WORKING PAPER

DIRECT EFFECTS OF SULFUR ON FORESTS IN EUROPE – A REGIONAL MODEL OF RISK

Annikki Mäkelä
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April 1987
WP-87-57

IIASA
International Institute
for Applied Systems Analysis

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Preface

The relationship between acid rain and forest damage has been a topic of very diverse opinions and debates. The new type of forest damage or "neuartige Waldschaden" (in German language) which was observed in the beginning of the 1980s triggered a fierce scientific debate about its causes. Various hypotheses were developed, some were tested. Both in Europe and North America research in forest growth processes increased. Until now no unified theory does exist. Two opposite conclusions could be drawn from this statement. One is, that basic research efforts should continue and more research funds should be directed towards basic understanding of tree physiology and a tree's reaction to environmental stresses. Furthermore, models are not particularly useful at this stage. The other conclusion is that basic research and modeling should develop in parallel. Models can be based on what we already know and research agenda could be modified based on modeling results. In the next iteration models could then be adapted to new scientific results.

It is this hand-in-hand approach which has been adapted in IIASA's Acid Rain Project. The RAINS model developed in this project combines energy scenarios, emission calculation, long-range transport of pollutants, and deposition with effects on forest soils, lakes, groundwater and forests. This paper presents a simple dynamic model for the sensitivity and risk of forest under long-term exposure to airborne sulfur.

The authors are among the first to develop a regional model of forest effects and are to be congratulated for their important work. I hope that the paper will stimulate discussion on modeling effects of air pollution on forests.

Leen Hordijk
Leader
Acid Rain Project

Abstract

A simple dynamic model for the sensitivity and risk in forests under long-term exposure to airborne sulfur is presented. The model is an interpretation of results from long-term forest damage and sulfur dioxide measurements in Czechoslovakia, and it focuses on damage caused by direct, foliar impacts. The input to the model is the annual average SO_2 concentration, and the accumulation of impact over time is incorporated. In a regional application of the model, sensitivity is defined as a function of the effective temperature sum. Sensitivity and risk maps of Europe in relation to direct impacts of sulfur are presented.

List of Symbols

Symbol	Meaning
ETS	effective temperature sum
HF	Hydrogen flouride
Q	dose
Q_o	threshold dose
S	annual average sulfur dioxide concentration
S_{av}	long-term average sulfur dioxide concentration
S_o	threshold annual average sulfur dioxide concentration
T_L	maximum normal lifetime
T_M	maximum lifetime under sulfur exposure
T_R	rotation time
x	strain
x_{av}	average age
x_o	threshold strain

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DIRECT EFFECTS OF SULFUR ON FORESTS IN EUROPE – A REGIONAL MODEL OF RISK

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1. INTRODUCTION

There is ample evidence that airborne SO_2 can cause alterations in the structure and function of tree foliage (Grill, 1973; Keller, 1978; Jäger and Klein, 1980; Materna, 1979; Cape, 1983; Soikkeli, 1981; Huttunen and Laine, 1983), but controversy still remains as to whether or not the prevailing SO_2 levels in Europe can give rise to foliar injuries that affect the growth and mortality of forests. While the analysis of the physiological pathways from foliage injury to whole tree damage is still faced with a number of unresolved questions (e.g. Luxmoore, 1980; Waring, 1986), the conclusion has been drawn from empirical dose-response studies that the present sulfur levels are not likely to cause growth reductions or enhanced mortality (Roberts *et al.*, 1983). On the other hand, in Czechoslovakian sulfur-imposed defoliation has been claimed responsible for observed damage to spruce stands under annual average SO_2 concentrations as low as 20–30 $\mu g\ m^{-3}$ (Materna, 1985).

The dose-response studies in the laboratory seem to have failed in analyzing two aspects that would be crucial in a regional assessment of the future risk to forests; first, the possibility of slowly accumulating strain, and second, the interaction of pollutants with natural stress factors. Although field studies could potentially overcome these problems, they have other drawbacks, the most important obviously being that it is often difficult to separate the role of the numerous potential causal agents. In the Ore Mountains, the fact that the damage could not be attributed to soil acidification, for instance, possibly also speaks of a lack of measurements.

Inspite of their circumstantial characters, the results in the Ore Mountains appear so interesting that they should receive some further attention in the context of regional assessment of future risk due to foliar impacts of sulfur. First, some features of the study make it more easily generalizable than many other similar field studies (Knabe, 1970; Lux, 1976; Wentzel, 1979; Freedman and Hutchinson, 1980; Bucher, 1984; Molski *et al.*, 1983). These features include both the variability of the natural environment and the pollutant concentrations, the dominance of sulfur in the pollutant profile, and the length of the monitoring period. Secondly, and more alarmingly, the results seem to suggest that damage due to foliar impacts of sulfur should be anticipated in other areas of Europe also.

The present study aims at displaying some regional, long-term implications of the findings in the Ore Mountains in connection with future scenarios of sulfur pollution. The scenarios are obtained from the Regional Acidification INformation and Simulation (RAINS) model developed at the International Institute for Applied Systems Analysis (Alcamo *et al.*, 1985, 1987; Kauppi *et al.*, 1986). The model calculates the transboundary fluxes, deposition and airborne sulfur dioxide concentration as a function of energy consumption and sulfur abatement strategies in 27 European countries, and can hence be used for comparing different energy policies.

In this report, we review the main results from the Ore Mountains and present a simple dynamic model consistent with the empirical findings. We use the model to derive a regional indicator of risk to forests, and apply this indicator to Europe in the RAINS framework. We also consider the possibilities of improving the model by more systematic treatment of the data, and discuss the limitations of the approach.

2. STUDIES IN CZECHOSLOVAKIA

2.1. Observations

The measurements of pollutant concentrations and forest damage in Czechoslovakia began in 1966 in some locations. A systematic monitoring network was set up in 1970–1972, comprising 25–30 stations of the Hydrometeorological Institute and 30 stations newly built for the purpose of forestry measurements. The majority of the stations represent stands of Norway spruce (*Picea abies*), yet some of them are applicable to Scots pine and common beech also.

The pollutant measurements in the stations include SO_2 measurements by the West-Gaecke method at 24 hours air sampling, and monitoring of other substances such as HF (hydrogen flouride) and NO_x at longer intervals. The emissions of the neighbouring industrial area have been recorded also (Materna, 1981a).

Observations of forest damage concern the percentage of heavily damaged individuals, the degree of damage being judged on the basis of thinning of the foliage (Materna, 1983). Measurements have been taken on foliar concentrations of sulfur and other elements which have been analyzed against the ambient pollutant concentrations (Materna, 1981a; Materna *et al.*, 1982), and the soil properties and site quality have been studied (Materna, 1981b; Lettl, 1984). There is also a record of the temperature development of the winters, and the relationship of forest damage and frost occurrence together with sulfur impacts has been discussed (Materna, 1974; 1979).

Although the study area is relatively small, it manifests considerable variation in both pollutant concentrations and site properties. A great deal of the variation in growing conditions is generated by the fact that the sites are located in a wide altitude range between 200 m and 1260 m. Secondly, the stations are distributed over a range of different site conditions. The long-term averages of the SO_2 concentrations fall between 10 and 90 $\mu g\ SO_2\ m^{-3}$, the areas located far from industrial and residential areas having concentrations around 20 $\mu g\ SO_2\ m^{-3}$. There was also considerable year-to-year variation in the annual average sulfur concentration even if the emissions of the neighboring industries remained the same, obviously due to meteorological conditions.

2.2. Conclusions

Pollutant input

The annual average sulfur dioxide concentration was concluded to be a sufficient description of the pollutant environment. First, sulfur was found to be the only relevant pollutant species – no long-lasting concentrations of HF or NO_x could be detected in any of the measurement stations. Secondly, the annual average concentration showed a highly significant correlation with the percentile of high concentrations, e.g. 97.5 (see Figure 1, taken from Materna, 1981a). Hence the annual average gave a good indication of the variation of the concentrations as well. Thirdly, as an indicator of the sulfur-imposed strain in the trees, the foliar concentration of sulfur was monitored, and it was found that although this concentration was explained best by the average concentration of the vegetative period, the explanation was not considerably reduced with the whole-year average (Materna, 1981a).

Damage

The analysis of the relationship between damage and sulfur concentration was guided by the dose-response approach, and the objective was to explain the time from the beginning of exposure to occurrence of damage in terms of sulfur dioxide concentration and environmental factors. Occurrence of damage was defined as the beginning of disintegration of the stand, i.e. the time when a certain percentage of the trees was heavily damaged. No significant correlations were found between the ambient SO_2 and the required time of exposure if the whole study area

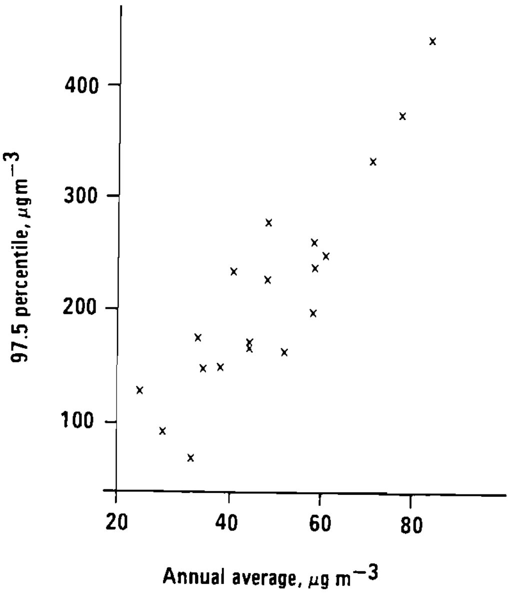

Figure 1. Relationship between the annual average SO_2 concentration and the 97.5 percentile in the measurement stations.

was considered at a time. However, if the study area was classified according to environmental factors, *altitude* appeared to explain the differences in the response best (Kucera, 1979; Materna, 1983). The differences in response due to other factors became apparent in extreme cases only, such as elevated groundwater level or extremely low nutrient content. Since the nutrient and water relations of the soils at different altitudes are variable, whereas many characteristics of the climate correlate with elevation, the results were interpreted as evidence for the direct impact pathway in interaction with climatic factors.

The main result that the annual average sulfur dioxide concentration, exposure time and altitude together explain the greatest part of the occurrence of forest damage in Czechoslovakia, is summarized in Table 1 (Materna, 1985).

Table 1. The time in years between the beginning of air pollution influence and the disintegration of Norway spruce stands.

SO_2 in $\mu g\ m^{-3}$	Elevation above sea level in m −600	−900	−1050	1050 +
−20				
20–30			30–40	20
30–50	50–60	20–30	20	
50–70	40–50	20	10	
70–90	30–40	10–15		
90 +	20–30	−10		

3. MODEL FOR DAMAGE DEVELOPMENT

3.1. General Framework

By direct impacts of pollutants on trees we understand any potentially injurous alterations in the structure or function of the foliage which are caused by a direct contamination through the air. We assume that such alterations can gradually cause increased *strain* in the whole tree (cf. Levitt, 1972). Hence, if we denote foliar strain by x, we can say

$$\frac{dx}{dt} = f(x, s, u) \tag{1}$$

where s denotes pollutant and u denotes the other environmental factors interacting with strain development. For instance, if we assume that strain increases as nutrients are leached from the foliage by acidity, u can be a measure of the occurrence of fog which enhances the leaching of nutrients in the presence of ambient sulfur.

When we consider forest damage caused by the direct impacts of pollutants, we are interested in how tree mortality is enhanced by foliar changes. We shall assume that for any environment u there is a critical level $x_0(u)$ of strain which leads to the death of a tree. Hence the tree dies if

$$\int_0^t f(x,s,u)dt \geq x_0(u). \tag{2}$$

Genetic and microclimatic variation within a stand causes differences in the rates of strain development and the threshold strains of individual trees. If the stand is sufficiently homogeneous as regards, e.g. age structure, this variation can reasonably be described by introducing stochastic variation in the threshold strain x_0. In such a case, the mortality of the stand can conveniently be described with a logistic function. Denote the fraction of dead trees in the stand by N. As a function of average strain x_0, N becomes

$$N = \frac{1}{1 + exp\,(-2(x - x_0)/\,\beta)} \tag{3}$$

where β depends on the variance of x_0 in the population (see Figure 2).

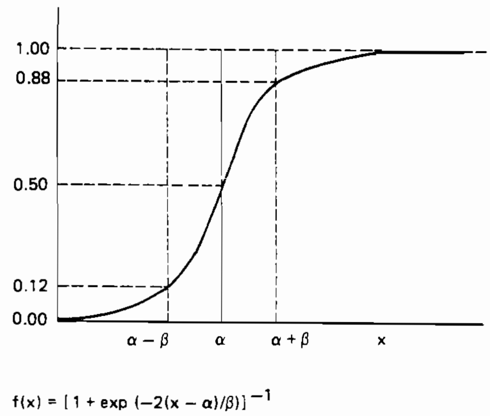

Figure 2. The logistic model for the progress of damage in a stand, measured as the number of heavily damaged individuals.

Our aim in the following sections is to identify a model which is consistent both with this general framework, and with the empirical findings in Czechoslovakia.

3.2. Driving Variables

In the empirical observations the accumulation of strain was explained best by the annual average SO_2 concentration and altitude. Among the reasons that the annual average gave a good explanation was probably the fact that the percentile of the higher concentrations showed a significant correlation with the average, hence the impacts of peak concentrations were not properly separable from the mean. Whether or not this is true of other areas is not clear; however, until better information is available we shall use the annual average SO_2 concentration as input to the model.

The sensitivity parameter, altitude, is not a causal factor in damage and cannot hence be generalized for larger areas. The good explanatory power is attributable to the fact that many climatic variables that are known to affect foliar injury and tolerance, correlate locally with altitude. Among these are occurrence of fog, amount of precipitation, windspeed, intensity of solar radiation, and most of all, temperature (e.g. Taylor, 1976). We have chosen to describe the effect of altitude with the *effective temperature sum* (ETS), which is probably the most aggregate index available for the purpose.

ETS is defined as the annual sum of daily temperatures that exceed a threshold value, conventionally 5 °C, less the threshold:

$$\mathrm{ETS} = \sum_{i=1}^{n} \delta_i \, (T_i - T_0) \tag{4}$$

where

$\delta_i = 1$ if $T_i > T_0$

$\delta_i = 0$ if $T_i \leq T_0$

n = number of days in the year

It is therefore an integrated measure of the length and warmth of the growing season. Owing to the approximately linear lapse rate of temperature along an elevation gradient, ETS is almost linear in altitude (Figure 3). It is therefore as capable of explaining the observed damage pattern as the altitude itself.

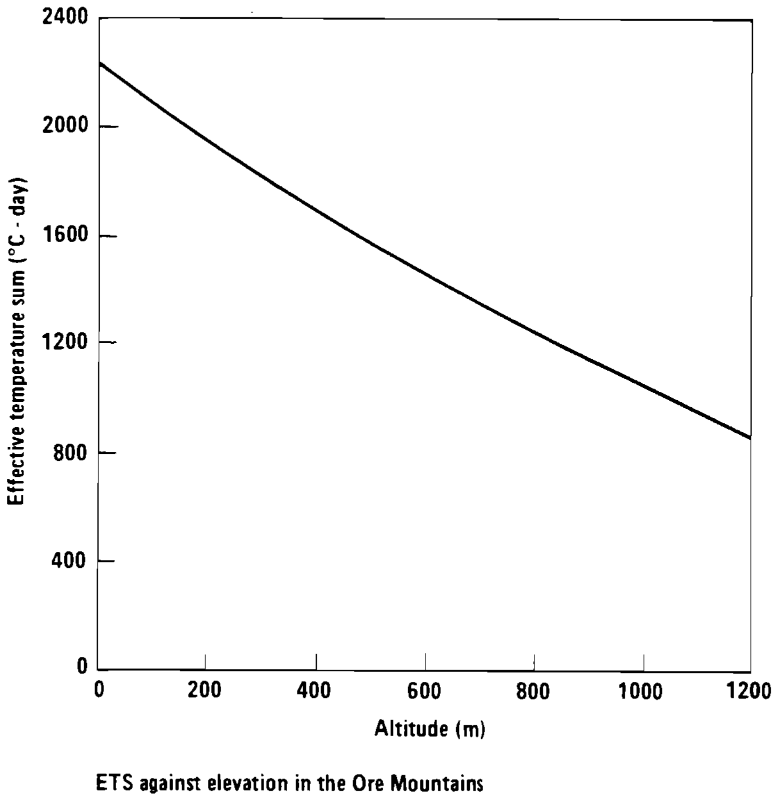

Figure 3. Relationship betwen ETS and altitude in the Ore Mountains. The method used for calculating the ETS is explained in Chapter 5.

There is also some ecological support for the choice of ETS as a resistance variable. ETS has been found to describe the regional variation in potential productivity reasonably well in those parts of Europe where the aridity of climate is not an outstanding growth-reducing factor (Sarvas, 1972; Kauppi and Posch, 1985). Productivity in turn has often been related to the surplus of carbohydrates available, e.g. for eliminating stress effects (Waring and Schlesinger, 1985). ETS can hence be considered to describe well the part of variation in response which is due to tolerance of strain, i.e. the environmental variables u in x_0 (Eq. 2). It also reflects at least some aspects of the environmental impact on the rate of accumulation of strain (Eq. 1). It has been argued that foliar injuries occur faster if the winter is longer because the frost and winter time drought stresses act synergistically with air pollutants (Materna, 1979; Huttunen *et al.*, 1981; Friedland *et al.*, 1984; Laine *et al.*, 1984; Feiler, 1985). Clearly, long winter and low ETS correlate; however, the correlation may vary from maritime to continental areas.

3.3. Model Structure

As the data set is not large enough for comparisons between many alternative model structures, we adopt the simplest possible assumption; that the rate of development of strain, x, is directly proportional to the sulfur dioxide concentration, S, less a threshold value, S_0. The threshold depends on the nutritional status of the plant. Since we focus on direct rather than indirect effects, we assume that S_0 is a spatial (and temporal) constant. Secondly, the rate of strain development may depend on the resistance factor ETS. Let us denote this dependence by r(ETS). Hence

$$\frac{dx}{dt} = \begin{cases} r(\mathrm{ETS})(S - S_0) & \text{if } S > S_0 \\ 0 & \text{if } S \leq S_0 \end{cases} \tag{5}$$

Further, we say that standard injury occurs when 50% of the trees in the stand are damaged, i.e. when

$$x = x_0(\mathrm{ETS}) \tag{6}$$

where x_0 is the threshold strain triggering injury.

Note that the model does not include reduction of strain. Although it is known that recovery may occur (Drummond and Wood, 1967), it was not possible to identify such a term from the measurements because the trend in pollutant concentrations was primarily ascending. On the other hand, the empirical conclusions indicate very long delay times.

3.4. Parameters

Identifiability of the model

The results of the Ore Mountains study can be used for estimating the parameter values for the model as regards Norway spruce (*Picea abies*). The data available are of the type shown in Table 1, i.e. observations concern the time from beginning of exposure to standard damage, the corresponding long-term average sulfur dioxide concentration, and altitude (or ETS) class.

If the temporal average of S is S_{av} and for all times t the actual concentration exceeds the threshold, $S(t) > S_0$, then

$$\int_0^t (S(\tau) - S_0)\, d\tau = (S_{av} - S_0)\, t \tag{7}$$

and hence at the time of damage occurrence, t_f, the following holds [Eqs. (5) and (6)]

$$(S_{av} - S_0)\, t_f = \frac{x_0(\text{ETS})}{r(\text{ETS})} \tag{8}$$

If we have data concerning S_{av}, t_f and ETS, this equation does not allow us to separate the functions x_0 and r. Therefore, let us denote

$$Q_0(\text{ETS}) = \frac{x_0(\text{ETS})}{r(\text{ETS})}. \tag{9}$$

Given S_0 and data points (S_{av}, t_f, ETS), we can now select the function $Q_0(\cdot)$ to fit the left-hand side of (8). However, to be able to utilize this relationship in the model, we have to modify Eqs. (5) and (6), respectively. Let us define $Q(t)$ as follows

$$Q(t) = \frac{x(t)}{r(\text{ETS})} \tag{10}$$

Substituting this into (6) implies that damage occurs when

$$Q(t) = Q_0\ (\text{ETS}) \tag{11}$$

This reduces the model to the following form

$$\frac{dQ}{dt} = \begin{cases} (S - S_0) & \text{if } S > S_0 \\ 0 & \text{if } S \le S_0 \end{cases} \tag{12}$$

with damage occurring if

$$Q \ge Q_0(\text{ETS}) \tag{13}$$

Eqs. (12) and (13) constitute the conventional dose-response model (O'Gara, 1922), with the modifications that it is in differential instead of static form, and that the threshold dose, Q_0, has been parameterized in terms of ETS. This model can be uniquely identified from the type of available data that we have.

Estimation of parameters

The information in Table 1 is the only source of data that has been available for parameter estimation to date. Instead of a collection of points in the (S_{av}, t_f, ETS) space the table provides cubes where such points are most likely to be located, but we have no information on the actual occurrence of points within each cube. So as to estimate model parameters on the basis of this information, we drew points from the cubes at random from a uniform distribution and fitted the model to these fake data points.

Table 2. Cubes in the (S_{av}, t_f, ETS) space used in parameter estimation.

ETS S	850–950	950–1150	1150–1500	1500–1950
20–30	19–21	30–40		
30–50		20–30	20–30	50–60
50–70		10–20	15–20	15–20
70–90			10–15	30–40
90–110			5–10	20–30

The ranges of the variables that were used in the estimation are shown in Table 2. The altitude classes were converted to ETS classes using the method of Henttonen and Mäkelä (1987), already referred to in Figure 3. The higher and lower bounds correspond to those of the monitoring area, viz. 200 m and 1240 m.

Note that even if no range for t_f is given in Table 1, we have considered a range of values rather than a single point.

An equal number of points, N=816, was drawn from all ETS classes. If several S_{av} classes occurred in the same ETS class, i, an equal number of points, m_i, were drawn from all. The number of points was chosen large enough such that the original information was conserved and the points filled the cubes approximately uniformly. In comparison with the theoretical distribution, the maximum error in the mean within a cube was 0.9%. The maximum error in the 25%, 50% and 75% percentiles as well as in the maximum and minimum values was ~2%.

The task for parameter estimation is to find (1) a threshold value S_0 and (2) a polynomial Q_0(ETS) such that the model

$$y(S_0) = Q_0(\text{ETS}) \tag{14}$$

where

$$y(S_0) = (S_{av} - S_0)\, t_f \tag{15}$$

provides the best fit to the data.

First, we selected the order of the polynomial Q_0(ETS) by fitting a first, second and third order polynomial to $y(0)$ and comparing the residuals visually against ETS. The conventional least squares method was used. Since the trend shown by a straight line was removed by introducing a quadratic term, but a third order term no longer improved the result, the quadratic curve was selected. Second, the threshold S_0 and the corresponding coefficients of the polynomial were chosen by comparing the correlation coefficients of the best fit curves for a number of S_0 values.

The results are summarized in Tables 3 and 4.

Table 3. R^2 in the best fit quadratic model for a range of threshold values S_0.

S_0	0	3	4	5	6	7	9	11
R^2	0.769	0.771	0.772	0.772	0.772	0.772	0.770	0.768

Table 4. Best fit coefficients for S_0 = 5.

Variable	Coefficient	t Ratio
1	367.0723	2.91921
ETS	−0.8950009	−4.54854
ETS_2	0.001113854	15.27340

4. ASSESSMENT OF RISK

When applying the derived model for assessment of risk, we have to take into account the time span of the future projections and the spatial scale of the desired output, and attempt to simplify the regional-temporal output to be informative in a large-scale system also. The following two sections aim at such simplifications, and Subsection 4.3 summarizes the application of the model for deriving regional indicators of future risk of damage.

4.1. Temporal Limits of Strain Development

The theoretical maximum time of accumulation of strain is the lifetime of the tree. If the critical dose is not achieved in this time, damage will not occur. The average growth rates of stands vary according to the climate. Consequently, the generally applied rotation times vary. This variation roughly follows the effective temperature sum which is an indicator of the average growth rate.

We have used information from an international questionnaire to estimate the relationship between the rotation time, T_R, and ETS. Rotation times were provided by region and altitude in a number of countries. The corresponding ETS values were calculated at the center points of the region and the altitude class using the method of Henttonen and Mäkelä (1987). An exponential function,

$$T_R = \alpha e^{k \, \mathrm{ETS}}, \tag{16}$$

was fitted to the points with the least squares method (see Figure 4).

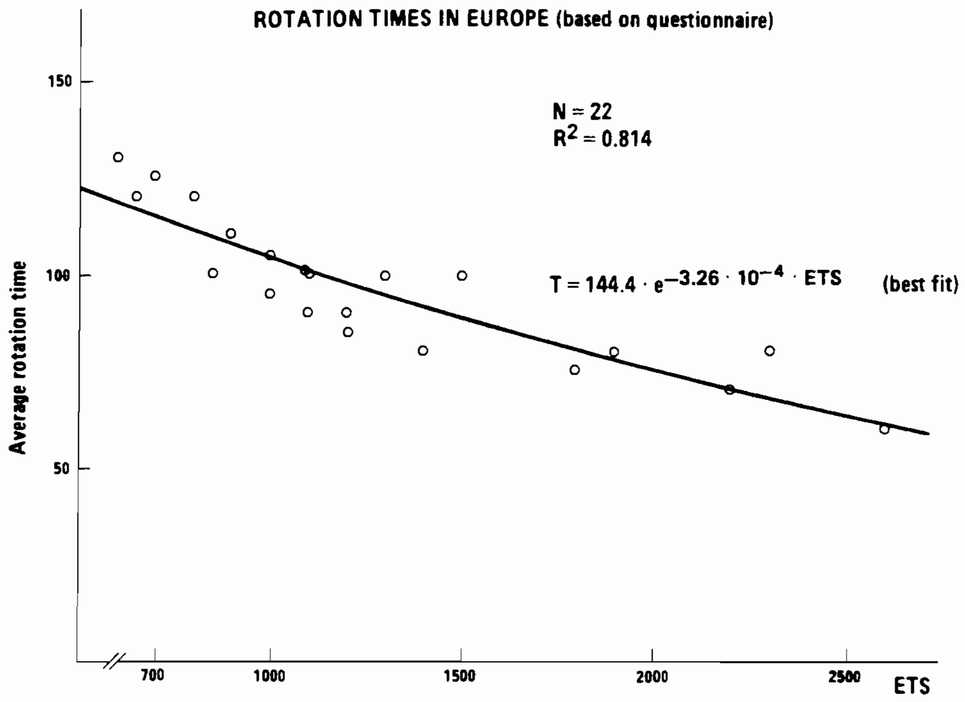

Figure 4. Rotation times of spruce forests as a function of ETS. The data points represent Sweden, Norway, Finland, Austria and Hungary.

If we require that the threshold dose is not reached during the rotation time of the stand, then, by Eqs. (12) and (13), the concentration development has to fulfill the following

$$\int_{t-T_R}^{t} \max\{0, (S(\tau) - S_0)\} d\tau \leq Q_0 \tag{17}$$

If $S(\tau)$ is constant, then

$$S \leq S_0 + \frac{Q_0}{T_R} \tag{18}$$

Since both Q_0 and T_R are functions of ETS, we can express the "threshold concentration", S_T, of no damage during the rotation time as a function of ETS:

$$S_T = S_0 + \frac{1}{a} e^{-k\,\mathrm{ETS}}(a_0 + a_1\,\mathrm{ETS} + a_2\,\mathrm{ETS}^2) \tag{19}$$

This relationship is depicted in Figure 5, and it roughly coincides with the intuitive conclusions made earlier (Materna, 1985). The same can be done for the maximum general lifetime, resulting in slightly lower threshold concentrations.

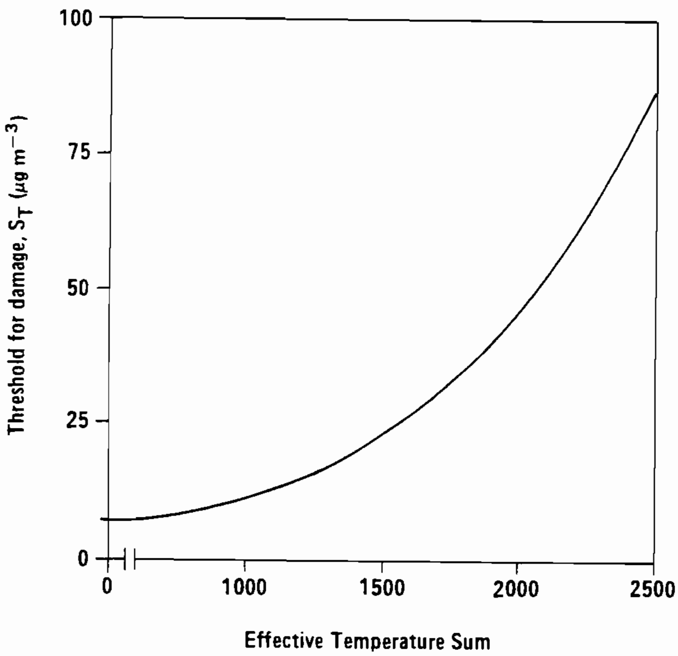

Figure 5. Calculated threshold concentrations of sulfur as a function of ETS.

4.2. Risk Levels of Forest Areas

Consider a forest area with a distribution of stands of various ages at a moment t. We say that there is no risk of damage at that moment if the accumulated dose for the eldest stand in the area has not reached the critical dose. If it has, the degree of risk can be measured as the areal fraction of stands that are old enough to have received the critical dose. We shall evaluate this measure by comparing the exposed situation with the normal desirable situation at a steady state, omitting the actual dynamics of mortality and regeneration.

Let $T_M(t)$ denote the minimum age of stands that have reached the critical dose by the year t. $T_M(t)$ has to satisfy the condition

$$\int_{t-T_M}^{t} \max\{0, (S(\tau) - S_0)\} d\tau = Q_0 \tag{20}$$

Further, denote the normal maximum lifetime of stands by T_L. If the desired density distribution of forest into age classes is $f(x)$, the areal fraction of damaged stands is

$$\int_{T_M}^{T_L} f(x)dx \tag{21}$$

We define this fraction as the ***degree of damage***.

Figure 6 shows a frequent age distribution of forests (example from Austria). In this case, $f(x)$ can be estimated with a linear function

$$f(x) = \frac{2}{3}\frac{1}{x_{av}}(1 - \frac{1}{3}\frac{x}{x_{av}}) \tag{22}$$

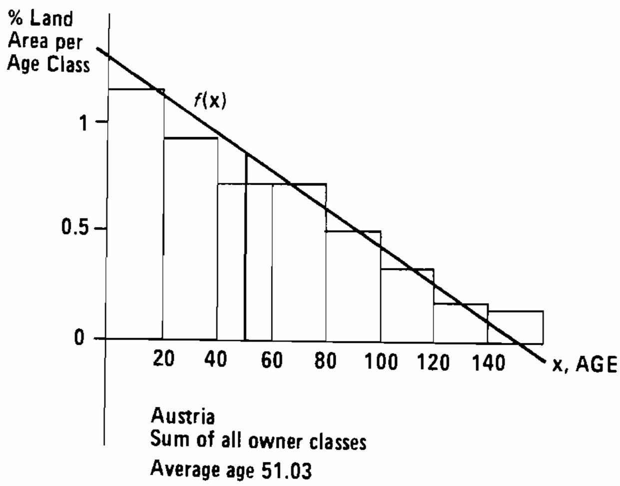

Figure 6. The age distribution of forest area in Austria (Osterreichische Forstinventur 1971–1980).

where x_{av} is the average age. The maximum age in the function is $3x_{av}$. The corresponding degree of damage as a function of T_M is shown in Figure 7, calculated by Eq. 18. It is also compared with a linear estimate of degree of damage which obtains the value 0 at $2x_{av}$, a reasonable estimate for the rotation time.

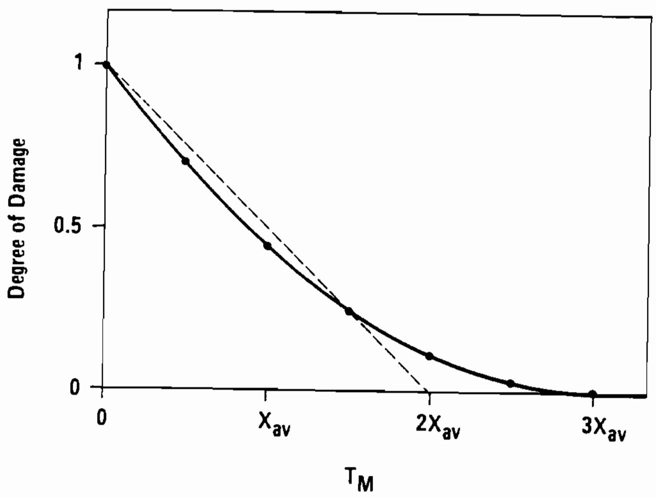

Figure 7. Calculated degree of damage in a forest area where the age distribution is as in Figure 6 (solid line) and uniform between 0 and $2x_{av}$ (broken line), as a function of the maximum lifetime T_M under the prevailing pollutant conditions.

4.3. Summary of the Model

Figure 8 summarizes the model derived above. The inputs are ETS and the time development of the annual average sulfur dioxide concentration, and the output is risk of damage, R. As intermediate variables, we determine the maximum tolerable dose, Q_0, and the rotation time, T_R, on the basis of ETS

$$Q_0 = a_0 + a_1 \mathrm{ETS} + a_2 \mathrm{ETS}^2 \tag{23}$$

$$T_R = a\, e^{k\,\mathrm{ETS}} \tag{24}$$

Then we calculate the time that is sufficient to reach the maximum dose under the prevailing conditions and the given ambient sulfur history, T_M. By definition, it has to fulfill the following

$$\int_{t-T_M}^{t} \max\{0, (S(\tau)-S_0)\}\, d\tau = Q_0 . \tag{25}$$

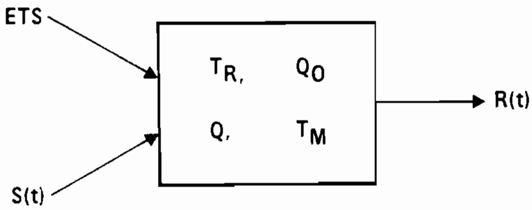

Figure 8. Illustration of model input, output and internal variables. Explanation of symbols in the text.

The risk level is calculated using the assumption that the unpolluted age distribution is linear, as in Figure 7, and taking the rotation time as double the average age. It follows that the maximum age in the distribution is 3/2 T_R. Hence, using Eq. (22)

$$R = \int_{T_M}^{\frac{3}{2}T_R} \frac{1}{3}\frac{1}{T_R}\,(1-\frac{2}{3}\frac{x}{T_R})\, dx \tag{26}$$

Table 5 summarizes the model parameters for Norway spruce.

Table 5. Parameter values.

Symbol	Value	Unit
S_0	5	$\mu g\ m^{-3}$
a_0	367	$\mu g\ m^{-3}$ a
a_1	-0.895	$\mu g\ m^{-3}$ (°C d)$^{-1}$
a_2	1.11 10^{-3}	g m^{-3} (°C d)$^{-2}$
α	144.4	a
k	-3.26 10^{-4}	°C^{-1-1}

5. RISK LEVELS IN EUROPE

In this chapter we display the model output in Europe, as it results from different sulfur emission scenarios for the period 1960–2040. We use the RAINS model for projecting the ambient sulfur levels, and a three-dimensional, geographic data base for ETS and forest area.

5.1. Input

Sulfur dioxide

The sulfur dioxide scenarios are obtained from the energy and emission submodules of the RAINS model (Alcamo *et al.*, 1985; 1987). The model uses annual energy consumption data which have been split up by energy sectors and computes the corresponding sulfur emissions by sector and country. Official energy data in the period 1960–1985 are used, and future scenarios provided by individual countries and international organisations project the energy use up until 2040. We initialize the model with a "historical sulfur emission scenario" by setting the SO_2 concentrations between 1900 and 1960 proportional to estimates of European scale SO_2 emissions by Müller (1984) and Semb (1978).

For calculating sulfur transport and deposition, Europe is divided into a geographical grid with elements of the size 150 × 150 km^2. The country-based emission information is distributed over the grid elements according to a 1980 emission inventory. This assumes that the geographical location of emittors does not change over time. A source-receptor matrix is used for transforming the annual emissions to annual deposition and SO_2 concentration per grid element. The matrix is based on the EMEP transport model (Eliassen and Saltbones, 1983) which uses detailed meteorological data for calculating individual trajectories of sulfur particles. This model describes sulfur transport in a 1 km high mixing layer, not accounting for surface roughness.

Three energy scenarios are used in the model runs: (1) the ***official energy pathway***, as published by the International Energy Agency and the Economic Commission for Europe, (2) ***30% reductions*** in sulfur emissions from the 1980 level, and (3) ***major sulfur controls***, involving a concerted SO_2 emission reduction program (for details, see Alcamo ***et al.***, 1987). Figure 9 shows more isolines of the annual average SO_2 concentration (in units $\mu g\ S\ m^{-3}$ in Europe.

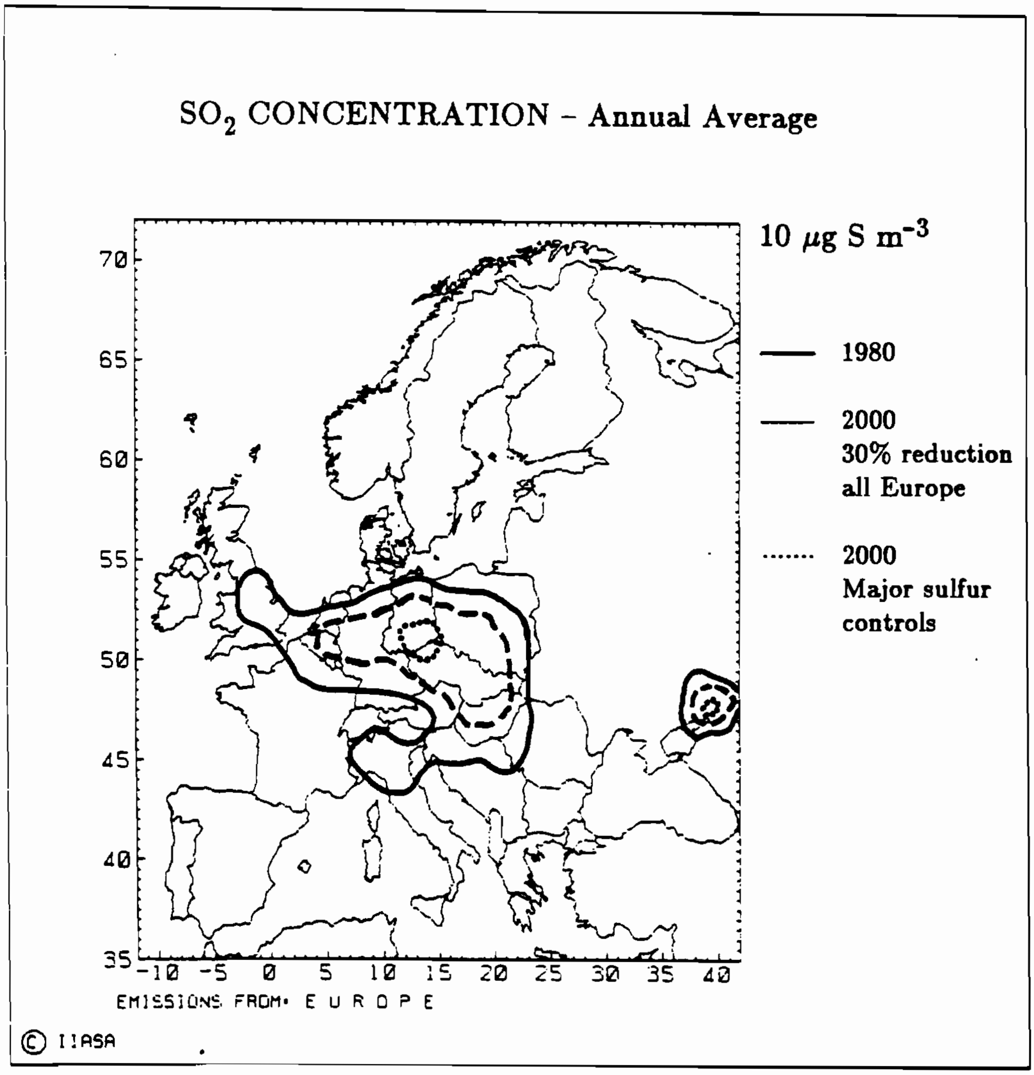

Figure 9. Isolines of annual average SO_2 concentrations in Europe (in units μg S m^{-3}).

Effective temperature sum

For estimating the ETS, we use the $150 \times 150\,km^2$ EMEP grid, subdivided into altitude classes. The resolution of the vertical axis varies with respect to the maximum altitude, comprising 300 m in Central Europe and 100–200 m in Northern Europe. ETS values are calculated at the centre point of each grid element and altitudinal range.

The ETS values for each location are calculated from corresponding estimates of monthly average temperatures. A spline of daily temperatures is fitted to the monthly mean values, accounting for the standard deviation of temperature such that the mean values are conserved. The ETS is calculated in a standard way using the resulting daily values (Ojansuu and Henttonen, 1983). The monthly mean temperatures are obtained from standard weather station data using an interpolation method; 1088 weather stations are included, with dense networks in Austria, Britain and Scandinavia, and a sparser network for the rest of Europe (Müller, 1980). The data are mostly average values from 1930–1960, but some of them represent the period 1950–1985. The interpolation is based on fitting a linear function that depends upon the spatial coordinates (latitude, longitude and altitude) and the distance from the sea, to all data, and correcting the result with information from the nearby stations. The method is described in detail in Henttonen and Mäkelä (1987).

In Figure 10, the ETS values in Europe are depicted for the area that has been included in the computerized data base to date. The value in each grid element is the mean over altitude classes, weighted linearly with the area of forest.

Forest area

In the calculations, only forest area is considered. The distribution of forested area in Europe is stored in the data base with the resolution of 1° latitude and 0.5° longitude. The distribution of forested area was obtained from two map series, both including the altitudinal variation and forest cover (1404 World,

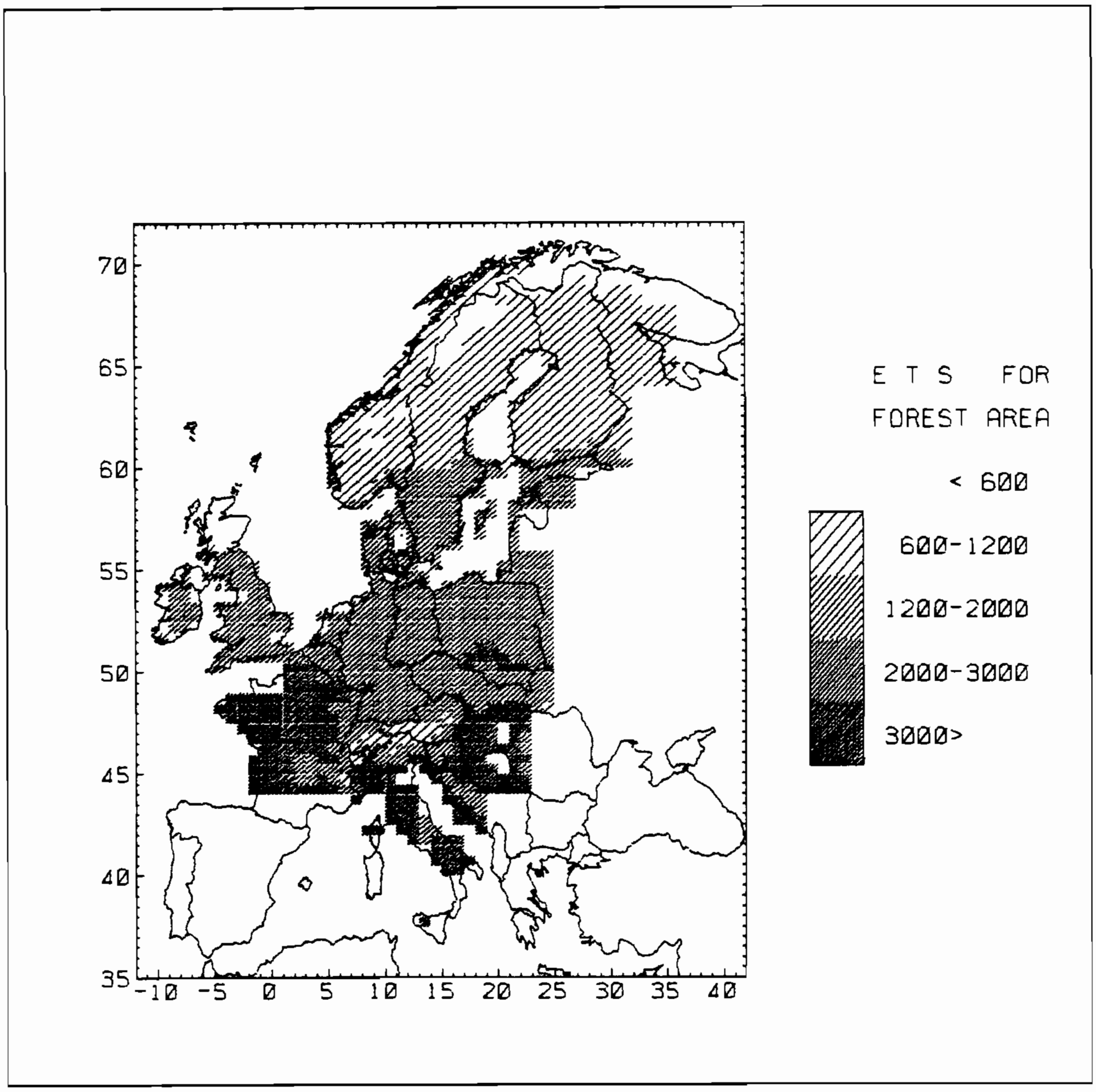

Figure 10. Effective Temperature Sum (ETS) in Europe. The value in each grid element is the mean over altitude classes, weighted with the forest area.

1:500,000, topographic map series, and TPC 1:500,000, aeronautical map series).

Figure 11 shows the geographic distribution of forest coverage in Europe in the part of the data base that has been computerized to date.

5.2. Output: Risk Levels

We display the degree of risk as defined in Subsection 4.2, classified into three categories:

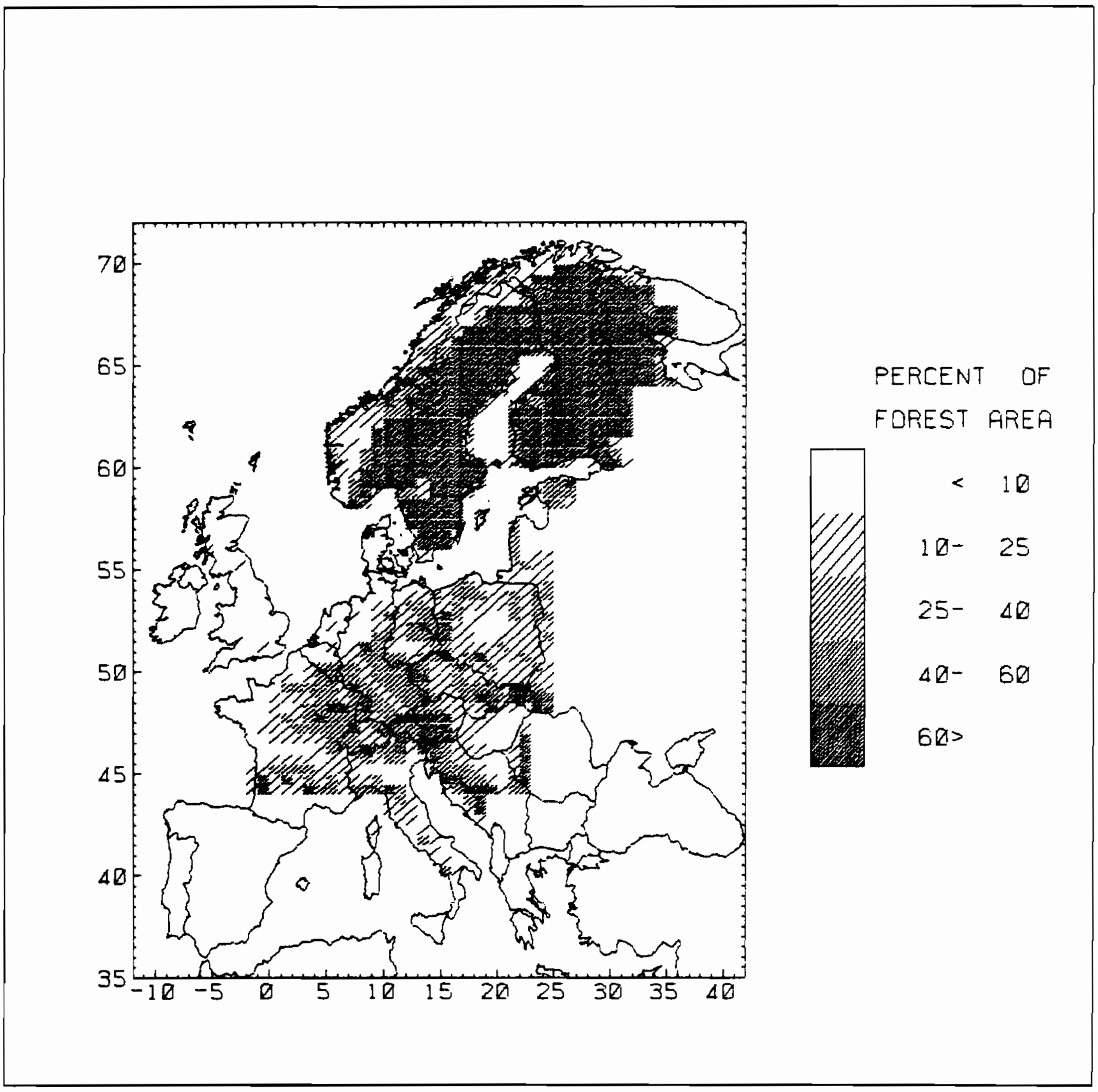

Figure 11. Forest coverage in Europe.

(1) high risk $T_M \leq \frac{1}{2} T_R$

(2) medium risk $\frac{1}{2} T_R \leq T_M \leq T_R$

(3) low risk $T_R \leq T_M \leq \frac{3}{2} T_R$

where T_M is the maximum lifetime of trees under the prevailing pollutant conditions, and T_R is the rotation time.

Figure 12 shows model prediction of the distribution of high risk areas in Europe in the year 2000 under different energy pathways. As the sulfur history is the same until 1980 for all scenarios, and the reductions do not become really effective until after the year 1990, there are only minor differences between scenarios. In accordance with the assumptions, the model picks out those high altitude areas where the SO_2 concentration is permanently high. The model implies relatively high risk for the Alps, probably mainly because of the altitude factor. The Black Forest in the Federal Republic of Germany, where heavy damage has been reported, does not seem to be susceptible to foliar effects of sulfur.

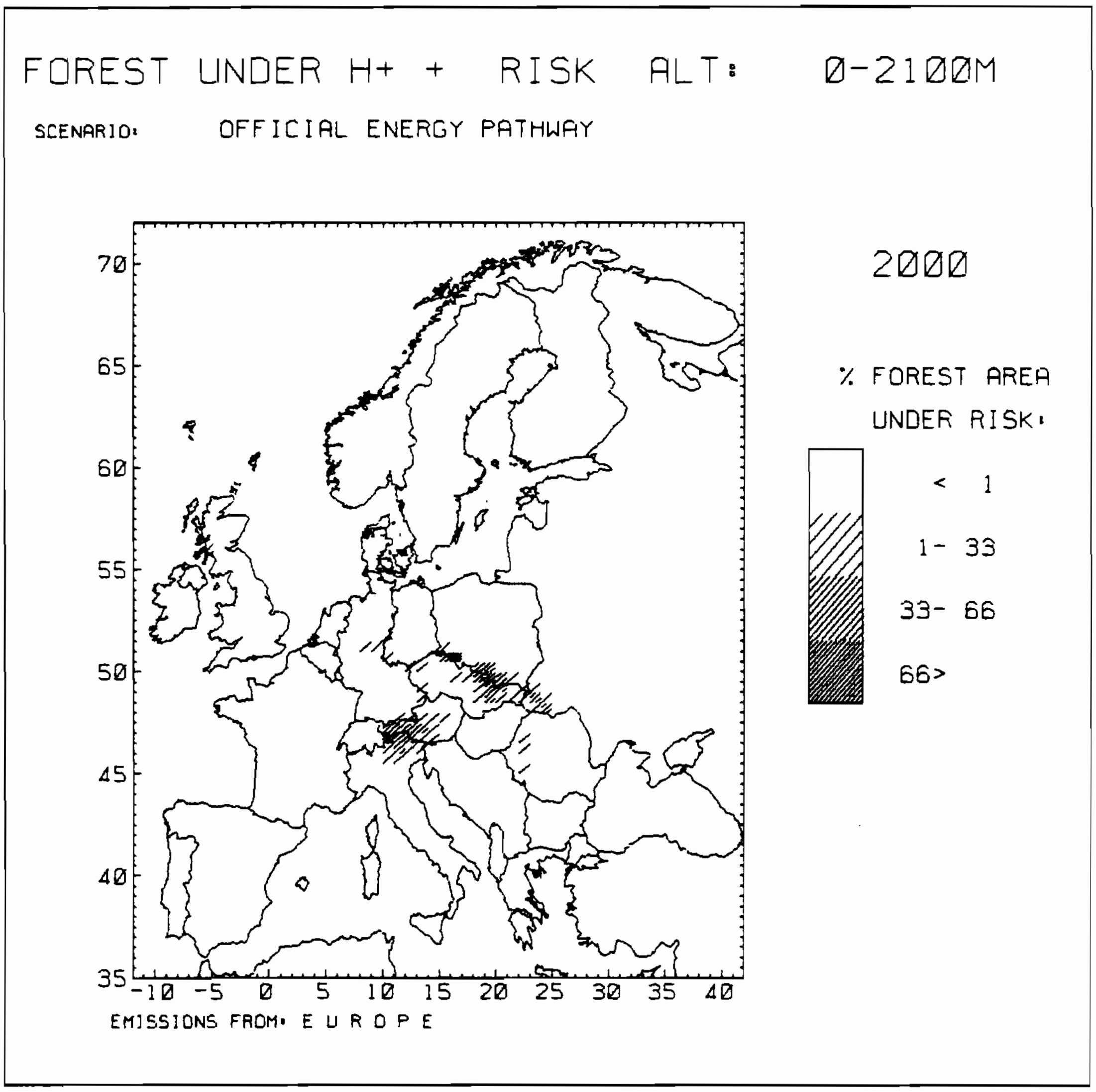

Figure 12. Areas of high risk ($T_M \geq 1/2\ T_R$) for the year 2000. (a) official energy pathway; (b) 30% reductions; (c) major sulfur controls.

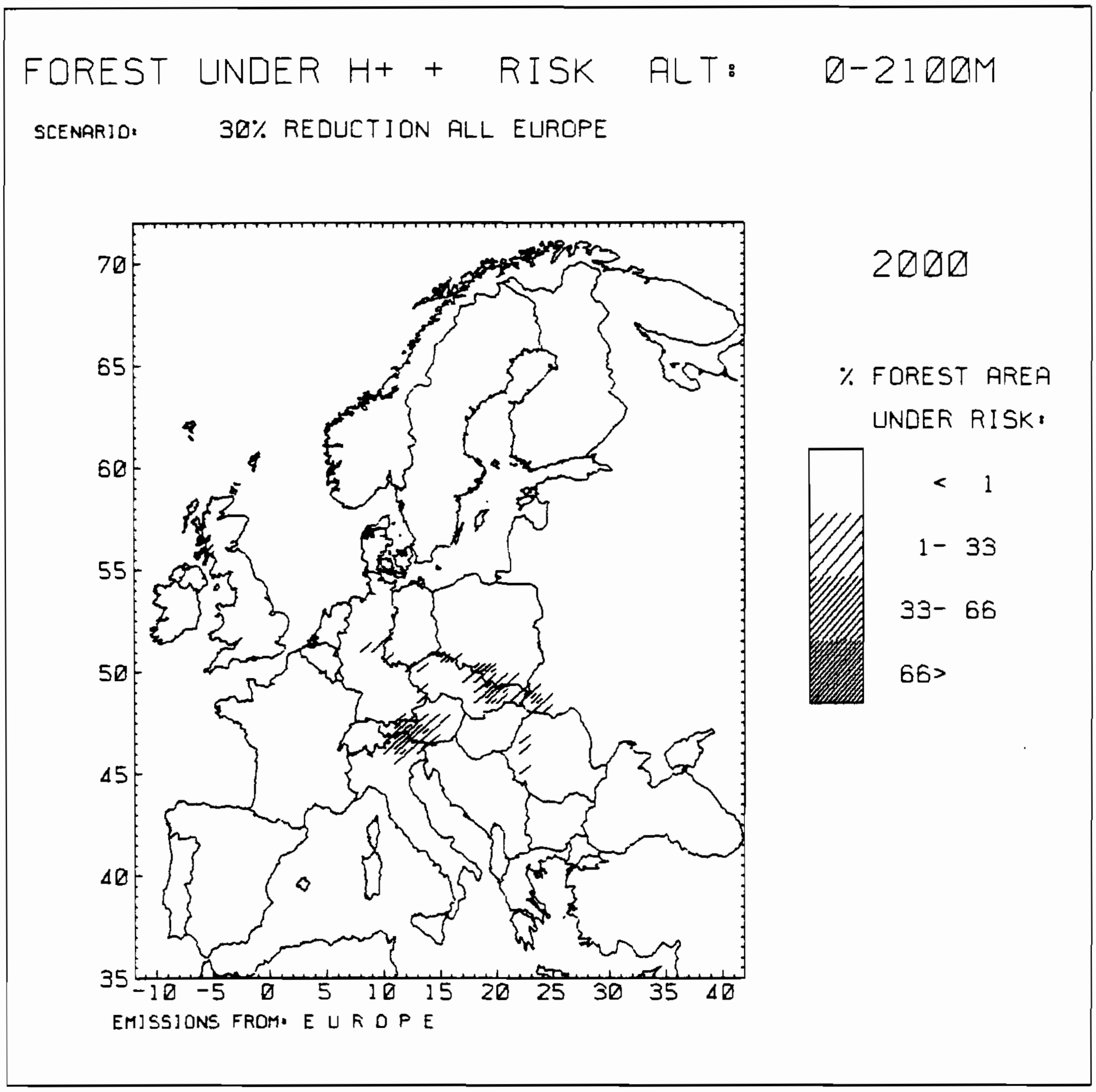

Figure 12. continued

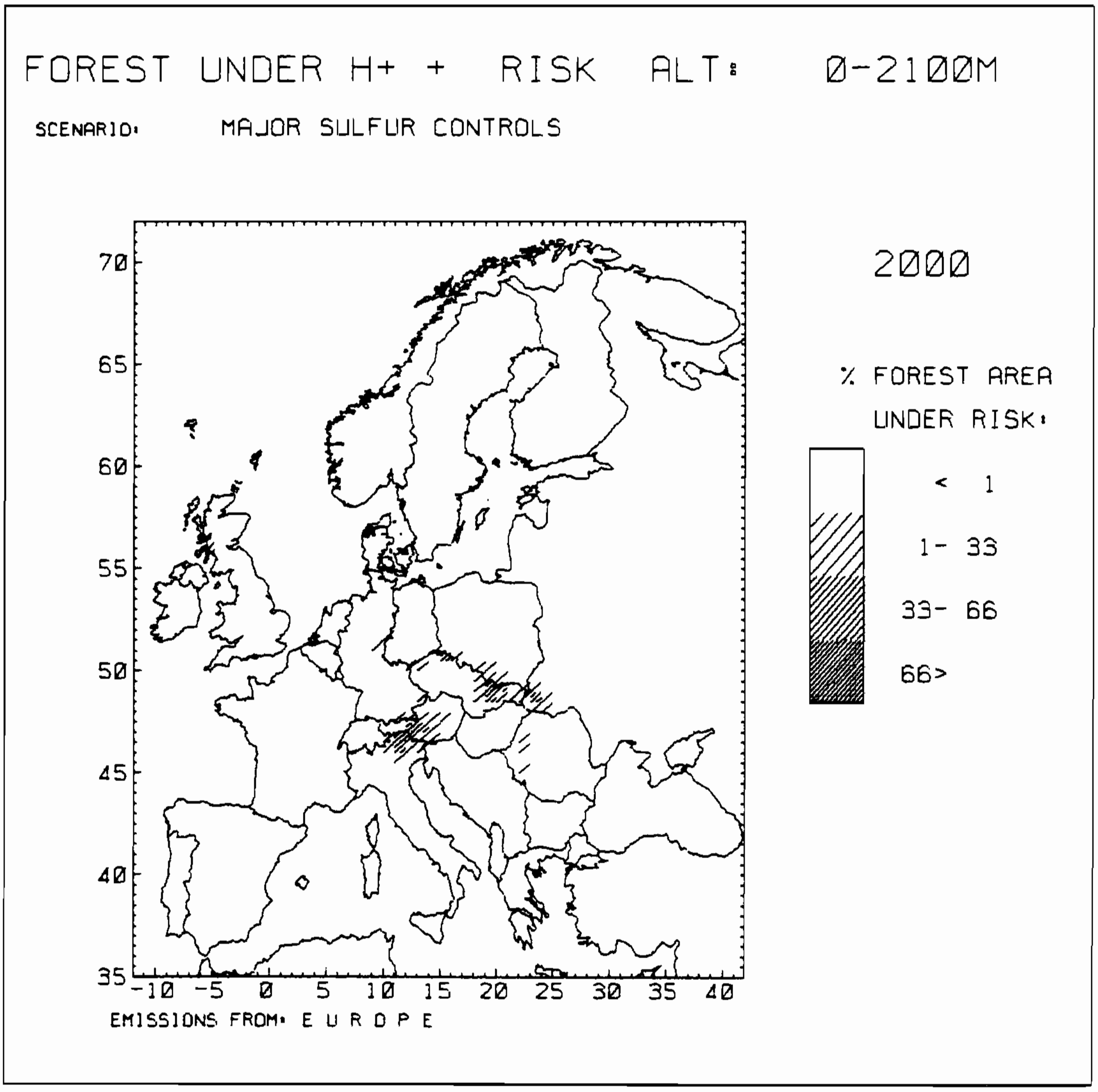

Figure 12. continued

Figure 13 repeats the comparison of scenarios for the year 2040. The differences between the scenarios now become apparent. The official energy pathway implies an increase in the high risk areas, and the 30% reduction scenario more or less conserves the situation of 2000, with the only exception that the risk area around the Harz Mountains has disappeared in the 2040 situation. The major sulfur controls scenario produces a significant reduction in the area of high risk.

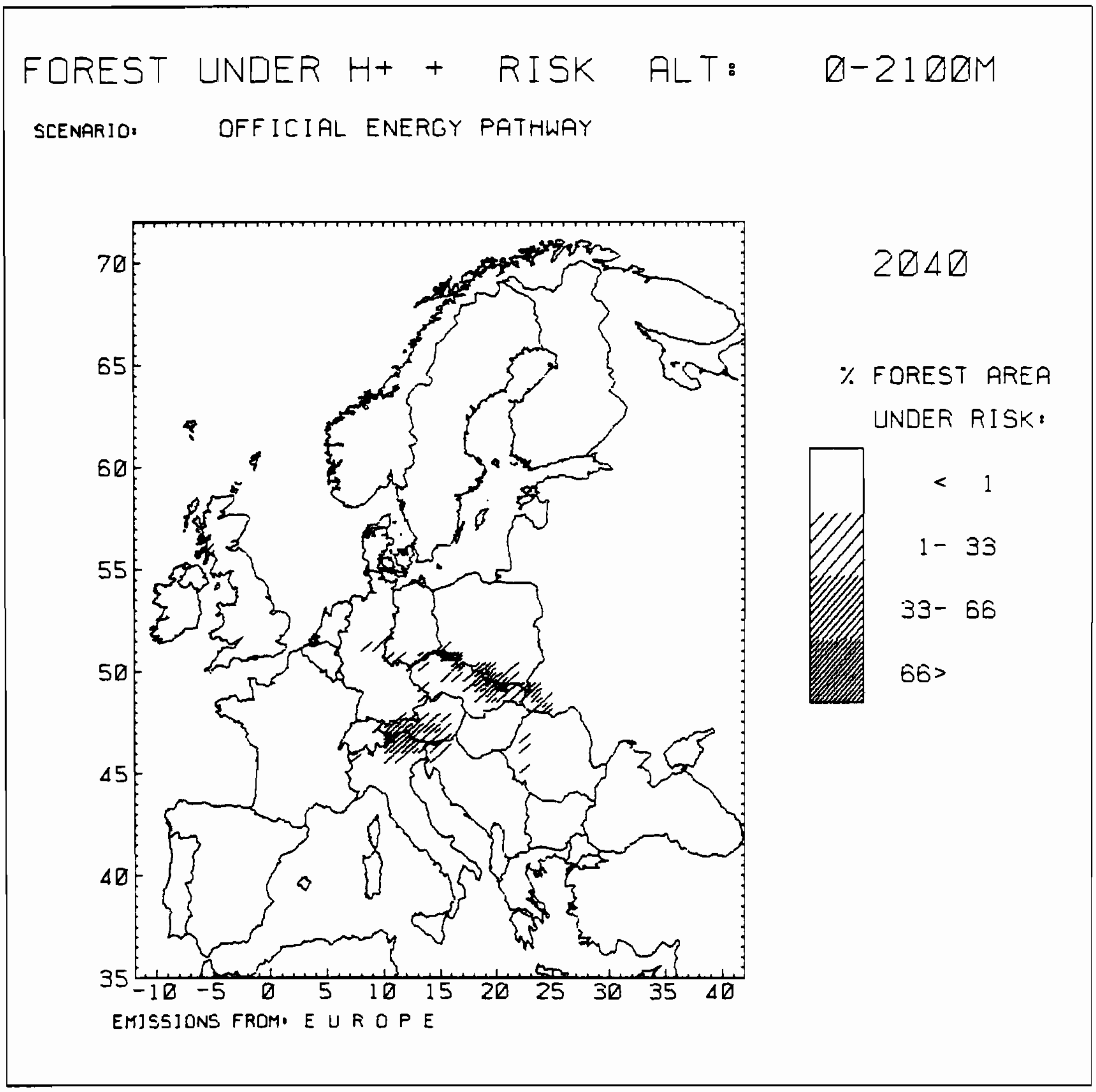

Figure 13. Areas of high risk ($T_M \geq 1/2\ T_R$) for the year 2040. (a) official energy pathway; (b) 30% reductions; (c) major sulfur controls.

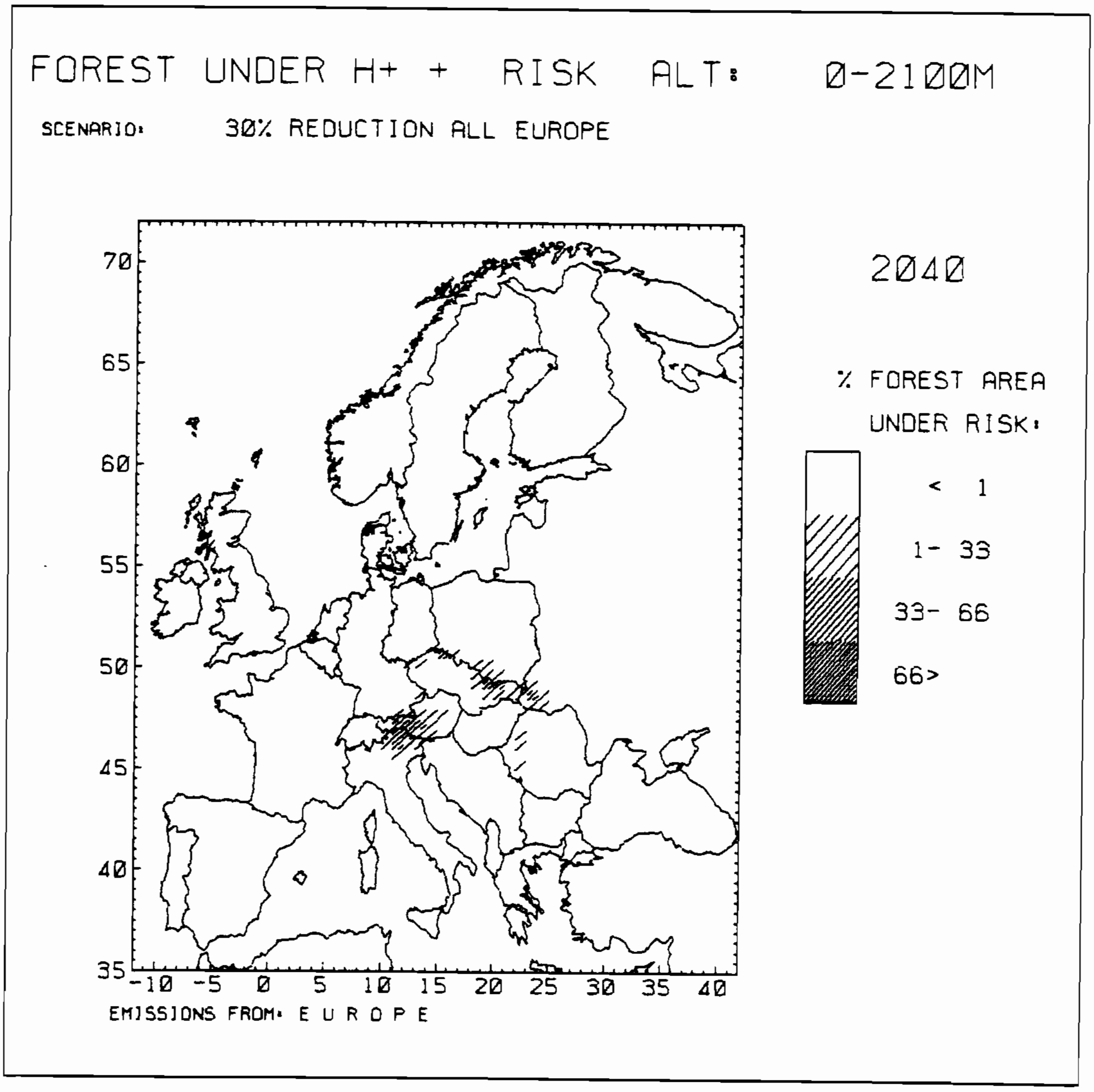

Figure 13. continued

For reference, Figure 14 shows areas of high risk in 1960 and 1980 as model 'predictions'. Figure 15 depicts high and medium risk in the year 2000 both in all altitudes and altitudes below 1050 m, to illustrate that the risk area in the Alps is in the high altitude classes only. The comparison of Figure 15 with Figure 12 shows that the high and medium risk areas occur in the same locations, the difference between them being only the intensity of predicted risk.

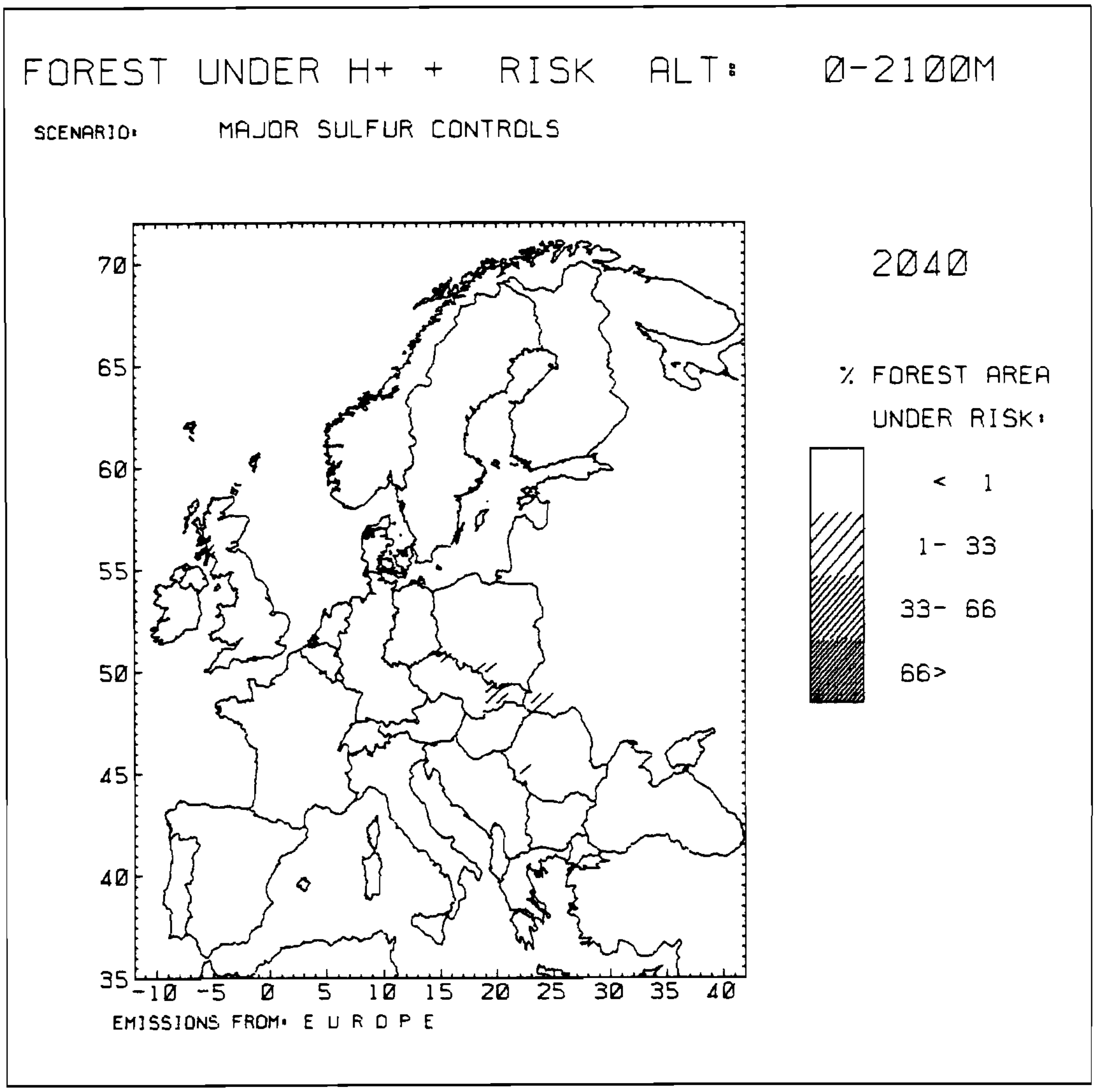

Figure 13. continued

6. DISCUSSION

The present model is built upon two basic assumptions that (1) foliar injury can cause an accumulation of strain which is not discharged, and (2) the effective temperature sum aggregates the climatic variables that are relevant for (a) the avoidance of accumulation of strain, and (b) the tolerance of the accumulated strain. As already noted, the first assumption relates to the observation that there is a considerable delay between beginning of exposure and occurrence of

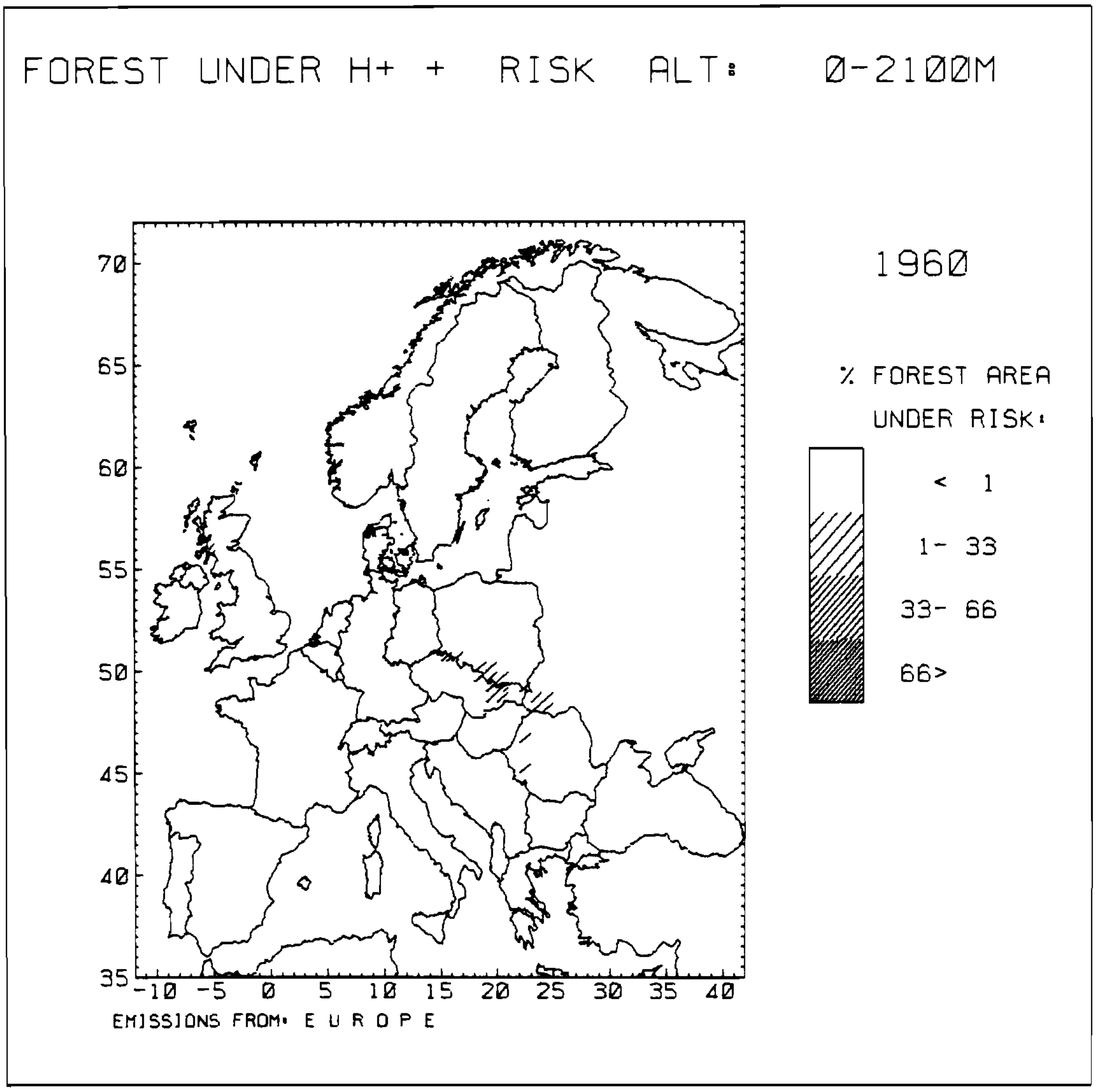

Figure 14. "Risk history" as predicted by the model. (a) high risk areas in 1960; (b) high risk areas in 1980.

damage on one hand, and the failure of soil acidification to explain the pattern of damage on the other hand. However, the mechanisms of a delayed response to injury have not yet been physiologically explained.

The fact that the model fails to account for the possible impacts of climatic factors not correlated with ETS, is particularly important as regards wind speed and occurrence of mist. The former has been claimed to increase pollutant uptake by the canopy, and the latter has an impact on the rate of cuticular erosion caused

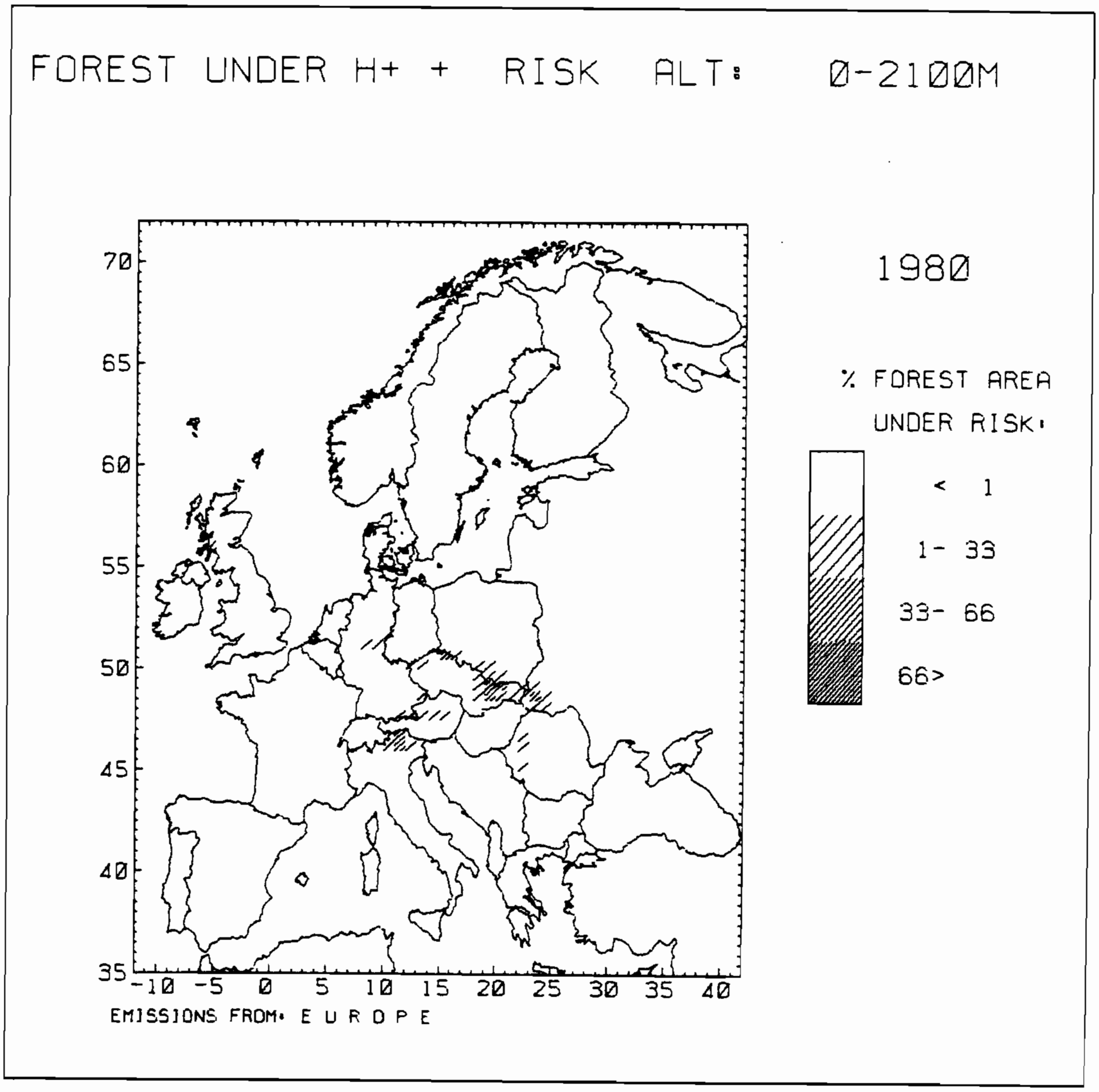

Figure 14. continued

by sulfur (Materna, 1986). Both effects thus increase the rate of foliar strain development. As regards the reaction of the whole tree to the foliar changes, we have deliberately chosen to exclude factors such as site class and stand age from the model, because (1) the empirical observations do not provide enough material for deriving proper relationships, (2) we are basically interested in direct impacts, and (3) in the regional application the site quality and age classes have high resolution and are likely to average out over the grid elements.

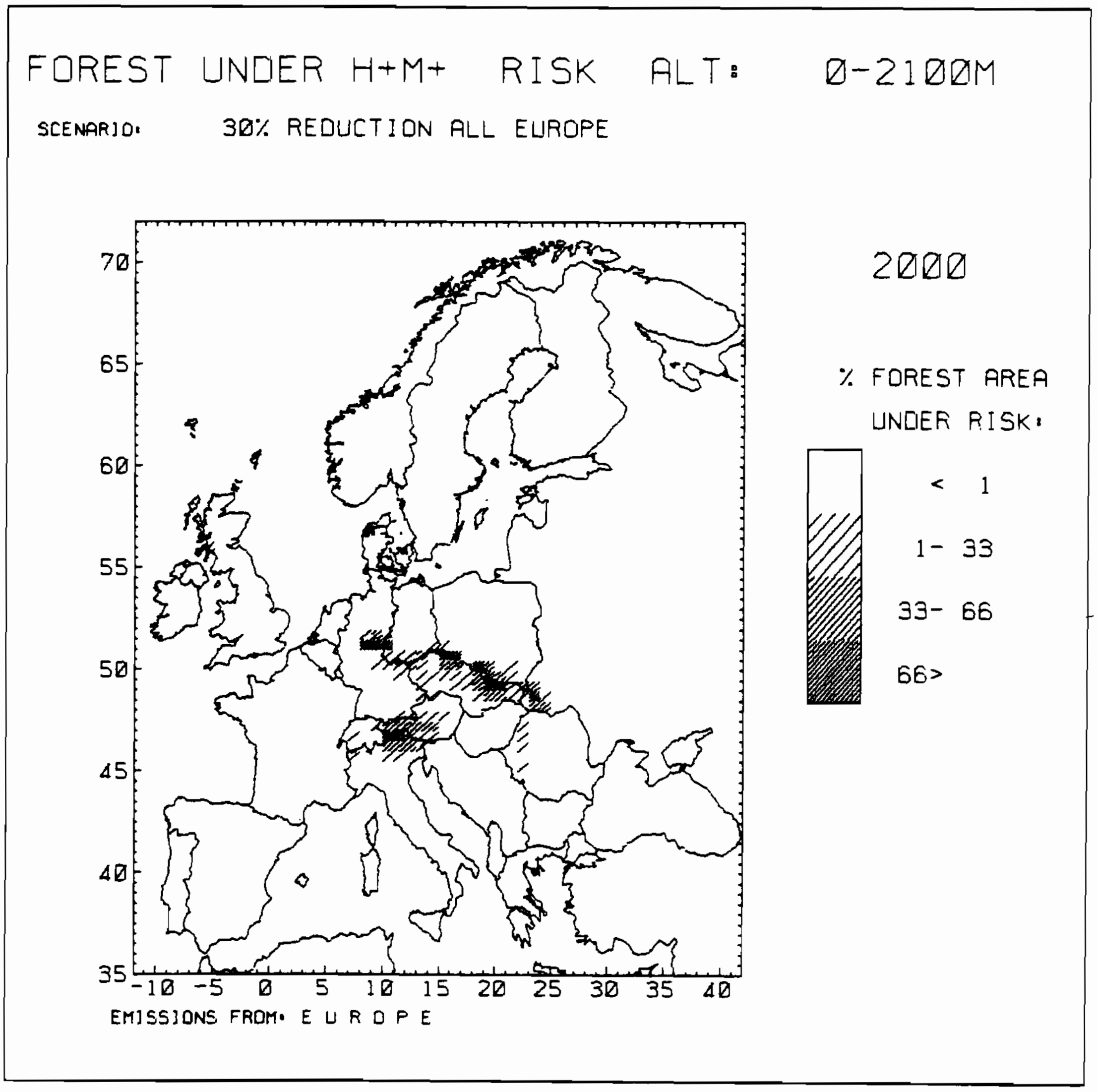

Figure 15. Distribution of high and medium risk ($T_M \geq T_R$) in the year 2000. (a) all altitude classes; (b) altitudes below 1050 m.

Although these questions cannot be properly settled without studying the actual mechanisms of damage development, a better interaction between model building and the analysis of data could probably also help in solving some of them. In the present study, the authentic measurements were not available for model identification. Instead, we drew from conclusions obtained independently, and fed these conclusions into the general model structure of Chapter 3 in a more or less *ad hoc* way. This drawback can hopefully be overcome in the future, and the model

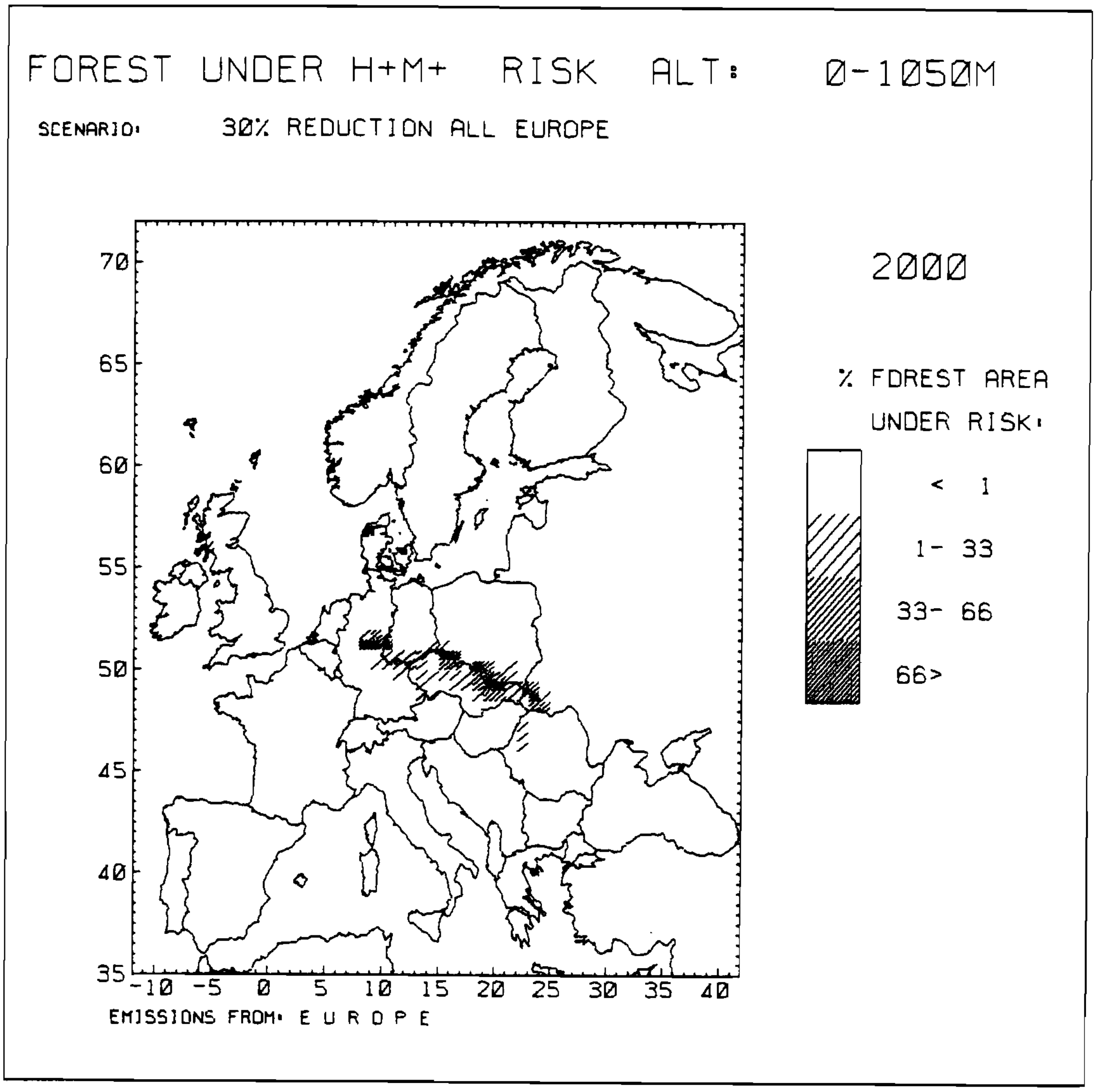

Figure 15. continued

can be tested against the actual observations.

The regional application of the model includes some technical assumptions that emphasize the indicator character of the results. First, all the empirical results concern Norway spruce only, yet the application covers total forest area. This was not considered fatal because (1) we were interested in a relative measure of risk, and (2) Norway spruce is by far the most common commercial species in Europe, comprising 25% of growing stock. This is particularly true of the areas which the present model regards as the most sensitive: In the Nordic countries and Central Europe the fraction of spruce is nearly 60% (The Forest Resources of the ECE Region, 1985). Second, the fact that the actual age structure of forests is not included may present some bias in the results in areas where the age distributions are skewed. Figure 7 suggests, however, that the results are not very sensitive to this assumption, especially if we interpret them as a relative indicator rather than an absolute value.

In summary, we have displayed some regional, long-term implications of conclusions based on an individual field study. No matter how comprehensive the field study, the evidence remains circumstantial and the conclusions must be regarded as empirical generalizations. We trust that the numerous ongoing studies on forest dieback will help us test and improve the model in relation to the ecophysiological pathways of damage.

ACKNOWLEDGMENTS

The authors wish to acknowledge H. Hettonen for providing models for the ETS computations, and M. Yamada for transferring the altitudinal information on forest area from topograhic maps to the computerized grid.

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