

The RAINS Model of Acidification Science and Strategies in Europe

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Foreword

Since the late 1960s Europe has been aware of a new threat to the environment: the effects of pollutants that have been transported over a long distance. Contrary to the situation in decades before the 1960s, when pollution had a predominantly local character, the current effects of our pollution are visible in areas far away from large emission sources.

As a consequence, international deliberations on coordinated policies started in the 1970s. At the UN Conference on the Human Environment in Stockholm (1972), many governments still continued to view acidification as a local, geographically limited problem concerning mainly Scandinavian and Canadian lake areas. However, at the end of the 1970s, the acid rain problem became recognized in Europe and North America as one of the most severe threats to the environment. On the occasion of a high-level meeting on environmental protection within the framework of the United Nations Economic Commission for Europe (ECE), the Convention on Long-Range Transboundary Air Pollution was adopted in Geneva on 13 November 1979. By the time the Convention entered into force on 16 March 1983, the parties were determined to put it to more than symbolic use. As a major effort they strengthened the Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP), which had been established in 1977 by ECE with support from the UN Environment Programme (UNEP) and in cooperation with the World Meteorological Organization (WMO).

A second major step to implement the Convention was the Protocol on the Reduction of Sulphur Emissions or Their Transboundary Fluxes by At Least 30 Percent adopted at Helsinki on 8 July 1985. The Protocol entered into force on 2 September 1987.

Another Protocol concerning the control of emissions of nitrogen oxides (or their transboundary fluxes) was signed in Sofia on 1 November 1988 by 25 countries in Europe and North America. The Protocol calls for a stabilization of the emissions of nitrogen oxides. At the same occasion, 12 countries signed a declaration on 30% reduction of nitrogen oxides emissions.

From the above very brief overview of major international activities it can be concluded that the abatement of effects of acid rain ranks high on the agenda of many European governments.

Parallel to these multinational activities, several countries established bilateral agreements on environmental protection. An example of such a collaboration is the Memorandum of Understanding between the governments of Poland and the Netherlands. A major result from this collaboration is the installation of an air pollution monitoring station in southwest Poland (Jelenia Góra region). The government of the Netherlands has contributed to the costs of the station, which will be connected to the computer at the National Institute of Public Health and Environmental Protection (RIVM) in the Netherlands. In that way the data produced by the monitoring station can be used in modeling exercises.

Modeling is the main theme of this book, which results from six years of research at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. Both the Netherlands and Poland participate in IIASA. Our countries have been particularly interested in the Acid Rain Project at IIASA since the beginning of the project in 1983. In Poland, the Institute for Meteorology and Water Management has been a major collaborator in the project, whereas in the Netherlands, several research institutes and the Ministry of Public Housing, Physical Planning, and the Environment took part in research and funding of the project.

We consider IIASA's Acid Rain Project as a major effort toward establishing science-based abatement strategies for acid rain in Europe. Its Regional Acidification Information and Simulation (RAINS) model's particular strength lies in the connection of data on energy use, long-range transport of pollutants, and effects of acidification on the environment. Furthermore, IIASA has succeeded in establishing a solid collaboration with the Economic Commission for Europe, which oversees the international deliberations on the reduction of acid rain. In this way, scientific results have been made available to policymakers in a very effective way.

We are convinced that the RAINS model is a credible tool for assisting in environmental policymaking, and we would like to compliment IIASA for producing it. We sincerely hope that results of the modeling work described in this volume will contribute to the efforts to reduce acidification in Europe.

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the Environment of the Netherlands

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July 1989

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The RAINS Model of Acidification

1. Introduction

Acidification in Europe may be viewed as a prototype in a new era of emerging environmental problems. These problems affect vast areas far from pollution sources, have no respect for national borders, and simultaneously degrade water, air, and soil. They resist easy solutions; they are difficult for scientists to comprehend, and for governments to act on. The gap between scientific results and governmental action is greater than ever.

Such problems require new tools. This book describes such a tool, a computer model called RAINS, which provides a scientific overview of acidification, and links the science with policies for controlling acidification. It is called the RAINS (Regional Acidification INFORMATION and Simulation) model because it has a *regional* scope, it assembles and integrates *information* necessary to understand the problem of acidification, and it uses computer *simulation* as a problem-solving approach. RAINS is a kind of *scenario-generating device* that allows its users to visualize the future impacts of current actions (or inaction), as well as to design a transition strategy toward long-term environmental goals. It can complement, but not substitute for our imagination.

Like all computer models, RAINS is a simplification of reality. Since it cannot cover all the scientific or policy aspects of the problem, it is essential to specify its limitations as we do later in this overview. It follows that the RAINS model should not be the only basis for selecting a strategy to control acidification. Limiting the scope of the model, however, allows us to quantify some important aspects of the acidification problem.

To make the model a more useful tool in decision making, we have given special attention to its flexibility and comprehensibility. It is designed to be operated interactively and to provide users with a wide range of options for building emission control scenarios, investigating optimization of emission reductions, and examining several different acidification impacts. The model was built stepwise in collaboration and consultation with both scientific experts and potential model users in the policymaking community.

RAINS has already been used by agencies in Finland, the Netherlands, Norway, and Sweden to investigate the effect of national and international emission control policies. It has also been used as the starting point for country-scale integrated models for Finland and Hungary, and parts of it have been used in the national acidification model of the German Democratic Republic. In addition, it provides a method for identifying research priorities and for assembling internationally comparable databases.

One of the principal motives for developing the RAINS model has been to provide scientific support for negotiations in Europe under the Geneva Convention on Transboundary Air Pollution in Europe. Negotiations are held within an Executive Body of this Convention. In commenting on the RAINS model, a task force of this Executive Body noted:

An integrated assessment model that can assist in cost-effectiveness analysis is now available... The Task Force ... recommends that the RAINS model be used by the Parties to the Convention, the Executive Body, and the various subsidiary bodies.

2. Scope and Overview of the RAINS Model

The RAINS model focuses primarily on acidification of Europe's environment and on the sulfur and nitrogen deposition that leads to acidification. However, the model also examines related problems such as the impact on forests of airborne SO_2 . The RAINS model is made up of a set of linked submodels which are depicted in *Figure 1* and which organize the information and computation into three main categories: pollution generation and control (including costs), atmospheric transport and deposition, and environmental impacts. Depending upon its role, each submodel is made up of data bases (for example, energy use and pollutant emissions) and mathematical equations describing a process of interest, such as soil acidification.

Since our principal aim is to provide a temporal-spatial overview of acidification in Europe, the time and space scales of RAINS are accordingly

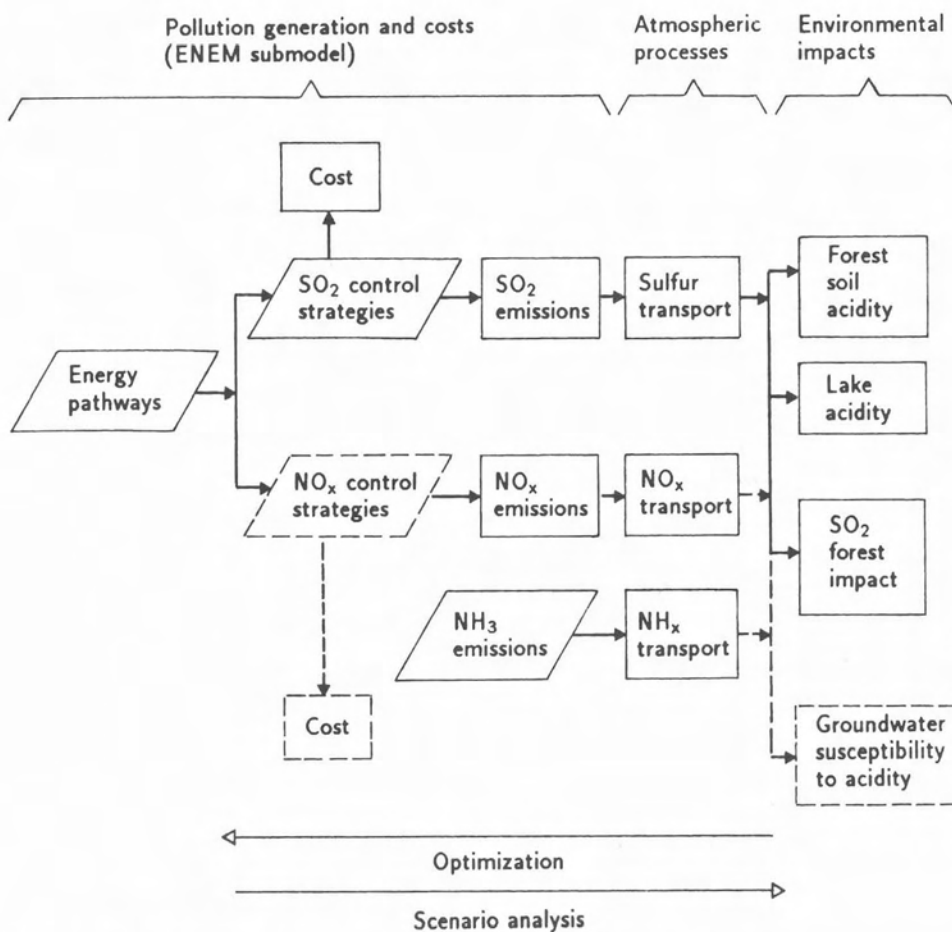


Figure 1. Schematic diagram of the RAINS model.

large. The model covers all of Europe, including the European part of the USSR, with a resolution of $150 \text{ km} \times 150 \text{ km}$ for emissions and atmospheric processes, and 0.5° latitude \times 1.0° longitude for environmental impacts. Simulations extend back to 1960 for historical perspective, and forward to 2040 to ensure that long-term consequences of different control policies are adequately taken into account. Because of the large spatial coverage and time horizon, the time step of calculations must be rather large (seasonal or annual).

The RAINS Submodels

Pollutant emissions and costs. The calculations of emissions and costs in RAINS are performed by a submodel called ENEM. ENEM calculates country-scale emissions of SO₂ and NO_x for 27 of the largest European countries. SO₂ emissions are computed by mass balance using data on the energy consumed in several sectors in each country (such as power plants and industry), together with information about the sulfur content of fuel, its heat value, and the amount of sulfur in fuel retained in combustion ash. NO_x emissions are based on the same energy database, but fuel and sector-specific emission factors are used rather than fuel characteristics.

Reference energy data for 1960–2000 are taken from UN statistics provided by the Economic Commission for Europe. Users of RAINS will have the option to input interactively their own energy projections for one or several countries to assess the effect on emissions and environmental impacts of drastically changed fuel mixes.

There are basically four ways to reduce sulfur emissions originating from energy combustion: (1) energy conservation, (2) fuel substitution, (3) use of low-sulfur fuels, and (4) desulfurization during or after fuel combustion. For options (2) to (4) RAINS contains a formal procedure to estimate potential reductions and costs of application. Costs of energy conservation strategies are not yet included in RAINS because adequate data are not currently available for most countries.

Cost estimates for implementing emission reductions take into account country- and sector-specific factors such as labor costs. Much of the information on costs was taken from power plants in the Federal Republic of Germany and from international organizations, such as the Organisation for Economic Co-operation and Development, and the UN Economic Commission for Europe. The resulting national cost curves for emission reductions incorporate the most important factors influencing costs in an internationally comparable way.

Atmospheric transport and deposition. The atmospheric transport models compute how emissions are redistributed throughout Europe as sulfur and nitrogen deposition. For sulfur deposition calculations, RAINS uses a transfer matrix that expresses the relationship between country emissions and local deposition. This transfer matrix is based on the EMEP (Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe) long-range transport model of sulfur in Europe,

and incorporates the effects of winds, precipitation, and other meteorological and chemical variables on sulfur deposition and SO_2 air concentration.

Nitrogen deposition calculations are based on transfer matrices of oxidized nitrogen (NO_x) and ammonia–ammonium nitrogen (NH_x). Results from these matrices are summed to obtain total ($\text{NO}_x + \text{NH}_x$) nitrogen deposition. The NO_x transfer matrix is based on a linearized version of a long-range transport model with nonlinear chemistry. The nonlinear model was developed at Harwell Laboratories in the United Kingdom, and its linearized version was developed at IIASA. The NH_x transfer matrix is derived from a model developed at the Institute of Meteorology and Oceanography, University of Utrecht in the Netherlands, that describes the long-range transport of ammonia–ammonium in Europe.

Future versions of RAINS will also include NO_x and NH_x transfer matrices based on the EMEP nitrogen model of Europe.

Soil acidification. The RAINS soil model focuses on year-to-year development of soil acidification owing to sulfur deposition. In a new version of this model, nitrogen will also be included. The model specifically computes acidification in *forest* soils; some factors that may influence acidification in agricultural and other soils are not included. The possible impact of soil acidification on forest health is assessed by setting a simple threshold of pH or base saturation where this risk is assumed to occur. Soil acidity is computed in an idealized 50-cm deep soil layer by taking into account *acid load* (i.e., acid flux) to the soil and the soil's buffering characteristics. The computation of acid load assumes that all sulfur deposition contributes to acidity, that deposition is filtered by forest foliage, and that some acid deposition is neutralized by the deposition of base cations, such as magnesium and calcium.

Buffering characteristics of soil are divided into *buffer capacity*, the total reservoir of buffering compounds in soil, and *buffer rate*, the maximum potential rate of the reaction between buffering compounds and acid load. In some cases, even though buffer capacity is high, a low rate of buffering may nevertheless limit the ability of soil to neutralize the acid load. Both buffering characteristics reflect intrinsic properties of soil such as lime content, silicate weathering rate, cation exchange capacity, and base saturation.

To compute soil acidity, the model compares the cumulative acid load with the buffer capacity and the rate of acid loading with the buffer rate.

Lake acidification. The RAINS lake submodel provides a quantitative overview of key lake acidification processes. It computes the percentage of lakes in lake regions that are in specified pH and alkalinity classes. Only Fennoscandia (Finland, Norway, and Sweden) is covered by the model because comprehensive data were unavailable for other large European regions. Moreover, Fennoscandia is among the areas most susceptible to lake acidification in Europe. For the purpose of this study, the entire area of Fennoscandia was divided into 14 lake regions.

As a first step in model calculations, annual sulfur deposition computed by the air pollutant transport model is transformed into acid load to various sectors of the catchment. To simulate flows within the catchment, the terrestrial catchment is vertically segmented into two soil layers (A and B reservoirs). Precipitation is routed into quickflow, baseflow, and percolation between soil layers. The B reservoir in the model provides the baseflow, which presumably comes largely from deeper (> 0.5 m) soil layers. The computation of flows is based on rates of precipitation and evapotranspiration, together with catchment characteristics such as soil depth, surface slope, and hydraulic conductivity.

To compute the ion concentrations of the internal flows, the same analytical approach is applied as in the RAINS soil acidification model. The leaching of acidity to surface waters is simulated on the basis of simulated hydrogen ion concentrations in the soil solution and the discharges from both reservoirs.

The change in lake water chemistry is predicted by titration of the base content of the lake, total alkalinity, with strong acid originating from the atmospheric acid load.

The approach for assessing regional lake impacts has two distinct spatial levels. On the first level, a catchment model analyzes changes over time in the chemistry of any single lake. On the second level, the catchment model is regionalized by expanding the set of parameters to include characteristics of a large number of lakes within a particular region.

Groundwater sensitivity to acidification. Although the hydrological and geochemical mechanisms behind groundwater acidification are qualitatively well known, it is difficult to quantify the relevant processes and flow patterns on a regional scale. Hence, we have chosen a non-modeling approach to this analysis and have implemented a groundwater *sensitivity mapping system*, which produces European maps of aquifer susceptibility to acidification.

Various factors important to groundwater acidification, such as soil type and mineral composition, are compiled on a European grid. Using weighting factors, the susceptibility and risk of acidification of groundwater at different locations can then be evaluated.

SO₂ forest impact. RAINS examines two types of air pollution impacts on forests. The first type, the indirect impact of soil acidification on forest health, has been mentioned above. The second type is the direct effect on trees of exposure to gaseous SO₂. This is taken into account by the SO₂ forest impact model. The effects on forests of other air pollutants such as ozone and heavy metals are not examined, principally because RAINS does not yet have the capability to compute the long-term atmospheric levels of these pollutants on a European scale.

The SO₂ forest impact model is based on empirical data of forest dieback from Czechoslovakia's Erzgebirge Mountain region. The main input to this model is annual average SO₂ air concentration, as computed by the sulfur transport model. The principal output is the accumulated dose of SO₂ to trees, which is a simple computation of concentration multiplied by exposure time. Dose accumulates if a threshold SO₂ concentration is exceeded; damage to trees is assumed to occur if the accumulated dose exceeds a threshold level, which depends strongly upon climate.

Climate stress is known to increase the susceptibility of trees to air pollutant damage and is therefore taken into account in the SO₂ forest impact model. Temperature is used in the model as an indicator of climate stress; in general, the colder the temperature, the greater the stress on trees. Threshold levels and doses are decreased in the model as climate stress increases, making the trees more susceptible to lower concentrations of SO₂. This method provides a consistent way to take into account the different levels of climatic stress experienced by trees at different elevations and latitudes in Europe.

Using the RAINS Model

There are two basic ways of using the model: scenario analysis and optimization analysis. To conduct scenario analysis the user essentially moves from left to right through the model as depicted in *Figure 1*. A user first specifies an energy pathway and a control strategy. The implications of these inputs can then be examined. The user has the option of examining output from any of the submodels, e.g., sulfur emissions in a particular country or

group of countries, costs of sulfur control on a country basis, sulfur deposition or SO₂ concentration at different locations in Europe or mapped for all Europe, maps or time history of soil acidification, lake acidification, or risk to forest area from exposure to SO₂. Since this is an iterative process, the user normally examines this output and based on subjective evaluation selects an alternative control strategy for comparison.

In optimization analysis, the user in a sense inverts the scenario analysis procedure by starting with goals of environmental protection and/or economic constraints and having the model work “backward” to determine a country-by-country strategy for reducing sulfur emissions in Europe to accomplish these goals. The RAINS optimization analysis uses a single objective, linear programming approach and can accomplish the following tasks:

- Given a fixed upper limit on expenditures for emission control, the RAINS model can determine where the most sulfur can be removed from emissions.
- Given an environmental target (sulfur concentration or deposition) in a specified region of Europe, the model can determine where the minimum amount of emissions should be removed to meet that target.
- Given an environmental target, the model can determine where emissions should be reduced to minimize the cost of removal and still meet the target.

3. Selected Policy-Related Findings from Using the RAINS Model

Selected main findings from applying the RAINS model to several policy-related questions can be summarized in six main points found in *Table 1*. More detailed results are shown in *Table 2* and in *Figures 2 to 8*.

(1) *Doing What is Planned is Not Enough*

As of the writing of this book, 16 countries had signed the 1985 Helsinki Protocol for reducing SO₂ emissions, and 25 countries the 1988 Sofia Protocol on NO_x emissions. Officials involved with these agreements view these emission reductions as only interim steps to be taken until larger reductions can be agreed upon. Indeed, many countries have already announced plans to reduce emissions beyond what is required by these protocols. We have

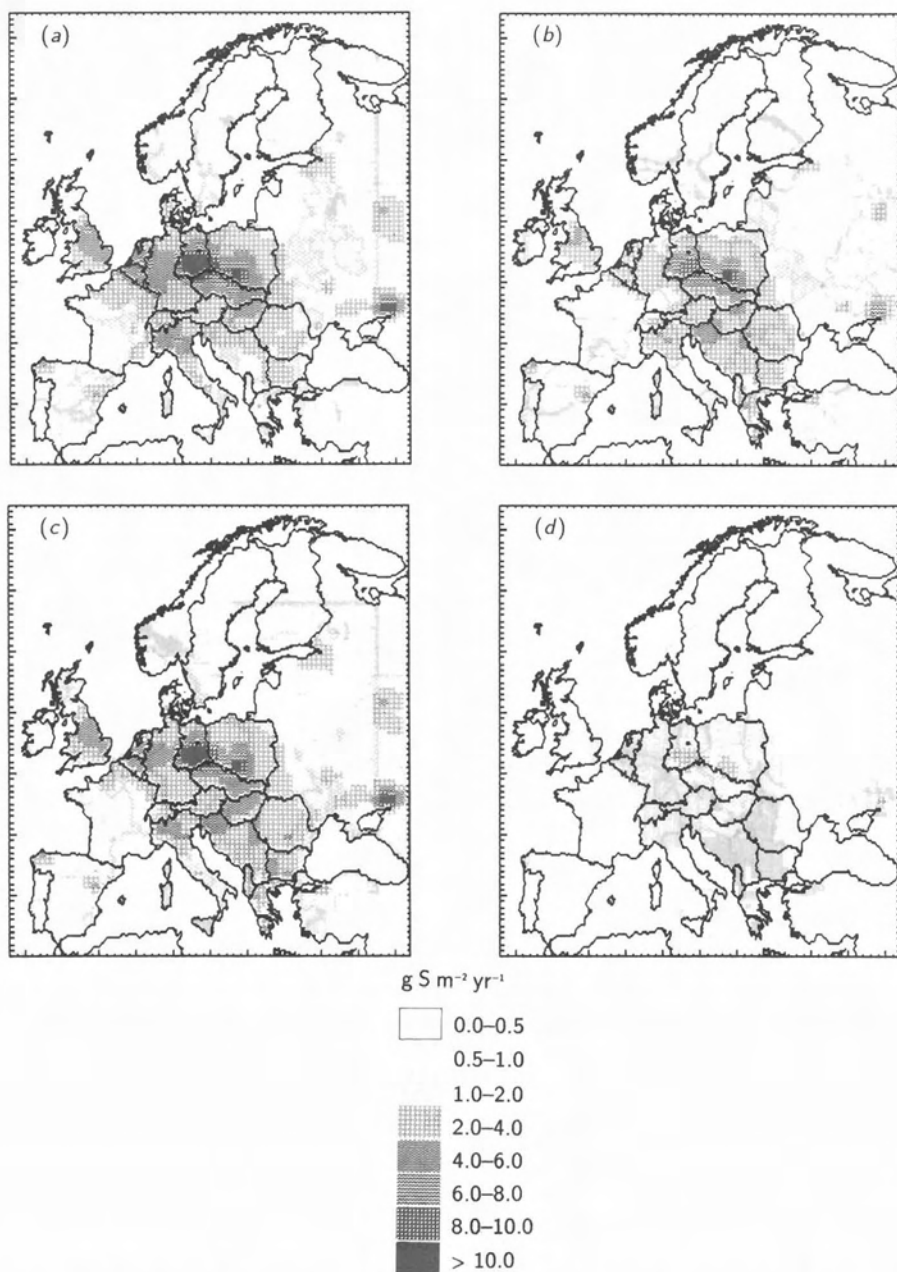


Figure 2. RAINS-generated maps of S deposition for the following scenarios and years: (a) 1980, (b) year 2000 using Current Reduction Plans (CRP) scenario, (c) year 2000 using No Controls scenario, and (d) year 2000 using Best Available Technology (BAT) scenario.

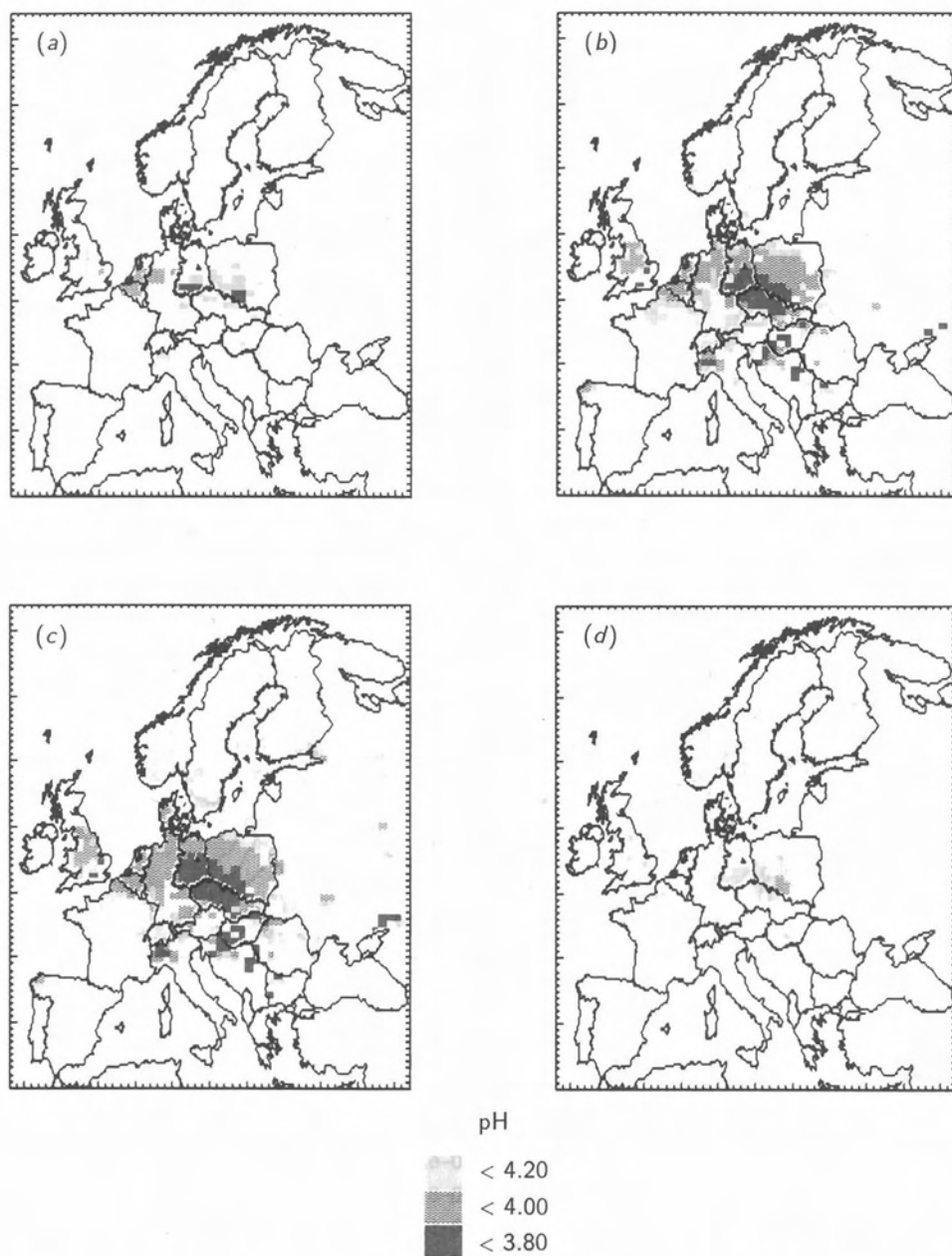


Figure 3. RAINS-generated maps of calculated soil pH in Europe for the following scenarios and years: (a) 1980; (b) Current Reduction Plans, 2040; (c) No Controls, 2040; and (d) Best Available Technology, 2040.

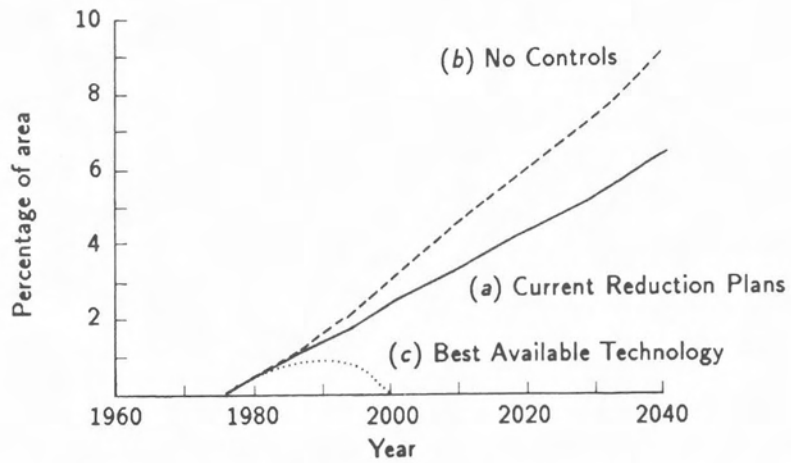


Figure 4. Time trends of percentage area of forest soil in Europe with $\text{pH} < 4.0$ for the following scenarios: (a) Current Reduction Plans; (b) No Controls; and (c) Best Available Technology.

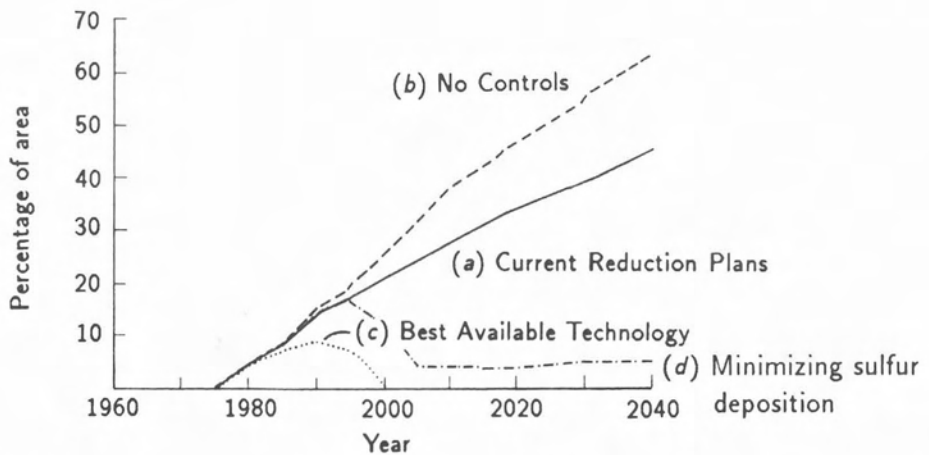


Figure 5. Time trend of percentage area of forest soil in Central Europe with $\text{pH} < 4.0$ for the following scenarios: (a) Current Reduction Plans; (b) No Controls; (c) Best Available Technology; and (d) minimizing sulfur deposition in Europe using the presently committed funds.

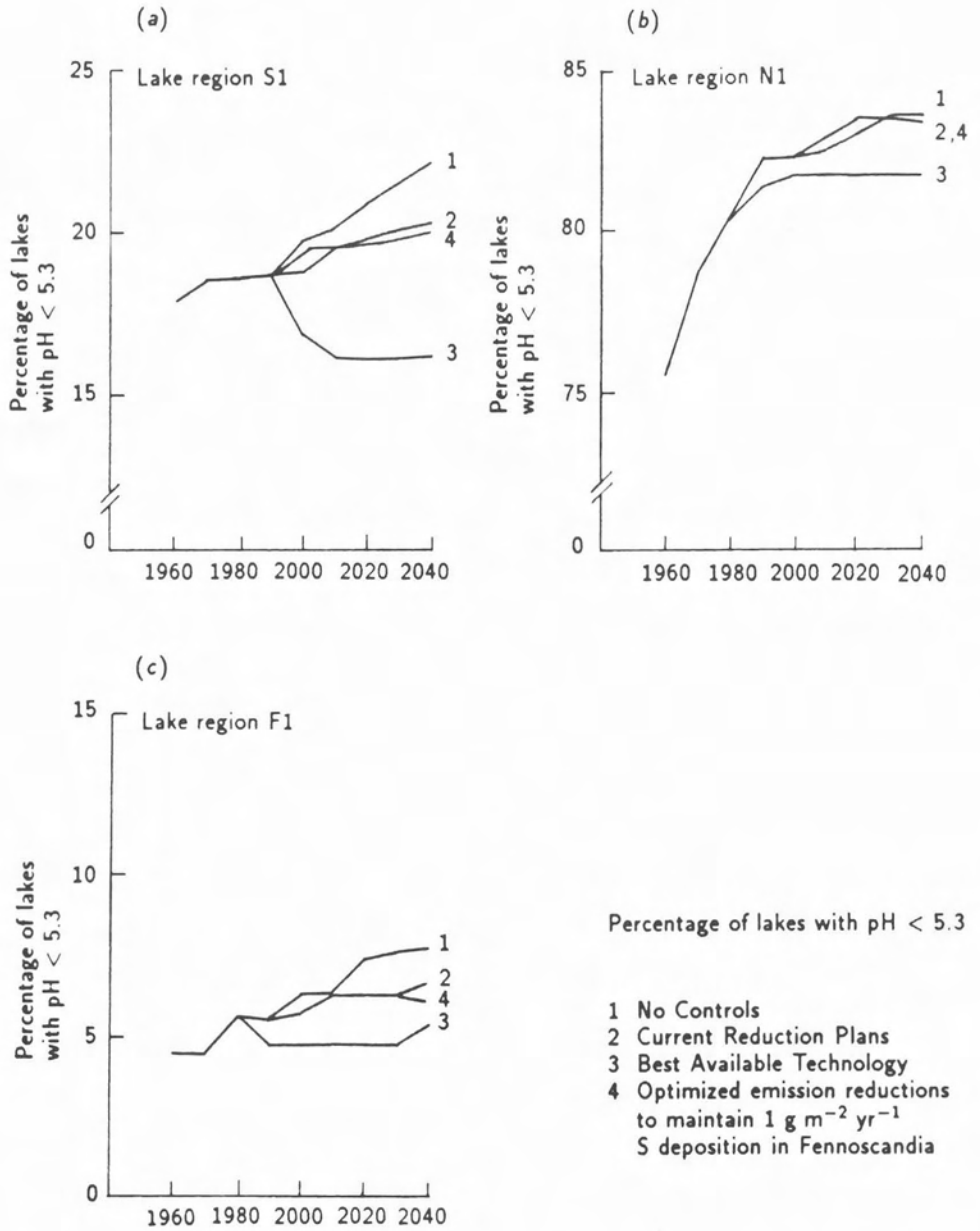


Figure 6. Time trend of percentage of lakes with pH < 5.3 resulting from various emission scenarios. (a) Southern Sweden; (b) Southern Norway; (c) Southern Finland.

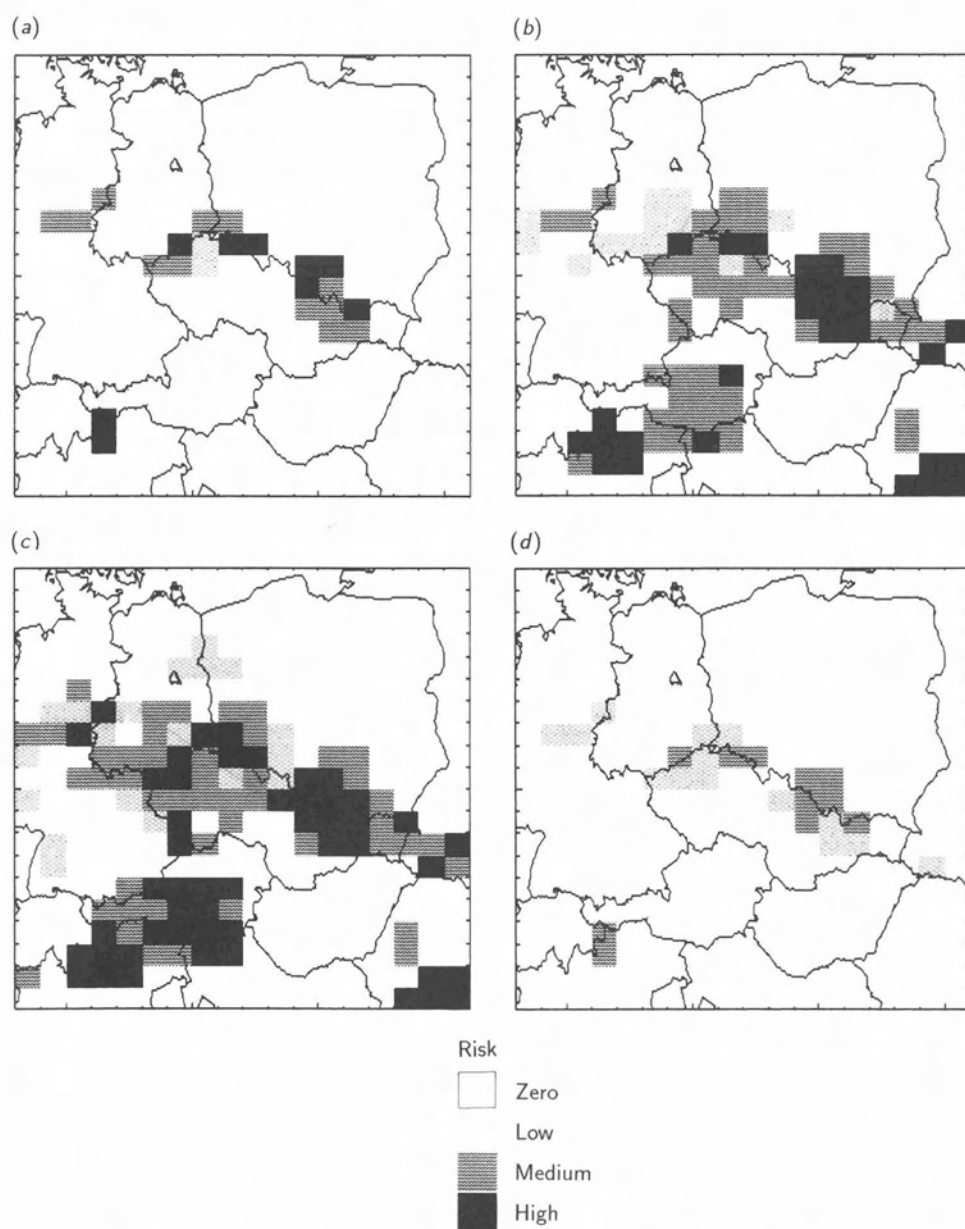


Figure 7. RAINS-generated maps of calculated SO₂ risk to forests in Central Europe for the following scenarios and years: (a) 1980; (b) Current Reduction Plans, 2040; (c) No Controls, 2040; and (d) Best Available Technology, 2040.

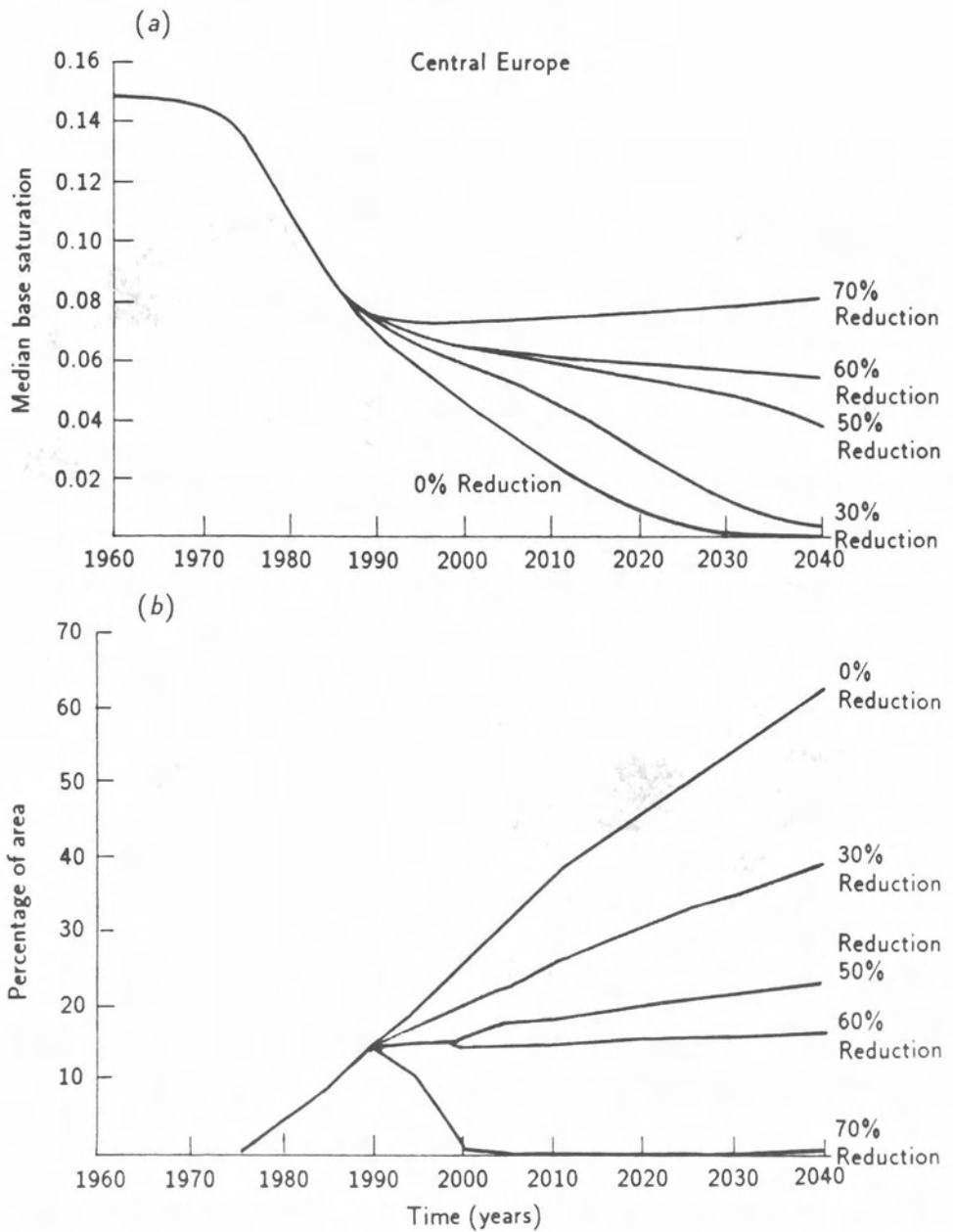


Figure 8. Time trend of soil acidification in Central Europe for specified uniform reductions in sulfur deposition relative to 1980. (a) Median base saturation in forest soils; (b) percentage of area of forest soils with pH < 4.0.

Table 1. The main policy-related findings in this book.

(1)	Doing what is planned is not enough.
(2)	However, the planned reductions are better than doing nothing.
(3)	Doing our best would be worthwhile.
(4)	But the best will be expensive.
(5)	Cooperation saves effort and money.
(6)	If you're not sure about points (1) to (5), use the RAINS model yourself.

examined the environmental consequences of these protocols, including the additional reductions currently pledged by European nations. Results for this scenario, which we call *Current Reduction Plans*, are summarized in *Table 2* and include the following:

- Current plans by various countries to reduce SO₂ emissions will result in a total European emission reduction by the year 2000 of 18% relative to 1980 levels. SO₂ emissions will be 31% lower in Central Europe (i.e., Austria, Czechoslovakia, the Federal Republic of Germany, the German Democratic Republic, Hungary, and Poland) and 56% lower in Fennoscandia (Finland, Sweden, and Norway).
- Current plans to reduce NO_x emissions will result in an overall decrease in Europe of only about 5% relative to 1980, with a 16% decrease in Central Europe and 30% decrease in Fennoscandia.
- Maximum sulfur deposition levels in year 2000 will reach about 7.5 g S m⁻² yr⁻¹ in Central Europe compared with more than 10.0 g S m⁻² yr⁻¹ in 1980 (*Figures 2a* and *2b*). About 53% of Europe's total area will have deposition greater than 1.0 g S m⁻² yr⁻¹ as compared with 62% in 1980. A sulfur deposition level of 1.0 g S m⁻² yr⁻¹ is a representative critical load for protecting sensitive ecosystems recommended by a Working Group of the Economic Commission for Europe and the Nordic Council. Their actual recommendations ranged from about 0.2 to 2.0 g S m⁻² yr⁻¹ depending on the ecosystem and its sensitivity.
- The area of Europe with nitrogen deposition greater than 1.0 g N m⁻² yr⁻¹ is 51% in year 2000. As with sulfur, a nitrogen deposition level of 1.0 g N m⁻² yr⁻¹ is also a representative critical load. The ECE-Nordic Council committee recommended limits between about 0.2 and 2.0 g N m⁻² yr⁻¹ to protect sensitive ecosystems from excess nitrogen. These levels will be exceeded unless ammonia emissions are controlled

Table 2. Selected results of scenarios.

Item	Scenario			
	1980	Current Reduction Plans ^a	No Controls ^a	Best Available Technology ^c
Total SO ₂ emissions in Europe (MT yr ⁻¹ as SO ₂)	54.2	44.6	55.0	10.0
Total annual cost of controlling SO ₂ emissions in Europe (DM billion)	-	12	0	83
Total NO _x emissions in Europe (MT yr ⁻¹ as NO ₂)	24.2	22.9	31.6	10.8
Percentage of land area in Europe with S deposition > 1 g S m ⁻² yr ⁻¹	62	53	62	5
Percentage of land area in Europe with N deposition > 1 g N m ⁻² yr ⁻¹	52 ^c	51 ^c	55 ^c	41 ^c
Percentage of Central European forest soils with pH < 4	5	20 ^a	25 ^a	0 ^a
Percentage of lakes in southernmost Fennoscandia with pH < 5.3	<i>Finland</i>	45 ^b	65 ^b	0 ^b
	<i>Sweden</i>	7 ^b	8 ^b	5 ^b
	<i>Norway</i>	18	20 ^b	16 ^b
European forest areas under risk from exposure to airborne SO ₂	75	83 ^b	83 ^b	81 ^b
	Limited mountain areas of Czech. FRG, GDR, Pol.	Large areas of Austria and Czech. Parts of FRG, GDR, Italy, Poland, Romania ^b		Similar to 1980 ^b

^aYear 2000, unless specified otherwise. Emissions, and therefore deposition, are assumed to remain constant between 2000 and 2040 at their year 2000 values.

^bYear 2040.

^cIncludes ammonia/ammonium deposition.

in addition to NO_x emissions. This applies to all scenarios including the most stringent, i.e., *Best Available Technology*.

- The area of Europe with forest soil $\text{pH} < 4.0$ was about 1% in 1980, doubles in size by the year 2000, and reaches 6% in year 2040 (*Figures 3 and 4*). Soil acidification is thought to pose a risk to forests when pH is < 4.0 . The area of heavily impacted Central Europe (with forest soil $\text{pH} < 4.0$) was 5% in 1980 and increases to 20% in 2000 and 45% in 2040 (*Figure 5*).
- The mean base saturation in heavily impacted Central Europe declines from about 0.10 in 1980 to half that value in year 2000, and approaches zero by the year 2040. Base saturation can take values from zero to one, and it is a general measure of the soil's ability to neutralize acids; its decline indicates the advance of soil acidification.
- In most regions of Fennoscandia, the percentage of lakes with $\text{pH} < 5.3$ continues to increase. A lake $\text{pH} < 5.3$ indicates that alkalinity is not available in a lake to neutralize acidity. In the southernmost lake region of Sweden, the percentage of lakes in this category hardly increases; however, in the southernmost Norwegian and Finnish lake regions the number of acidified lakes increases by several percentage points (*Figure 6*). These increases would represent hundreds of additional strongly acidified lakes.
- The forest area at risk due to exposure to gaseous SO_2 expands from relatively small mountainous regions of Central Europe in 1980 to large areas of Austria and Czechoslovakia, and parts of the German Democratic Republic, Federal Republic of Germany, Italy, Romania, and Poland in 2040 (*Figures 7a and 7b*).

We conclude from the preceding calculations that current reduction plans will be insufficient to halt the progression of acidification and its impacts in Europe. Furthermore, these impacts are likely to increase substantially in scope and severity into the next century. Our calculations show that acidification-related problems may only appear after the year 2000 in many areas. Hence, it is crucial to take long-term environmental consequences (on the order of several decades) into account when assessing the effectiveness of an emissions reduction plan.

(2) *However, the Planned Reductions Are Better Than Doing Nothing*

Despite the rather unpleasant picture painted above, we should compare the effect of Current Reduction Plans with the alternative of doing nothing. This scenario, which we term *No Controls*, assumes that nations will consume energy according to the official predictions compiled by the ECE, and that the SO₂ and NO_x emissions produced by this energy consumption will be uncontrolled. As in the other scenarios, we assume further that these emissions will remain at the same level between year 2000 and 2040. The implications of this scenario are as follows:

- Total European SO₂ emissions will increase by only 2% over its 1980 value (*Table 2*). A larger increase is not expected because official energy forecasts call for a shift in some countries from sulfur-containing fuels, such as coal and oil, to non-sulfur-emitting nuclear energy. Emissions of NO_x are expected to increase by 31% overall in Europe compared with 1980 levels.
- Both the average sulfur deposition and the area with deposition > 1.0 g S m⁻² yr⁻¹ in Europe will remain about the same in year 2000 as they were in 1980 (*Figure 2c*). Under the Current Reduction Plans scenario, however, average deposition would have decreased by 18% and the area with deposition > 1.0 g S m⁻² yr⁻¹ would have decreased from 62% in 1980 to 53% in 2000.
- Nitrogen deposition from NO_x emissions will increase by 27% from 1980 values, and the area receiving NO_x – N deposition will increase from 11% in 1980 to 14% in the year 2000.
- If ammonia–nitrogen is included in the calculations, however, the total nitrogen deposition in Europe will increase by 12% from 1980 to 2000, but the percentage area of Europe receiving deposition greater than 1.0 g N m⁻² yr⁻¹ will increase from 52% to 55%.
- Regarding soil acidification, the area in Europe having pH < 4.0 increases from about 1% in 1980 to 9% in 2040 as compared with 6% in 2040 under the Current Reduction Plans scenario (*Figures 3c and 4*). Hence, 50% more area will have soil pH below 4.0 under the No Controls scenario. In Central Europe, the area with pH < 4.0 increases from about 5% in 1980 to 65% in 2040, as compared with 45% under the Current Reduction Plans scenario (*Figure 5*).
- The percentage of lakes in the southernmost regions of Fennoscandia with pH < 5.3 increases slightly more than it would under the Current

Reduction Plans except for Norway where the percentage is already very high (*Figure 6*).

- For the No Controls scenario, the forest area affected by exposure to SO₂ in the year 2040 includes all the areas affected in the Current Reduction Plans scenario plus larger parts of Austria, Poland, and the Federal Republic of Germany (*Figure 7c*).

In conclusion, we expect to see moderate environmental benefits if European nations comply with their current plans to reduce SO₂ emissions as compared with doing nothing. Note that this is partly due to our assumption that the emissions in countries that have not committed to reductions will continue to increase substantially in the future.

(3) *Doing Our Best Would Be Worthwhile*

We now shift from one side of the control spectrum to the other, as we examine the implications of each country in Europe using the best technical controls currently available on all major sources of SO₂ and NO_x emissions. We call this scenario the *Best Available Technology* scenario. For SO₂ emissions these controls include flue gas desulfurization units on large boilers in power plants and factories (including advanced technology such as the Wellman-Lord process) and use of low-sulfur oil in small boilers. For NO_x emissions this scenario includes three-way catalysts on all gasoline cars, exhaust gas recirculation on all diesel vehicles, selective catalytic reduction units on all power plants, and a combination of low NO_x burners and selective catalytic reduction units on industrial combustion installations.

We emphasize that this scenario only examines the effects of *currently* available technical controls; future technological developments are likely to allow higher percentages of pollutant removal. We also did not account for energy conservation in these scenarios, even though we expect this to be an important strategy for reducing emissions in the long run. Because of these assumptions we believe that *technically feasible reductions of emissions can be greater than we assumed*, especially for NO_x emissions.

- We estimate that using the best available technology would reduce total SO₂ emissions in Europe by 82% relative to 1980, and NO_x emissions by 55% (*Table 2*).
- Only 5% of Europe's area has sulfur deposition > 1.0 g S m⁻² yr⁻¹ in the year 2000 under this scenario, as compared with 62% in 1980

and 53% under the Current Reduction Plans. Peak sulfur deposition in Central Europe decreases from more than $10.0 \text{ g S m}^{-2} \text{ yr}^{-1}$ in 1980 to $2.0\text{--}3.0 \text{ g S m}^{-2} \text{ yr}^{-1}$ (Figure 2d). However, the area with nitrogen deposition $> 1.0 \text{ g N m}^{-2} \text{ yr}^{-1}$ is still 41% because of the influence of ammonia-ammonium deposition. It is clear that ammonia emissions must be reduced in *addition* to NO_x emissions to reach acceptable levels of nitrogen deposition in Europe.

- Under the Best Available Technology scenario the area of Europe having forest soil $\text{pH} < 4.0$ decreases to zero by the year 2000 (Figures 3d and 4). The mean base saturation in Europe increases slowly from 0.10 in 1980 to 0.17 by 2040. In a related calculation, we found that the trend of soil acidification in Europe as a whole will level off if sulfur deposition is reduced everywhere by 50% to 70%.
- In most lake regions of Finland and Sweden, the percentage of lakes with $\text{pH} < 5.3$ returns to its 1960, or pre-1960, level. Exceptions are the southernmost lakes in these countries (Figures 6a and 6c). By comparison, most of Norway's lakes remain acidified even under this scenario (Figure 6b).
- The forest area at risk owing to airborne SO_2 stabilizes at about its 1980 coverage (Figure 7d).

We conclude from these calculations that doing our best would be worthwhile for the nations of Europe and our natural environment: the progress of acidification will be at least halted in nearly all areas, and further impacts averted. The only qualification we have to this positive picture is that the forest areas at risk owing to exposure to SO_2 , soil acidification, and lake acidification will *stabilize* rather than return to their 1960 condition, and some areas will still be exposed to sulfur and nitrogen deposition above recommended critical loads. Exceptions to this are most Finnish and Swedish lakes, which we estimate will recover under the Best Available Technology scenario.

(4) *But the Best Will Be Expensive*

Using RAINS, we estimate the annual costs of the Best Available Technology scenario to be 83 DM billion (at 1980 prices), or 0.8% of current European gross national product (GNP). By comparison, Current Reduction Plans are estimated to cost 12 DM billion, or 0.1% of the current (1980) European GNP. (This may be compared with the 2% of GNP spent in the Netherlands

in 1988 for environmental research and pollution control.) These are only rough estimates because it is difficult to select a common basis for comparing costs between all European nations, and impossible to anticipate all factors influencing the costs of pollution control. But even with a large margin of error, it is easy to appreciate the magnitude of the investments necessary for the Best Available Technology scenario.

(5) *Cooperation Saves Effort and Money*

Intuitively, it would seem that European environmental goals could be achieved most effectively and inexpensively by concentrating on the hardest hit areas first, and investing in emission reductions in countries that have the greatest effect on deposition in these areas and the cheapest marginal costs for controlling emissions. The RAINS model ties these factors together quantitatively, and can be used to explore a variety of cost-saving approaches for reducing acidification impacts in Europe. We now present two examples of these approaches.

Example 1. We noted above that the estimated cost of Current Reduction Plans is in the order of DM 12 billion per year. Rather than assuming that each country will invest its committed portion of this sum within its own borders, let us assume that this money is put into a common fund and then redistributed in a way that would achieve the greatest level of environmental improvement throughout Europe. For this example, we define greatest level of environmental improvement as the lowest attainable level of sulfur deposition in Europe as a whole for a given financial investment. We estimate that for the sum of DM 12 billion per year an *additional* 3,000 kt yr⁻¹ of SO₂ emissions can be reduced in all Europe if the money is given to those countries that are major contributors to high deposition levels in Europe and can reduce their emissions most cheaply. Furthermore, peak deposition in Central Europe can be reduced to 4.0 to 5.0 g S m⁻² yr⁻¹ compared with about 7.5 g S m⁻² yr⁻¹ under the Current Reduction Plans for the same financial investment, and the area of forest soil in Central Europe with pH < 4.0 will decrease from 17% to 4% between the years 1995 and 2000 (*Figure 5d*).

Example 2. The RAINS soil acidification model indicates that a deposition level of about 3.0 g S m⁻² yr⁻¹ is required to stabilize soil acidification in Central Europe. (It is assumed that acidification is stabilized when base saturation increases and the forest area having pH < 4.0 decreases.) This is equivalent to reducing sulfur deposition in Central Europe by 80% (*Figure*

8). One way to accomplish this would be to reduce emissions everywhere in Europe by about 70% relative to 1980 at a cost of roughly DM 52 billion per year. Rather than each country reducing its emissions by the same substantial percentage, another way to attain this deposition level would be, as in the first example, to reduce emissions in the countries that have the greatest effect on deposition and the cheapest marginal costs of controlling sulfur. Using the RAINS optimization routine, we identified the country-by-country reduction in SO₂ emissions that would be required to reach the stated goal. The sum of these country emission reductions adds up to only a 23% reduction of total European emissions as compared with a 70% reduction if each country reduced emissions by a flat rate. The cost of this optimized strategy would be about DM 15.4 billion per year, or less than one-third the cost of the 70% flat-rate reduction, and only about DM 3.4 billion per year more than the Current Reduction Plans scenario.

These are only two of the many possible illustrations of the benefits of international financial cooperation to reduce transboundary air pollution in Europe. Other examples are presented in Chapter 9 of the book.

Now that we have reviewed the first five findings in *Table 1*, the reader might be curious about the detailed calculations behind these findings, or might have ideas for alternative calculations to perform. This is consistent with our objective to make RAINS available as a tool for others, which leads to our sixth point:

- (6) *If You're Not Sure About Points (1) to (5),
Use the RAINS Model Yourself*

Other Policy-Related Findings

Energy conservation. Improved energy efficiency and use of renewable energy can have an important role in reducing SO₂ and NO_x emissions in Europe. Based on our analysis of low-energy scenarios developed by researchers in 10 Western European countries, we have estimated that energy efficiency (including renewable energy use) without other emission controls can reduce SO₂ emissions by 60% relative to 1980. It is also likely that NO_x emissions would be substantially reduced, but we have not yet performed these calculations. These scenarios are based on the technical feasibility of energy savings; the economic aspects must still be examined.

A critical question is how soon these energy savings can contribute to significant reductions of SO₂. An implicit assumption of the low-energy

scenarios we examined was that renewable energy would only be phased in as the current energy infrastructure is phased out. Hence, the full emission reductions of these scenarios would not be realized for some decades. Because of the consequences in delaying SO₂ emission reductions, we believe that in the short run we should not rely exclusively on energy conservation to reduce emissions. Instead, a mix of energy conservation, new fuels, and technical controls should be used.

However, new factors (oil spills, CO₂-related global warming, problems with nuclear waste), in addition to acidification of Europe's environment, could provide the impetus for faster adoption of concerted energy savings and renewable energy use. Without these considerations it might be considered uneconomic to implement rapidly low-energy scenarios; with these considerations in mind, it may be more costly not to.

Environmental revitalization. We pointed out that using best available controls on current SO₂ emissions before the year 2000 would more or less stabilize acidification throughout Europe. Although acidification will not worsen under these circumstances, our results show that Europe's rural environment will not recover to its pre-1960 state in our lifetime. Considering the enormous expenditures required simply to stabilize acidification impacts – in other words, maintain the status quo – we recommend that European governments invest not only in emission controls but also in large-scale environmental revitalization such as liming of lakes, reforestation, and soil fertilization. These revitalization efforts, however, *should accompany and not replace* significant emission reductions.

It remains to be seen if nations can negotiate international agreements quickly enough to keep pace with the worsening of existing problems like regional acidification, or with the appearance of new problems we cannot yet imagine. Nevertheless, we believe tools such as the RAINS model can help the negotiating effort by providing the holistic and long-term perspective needed for anticipating future problems, and for identifying what needs to be done if we choose to act.