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Integrated Analysis of Acidification in Europe

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This paper presents the interim status of the RAINS model developed at the International Institute for Applied Systems Analysis. The principal purpose of the model is to provide a tool to assist decision-makers in their evaluation of strategies to control acidification of Europe's environment. Model design emphasizes user comprehension and ease of use. The overall framework of RAINS consists of three linked compartments: *Pollutant Generation, Atmospheric Processes* and *Environmental Impact*. Each of these compartments can be filled by different substitutable submodels. The four submodels currently available are *Sulfur Emissions, EMEP Sulfur Transport, Forest Soil Acidity* and *Lake Acidity*. Submodels which deal with NO_x emissions and deposition and other environmental impacts will be added to the model.

To operate the model, a user must select (1) an energy pathway, (2) a pollution control strategy and (3) an environmental impact indicator. This information is input to RAINS and yields a *scenario* which is a consistent set of energy pathway, sulfur emissions, forest soil acidity and lake acidity. In an iterative fashion, a model user can quickly evaluate the consequences of many different alternatives to control acidification in Europe.

Keywords: control strategies, decision-making, acid rain, acidification, scenario analysis, indicators, integrated analysis.

1. Introduction

Governments of North America and Europe are under increasing pressure to take remedial action against acidification of the environment. Also increasing is the amount and diversity of scientific and engineering research devoted to this subject (c.f. Environmental Resources Limited, 1983). Unfortunately, to date, there has been only a tenuous link between political decisions and scientific evidence concerning acidification.

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For example, the most common policy discussed in Europe for controlling acidification impacts is a 30% reduction of sulfur emissions by 1993 relative to their 1980 level (Anon., 1984). Although this policy will be costly to virtually every European country, the actual benefits of such a policy in protecting the natural environment are rarely investigated. This omission is understandable because acidification of Europe's environment involves a bewildering array of factors and interrelationships. But augmenting scientific information about the problem will not necessarily lead to identification of suitable policies for its control. This information must also be structured in a form *usable* to decision-makers. The RAINS (Regional Acidification Information and Simulation) model of the International Institute for Applied Systems Analysis (IIASA) attempts to provide such a structure. The purpose of the model is to provide a tool to assist decision-makers in their evaluation of control strategies for acidification in Europe. This paper presents a description of the *interim state* of the model.

Design of any model system depends very much on (1) the temporal and spatial dimensions of the problem it describes, and (2) the users of the model system. Some of the dimensions of the acid rain problem in Europe most relevant to the model system design are as follows.

(1) *It is transboundary in nature.* Closely related to this feature is the fact that different countries produce different levels of air pollutants and acidifying compounds and differ in susceptibility to air pollution deposition.

(2) *The problem is poorly understood.* There is much uncertainty in the underlying scientific processes of acid deposition and its environmental impact. Moreover, there are conflicting scientific views of these processes.

(3) *Different time scales are important.* The travel time of air pollutants from one country to another may be a few hours to a few days; snowmelt releases acidity to lakes over a few weeks; it may take years or decades for soil to acidify; some air pollution control policies may be applied within a year or two, others may take decades.

(4) *Many different disciplines are needed to understand and solve the problem.* These range from economics and political science to engineering, biology, cloud physics, meteorology, and others.

(5) *New information about the problem is continuously available.* With growing awareness of the problem, more and more funds are being invested in acid deposition research. Results of this research sometimes invalidate past understanding of the problem.

Regarding the question of model users, we expect that they will be mainly *decision-makers* concerned with the costs and benefits of acid deposition abatement. The term *decision-maker* is, of course, open to interpretation, but we take it to mean scientific advisors or administrators affiliated with government, some of whom may have a scientific background, but all of whom are principally concerned with policy development. We expect also that the model will be used by many others for educational and research purposes.

2. Model system guidelines

Combining the dimensions of the problem with assumptions about model users has led us to adopt the following guidelines for our model system.

As the model is designed for the use of decision-makers, we believe it should be both *comprehensible* and *easy to use*. In addition, it should incorporate past and current research in the field of acid deposition research, yet deal with the most important issues first. In other words, the model builders should act as *neutral interpreters* of the existing state of knowledge. Other desirable characteristics are (1) flexibility in incorporating new information as it becomes available and (2) explicitness in treating uncertainty.

Following from the above general criteria, we adopt the following more specific guidelines.

(1) *The model system should be co-designed by analysts, experts, and potential users.* Though this requires special effort, ultimately it will lead to greater comprehension and relevance of the model system. The analysts should also represent different disciplines.

(2) *The model should be of modular construction.* Each aspect of the problem should be represented by a separate *compartment*. These compartments should then be linked together. Each compartment can be filled by a number of interchangeable *submodels* which permits comparison of different points of view.

(3) *Submodels should be as simple as possible and yet be based, where possible, on more detailed data or models.* Model *simplicity* is a relative term, but, in the context of acid rain, for example, a source-receptor matrix based on a linear relationship between emissions and deposition is quite simple, compared to a model based on non-linear atmospheric chemistry. Advantages of simplicity include the following: (i) computer response and computational time is short, which permits interactive computer use, (ii) models are easier to understand, (iii) model inputs are simpler, which permits simpler and quicker model use. However, each simple submodel should be supported, where possible, by detailed models and data in order to increase the validity of the submodel's estimates. Though submodels should initially be as simple as possible, they can also be made more complex if model users and scientific experts feel that more detail is required.

(4) *To facilitate its use, the model should have interactive inputs and clear graphical outputs.* Communication of the model's operation and results should not be an afterthought of model development.

(5) *The model should be dynamic in nature.* It is important for decision-makers to see how a problem evolves and how it can be corrected over time. Thus, it is important for the model to provide a "picture" in time, from past to future, of the causes and effects of acidification.

3. Current model status

One of the above maxims calls for co-design of the model by model builders and users. As this is a continuing process, the following model description should be viewed as only the *current status* of the model which is subject to revision.

The model currently consists of three linked *compartments*: Pollutant Generation, Atmospheric Processes and Environmental Impact.

Though we imagine that many different *submodels* can be inserted into these compartments, we have begun with four linked submodels illustrated in Figure 1(b).

The first submodel, the *Sulfur Emissions* submodel, computes sulfur emissions† for each of 27 European countries based on a user-selected *energy pathway* for each country. The model user has a choice of three possible pathways for each country, each of which is based on published estimates from the Economic Commission for Europe (ECE, 1983). Additional energy pathways are being constructed to give the model user a wider range

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† Sulfur emissions in this paper refers to total sulfur emissions including sulfur dioxide and sulfate.

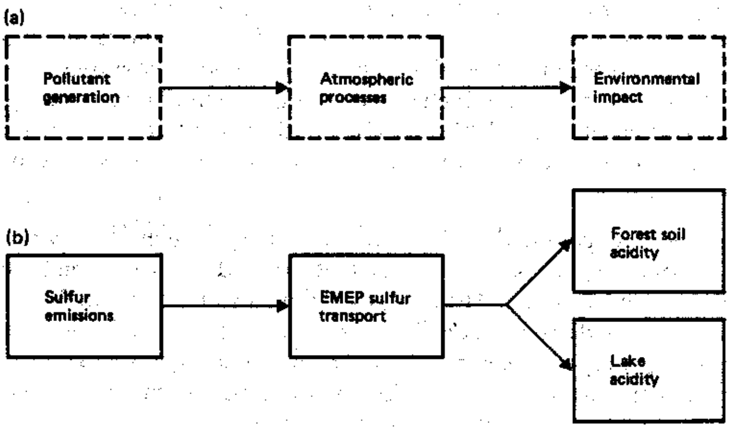

Figure 1. Schematic diagram of RAINS compartments (a) and submodels (b).

of choices. Each energy pathway specifies how much energy will be used by four fuel types in a country: oil, coal, gas and *other*. The sulfur-producing fuels, oil and coal, are broken down further into 11 sectors. Oil has the following sectors: conversion, conventional power plants, low sulfur power plants, industry, domestic, and transportation. Coal sectors include: conversion, conventional power plants, low sulfur power plants, industry and domestic. There is an additional sector which accounts for sulfur emissions which do not originate from fossil fuel use, for example the sulfur emitted by sulfuric acid plants. In RAINS, these are termed *process* emissions.

The model can compute sulfur emissions for each country with or without pollution control. To reduce sulfur emissions, the user may specify any combination of the following four pollution control alternatives: (1) fuel cleaning; (2) flue gas control devices; (3) low sulfur power plants, e.g. fluidized bed plants with limestone injection; (4) low sulfur fuel. The sequence of calculations in the Sulfur Emissions submodel is illustrated in Figure 2.

The sulfur emissions computed for each country are then input into the second submodel, the *EMEP Sulfur Transport* submodel. This submodel computes sulfur deposition in Europe due to the sulfur emissions in each country, and then adds the contributions from each country together to compute the total sulfur deposition at any location in Europe. The submodel consists of a source-receptor matrix illustrated in Figure 3, which gives the amount of sulfur deposited in a grid square (150 × 150 km) due to sulfur emissions originating from grid squares in each country of Europe. The source-receptor matrix is based on a more complicated model of long-range transport of air pollutants in Europe, developed under the Organization of Economic Cooperation and Development (OECD) and the Co-operative Program for The Monitoring and Evaluation of Long Range Transmission of Air Pollutants in Europe (EMEP). This model accounts for the effects of wind, precipitation and other meteorological and chemical variables on sulfur deposition (Eliassen and Saltbones, 1983). The source-receptor matrix was made available to IIASA by EMEPs Meteorologic Synthesizing Center-West in Oslo, Norway.

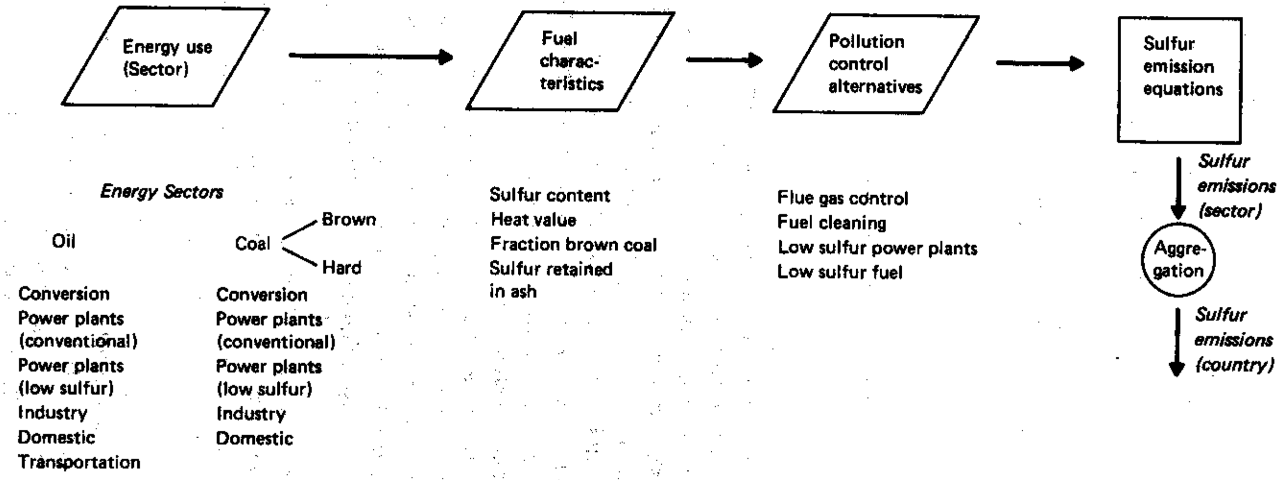

Figure 2. Sequence of calculations in Sulfur Emissions submodel.

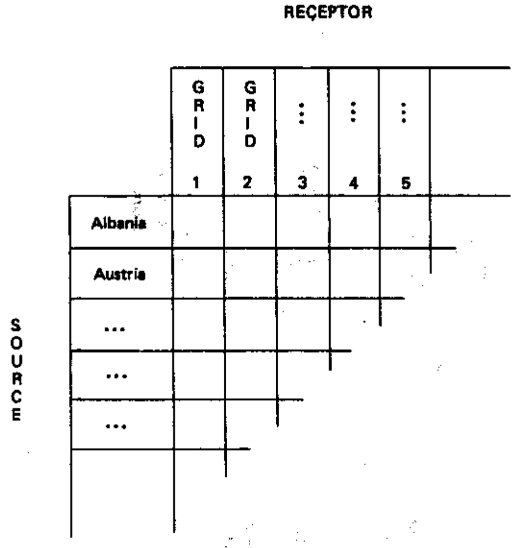

Figure 3. Concept of source-receptor matrix.

The sulfur deposition computed by the second submodel is then input to the third submodel, the *Forest Soil Acidity* submodel. We analyse soil acidity as an indicator of potential forest impact of acidification. This submodel was based largely on the work of Ulrich and his co-workers at the University of Göttingen (Ulrich, 1983) and is reported in detail elsewhere (Kauppi *et al.*, 1985). The submodel relies on three key concepts: acid stress, buffer rate and buffer capacity. Acid stress is defined as the input of hydrogen ions to the top layer of soil. *Buffer rate* is the maximum potential rate of reaction between buffering compounds in the soil and hydrogen ions, and *buffer capacity* is the total reservoir of buffering compounds.

Soils are divided into a series of *buffer ranges* according to the dominant neutralizing chemical reaction. These extend from the alkaline soils of the *carbonate* range through the *silicate* and *cation exchange* ranges into the acidic soils of the *aluminium* buffer range. Each range has a buffer rate and capacity associated with it.

The submodel is used by assigning buffer capacities and buffer rate to each of the above buffer ranges and to 88 soil types in Europe. Each grid element in the model contains a maximum of seven soil types. In general, if the acid stress exceeds the buffering rate, or if the buffer capacity is depleted, the model shifts to the next buffer range, i.e. the buffer range with remaining buffer capacity. The pH of forest soil is estimated from the computed buffer range. These computations are illustrated in Figure 4.

The fourth submodel, *Lake Acidity* submodel, computes lake acidity levels as a function of catchment characteristics and local acid deposition. Details of the model are presented by Kämäri *et al.* (1984). Each watershed is divided conceptually into four spatial sectors: snowpack (if consistent with local climate), upper soil layer A, lower soil layer B and lake volume. Different modules of this submodel compute the hydrology and flux of ions contributing to the acidity and alkalinity of the lake water.

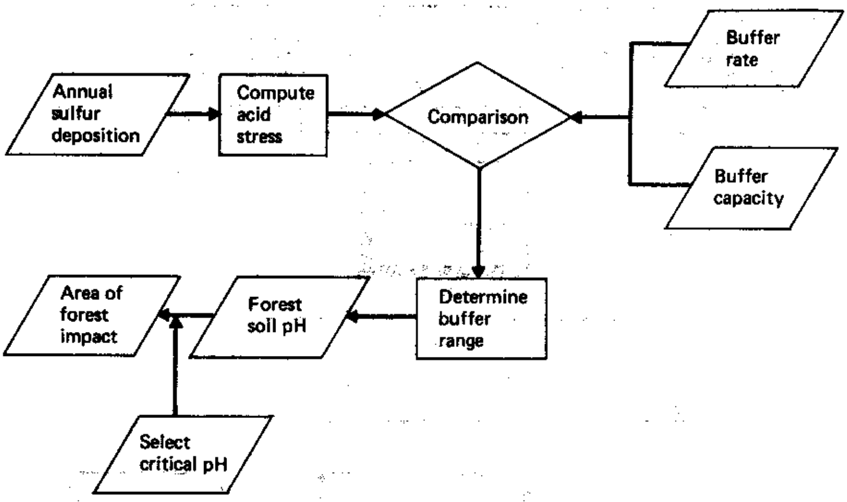

Figure 4. Sequence of calculations in Forest Soil Acidity submodel.

The *Meteorological Module* transforms monthly sulfur deposition, computed by the EMEP Sulfur Transport submodel, into acid stress to various sectors of the catchment. Nitrogen deposition will be included in these computations once NO_X emissions and atmospheric submodels are added to RAINS. The monthly mean precipitation is broken down into rain and snow according to local mean monthly temperature. Snowpack accumulates and melts at a temperature-dependent rate. Other equations in this module account for storage of wet and dry deposition in snowpack, release with meltwater, and direct H^+ deposition to soil and lake.

The *Hydrological Module* routes precipitation into *quickflow, baseflow* and flow between soil layers. The computation of these flow components is based on rates of precipitation and evapotranspiration, and catchment characteristics such as soil depth, surface slope, hydraulic conductivity and volumetric water content of soil.

The *Soil Chemistry Module* uses the same analytical approach as the *Forest Soil Acidity* submodel to estimate $[H^+]$ in the A and B soil layers. However, *acid stress* in this module is input on a monthly, rather than annual, basis. This monthly input is based on deposition, snowmelt rate, relative amount of rainfall versus snowfall, and other considerations derived from the Meteorological Module. The loads of ions which contribute to acidity and alkalinity (H^+ and HCO_3^-) of the lake are then computed from a mass balance equation.

The *Lake Response Module* calculates the $[H^+]$ of the lake based on the ion loads. These loads are assumed to be mixed within a mixing layer which depends on location and season. Finally, the change in lake acidity is calculated according to equilibrium reactions of inorganic carbon species.

In practice, the sequence of computations reviewed above, and presented in Figure 5, is repeated for various hypothetical *type-lakes* in each grid element of the RAINS model. As a result, the Lake Acidity submodel estimates the *likelihood* of lake acidification for different types of lakes (if they exist) at different locations in Europe.

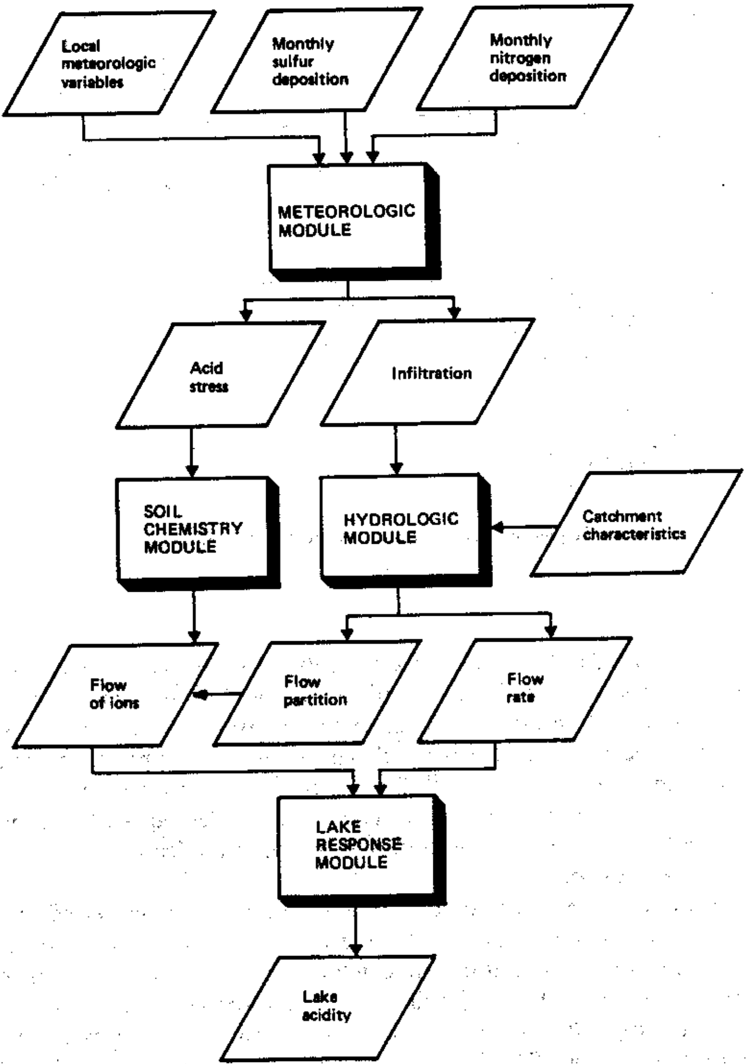

Figure 5. Sequence of calculations in Lake Acidity submodel.

4. Other model characteristics

The time horizon of the RAINS model is 1960–2030. The simulation period begins 25 years in the past, so that the model can be tested against historical data trends. The long time horizon to year 2030 permits examination of possible long-term impacts such as soil and groundwater acidification. In addition, this period encompasses the turnover time of a country's energy system which permits the possibility of modifying a country's energy system to control air pollution. The time resolution of the model is one month, so that seasonal differences in lake acidity may be simulated. However, a one-year period is used in other model calculations.

The model covers all of Europe, including the European part of the USSR. The spatial resolution is roughly 100 × 100 km.

The model is sulfur-based because it is generally accepted by the scientific community that sulfur is currently the principal contributor to acidification in Europe. In the future, however, we will include NO_x and other pollutants in our calculations.

The model characteristics are summarized in Table 1.

TABLE 1. Current (early 1985) model characteristics

Sulfur based
70 year simulation period (1960–2030)
Month–year time resolution
Spatial coverage: all Europe including European USSR
Spatial resolution: approximately 100 × 100 km
Three linked compartments
Interchangeable submodels
Dynamic simulation

5. How the model is used: scenarios

The model can be used by the procedure illustrated in Figure 6. Typically, the model user first selects an *energy pathway* for each country, and then a pollution control program. This information is input to the model which calculates and displays the sulfur emissions of each country, the sulfur deposition throughout Europe resulting from these emissions, and the resultant environmental impact. These calculations are performed for the 70-year time horizon of the model. A consistent set of energy pathway, sulfur emissions, sulfur deposition, forest soil acidity and lake acidity is called a *scenario*, and the type of analysis is termed *scenario analysis*

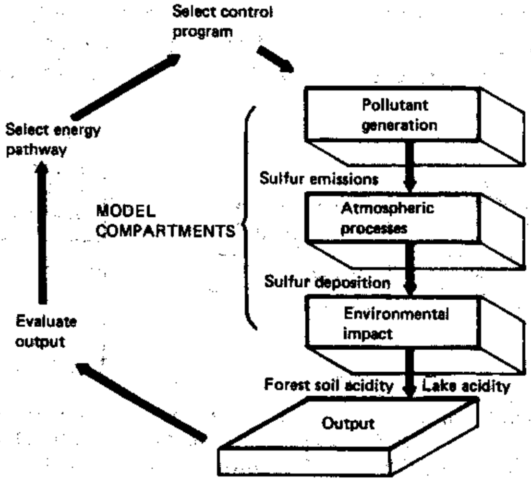

Figure 6. Model use procedure.

Based on this output, the model user may select another energy pathway or control program to evaluate with the model. In this iterative way, a decision-maker can analyse quickly the impact of many different policies. Computational and output processing of the Sulfur Emissions and Sulfur Transport submodels takes only a few CPU (Central Processing Unit) seconds on a VAX 11/780. The Forest Soil Acidity and Lake Acidity submodels require a few minutes of CPU time.

The flexibility of the model is illustrated by the examples in Figures 7–9. A model user has a choice of both *entry points* and *impact indicators. Entry points* refer to the place where the model user begins an analysis. A user may begin by either (1) specifying an energy pathway and a pollution control program for each country and having the model automatically compute sulfur emissions, or (2) bypassing the energy systems of each country and instead prescribing sulfur emissions for each country.

The decision-maker also has a choice of three *impact indicators*, annual sulfur deposition, forest soil acidity or lake acidity.

In Figures 7 and 8, the model user begins the analysis by prescribing sulfur emissions for each country and selecting forest soil acidity as a damage indicator. In Figures 9–11, the model used selects an energy pathway for each country and sulfur deposition as an indicator.

Scenario analysis was selected as the first *operational mode* for the RAINS model because it permits great flexibility to the model user; he or she may examine the consequences of many different pollution control programs that are optimal or desirable to the user because of the user's unexpressed cost or institutional considerations. However, to increase the utility of the RAINS model, other operational modes will be added. For example, the user will be able to run the model "backwards", i.e. set an environmental or deposition objective and then compute a desirable emissions reduction plan according to specified cost and institutional constraints. These computations will be accomplished by mathematical "searching techniques" which draw on linear programming or other similar mathematical algorithms.

6. Model testing

A model which is intended for use in decision-making merits a vigorous testing program to strengthen the confidence of users in its estimates. Such a program is currently under way at IIASA to test the RAINS model. Part of the approach involves conventional model validation and verification. *Validation* is taken to mean examining the

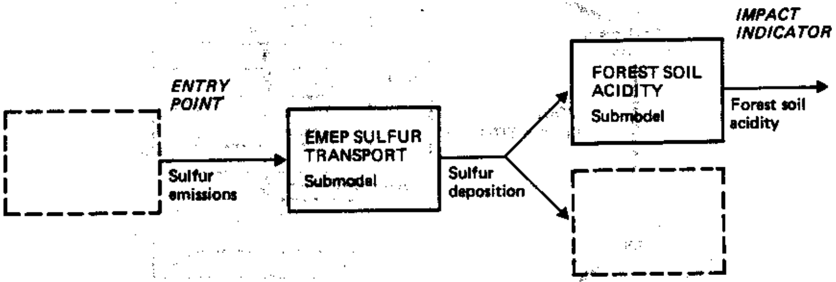

Figure 7. Scenario Comparison One. Computer generated results. This computer run compares the impact of two scenarios: (i) 30% reduction of sulfur emissions by 1990 in each European country, relative to their 1980 levels, (ii) energy pathway number three (see text for definiton of *energy pathway*) without pollution controls. Figure 7 shows that sulfur emissions are the *entry point* of this computer run and forest soil acidity is selected as an *indicator*.

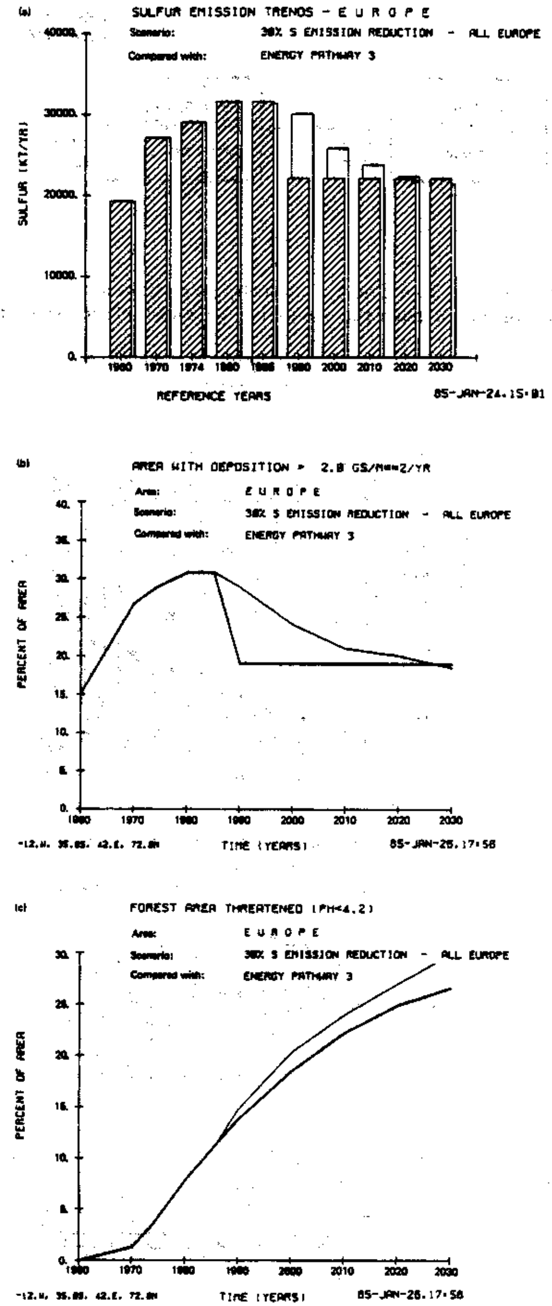

Figure 8(a). The total European sulfur emissions for both scenarios. The lined bars refer to the scenario of 30% sulfur emissions reduction while the open bars refer to the scenario of energy pathway number three. Note that sulfur emissions of both scenarios are roughly equal after the year 2020. (b) The area of Europe covered by $\geqslant 2.0$ g m^{-2} year^{-1} of sulfur deposition for the two scenarios. The heavier line refers to 30% sulfur emission reductions and the lighter line to energy pathway number three. (c) The computed "forest area threatened" in Europe, as defined by soil pH < 4.2. The heavier line refers to the scenario of 30% sulfur emissions reduction and the lighter line to the scenario of energy pathway number three.

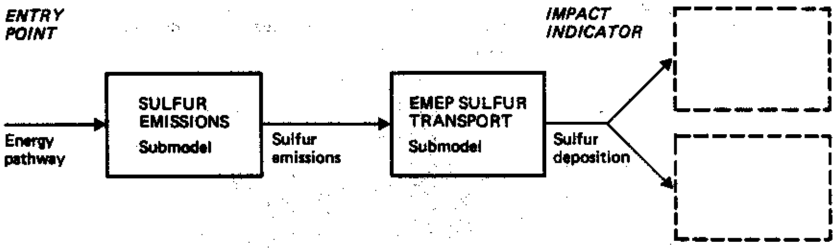

Figure 9. Scenario Comparison Two. Energy is the entry point of the analysis and sulfur deposition is used as an impact indicator, for the computer run comparing the impact of the two energy pathways in Figure 10.

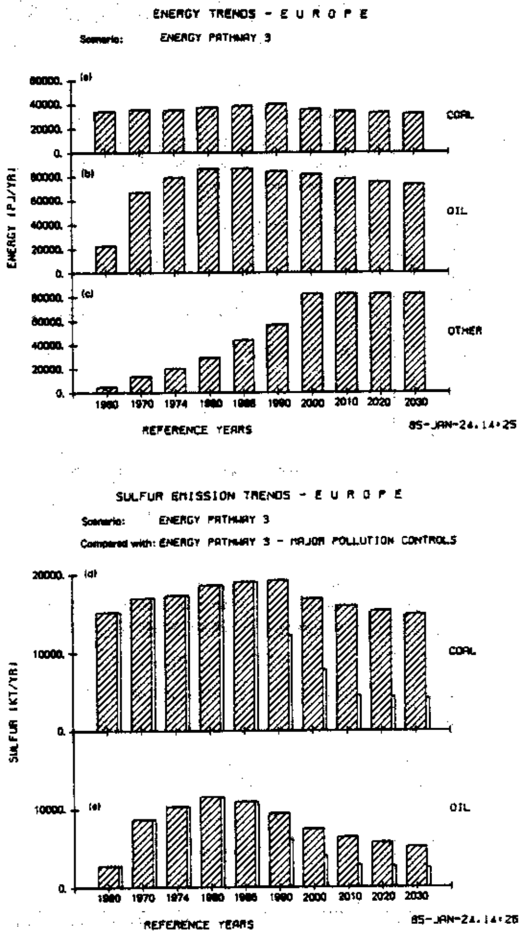

Figure 10. Scenario Comparison Two: Computer-generated results. This computer run compares energy pathway three without pollution controls with energy pathway three with "major pollution controls". These controls are defined as (1) pollution control devices on all power plants and (2) fuel cleaning in the domestic energy sector.

(a)–(c) Summary of the energy use assumed for "energy pathway three" for coal (a), oil (b) and other energy sources (c). In practice an "energy pathway" prescribes the energy used in each of 11 energy sectors for each of 27 countries in Europe. RAINS computes sulfur emissions for each of these sectors and countries.

(d) and (e) Summary of these computations for the two scenarios for coal (d) and oil (e): ■, energy pathway three without controls; □, with "major pollution controls".

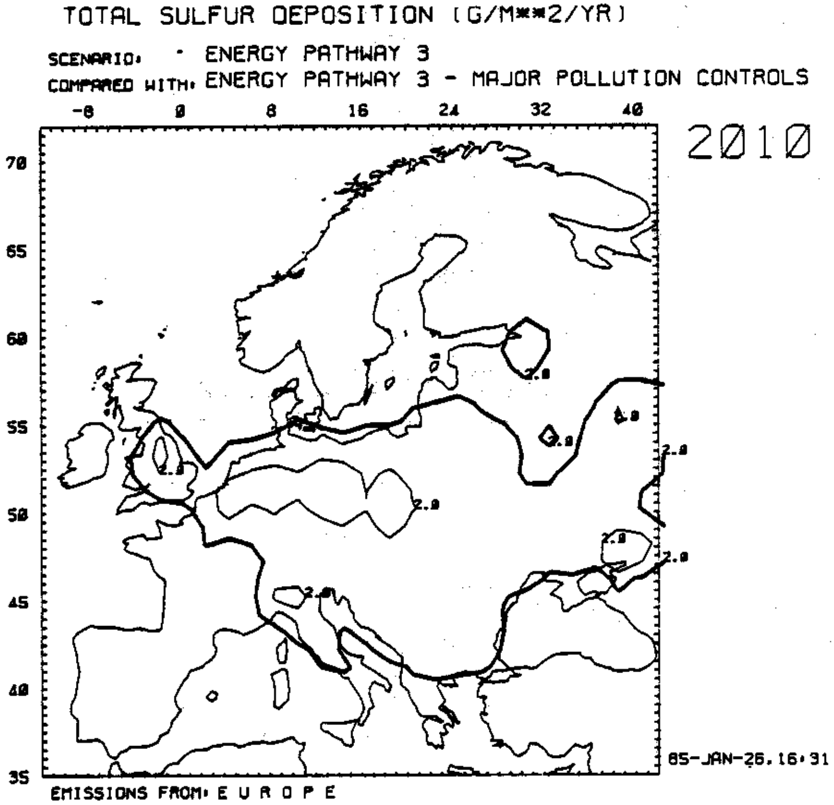

Figure 11. Computed sulfur deposition in Europe for the two scenarios in Figure 10. Computed location of the line of 2 g m^{-2} year^{-1} total sulfur deposition: ———, energy pathway three without pollution controls; . . . ., energy pathway three with "major pollution controls".

reasonableness of model behaviour in a qualitative sense. Figure 12 illustrates a validation test of this sort. In this example, sulfur emissions throughout Europe [Figure 12(a)] are set to zero in the year 2000. Figure 12(b) shows that levels of sulfur deposition (greater than or equal to 1·0 g m^2 year^{-1}) also decrease to zero. Other tests show that only small background levels (less than 1·0 g m^2 year^{-1}) of sulfur deposition are computed by the model after the year 2000. Forest area threatened by soil acidification [Figure 12(c)] also decreases, but not to zero, because (according to the model) certain soils are unable to recover before the year 2030 from the acidification they experienced before the year 2000.

Additional validation experiments are presented in Alcamo *et al.* (in press).

Verification normally implies testing the model against data. There is some doubt whether a true verification can be performed on a model with a spatial resolution of 100 × 100 km. Nevertheless, some comparisons are being made of model calculations versus time series data.

A less conventional approach is also being taken by acknowledging that model uncertainty exists and that it should be incorporated explicitly in RAINS. This *uncertainty analysis* involves three steps: (1) identification and classification of uncertainty, (2) screening and ranking of uncertainty sources, and (3) quantitative

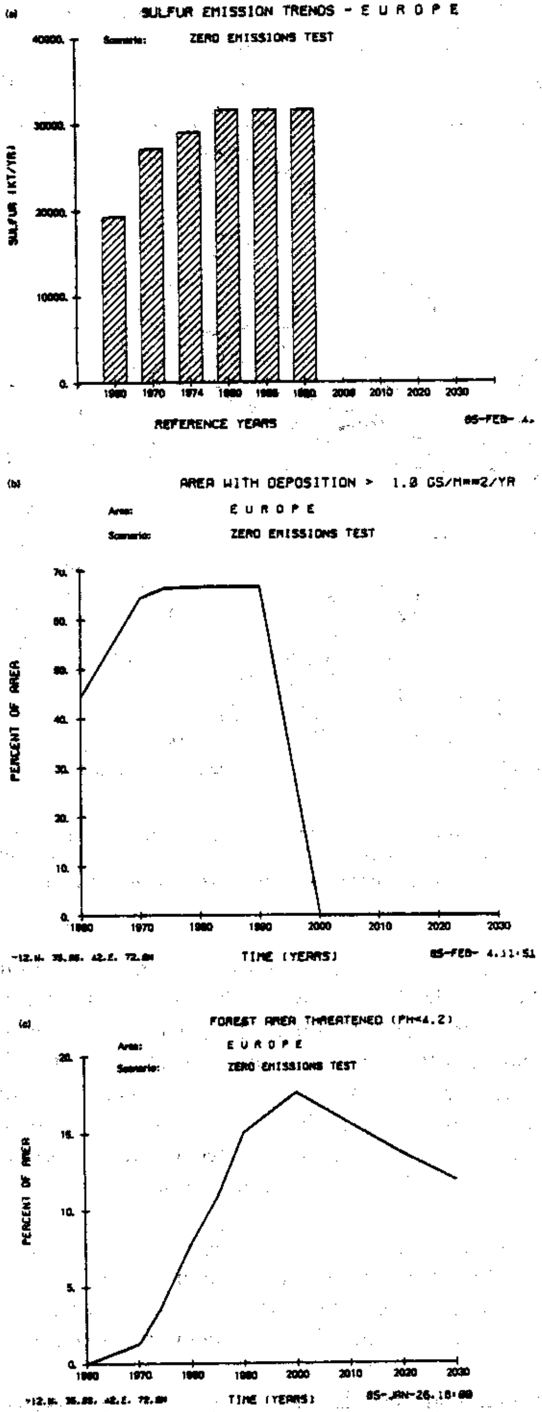

Figure 12. Results from test of model behavior-sulfur emissions set to zero after year 2000. (a) Sulfur emissions in Europe. (b) Area of Europe with sulfur deposition $> 1{\cdot}0\,g\,m^{-2}\,year^{-1}$. (c) Forest area in Europe threatened (soil pH $< 4{\cdot}2$)

evaluation of aggregate uncertainty due to its most important sources. Results from the uncertainty analysis are not yet available.

7. Conclusions and further research

The foregoing paper describes the interim state of the IIASA RAINS model, which is a tool to assist decision-makers in their evaluation of strategies to control acidification in Europe. The RAINS model has already been presented at several international meetings, including the September 1984 meeting in Geneva of the Executive Body of the Geneva Convention on Long Range Transboundary Air Pollution, and the May 1984 meeting in Paris of the State of the Environment Committee of the OECD. The model has also been demonstrated to invited scientific experts and policy-makers at review meetings held at IIASA in November 1983 and June 1984. Based on written and verbal comments of participants from these review meetings, we tentatively conclude that (1) the modular and flexible design of RAINS makes it possible to easily update the model, as additional expert opinion and data become available; and (2) RAINS links many different parts of the acidification problem in Europe in a comprehensible and usable manner to both scientists and non-scientists.

Research will continue at IIASA till the end of 1987 to improve and apply the RAINS model. These efforts will focus on (1) expanding the model to include cost analysis and additional submodels—NO_x emissions, NO_x transport and deposition, direct forest impact of air pollutants, and other environmental impacts; (2) model testing and uncertainty analysis; (3) development of other *operational modes* to RAINS, for example implementing *searching techniques* as described above; (4) applying the model to policy analysis; and (5) distributing RAINS to international and national institutions for their use in policy analysis.

The authors are indebted to the many individuals who have supported the development of the RAINS model at IIASA. We wish especially to acknowledge J. Bartnicki, J. den Tonkelaar, A. Eliassen, G. Gravenhorst, L. Kauppi, A. Mäkelä, E. Matzner, G. Persson, J. Saltbones, B. Ulrich and E. Weber. The authors are also indebted to the following IIASA personnel: V. Hsiung, M. Khondker and S. Orlovsky.

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