	103	20	24	31	13	15	18
Portugal	14	3.3	4.7	7	3.1	4.1	4.9
Spain	72	11	16	31	8.4	11	15
Sweden	19	1.7	2.3	3.5	0.94	1.2	1.8
UK	190	37	42	56	21	24	29
Total EU	1500	250	310	430	180	220	270

Table 13d. Life years lost to chronic effects of exposure to fine particles. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	49000	4700	6200	9000	2900	4300	5700
Belgium	52000	9500	12000	17000	5300	6300	8100
Denmark	11000	970	1300	2200	370	530	800
Finland	4300	160	230	370	53	82	150
France	200000	34000	43000	64000	23000	29000	36000
Germany	420000	50000	63000	93000	24000	35000	48000
Greece	12000	1100	680	830	1100	550	580
Ireland	4500	490	610	1100	140	170	240
Italy	180000	22000	33000	47000	19000	29000	35000
Luxembourg	11000	2000	2500	3500	1200	1500	1900
Netherlands	106000	16000	21000	31000	7900	10000	14000
Portugal	9300	2500	3500	5500	2300	2900	3500
Spain	52000	6400	10000	22000	4300	5800	8900
Sweden	17000	1200	1700	2800	450	660	1100
UK	220000	22000	27000	51000	6700	8200	11000
Total EU	1300000	170000	230000	350000	99000	130000	170000

Table 13e: 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 ECU (MECU), base year 1990. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	3300	310	420	600	190	290	380
Belgium	3500	640	800	1200	360	420	540
Denmark	740	65	88	150	25	36	53
Finland	290	11	15	25	3.6	5.5	10
France	13000	2300	2900	4300	1600	1900	2400
Germany	28000	3300	4200	6200	1600	2300	3200
Greece	800	71	46	56	75	37	39
Ireland	300	33	41	75	9.3	11	16
Italy	12000	1500	2200	3200	1300	2000	2300
Luxembourg	770	130	170	240	83	100	130
Netherlands	7080	1100	1400	2100	530	680	940
Portugal	620	170	230	370	150	190	230
Spain	3500	430	680	1500	290	390	600
Sweden	1100	81	110	190	30	44	72
UK	14000	1500	1800	3400	450	550	750
Total EU	89000	12000	15000	24000	6600	8900	12000

Table 13f**.** 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 ECU (MECU), 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	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	5400	520	680	980	320	470	620
Belgium	5800	1000	1300	1900	590	700	890
Denmark	1200	110	150	240	41	59	88
Finland	470	18	25	41	5.9	9.1	16
France	22000	3700	4800	7100	2600	3100	3900
Germany	46000	5500	6900	10000	2600	3800	5300
Greece	1300	120	75	92	120	61	64
Ireland	490	54	67	120	15	19	26
Italy	19000	2400	3600	5200	2100	3200	3800
Luxembourg	1300	220	270	390	140	170	210
Netherlands	12000	1800	2300	3400	870	1100	1500
Portugal	1030	280	380	610	250	320	390
Spain	5700	710	1100	2400	480	640	980
Sweden	1900	130	190	310	49	73	120
UK	24000	2400	3000	5600	740	900	1200
Total EU	150000	19000	25000	39000	11000	15000	19000

3. Approach to valuation of mortality.

Table 13b and Table 13c 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 year. 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 MECU per premature death adopted here. As noted in our 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. Subsequent work in the UK, yet to be completed, appears close to recommending the VOSL approach, but adopting a value similar to that of the VOLY used here. 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 MECU.

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 F3 ozone scenarios, rather than the joint acidification, eutrophication, ozone scenarios (F1, F4, and F5).

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

The range of ozone formation 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. This provides a tendency to underestimation of benefits in this study, though of course should be offset against other areas of possible over-estimation. 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.

4.3 IMPACTS ON MATERIALS

4.3.1 Results

Results for benefits in terms of reduced damage to building materials are shown in Table 14. The difference between scenarios F4/F1/F5 and the F3 scenarios demonstrates the dominant role of SO^2.

Table 14. Annual benefits for 2010 of reduced damage to materials from moving to the scenarios examined from REF. All figures in million ECU (1990).

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	24	2	2	3	1	1	1
Belgium	22	8	10	12	1	1	1
Denmark	4	0	1	1	0	0	0
Finland	2	0	0	0	0	0	0
France	53	14	16	22	4	4	4
Germany	380	20	27	36	5	7	6
Greece	4	0	0	0	0	0	0
Ireland	2	0	1	1	0	0	0
Italy	80	5	6	8	3	5	4
Luxembourg	7	1	1	2	0	0	0
Netherlands	86	13	16	20	2	2	2
Portugal	4	0	1	1	0	0	0
Spain	27	2	2	8	1	1	1
Sweden	10	1	1	2	0	0	0
UK	267	36	39	53	2	2	2
Total EU	970	100	120	170	18	24	23

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 15.

Table 15. Estimated annual benefits to agriculture in 2010 of reducing emissions. All figures in million ECU (MECU), base year 1990. All results show difference to REF scenario.

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	120	20	24	30	20	25	31
Belgium	70	38	39	32	49	53	55
Denmark	66	12	13	17	12	14	17
Finland	9.7	0.62	0.77	0.99	0.51	0.59	0.86
France	1900	630	730	890	670	750	860
Germany	930	200	210	280	220	260	300
Greece	160	41	28	31	45	28	31
Ireland	16	6.7	7.4	8.2	6.3	7	7.9
Italy	1600	410	570	690	410	570	690
Luxembourg	0.46	-0.18	-0.37	-0.57	-0.15	-0.17	-0.21
Netherlands	87	62	62	38	87	87	85
Portugal	65	22	31	38	21	29	34
Spain	618	130	200	330	120	150	210
Sweden	18	1.7	2	2.6	1.6	1.8	2.6
UK	12	93	98	58	99	110	120
Total EU	5700	1700	2000	2500	1800	2100	2400

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 16. Both the function derived experimentally for Norway spruce and the one 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 16. 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	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	55	12	14	17	11	14	17
Belgium	10	5.1	5.6	5.5	5.7	6	6.3
Denmark	1	0.23	0.26	0.32	0.22	0.25	0.29
Finland	19	1.6	2	2.5	1.4	1.6	2.1
France	166	54	63	79	56	63	72
Germany	137	36	40	50	36	41	48
Greece	2	0.59	0.47	0.52	0.65	0.46	0.52
Ireland	0	0.17	0.19	0.2	0.16	0.18	0.2
Italy	29	8.1	11	13	8.1	11	13
Luxembourg	0	0	0	0	0	0	0
Netherlands	1	0.72	0.75	0.47	0.93	0.91	0.86
Portugal	15	4.1	6.1	7.5	4.1	5.8	6.7
Spain	29	6	9.1	14	5.6	7.2	9.5
Sweden	28	3.9	4.7	5.6	3.5	3.9	5.1
UK	2	2.2	2.4	1.9	2.1	2.4	2.7
Total EU	500	130	160	200	140	160	180

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* (1998c) which describe exceedence of critical loads for acidification and eutrophication for the 1990, REF, F1, F4 and

F5 scenarios, in order that these measures of risk can be set alongside the other effects quantified. We do not reproduce the ozone exposure index data presented by Amann *et al* (1998c), as these data do not provide any real indication of the scale of impacts, beyond the likelihood that impacts will occur.

Table 17a. Ecosystems with acid deposition above their critical loads for acidification for 1990 and the REF case.

	1000 ha		Percent of ecosystems	
	1990	REF	1990	REF
Austria	2373	189	47.5%	3.8%
Belgium	410	162	58.3%	23.1%
Denmark	54	9	13.9%	2.3%
Finland	4722	1166	17.3%	4.3%
France	8191	226	25.8%	0.7%
Germany	8156	1750	79.5%	17.1%
Greece	0	0	0.0%	0.0%
Ireland	97	12	10.7%	1.4%
Italy	2064	87	19.5%	0.8%
Luxembourg	58	6	66.7%	6.7%
Netherlands	285	198	89.3%	61.9%
Portugal	1	1	0.0%	0.0%
Spain	78	18	0.9%	0.2%
Sweden	6344	1599	16.4%	4.1%
UK	4117	1200	43.0%	12.5%
EU-15	36950	6623	24.7%	4.4%

Table 17b. Ecosystems with nitrogen deposition above their critical loads for eutrophication for 1990 and the REF case.

	1000 ha		Percent of ecosystems	
	1990	REF	1990	REF
Austria	5379	3499	90.1%	58.6%
Belgium	700	683	99.6%	97.3%
Denmark	197	122	62.6%	38.7%
Finland	7376	2292	44.7%	13.9%
France	29319	26563	92.3%	83.6%
Germany	10156	9324	99.0%	90.9%
Greece	295	226	12.0%	9.2%
Ireland	91	59	10.0%	6.5%
Italy	5920	3806	49.4%	31.8%
Luxembourg	88	82	100.0%	93.2%
Netherlands	312	293	97.8%	91.6%
Portugal	913	760	32.3%	26.9%
Spain	2389	1344	28.0%	15.8%
Sweden	2581	886	13.7%	4.7%
UK	1030	128	11.2%	1.4%
EU-15	66746	50065	55.3%	41.5%

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. Elsewhere, Belgium, Germany and the UK would have more than 10% of ecosystems with exceedence. Eutrophication appears a more difficult problem with the number of countries with more than 25% of ecosystems with exceedence declining only from 11 to 9 by 2010. Several countries have almost 100% exceedence.

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 (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 3 countries there is still a 10% reduction (in absolute terms) in ecosystems at risk from acidification under the F1 scenario (Table 18a. Ecosystems). 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.

Table 18a. Ecosystems with acid deposition above their critical loads for acidification for the joint scenario F1 and for the scenarios with modified ambition levels.

	1000 ha				Percent of ecosystems			
	REF	F4	F1	F5	REF	F4	F1	F5
Ambition		Low	Mid	High		Low	Mid	High
Austria	189	108	94	79	3.8%	2.2%	1.9%	1.6%
Belgium	162	105	53	24	23.1%	15.0%	7.6%	3.4%
Denmark	9	6	5	4	2.3%	1.6%	1.3%	1.1%
Finland	1166	1141	1130	1112	4.3%	4.2%	4.1%	4.1%
France	226	111	90	73	0.7%	0.4%	0.3%	0.2%
Germany	1750	964	691	543	17.1%	9.4%	6.7%	5.3%
Greece	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Ireland	12	9	9	9	1.4%	1.0%	1.0%	0.9%
Italy	87	62	58	53	0.8%	0.6%	0.6%	0.5%
Luxembourg	6	4	1	1	6.7%	4.2%	0.9%	0.6%
Netherlands	198	134	76	63	61.9%	41.9%	23.7%	19.6%
Portugal	1	1	1	1	0.0%	0.0%	0.0%	0.0%
Spain	18	17	17	0	0.2%	0.2%	0.2%	0.0%
Sweden	1599	1452	1356	1240	4.1%	3.7%	3.5%	3.2%
UK	1200	753	680	381	12.5%	7.9%	7.1%	4.0%
EU-15	6623	4867	4260	3581	4.4%	3.3%	2.9%	2.4%

Table 18b. Ecosystems with nitrogen deposition above their critical loads for eutrophication for the joint scenario F1 and for the scenarios with modified ambition levels.

	1000 ha				Percent of ecosystems			
	REF	F4	F1	F5	REF	F4	F1	F5
Ambition		Low	Mid	High		Low	Mid	High
Austria	3499	3054	2728	2412	59%	51%	46%	40%
Belgium	683	646	597	509	97%	92%	85%	72%
Denmark	122	95	88	73	39%	30%	28%	23%
Finland	2292	2018	1908	1723	14%	12%	12%	10%
France	26563	24559	22594	20753	84%	77%	71%	65%
Germany	9324	8045	7348	6562	91%	78%	72%	64%
Greece	226	215	219	218	9%	9%	9%	9%
Ireland	59	57	52	53	6%	6%	6%	6%
Italy	3806	3564	3425	2266	32%	30%	29%	19%
Luxembourg	82	75	67	59	93%	86%	76%	67%
Netherlands	293	285	279	274	92%	89%	87%	86%
Portugal	760	679	575	566	27%	24%	20%	20%
Spain	1344	1131	1007	717	16%	13%	12%	8%
Sweden	886	764	707	594	5%	4%	4%	3%
UK	128	70	64	1	1%	1%	1%	0%
EU-15	50065	45257	41657	36779	41%	38%	35%	30%

A slow decline in the rate of exceedence of the critical load for eutrophication is evident in Table 18b. Under the F1 scenario 8 countries still have more than 25% of ecosystems under threat. Five of these countries have more than 70% at risk. As was the case for acidification, spatial variation in deposition rates will mean that certain types of ecosystem, particularly those at high elevation, will be at much greater threat than ecosystems elsewhere. These factors imply that reduction in exceedence of the critical load for eutrophication could well 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.

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

Country	1990	F4	F1	F5	F3/1	F3	F3/3
Austria	190	24	32	46	14	22	29
Belgium	190	45	57	84	25	29	38
Denmark	59	6.5	8.9	15	2.4	3.5	5.3
Finland	33	1.4	2	3.2	0.46	0.7	1.3
France	800	170	220	340	120	140	180
Germany	1400	230	290	440	110	160	220
Greece	44	4.2	2.7	3.3	4.5	2.2	2.3
Ireland	40	5.1	6.4	12	1.4	1.8	2.5
Italy	640	96	140	210	81	130	150
Luxembourg	38	8.5	11	15	5.2	6.4	8.2
Netherlands	360	74	96	150	36	46	64
Portugal	44	13	18	29	12	15	18
Spain	240	33	53	120	22	30	46
Sweden	98	8	11	19	2.9	4.3	7.1
UK	1050	140	170	340	41	50	69
Total EU	5200	860	1100	1800	470	640	840

4.7.2 Uncertainties

It is easy to say that analysis 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.

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

Table 20. 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
Natural ecosystems	6.0	36.0	C
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 MECU, Geometric standard deviation: 4

68% confidence interval:	2.5 to 40 MECU
95% confidence interval:	0.63 to 160 ECU

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). For some other impacts (e.g. effects on ecosystems) it seems likely that our results underestimate the benefits of pollution abatement. In both these cases, the doubts stem from concerns about the validity of the valuation model. However, in 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 1990, F4, F1, and F5, and NO_x then O_3 for the F3 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 are not quantified ('nq' in the Tables).

Table 21. Benefits by pollutant for the 1990 scenario (MECU/year).

1990	**NO_x**	**NH_3**	**SO_2**	**O_3**	**Sub-Total**
Health-Morbidity	8836	445	7582	166	17030
Health-Mortality(VOSL)	83406	4205	58846	7067	153525
Health-Mortality(VOLY)	50858	2564	35881	176	89480
Materials	126	-	917	nq	1044
Agriculture	-60	-60	-414	5615	5079
Forestry	nq	nq	nq	494	494
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	92309	4589	66932	13343	177173
Sub Total (VOLY)	59760	2949	43967	6452	113128
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 22. Benefits by pollutant for the F1 scenario (MECU/year).

F1	NO_x	NH_3	SO_2	O_3	Sub-Total
Health-Morbidity	1707	378	659	87	2832
Health-Mortality(VOSL)	16116	3571	5098	3707	28493
Health-Mortality(VOLY)	9827	2177	3108	92	15206
Materials	24	-	97	nq	121
Agriculture	-21	-21	-71	2138	2023
Forestry	nq	nq	nq	159	159
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	17827	3928	5784	6092	33632
Sub Total (VOLY)	11538	2534	3795	2477	20344
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 23. Benefits by pollutant for the F4 scenario (MECU/year).

F4	NO_x	NH_3	SO_2	O_3	Sub-Total
Health-Morbidity	1368	201	546	74	2190
Health-Mortality(VOSL)	12916	1897	4238	3181	22232
Health-Mortality(VOLY)	7876	1157	2584	79	11696
Materials	19	-	83	nq	102
Agriculture	-13	-13	-56	1746	1662
Forestry	nq	nq	nq	134	134
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	14219	2085	4810	5136	26323
Sub Total (VOLY)	9250	1345	3157	2034	15786
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 24. Benefits by pollutant for the F5 scenario (MECU/year).

F5	NO_x	NH_3	SO_2	O_3	Sub-Total
Health-Morbidity	2726	598	918	87	4330
Health-Mortality(VOSL)	25731	5650	7165	3735	42281
Health-Mortality(VOLY)	15689	3445	4369	93	23597
Materials	41	-	127	nq	169
Agriculture	-35	-35	-98	2618	2450
Forestry	nq	nq	nq	199	199
Ecological Damage	nq	nq	nq	nq	nq
Sub Total (VOSL)	28466	6213	8113	6641	49430
Sub Total (VOLY)	18422	4008	5317	2999	30746
Effects not quantifiable	nq	nq	nq	nq	nq
Total	nq	nq	nq	nq	nq

Table 25. Benefits by pollutant for the F3/1 scenario (MECU/year).

F3/1	NO_x	O_3	Sub-Total
Health-Morbidity	1152	78	1231
Health-Mortality(VOSL)	10880	3332	14213
Health-Mortality(VOLY)	6634	83	6717
Materials	18	nq	18
Agriculture	-9	1768	1759
Forestry	nq	135	135
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	12042	5315	17357
Sub Total (VOLY)	7796	2066	9862
Effects not quantifiable	nq	nq	nq
Total	nq	nq	nq

Table 26. Benefits by pollutant for the F3 scenario (MECU/year).

F3	NO_x	O_3	Sub-Total
Health-Morbidity	1554	88	1642
Health-Mortality(VOSL)	14670	3768	18438
Health-Mortality(VOLY)	8945	94	9040
Materials	23	nq	23
Agriculture	-12	2103	2091
Forestry	nq	157	157
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	16237	6117	22354
Sub Total (VOLY)	10512	2443	12955
Effects not quantifiable	nq	nq	nq
Total	nq	nq	nq

Table 27. Benefits by pollutant for the F3/3 scenario (MECU/year).

F3/3	NO_x	O_3	Sub-Total
Health-Morbidity	2030	100	2131
Health-Mortality(VOSL)	19168	4273	23442
Health-Mortality(VOLY)	10512	106	11795
Materials	30	nq	30
Agriculture	-15	2464	2448
Forestry	nq	183	183
Ecological Damage	nq	nq	nq
Sub Total (VOSL)	21214	7023	28237
Sub Total (VOLY)	13714	2856	16590
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* (1998c).

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 V 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 this study, and so the listing derived by Holland *et al* (1998) is 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 28a. Comparison of costs and benefits of moving from 1990 to the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs. Confidence in benefit estimates declines from Group I to Group V.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	REF Costs
Austria	185	431	826	4111	4305	958
Belgium	158	363	787	4260	4447	1341
Denmark	23	114	203	936	995	498
Finland	15	36	71	371	405	729
France	590	2970	4553	17662	18461	7184
Germany	1739	3812	7176	34806	36205	10850
Greece	34	226	322	1110	1154	1264
Ireland	11	41	77	373	413	527
Italy	517	2568	3993	15665	16307	8470
Luxembourg	38	73	166	923	961	84
Netherlands	333	696	1550	8531	8895	2029
Portugal	33	125	200	831	875	1244
Spain	186	933	1355	4827	5068	5499
Sweden	47	113	249	1389	1486	1382
United Kingdom	747	1353	3095	17332	18386	7082
Total	4656	13854	24622	113128	118364	49141

Table 28b. Comparison of costs and benefits of moving from 1990 to the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	REF Costs
Austria	128	375	3029	3085	6758	958
Belgium	103	308	2928	2937	6866	1341
Denmark	11	102	670	671	1522	498
Finland	10	31	299	318	655	729
France	349	2728	13972	14137	28921	7184
Germany	1291	3364	24659	24796	55771	10850
Greece	18	210	953	955	1849	1264
Ireland	6	36	267	267	627	527
Italy	298	2349	12533	12563	25794	8470
Luxembourg	25	60	684	684	1539	84
Netherlands	229	592	5579	5580	13478	2029
Portugal	19	111	731	746	1455	1244
Spain	115	862	4149	4178	8137	5499
Sweden	28	94	1006	1034	2334	1382
United Kingdom	559	1164	10442	10443	26863	7082
Total	3188	12385	81900	82395	182569	49141

Table 29a. Comparison of costs and benefits of moving to the F4 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	13	48	86	408	431	124
Belgium	35	103	180	813	858	929
Denmark	2	18	26	90	97	0
Finland	1	2	3	15	17	0
France	114	851	1126	3431	3603	876
Germany	138	499	901	4216	4441	2011
Greece	3	48	56	127	131	172
Ireland	2	10	14	46	52	25
Italy	64	544	723	2195	2291	325
Luxembourg	7	13	29	162	170	45
Netherlands	56	168	299	1369	1443	259
Portugal	6	35	56	226	239	186
Spain	20	167	219	649	682	10
Sweden	3	9	19	103	111	12
United Kingdom	124	286	466	1935	2077	779
Total	588	2802	4202	15786	16643	5754

Table 29b. Comparison of costs and benefits of moving to the F4 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	6	42	343	355	714	124
Belgium	23	91	653	658	1381	929
Denmark	1	17	79	79	155	0
Finland	0	1	15	17	30	0
France	63	800	3131	3185	5791	876
Germany	76	437	3351	3387	7158	2011
Greece	1	46	136	136	216	172
Ireland	1	10	43	43	83	25
Italy	29	509	2086	2094	3776	325
Luxembourg	4	10	137	137	289	45
Netherlands	36	149	1062	1063	2292	259
Portugal	2	32	186	190	383	186
Spain	10	156	632	638	1130	10
Sweden	2	7	87	91	185	12
United Kingdom	87	249	1891	1894	3617	779
Total	341	2555	13834	13968	27200	5754

Table 30a. Comparison of costs and benefits of moving to the F1 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	16	61	111	535	567	137
Belgium	42	120	217	1015	1072	1361
Denmark	3	21	32	119	128	22
Finland	1	2	4	21	23	0
France	132	999	1348	4264	4484	1453
Germany	175	593	1102	5299	5587	3181
Greece	2	33	38	84	87	19
Ireland	2	12	17	57	63	77
Italy	90	766	1032	3221	3366	640
Luxembourg	8	16	36	200	210	46
Netherlands	69	195	362	1726	1822	944
Portugal	8	50	78	312	330	284
Spain	30	267	349	1031	1083	30
Sweden	5	13	26	142	154	40
United Kingdom	137	320	538	2318	2490	904
Total	721	3467	5290	20344	21467	9138

Table 30b. Comparison of costs and benefits of moving to the F1 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	8	52	439	453	929	137
Belgium	28	105	796	801	1714	1361
Denmark	1	19	100	100	203	22
Finland	0	2	21	23	41	0
France	69	936	3813	3876	7182	1453
Germany	98	516	4109	4149	8930	3181
Greece	1	32	91	91	143	19
Ireland	1	11	51	51	101	77
Italy	41	716	2975	2986	5490	640
Luxembourg	5	12	165	165	352	46
Netherlands	45	171	1299	1300	2868	944
Portugal	3	45	261	267	533	284
Spain	14	250	978	987	1768	30
Sweden	3	10	117	122	253	40
United Kingdom	95	278	2182	2185	4274	904
Total	410	3157	17397	17556	34782	9138

Table 31a. Comparison of costs and benefits of moving to the F5 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	22	81	153	761	808	98
Belgium	52	139	278	1418	1503	1516
Denmark	4	30	48	194	209	74
Finland	1	3	6	33	37	0
France	178	1282	1800	6115	6450	4185
Germany	235	812	1564	7758	8196	6021
Greece	3	36	43	98	102	0
Ireland	3	15	24	97	110	48
Italy	118	963	1344	4476	4685	1222
Luxembourg	10	21	50	284	299	47
Netherlands	85	217	465	2490	2639	1441
Portugal	13	68	113	486	515	311
Spain	70	469	648	2120	2237	303
Sweden	7	19	42	232	250	33
United Kingdom	177	392	805	4181	4524	2678
Total	979	4548	7382	30746	32564	17977

Table 31b. Comparison of costs and benefits of moving to the F5 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	11	69	602	619	1305	98
Belgium	33	120	1031	1037	2348	1516
Denmark	1	27	150	150	324	74
Finland	1	3	29	32	62	0
France	91	1194	5210	5290	10206	4185
Germany	129	705	5717	5767	12849	6021
Greece	1	35	104	104	167	0
Ireland	2	13	77	78	169	48
Italy	50	895	3982	3996	7583	1222
Luxembourg	6	17	224	224	493	47
Netherlands	53	186	1681	1681	4018	1441
Portugal	6	61	387	395	820	311
Spain	39	438	1857	1872	3564	303
Sweden	4	16	176	182	400	33
United Kingdom	121	336	2993	2995	6982	2678
Total	547	4116	24222	24421	51290	17977

Table 32a. Comparison of costs and benefits of moving to the F3/1 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	8	38	61	262	277	125
Belgium	15	81	124	483	508	856
Denmark	1	14	17	42	44	0
Finland	0	1	1	6	7	0
France	73	819	1008	2611	2728	935
Germany	71	367	561	2180	2287	956
Greece	4	53	62	136	141	215
Ireland	1	7	9	18	19	0
Italy	56	523	675	1922	2003	318
Luxembourg	4	7	17	99	104	45
Netherlands	24	135	200	725	761	136
Portugal	5	34	52	207	218	189
Spain	14	144	179	471	493	0
Sweden	2	5	8	41	44	0
United Kingdom	38	159	213	657	698	487
Total	315	2388	3188	9862	10333	3962

Table 32b. Comparison of costs and benefits of moving to the F3/1 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	4	33	249	259	480	125
Belgium	7	73	453	458	865	856
Denmark	0	14	48	48	77	0
Finland	0	1	9	10	14	0
France	31	777	2633	2689	4483	935
Germany	31	327	2112	2149	3970	956
Greece	2	51	147	148	232	215
Ireland	0	7	24	24	35	0
Italy	24	491	1911	1919	3343	318
Luxembourg	2	5	98	98	192	45
Netherlands	11	122	712	713	1318	136
Portugal	2	31	173	177	352	189
Spain	6	136	505	511	843	0
Sweden	1	4	45	49	83	0
United Kingdom	17	138	1029	1031	1551	487
Total	137	2209	10148	10283	17840	3962

Table 33a. Comparison of costs and benefits of moving to the F3 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	11	50	85	382	403	169
Belgium	18	89	141	565	594	856
Denmark	1	17	22	57	61	0
Finland	0	1	2	9	10	0
France	86	928	1159	3112	3255	1290
Germany	89	455	734	3062	3217	1410
Greece	2	32	36	73	75	16
Ireland	1	8	10	21	23	0
Italy	81	744	980	2914	3041	645
Luxembourg	4	9	21	123	129	45
Netherlands	27	145	227	894	940	136
Portugal	7	45	69	265	280	288
Spain	19	191	238	629	659	1
Sweden	2	6	11	59	63	2
United Kingdom	43	180	246	791	841	639
Total	392	2902	3981	12955	13592	5497

Table 33b. Comparison of costs and benefits of moving to the F3 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	5	44	340	354	682	169
Belgium	8	80	515	521	1004	856
Denmark	0	16	60	60	102	0
Finland	0	1	11	12	19	0
France	36	879	3075	3138	5329	1290
Germany	39	404	2708	2750	5382	1410
Greece	1	31	84	84	126	16
Ireland	0	8	27	27	41	0
Italy	35	698	2776	2787	4999	645
Luxembourg	2	7	116	116	232	45
Netherlands	12	130	812	813	1581	136
Portugal	3	41	228	234	456	288
Spain	8	180	662	669	1114	1
Sweden	1	5	59	63	114	2
United Kingdom	19	156	1184	1187	1825	639
Total	169	2680	12658	12815	23006	5497

Table 34a. Comparison of costs and benefits of moving to the F3/3 scenario from the REF scenario with mortality valuation based on VOLY with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	15	64	109	501	530	238
Belgium	21	100	165	704	742	856
Denmark	2	22	28	81	86	0
Finland	1	2	3	15	17	0
France	102	1070	1357	3774	3953	2023
Germany	114	565	951	4160	4377	2910
Greece	2	35	40	78	81	0
Ireland	1	10	12	27	30	0
Italy	98	901	1183	3500	3654	1202
Luxembourg	5	11	27	155	163	45
Netherlands	33	160	273	1201	1265	234
Portugal	8	53	81	319	337	349
Spain	26	265	336	934	980	17
Sweden	3	9	18	94	101	39
United Kingdom	52	211	301	1044	1113	1032
Total	482	3476	4886	16590	17430	8945

Table 34b. Comparison of costs and benefits of moving to the F3 scenario from the REF scenario with mortality valuation based on VOSL with values in MECU/year. The highlighting identifies the benefits that need to be added together for overall benefit to exceed costs.

Country	I	I+II	I+II+III	I+II+III +IV	I+II+III+IV +V	Costs
Austria	6	55	436	453	888	238
Belgium	9	89	611	618	1232	856
Denmark	1	20	79	79	141	0
Finland	0	2	17	19	31	0
France	43	1011	3639	3711	6432	2023
Germany	49	500	3478	3526	7169	2910
Greece	1	34	91	92	135	0
Ireland	0	9	33	33	53	0
Italy	42	845	3363	3377	6027	1202
Luxembourg	2	8	140	140	287	45
Netherlands	15	142	984	985	2053	234
Portugal	3	48	273	279	548	349
Spain	11	249	930	940	1623	17
Sweden	1	7	88	93	177	39
United Kingdom	23	182	1427	1430	2301	1032
Total	208	3202	15590	15774	29098	8945

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 35. The higher the figure, the more cost-effective the measures applied, in terms of the measures quantified here. The table shows that the increment between the 1990 and REF scenarios is not seen here as the most cost-effective batch of measures, which appears to contradict the least-cost basis of the IIASA modelling. Otherwise the patterns observed agree with the expectation that benefit per unit cost should fall as emission standards are tightened.

Table 35. Benefit:cost ratios for each scenario; benefits based on VOLY valuation of mortality, with all quantified benefits included.

Scenario	Benefit	Cost	Ratio
1990	120,000	49,141	2.41
F4	17,000	5,754	2.89
F1	21,000	9,138	2.35
F5	33,000	17,977	1.81
F3/1	10,000	3,962	2.61
F3	14,000	5,497	2.47
F3/3	17,000	8,945	1.95

We have to ask why the increment from 1990 to the REF scenario does not appear more cost-effective than some of the scenarios beyond REF. There are several possible reasons for this. Firstly, the driver for much of the 1990-REF emission abatement is concern over ecological impacts which are of course not monetised here. Given the uneven distribution of acid sensitivity (both chemically and societally) over Europe it is not too surprising that the package of measures introduced to deal with this specific problem is not necessarily the most cost-effective way of dealing with other problems caused by the same air pollutants, most notably effects on health. Secondly, the present analysis is restricted to benefits in EU Member States; significant benefits in the states to the east of the EU could alter the ratio substantially (this may well be the most important factor). Thirdly, RAINS is constrained externally in the REF scenario by national emission targets. Whilst it will predict the least-cost solution for each country, overall costs across the EU will inevitably be predicted to rise when countries do not abide by the precise results generated by RAINS

5.3.1.2 Scenario F1, F4, F5: 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 factors of 2.74 for F4, 2.23 for F1, and 1.71 for F5. This demonstrates the expected decline in the cost-benefit ratio as emissions abatement increases.

Costs exceed total benefits in Belgium and Greece for F4 and in Belgium and Ireland in F1, but for no countries in F5

5.3.1.3 Scenario F1, F4, F5: 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 exceeded costs by factors of 2.4 for F4, 1.90 for F1, and 1.34 for F5. Again, this demonstrates the expected decline in the cost-benefit ratio as emissions abatement increases.

Overall, bringing in all 5 categories in the confidence ranking, no country experienced cost in excess of benefit.

5.3.1.4 Scenarios F3/1, F3, F3/3: Ozone targets only, mortality valuation using VOLY

Similar patterns are observed for this suite of scenarios as for F1/4/5; 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 and Greece in F3/1, and Belgium and Portugal in both F3 and F3/3. Overall, once category IV impacts are introduced benefits exceed costs by a factor between 2.5 (F3/1) and 1.9 (F3/3).

5.3.1.5 Scenarios F3/1, F3, F3/3: Ozone targets only, mortality valuation using VOSL

Similar trends are observed here as in the case of the F1/4/5 scenarios when mortality valuation was based on the VOSL. Only Belgium and Portugal (all three scenarios) and Greece (scenario F3/1) required further benefits to be added after the inclusion of the effects of acute exposure to ozone and fine particles on mortality.

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 ECU applied to these chronic effects for costs and quantified benefits to balance. The VOLY required to do this ranges from about 9,000 ECU to 35,000 ECU, depending on scenario.

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. 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.

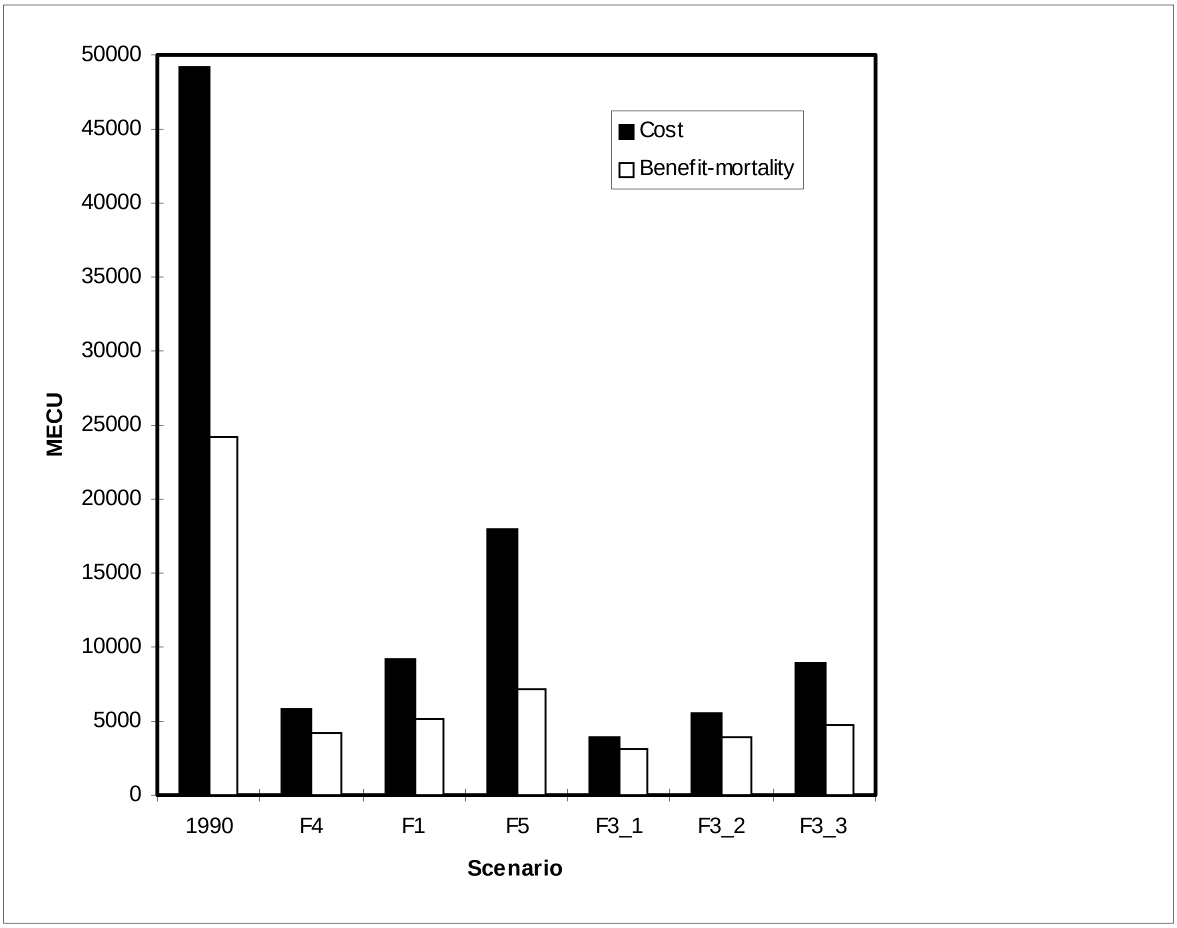

Figure 1. Comparison of costs with benefits without accounting for pollution-related mortality and effects on visibility, and other effects not quantified in this study (e.g. those listed in section 5.3.2.9).

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 difference between costs and benefits ranges from 20% (F3/1) to 60% (F5). 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. The authors of the present report are unaware of the extent to which industry has considered the availability of potentially cheaper options that are not included in 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.

5.3.2.11 Starting point bias

Starting point bias relates to the use of the REF scenario, rather than current or 1990 emissions data as the point for comparison in this study. Some commentators have argued that use of the REF scenario gives the impression that the overall cost burden to industry will be lower than the true costs. The reason for using the REF scenario is that this study needs to consider the position once all current legislation is enacted. However, in this report we provide for the first time estimates of the benefits of moving from 1990 to REF, allowing inspection of the effect of this decision.

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).

4. Adopting the first approach involves taking a necessarily subjective position on how good the evidence must be on a given effect for analysis to be considered robust. 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.

5. 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. Provided that information is presented clearly, enabling readers to see for themselves the effects of different uncertainties, we feel that it is also likely to offer far greater transparency than the first approach.

6. 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.

7. 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.

8. 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.

9. 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.

10. 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.

11. 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.

12. 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, October 1998), 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 (1990ECU)
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 (1990ECU)
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 ECU 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 = $1\text{-}\exp[-0.121.R_H/(100\text{-}R_H)]$
TOW = fraction of time relative humidity exceeds 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 [ECU/m^2] applied in this analysis.

Material	**ECU/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 1970's 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 ECU 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 is thus beneficial (assuming that the dosage of any fertiliser applied by a farmer is not excessive). The analysis quantifies total deposition of nitrogen to arable land and permanent pastures. The benefit is calculated directly from the cost of nitrate fertiliser, ECU 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
barley
wheat
sorghum
oats
rye
millet
rice
leaf crops
sugar beet
raspberries
strawberries
soybeans
beans
potato
tomato
sunflower
carrots
cucumber
flax
hops
hemp
linseed
sesame seed
tobacco

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.

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

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* (1998). They provide estimated exceedence of critical loads for acidification and eutrophication in each country in the European Union. No attempt is made here to value these impacts: this issue was explored in detail by Holland *et al* (1998a) where it was concluded that a reliable valuation was not possible at the present time.

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;

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

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;

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

The 'haziness index' (dv) suggested by Pitchford (1994), can be combined with a value of 8ECU/dv to quantify value (in ECU) 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 ECU, 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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