Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM)

Progress Report 1

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SUMMARY

Objectives

Despite the many overlaps of regional air pollution and climate change European policymakers have handled these two environmental problems separately up to now. One reason for this separate approach has been that policymakers do not have the quantitative information needed to develop policies that address both regional air pollution and climate change in Europe. This project aims to perform an integrated analysis of the linkage between the two problems in Europe and to produce results that are relevant to European policy. Specific objectives are:

1. To examine whether climate change will alter the effectiveness of agreed-upon or future policies to reduce regional air pollution-causing emissions in Europe, and vice versa.
2. To identify the relative importance and overlap of regional air pollution and climate change impacts under a consistent set of assumptions about future developments of emissions.
3. To identify and evaluate comprehensive policy strategies for controlling both regional air pollution and climate change in Europe.

Objectives for this reporting period were:
1. To develop consistent emission scenarios as a starting point for the analysis.
2. To compute changes in atmosphere and climate based on the emission scenarios.
3. To compute impacts of regional air pollution and climate change.

Compiling a Framework for Integrated Analysis

An integrated modeling framework is used to meet the objectives of the project. This framework consists of parts of two state-of-the-art integrated models covering regional air pollution in Europe (RAINS) and global climate change (IMAGE), supplemented by new components. RAINS is an integrated model of regional air pollution in Europe, describing the coupling between energy scenarios: country-scale emissions of sulfur and nitrogen; ambient concentrations and depositions of acidifying substances; and critical loads to ecosystems. The IMAGE 2 model is RAINS' counterpart for global climate change, coupling regional developments of energy and agriculture: emissions of greenhouse gases, and SO_2; changes in land cover and carbon fluxes between the biosphere and atmosphere; the build-up of greenhouse gases in the atmosphere; and flux of heat in the atmosphere and ocean. The additional components used in this project are:
(i) a module to calculate the ammonia (NH_3) emissions in Europe after 2010,
(ii) an atmospheric transfer matrix that links regional air pollution and climate change in the atmosphere,
(iii) maps of critical thresholds of regional air pollution in Europe that take into account climate change,
(iv) maps of critical thresholds of climate change in Europe.

NH_3 module. NH_3 emissions per country up to 2100 are an important input to calculate the acid and nitrogen deposition in Europe. While the RAINS model calculates NH_3 emissions only up to 2010, the IMAGE model does not calculate NH_3 at all. Thus, there is a need to extend the IMAGE model to include the calculation of NH_3 emissions in Europe up to 2100. Based on the RAINS database the relevant sources for NH_3 emissions were identified. Most of

these activities are modeled per region in IMAGE up to 2100. NH_3 emission factors for the IMAGE regions OECD Europe, East Europe and CIS (including the Asian part) are specified based on the emission factors in RAINS. Regional emissions are calculated by multiplying the activity levels calculated by IMAGE with the emission factors. The regional emissions are allocated to countries based on the distribution of the emissions in 2010 according to RAINS.

Climate dependent critical thresholds of acidity (critical loads). Critical loads depend among others on climate factors, which means that critical loads could be sensitive to climate change. This sensitivity provides an important linkage between regional air pollution and climate change. Critical loads of acidity for forest soils are calculated with the so-called simple mass balance (SMB) model. The SMB model is the most commonly used method for deriving acidity critical loads in the UN/ECE context. Because weathering rates are influenced by soil temperatures and leaching by precipitation and evapotranspiration rates, the critical load of acidity is affected by temperature, precipitation and evapotranspiration rates. Thereby, in total an increase in temperature can (partially) be compensated by a decrease in precipitation surplus, i.e. precipitation minus evapotranspiration. Whether the precipitation surplus will increase or decrease under a changing climate depends on a fine balance between increasing precipitation and increasing evapotranspiration due to a higher temperature. Variation of both factors within reasonable ranges i.e. ranges expected in a warming climate up to 2100, indicated that critical loads will change at most about 10%. A first tentative conclusion is thus that the sensitivity of ecosystems to acid deposition is noticeably influenced by climate change although the effect is limited.

Climate-dependent critical thresholds for SO_2 *and* NO_x *(critical levels)*. For the integrated analysis of regional air pollution and climate change it is necessary to identify an effective way to simulate the potential impact of varying climate conditions on the direct effects of air pollutants on vegetation. For that purpose a model is developed that can be used to organize the available quantitative information on the response of different species.

The model is based on the assumption that the concentrations of pollutants in plants under present conditions when the ambient pollutant concentrations do not exceed the critical levels are ‘safe’ in-plant concentrations. So, the pollutant flux into the plant leaves under current climatic conditions - called reference flux - is estimated. In the second step the model will calculate the fluxes under different climatic scenarios. With this information ambient concentrations can be derived then for which the identified ‘safe’ in-plant concentrations are not exceeded. These ambient concentrations will be used as climate-specific critical levels of air pollutants.

Critical climate thresholds. In the last years climate impact research has sometimes identified breaking points of climate change leading to rapid changes in various impact categories. This research has yet not been applied to Europe in a consistent way. The Climate Isoline Diagram (CID) approach was developed to present exceedances of “critical climate thresholds“. We define critical climate thresholds as ‘*quantitative values of climate change, below which only acceptable long-term effects on ecosystem structure and functioning occur, according to current knowledge*’.

CIDs are two-dimensional diagrams of temperature and precipitation changes in which temperature/precipitation combinations are identified for which only acceptable changes are expected. The diagrams can be used to evaluate different combinations of changes in temperature and climate and to examine the consequences of different climate thresholds. Up to now, however, we have not yet identified climate thresholds. The current method has been applied to agriculture and natural ecosystems in Europe. The CID concept is still under development and may be adapted in further stages of the AIR-CLIM project.

Test scenario development

An objective of the AIR-CLIM project is to derive reduction scenarios which consider reductions of both greenhouse gases and air pollutants. But before deriving a reduction scenario it is necessary to derive a reference, no-reduction scenario. We call the first reference scenario which we have derived in the AIR-CLIM project the ‘test scenario’. The test scenario uses the IMAGE Baseline A scenario, which has similar driving forces to the IS92a scenario of the IPCC. The greenhouse gas emissions of this scenario have been adjusted so that the Kyoto Protocol objectives of reducing greenhouse gas emissions have been met. For the Annex I-countries (most industrialized countries) the Kyoto greenhouse gas reduction targets are applied in 2010. After 2010 it is assumed that the greenhouse gas emissions remain constant till 2100. For Non-Annex I-countries (most developing countries) emissions levels are assumed to follow Baseline A for the whole time period under analysis.

A first analysis showed that it is difficult to use the Energy-Industry-System (EIS) module of IMAGE 2.1 to derive energy profiles for a certain greenhouse gas emission pathway. Thus, it was decided to use the equivalent module of Version 2.2 of IMAGE, called TIMER. TIMER provides fully developed price mechanisms for electricity and heat production and the price elasticities are further developed than in the EIS module. While the globally aggregated version of TIMER has been introduced in 1995, the TIMER version disaggregated to 13 world regions was not finalized before the end of 1998. Therefore, for the test scenario the EIS of IMAGE 2.1 was used.

To compute SO_2 emissions, we have used the *Pollutant Burden Approach* (PBA). The PBA computes the point in time at that regions begin SO_2 controls, and at what rate these controls are implemented. For industrialized regions where controls have already begun, it is assumed that the past trend on SO_2 control is continued. CIS was identified as a problematic area with respect to the modeling of the future SO_2 emissions. Due to its economic breakdown in the early nineties, energy consumption decreased drastically and thus also the SO_2 emissions. According to the Baseline A scenario, the economy of the CIS will recover about 2010, leading (even with the PBA) to total SO_2 emissions above the level of 1990 despite a continuous increase of SO_2 reduction factors. This is an area that will be further analyzed in the future.

Calculated climate change

An IMAGE 2.1 run has been carried out for the test scenario described above yielding temperature and precipitation changes on a 0.5x0.5° grid and land cover changes. According to the test scenario, the globally averaged temperature will rise until 2100 about 0.1° less than without the Kyoto agreement. The realized global temperature change in 2100 relative to 1990 will still be 2.7°.

Impacts

Impact of climate change on critical loads of acidity of forests in Europe. Critical loads have been computed using the results of the test scenario for temperature and precipitation data in 2100. A comparison of the resulting 5-th percentile critical loads to the present critical loads shows that under the changed climate the critical loads are higher than at present (1990) in most parts of Europe. This can probably be explained by the increase in weathering due to higher temperatures. In a few regions, however, - such as western Norway, Portugal or Albania - the critical loads are lower than at present; and this is probably due to a decrease in percolation which offsets the increase in temperature. This means that in these regions forest soils become more sensitive, and thus require special attention when studying the impact of emission reduction scenarios.

Impacts of climate change on agriculture/natural ecosystems in Europe. The consequences of the AIR-CLIM test scenario were evaluated by estimating where a 20% loss of the potential wheat production and a 0% change in the potential distribution of natural ecosystem occurred. We allowed no changes in ecosystem composition, focusing on the public policy to keep nature reserves in their current state.

Sample results for Spain and Germany are presented. Large reduction in potential wheat production is computed in southern Europe (especially Spain, Portugal and western France). Small decreases (or even slight increases due to CO_2) are calculated in central Europe, while northern Europe becomes more productive. 20% production reductions are only computed in southern Spain, if the analysis restricts itself to the current wheat areas in Europe. Under the described climatic changes the production levels of wheat in these areas nearly diminish.

For natural ecosystems three states are distinguished in the exceedance maps: (1) unchanged: the land cover type does not change and its productivity is not impaired, (2) changed: the land cover type changes under climate change, and (3) degraded: the land cover type does not change but its productivity is lower than the original state. To compute these states the sensitivity of natural ecosystems to growth and C dynamics is taken into account.

About 30% of the natural reserves areas are stable, i.e. not degraded and/or replaced by another biome type. The number increases up to 50% if vegetation migration is taken into account. Then, for Germany about 77% of the current nature reserves area is stable, too. Under the same assumption, the impacts computed for Spain are more severe (only 30% are stable). However, assuming instantaneous conversion of vegetation instead, similar responses to the AIR-CLIM test scenario are calculated for Spain and Germany (about 30% of the potential ecosystems are stable). The difference between the two conversion assumptions is especially large in Germany, because the main land-cover conversions that will occur in Germany are between different forest types. Such transitions require decades, and will therefore only slowly occur if transient dynamics are included in an analysis.

Uncertainty analysis

To uncover this uncertainty in the AIR-CLIM Modeling Framework, a five-step uncertainty analysis can be used:

1. *Problem formulation*, in which the time and space scales of the problem are established,
2. *Inventory of uncertainties*, to collect possible sources of error in a systematic fashion,
3. *Screening and ranking of uncertainties*, to set priorities for quantitative evaluations,
4. *Quantitative evaluation of uncertainties*, which draws on a variety of analytical techniques,
5. *Application to routine calculations,* in which information about model error is used to supplement routine calculations.

Before the end of the AIR-CLIM project, we expect to accomplish Steps 1 and 2, and to make preliminary estimates for Step 3. This report presents first results for steps 1 and 2. However, Steps 4 and 5 are not covered under the current AIR-CLIM project because they require a major research effort, which is outside the scope of the current project.

Final Remarks

While there remain many possibilities to improve the methodologies developed so far, the AIR-CLIM team has made significant progress in the first reporting period with respect to the objective of the project. In the next reporting period the following work is planned:

To further improve the analysis:

- The NH_3 model will be transferred from spreadsheet to a programmed module.
- Source-receptor matrices for air pollution transport under climate change will be constructed.
- For the critical level model the simulations for some of the main vegetation types will be finalized and calculations performed for the AIR-CLIM scenarios.
- For the critical load model the forest cover used will be harmonized with the IMAGE forest cover. Furthermore the inclusion of semi-natural vegetation and of land cover/use changes will be looked into.
- Critical climate thresholds will be identified and the CID approach will be used to map exceedances of these thresholds.
- The hierarchical step-procedure for the integration of the impacts will be further worked out.
- Mitigation costs for air pollution and greenhouse gases will be calculated.

1 INTRODUCTION

1.1 Background

Among the many challenges facing Europe as a community are the environmental problems that transcend its borders. One such challenge – regional air pollution – has been partially addressed during the last decade through negotiation of international agreements under the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP). These agreements have led to partial controls of some of the pollutants that cause regional air pollution.[1]

Policies to control another problem – climate change – have been negotiated at the so-called Conferences of the Parties (COP) in Berlin (1995), Geneva (1996), Kyoto (1997) and Buenos Aires (1998) under the 1991 U.N. Framework Convention on Climate Change (FCCC). At the COP in Kyoto a protocol was agreed on that is yet not come into force as so far (March 1999) only two states have ratified it. According to the Kyoto Protocol the EU has to reduce their greenhouse gas emissions by 8% until the first commitment period (2008–2012) compared to 1990.

There are important overlaps between regional air pollution and climate change from the perspective of both policy and science:

1. *Climate change may alter the environmental impacts of regional air pollution, and vice versa*:
   Up to now, one of the main objectives of policies to control regional air pollution (as compared to urban air pollution policy) has been to protect Europe's soils and vegetation. For example, an international treaty to reduce sulfur dioxide emissions in Europe ('the Second Sulphur Protocol' of 1994) at least partially took into account the protection of ecosystems in Europe. However, climate change could alter the effects of the treaty because:

   (1) Climate change is likely to alter European weather patterns, and this will affect the distribution of air pollutants throughout Europe;
   (2) Climate change will lead to long-term changes in temperature and precipitation that will affect the rate of acidification of soil and water.

   Hence, policies that are aimed to reduce regional air pollution impacts in the soil and water under current climate conditions, may not be successful under future climate conditions (and some might be more successful). Conversely, the level of regional air pollution also will have an effect on climate change and its impacts. For example, the emissions of sulfur dioxide (an important regional air pollutant) result in a layer of sulfate particles (aerosol) in the European atmosphere, and these particles reflect solar radiation and partly mask climate warming in Europe.

[1] Here, the term 'regional air pollution' is used to mean transboundary air pollution problems that occur in Europe that result in (1) high ground-level concentrations of ozone, sulfur dioxide, nitrogen oxides and other substances, (2) the deposition of trace toxic substances, and (3) acid deposition due to sulfur and nitrogen in the atmosphere.

2. *The causes of climate change and regional air pollution are linked in the European economy*:
   The issues of regional air pollution and climate change are linked in various ways in Europe's economy. For example, changes in the amount and types of fuels that are consumed will affect the rate of emissions of both regional air pollution-causing substances and greenhouse gases. At the same time deliberate policies to reduce regional air pollution-causing emissions, such as switching from high-sulfur coal to low-sulfur natural gas, will also reduce the emissions of some greenhouse gases.

3. *Not only the causes, but also the impacts, of regional air pollution and climate change are linked in the economy*:
   For instance, changes in temperature and precipitation will affect the rate at which regional air pollution corrodes building materials. Another example is that both regional air pollution and climate change are important sources of environmental stress to forests, and this stress could eventually endanger the ecological and economic viability of these forests.

Despite these overlaps European policymakers have handled these two environmental problems separately up to now. One reason for this separate approach has been that policymakers do not have the quantitative information needed to develop policies that address both regional air pollution and climate change in Europe. This project aims to perform an integrated analysis of the linkage between the two problems in Europe and produce results that are relevant to European policy.

1.2 Previous Studies

Some research has already been carried out to link regional air pollution and climate change issues. With regard to impacts on freshwater streams, a study of catchment processes in Finland found that on the one hand the direct impacts of climate change almost cancel out (Forsius *et al*. 1997), i.e. the increase in precipitation is compensated by higher evapotranspiration due to the temperature increase, resulting in only a small change in runoff. On the other hand the influence on nitrogen processes (leaching) can be considerable. It is, however, an open question how this translates to other climatic regions in Europe. With regard to vegetation impacts, (Johnson *et al.* 1995) found that elevated CO_2 and nitrogen deposition had significant effects on available phosphorus in the soils of a ponderosa pine forest in the western United States. These, and other local studies (such as those summarized in (Grennfeldt *et al.* 1995)) are useful for the insight they give into the interaction of processes relevant to both regional air pollution and climate change, but they cannot be generalized to the European scale.

Current work at the International Institute for Applied Systems Analysis in Austria is concerned with linking climate change and sulfur dioxide impacts on European crops (Fischer, Amann 1996). Several other research projects have dealt with climate change impacts and agriculture (e.g. Harrison *et al.* 1995, Semenov *et al*. 1996). Results of these studies are useful to get insights in the sensitivities of particular crops to climate change and increased CO_2 levels. Harrison *et al*. (1995), for example, found that currently important crops in Europe will benefit from climate change (e.g. main yield improvement is 50%). But in our opinion it is still an open question whether the results can be generalized throughout the European continent, since most of the projects describe the impacts on the local scale. Moreover, the studies only analyse a limited number of combinations of temperature, precipitation, and CO_2, derived from General Circulation Models (GCM). An aim of the AIR-

CLIM project is to develop an approach suitable for the evaluation of various climate change options on the European scale agriculture.

In a study that came most close to the proposed study (Alcamo *et al.* 1995, Posch *et al.* 1996) a first attempt was made to use consistent scenarios of sulfur emissions to assess their impacts on terrestrial ecosystems (critical loads for deposition and potential vegetation change for climatic warming). The studies showed that higher sulfur emissions increase the exceedance of critical loads, but reduce the effects of a climate warming due to increased amounts of sulfate aerosols in the atmosphere, thus demonstrating the importance of linking the climate system with regional air pollution. The framework outlined in those two studies will be greatly expanded and used for the assessments in this project.

1.3 Objectives

The overall goal of this project is to provide scientific information about key policy-relevant issues concerning the linkage between regional air pollution and climate change in Europe. Specific objectives are:

1. To examine whether climate change will alter the effectiveness of agreed-upon or future policies to reduce regional air pollution-causing emissions in Europe, and vice versa.
2. To identify the relative importance and overlap of regional air pollution and climate change impacts under a consistent set of assumptions about future developments of emissions.
3. To identify and evaluate comprehensive policy strategies for controlling both regional air pollution and climate change in Europe.

Objectives for this reporting period were:

1. To develop consistent emission scenarios as a starting point for the analysis.
2. To compute changes in atmosphere and climate based on the emission scenarios.
3. To compute impacts of regional air pollution and climate change.

2 Compiling a Framework for Integrated Analysis

2.1 Integrated Modeling framework

Purpose of this Task

A tool is assembled for examining the linkage between two important environmental problems in Europe: climate change and regional air pollution.

Significance of this Task to Policy and Science

The framework will enable the analysis of two environmental problems - climate change and regional air pollution - together in an integrative way. That means the linkages of these two issues are taken into account on all levels. From the policy perspective, it will thus be possible to provide quantitative information to support European policymakers in developing policies that address both regional air pollution and climate change in Europe. From the scientific perspective the approach provides a method for harmonizing information from different disciplines into a single integrated framework.

Analysis to Date

An integrated modeling framework[2] (Figure 1) is used to meet the objectives of the project. This framework consists of parts of two state-of-the-art integrated models covering regional air pollution in Europe (RAINS) and global climate change (IMAGE), supplemented by new components. RAINS is an integrated model of regional air pollution in Europe, describing the coupling between energy scenarios: country-scale emissions of sulfur and nitrogen; ambient concentrations and depositions of acidifying substances; and critical loads to ecosystems (Alcamo *et al.* 1990), (Amann *et al.* 1995). The IMAGE 2 model is RAINS' counterpart for global climate change, coupling regional developments of energy and agriculture: emissions of greenhouse gases, and SO_2; changes in land cover and carbon fluxes between the biosphere and atmosphere; the build-up of greenhouse gases in the atmosphere; and flux of heat in the atmosphere and ocean (Alcamo *et al.* 1998). The additional components used in this project are:

(i) a module to calculate the ammonia (NH_3) emissions in Europe after 2010,
(ii) an atmospheric transfer matrix that links regional air pollution and climate change in the atmosphere,
(iii) maps of critical thresholds of regional air pollution in Europe that take into account climate change,
(iv) maps of critical thresholds of climate change in Europe.

Indicators. For regional air pollution, the following indicators are used in the study: atmospheric concentrations of sulfur dioxide (SO_2), and nitrogen dioxides (NO_x), and deposition of sulfur and nitrogen. Together with ozone these are the regional pollutants that are currently receiving the most attention from European policymakers because there is a clear connection between these pollutants and the acidification of soil and surface waters, health impacts, material damage and other impacts (for a recent overview, see (Grennfeldt *et al.* 1995)). Ozone is not included in the AIR-CLIM project because of the project's limited scope. Nonetheless, it is intended to extend the analysis to this pollutant in a follow-up project as well as to other potentially important regional air pollutants, e.g. persistent organic pollutants and heavy metals[3]. In order to compute the atmospheric concentrations of SO_2 and NO_x, and the deposition of sulfur and nitrogen, emissions of the following substances are taken into account in this study: nitrogen oxides, sulfur dioxide, and ammonia.

As indicators of climate change surface temperature and precipitation are selected. Different temporal scales of these data will be used, depending on the type of analysis. To compute climate change, it is necessary to take into account the global emissions of a wide range of greenhouse gases including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as emissions that lead to the formation of ozone in the atmosphere.

[2] In this study the expression 'framework' is more appropriate than model because many of its components are not electronically 'hard' linked, i.e. they are not components of the same computer programs. In some cases output from one component has to be processed externally before used as input to the next component.

[3] Another reason not to analyze persistent organic pollutants and heavy metals in this study is that there is insufficient scientific information about these substances to conduct an integrated analysis. For example, an integrated analysis requires information about source-receptor relationships for different regional air pollutants. While this information exists for ozone, nitrogen and sulfur in Europe's atmosphere, it is only now being developed for persistent organic pollutants and heavy metals. This study, however, can provide a strong foundation for a follow-up integrated analysis of these other pollutants.

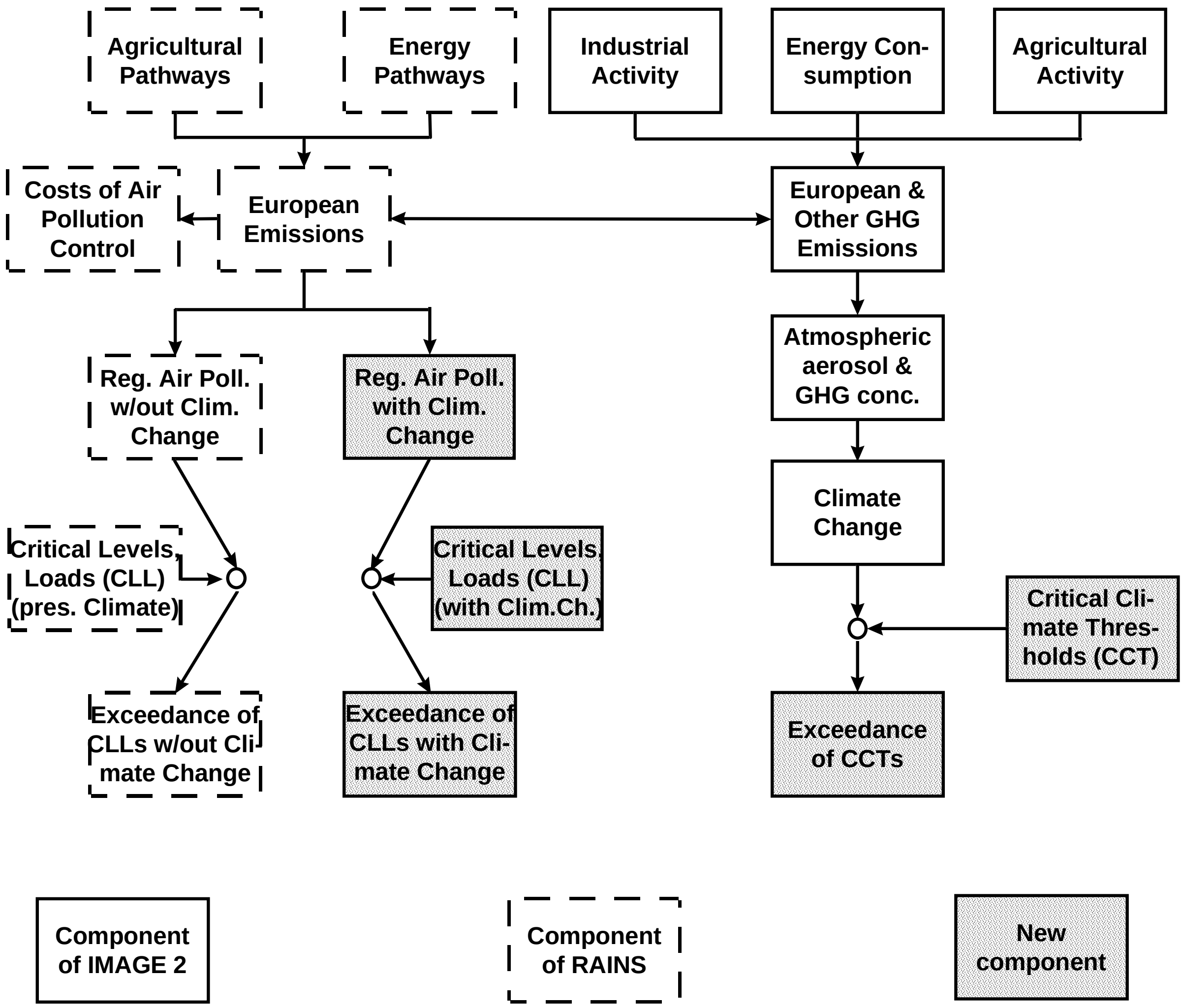


Figure 1 Integrated modeling framework for climate change and regional air pollution

Global emissions. Using the IMAGE 2 model, time series of greenhouse gas emissions, precursors of ozone (including NO_x), and SO_2 are computed for each of the 13 world regions (regions include Western Europe, Eastern Europe, and the European part of the former USSR). This information is needed to compute climate change in Europe (see below). The emission calculations are based on scenarios for the consumption of energy, the level of industrial activity, and land use activity, for the years 1990-2100. The consumption of energy, in turn, is computed from the growth in population and economy and assumptions about technological development (de Vries *et al.* 1994). Emission factors for the different gases take into account regional differences in types of energy equipment and other regional factors.

European country emissions. Country-scale emissions from the RAINS model are then used to downscale emissions important to regional air pollution from the regional- to the country-level. This information is needed to compute regional air pollution in Europe (see below).

Regional Air Pollution without Climate Change. To compute grid-scale atmospheric concentration and deposition of regional air pollutants from country-scale emissions, the source-receptor matrices contained in the RAINS models are used. These matrices summarize the various chemical and transport processes of sulfur, nitrogen, ozone, and other substances in the atmosphere, and link emissions to depositions by linear equations. The European country-to-grid matrices are derived from EMEP (European Monitoring and Evaluation Programme) model results and are based on average annual data for the period 1985 to 1994.

Regional Air Pollution under Climate Change. It is likely that climate change will lead to long term and seasonal changes in wind and precipitation patterns in Europe. These changes will, in turn, cause changes in the pattern of acid deposition (sulfur and nitrogen) in Europe. This is important from the policy standpoint because existing agreements to control sulfur dioxide emissions were based on reducing sulfur deposition under current climate conditions. However, if climate conditions change, then the goals of reducing sulfur deposition may not be met at different locations. To take into account the possible effect of climate change on the distribution of regional air pollutants in Europe, the framework will use modified atmospheric transfer matrices. To compute these matrices, model experiments will be conducted with the EMEP long range transport model. These experiments will use meteorological data for future climate conditions produced by the advanced climate model of the Max Planck Institute, Hamburg. The long range transport model to be used (the 'EMEP' model) is the standard model used for computing transboundary air pollution in Europe. Results from these model experiments will be expressed in the form of source-receptor matrices which describes the relationship between unit emissions in different European countries, and resulting deposition on a grid covering Europe.

Climate Change and Sulfate Aerosol. After SO_2 is emitted to the atmosphere, a fraction of it is re-deposited within hours or days as wet and dry sulfur deposition. The remaining air fraction will form SO_4^{2-} aerosols, which are important from the climate change perspective because they reflect a portion of the sun's incident radiation. The build-up of SO_4^{2-} aerosols in the troposphere is computed with a linear source-receptor matrix contained in the IMAGE 2 model (Alcamo *et al.* 1998). The matrix is derived from the two-dimensional global model of atmospheric chemistry of TNO (Roemer 1991), (Baart *et al.* 1995). A portion of the tropospheric aerosol stems from natural sources such as biogenic emissions of dimethylsulfide and volcanic emissions of SO_2. This portion is assumed to remain constant at its current estimated level. The effect of SO_4^{2-} aerosol on increasing atmospheric albedo and cooling the atmosphere is estimated with the formulation of Charlson *et al.* (1992), together with updated coefficients. Other potential effects of SO_4^{2-} on the atmosphere, such as changes in cloud cover/depth and occurrence of precipitation, are not taken into account.

Climate Change and Temperature and Precipitation. Climate change is computed by the coupled atmosphere-ocean climate submodel of IMAGE 2 (de Haan *et al.* 1994), taking into account SO_4^{2-} aerosol and the build-up of greenhouse gases. The main outputs of the climate submodel are changes in precipitation and surface temperature. Zonal averages from the climate submodel are scaled down to a global terrestrial grid of 0.5° latitude x 0.5° longitude, using results from the climate model of the Max Planck Institute (MPI) (Cubasch *et al.* 1992) and an updated version of the climate data base of Leemans and Cramer (1991).

Although estimates of regional climate change from climate models are uncertain, they are considered adequate by the scientific community for conducting impact analysis of the type presented in this paper. Moreover, a sensitivity analysis presented in Alcamo *et al.* (1995) indicates that the general approach of our impact analysis is robust even when the uncertainty of regional climate calculations are taken into account.

Evaluation of impacts. Once calculations are made of regional air pollution and climate change, these data are used to evaluate the impacts of these problems. This framework uses two different approaches to evaluate impacts of regional air pollution and climate change.

(i) The ‘risk of impacts’, by comparing levels of regional air pollution and climate change against their ‘critical thresholds’ (see Sections 2.3 to 2.4).
(ii) The ‘environmental balance sheet’, by compiling and comparing the abatement costs for different scenarios, and a measure of impacts for different scenarios (see Section 0).

Scenarios. The framework is used to develop scenarios which explore the identified issues. The scenarios cover the time from 1995 to 2100, with a spatial resolution ranging from the country-scale to grid-scale, and consist of:

(i) Emissions leading to regional air pollution and climate change;
(ii) Changes in the atmosphere including the build-up of regional air pollutants and greenhouse gases together with deposition of air pollutants and changes in temperature and precipitation;
(iii) Impacts of climate change and regional air pollution based on critical thresholds and an environmental balance sheets; and finally,
(iv) Abatement costs for the reduction of air pollutants and/or greenhouse gases compared to a reference scenario.

Summary of Progress to Date and its Significance

The framework was established and tested in the first reporting period. Thus, it is possible now to analyze scenarios that address both regional air pollution and climate change in Europe.

2.2 Simulation of NH_3 Emissions in Europe after 2010

Purpose of this Task

One of the objectives of the AIR-CLIM project is to analyze the effects of acid and nitrogen deposition up to the year 2100. For that purpose the NH_3 emissions have to be modeled up to that year - in addition to the SO_2 and the NO_x emissions. The RAINS model calculates the European NH_3 emissions per country up to the year 2010 based on specified agricultural pathways while IMAGE calculates greenhouse gas emissions per region up to 2100, but not NH_3 emissions. Thus, there is a need to extend the IMAGE model to include the calculation of NH_3 emissions in Europe up to 2100.

Significance of this Task to Policy

The interest in NH_3 emissions significantly increased in the last 15 years. Along with SO_2 and NO_x it is one of the main primary pollutants leading to acidifying deposition. Together with NO_x it causes the eutrophication of ecosystems. Last, but not least, the atmospheric sulfate aerosols acting as cloud condensation nuclei are neutralized to various degrees by ammonia. As NH_3 emissions increased in recent years and SO_2 emissions decreased (at least in Europe) there has been a shift in the focus of the activities of the UN/ECE concerning the LRTAP. The muli-effect multi-pollutant protocol currently negotiated will also consider controls on NH_3 emissions. While there are several detailed NH_3 emission inventories available by now, the work in this task will be one of the first to provide a long-term perspective on the development of the NH_3 emissions in Europe.

Analysis to Date

In Europe the following sources of ammonia (NH_3) emissions are important (Klaassen, 1991), (Klaassen, 1992):

- livestock farming: dairy cows, other cattle (including buffaloes), pigs, poultry, sheep and goats, and horses;
- nitrogen fertilizer consumption;
- industry (fertilizer and ammonia production plants); and
- other anthropogenic sources (i.e. other industry, waste treatment, human respiration).

Ammonia emissions will be proportioned to the level of activity of these sources. Therefore it is important to estimate the future level of their activity in Europe. Most of these activities are modeled per region in IMAGE up to 2100:

- The Agricultural Economy Model (AEM) of IMAGE 2 computes the livestock population driven by the demand for animal commodities, which is in turn driven by population and income growth (Zuidema *et al.* 1994). AEM distinguishes 7 livestock groups: (1) dairy cows, (2) other cattle, (3) pigs, (4) sheep and goats, (5) poultry, (6) horses, and (7) mules. Thereby, the latter two animal types are exogeneously set and not modeled.
- In addition, AEM calculates the amount of fertilizer use.
- The Energy-Industry System (EIS) Model of IMAGE 2.1 calculates the industrial ammonia production by scaling the 1990 activity level based on the development of energy consumption in industry.

In summary, for all the relevant emission sources of NH_3 activity levels are modeled in IMAGE.

NH_3 emission factors for the IMAGE regions OECD Europe, East Europe and CIS (including the Asian part) are specified based on the emission factors in RAINS. Regional emissions are calculated by multiplying the activity levels calculated by IMAGE with the emission factors. The regional emissions are allocated to countries based on the distribution of the emissions in 2010 according to RAINS.

Summary of Progress to Date and its Significance

A model for the assessment of NH_3 emissions in Europe up to 2100 was developed. It is one of the first to provide a long-term perspective on the development of the NH_3 emissions in Europe. Therefore, the model provides information not available from current NH_3 emission inventories with a much shorter time frame. This long-term perspective becomes more relevant as livestock numbers and fertilizer use change, and thereby change the rate of NH_3 emissions.

Next Task

The present spreadsheet model for NH_3 will be transferred to a programmed model. Emission factors and sources will be revised as necessary.

2.3 Critical Loads and their Dependence on Climate Change

Purpose of this Task

Critical loads depend among others on climate factors, which means that critical loads could be sensitive to climate change. This sensitivity provides an important linkage between regional air pollution and climate change. Therefore, the purpose of this task is to include the dependence of critical loads on climate change in the AIR-CLIM integrated modeling framework.

Significance of this Task to Policy and Science

Since more than a decade the concept of critical loads has been discussed. About five years ago critical loads were used in negotiating the Second Sulphur Protocol, and currently they are playing an important role in the negotiations of a revised N protocol (multi-pollutant multi-effects protocol). This analysis gives a first indication whether climate change will affect the effectiveness of these policies. From the scientific perspective it is of interest how the sensitivity of ecosystems to acid deposition is influenced by climate change.

Analysis to Date

A critical load is defined as 'the quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson, Grennfelt 1988). Methods for calculating critical loads have been elaborated in several (UN/ECE) Task Force meetings and workshops (see Nilsson, Grennfelt 1988, Sverdrup *et al.* 1990, Grennfelt, Thörnelöf 1992, Hornung *et al.* 1995, Posch *et al.* 1995) and are summarized in the so-called Mapping Manual (UBA 1996).

Here we consider critical loads for forest soils calculated with the so-called simple mass balance (SMB) model. In this model the soil is treated as a homogeneous compartment with the depth equal to the rooting zone, and after several simplifications and assumptions (e.g., complete nitrification) the following balance equation is obtained (UBA 1996):

$$S_{dep} + (1 - f_{de}) N_{dep} = BC_{dep} - Cl_{dep} + BC_w - BC_u + (1 - f_{de})(N_i + N_u) - ANC_{le} \qquad (1)$$

where BC stands for the sum of base cations ($BC=Bc+Na=Ca+Mg+K+Na$), ANC is the acid neutralization capacity (sum of base cations minus strong acid anions), f_{de} ($0 \le f_{de} \le 1$) is the so-called denitrification fraction (a soil property) and the subscripts *dep*, *w*, *i*, *u* and *le* stand for deposition, weathering, immobilization, (net) uptake and leaching, resp.

Eq. 1 holds for every deposition of S and N. Specifying a so-called critical ANC leaching, $ANC_{le(crit)}$, which links soil chemical changes to a 'harmful effect', allows to compute the excess leaching Ex_{le} for all depositions of N and S:

$$Ex_{le} = S_{dep} + (1 - f_{de}) N_{dep} - BC_{dep} - Cl_{dep} + BC_w - BC_u + (1 - f_{de})(N_i + N_u) - ANC_{le(crit)} \qquad (2)$$

Those combinations of N_{dep} and S_{dep} which result in $Ex_{le}=0$ are called **critical loads**. Obviously, eq. 2 does not define unique critical loads of S and N, only a functional relationship between them which has been termed critical load function (see Posch *et al.* 1995, UBA 1996). If the depositions are such that $Ex_{le}>0$, we say that critical loads are exceeded; for

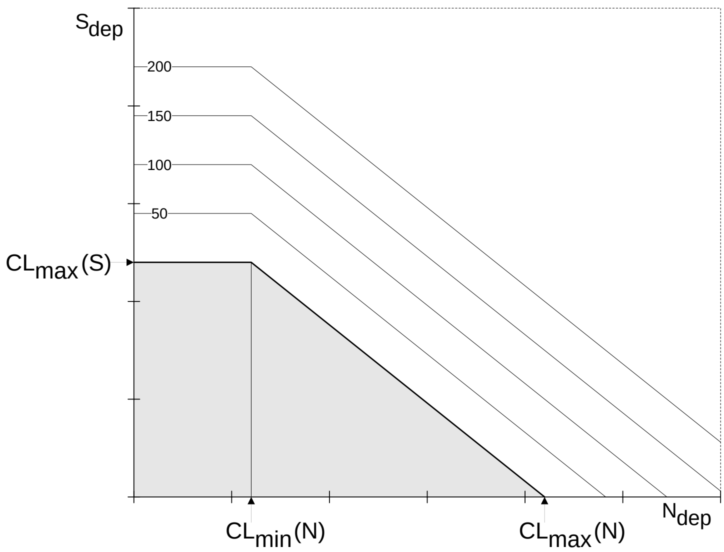


Figure 2 Hypothetical critical load function of acidifying N and S (thick line) and isolines of constant excess leaching. The values of Ndep and Sdep for which there is non-exceedance (Exle<0) are indicated as grey-shaded area.

$Ex_{le}\leq 0$ we have non-exceedance. Since nitrogen sinks cannot compensate sulfur acidity, the maximum critical load of sulfur is given by

$$CL_{max}(S) := BC_{dep} - Cl_{dep} + BC_w - BC_u - ANC_{le(crit)} \tag{3}$$

which is also called the (potential) **critical load of acidity**. Furthermore, if $N_{dep}\leq CL_{min}(N):=N_i+N_u$, all deposited N is consumed by N sinks and sulfur can be considered alone. Finally, the maximum critical load of nitrogen (for $S_{dep}=0$) is given by $CL_{max}(N):=CL_{min}(N)+CL_{max}(S)/(1-f_{de})$. In Figure 2 a hypothetical critical load function is shown together with isolines of excess leaching. It should be noted that Ex_{le} is in general not the amount by which to reduce N and/or S deposition to reach non-exceedance.

In the following we restrict ourselves to the acidity critical load, $CL_{max}(S)$, and its dependence on climate related parameters:

The dependence of weathering rates on the (soil) temperature is given by:

$$BC_w(T) = BC_w(T_0)\exp\left(\frac{A}{T_0} - \frac{A}{T}\right) \tag{4}$$

where T is the mean annual temperature (in K), T_0 a reference temperature and A=3600K.

ANC leaching is given by $-Al_{le}-H_{le}$, and the critical Al leaching is calculated from the leaching of base cations and a critical molar Bc/Al ratio in soil solution:

$$Al_{le(crit)} = 1.5\frac{Bc_{le}}{(Bc/Al)_{crit}} \quad \text{with} \quad Bc_{le} = Bc_{dep} + Bc_w - Bc_u \tag{5}$$

Using $X_{le}=Q[X]$, where Q is the annual mean precipitation surplus (=precipitation minus evapotranspiration or percolation), $H_{le(crit)}$ is computed from $[H]$ and the gibbsite equilibrium, $[Al]=K_{gibb}[H]^3$. $ANC_{le(crit)}$ is thus given by

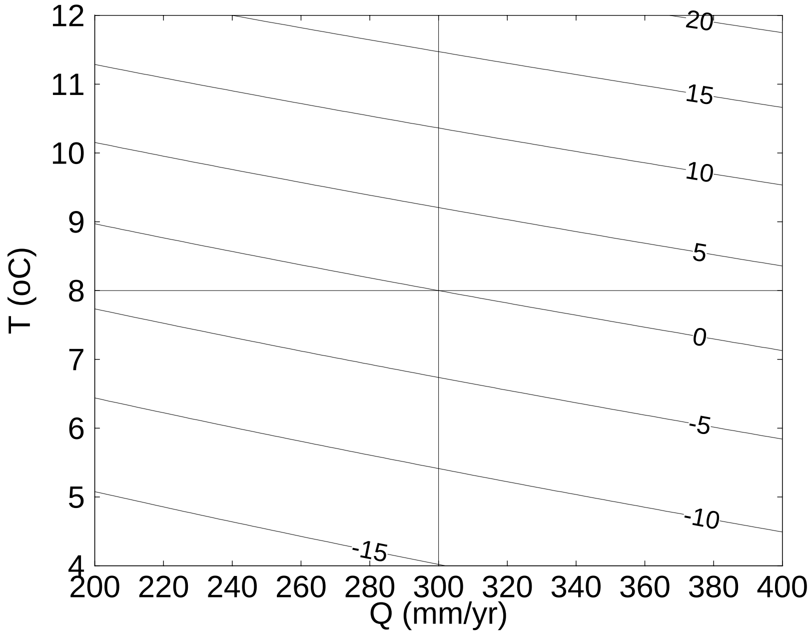


Figure 3 Isolines of changes (in %) of the critical load of acidity, CLmax(S), as a function of the (mean annual) temperature T and percolation (runoff) Q with respect to a reference value (see text for details).

$$- ANC_{le(crit)} = 1.5\frac{Bc_{dep} + Bc_w - Bc_u}{(Bc/Al)_{crit}} + Q^{2/3}\left(1.5\frac{Bc_{dep} + Bc_w - Bc_u}{(Bc/Al)_{crit} K_{gibb}}\right)^{1/3} \tag{6}$$

Preliminary Estimates: Sensitivity of the acidity critical load on T and Q

For the investigation of the sensitivity of $CL_{max}(S)$ on the climate parameters T and Q we make the following assumptions: $Na_{dep}=Na_w=0$, $Bc_{dep}=Bc_u$, T_0=8°C=281K, $BC_w(T_0)$=600eq/ha and $(Bc/Al)_{crit}$=1 mol/mol, K_{gibb}=300m^6/eq^2.

Choosing "average values" of T_{ref}=8°C and Q_{ref}=300mm/yr we obtain $CL_{max}(S)_{ref}$=1800eq/ha. In Figure 3 the percentage change in $CL_{max}(S)$ as a function of changing T and Q is presented (as $100(CL_{max}(S)/CL_{max}(S)_{ref}-1)$). As can be seen, an increase in T is (partially) compensated by a decrease in Q. Whether Q will increase or decrease under a changing climate depends on a delicate balance between increasing precipitation and increasing evapotranspiration due to a higher temperature. The maximum changes in critical load values will lie in the range of about 10%.

Results and their Significance

A first analysis of the influence of climate change on critical loads of acidity has been carried out. The analysis showed the sensitivity of critical loads to different combinations of precipitation and temperature. Variation of both factors within reasonable ranges i.e. ranges expected in a warming climate up to 2100, indicated that critical loads will change at most about 10%. A first tentative conclusion is thus that the sensitivity of ecosystems to acid deposition is noticably influenced by climate change although the effect is limited.

2.4 Critical Levels and their Dependence on Climate Change

Purpose of this Task

The purpose of this task is to identify an effective way to simulate the potential impact of varying climate conditions on the direct effects of air pollutants on vegetation. A framework is developed for that purpose that can be used to organize the available quantitative information on the response of different species.

Significance of this Task to Policy and Science

In addition to critical loads of acidity, the concept of critical levels is an important tool for taking into account environmental impacts in the current negotiations of a revised N protocol (multi-pollutant multi-effects protocol) in the LRTAP framework. So, from the policy perspective it is of special interest whether climate change will affect critical levels and thus the effectiveness of air pollution policy.

Up to now there has been little research on the influence of climate change on the sensitivity of vegetation to pollutants in the atmosphere. Thus, from the scientific perspective, this task will considerably further the knowledge of the linkage of these two environmental issues.

Analysis to Date

Critical levels are defined as (UN/ECE 1996)

> 'concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as human beings, plants, ecosystems or materials, may occur according to present knowledge.'

The first attempts at establishing critical levels for SO_2 were made by the International Union of Forest Research Organization (IUFRO) in 1978, the next major step was the preparation (1985) and publication (1987) of the World Health Organization Air Quality Guidelines, based on a thorough review of the literature up to 1985. The UN ECE produced the first agreed critical levels for SO_2 in 1988 based on a substantive review (Jager, Schultze 1988). The 1988 critical levels for higher plants where reviewed and reassessed in 1992 (Ashmore, Wilson 1994) based on an updated review paper by Bell (1994). Table 1 shows the resulting critical levels of SO_2. The critical levels for forest ecosystems and natural vegetation in that table should be lowered for conditions of low effective temperature sum (ETS).

Critical levels for NO_2 and NH_3 were established in 1988 and revised in 1992 (Ashmore, Wilson 1994) (see Table 2 and Table 3). Critical levels for ozone where established in 1988 and revised in 1992 (Ashmore, Wilson 1994), in 1993 (Fuhrer, Achermann 1994) and 1996 (Kärenlampi, Skärby 1996). Table 4 shows the presently specified critical levels for ozone.

Table 1 Critical levels for SO_2 alone by vegetation category (UN/ECE 1996)

Vegetation types	Critical level	Time period (μg SO_2 m^{-3})
Cyanobacterial lichens	10	Annual mean
Forest ecosystem and understory	20*	Annual mean and half – year mean (October-March)
Natural vegetation	20*	Annual mean and half – year mean (October-March)
Agricultural crops	30	Annual mean and half – year mean (October-March)

* 15 for ETS < 1000°C days (ETS is effective temperature sum above 5°C)

Table 2 Critical levels for NO_x (NO and NO_2 added in ppb), expressed as NO_2 (μg/m^3) (UN/ECE 1996)

Criteria	Annual mean	4-hour mean
Adverse ecophysiological effects All vegetation types	30	95

Table 3 Critical levels for NH_3 (μg/m^3) (UN/ECE 1996)

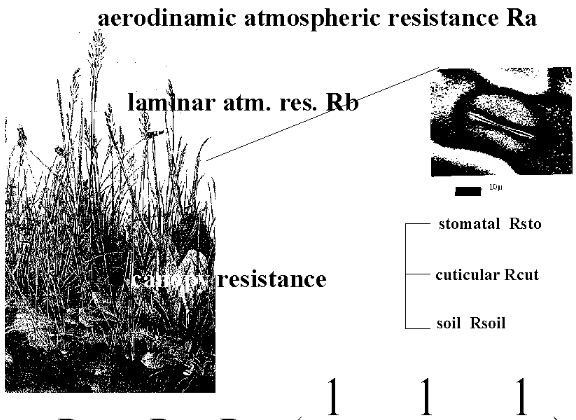
Critical Levels (all vegetation types)	Time period
3300	1 hour
270	1 day
23	1 month
8	1 year

Table 4 Critical levels for O_3

Critical level for crops yield reduction	3000 ppb·h above 40ppb ozone accumulated during daylight hours for three months when the crop is most sensitive to ozone (May, June and July for northern Europe)
Critical level for crops visible injury	500 ppb·h above 40 ppb accumulated during daylight hours (9:00 to 17:00) over five consecutive days, when the mean vapor pressure deficit exceeds 1.5 kPa
Critical level for forest trees	1000 ppb·h above 40 ppb ozone accumulated during daylight hours over a 5 months growing season, based on a five year mean

A model was developed to simulate the dependence of critical levels of SO_2 and NO_x on climate change. The interest of this model is twofold. First, it provides a framework to organize in a reasonable and accessible way the vast amounts of available quantitative information on the climatic modulation of plant response to air pollution. Second, it is able to simulate, admittedly in a very preliminary and simplified way, the potential impact of different air pollution and climate scenarios.

As a first step, the in-plant concentrations of S and N connected to the established critical levels are estimated. The in-plant concentration is assumed to be ‘safe’, too. For that purpose the pollutant flux into the plant leaves under current climatic conditions - called reference flux



$$R_{total} = R_a + R_b + \left(\frac{1}{R_{sto}} + \frac{1}{R_{cut}} + \frac{1}{R_{soil}}\right)^{-1}$$

Figure 4 Components of resistance to flow of gaseous air pollutants into plants

- is calculated. In the second step the model is used to calculate fluxes under different climate scenarios and estimate what the critical levels should be to keep the in-plant concentration identified as ‘safe’.

There are several resistances to the flux of pollutants into plant leaves. Figure 4 identifies the components used in many deposition models for gaseous air pollutants (e.g. (Fowler *et al.* 1997)). The aerodynamic and laminar atmospheric resistances and the canopy resistance are modeled in series. The canopy resistance is in turn modeled as a set of three parallel resistances: stomatal, cuticular and soil.

The inverse of the stomatal resistance is called, in the same electrical analogy, stomatal conductance. Following Emberson *et al.* (1998) the model relates stomatal conductance ($G_{sto} = 1/R_{sto}$) with climate variables using response functions obtained for different vegetation types by experiments and measurements in the last decades:

$$G_{Sto} = G_{max} \cdot g_{pot} \cdot g_{light} \cdot g_{temp} \cdot g_{VPD} \cdot g_{SWP} \tag{2-1}$$

where

G_{max} the maximum stomatal conductance [mmol $O_3/m^2/s$]
g_{pot} the potential maximum stomatal concuctance as relative *g* (0 to 1)
g_{light} the relative g determined by irradiance
g_{temp} the relative g determined by temperature
g_{VPD} the relativeg determined by leaf to air vapour pressure deficit
g_{SWP} the relative g determerminded by soil water status

Taking into account that most of the experimental data on stomatal conductance relate in fact to water flow, we will use similar functions to describe the flows of sulfur dioxide, oxidized and reduced nitrogen and ozone. If possible, adjustments to account for different solubility will be included.

The pollutant flux *F* into the plant leaves is a product of the ambient concentration *X* and the total conductance G_{total} (which is the inverse of R_{total})

$$F = X \cdot G_{total} \tag{2-2}$$

It is clear at this stage that there are vast uncertainties in many steps, including the assignment of vegetation type, the procedures used to link climatic data to modulating factors, and the functions used for different vegetation types. Therefore, at this stage caution should be applied in the interpretation of the results. The main effort in the next few months will be to include the best information available for the different necessary assumptions.

There is still a considerable amount of work to do, especially to convert the input data available from IMAGE into the data needed for the model. Also the impact of CO_2 has not been included so far.

Summary and Significance

A model is developed to simulate the dependance of critical levels for air pollution on climate factors. This model can be used to organize the available quantitative information on the response of different species. From the scientific perspective the work done in this task will further the knowledge on the linkage of these two environmental issues considerably. From the policy perspective it is of importance for the current negotiations on another N protocol in the LRTAP framework whether climate change will affect critical levels.

Future work

In the second phase of the project the simulations for some of the main vegetation types will be finalized and first calculations performed for the AIR-CLIM scenarios.

2.5 Climate thresholds

Purpose

The purpose of this task in the AIR-CLIM project is to define a transparent concept of critical thresholds for climate change that allows an analysis of the consequences of climate change under different scenarios for Europe that is consistent to the analysis of regional air pollution with the critical levels/loads-concept.

Significance to Policy and Science

In the last years climate impact research has sometimes identified breaking points of climate change leading to rapid changes in various impact categories. This research has yet not been applied to Europe in a consistent way. Thus, this study will provide new insights with respect to European areas vulnerable to climate change.

Similar to the critical levels/loads-concept, climate thresholds aggregate various types of information about the sensitivity of ecosystems to climate change in one indicator. Thus, climate thresholds are convenient tools for policymakers to examine the effectiveness of European policies to control greenhouse gas emissions.

Analysis to Date

Definition. The critical-level/load concept has been developed as a clear and transparent instrument for examining the negative impacts of regional air pollution (see e.g. (UBA 1996)).

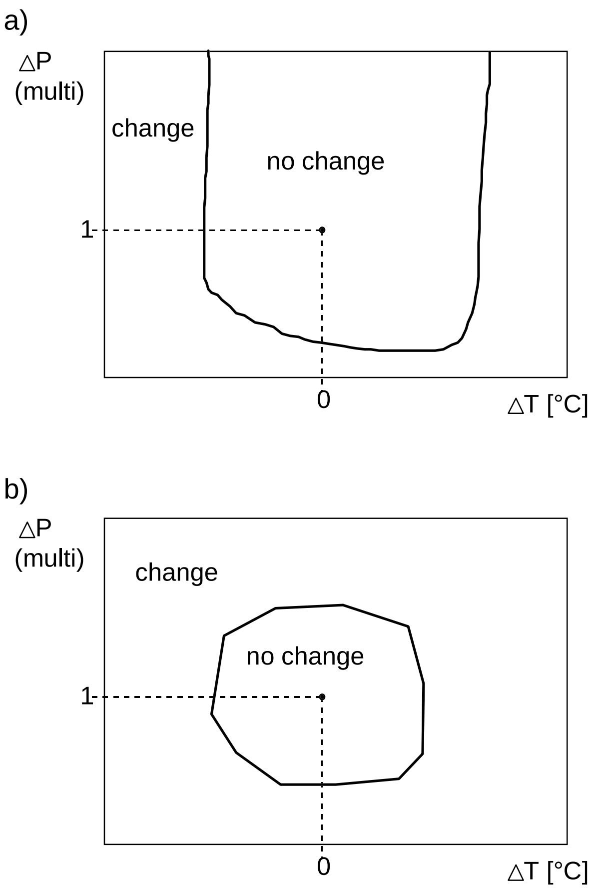


Figure 5 Examples for Climate Isoline Diagrams (CIDs) - two of several possible shapes - CID show change/no change areas with respect to a selected critical value of change (precipitation change expressed as multiple of present precipitation in respective grid cell)

No analogue exists to our knowledge regarding the problem of climate change, although various recent publications address this issue (e.g. (Parry *et al.* 1996), (Leemans, Hootsman 1997)). We developed the Climate Isoline Diagrams (CID) approach to help identify "critical climate thresholds". We define critical climate thresholds as '*quantitative values of climate change, below which only acceptable long-term effects on ecosystem structure and functioning occur, according to current knowledge*'.

CIDs are two-dimensional diagrams of temperature and precipitation changes in which temperature/precipitation combinations are identified for which only acceptable changes are expected. Such two and three dimensional diagrams are often used in systems science for depicting the response of a state variable to two forcing variables (details in e.g. (Van Minnen *et al.* 1999a), (Van Minnen *et al.* 1999c)). The diagrams can be used to evaluate different combinations of changes in temperature and climate and to examine the consequences of different climate thresholds. Up to now, however, we have not yet identified climate thresholds. The CID concept is still under development and may be adapted in further stages of the AIR-CLIM project.

Figure 5 shows two possible shapes CIDs can have. Figure 5 a) shows the case of temperate deciduous forests in Europe that are mainly sensitive to changes in temperature and severe reductions in precipitation. Under conditions of higher temperatures these forests will become replaced by more Mediterranean forest types, while more drought conditions will result in forest degradation and replacement by grassland or shrub types. This results in the U-shape of the CID.

Figure 5 b) shows the case of grasslands in Europe that are threatened by climatic change. In case of increasing temperature and especially precipitation, such ecosystems are no longer as competitive as wooded/forest vegetation types. In case of lower temperature and/or more severe dry conditions grassland is degraded (i.e. becomes less productive) and is eventually replaced by shrubby or drought-tolerant vegetation types. This results in a CID with a limited 'no change'-area.

The current CIDs include the responses of both agricultural crops and natural ecosystems on a 0.5° longitude by 0.5° latitude grid within Europe (in total more than 3000 grid cells). The diagrams differ due to different sensitivities of crops and ecosystems, and differences in climate and soil conditions.

Aggregating the CIDs on country levels yields the so-called Climate Impact Diagrams Aggregated to Country level (CIDAC). These diagrams depict the overall response of a political region (e.g. country) to changes in climatic conditions, e.g. how much forest area will disappear in Germany if the temperature increases by 2°C. We consider the country-level to be the most relevant scale from the standpoint of climate policy because countries are motivated to control emissions by the possible climate impacts to their territory. Furthermore, since the CIDACs differ between countries, they can also be used to compare the relative sensitivities of different countries to climate change.

Consistency to critical level/load concept. In order to harmonize the assessment of impacts in the AIR-CLIM project the CID approach uses similar principles as the critical level/load concept. First, CIDs demonstrate the sensitivity of a receptor, i.e. a specific ecosystem, in a particular area (e.g. grid cell) to changes in precipitation and temperature. The dependency on two variables is an equivalent to the protection isolines for sulfur and nitrogen within the critical levels/loads concept. Growth stimulation due to CO_2 fertilization is also considered in the analysis by developing different CIDs for various CO_2 levels in the atmosphere. Secondly, the CIDs use the same receptor systems as the critical levels/loads concept, namely agricultural crops and natural vegetation.

Acceptable effects. As for critical levels and loads the derivation of climate thresholds hinges on the underlying criterion, i.e. the potential damage avoided by keeping climate change within the boundaries of the climate thresholds. That criterion cannot be the level at which no change occurs as ecosystems are constantly changing even under already existing environmental conditions, e.g. due to climate variability. Thus, the definition of climate thresholds has to based on *acceptable* effects.

These acceptable effects *cannot* purely be set based on science. Instead desirable criteria have to be derived in the policy context. In this study criteria will be used that have been applied to other environmental issues. For example, the critical level of ozone for crops is set based on the criterion that crop yield loss due to atmospheric ozone concentrations should be below 5% (UN/ECE 1996). Similar criteria will be compiled from various sources during the project and climate thresholds derived based on these. Furthermore, at the end of the project the *methodology* to derive the climate thresholds will be available to calculate thresholds based on other criteria discussed in the policy context.

Impact Indicators. The potential suitability of an agricultural crop and natural ecosystem to a particular location and their potential productivities are used as indicators of climate impacts (Table 5). For crops, we use the FAO definition of potential productivity, i.e. the harvestable part of the dry weight production of particular crops under ambient climatic conditions. Anthropogenic factors affecting the production, such as the amount of applied fertilizer and management practices, are neglected. In addition to the FAO definition, the crop production rates depend on the present soil conditions at a particular location.

The CIDs for the potential distribution of natural vegetation include diagrams for single biomes (i.e. large scale vegetation patterns such as boreal needle leafed forest) and for total forested area. The latter indicator is used to distinguish between ecosystems with different carbon (C) storage capacities. This, in turn, can be useful to evaluate different options to mitigate climate change.

Development of CIDs. The models used for the development of the CIDs are cited in Table 5. The first step in developing the CIDs for agriculture and natural vegetation was to compute the reference state based on current climate. We used the AEZ and BIOME model as implemented in the IMAGE 2 model (Leemans, van den Born 1994) with a new climate data set for monthly ambient air temperature, precipitation and cloudiness (based on 1961-1990 average (New *et al.* 1998)). The monthly climate data were temporally interpolated, because the models require (quasi) daily input.

The second step was to compute the impact indicators under changed climatic conditions. For these calculations we adapted the gridded values of current precipitation by multiplying them in a step-wise manner by factors from 0.5 to 2.5, in increments of 0.25 (0.5x, 0.75x, 1.0x, etc.). Current gridded temperature values are changed by varying them within the range of -2°C to +7°C in increments of 0.5°C. We also considered temperature decreases to examine the trend of the response, although all climate models we are aware of only compute increases in temperature. Cloudiness is kept constant at the current values.

In the third step we repeated the calculations, varying the CO_2 concentrations in the atmosphere from 325 ppm (about the value of 1970) up to 1000 ppm (about 4 times historical concentrations). The agricultural model uses the CO_2 concentration both for crop distribution and production (details in (Van Minnen *et al*. 1999a)). The model for natural ecosystems distribution considers atmospheric CO_2 as it affects the water use efficiency of plants and therefore the moisture threshold below which plants cannot exist. In principle, the C cycle model of IMAGE includes the effect of changing CO_2 levels in a similar approach as the crop model. However, as mentioned before, the C cycle model is not used in the current development of the CIDs. The C cycle model, however, might be considered in future stages of the project.

Finally, the CIDs are used to examine the consequences of the test scenario (see Chapter 3 for details about the scenario). Thresholds or critical values for climate change are assigned to each impact indicator. The critical values, in turn, are used to establish exceedance maps. We examined the consequences of climate change for countries in total as well as for selected spatial sub-areas. The current crop areas (based on (Espenshade, Morrison 1991)) and current protected areas (based on (UNEP/GEMS 1993)) are used as subsets for agriculture and natural vegetation, respectively. Examining the impacts on a spatial subset neglects different adaptation strategies, as, for example, the possibility to explore new areas to compensate for production losses in current regions. Neglecting this adaptation potential may lead to an overestimate of the response of the European agricultural system. Nature reserves are set aside

Table 5 Receptor systems and impact indicators as considered in the AIR-CLIM project to examine climate change impacts

Receptor system	Impact indicators	Models used for calculations	Reference
Agriculture	Potential. crop production	IMAGE-AEZ	Leemans & van den Born, 1994
	Potential crop distribution		
Natural vegetation distribution	Potential ecosystem distribution	IMAGE-BIOME	Leemans & van den Born,1994
	Potential forest distribution		
	Changes in ecosystem productivity	IMAGE-C cycle	Klein Goldewijk *et al*., 1994

for protecting the current state of nature. Hence, vegetation changes in these areas are useful indicators of undesirable climate changes.

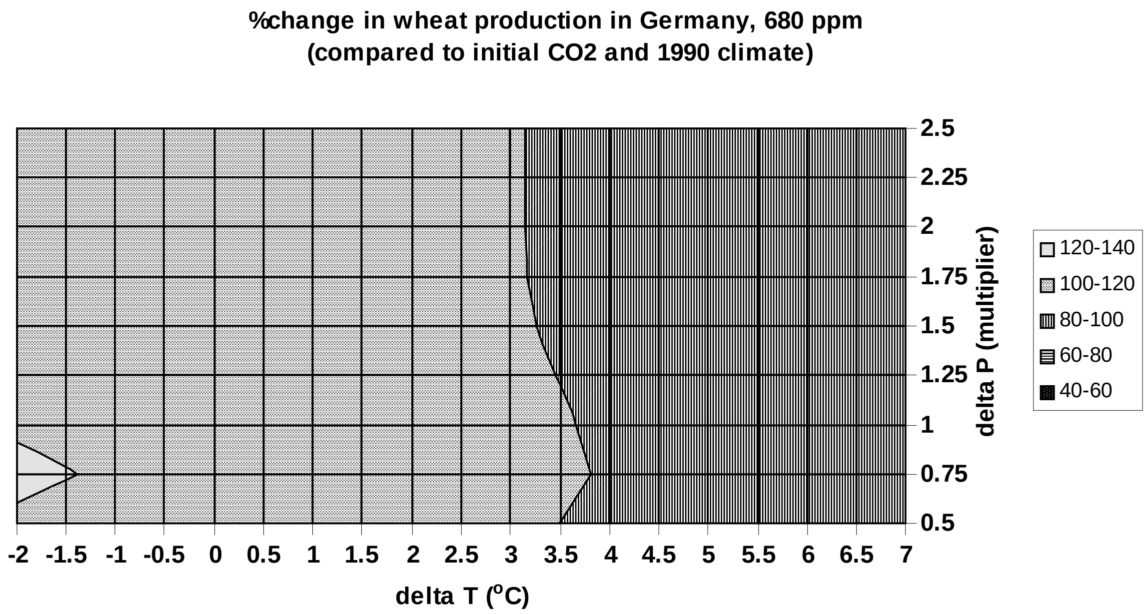
Application of CIDs. In this stage of the project three steps can be distinguished in the application of the climate threshold approach. First, the scenario-independent CIDs demonstrate the sensitivity of the receptor systems in an area. Secondly, the grid cell specific sensitivities are aggregated to the country level yielding CIDACs, which are also scenario-independent. Finally, the consequences of a particular climate change scenario (here the AIR-CLIM test scenario) are evaluated by developing exceedance maps (section 3.3.4).

Application to agriculture. In this stage of the project we investigate the applicability of the climate threshold approach. CIDACs are shown here for two example countries - Spain and Germany - to demonstrate the approach. However, diagrams for the entire European area are available. Figure 6 shows the CIDACs depicting the sensitivities of potential wheat production (relative to the 1990 situation) in Spain and Germany. The wheat production in Germany is especially sensitive to changes in temperature and CO_2. The potential production of wheat is for a CO_2 concentration of 680 ppm (about 2100 value) 18% higher than under current CO_2 levels. Combined CO_2 and temperature changes lead to declining production rates. The 18% production gain under current climatic conditions and 680 ppm diminishes when the temperature rises 3-3.5°C (country average). The production levels in Germany fall below the 1990 values under more severe temperature changes.

The CIDAC for Spain indicates that the potential wheat production would be stimulated under increasing CO_2 levels. Furthermore, the diagram indicates that the wheat production in Spain is especially sensitive to reductions in precipitation. For the country in total about 20% production losses are computed at half of the current amount of precipitation. The impacts are more severe for a part of Spain as there is a large spatial variation within the country. Severe reductions are simulated for parts of southern Spain, while the decline in northern Spain is limited (or there is even an increase instead). The differences are caused by the spatial variation in precipitation.

Application to natural ecosystem dynamics. We developed CIDACs for all European countries to illustrate the sensitivities of natural ecosystems. Again, here only example results for Spain and Germany are described. The analysis focuses on the sensitivities of the vegetation *distribution* to changes in precipitation and temperature. Integrating growth rates and carbon (C) sensitivities into the CID approach is planned for the next reporting period.

a)



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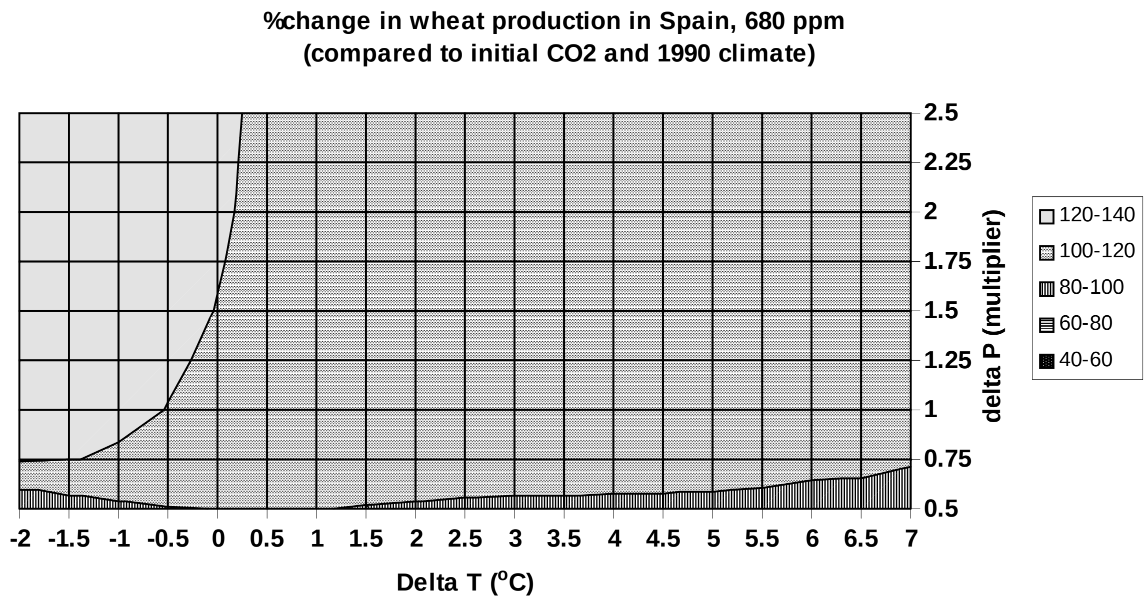
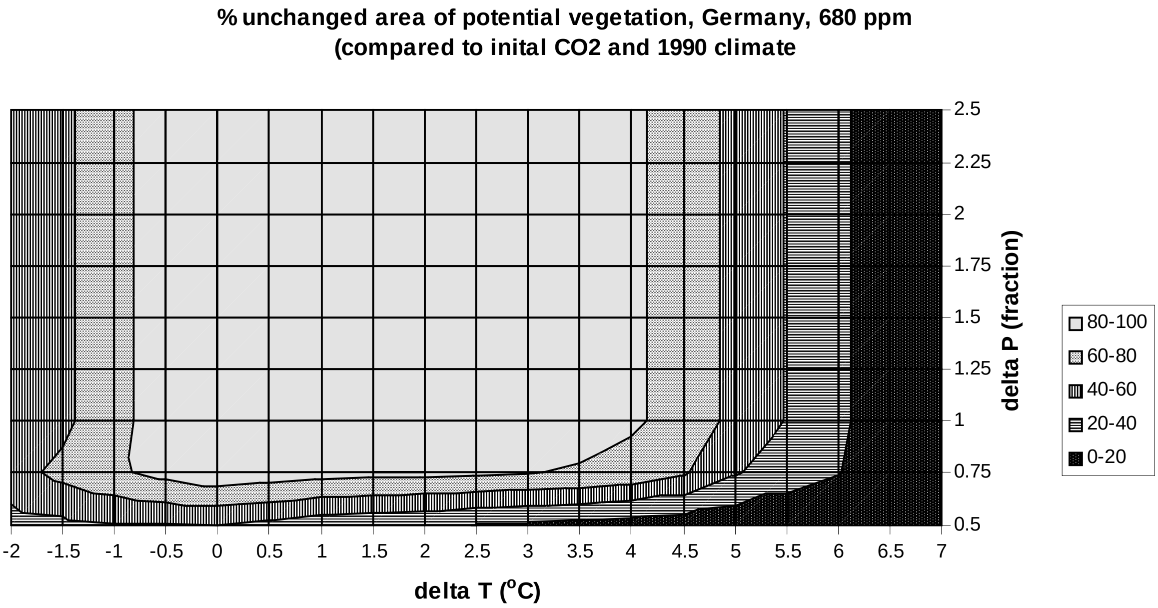


Figure 6 CIDACs for wheat production in Germany (a) and Spain (b), assuming an atmospheric CO_2 concentration of 680 ppm

a)



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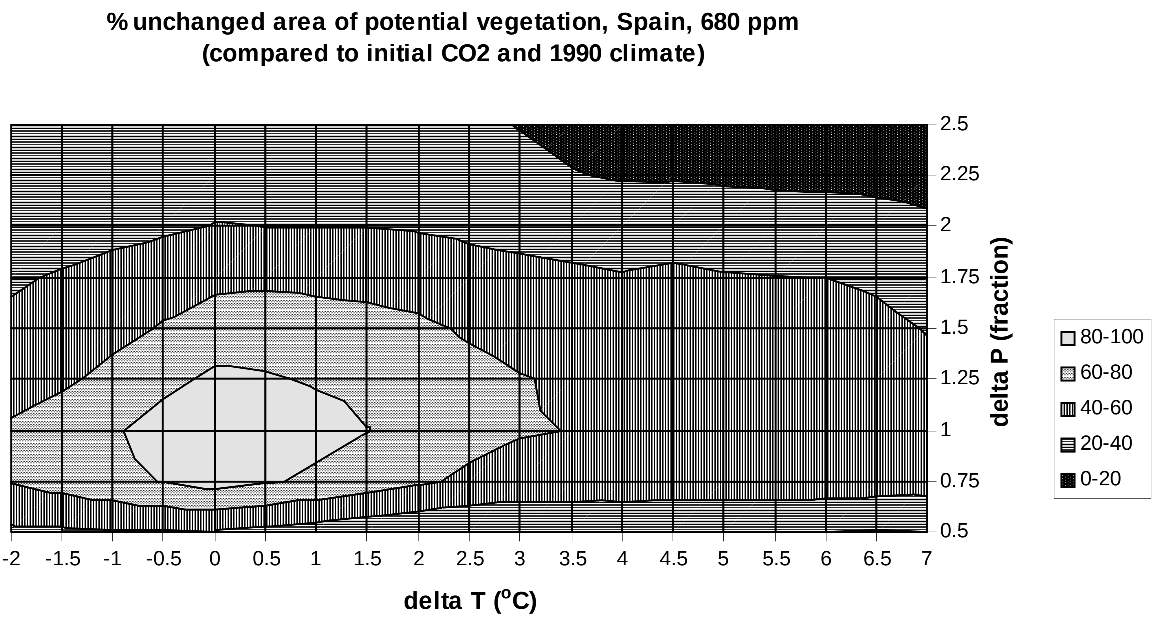


Figure 7 CIDACs for natural ecosystems, depicting the unaffected areas (in % of total (ecosystem?) area) in 2100 for Germany (a) and Spain (b)

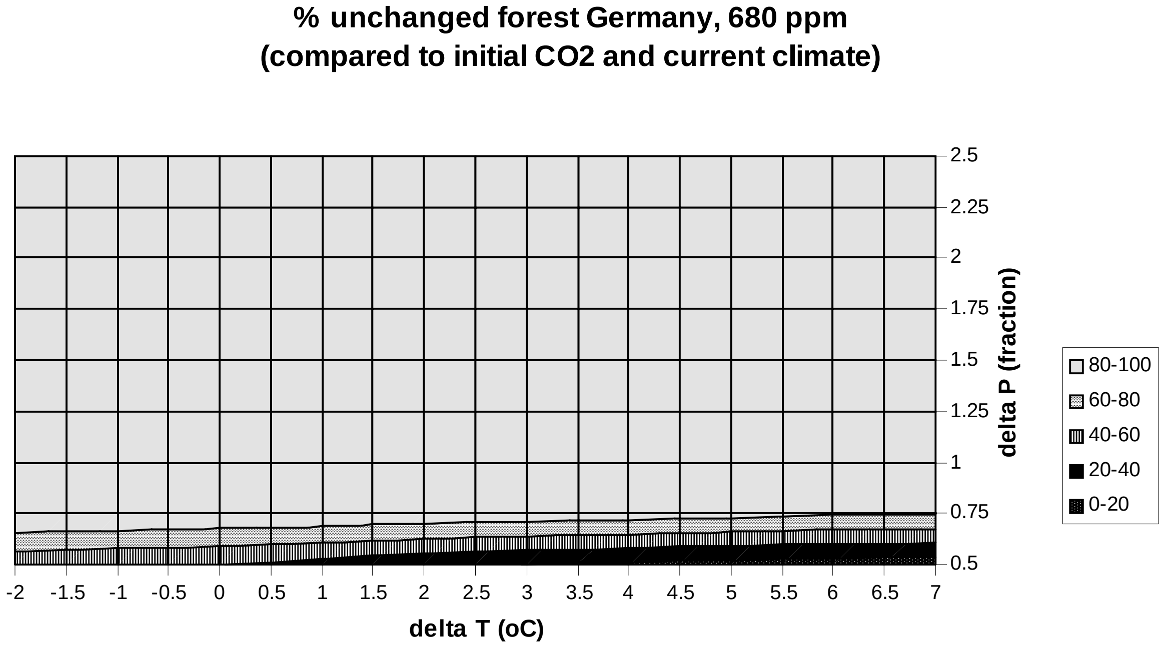


Figure 8 CIDAC for the forest area in 2100 in Germany (% change)

We note that although transient land-cover conversions are part of the IMAGE 2 model (Van Minnen *et al.* 1999b), it is yet not included in the current analysis, i.e. the diagrams do not consider the time that biome 'x' requires to migrate into a new location, to establish itself and to replace the vegetation in that area. By neglecting transient land-cover conversions, on the one hand the current approach is time/scenario independent. On the other hand thus the impacts might be overestimated. Further research in AIR-CLIM will pick up this aspect.

In general, the current CIDACs show that the potential natural vegetation of most European countries is very sensitive to both changes in precipitation and temperature (Figure 7). The strongest responses of forests occur under decreasing precipitation rates (Figure 8).

Countries differ more in their sensitivity to temperature than to precipitation. The potential vegetation in countries with diverse landscapes is more sensitive to small changes than in relatively homogenous countries, due to the high variety of biomes. However, the same variety prevents severe changes under large temperature changes. For example, in Spain (potentially covered by many biomes) a change in temperature of 1.5°C results in a 20% change of the current potential vegetation cover. The same percentage in Germany (where the potential vegetation is dominated by one biome, broadleaved forest) is reached when the temperature rises by more than 4°C. However, if the temperature rises more than 6°C in both countries we compute changes of 77% and 50% in Germany and Spain, respectively. Under such large temperature changes, all the forest cover in a temperate region like Germany is replaced by either Mediterranean forest types or grassland (depending on whether the temperature change is accompanied by a decrease in precipitation). In heterogeneous countries like Spain changes are limited because certain biomes, like shrubland, are better adapted to severe climatological conditions.Summary and Significance

A method called Climate Isoline Diagrams (CID) has been developed to aggregate information about the sensitivity of ecosystems to climate change in a way that is consistent to the critical level/load concept. The method has been applied to agriculture and natural ecosystems in Europe yielding new insights with respect to European areas vulnerable to climate change. CIDs provide a new tool to examine the effectiveness of European policies to control greenhouse gas emissions.

2.6 Integration of Air Pollution and Climate Change Impacts

Purpose of this Task

The purpose of this task is to look at the interaction of climate change and regional air pollution on the impact level. One aspect, the influence of climate change on critical levels/loads, has been analyzed in sections 2.3 and 2.4. The integration of climate change impacts and air pollution impacts is covered in this section of the report.

Significance to Policy and Science

The environmental issues global warming and air pollution have been handled separately in policymaking so far, because, among other reasons, there is no approach available to examine their impacts in an integrated way. Here we present the first steps in an integrated approach to assess the impacts of global warming and regional air pollution.

From the scientific perspective the approach provides a method for combining disparate information from different disciplines having to do with the environment in an integrated way.

Analysis to Date

In order to harmonize the assessment of climate change and air pollution impacts, we take a hierarchical approach. According to present knowledge one of the most important impacts of climate change could be major shifts of vegetation in Europe (see section 2.4 for example), but such shifts are not expected because of air pollution. Thus, the first step of the analysis is to assess the land cover changes due to climate change. The second step is to recompute the critical levels/loads under climate change for the new land cover type. And the third step is to compute the area in which air pollution exceeds the new critical loads (Figure 9). It remains to be explored how ecosystems degraded because of climate change react to air pollution effects. Furthermore, it is still under discussion how to define ‘degraded’ ecosystems: ecosystems with a lower average productivity than today, or ecosystems which are no longer the most competitive ones for the location they inhabit.

Summary and Significance

A preliminary approach for the integration of climate change and regional air pollution on the impact level has been developed. This approach combines disparate information from different disciplines connected to environmental issues in a semi-unified way. Thus, the approach will support policymakers in looking at these environmental problems in a holistic way.

Future work

The hierarchical step-procedure will be worked out with respect to definition of ‘degraded’ ecosystems and to air pollution effects on these ‘degraded’ ecosystems.

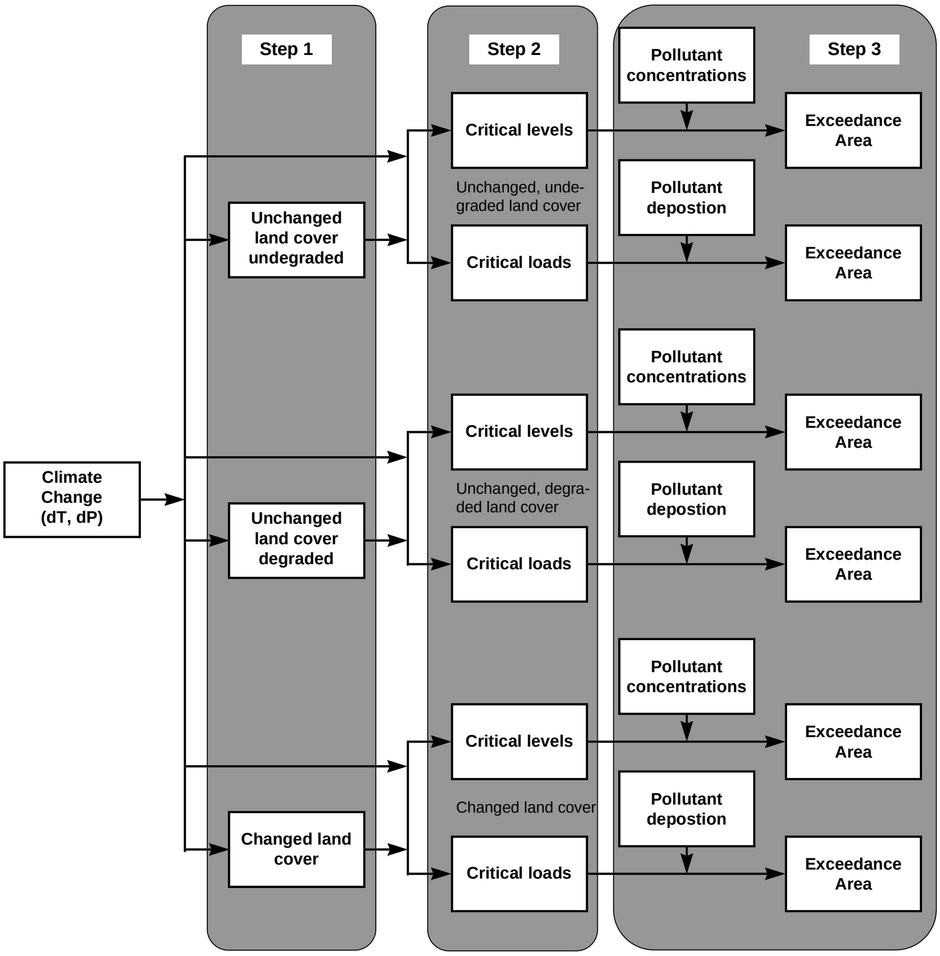


Figure 9 Hierarchical procedure for the integrated assessment of climate and air pollution impacts

2.7 Environmental Balance Sheets

Purpose of this Task

The assessment of costs and benefits is becoming increasingly important to the assessment of alternative policies for regional air pollution. However, it is not feasible to perform a classic cost-benefit analysis for the objective of this project as the basic information, especially on the impact, i.e. benefit, side is not available. Thus, there is the need to develop another approach to compare the costs and 'benefits' of measures to mitigate climate change and air pollution.

Significance to Policy and Science

From the policy perspective, it is desirable to have an overview of not only the risks of impact, but also the costs to avert these risks to properly evaluate measures to mitigate climate change and air pollution.

While cost-benefit analysis of mitigation measures for air pollution in the short-term have been comparatively successful in the last years, the application of the 'classic' cost-benefit analysis to the issue of global warming has been controversially discussed in the last years, see e.g. the discussion around the chapter on cost-benefit analysis of the second assessment of the

IPCC. Thus, from the science perspective it is necessary to develop approaches that meet the needs of the public.

Analysis to Date

Environmental Balance Sheets help to identify the tradeoffs between the risk of damage on one hand and cost of abatement strategies on the other. Scenario assessments of cost of end-of-pipe strategies to reduce sulfur dioxide, nitrogen oxides and secondary pollutants of tropospheric ozone formation are well established and reviewed using the RAINS model in the framework of the UN/ECE Convention on Long Range Transboundary Air Pollution ((Amann *et al.* 1995); also see the IIASA RAINS manual). Cost functions for the application of add-on abatement techniques to reduce sulphur nitrogen oxide emissions and emissions of ozone precursors are available in RAINS for every country in Europe (Amann *et al.* 1995). The cost functions reflect the average and marginal cost of the application of several add on techniques to a variety of economic sectors and energy sources. Abatement cost of carbon dioxide are available from IMAGE 2 and related models. Risk of damage is addressed, as described before, by investigating the excess of critical thresholds in terms of absolute magnitudes as well as area protected.

Environmental Balance Sheets provide a simple means to compare scenarios, *with and without climate change*, in terms of (1) cost of emission abatement per scenario, and (2) risk of damage per scenario.

This approach provides a quick overview of the performance of scenario alternatives, thus enhancing the iteration between

(a) the formulation of policy objectives,
(b) the application of RAINS and IMAGE 2 for the analysis of scenarios with and without climate change, using the sweep of critical thresholds described before, and finally
(c) inspect the relative performance of each scenario in comparison to one another by inspecting changes of abatement costs and risks of impacts.

From the policy perspective, it is desirable to have an overview of not only the risks of impact, but also the costs to avert these risks. Indeed, the assessment of cost and benefits is becoming increasingly important to the assessment of alternative policies for regional air pollution. An important example of such an assessment for energy externalities is the ExternE project (e.g. (European Commission, 1995), (European Commission, 1997)). However, it is not feasible to perform such a detailed assessment of costs and benefits in the proposed project because the basic information needed to assess costs and benefits of policies for both regional air pollution and climate change in Europe are not available. Instead, we propose to perform an 'order of magnitude' cost-benefit assessment by compiling environmental balance sheets. Figuratively speaking, one side of the balance sheet shows the costs to abate emissions. These data are organized so that the costs of different emission scenarios can be compared. On the other side of the balance sheet is a quantitative measure of impacts, specifically the area in which critical thresholds are exceeded. These data are also organized so that results from different scenarios can be compared. An example of an environmental balance sheet is given in Table 6. This example, however, covers only costs of controlling SO_2 emissions. In this project environmental balance sheets will include the costs of 'end-of-pipe' controls on nitrogen oxides, sulfur dioxide, and ammonia; and the costs of reducing CO_2 through energy strategies. Also, Table 6 only presents the area protected from sulfur deposition. In this project sulfur and

Table 6 An example of an Environmental Balance Sheet produced as result of scientific assessments of alternative scenarios in the support of sulfur protocol negotiations of the Convention on LRTAP of the UN/ECE using the RAINS model (Hettelingh, 1996)

Scenario	Emission Reduction of 1980 levels (%)	Cost (Billion DM)	Ecosystem Protection against acidification (% ecosystem area)
60% Flat Rate	58	34	86
60% Gap Closure	59	26	93
Current Reduction Plans	29	15	78
Best Available Technology	83	82	97
Second Sulfur Protocol	53 (2000)	29	86 (2000) 90 (2010)

nitrogen deposition, air concentrations of SO_2, NO_x, O_3, and changes in temperature and precipitation are taken into account.

Cost Estimates for the Environmental Balance Sheets. The procedure for estimating the costs of end-of-pipe controls of sulfur dioxide, nitrogen oxides and secondary pollutants of tropospheric ozone formation is well established and included in the RAINS model (Amann *et al.* 1995). Less well-established is the procedure for computing the costs of controlling carbon dioxide and other greenhouse gases because only a small amount of these gases can be controlled by well-defined end-of-the-pipe measures. For example, most strategies for reducing carbon dioxide emissions focus on reducing fossil fuel use, the main source of carbon dioxide. In this project we will estimate the costs of reducing carbon dioxide emissions through energy strategies by using the IMAGE 2 model (Bollen *et al.* 1996).

Summary and Significance

The basis for another approach to the comparison of costs and ‘benefits’ of measures to mitigate climate change and air pollution has been developed. The environmental balance sheets are a ‘order of magnitude’ cost-benefit assessment that gives policymakers an overview of the risks of impact and of the costs to avert these risks. This approach extends the cost-benefit methodology available so far (e.g. cost-benefit analysis, cost-effectiveness analysis).

3 FRAMEWORK IMPLEMENTATION AND TESTING

3.1 Purpose of this Task

One objective of the reporting period was to set-up the integrated modeling framework and to test it with a scenario to identify possible problems. For that purpose a test scenario was defined featuring the Kyoto greenhouse gas reductions.

3.2 Significance to Policy and Science

Nowadays, the negotiation of climate change and air pollution policy relies heavily on the analysis of scenarios. The scenario analyses carried out in this task will be one of the first to provide integrated information on both environmental problems. This information will help to integrate the two issues in the policy process.

The cooling effect of sulfur aerosols on climate was one of the most important that changed the scientific assessment of global warming in the last decade. While this factor is now routinely included in scientific assessments, other aspects of the interaction of climate change and air pollution have not been closely studied. We expect that the scenario analyses carried out in the AIR-CLIM project will contribute to the scientific understanding of this interaction.

3.3 Analysis to Date

3.3.1 Test Scenario Definition and Emissions

One objective of the AIR-CLIM project is to derive reduction scenarios that consider reductions of both greenhouse gases and air pollutants. Leaving CO_2 disposal in the deep sea or in gas fields out of consideration, CO_2 emissions from energy production can only be reduced by consuming less energy and by shifting the energy mixes to energy sources that emit less CO_2. By comparison SO_2 has up to now been mostly abated by end-of-pipe technologies like flue gas desulfurization (FGD) although lower energy consumption and a shift to low SO_2 energy sources like gas or non-fossil sources also reduce SO_2 emissions. Therefore the policy scenarios investigated in the AIR-CLIM project focus on reducing CO_2 emissions by decreasing the amount or adapting the mix of fuels used. For the resulting energy profiles the ‘unmitigated’ SO_2 emissions, i.e. the emissions without any end-of-pipe measures, are calculated. As a final step, we assign end-of-pipe reductions to the unmitigated SO_2 emissions in order to achieve the desired level of SO_2 emissions.

In the Energy-Industry-System (EIS) submodel of IMAGE 2.1, the energy mix for electricity production is exogeneously set while the energy mix for heat production (including mechanical energy for industry and vehicles) is determined by market prices and technological constraints (Bollen *et al.* 1995). A first analysis indicated that a variation of the market prices in a reasonable range (up to factor 5) hardly affects the energy mix for heat production. As under these conditions it is difficult to derive an energy profile for a certain greenhouse gas emission pathway, it was decided to use the equivalent module of Version 2.2 of IMAGE, called TIMER, in the next phase of the project. TIMER provides fully developed price mechanisms for electricity and heat production and the price elasticities are further developed than in the EIS module (de Vries, van den Wijngaart 1995), (de Vries, Janssen 1996). While the globally aggregated version of TIMER has been introduced in 1995, the TIMER version disaggregated to 13 world regions was not finalized before the end of 1998. Therefore, for the test scenario the EIS submodel of IMAGE 2.1 was used.

Definition of test scenario

The *test scenario* is based on the Baseline A scenario calculated with the IMAGE 2.1 model. It consists of the development of population and GDP in 13 world regions up to 2100, energy consumption, energy profiles, land-use changes and the resulting emissions (Alcamo *et al.*

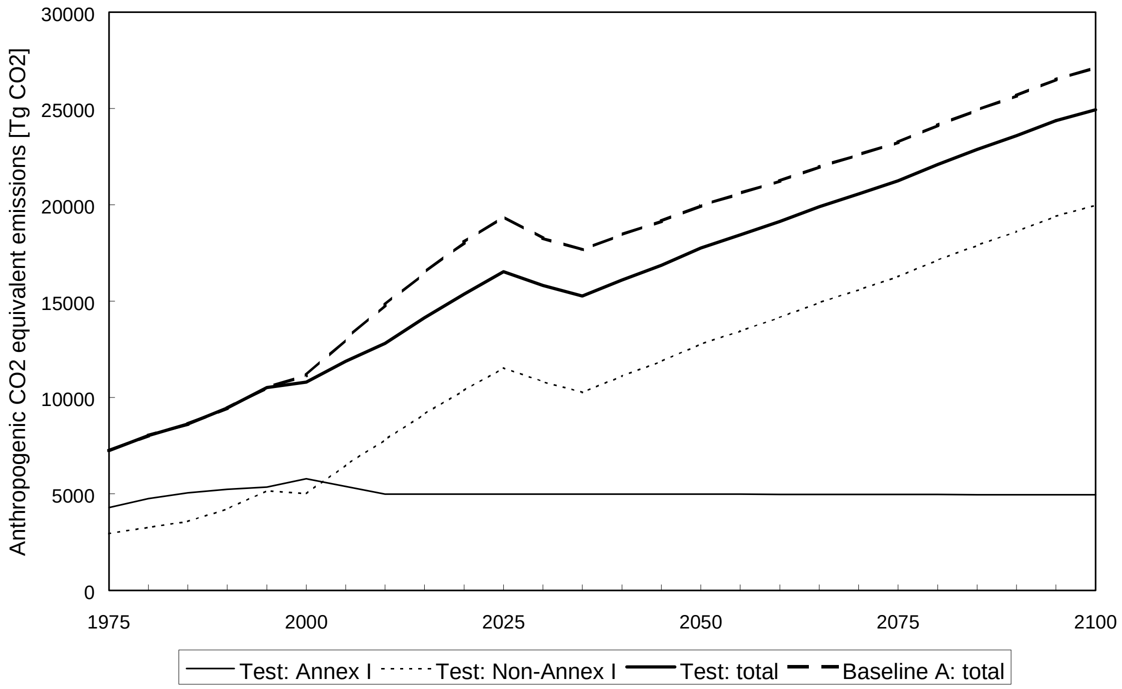


Figure 10 Anthropogenic CO_2 equivalent emissions [Tg CO_2] of the Test scenario compared to the Baseline A scenario

1996), and uses assumptions about population and economic growth that are consistent with the IS92a scenario of the IPCC (Leggett *et al.* 1992).

In the AIR-CLIM project the greenhouse gas emissions of this scenario have been adjusted so that the Kyoto Protocol objectives of reducing greenhouse gas emissions have been met. For the Annex I-countries (most industrialized countries) the Kyoto greenhouse gas reduction targets are applied in 2010. After 2010 it is assumed that the greenhouse gas emissions remain constant till 2100. For Non-Annex I-countries (most developing countries) emission levels are assumed to follow Baseline A for the whole time period under analysis (Figure 10).

The adjustments in the energy profiles and the land-use patterns that are needed to achieve these reductions are neglected. Thus, there are inconsistencies in the Annex I regions: (1) the SO_2 emissions are those of the Baseline A energy profiles; (2) the land-use emissions are reduced compared to Baseline A but the land-use distribution is still that of the Baseline A scenario.

SO_2 emissions

The SO_2 emissions of the IS92a scenario, and thus of the Baseline A scenario, have been criticized in the last years (Grübler, 1998) because:

- the 1990 base year estimates are outdated; and
- recent trends indicating significant sulfur emissions declines in Europe and substantial increases in Asia have not been included.

Thus, there is a need to improve the SO_2 emissions of the Baseline A scenario. Alcamo *et al.* (1999) have developed the so-called *Pollutant Burden Approach* (PBA) to generate SO_2 emissions for the 13 IMAGE world regions up to 2100. The PBA mainly focuses on the question, at what point in time will regions without any present SO_2 control begin these

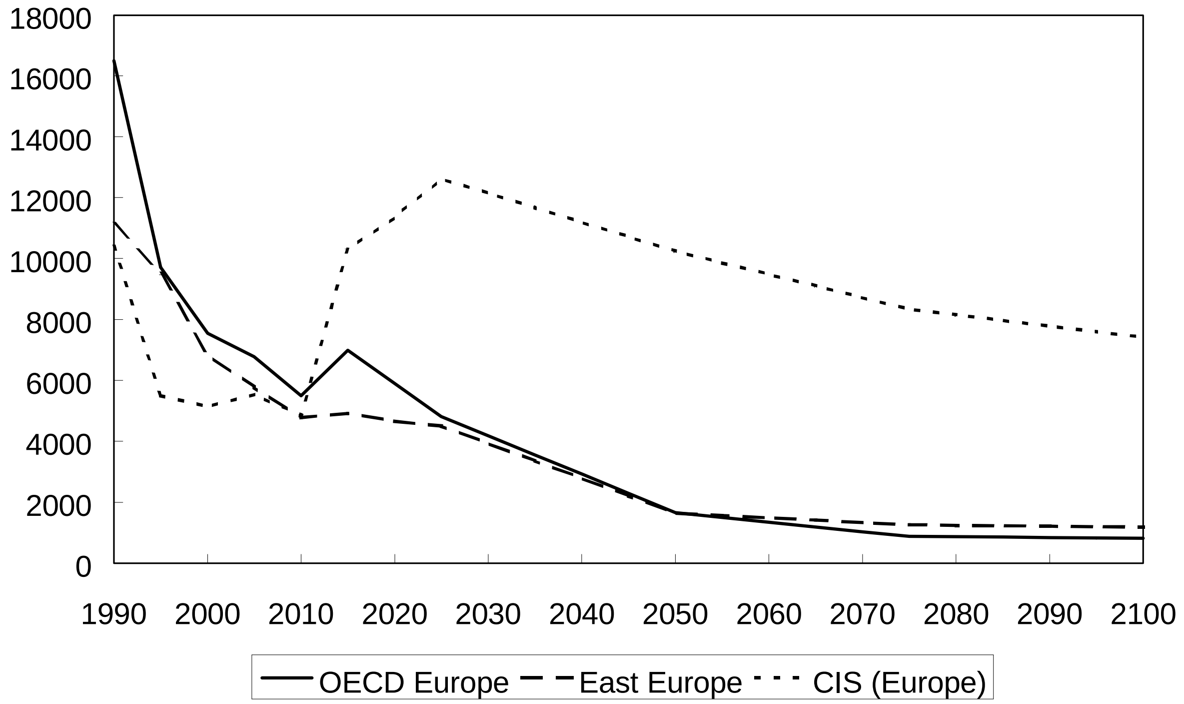


Figure 11 Anthropogenic SO_2 emissions [kt SO_2] of the Test scenario in the three European IMAGE regions. The sharp, but temporary decline in emissions in the CIS reflect assumptions about economic growth in this region.

controls? While for the industrialized regions it is assumed that the past trend on SO_2 control is continued, for non SO_2 control regions the PBA makes two basic assumptions:

(1) Developing regions are assumed to begin to reduce sulfur dioxide emissions when their 'pollutant burden' reaches the same magnitude as the pollutant burden of industrialized regions at the time when they began to reduce their emissions;

(2) Once emission reductions begin in developing regions, they are assumed to proceed at a pace similar to that observed in industrialized regions.

Instead of the original Baseline A SO_2 emissions, the emissions generated by applying the PBA to the Baseline A scenario have been used in this study. Figure 11 shows the resulting development of the SO_2 emissions in the three European IMAGE regions up to 2100. The time series for the European part of the CIS proves to be of special interest. Due to the economic breakdown in the early nineties the energy consumption decreased drastically and thus also the SO_2 emissions. According to the Baseline A scenario, the economy of the CIS will recover about 2010, leading to total SO_2 emissions above the level of 1990 despite a continuous increase of SO_2 reduction factors.

The case of the CIS is problematic. At least, two distinct assumptions are possible for these scenarios:

(1) The reduction factor increases following a logistic function, independent of the total 'unmitigated' emissions, which are determined by the energy consumption and supply. That is the assumption of the PBA. Such a development can be justified by autonomous technological improvement.

(2) The total of the SO_2 emissions of a region follows the past trend, independent of the economic development. In the case of the CIS, however, that would mean that after 2010

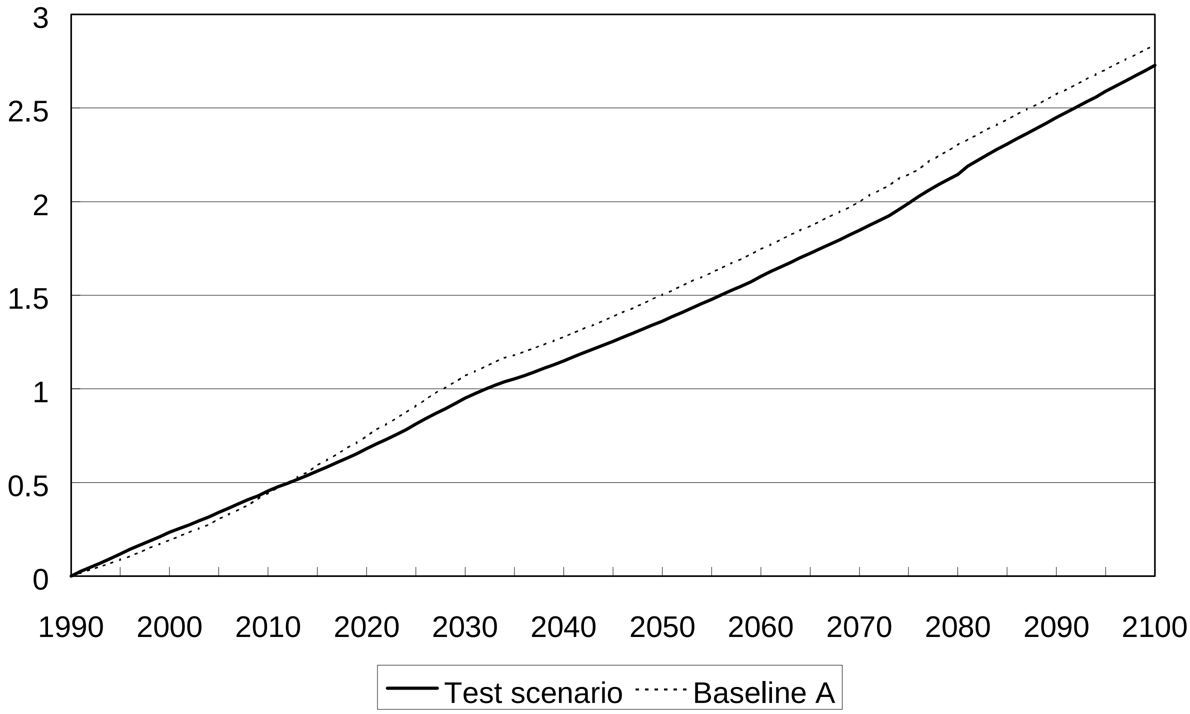


Figure 12 Global temperature change [°C] of Test scenario in comparison to Baseline A scenario

unrealistically high reduction factors would be needed to reach the low levels of emissions that would follow from this assumptions.

For future work it was decided to modify the approach for the CIS so that at least the 1990 levels of total SO_2 emissions are not exceeded after 2010.

Future work

In the second phase of the project it is planned to develop the final AIR-CLIM scenarios using TIMER. Thereby for SO_2 the Pollutant Burden Approach for SO_2 is used and the restrictions for the CIS are taken into account.

3.3.2 Calculated climate change

An IMAGE 2.1 run has been carried out for the Test scenario described above yielding temperature and precipitation changes on a 0.5x0.5° grid and land cover changes. According to the test scenario, the globally averaged temperature will rise till 2100 about 0.1°C less due to the Kyoto agreement than without it. The realized global temperature change in 2100 relative to 1990 will still be 2.7° (Figure 12). The AIR-CLIM test scenario shows an increase of the atmospheric CO_2 concentration from 354 ppm in 1990 up to 668 ppm in 2100.

In general, a relatively homogeneous temperature increase is calculated throughout the European continent (up to 5-7°C in 2100) while large differences are computed for precipitation. For example, Spain will become 35% dryer, while a 40% increase has been computed for Germany. Currently Spain is on average 5^{o}C warmer and about 20% dryer than

Table 7 Spatial average (avg.), minimum (min.), and maximum temperature (T) and precipitation (P) in Spain and Germany in 1990 and 2100. Numbers are annual results of the AIR-CLIM test scenario (T in °C, P in mm/a)

	Spain		Germany	
	1990	2100	1990	2100
T_{avg}	13.8	18.2	9.0	14.3
T_{min}	7.6	12.5	5.7	10.2
T_{max}	19.3	23.9	11.0	16.5
P_{avg}	650	427	814	1127
P_{min}	303	130	490	661
P_{max}	1974	1266	1749	2762

Germany. Spain also possesses a larger spatial variability, especially with respect to precipitation (Table 7**)**.

3.3.3 Change of Critical Loads in Europe under the 'Test Scenario'

Input data

In order to compute the critical load of acidity for European forest soils the following input data and parameters are needed (see Section 2.3.1): (a) base cation (and chloride) deposition, weathering and uptake and (b) climatic data such as temperature, precipitation and radiation to compute evapotranspiration and thus the amount of water percolating through the rootzone.

The base cation and chloride deposition was obtained by interpolating observations from about 100 background measuring stations in the network of the EMEP Chemical Coordination Center (at NILU in Norway, see Hjellbrekke *et al.* 1997) at each of the 0.5°×0.5° land-based grid cells covering Europe (including the European part of Russia). The method of interpolation is described in de Vries *et al.* (1994), but here we use more recent data and average them over the period 1991-95 to smooth inter-annual fluctuations:

- Base cation weathering rates are derived from soil texture and parent material classes assigned to the approx. 120 soil types of the FAO soil map (see UBA 1996, Appendix IV). The same methodology is for the background critical loads used in the negotiations under the LRTAP Convention (Posch *et al.* 1997).
- Base cation (and nitrogen) uptake is computed from (latitude dependent) element contents of the tree compartments and net forest growth, which in turn is estimated from site quality and climate region.
- Monthly temperature, precipitation and sunshine data produced by the IMAGE model, using the test scenario, for the reference years 1990, 2010, 2050 and 2100 are used to compute evapotranspiration. Actual evapotranspiration (AET) is computed with the same model as used in IMAGE (Prentice *et al.* 1993, Leemans and van den Born 1994), but for seven classes of soil water holding capacity in each grid cell, ranging from 50 to 250 mm/m.

Results

The above input data have been used to compute the critical loads of acidity, $CL_{max}(S)$, for each of the ca. 86,000 forest/soil combinations in about 4,500 grid cells covering Europe.

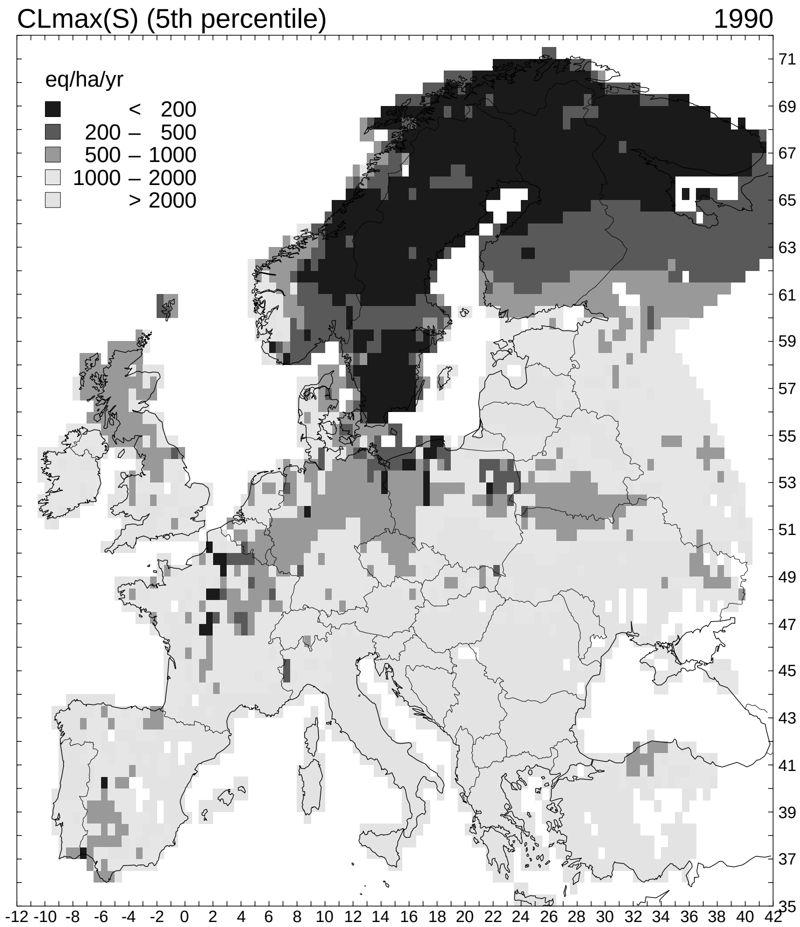


Figure 13 Map of the 5-th percentile of the distribution of acidity critical loads in each 0.5°x0.5° grid cell using present climate (1990). The map shows that the most sensitive forest soils are located in Northern Europe.

These forest/soil combinations were obtained by overlaying the latest version of the digital FAO soil map with a high-resolution forest cover map. This results in a (potentially) large number of critical load values within one grid cell. These values, together with the ecosystem area they represent, are used to construct the cumulative distribution function of critical loads within each grid cell. From this any desired statistical descriptor can be calculated and displayed. The map in Figure 13 displays the 5-th percentile of the critical load of acidity in each grid cell for the present (1990) climate. It clearly shows that the most sensitive forest soils are found in the Nordic countries.

Using the temperature and precipitation data from 2100 as a result of the ‘test scenario’, critical loads have also been computed using the climate dependence as described in section 2.2. In Figure 14 the resulting 5-th percentile critical loads are compared to the present critical loads. The map shows that under the computed changed climate of the test scenario the critical loads are higher than at present (1990) in most parts of Europe. This means that most vegetation areas would be less sensitive to acidic deposition than now. This can probably be explained by the increase in weathering due to higher temperatures. This weathering provides additional base cations for neutralizing acidic deposition. In a few regions, however, such as western Norway, Portugal or Albania, the critical loads are smaller than at present; and this is probably due to a decrease in percolation which offsets the increase in temperature. This means that in these regions forest soils become more sensitive, and thus require special attention when studying the impact of emission reduction scenarios.

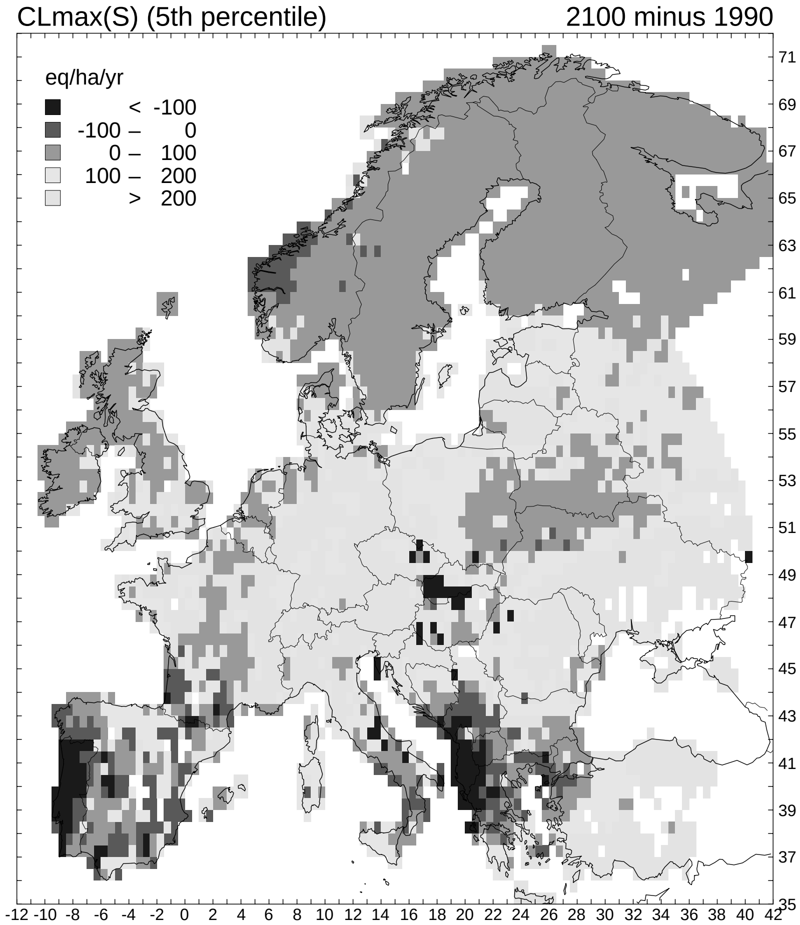


Figure 14 Map showing the differences between the 5-th percentile critical load of acidity using present day (1990) climate and changed climate in 2100 under the test scenario. Darker areas are more sensitive to acidic deposition

Future work

In addition to the further update of data bases and the comparison of various climate change scenarios we will concentrate on the following during the second phase of the project:

- Harmonize forest cover with IMAGE forest cover: The forest cover used for calculating critical loads will be compared with the much coarser forest cover (based on dominant land cover) used in the IMAGE model and harmonized where possible.
- Examine whether semi-natural vegetation can be included: It will be investigated how the methods for calculating critical loads can be extended to other semi-natural vegetation (e.g. heathlands).
- Examine how to take into account land cover and land use changes: Methods for incorporating land use changes as modeled by the IMAGE model will be developed.

3.3.4 Climate Impacts under the 'Test Scenario'

The consequences of the AIR-CLIM test scenario were evaluated by developing maps where specified climate thresholds were exceeded. A 20% loss of the potential wheat production and a 0% change in the potential distribution of natural ecosystem are selected as preliminary climate thresholds. We allowed no changes in ecosystem composition, which is consistent with the public policy to keep nature reserves in their current state.

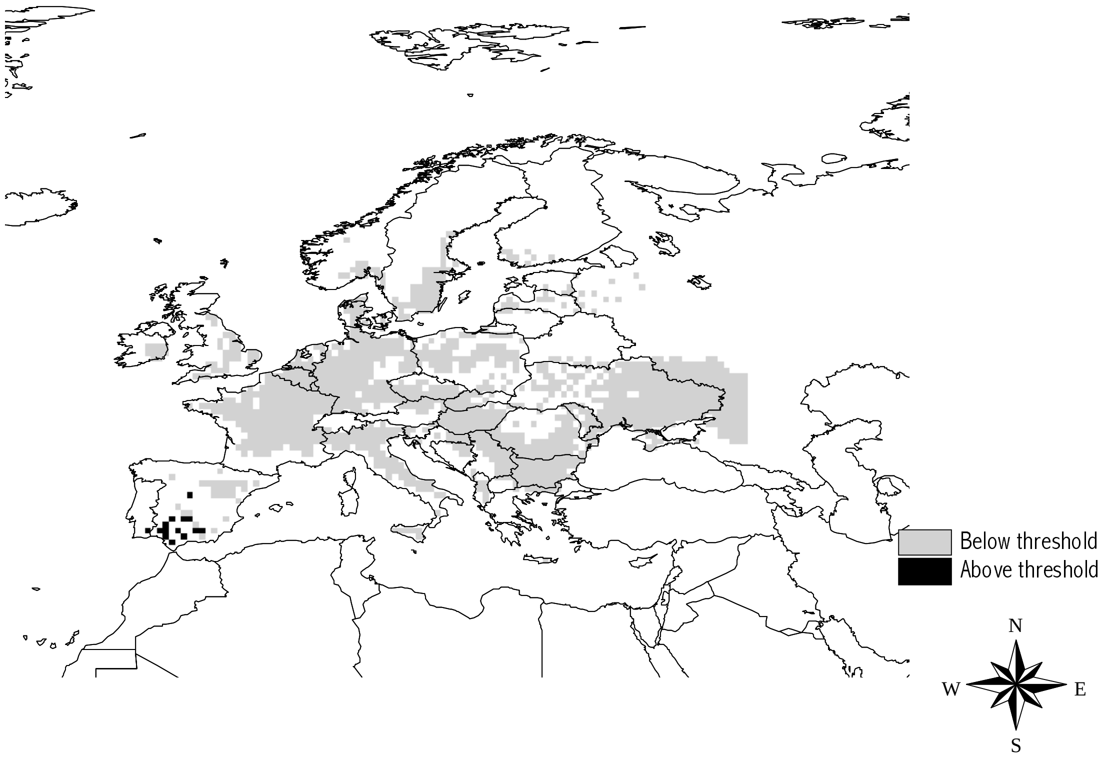


Figure 15 The exceedance in 2100 of the CIDs based on the criterion ‘20% loss of the potential wheat production’ under the test scenario

Agriculture

The large spatial variation of the precipitation pattern (Table 7) leads to a significant variation of potential wheat production in Europe. Severe potential production losses are computed in southern Europe (especially Spain, Portugal and western France). Small decreases (or even slight increases due to CO_2) are calculated in central Europe, while northern Europe becomes more productive. Exceedances of the specified 20% production loss are only computed in southern Spain, if the analysis restricts itself to the current wheat areas (rather than possible future areas) in Europe (Figure 15). Under the climatic changes, the production levels of wheat in these areas are diminished.

It is interesting to compare the sensitivities per country of the CIDACs derived in section 2.4 to the CID exceedances derived with CO_2 and climatic change under the AIR-CLIM test scenario. One should keep in mind that CIDACs represent country averaged sensitivities to changes in climatic conditions, while the exceedance maps demonstrate on a grid basis whether the CID (based on the criterion ‘20% production change’) is exceeded. Because of their aggregation, the CIDAC for wheat production in Spain does not show the large growth reduction as computed for the AIR-CLIM test scenario for southern Spain (Figure 15). On a country scale, the low production rates in southern Spain are (partly) compensated by a production increase in eastern Spain. In Germany a better agreement can be observed between the CIDACs and the exceedance map of the AIR-CLIM test scenario. This is, among others caused by the more homogeneous response of wheat to the changes in climatic conditions.

Table 8 Stable (unchanged) land cover in natural reserves area in 2100 under the AIR-CLIM scenario (compared to 1990 in %), taking into account transient conversions or not

	Entire Europe	Germany	Spain
transient conversions (i.e. incl. migration)	51	77	30
no transient conversions (i.e. excl. migration)	27	30	30

Natural ecosystems

For natural ecosystems three states are distinguished in the exceedance maps: (1) unchanged: the land cover type does not change and its productivity is not impaired, (2) changed: the land cover type changes under climate change, and (3) degraded: the land cover type does not change but its productivity is lower than the original state. To compute these states the sensitivity of natural ecosystems to growth and C dynamics is taken into account.

Figure 16 depicts the area with changed potential vegetation under the AIR-CLIM test scenario. We allowed no changes in ecosystem composition, considering the public policy to keep nature reserves in their current state. The analysis focused on current protected areas (about 13% of Europe according to (UNEP/GEMS 1993)). The diagrams demonstrate the impacts both for assuming instantaneous (Figure 16a) and transient (Figure 16b) land-cover conversions.

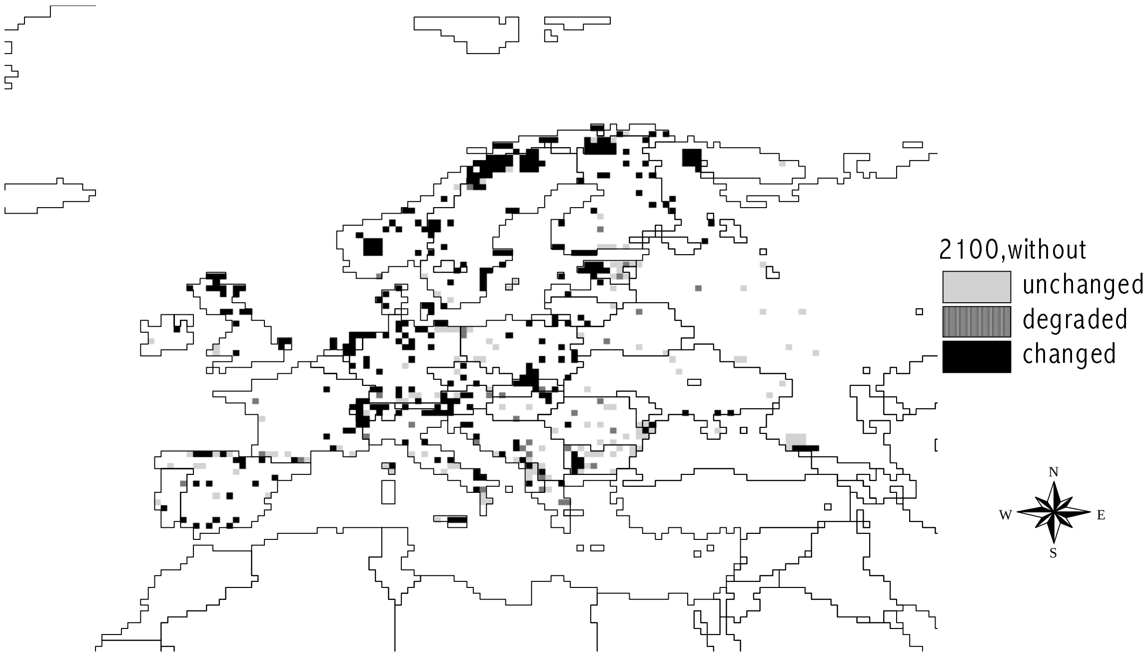
Examining Europe in total and assuming instantaneous land-cover conversions, about 30% of the natural reserves areas are stable, i.e. not degraded and/or replaced by another biome type (Table 8). As expected, the number increases up to 50% if vegetation migration is taken into account. Furthermore, we simulate large spatial differences throughout the continent (Figure 16, Table 8). For example, about 77% of the current area in Germany is stable when vegetation migration is taken into account. Under the same assumption, the impacts computed for Spain are more severe (only 30% are stable). However, assuming instantaneous conversion of vegetation instead, similar responses to the AIR-CLIM test scenario are calculated for Spain and Germany (about 30% of the potential ecosystems are stable). The difference between the two conversion assumptions is especially large in Germany, because the main land-cover conversions that will occur in Germany are between different forest types. Such transitions require decades, and will therefore only slowly occur if transient dynamics are included in an analysis.

Future work

The approach to assess impacts will be extended in the second phase of the AIR-CLIM project. In particular we will attempt to derive climate thresholds based on climate indicators other than change in temperature and precipitation. For example, Leemans and Hootsman (1997) propose the length of the growing period and temperature range exceedance as measures of climate thresholds. Another possible improvement of the approach consists of examining the importance of land-use changes and spatial dependence of conversions of natural ecosystems.

Another important activity in the second part of the project is the application of the climate threshold approach to quantify the consequences of the various AIR-CLIM scenarios.

a)



b)

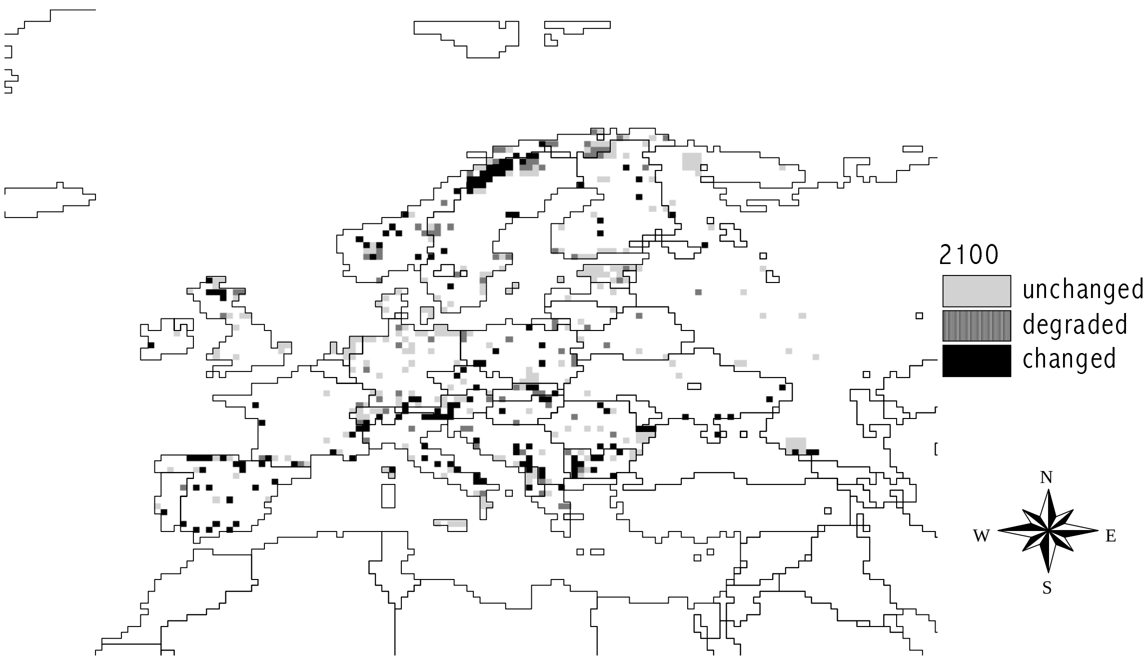


Figure 16 Potential changes in 2100 in the natural reserves areas under the AIR-CLIM test scenario (instantaneous [a] and transient [b] conversions in potential land cover)

3.4 Test Scenario Results and Their Significance

Test scenario development. The objective of the AIR-CLIM project is to derive reduction scenarios which consider reductions of both greenhouse gases and air pollutants. A first analysis showed that the Energy-Industry-System (EIS) module of IMAGE 2.1 is inadequate for this purpose. Thus, it was decided to use the equivalent module of Version 2.2 of IMAGE, called TIMER, in the future. TIMER provides fully developed price mechanisms for electricity and heat production and the price elasticities are further developed than in the EIS module. While the globally aggregated version of TIMER has been introduced in 1995, the TIMER version disaggregated to 13 world regions was not finalized before the end of 1998. Therefore, for the test scenario the EIS of IMAGE 2.1 was used.

The test scenario uses the IMAGE Baseline A scenario, which has similar driving forces to the IS92a scenario of the IPCC. The greenhouse gas emissions of this scenario have been adjusted so that the Kyoto Protocol objectives of reducing greenhouse gas emissions have been met. For the Annex I-countries (most industrialized countries) the Kyoto greenhouse gas reduction targets are applied in 2010. After 2010 it is assumed that the greenhouse gas emissions remain constant till 2100. For Non-Annex I-countries (most developing countries) emissions levels are assumed to follow Baseline A for the whole time period under analysis.

To compute SO_2 emissions, we have used the *Pollutant Burden Approach* (PBA). The PBA computes the point in time at that regions begin SO_2 controls, and at what rate these controls are implemented. For industrialized regions where controls have already begun, it is assumed that the past trend on SO_2 control is continued. CIS was identified as a problematic area with respect to the modeling of the future SO_2 emissions. Due to its economic breakdown in the early nineties, energy consumption decreased drastically and thus also the SO_2 emissions. According to the Baseline A scenario, the economy of the CIS will recover about 2010, leading (even with the PBA) to total SO_2 emissions above the level of 1990 despite a continuous increase of SO_2 reduction factors. This is an area that will be further analyzed in the future.

Calculated climate change. An IMAGE 2.1 run has been carried out for the test scenario described above yielding temperature and precipitation changes on a 0.5x0.5° grid and land cover changes. According to the test scenario, the globally averaged temperature will rise until 2100 about 0.1° less than without the Kyoto agreement. The realized global temperature change in 2100 relative to 1990 will still be 2.7°.

Impact of climate change on critical loads of acidity of forests in Europe. Critical loads have been computed using the results of the test scenario for temperature and precipitation data in 2100. A comparison of the resulting 5-th percentile critical loads to the present critical loads shows that under the changed climate the critical loads are higher than at present (1990) in most parts of Europe. This can probably be explained by the increase in weathering due to higher temperatures. In a few regions, however, - such as western Norway, Portugal or Albania - the critical loads are lower than at present; and this is probably due to a decrease in percolation which offsets the increase in temperature. This means that in these regions forest soils become more sensitive, and thus require special attention when studying the impact of emission reduction scenarios.

Impacts of climate change on agriculture/natural ecosystems in Europe. The consequences of the AIR-CLIM test scenario were evaluated by estimating where a 20% loss of the potential wheat production and a 0% change in the potential distribution of natural ecosystem occurred.

We allowed no changes in ecosystem composition, focusing on the public policy to keep nature reserves in their current state.

Sample results for Spain and Germany are presented. Large reduction in potential wheat production is computed in southern Europe (especially Spain, Portugal and western France). Small decreases (or even slight increases due to CO_2) are calculated in central Europe, while northern Europe becomes more productive. 20% production reductions are only computed in southern Spain, if the analysis restricts itself to the current wheat areas in Europe. Under the described climatic changes the production levels of wheat in these areas nearly diminish.

For natural ecosystems three states are distinguished in the exceedance maps: (1) unchanged: the land cover type does not change and its productivity is not impaired, (2) changed: the land cover type changes under climate change, and (3) degraded: the land cover type does not change but its productivity is lower than the original state. To compute these states the sensitivity of natural ecosystems to growth and C dynamics is taken into account.

About 30% of the natural reserves areas are stable, i.e. not degraded and/or replaced by another biome type. The number increases up to 50% if vegetation migration is taken into account. Then, for Germany about 77% of the current nature reserves area is stable, too. Under the same assumption, the impacts computed for Spain are more severe (only 30% are stable). However, assuming instantaneous conversion of vegetation instead, similar responses to the AIR-CLIM test scenario are calculated for Spain and Germany (about 30% of the potential ecosystems are stable). The difference between the two conversion assumptions is especially large in Germany, because the main land-cover conversions that will occur in Germany are between different forest types. Such transitions require decades, and will therefore only slowly occur if transient dynamics are included in an analysis.

Summing up. The scenario analyses carried out in this task is one of the first to provide integrated information on regional air pollution and climate change. This information gives a first indication how the two issues can be examined together instead of separately in the policy negotiation process that nowadays relies heavily on the analysis of scenarios. From the scientific perspective these preliminary results are among the first show the influence of climate change on air pollution and its impacts. It also provides new information about European areas vulnerable to climate change.

4 UNCERTAINTY ANALYSIS

The AIR-CLIM project aims to couple the many complex aspects of regional air pollution and climate change in Europe. In order to do this, we use the modeling framework of component models discussed earlier (see Chapter 2 of this report). An inescapable characteristic of models is that they are inexact approximations of reality. Hence, a key question in the AIR-CLIM Project and other model-based studies is, what is the extent of this uncertainty? Some information about uncertainty is needed in order to judge the worth of the information provided by the modeling framework.

To uncover this uncertainty in the AIR-CLIM Modeling Framework, a five-step uncertainty analysis as outlined in Alcamo and Bartnicki (1987) can be used:

1. *Problem formulation*, in which the time and space scales of the problem are established,
2. *Inventory of uncertainties*, to collect possible sources of error in a systematic fashion,
3. *Screening and ranking of uncertainties*, to set priorities for quantitative evaluations,

4. *Quantitative evaluation of uncertainties*, which draws on a variety of analytical techniques,
5. *Application to routine calculations*, in which information about model error is used to supplement routine calculations.

Before the end of the AIR-CLIM project, we expect to accomplish Steps 1 and 2, and to make preliminary estimates for Step 3. However, Steps 4 and 5 are not covered under the current AIR-CLIM project because they require a major research effort, which is outside the scope of the current project. Moreover, steps 4 and 5 can best be carried out after the AIR-CLIM modeling framework has been used for scenario analysis, and researchers gain experience with using its component models. In sections 4.1 and 4.2 we give some preliminary ideas about steps 1 and 2.

4.1 Uncertainty Problem Formulation

It is interesting but insufficient to ask, what is the uncertainty of the model? We must be more precise because the magnitude of uncertainty depends on the selected model variable and its time and space scales. One variable of particular interest is the "area of exceedance", i.e. the area over which regional air pollution and climate change exceed various "environmental thresholds"[4]. It is important because it is the common measure by which we compare the impacts of regional air pollution and climate change for various scenarios of emissions and emission control policies. Hence, the uncertainty analysis will give high priority to evaluating the uncertainty of the computed area of exceedance. To do so, we must also take into account the uncertainties of major variables that are used to compute the area of exceedance (see Figure 1). Consequently, the uncertainty of emission and deposition calculations will also be evaluated.

As to the scales of interest, the most relevant spatial scale is the area of exceedance for each European country and for Europe as-a-whole. These scales are relevant because they provide country-specific information needed by decision makers. The most relevant temporal scale is the annual average of exceedance. This scale corresponds to the annual time scale of emissions and deposition estimates. Regarding time horizon, information about exceedance is computed for the entire scenario period from 1995 to 2100.

4.2 Preliminary Inventory of Some Uncertainties

4.2.1 Introduction

The aim of this inventory is to make the analysis of uncertainty of the AIR-CLIM integrated framework more systematic. In this inventory we distinguish between five categories of uncertainties, as defined in Alcamo and Bartnicki (1987):

1. *Model structure* – Uncertainties related to the model's structure – i.e., the collection of all model parameters and forcing functions, and how they are related in model equations.
2. *Parameters* – Uncertainties related to model coefficients that are constant in time or space.
3. *Forcing functions* – Uncertainties related to coefficients that inherently change with time and space.
4. *Initial state* – Uncertainties that stem from boundary and initial conditions.

[4] As mentioned earlier, three environmental thresholds are considered – critical loads for air pollutant deposition, critical levels of air pollution concentration, and critical thresholds of climate change indicators

Table 9 Preliminary inventory of sources of uncertainties of critical load calculations

Type of Uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	Steady state assumption	Steady state assumption
Parameters	Coefficients for weathering and other soil processes	Coefficients for weathering and other soil processes
Forcing functions	Deposition of sulfur and nitrogen Current climate data	Deposition of sulfur and nitrogen
Initial state	Initial state of soil chemistry	Initial state of soil chemistry
Model operation	/	/

1. *Model operation* – Uncertainties that arise from the solution techniques of model equations, and pre- and post-processing of model information.

For each of these categories, a further distinction is made between diagnostic and prognostic uncertainty. Diagnostic uncertainty refers to the uncertainty in simulating past or current conditions with the modeling framework. Prognostic uncertainty refers to the uncertainty that arises when the framework is used for scenario analysis. Some types of uncertainties have both a diagnostic and prognostic component, whereas other types of uncertainty are only important for either the diagnostic or prognostic cases.

In the next sections we present preliminary inventories of two parts of the AIR-CLIM framework. The first inventory has to do with the calculation of area of exceedances, which we noted above is important output from the AIR-CLIM framework. For simplicity, we focus on one aspect of estimating areas of exceedance, namely the computation of critical loads.

The second inventory has to do with the calculation of emissions, which are used to compute deposition, which in turn are used to calculate area of exceedances as shown in Figure 1.

4.2.2 Inventory of Uncertainties of Critical Loads

Table 9 summarizes some of the uncertainties involved in estimating critical loads.

An important source of model uncertainty is the steady state assumption used to compute critical loads. Since the structure of the model is partly determined by this assumption, we call this a source of "model structure" uncertainty. Because ecosystems are seldom in steady state with the flux of acidifying substances, the steady state assumption adds a measure of uncertainty to the calculation of critical loads.

Specific parameters of the critical loads model represent different soil processes such as weathering and base cation leaching (see Section 2.3 of this report). The uncertainties of estimating these parameters adds uncertainty to critical load calculations. We call this "parameter" uncertainty.

The calculation of current critical loads depends especially on sulfur and nitrogen deposition and various climate variables. Neither deposition nor climate can be estimated exactly for all locations in Europe, and this inaccuracy is an important source of "forcing function" uncertainty.

Table 10 Preliminary inventory of sources of uncertainties of emission calculations

Type of Uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	Climate factors omitted	Climate factors omitted
Parameters	Emission factors	Emission factors
Forcing functions	Data about population, economic activity, and other driving forces of emissions	
Initial state	/	Base year emission estimate
Model operation	/	Scheme for allocating regional emissions to country-scale emissions.

An example of an "initial state" uncertainty is the initial state of soil chemistry which is used to estimate the acid-neutralizing capacity of soil moisture.

The solution techniques of the critical loads model ("model operation" uncertainty) is not thought to add a significant source of uncertainty to critical load calculations.

4.2.3 Inventory of Uncertainties of Emissions

Table 10 summarizes some of the key uncertainties involved in calculating emissions of sulfur dioxide, nitrogen dioxide, and ammonia in the AIR-CLIM Framework.

Emissions calculations are based on simple linear equations, that exclude the influence of climate and other factors that can sometimes have an important influence on emission rates. Omitting these factors is a type of "model structure" uncertainty.

The main parameters in emission equations are emission factors, and their uncertainty contributes to the uncertainty of emission estimates. This is an example of 'parameter' uncertainty.

To compute emissions we must estimate the driving forces that lead to emissions. Examples of these driving forces are the amount of energy consumed, number of vehicles driven, and number of livestock. The uncertainty of these driving forces contributes to the uncertainty of past and current emissions. We call this "forcing function" uncertainty. For scenario analysis of emissions, these driving forces are specified, and therefore do not contribute to the uncertainty of emission calculations.

In the AIR-CLIM modeling framework, equations for calculating future emissions are calibrated to current emission estimates. This means that the uncertainty of current emissions is a source of uncertainty in estimating future emissions. This is a type of "initial state" uncertainty.

Finally, various assumptions are made in order to convert emissions from the world-regional scale to the country-scale. The uncertainties of these assumptions contribute to the uncertainty of country-scale emission estimates. Since this conversion procedure involves the processing of data within the model, we call it a "model operation" source of uncertainty.

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