Project Number 282910

ÉCLAIRE

Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems

Seventh Framework Programme

Theme: Environment

18.2 Description of data for valuation of ecosystem effects quantified in ECLAIRE

Due date of deliverable: **01/10/2013**

Actual submission date: **19/08/2014**

Start Date of Project: **01/10/2011**

Duration: **48 months**

Organisation name of lead contractor for this deliverable:
EMRC

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	☐
PP	Restricted to other programme participants (including the Commission Services)	☒
RE	Restricted to a group specified by the consortium (including the Commission Services)	☐
CO	Confidential, only for members of the consortium (including the Commission Services)	☐

1. Executive Summary

Following from Deliverable 18.1, the following ecosystem services are priorities for valuation within ECLAIRE:

- Biodiversity
- Crop production
- Timber production
- Carbon balance via GHG emissions and sequestration

This paper describes the data needed for valuation of these services and the approach to be adopted when undertaking future policy analysis. It does not seek to repeat information, data needs, etc. on other models being developed in ECLAIRE, for example, those that quantify carbon uptake. Data needs are considered from two starting points. The first is analysis as will be conducted in ECLAIRE, where a full modelling framework is used to describe the impact pathway from emission to effect and then to valuation. The second considers future policy analysis, where simplified relationships may be needed to ensure that modelling can be completed within a required time-frame. Simplification of this type has long been a feature of the modelling of critical loads/levels exceedance within the GAINS model, where a simplified approach is based on the outputs of sophisticated and detailed European modelling.

A brief description is also given of the data needs for health impact assessment, for the sake of completeness.

The final chapter of the report considers the comprehensive evaluation of uncertainties affecting the analysis and their reporting in a concise format that is appropriate for policy related work.

2. Objectives:

- Define data needs for valuation of ecosystem services, as reflected by the change in various parameters (crop production, critical loads exceedance, etc.) quantified in other elements of ECLAIRE.
- Define protocols for handling uncertainty.

3. Activities:

- Review of ECLAIRE outputs from other work packages that are relevant to assessment of ecosystem services.
- Review of the broader modelling framework for use in policy support work for the European Commission.
- Consideration of the propagation of uncertainties through the modelling framework (bearing in mind that the valuation and CBA elements come at the end of the analysis and hence are influenced by all preceding uncertainties).

4. Results:

- Description of inputs to valuation when using a full modelling framework.

- Description of approaches for integrating the analysis with the policy-making framework where rapid modelling of costs and benefits of possible actions is required.
- Proposed framework for handling uncertainty.

5. Milestones achieved:

MS79 Agreed modelling framework in place

6. Deviations and reasons:

This deliverable was delayed for reasons described under Deliverable 18.1. The delay does not have consequences for other components as the valuation stage is at the end of the analysis and discussions have been on-going with other ECLAIRE participants to ensure, to the extent possible, that their outputs are consistent with the needs of valuation.

7. Publications:

Not applicable to this deliverable.

8. Meetings:

- NEBEI (Network of Experts on Benefits and Economic Instruments) workshop, St Petersburg, February 2012
- TFIAM (Task Force on Integrated Assessment Modelling)/NEBEI workshop, Zagreb, October 2013
- Workshop at RIVM, Netherlands, December 18 2013

These are reported on separately, under Deliverable 18.1.

9. List of Documents/Annexes:

Attached report.

Contents

1 Introduction

1.1 Objectives:

The valuation of effects of air pollutants on ecosystems in ECLAIRE provides input for cost-benefit analysis of air pollution policies. This deliverable has the following objectives:

1. Define data needs for the valuation component of ECLAIRE (Work Package 18).

2. Consider the way that models can be integrated with the cost-benefit analysis (CBA) work carried out for proposals from the European Commission, UNECE through the LRTAP Convention and other bodies

3. Define protocols for handling uncertainty.

The paper does not restrict attention to measures of impact that can be monetised. Other types of information, for example, photographs of crop damage or maps showing the change in distribution of a species over time, can convey a sense of value to stakeholders, either supporting monetised estimates or highlighting areas where monetisation proves impossible. Information presented in this form is vital for communicating the true nature of pollution effects as it addresses the issue of why society places a value on environmental protection and what is actually being valued This, in turn, helps stakeholders evaluate the credibility of estimates of damage that will be in the order of hundreds of millions or billions of Euro across Europe.

1.2 Structure

The paper is structured as follows:

- Chapter 2 provides an overview of European modelling frameworks for informing the development of policy on air pollution. This includes discussion of systems used for target setting, where the CBA work now plays a prominent role. Description of the overall modelling framework also provides a background to the later discussion of uncertainty.

- Chapter 3 considers the ecosystems services prioritised for this work, identifies required inputs for valuation and useful supporting evidence. Consideration is also given to ways in which different models can be used together.

- Chapter 4 provides discussion of the methods used for uncertainty assessment in the CBA and required inputs.

1.3 Meetings

This paper has been informed by discussion with other members of the ECLAIRE Consortium, for example at annual project meetings, and also with a wider audience at a series of additional meetings:

- NEBEI (Network of Experts on Benefits and Economic Instruments) workshop, St Petersburg, February 2012
- TFIAM (Task Force on Integrated Assessment Modelling)/NEBEI workshop, Zagreb, October 2013
- Workshop at RIVM, Netherlands, December 18 2013

These are reported on separately, under Deliverable 18.1.

2 European Air Pollution Policy Modelling

The purpose of Work Package 18 of ECLAIRE is to enable integration of project outputs with the frameworks in place for development of European and national policy on air quality and climate change, specifically through the use of cost-benefit analysis (CBA). Of the priorities considered under the Work Package, only crop production has routinely been integrated to the CBA previously, but even then using somewhat dated methods. This Chapter describes the overall modelling framework, and particularly how the CBA using the ALPHA-2 and ALPHA Riskpoll models links to the GAINS, EMEP and critical loads/levels modelling.

An understanding of the overall structure of the modelling framework is essential for consideration of how uncertainties propagate through the analysis: this is particularly important for this Work Package as it deals with the final stages of analysis and hence is affected by all of the preceding uncertainties.

2.1 Modelling framework

The overall modelling framework used for European air pollution policy assessments is shown in Figure 1, drawing on the structure refined during the EC4MACS Project. The GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model of IIASA is at the heart of the Framework and provides much of the key output for policy development.

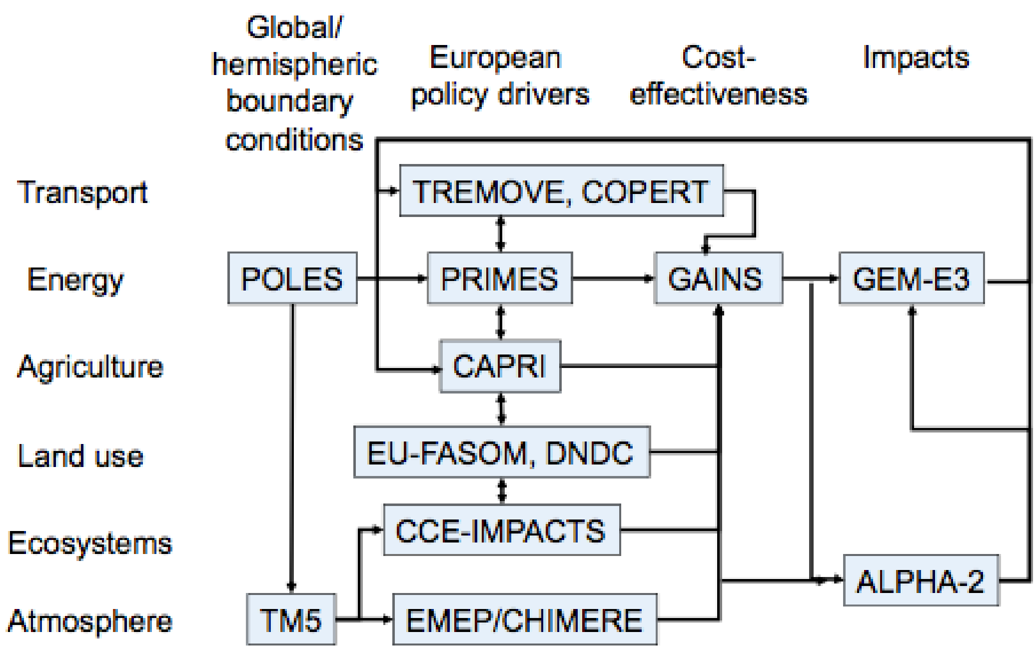

Figure 1. Modelling framework for assessment of European air pollution policies (from EC4MACS Project, Amann, 2013).

Models on the left hand side of the Figure address global and hemispheric conditions:

- POLES – Prospective Outlook on Long-term Energy Systems Model, which simulates energy demand and supply globally

(http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php).
- TM5 – a 3-dimensional global atmospheric model simulating the concentrations of various atmospheric gases such as greenhouse gases (CO_2, CH_4 and N_2O), O_3 and aerosols (http://ccaqu.jrc.ec.europa.eu/tm5_sci.php).

The second column (European policy drivers) contains a series of models that provide direct input to the GAINS model:
- TREMOVE - assesses the effects of different transport and environment policies on the emissions of the transport sector (http://www.tmleuven.com/methode/tremove/home.htm).
- COPERT – describes pollutant emissions from transport http://www.emisia.com/copert/General.html).
- PRIMES –models the energy systems of 35 European countries (http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35:primes&Itemid=80&layout=default&lang=en).
- CAPRI – Common Agricultural Policy (CAP) Regionalised Impact Modelling System, is designed to evaluate impacts of the CAP and trade policies on production, income, markets, trade, and the environment, from the global to the regional scale (http://www.capri-model.org/dokuwiki/doku.php?id=start).
- EU-FASOM - The European Forest and Agricultural Sector Optimization Model, addressing land use in forestry and agriculture (http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/schneider/sem1/Revised%20The%20European%20Forest%20and%20Agricultural%20Sector%20Optimization%20Model_toIAN.docx).
- DNDC – Denitrification, Decomposition model for the simulation of C and N turnover and associated exchange with the atmosphere (http://imk-ifu.fzk.de/823.php).
- CCE-CL – providing information on critical loads and levels from the Coordinating Center on Effects.
- EMEP-CHIMERE – two models providing dispersion modelling across Europe (http://www.emep.int/mscw/index_mscw.html, http://www.lmd.polytechnique.fr/chimere/).

The remaining models shown in Figure 1 are:
- GEM-E3 – a general equilibrium model that covers the interactions between the Economy, the Energy system and the Environment (E3) (https://ec.europa.eu/jrc/en/gem-e3).
- ALPHA-2 and ALPHA Riskpoll models – Atmospheric Long-range Pollution Health/ecosystem Assessment Model, the basis for the quantification of benefits to be fed into the CBA (Holland et al, 2013).

2.2 The ALPHA-Riskpoll model

During EC4MACS, two models were developed for quantifying health impacts in depth, valuation and then applying cost-benefit analysis. The ALPHA-2 Model was developed in Microsoft Access by AEA Technology (now Ricardo AEA). The ALPHA-Riskpoll model was developed in Microsoft Excel by EMRC, and subsequently used for analysis of the European Commission's Clean Air Policy

Package in late 2013. The assumptions and other details of the modelling contained by the two models are described in the CBA methods report from the EC4MACS study (Holland et al, 2013).

ALPHA-Riskpoll has been used for benefits assessment and CBA for both the revision of the Gothenburg Protocol under the Convention on Long-Rage Transboundary Air Pollution in 2012 and development of the European Commission’s Clean Air Policy Package in 2013. The model is most developed for health impacts, for which it contains the following information:

- Projected population by age group to 2100, based on the UN median scenario.
- Response functions for $PM_{2.5}$, ozone and NO_2 for a variety of effects (both mortality and morbidity) based on recommendations from the HRAPIE Project (WHO-Europe, 2013a).
- Fraction of population by age group sensitive to a specific effect (e.g. % of asthmatics, % of people in employment) drawing on various databases, identified by Holland (2014a).
- Incidence data for specific effects, again drawing on various databases, identified by Holland (2014a).
- Valuation data, discussed by Holland (2014b).

The input data required for this part of the model are pollutant concentrations for $PM_{2.5}$, ozone and NO_2. These can either be provided as population weighted concentrations at the national level (with data provided from GAINS) or gridded pollution data (provided by EMEP).

Effects of acidic deposition on materials used in utilitarian applications (i.e. excluding those used in buildings or structures of cultural significance) and effects of ozone on crops are also covered, though using simplified methods, extrapolating earlier estimates of damage per tonne emission for various pollutants. Input data required here are emissions of the pollutants of interest.

For the extension of the ecosystem modelling to be carried out under ECLAIRE the following alternative strategies could be adopted:

1. Continued use of separate models for all policy analyses.
2. Inclusion of full versions of impact assessment models within ALPHA-Riskpoll.
3. Development of simplified models within ALPHA-Riskpoll, based on the outputs of the full tools.

Continued use of separate models creates difficulties for policy analysis that needs to be done with very short turnaround times. The inclusion of full versions of the models into ALPHA-Riskpoll is not attractive, not least as it removes control of the models from the experts who developed them. The third option is preferred here, assuming of course that simple relationships can be determined with parameters representing pollutants levels and damage to crops and the different types of ecosystem.

It is stressed that the development of simplified tools does not negate the need for the continued use and development of the more sophisticated models on which they are based: these models will need to be refined in the future as understanding grows, and simplified relationships will thus need updating. With preliminary estimates of ecosystem damage extending to billions of Euro annually, the importance of a good understanding of what is most sensitive and how ecosystems are likely to change over time is clear, particularly when the funding required for these models is only a tiny fraction of the estimated damage.

The following table summarises the parameters at present delivered by default from the GAINS team[1] for the ALPHA-Riskpoll modelling (noting that a number of these are not yet utilised, but relevant here to show that they are already available).

Table 1. List of parameters currently supplied from the GAINS model for the cost-benefit modelling

1	Emissions of SO_2, NOx, NH_3, $PM_{2.5}$ and VOCs
2	Abatement costs for SO_2, NOx, NH_3, $PM_{2.5}$ and VOCs
3	Total population weighted $PM_{2.5}$ concentrations, by country
4	As [3], but including urban increment
5	Total population weighted $PM_{2.5}$ concentrations, gridded
6	As [5], but including urban increment
7	Years of Life Lost to $PM_{2.5}$ exposure (millions) by country
8	SOMO35 (ppb.days) by country
9	Premature deaths by country
10	POD1 (phytotoxic ozone dose, mmol/m^2, above a threshold of 1 nmol/m^2/s for 'generic tree' by country
11	POD3 (phytotoxic ozone dose, mmol/m^2, above a threshold of 3 nmol/m^2/s for 'generic crop' by country
12	POD6 (phytotoxic ozone dose, mmol/m^2, above a threshold of 6 nmol/m^2/s for 'generic crop' by country
13	% of forest area with critical load for acidification exceeded, by country
14	As [13], but by area for each country
15	% of semi-natural area with critical load for acidification exceeded, by country
16	As [15], but by area for each country
17	% of freshwater area with critical load for acidification exceeded, by country
18	As [17], but by area for each country
19	% of ecosystem area with critical load for acidification exceeded, by country
20	As [19], but by area for each country
21	% of ecosystem area with critical load for eutrophication exceeded, by country
22	As [21], but by area for each country
23	% of Natura 2000 area with critical load for eutrophication exceeded, by country
24	As [23], but by area for each country
25	Accumulated average exceedance (eq/ha/yr) for acidification for forests, by country
26	As [25], for semi natural vegetation
27	As [25] for catchments
28	As [25] for all ecosystems
29	Accumulated average exceedance (eq/ha/yr) for eutrophication for forests, by country
30	As [29], for semi natural vegetation
31	As [29] for catchments
32	As [29] for all ecosystems

[1] Data are normally supplied direct from GAINS outputs during the development of policy. For final policy scenarios data may also be derived directly from EMEP outputs.

2.3 Target setting in European Air Pollution Policy Analysis

2.3.1 Analysis to 2013

In past analysis (prior to 2013) for the European Commission and LRTAP Convention the approach to setting targets for emission controls was as follows:

- Define baseline emissions under the Current Legislation scenario (CLE).
- Define the maximum level of abatement and associated costs according to the measures and data contained in the GAINS model (the Maximum Technically Feasible Reduction scenario, MTFR).
- Describe key impact indicators (mortality linked to PM and ozone exposure, exceedance of critical load for nitrogen across all ecosystems, exceedance of critical load for acidity for forests, exceedance of critical level for ozone) for the CLE and MTFR scenarios.
- Debate how far along the cost curve between baseline and MTFR one should proceed.

Target setting in this way requires stakeholders to come to a view on what level of control is appropriate. Not surprisingly, different stakeholders will take different positions, with some placing more emphasis on keeping abatement costs down and others placing more emphasis on environmental and health protection. The role of cost-benefit analysis came after broad targets had been defined, to provide some fine tuning and a final check that there was an economic case underpinning proposed emission reductions, that the benefits of action would exceed the costs. It also highlighted impact indicators that were not considered by GAINS (and its predecessor, RAINS), notable examples from the past being effects of long-term exposure to PM and short-term exposure to ozone on mortality.

2.3.2 Analysis for the Clean Air Policy Package

For the analysis of the European Commission's proposals on the Clean Air Policy Package a different approach was adopted, bringing in economic assessment of the benefits of emission reductions (Figure 2). The term 'gap closure' is used, with the 'gap' being the difference in health impact (specifically, mortality related to fine particle exposure) between the current legislation (CLE) baseline and the MTFR scenarios. The solid black line shows the marginal abatement cost curve expressed in units of €billion per % gap closure per year. The solid blue line shows the marginal benefit curve, considering only mortality impacts for fine particles (these dominate the health impact assessment), with mortality valued using the most conservative estimate adopted for analysis by the European Commission.

The marginal abatement cost curve slopes upwards moving from left to right, because the higher the level of gap closure the more expensive the measures that need to be introduced. In contrast, the marginal benefit curve is flat, because the analysis adopts a linear response function with no threshold for effects of fine particles on mortality[2].

[2] Many have found this position surprising as they consider it logical that a threshold should be present: after all, most people will not experience discomfort or ill health on days when air pollution is considered high, particularly in regions like Europe where pollution levels are now lower than in the

Note that the marginal benefit curve would not be flat if ecosystem impacts were considered because of the existence of thresholds for ecosystem effects.

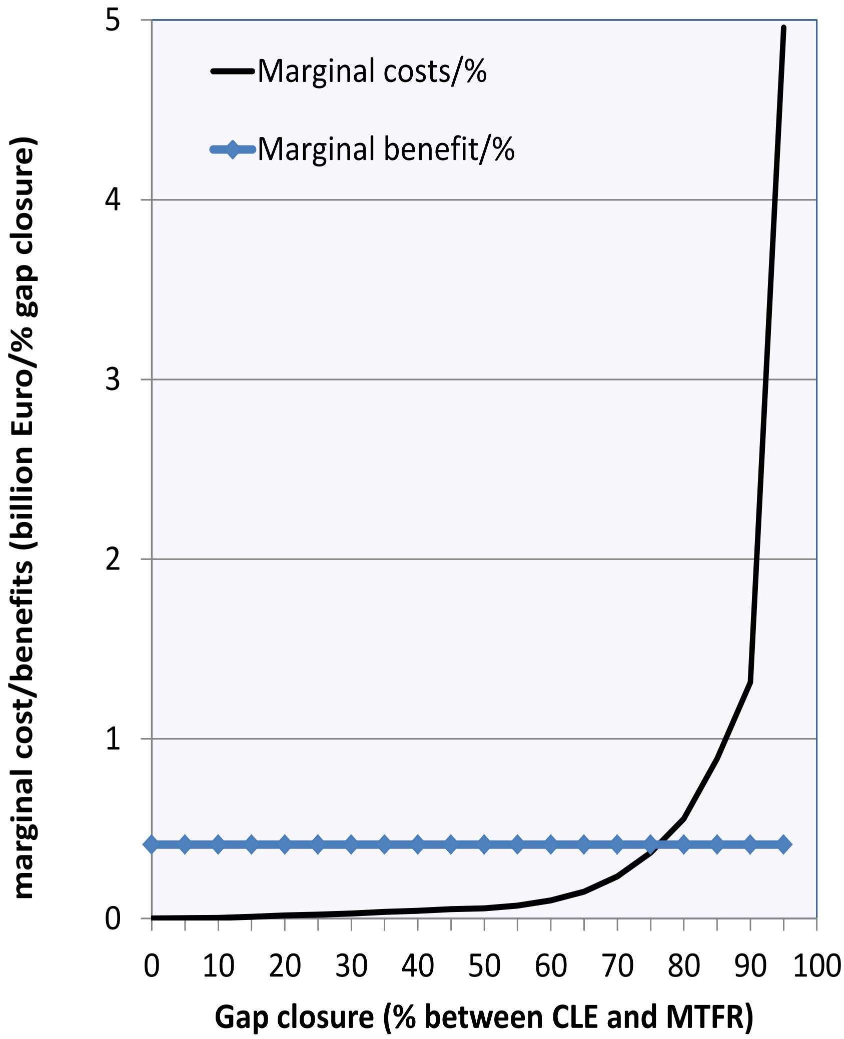

Figure 2. Target setting for the European Commission's Clean Air Policy Package of 2013 (adapted from IIASA, 2013[3]).

Figure 2 indicates that a target of around 75% gap reduction would be justified from an economic viewpoint. The Commission's proposal was close to this point.

---

past. However, the analysis deals with the whole population, including people of all ages and in differing states of health. Whilst most may not be adversely affected by air pollution, a significant fraction of the population at any time is sensitive. Further to this, air pollution is itself a factor in sensitization.

[3] The figure presented by IIASA 2013 includes an uncertainty range based on different valuation approaches for mortality. However, as this complicates the figure, and the Commission's proposal was based around the most conservative estimate, the full range is not presented here. No account was taken of uncertainty in the abatement costs.

From the perspective of ECLAIRE, the question arises of whether the inclusion of ecosystem impacts alongside mortality would have altered the conclusions of the analysis significantly. This is dependent on two issues:

1. The extent to which the marginal benefits would increase with ecosystem impacts added.
2. The extent to which the set of measures adopted for health protection associated with fine particle exposure is also protective of ecosystems.

In relation to the second point it should be noted that 'fine particles' include secondary aerosols associated with emissions of NH_3, NOx, SO_2 and VOCs as well as primary particles, so the abatement measures considered will reduce the types of ecosystem damage of interest to ECLAIRE.

Clearly, the best way to answer these questions is through the direct inclusion of ecosystem impacts into the marginal damage estimate. This is not as straightforward as the approach adopted in Figure 2, as the definition of gap closure would need to cover a set of different impacts (as noted above, the Figure 2 only deals with gap closure in terms of PM impacts on health). However, a more integrated approach could be developed once data are available.

2.4 Transfer matrices

In most cases below it is suggested that data on change in production, biodiversity, GHG emission, etc. is presented at the national level, for the country experiencing the change. The form of the CBA at national level is thus to compare cost to country *x* against benefit to country *x*. This approach has been standard practice in air pollution CBA work in Europe for many years because national governments like to know what a measure will cost them and by how much they will benefit.

Whilst this provides the correct total for benefit or damage across Europe (ignoring any leakage of pollution beyond the modelled or legislative domain) there is a second option that is theoretically more appropriate for the national level, the comparison of costs in country *x* against the benefits of emission reductions from country *x* wherever they occur.

This second form of calculation was used in the CBA for the revision of the Gothenburg Protocol (Holland et al, 2011). Whilst the benefit from emission reductions by each country does not appear automatically from the standard modelling, it can be approximated by taking results at the national level and back-calculating to allocate the change in damage using transfer matrices generated using EMEP data.

3 Data needs

3.1 Contextual information

The terms 'biodiversity' and 'environmental protection' are useful catchall terms, sufficient in many situations to indicate what is under investigation. However, for the purposes of valuation it is important to go further to describe what is being valued in order that stakeholders can understand the analysis more clearly: the valuation itself has little meaning without this understanding. The issue is particularly important when dealing with damage at national and international levels in the order of billions of Euro annually, which is not easy to visualise.

Maps generated with the GAINS model by IIASA providing an indication of the risk of critical loads exceedance have proved to be a useful communication tool (Figure 3) in the past. The maps show almost total presence of exceedance of nutrient critical loads in 2000 outside of the northern-most areas of Europe, with limited improvement out to 2030.

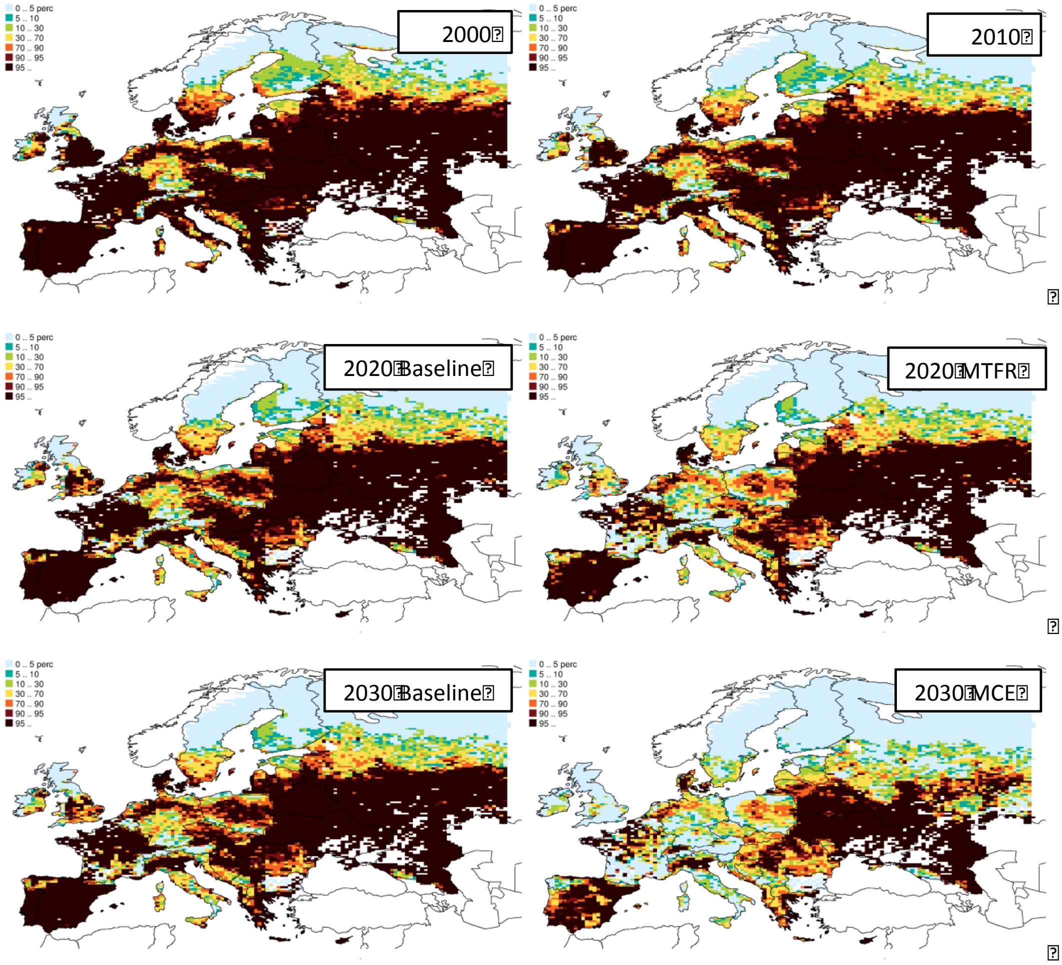

Figure 3. Percentage of ecosystems area with nitrogen deposition above their critical loads for eutrophication (IIASA, 2012).

However, the maps leave many questions unanswered, what is at risk, what sort of change is expected, and so on. The problem is particularly notable in the case of N deposition, given that this will in general act to promote growth, which many would assume to be a good thing. With this in mind, additional contextual information is an important aid to communicating what is at risk and what is being valued.

Examples of this contextual information include the following:

- Photographs of plants, etc. considered to be at specific risk from ozone or N deposition – in essence giving a more personal quality to the message that ‘ecosystems are at risk’
- Photographs of damage to plants or of changed ecosystems, with an indication of how widespread the conditions causing the damage may be across Europe
- Maps showing trends in the distribution of species over time.

These are only examples; other types of information that clearly communicate impacts could be equally useful.

A recent publication from ICP Vegetation (ICP Vegetation, 2014) provides some examples of the types of damage that are seen (Figure 4). The purpose of the document, produced alongside a mobile phone app to encourage the recording of symptoms, is to obtain information on the distribution of visible ozone injury across Europe. The map shown in Figure 4 demonstrates that such damage is widespread across Europe[4]. Taken together, the map and the photos demonstrate that ozone is having real effects across Europe, substantiating the economic analysis that follows.

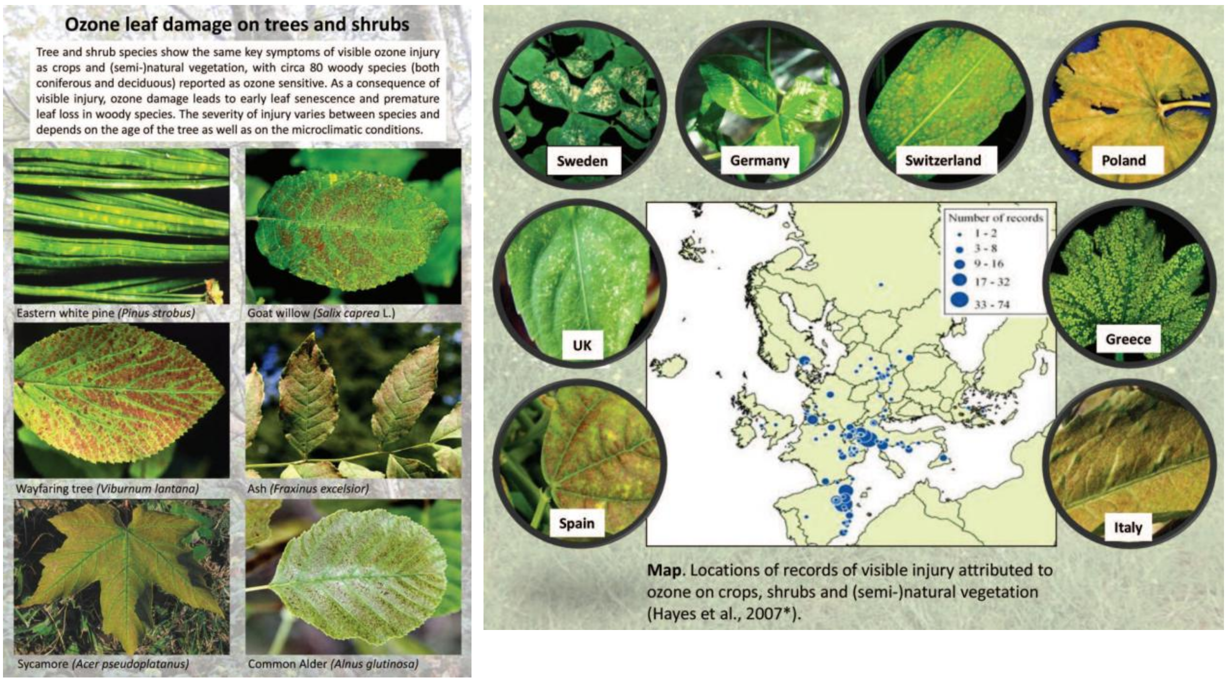

Figure 4. Example images from ICP Vegetation (2014).

[4] The precise distribution of damage shown in the map should not be taken too seriously at the present time as it will likely be based on information from a few researchers, and hence be correlated with their location and movements.

With respect to maps showing the distribution of species over time, it is appreciated that air pollution is only one stress of several that would affect distribution. Others, such as climate stress, land use change, use of herbicides and other land management practices will in many cases be more important than either ozone or N deposition, though the pollutant effect will add to other stresses. For the UK (as an example), a particularly useful source could be the Online Atlas of the British Flora (BSBI, 2012), which provides several types of map for each species (see example in Figure 5[5]). In addition to the factors just mentioned, interpretation of these maps requires understanding of the way that data are collected at various times, whether from systematic national surveys or from independent and more localised surveys.

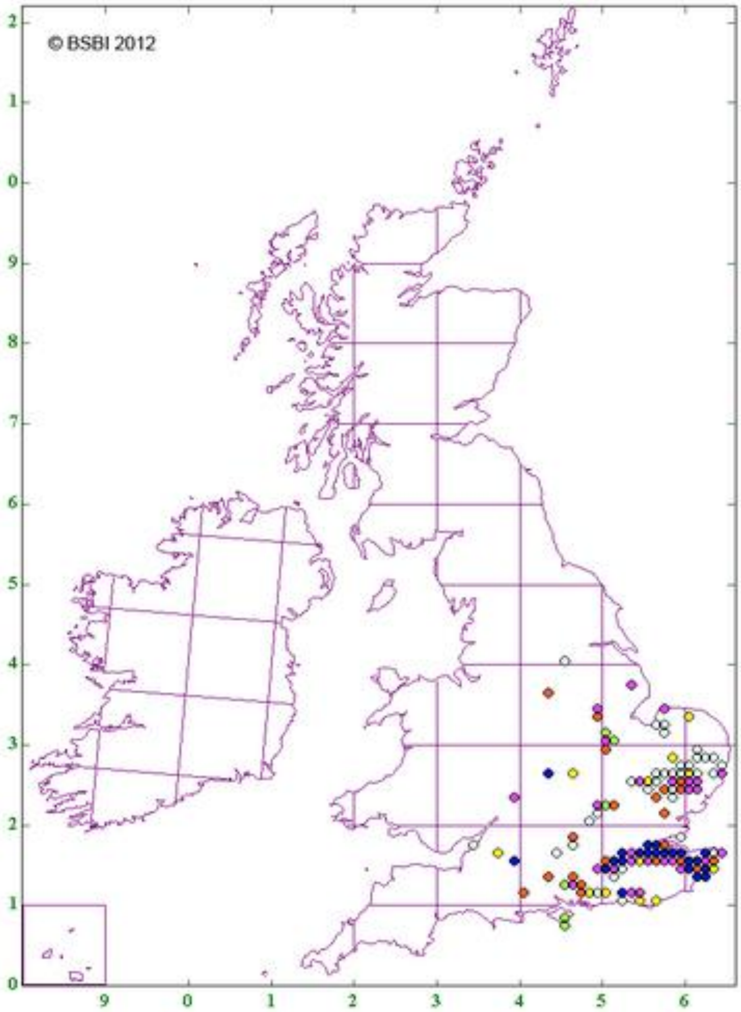

Figure 5. Map showing changes in the reported distribution of the Man Orchid (*Aceras anthropophorum*), 1930-2010. Records are shown as one of six symbols which denote the date of the latest record - blue squares (after 2010), purple squares (2000-2009), orange squares (1987-1999), green squares (1970-1986), yellow squares (1930-1969) and magenta squares (before 1930)

[5] The example shown, the Man Orchid (*Aceras anthropophorum*), was selected as it is listed as endangered (IUCN, 2001) in the UK and occurs in nutrient poor locations (Ellenberg N value of 3).

3.2 Biodiversity

3.2.1 Quantitative valuation methods

Following a workshop of this Work Package held at RIVM in December 2013, it was decided to investigate the use of three different approaches to the quantification of amenity-related damage to natural ecosystems.

The first of these is based on available information from stated preference studies on 'willingness to pay' (WTP) for protection of biodiversity, drawing on Christie et al (2011) and Jones et al (2013). This approach is consistent with that used for valuation of health impacts being based on stated preference. However, it is based on a small valuation literature, making it desirable to also consider other methods that may provide alternative perspectives. The second approach is based on use of repair costs drawing on the results of Ott et al (2006), and the third on the inferred costs of environmental policies ('regulatory revealed preference'). It was also decided that the work should focus initially on Natura 2000 areas, for which there is a legal responsibility on Member States to preserve, maintain and restore. The methods are discussed in detail in a separate deliverable (Holland and Maas, 2014, draft).

3.2.2 Stated preference approach

The question arises as to how the valuation of Christie et al can best be linked to an indication of ecological change. Options are:

- As a straightforward willingness to pay per household for ecological improvement. Investigation of this option suggests extremely high valuations per unit area in some countries, where critical loads exceedance is small
- Index of risk relative to the UK (the country for which the Christie et al estimates were derived), with various possible metrics:
    - Area of exceedance (the option used in the draft Holland and Maas paper, and a standard output from GAINS)
    - Accumulated Average Exceedance (standard output from GAINS)
    - Indicators of plant species richness, change in species, etc. (CCE, 2008 to 2012)

Whilst these indicators were not specifically referred to by Christie et al, they seem a reasonable proxy for valuation.

3.2.3 Repair cost approach

The use of repair costs assumes that repair would actually be undertaken, with repair costs representing a minimum valuation (the value has to be at least as large as the repair cost to justify expenditure). This is one reason for a focus on Natura 2000 areas, as the Birds and Habitats Directives of the EU require that the ecological status of these areas is at least maintained, and preferably improved. Two types of input are possible:

- Emissions of each pollutant,

- Area of ecosystem subject to critical loads exceedance

Both parameters are already provided through the existing link to GAINS (see Table 1). Valuation is then based on the values proposed by Ott et al (2006).

3.2.4 Regulatory revealed preference

This method is again based on the assumption that the costs of the Birds and Habitats Directives provide a minimal societal valuation for the protection of the Natura 2000 network, and that policy makers implicitly factored in necessary air pollutant abatement costs when designing the legislation. The following inputs are required:

- The extent of exceedance of the critical load for eutrophication in each country in Natura 2000 areas (terrestrial only)
- The costs of applying all technical NH_3 controls contained in the GAINS model (as represented through the costs of the MTFR, Maximum Technically Feasible Reduction, scenario which is routinely quantified in the IIASA modelling)
- The same for NOx
- In the event that the critical load is still not met after application of all measures in the MTFR scenario, the cost of further measures.

Again, these outputs, with the exception of the last, are already provided through the existing link to GAINS.

3.2.5 Adjustment for national circumstances

The need to differentiate unit values by Member State is dependent on the scope of the analysis. For analysis at the European Union level it is common practice to apply uniform values across the EU (as in the analysis of the benefits of reducing air pollution by Holland, 2014, for the Clean Air Policy Package). The assumption of different valuations in different places would run counter to the 'level playing field' philosophy that underpins much EU environmental regulation. On this basis, for decisions made at the EU level, the valuation of health should be consistent throughout the Union, as should valuation of concern for the environment.

However, the same does not apply to valuation for policies implemented at the national level. In that situation it is appropriate to use valuations that reflect national, rather than continental preference[6]. The Holland and Maas draft considers several approaches to adjusting the Christie et al results to reflect national conditions, including adjustment by:

- Average incomes (Eurostat, 2104a)
- Environmental protection expenditure (Eurostat, 2014b)

[6] Consider first the situation in a country that has a high WTP for environmental protection. There is no basis for dictating to that country that they should limit environmental expenditure to a level representative of the Union as a whole. Consider then a country that has a low WTP for environmental protection because of low average income. Why should the priorities for protection adopted elsewhere be assumed applicable here also, given that rich and poor may have very different ideas as to what is the most effective use of available resource?

- Levels of environmental concern as reported through Eurobarometer (Eurobarometer, 2011)

Of these, the most appropriate was concluded to be adjustment by income. Environmental protection expenditure and levels of environmental concern both vary for a large number of reasons, sometimes with counterintuitive consequences.

The opportunity remains open for alternative datasets for adjustment for national circumstance to be considered. The integration of such a dataset would only affect the valuation component, and even then would be applied at the end of the analysis without implications for other ECLAIRE activities. As a result, suggestions for such datasets could be made almost to the end of the ECLAIRE Project.

3.2.6 Required input for the economic assessment

For all analysis

- Contextual data on damage in the form of species distribution maps, photographs, etc.

For analysis of the scenarios to be considered within ECLAIRE:

- Data on pollutant emissions and inputs at national level
- Data on exceedance of critical levels and critical loads (area exceeded, average accumulated exceedance) at national level
- Data showing change in ecological indicators at national level
- Cost data for NH_3 and NOx measures
- Alternative datasets for national adjustment of economic estimates (non-essential).

For upgrading the ALPHA-Riskpoll model to permit rapid calculation for future policy analysis:

- Data on change in ecological status per unit change in (e.g.) N deposition or ozone exposure, by country.

3.3 Agriculture

3.3.1 Effects for consideration

Past analysis of impacts on crop production has focused on the effects of ozone on arable crops, as this is the area that has been subject to the most extensive research (Mills et al, 2013). Results indicate a significant loss of crop yield, in the order of 10% across Europe for wheat and tomato Mills and Harmens, 2011). Economic analysis of the impacts of N deposition on crop growth has focused on the costs of an equivalent amount of N fertiliser, with results indicating a very small potential benefit (various case studies in CIEMAT, 1999). This may be optimistic given the shape of the response curve for crops to N and is dependent on the optimality of fertilisation regimes being applied by farmers and whether they account for atmospheric deposition (Brink and van Grinsven, 2012).

A complete analysis of impacts of ozone and N deposition on agriculture would account for the following:

- Direct effects of ozone on productivity for both arable crops and pasture (Mills et al, 2013)
- Direct effects of ozone on food quality for both arable crops and pasture (Mills et al, 2013)
- Direct effects of ozone on productivity through injury to leaves (for example, damaging some salad crops and leaf crops like spinach sufficiently that they could not be marketed) for some arable crops (WGE, 2004; ICP Vegetation, 2014)
- Indirect effects of ozone on productivity through interaction with pests and pathogens for both arable crops and pasture (Riemer and Whittaker, 1989; Warrington, 1989; Houlden et al, 1990)
- Direct effects of nitrogen on productivity or fertiliser costs for both arable crops and pasture (CIEMAT, 1999)
- Indirect effects of nitrogen on productivity through interaction with pests and pathogens for both arable crops and pasture (Riemer and Whittaker, 1989; Houlden et al, 1990)

It is not anticipated that all of these categories of impact will be quantifiable: interactions with pests and pathogens for example may be significant but have attracted little attention from researchers over the last 20 years. Indeed, experimental work largely removes the opportunity to investigate interactions with pests and pathogens, as plants are treated to eliminate the potential for these stresses, of at best secondary interest to researchers, confounding the results of the experiments. However, a view on the completeness of any assessment is important, as it provides some understanding of the likelihood of results over- or under-estimating the true level of pollution damage.

3.3.2 Approaches

Ozone and yield

The preferred approach for quantification of ozone related damage to crop productivity is now based on the POD (phytotoxic ozone dose) metric rather than the concentration based AOT40 metric. A problem that arises is the availability of data for POD-based analysis, with response functions available for rather few crops. It is recommended here that reference be made available to the wider literature to assess crop-ozone sensitivity in order to generate more complete estimates of yield loss, as has been done previously by (e.g.) Mills et al (2006). The required output would be annual yield loss in tonnes by crop, covering the major European crops by production value.

A complexity for salad crops in particular arises because many are grown in glasshouses and this will affect the extent to which they are exposed to ozone. Further uncertainty will arise in relation to irrigation regimes. These will need to be addressed either quantitatively or qualitatively in the uncertainty analysis that follows (Chapter 4).

The situation is more complex for livestock and milk production, as farmers can take compensatory action against a reduction in the production or quality of pasture through the use of supplementary feed. For a closely managed herd, for example, there may be no change in production in a high ozone year, but there would be added feed costs and it is these that should be brought into the economic analysis. However, high and low ozone years are averaged out in the modelling of future scenarios, so there is no need to account for random inter-annual fluctuation in conditions (as opposed to the systematic change in concentrations associated with a change in emissions). An understanding of livestock management practices will be needed for correct accounting of impacts to livestock.

Ozone and food quality

With respect to food quality, it is not anticipated that sufficient data are available from research to enable quantification. In any case, the review by Mills et al (2013) notes both positive and negative effects of ozone on yield quality for potato and rapeseed, so the overall picture on this aspect may be very variable, and inevitably incomplete. An expert view on the likelihood of effects overall being positive or negative would be useful, to indicate whether or not results excluding this effect are likely to over- or under-estimate damage.

Ozone and visible injury

Systematic observations of direct damage from high concentration ozone episodes are only just starting at the European level (ICP Vegetation, 2014, see Figure 4) and so it is not expected that quantification will be possible. Results are extremely variable: observations have shown plants in neighbouring plots to be affected to very different degrees, depending on irrigation regimes. Figure 2.16 in WGE (2004) shows plants irrigated at a time that coincides with high ozone exposure being severely damaged and whilst those in a neighbouring area that was not irrigated at the time of high exposure show no or very little injury.

It is suggested here that this effect does not account for a large amount of crop loss across Europe. If it did, it is surprising that it has not attracted more attention in the past unless of course observers have failed to recognise it s ozone related injury. However, when impacts do occur, they can be very serious over a restricted area, perhaps wiping out a farmers complete crop.

Again, an agreed expert view on this type of impact and its severity would be useful.

Indirect effects of ozone on yield via interaction with pests and pathogens

Little research has been carried out in this area for a number of years. The research that was done primarily through the 1980s suggested a negative interaction with pests. Efforts to quantify this effect under the ExternE programme were not successful in the early 2000s, and we are aware of no further literature since that would permit quantification. A recent workshop in the USA concluded that such effects would be unquantifiable (Garrett et al, 2013). Again, an agreed expert view on this type of impact and its severity would be useful. The issue (for both ozone and nitrogen) has been raised at the annual ECLAIRE and other meetings, where there has been a general agreement that the impact could be significant, but no further data have been identified.

Direct effect of nitrogen deposition on productivity

The effects of nitrogen on productivity follow a non-linear curve (Figure 6, taken from von Blottnitz, 2006 and Brink and van Grinsven, 2011). There is therefore a point at which the yield change associated with added N moves from positive to negative. The figure is of course based on deliberate fertiliser inputs to agriculture rather than atmospheric deposition.

Three points are highlighted in the figure. The first is N_{max}, the N input rate for maximum yield. The second is the PONR, the privately optimal N r input rate (i.e. the rate at which farmer's profits are maximised). This is lower than N_{max} as the net benefit (increased yield – cost of fertiliser) of adding more N becomes negative as N_{max} is approached. The third point is the SONR, the socially optimal N r input rate, which accounts for the external costs associated with N additions.

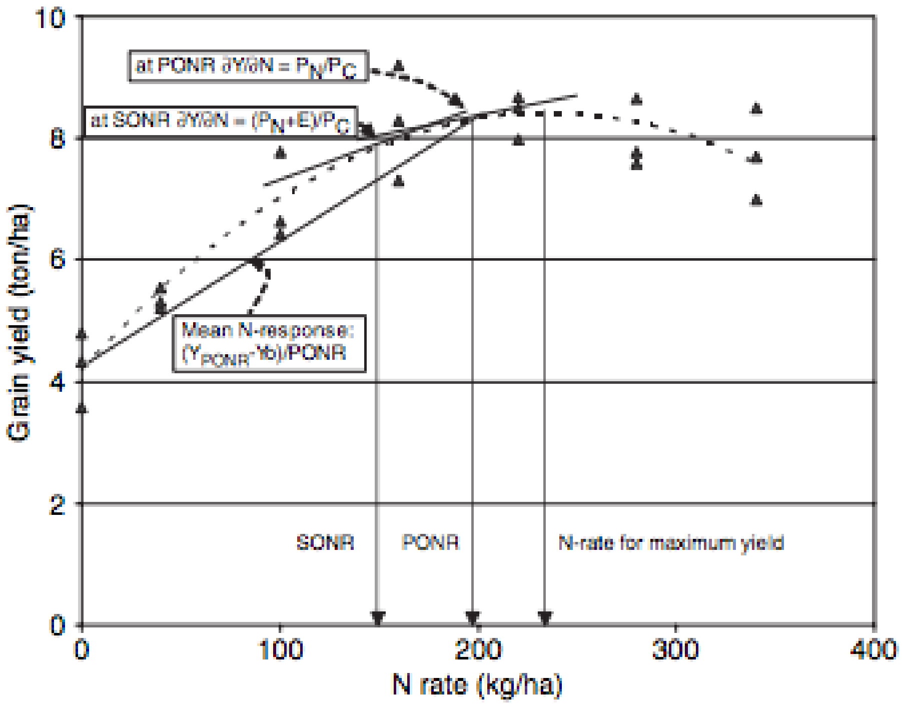

Figure 6. Example of a yield response curve for winter wheat in the UK demonstrating the marginal and average unit benefit of annual nitrogen fertilizer inputs. (from Brink and van Grinsven, 2011, drawing on von Blottnitz et al, 2006).

Key:
(d Y /d N) PONR = PN / PC
(d Y /d N) SONR = (PN + E)/ PC

where:
Y = crop yield (kg/ha)
N = input rate of reactive nitrogen (kg/ha)
PONR = privately optimal N r input rate (kg/ha)
SONR = socially optimal N r input rate (kg/ha)
PN = price of N r (purchase and handling; euro/kg)

[continues from left column]

where:
D = social damage caused by nitrogen (euro/impact)
Ni = emission of N r compound (kg/ha)
Ni = ef A or ef N
ef = emission factor
A = economic activity
PD = social cost of environmental damage (impact/kg N r)

PC = price of crop (euro/kg)
E = externalities; sum of environmental damage costs (euro/kg)
E = ∑ D (Ni) PD
[continues in right column]

UBoN = (YPONR−YN=0)* PC /PONR – PN

where:
UBoN = net unit crop benefit of N r (euro/kg N)

The key question for determining the economic effect of N deposition to agriculture in terms of yield change is thus at what level do farmers generally apply nitrogen relative to N_{max}? Brink and van Grinsven suggest that farmers tend to err towards generosity in fertiliser applications (going beyond PONR), suggesting that the starting position, at least for intensive agriculture, is most likely to be in the very flat part of the curve shown in Figure 6. The direct effect on crop yield of N deposition in this area of the graph would be negligible.

Of course, not all agriculture is subject to high levels of fertiliser input. Ironically, N deposition may be most advantageous for organic production. It may also be advantageous for upland livestock production, particularly sheep. Against this could be the impacts of

Indirect effects of nitrogen deposition via interaction with pests and pathogens

Again, little research has been carried out in this area for a number of years and past work to investigate the potential for quantification has been unsuccessful. An agreed expert view on this type of impact and its severity would be useful.

3.3.3 Required input for the economic assessment

For all analysis

- Contextual data showing photographs of ozone injury and maps showing the distribution of injury in the field from observations linked to natural exposures.

For analysis of the scenarios to be considered within ECLAIRE:

- Change in yield by crop, including grass, for each country.
- List of crops addressed by the analysis (including those which are insensitive to ozone and hence for which zero response is anticipated).

For upgrading the ALPHA-Riskpoll model to permit rapid calculation for future policy analysis:

- Data on change in agricultural production per unit change in N deposition and ozone exposure, by country.

Further to this, consideration should be given to feedbacks to the CAPRI and EU-FASOM models.

3.4 Forest production

3.4.1 Effects for consideration

A complete analysis of impacts of ozone and N deposition on forestry would account for the following:

- Direct effects of ozone on productivity for both coniferous and deciduous species (Mills et al, 2013)
- Indirect effects of ozone on productivity through interaction with pests and pathogens (Karnosky et al, 2005; Karnosky and Pregitzer, 2005)
- Direct effects of nitrogen on productivity (Thomas et al, 2010)
- Indirect effects of nitrogen on productivity through interaction with pests and pathogens (Wainhouse, 2005)

Another possible impact of air pollution is through effects on timber quality. The literature in this area has been reviewed and found to be inconclusive. Another possible effect is linked to premature senescence of leaves leading to some amenity loss. Again, there is a lack of literature to enable a firm conclusion on the importance of this effect.

3.4.2 Data needs

As for agriculture, it is not anticipated that all of these categories of impact will be quantifiable: interactions with pests and pathogens for example may be significant but have attracted little attention from researchers over the last 20 years. However, a view on the completeness of any assessment is important, as it provides some understanding of the likelihood of results over- or under-estimating the true level of pollution damage. The approach to evaluation of impacts other than those on productivity will thus be an expert evaluation of the potential importance of effects.

So far as other ECLAIRE team members are concerned, the necessary quantitative outputs for valuation concern changes in forest production. The further this can be disaggregated to timber, pulp and harvestable biomass (for combustion) the better.

Turning to the valuation of effects on forest productivity, there are three issues of basic importance to the economic modelling of changes in forest productivity:

- Effects on productivity in the long term, in particular, whether the stimulation of growth by N deposition will be maintained for many years to come
- Demand for forest products in the future, noting predictions of a paperless society and increased rates of recycling on the one hand, and increased demand for biomass for combustion as a response to climate change on the other.
- The response of forest managers to changes in growth and changes in demand for forest products.

These issues will be the subject of further discussion.

Following on from this, as was the case for agriculture, there is a need for contextual information in the form of photographs of visible injury from ambient exposure, maps showing the location of visible symptoms, maps showing where critical loads are exceeded and any other illustrative material that demonstrates both that damage is occurring and how widespread it appears to be. This will help to substantiate the results of the quantitative assessment.

3.4.3 Required input for the economic assessment

For all analysis

- Contextual information showing photographs of ozone injury and maps showing the distribution of injury in the field from observations linked to natural exposures.

For analysis of the scenarios to be considered within ECLAIRE:

- Change in yield by species, for each country, accounting for the proportion of trees that are in productive forestry (as opposed to amenity woodland).
- List of crops addressed by the analysis (including those which are insensitive to ozone and hence for which zero response is anticipated).

For upgrading the ALPHA-Riskpoll model to permit rapid calculation for future policy analysis:

- Data on change in agricultural production per unit change in N deposition and ozone exposure, by country.

3.5 Greenhouse gases

3.5.1 Modelling approach

The mechanics involved in valuation of greenhouse gases is straightforward. A value is selected, typically per tonne of CO_2eq and applied per tonne emitted or sequestrated. Given that the pollutants concerned have long atmospheric residence times and the effects operate at the global scale, there is no need to adjust values to account for the site of emission/sequestration. There are broadly two types of value that can be used according to circumstance, these concerning damage costs from climate change and marginal abatement cost.

Marginal abatement costs are most clearly applicable when working within the constraints of agreed emission ceilings. Under this condition, an increase in emission from any source covered under the ceiling will require additional abatement from another source within the ceiling, which will presumably be undertaken by adopting measures at the margin. Similarly, emission reductions within the ceiling would enable other sources to increase emission, removing the need for implementation of some measure at the margin. Either way, there is no change in damage because the overall emission of greenhouse gas is the same, and hence the marginal effect is a change in abatement cost. In the absence of a ceiling it is more appropriate to use the change in damage cost.

A complication of course is that damage costs for climate effects are associated with a high degree of uncertainty (highlighted by the 2006 Stern Review and subsequent discussions of it). One reason for this is the difficulty in quantifying some potentially major impacts of climate change, such as from severe weather events, population migration and so on. Another reason is that important judgement calls need to be made for the economic modelling, for example on the treatment of equity and discounting. Different assumptions in these areas lead to order of magnitude differences in outcome. A lack of agreement in how to deal with these issues has led much policy analysis to adopt marginal abatement costs, though their true applicability is often questionable. However, these concerns do not affect the fact that the input immediately prior to valuation will need to be expressed as tonnes of CO_2eq.

3.5.2 Required input for the economic assessment

For analysis of the scenarios to be considered within ECLAIRE:

- Data on change in CO_2eq (tonnes emitted or sequestered) and associated time profile. These data to be provided at national level

For upgrading the ALPHA-Riskpoll model to permit rapid calculation for future policy analysis:

- Data on change in CO_2eq (tonnes emitted or sequestered) and associated time profile per unit change in (e.g.) N deposition or ozone exposure, by country.

3.6 Health

Methods for health impact assessment are described by WHO-Europe through the outputs of the REVIHAAP and HRAPIE Projects (WHO-Europe 2013a, b respectively), and by Holland (2014b). Whilst further research on health impact assessment is outside the scope of ECLAIRE, it will be included in scenario analysis undertaken for the project. The input data required are pollutant concentrations for $PM_{2.5}$, ozone and NO_2. These can either be provided as population weighted concentrations at the national level (with data provided from GAINS) or gridded pollution data (provided by EMEP).

4 Framework for dealing with uncertainty

4.1 Uncertainty in context

Before describing protocols for dealing with uncertainty it is necessary to define the context within which uncertainties need to be considered within this Work Package of ECLAIRE. The methods so developed are intended primarily for use in CBA, rather than stand-alone estimates of impact. The ultimate question to be investigated, therefore, is not:

"*How big are the benefits associated with a particular policy?*"

but

"*Do the collective benefits of action outweigh the costs?*"

Views on whether the uncertainty in a particular result (such as reduced agricultural yield losses) is 'large' or 'small' are largely irrelevant. What is important is the *robustness* of the final conclusion that, overall, benefits will or will not outweigh the costs of some action. A result may appear to be associated with a high level of uncertainty, but in many cases this will not affect the robustness of the conclusions reached in the policy analysis, as there may be little or no overlap in the ranges for costs and benefits of action. In contrast, where costs and benefits are close to each other, an apparently small amount of uncertainty can have an important effect on the robustness of decisions taken.

It will be noted that this Chapter takes a broad definition of the word uncertainty, incorporating anything (statistical uncertainties, methodological uncertainties, etc.) that has the potential to reduce the robustness of conclusions drawn from analysis.

4.2 Past development of methods for uncertainty appraisal in EC CBA work

Early work on uncertainty in CBA work of European air quality policies used a method described as a stratified sensitivity analysis (Holland, Forster and King, 1999). Prior to quantification, effects were ranked according to the perceived level of confidence in their quantification and then allocated to five groups ranging from good to low confidence (Box 1). Grouping was done to simplify the analysis and also to acknowledge the subjectivity in ranking effects in different impact categories (health, materials, crops, etc.

Following quantification, totals were calculated first for Group I (good confidence) and then the other groups were added in, in order of decreasing confidence. Results were inspected to identify how many groups were required for benefits to exceed costs. Clearly, the fewer groups that were needed, the higher the confidence that benefits would indeed exceed costs.

Box 1: Grouping of effects by perceived confidence in quantification (Holland et al, 1999)

Group I (effects quantifiable with the highest level of confidence):
- Materials damage (excluding paint)
- Crops – N fertilisation
- Health – acute mortality impacts (VOLY, value of life year, valuation)

Group II:
- Health – restricted activity days
- Materials – paint damage
- Crops – SO_2 and ozone effects

Group III:
- Health – acute mortality impacts (VSL, value of statistical life, valuation)
- Health – chronic bronchitis

Group IV:
- Forests – ozone effects
- Health – chronic mortality impacts (VOLY, value of life year, valuation)

Group V (effects quantifiable with the lowest level of confidence):
- Health – chronic mortality impacts (VSL, value of statistical life, valuation)
- Visibility

Although this approach was well received and is still well regarded by many, it was not used in the work on the European Commission's Clean Air For Europe (CAFE) Programme (Holland et al, 2005a). By the time of CAFE, views on quantification had changed. Effects on forests and visibility, for example, were no longer included and quantification of chronic mortality effects was considered far more robust than in the 1999 analysis, indeed sufficiently so that it was accepted as a core indicator in the RAINS/GAINS model. Continuation of this approach would require further multi-disciplinary consultation which would be subject to the same concerns as expressed previously, that conclusions on groupings were very subjective as respondees found it very difficult to rank impacts that were outside their own field.

Methods for uncertainty assessment in CAFE are reported by Holland et al (2005b) and further developed and implemented in the various analyses performed to inform the development of the Thematic Strategy on Air Pollution and the revision of the National Emission Ceilings Directive (AEA Energy and Environment 2005a, b, c; 2006, 2008). These methods are discussed in the following sections. Within the EC4MACS project the TUBA Framework (Treatment of Uncertainties in Benefits Assessments) has been formalised, to collate all available information on uncertainty (Holland et al, 2013).

The non-expert (which, with no disrespect intended, will include most policy makers) will need to know the following about the uncertainty analysis:
1. That uncertainties have been investigated
2. That uncertainty analysis is comprehensive
3. What results indicate for the robustness of the policy conclusions that are informed by the analysis.

With respect to the last point in the list, it is necessary that the uncertainty analysis is presented in a way that is easy to understand. This will not be achieved by presenting pages and pages of sensitivity analysis, or presenting results separately for the different models used. This may be necessary in the early stages of the analysis, but the final outputs need to brought together more succinctly. An example is presented below in Figure 7.

4.3 Types of uncertainty

In order to take a comprehensive assessment of uncertainty it is necessary to recognise that a full assessment should account for different kinds of uncertainty. Here, we separate uncertainties into the following classes:

- Statistical uncertainties
- Biases
- Methodological sensitivities
- Model uncertainties

4.3.1 Statistical uncertainties

Discussion of uncertainty often focuses purely on those aspects of analysis that can be quantified using statistical techniques. These techniques address uncertainty associated with the extraction of information from observations on a limited sample drawn from a population of people, crops, industrial plant, etc. They describe the behaviour of the sample (e.g., how it responds to change in a variable such as increased air pollution) and show how reliable the conclusions drawn from use of the sample are as a representation of the behaviour of the total population. Key characteristics of a sample are average (also referred to as 'mean') or median values and the spread of values around them. Spread is typically characterised as the standard deviation and the range within which 90, 95 or 99% of observations are likely to occur.

A simple approach would investigate uncertainty by applying the limits of a confidence interval to generate a range. This approach can work well when analysis contains rather few parameters. The more parameters present, however, the less likely that the resulting range is a reliable reflection of the underlying data. Reference back to Figure 1 showing the extensive suite of models brought together for European air pollution policy analysis demonstrates that final outputs are a function of a very large number of variables. In reality, combinations where all parameters are at the upper or at the lower end of their confidence interval are very unlikely. Interpreting a range based on combination of (e.g.) 95% confidence intervals in this way as the overall 95% confidence interval is incorrect and will give too broad a range. A more reliable approach is to bring ranges together using Monte Carlo or similar sampling techniques that account not only for the input ranges but also for the distribution of values across those ranges.

Required input:

- Best estimate for any parameters used in the analysis, with x% confidence interval and shape of range

In the interests of consistency it may be advantageous for the statistical analysis of uncertainty to be undertaken centrally by the Work Package 18 team, rather than by different groups across ECLAIRE. This can be done using dummy variables for simplicity, which will provide a reliable indication of spread around best estimates.

4.3.2 Biases

Biases, as considered here, are factors for which quantification and associated assessment of uncertainty in a sufficiently detailed and quantitative manner for inclusion in the analysis is not possible. An example of bias in past CBA work for the European Commission is the complete omission of impacts of N deposition on biodiversity.

The treatment of biases proceeds through the following stages:

- Identification of biases
- Assessment of the direction of bias
- Assessment of the potential effect of biases on the cost-benefit balance
- Interpretation of the overall effect of the biases identified.

Required input:

- Identified biases, direction of bias if known, perceived importance of bias

'Perceived importance' will require some discussion across Work Packages.

4.3.3 Sensitivities

There are several methods available that come under the general title of sensitivity analysis that seem relevant here:

- Observation of the effect on outputs of a systematic stepwise change in one or more variable(s). This could, for example, involve assessment of the effect of a series of incremental changes of 5% or 10% around the core estimate for a specific variable.
- Use of alternate estimates for a specific parameter based on different methodologies. Examples include:
    - Monetisation of mortality impacts using willingness to pay or repair cost methods.
    - Use of alternative flux indicators for ozone (POD1, POD3, POD6…), noting that this applies to any critical load or critical level)
- Division of impacts into confidence bands, to differentiate between those effects that can be assessed with greatest confidence and those that can be quantified with less confidence (as discussed above).

For ecological impact assessment particular sensitivity will relate to the choice of threshold (as critical level or critical load). The same has not applied to health impact assessment much at all in the past as no threshold has been found for health effects of fine particles that dominate the analysis. This situation for health impact assessment may change in the future. Ozone effects have routinely been quantified over 35 ppb, defined as a 'cut point' for analysis, above which quantification is considered more robust than below. Resulting impacts have been small, a few percent of those for fine particles. However, a reduction in the cut point to 10 ppb as discussed in the HRAPIE report (WHO-Europe, 2013b) would greatly increase estimates of effect, with preliminary analysis suggesting a factor 4 change at the European level.

Linked to this are uncertainties from modelling; how good are the models at predicting concentration and deposition above a particular threshold?

There are further sensitivities that are relevant to analysis but are outside of the core considerations of ECLAIRE. A good example concerns the definition of baseline scenarios for future emissions.

Required input:
- Identification of sensitivities, conclusion of which approach is best suited to dealing with them, specification of alternative positions and outcomes

4.3.4 Model uncertainties

There is a risk of error in any analysis during model construction, the handling of data and processing and handling of results. The complexity and multi-disciplinary nature of the analysis to support European policy development in air quality raises the potential for such error. Added to this, there is no real understanding of how large damage estimates should be prior to analysis being undertaken, so there lacks a direct approach to validation of model outputs. To deal with this problem the following are suggested:

- Development of separate modelling tools to enable comparison of outputs. There is no need for such tools to be equally complex; indeed, there is much to be said for developing very simple tools that are much more transparent for the purpose of checking the logic of analysis.
- Comparison of results against background rates, crop yield, etc., to assess whether or not they are plausible.

Required input:
- Results from simplified tools or models to provide a transparent check on outcomes.

4.4 Bringing the methods together

Figure 7 provides an illustration of the way that the results of uncertainty analysis can be brought together. The y-axis shows the probability of benefits exceeding costs for a particular scenario investigated in the CAFE programme. The other parts of the figure address:

1. On the x-axis, uncertainty in estimated abatement costs (sensitivity analysis)
2. In the four lines shown on the graph, uncertainty in methods for mortality valuation (sensitivity analysis)
3. For each point of the graph, statistical/Monte Carlo analysis of the uncertainties across all input parameters except cost and the method used for mortality valuation.

Thus, within a single figure, a large number of uncertainties are brought together. There is then the question of interpretation. The following guidance could be provided:

1. If it is considered that the most appropriate estimates of mortality value are contained within the three upper lines, there is a very high probability that benefits will exceed costs, irrespective of uncertainty in abatement costs.
2. If it is considered that the lower line contains the most appropriate valuation of mortality there is roughly a 50% chance of deriving a net benefit, thought this is sensitive to one's views on the reliability of the abatement cost estimates.

The example given in the figure was selected because it shows one case (the red line) where different conclusions can be drawn, requiring thought to be given to the role of bias (e.g. in cost estimates) in the outcome of the CBA and the likelihood of different sensitivity cases. Other scenarios studied in the course of numerous policy analyses over the years have tended to demonstrate clearer outcomes, with all sensitivity cases having a high probability of generating a net benefit irrespective of the position on cost.

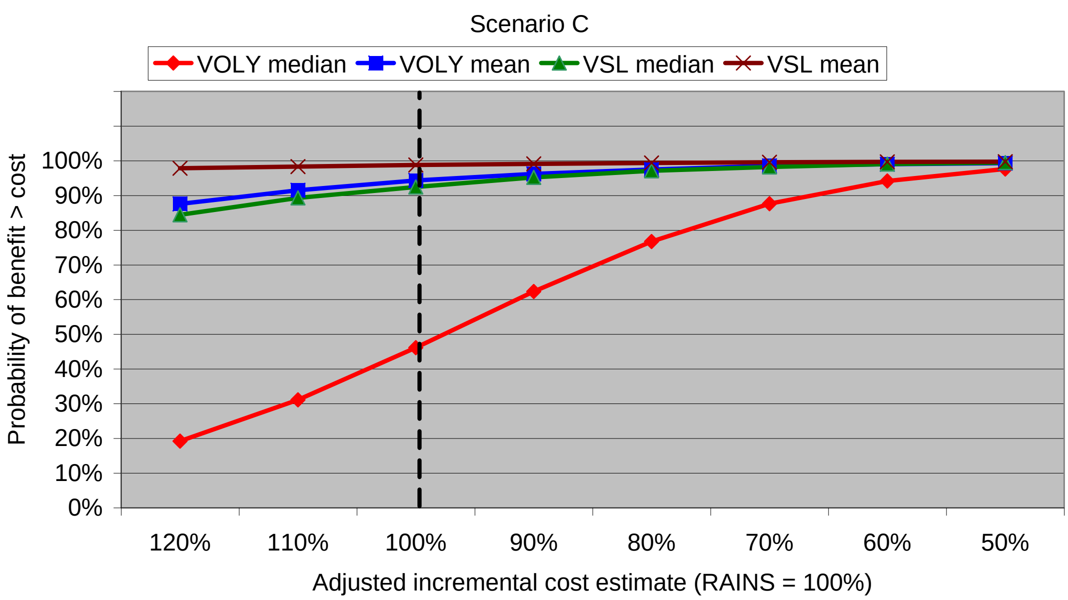

Figure 7. Sensitivity to uncertainty in incremental costs of pollution abatement of the probability of a net benefit in moving from Scenario B to Scenario C.

For the purposes of ECLAIRE the approach to aggregation of different elements of uncertainty may be different to that suggested above. The figure is intended simply to demonstrate that it is possible to bring together different elements of an uncertainty analysis in a way that simplifies communication.

4.5 The TUBA Framework

This section provides the data sheets that comprise the TUBA (Treatment of Uncertainty in Benefits Analysis) Framework. The TUBA Framework seeks to bring all information on uncertainty together in a concise manner, focused on the question of whether the relationship between costs and benefits revealed by the analysis is robust. By doing so, it becomes easy to see whether the treatment of uncertainty is comprehensive or whether certain elements have been omitted. The structure used does not require full quantification. Whilst this would be preferable, it is not currently practicable, so recognising this, the framework includes review of unquantified ‘biases’. A further advantage is that the added transparency that the Framework should bring, makes it easier to challenge uncertainty analysis. This has to be a good thing given that the EC4MACS Project has already recognised the uncertainty in describing uncertainty and seems likely to be of benefit both to analysts and stakeholders.

In order to be informative, the Framework is shown completed, using the example of the final assessment undertaken as part of EC4MACS. Six cases are considered (corresponding to the six blocks on the next page), dealing with:

- CBA for all Europe, baseline vs. MFR in 2020, 2025 and 2030
- CBA for the EU27, baseline vs. MFR in 2020, 2025 and 2030

The information provided is taken from analysis for the EC4MACS project and quantification is based very much on health impacts. It is of course intended to extend this under ECLAIRE, but for the time being the example provides illustration of the tool.

The first part of the TUBA Framework addresses the elements of uncertainty that can be addressed quantitatively. This uses information on the distribution of estimated impacts derived using the Monte Carlo analysis developed in CAFE-CBA (Holland et al, 2005b). These distributions were described having defined the variability of all inputs to the health impact assessment.

Combined with this is the sensitivity analysis that here covers different views on the valuation of mortality (identified by the ‘case names’ on the right hand side of the table). Best estimates for each sensitivity case are entered in the left hand column. TUBA then approximates the probability distribution in each case and compares against abatement costs to assess the probability of benefits exceeding costs.

The following page then reviews unquantified elements of the analysis, first identifying possible biases, then assessing which direction they are likely to drive the results. They are then weighted to identify what are considered as the most important biases. Totals (weighted and un-weighted) are given at the foot of the table in order to provide an indication of the likely overall direction of bias. Given that this part of the analysis is not quantified in detail, but comes down to expert judgement, the totals shows are not definitive indicators of overall bias.

The third page of the Framework provides the conclusions of the uncertainty analysis, linking to the information on the preceding pages.

TUBA: Treatment of Uncertainty in Benefits Analysis (Page 1/3)

Quantitative assessment of uncertainty including sensitivity runs

Figures below highlighted green show where benefits>costs. Pink shading where costs>benefits.

Scenario: 2020, All countries

Abatement costs for scenario: 56

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
125	73	90	99	115	135	149	191	Median VOLY
252	146	181	199	232	272	300	386	Mean VOLY
203	118	146	160	187	219	242	311	Median VSL
380	220	274	300	350	410	452	581	Mean VSL
96	56	69	76	88	104	114	147	Desaigues VOLY
471	273	339	372	433	509	560	721	OECD VSL

Scenario: 2025, All countries

Abatement costs for scenario: 59

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
118	68	85	93	109	127	140	181	Median VOLY
239	139	172	189	220	258	284	366	Mean VOLY
201	117	145	159	185	217	239	308	Median VSL
377	219	271	298	347	407	449	577	Mean VSL
91	53	66	72	84	98	108	139	Desaigues VOLY
468	271	337	370	431	505	557	716	OECD VSL

Scenario: 2030, All countries

Abatement costs for scenario: 60

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
118	68	85	93	109	127	140	181	Median VOLY
238	138	171	188	219	257	283	364	Mean VOLY
211	122	152	167	194	228	251	323	Median VSL
395	229	284	312	363	427	470	604	Mean VSL
92	53	66	73	85	99	109	141	Desaigues VOLY
490	284	353	387	451	529	583	750	OECD VSL

Scenario: 2020, EU27

Abatement costs for scenario: 38

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
62	36	45	49	57	67	74	95	Median VOLY
123	71	89	97	113	133	146	188	Mean VOLY
105	61	76	83	97	113	125	161	Median VSL
195	113	140	154	179	211	232	298	Mean VSL
49	28	35	39	45	53	58	75	Desaigues VOLY
241	140	174	190	222	260	287	369	OECD VSL

Scenario: 2025, EU27

Abatement costs for scenario: 40

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
59	34	42	47	54	64	70	90	Median VOLY
115	67	83	91	106	124	137	176	Mean VOLY
104	60	75	82	96	112	124	159	Median VSL
193	112	139	152	178	208	230	295	Mean VSL
46	27	33	36	42	50	55	70	Desaigues VOLY
238	138	171	188	219	257	283	364	OECD VSL

Scenario: 2030, EU27

Abatement costs for scenario: 41

€M/year Benefits	10%ile	25%ile	33%ile	50%ile	67%ile	75%ile	90%ile	Case name
59	34	42	47	54	64	70	90	Median VOLY
115	67	83	91	106	124	137	176	Mean VOLY
109	63	78	86	100	118	130	167	Median VSL
202	117	145	160	186	218	240	309	Mean VSL
46	27	33	36	42	50	55	70	Desaigues VOLY
251	146	181	198	231	271	299	384	OECD VSL

Bias assessment for unquantified uncertainties (Page 2 of 3)

The views expressed here are those of the author.

	Direction of bias			
	Costs up or impacts down?	**Costs down or impacts up?**	**Weight**	**Comments**
Emissions				
Energy	0	0	0%	Associated emissions from the energy sector are well researched with no evidence of any significant bias.
Transport	0	0	0%	As above
Agriculture	0	0	0%	As above
Dispersion modelling				
Ozone concentrations	0	0	0%	Overall, assumed that average concentrations are reasonable, with no systematic bias.
PM2.5 concentrations	0	0	0%	As above
Impacts				
Health	1	0	50%	Believed that some health impacts are excluded, moderated by concern over some valuations possibly being too high, e.g. for chronic bronchitis.
Materials	0	0	0%	Utilitarian material damage makes minimal contribution to overall effects
Materials in cultural heritage	1	0	20%	Low urban SO2 levels suggest this is of limited importance
Crops	0	0	0%	Accounted for in the modelling
Other agriculture	0	0	0%	Considered unimportant
Ecosystems	1	0	100%	Not included. Extent of exceedance of eutrophication in particular suggests that this effect is significant.
Cobenefits and trade offs				
Greenhouse gas emissions	1	0	10%	Small effect on GHG emissions unaccounted for
Discharge to water (not for treatment)	0	1	10%	Considered unimportant as plant will operate within discharge consents. However, linked with solid waste arisings (see below)
Discharge to water treatment system	0	0	0%	Again, discharge consents apply
Other pollutant emissions	1	0	1%	Heavy metal and other unaccounted for emissions considered trivial.
Solid waste generation	0	1	100%	Long term capacity for dealing with solid waste generated by abatement options is unclear.
Noise	0	0	0%	No change in noise identified.
Other cobenefits, trade offs	0	0	0%	No other cobenefits and trade offs identified.
Cost data				
Costs to agriculture	?	?	?	Direction of bias unclear
Costs to transport	1	0	100%	Potential for overestimation of costs as a result of improved efficiency of technologies over time, and effects of climate policy
Costs to industry	1	0	100%	As transport
Costs to domestic users	?	?	?	Direction of bias unclear
Costs to commercial users	1	0	50%	As transport
Un-weighted total	**8**	**2**		
Weighted total	**4.31**	**1.1**		

Conclusions (Page 3 of 3)

[*Opening comment: A marginal CBA carried out directly to inform the EU's policy making process would focus attention down to a smaller region of the cost curve for identification of the most efficient and justifiable levels of abatement. Here, however, this is not possible as analysis has considered only baseline and MFR scenarios, so results are taken as they stand, to demonstrate use of the TUBA framework. It must be recognised, however, that there will be very high positive benefit-cost ratios for some measures within the MFR 'package' and very low ratios for others.]*

The analysis of uncertainties has quantified the possible consequences of variability with respect to data used for (e.g.) response functions and valuation, and sensitivity to key assumptions. It has also sought to provide a comprehensive overview of unquantified biases that affect the results, focusing on the likelihood that the benefits of action will exceed costs. By accounting for these various elements the analysis of uncertainties provides a comprehensive overview of the robustness of results.

Results of the quantitative uncertainty analysis indicate that in all cases where analysis considers all European countries, there is at most a 10% probability that benefits would not exceed costs. In all cases using a VOLY higher than from Desaigues et al (2011) or using the VSL, the probability of costs exceeding benefits is less than 10%. Restricting analysis to the EU27 reveals a slightly different pattern. There is around a 10% probability of costs exceeding benefits when mortality is valued with the median VOLY and a 25 to 40% probability when the Desaigues et al VOLY is applied. Again, there is substantially less than a 10% probability of a net cost when applying the VSL. Overall, results consistently indicate that the move to the MFR scenario would be beneficial to society on economic grounds. *[Leaving aside the non-marginal nature of the scenario comparison, for the purposes of illustration.]*

The bias analysis indicates that (in the opinion of the author) there are more biases that either reduce estimates of benefits or increase estimates of cost than vice versa; in other words the biases overall appear likely to act against any package of measures passing a cost-benefit test. The weighted equivalent (again, here based on the author's views, rather than, e.g. an expert panel though there is no reason that such a panel could not be convened in the future) provides a very similar outcome. Accepting the views expressed in the bias analysis as a reasonable representation of reality would suggest that the conclusion above that benefits are likely to exceed costs becomes more robust when additional uncertainties are brought into the equation.

A caveat in relation to the bias analysis concerns those elements where it was concluded that the direction of bias was unclear (these concerned costs to agriculture and costs to domestic users). Here and elsewhere, the robustness of the analysis could be improved through further discussion and data collection if it was thought necessary.

[Closing comment: The material presented here indicates how uncertainty analysis to support cost-benefit analysis can be structured in such a way as to provide an overview of the uncertainties affecting the results. It is kept intentionally brief in order to assist stakeholders develop such an overview. Alternative views and feedback are welcome.]

4.6 Discussion

If the costs and benefits of air pollution control were known with absolute confidence there would be no problem in comparing the two. However, costs and benefits are subject to uncertainties and some of them (on both sides of the cost-benefit equation) are significant. The quality of knowledge for identification of these uncertainties is variable, as is the availability of quantitative data with which to describe them. Further to this, some uncertainties are statistical and continuous in nature, some relate to discrete choices (e.g. selection of approaches for the valuation of air pollution – related mortality) whilst some simply relate to a lack of knowledge. It is clear from this that the development of a fully consistent approach to description of uncertainty across the analysis is not straightforward.

The extent to which uncertainty needs to be considered in any situation is largely dependent on the balance of costs and benefits. Where estimated costs far exceed estimated benefits it is unlikely that any assessment of uncertainty would change the perception of that relationship unless some possible outcomes were politically untenable (very major impacts on agricultural production or widespread loss of natural species within a short time-frame). Similarly, where benefits far exceed costs, uncertainties should be of limited importance.

Consideration of uncertainty in comparison of costs and benefits cannot, therefore, be an automatic process. Awareness needs to be raised of the component uncertainties of each part of the analysis.

This Chapter has identified three main strands for assessment of uncertainty, these being statistical analysis, sensitivity analysis and assessment of biases, the latter being largely associated with gaps in knowledge. Some of these can be addressed relatively easily in quantitative terms. Others cannot, and require a more subjective assessment. Irrespective of whether they can be addressed quantitatively or semi-quantitatively, all of the uncertainties identified here are potentially important and need to be considered. This Chapter has also raised the problem that given the multi-component nature of the CBA modelling framework, consideration of uncertainties in the CBA can be extremely long-winded, which in turn reduces the ease with which non-experts can interpret the outcomes. This has led to the development of the TUBA Framework, designed to report uncertainty in a reasonably concise way, and to focus its reporting on potential consequences for the robustness of conclusions drawn.

Whilst it is clear that there are a large number of uncertainties that affect the analysis it is our view that this is not a barrier to effective and efficient decision making, because:

- We know a lot about the uncertainties that are present.
- We have a range of tools for assessment of these uncertainties.
- We can use these tools to see how uncertainty could influence the reported relationship between costs and benefits.
- We now have a concise system for summarising information on uncertainty.

It is worth considering the objective of cost-benefit analysis, namely to identify approaches that represent least cost to society. 'Cost' here includes environmental and health costs as well as pollution abatement costs. Rabl et al (2005) focused on the effect of uncertainty in determining the least cost position. They concluded that for continuous choices such as the development of emission ceilings for sectors or regions, the cost penalty turns out to be "*remarkably insensitive to error*". They observed that an error of a factor 3 up or down in damage estimates for NOx and SO_2 would potentially increase the social cost <u>by at most 20%</u> and in many cases much less.

5 References

AEA Energy and Environment (2005a) CAFE CBA: Baseline Analysis 2000 to 2020. http://www.cafe-cba.org/assets/baseline_analysis_2000-2020_05-05.pdf

AEA Energy and Environment (2005b) Cost-Benefit Analysis of Policy Option Scenarios for the Clean Air for Europe programme. http://www.cafe-cba.org/assets/thematic_strategy_analysis_v3.pdf

AEA Energy and Environment (2005c) Cost-Benefit Analysis of the Thematic Strategy on Air Pollution. http://www.cafe-cba.org/assets/thematic_strategy_scenario_v4.pdf

AEA Energy and Environment (2006) Assessing the air pollution benefits of further climate measures in the EU up to 2020. http://www.cafe-cba.org/assets/further_climate_measures_benefits.pdf

AEA Energy and Environment (2008) Evaluation of the Costs and Benefits of Proposed Revisions to the National Emission Ceilings Directive.

Amann, M. (ed) (2013) Baseline Projections of Greenhouse Gases and Air Pollutants in the European Union up to 2030. EC4MACS Final Assessment. http://www.ec4macs.eu/downloads/EC4MACS-FINAL-20130515.pdf

Brink, C., and van Grinsven, H., eds. (2011) Costs and benefits of nitrogen in the environment. Chapter 22, European Nitrogen Assessment (see Sutton et al, 2011). http://www.nine-esf.org/sites/nine-esf.org/files/ena_doc/ENA_pdfs/ENA_c22.pdf

BSBI (2012) Botanical Society of Britain and Ireland. Distribution Maps of Plants. http://www.bsbi.org.uk/maps_and_data.html

CCE (2008) Coordinating Center for Effects, Netherlands. http://wge-cce.org/Publications/CCE_Status_Reports/Status_Report_2008

CCE (2009) Progress in the modelling of critical thresholds, impacts to plant species diversity and ecosystem services in Europe. Coordinating Center for Effects, Netherlands. http://wge-cce.org/Publications/CCE_Status_Reports/Status_Report_2009

CCE (2010) Progress in the Modelling of Critical Thresholds and Dynamic Modelling, including impacts on Vegetation in Europe. Coordinating Center for Effects, Netherlands. http://wge-cce.org/Publications/CCE_Status_Reports/Status_Report_2010

CCE (2011) Modelling Critical Thresholds and Temporal Changes of Geochemistry and Vegetation Diversity. Coordinating Center for Effects, Netherlands. http://wge-cce.org/Publications/CCE_Status_Reports/Status_Report_2011

CCE (2012) Modelling and Mapping of Atmospherically-induced Ecosystem Impacts in Europe. Coordinating Center for Effects, Netherlands. http://wge-cce.org/Publications/CCE_Status_Reports/Status_Report_2012

Christie, M., Hanley, N., Warren, J., Murphy, K., Wright, R., and Hyde, T. (2006) Valuing the diversity of biodiversity. Ecological Economics, Volume 58, Issue 2, June 2006, pages 304 – 317.

Christie, M., Hyde, T., Cooper, R., Fazey, I., Dennis, P., Warren, J., Colombo, S., and Hanley, N. (2011) Economic Valuation of the Benefits of Ecosystem Services Delivered by the UK Biodiversity Action Plan. Final Report to Defra.

CIEMAT (1999) ExternE: Externalities of Energy – Vol. 10 National Implementation. http://www.externe.info/externe_d7/?q=node/41

Eurobarometer (2011) Special Eurobarometer 365: Attitudes of European citizens towards the environment. European Commission Directorate-General for the Environment, Directorate-General for Communication. http://ec.europa.eu/environment/pdf/EB_summary_EB752.pdf

Eurostat (2014a) GDP per capita, consumption per capita and price level indices. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/GDP_per_capita,_consumption_per_capita_and_price_level_indices

Eurostat (2014b) Environmental Protection Expenditure. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Environmental_protection_expenditure

Garrett, K., Mauzerall, D., Confalonieri, R., Donatelli, M., Jones, J., Manici, L. Baigorria, G. and Andresen, J. (2013) Work Group Report: Pests, Diseases, Weeds, Ozone. AgMIP 2013 (The Agricultural Model Intercomparison and Improvement Project), 4th Annual Global Workshop, October 2013, New York. http://www.agmip.org/wp-content/uploads/2013/11/Work-Group-Report-pests-diseases-weeds-ozone-3_dlm.pdf

Holland, M. (2014a) Implementation of the HRAPIE Recommendations for European Air Pollution CBA work. Report to European Commission DG Environment. January 2014. http://ec.europa.eu/environment/air/pdf/review/CBA%20HRAPIE%20implement.pdf

Holland, M. (2014b) Cost-benefit analysis of final policy scenarios for the EU Clean Air Package. Corresponding to IIASA TSAP report no.11. Report to European Commission DG Environment. March 2014. http://ec.europa.eu/environment/air/pdf/review/TSAP%20CBA%20corresponding%20to%20IIASA11%20v2.pdf

Holland, M. and Maas, R. (2014) Quantification of economic damage to biodiversity. ECLAIRE Project, Work package 18. Version 2 draft.

Holland M, King K and Forster D. (1999) Cost-Benefit Analysis for the Protocol to Abate Acidification, Eutrophication and Ground Level Ozone in Europe http://www.unece.org/env/lrtap/TaskForce/tfeaas/4meeting/aea2_final.pdf

Holland, M., Hunt, A., Hurley, F., Navrud, S., Watkiss, P. (2005a) Methodology for the Cost-Benefit analysis for CAFE: Volume 1: Overview of Methodology. http://www.cafe-cba.org-

Holland, M., Hurley, F., Hunt, A. and Watkiss, P. (2005b) Methodology for the Cost-Benefit analysis for CAFE: Volume 3: Uncertainty in the CAFE CBA. Available at: http://cafe-cba.aeat.com/files/cba_method_vol3.pdf .

Holland, M., Wagner, A., Hurley, F., Miller, B. and Hunt, A. (2011) Cost Benefit Analysis for the Revision of the National Emission Ceilings Directive: Policy Options for revisions to the Gothenburg Protocol to the UNECE Convention on Long-Range Transboundary Air Pollution. Contract report for European Commission DG Environment. http://ec.europa.eu/environment/air/pollutants/pdf/Gothenburg%20CBA1%20final%202011.pdf.

Holland, M., Pye, S., Jones, G. Hunt, A. and Markandya, A. (2013) EC4MACS Modelling Methodology: The ALPHA Benefit Assessment Model. EC4MACS: European Consortium for Modelling of Air Pollution and Climate Strategies. http://www.ec4macs.eu/content/report/EC4MACS_Publications/MR_Final%20in%20pdf/Alpha_Methodologies_Final.pdf.

Houlden, G., McNeill, S., Aminu-Kano, M. and Bell, J.N.B. (1990) Air pollution and agricultural aphid pests. I. Fumigation experiments with SO_2 and NO_2. Environmental Pollution, 67, 305-314.

ICP Vegetation (2014) Have You Seen These Ozone Injury Symptoms? http://icpvegetation.ceh.ac.uk/publications/documents/CEHOzoneInjury_webmidres.pdf

IIASA (2012) TSAP-2012 Baseline: Health and Environmental Impacts. TSAP Report #6, Version 1.0. Service Contract on Monitoring and Assessment of Sectorial Implementation Actions (ENV.C.3/SER/2011/0009). http://www.iiasa.ac.at/web/home/research/researchPrograms/MitigationofAirPollutionandGreenhousegases/TSAP-_IMPACTS-20121126.pdf

IIASA (2013) The final policy scenarios for the revision of the EU Clean Air Package. February 2014. TSAP report no.11, International Institute for Applied Systems Analysis, Laxenburg, Austria.Jones et al (2013)

Karnosky D.F. & Pregitzer K.S. (2006) Impacts of elevated CO2 and O3 on northern temperate forest ecosystems: Results from the Aspen FACE experiment. In Managed Ecosystems and CO2: Case Studies, Processes and Perspectives. Ecological Studies. (eds J. Nösberger, S.P. Long, G.R. Hendry, M. Stitt, R.J. Norby & H. Bum). Springer-Verlag, Berlin, Germany. Ecological Studies, volu. 187.

Karnosky, D.F., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M. and Percy, K.E. (2005) Scaling ozone responses of forest trees to the ecosystem level in a changing climate. Plant, Cell and Environment (2005) 28, 965–981. http://onlinelibrary.wiley.com/store/10.1111/j.1365-3040.2005.01362.x/asset/j.1365-3040.2005.01362.x.pdf;jsessionid=25DDE88463597495A988C6FFE26A8B9C.f03t03?v=1&t=hz0308x2&s=fbb9279372255e59715e152d25905cbe9319c3e1

Mills, G. and Harmens, H. (eds) (2011) Ozone Pollution: A Hidden Threat to Food Security. Report Prepared by the ICP Vegetation, September 2011. http://icpvegetation.ceh.ac.uk/publications/documents/ozoneandfoodsecurity-ICPVegetationreport%202011-published.pdf

Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L. and Pleijel, H. (2007) A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. Atmospheric Environment, Volume 41, 2630–2643.

Mills, G., Wagg, S. and Harmens, H. (eds) (2013) Ozone Pollution: Impacts on Ecosystem Services and Biodiversity. Report Prepared by the ICP Vegetation, April, 2013. http://icpvegetation.ceh.ac.uk/publications/documents/ICPVegetationozoneecosystemservicesandbiodiversityreport2013_FULL.pdf

Ott, W., Baur, M. and Kaufmann, Y. (2006) Deliverable D.4.2.-RS1b/WP4 – July 06: Assessment of Biodiversity Losses. NEEDS Project. http://www.needs-project.org/RS1b/RS1b_D4.2.pdf.

Riemer, J. and Whittaker, J.B. (1989) Air pollution and insect herbivores: observed interactions and possible mechanisms. Insect Plant Interactions, 1, 73-105.

Thomas, R.Q., Canham, C.D., Weathers, K.C. and Goodale, C.L. (2010) Increased tree carbon storage in response to nitrogen deposition in the US. Nature Geoscience 3, 13 – 17.

Von Blottnitz, H., Rabl, A., Boiadjiev, D., Taylor, T. and Arnold, S., (2006) Damage costs of nitrogen fertilizer in Europe and their internalization. Journal of Environmental Planning and Management , 49 , 413 –433.

Wainhouse, D. (2005) Ecological Methods in Forest Pest Management. Oxford University Press.

Warrington, S. (1989) Ozone enhances the growth rate of cereal aphids. Agriculture, Ecosystems and Environment, 26, 65-68.

WGE (2004) Review and Assessment of Air Pollution Effects and their Recorded Trends. Working Group on Effects of the UNECE Convention on Long Range Transboundary Air Pollution. http://www.unece.org/fileadmin/DAM/env/documents/2004/eb/wg1/InformalDocument4_SubstantiveReport2004FinalDraft.pdf

WHO-Europe (2013a) HRAPIE: Health risks of air pollution in Europe – HRAPIE project Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide. World Health Organization, Regional Office for Europe, Bonn, Germany. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project-recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide

WHO-Europe (2013b) REVIHAAP: Review of evidence on health aspects of air pollution – REVIHAAP project: final technical report. World Health Organization, Regional Office for Europe, Bonn, Germany. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report.