Toward Ecological Sustainability in Europe (Climate, Water Resources, Soils, and Biota)

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TOWARD ECOLOGICAL SUSTAINABILITY IN EUROPE
Climate, Water Resources, Soils, and Biota

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Foreword

Ecologically sustainable development is a condition in which society's use of renewable resources takes place without destruction of the resources or of the environmental context which they require. One problem for society in such use is the inadequacy of the knowledge required to define sustainability limits for specific characteristics of the environment. Thus, continuing regional economic development, combined with anthropogenic changes at global scales may inadvertently and unnecessarily obliterate plant and animal populations, impoverish forest ecosystems, destroy soil fertility and structure, and contaminate water supplies. Therefore, identification of requirements for attaining ecological sustainability, and the features of renewable resources most vulnerable to side-effects of development, provide the ultimate objective of the work we propose. A preliminary phase of that work was carried out at IIASA and funded in 1987 and 1988 by the Bundesministerium für Forschung und Technologie. The present report completes that initial phase.

Our approach involves assessment of the nature of European environmental issues, their scientific basis, and the data needed to define and quantitatively model their implications. The areas of study are natural and anthropogenic changes in climate and atmospheric chemistry, and the resulting responses of renewable resource characteristics of soils, vegetation, and water. The assessments concentrated on issues selected for their relevance to sustainability questions, and were derived from data and hypotheses concerning presently-perceptible trends in climatic, pedogenic, hydrologic, and biotic aspects of the present European landscape. The work led to recommendations for additional data collections and analyses designed to resolve or clarify the issues.

Our strategy included three sequential stages. The first portion of the research was descriptive, aimed at obtaining the data to examine current and future (the next 50 to 100 years) anthropogenic environmental problems of Europe. The work was initiated with a series of discussions with European scientists aimed at defining issues of environmental and political significance (see listing of visits and meetings in Appendix). Second, our subsequent analyses involved the assembly of data and literature on climate, soils, vegetation, and water supplies of Europe. Third, this research was synthesized into six reports, each concerned with one or more issues most likely to be important (ecologically significant, politically sensitive) in the European future. The results of these analyses are provided below.

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Preface

Human activities have induced ecological change for thousands of years. Recently, however, these activities have generated global-scale ecological changes, threatening the delicate relationship between the earth's ecosystems which support life, and the environmental characteristics which are required for survival of the ecosystems. At the same time, it is clear that additional global development is both desirable and inevitable. IIASA's Biosphere Dynamics Project addresses these long-term and large-scale interactions between human activities and the ecological aspects of the environment. Four features distinguish the Project:

(1) The project deals with the subset of environmental issues which are *ecological*, that is, focussed on the interactions among organisms and the relationships between organisms and their environment. As a result, the project seeks particularly to predict effects of environmental change upon unmanaged biotic communities and ecosystems, endangered species, biotic reserves, and the like.

(2) The project is concerned with *sustainability* and hence, with time scales long enough to establish that systems are sustainable. The annual to decadal time horizon looks several centuries into the past and a century or more into the future; this aspect of research in the Biosphere Project includes the unanticipated long-term ecological consequences of development activities which were undertaken for their short-term benefits.

(3) The project focus upon sustainable *development* results in the examination of the role played by human activities in ecological and environmental problems. The activities of interest are those whose effects cross international boundaries, and whose effects cannot be ameliorated by individual countries working independently.

(4) The project examines *biospheric* problems, rather than more regional concerns. We try to "think globally while measuring locally", i.e., to link large-scale consequences and implications of development to the causal

processes at smaller scales at which specific actions and policy choices are undertaken, and at which their impacts are experienced.

Products of these four features of the project have been implemented in the current study of Ecological Sustainability in Europe, which examines widespread, transboundary environmental difficulties involving both ecological and political significance in Europe. The objective was to analyze and quantify the interactions between human activities and these ecological changes, in order to estimate how they might constrain future development. In addition, much of the effort is concentrated on delivering scientific research results to end users in the arenas of science policy and political action. The success of this effort contributes significantly to the goals of IIASA's Environment Program.

B.R. Döös, *Leader*
Environment Program

Acknowledgments

The editors and authors express their deepest appreciation to the many people who contributed substantively to these studies: Dr. I. Aselmann, Professor P. Fritz, Professor W. Haber, Dr. P. Hari, Academician A.S. Isaev, Academician Dr. Z. Kaczmarek, Dr. N.A. Karavaeva, Dr. P. Kauppi, Dr. F. Kienast, Dr. M. Korzukin, Professor K. Kuusela, Mrs. N. Larionova, Mr. R. Lemmelä, Professor H.J. Liebscher, Dr. A. Mandych, Dr. D.W. Mooneyhan, Dr. F. Nobilis, Professor B. Prinz, Mr. M.F. Purnell, Dr. F.W. Schweingruber, Dr. A. Schwidenko, Professor W.G. Sombroek, Dr. L. Somlyody, Mr. M. Ter-Mikhaelian, Dr. A. Tishkov, Mr. A. Voropaev, Dr. W. de Vries, and Dr. R.I. Zlotin.

Finally, our thanks are given to the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany, which provided the financial support to develop and complete the study.

Contents

Introduction

The perception among citizens and decision makers of an environmental deterioration essentially began with the publication of Rachel Carson's "Silent Spring" over 25 years ago. Today, a host of recent documents detail a wide range of concerns (e.g., Conservation Foundation, 1987; Brown, 1988; WCED, 1987; NAS, 1988). Two global trends, population increase and energy use, are responsible for much of the perceived loss in environmental quality (Conservation Foundation, 1987). Obviously, people require resources for food, shelter, and living, and the resources required per person increase with the level of technological development of the country. Yet, it is less obvious that the annual global resource harvest, which is the direct cause of much of the environmental deterioration, will significantly increase when we are required to produce a whole new world of farms and cities to feed and house a whole new global population, when the current one doubles in about 40 years.

If intense land use to support a growing global population is the principal source of direct environmental degradation, then indirect degradation is caused primarily by the use of fossil energy, which has seen a four-fold increase since 1950 (Brown, 1988). Energy use is the predominant origin of increasing atmospheric CO_2, which has expanded about 25% in the past 140 years, and which may reach twice the preindustrial level in the same 40 year period in which global population doubles. Effects on climate (Jäger, 1988), and subsequently on other renewable resources (White, 1985), of the increased greenhouse gas concentrations in the atmosphere could be devastating. Equally or more important may be the related acidification of lakes and soils (NAS, 1986), the loss of productivity in forests (Nilsson and Duinker, 1987), and the increase in pollutant-related diseases (Brown, 1988; p. 7).

The application of these global-scale changes to the European scene requires some adjustment. First, consider the direct effects of changing land uses. On the one hand, European land used in agriculture has been declining over the past several decades and will probably continue decreasing in the future (Brouwer and Chadwick, 1988). Also, population is not growing in Europe and is unlikely to increase significantly in the next few decades (Wolf *et al.*, 1988).

On the other hand, population density in Europe is already among the highest in the world, and the high level of technological development induces a high per capita cost in terms of environmental degradation (Norberg-Bohm *et al.*, 1988). As a result, direct effects on European environmental quality are likely to increase in some, though not all, of the ways which are troubling the rest of the globe.

Next, consider the differences between the characteristics of the indirect effects of energy use on environmental quality, for the globe and for Europe alone. Europe is likely to undergo considerably greater warming than the world in general, due to its geographical position at higher latitudes where climate changes are expected to be greatest (Jäger, 1988). In addition, the emissions and effects of atmospheric pollutants related to energy use are as great in Europe as in any region of the world (e.g., Alcamo *et al.*, 1985; Alcamo and Bartnicki, 1988). Consequent European environmental degradation is likely to either exceed that encountered in the world as a whole, or to reach unacceptable levels much more quickly than will be reached in the world as a whole. Therefore, an assessment of European environmental futures can highlight ecological vulnerabilities and nonsustainable resource use that are not necessarily evident from examination of the current literature on global environmental change.

When we consider all the kinds of environmental issues of potential importance to sustainability of development in Europe's future, they seem unending. Many of these (but probably, not nearly all) are obvious from trends we can detect now. Direct effects of human occupation of the Continent are probably most important in terms of soil erosion from land disturbance, ground water contamination by agricultural pesticides and fertilizers, loss of productive land to the accumulation of chemical and bulk wastes, inadvertent air pollution by toxic chemicals, forest decline from the release of ozone and other gaseous pollutants, and so on. More indirect effects of human activities include the potential warming of winters and decreases of moisture in already water-stressed environments as greenhouse gases modify world climate. Forest decline as a result of silvicultural practices and by climate change may be even more important than declines caused by air pollutants. The same climate changes are likely to increase sea-level, destroying coastal cities and inundating the few estuarine habitats remaining to European wildlife. Destruction of the global atmospheric ozone shield by continuing use of CFCs has severe implications for lifestyles in Europe, as well as elsewhere.

Our assessment of European ecological sustainability will not and cannot possibly be comprehensive; instead we focus on only a few issues which are selected based on the following criteria:

- The issues or problems are transboundary problems, i.e., those which have international causes and which cannot be understood or solved by individual governments acting independently of one another. Specifically, we are examining environmental problems which are caused by climate change induced by increased greenhouse gases, and problems which result from air and water pollution.

- The issues or problems are geographically and internationally wide-spread rather than being limited to one small portion of the European continent. A problem even as massive as the eutrophication of the Baltic Sea is still limited in concern to coastal areas and the economies of those countries which utilize the Baltic. We wanted instead to select problems which had widespread significance in Europe.
- The issues or problems are of ecologically functional significance, i.e., they cause obvious change in how ecosystems function. Many of the most obvious and severe environmental problems in Europe today have little effect upon ecological communities. Permanent contamination of drinking water supplies, potential nuclear accidents, and so on, are among these. They greatly affect the welfare of human communities, but not of unmanaged populations or communities of wild organisms.
- The issues or problems are of obvious political or aesthetic significance, i.e., they are important enough that policymakers and citizens demand their resolution. Many environmental problems of great ecological significance are of little concern to policymakers in Europe. Endangerment of species, decreases in European biotic diversity, and landscape dissection by agriculture are trends of great ecological consequences, but are not important enough to society that their prevention is of political concern.
- The issues or problems involve obvious undesirable consequences to the environment; those issues which produce primarily neutral or desirable consequences are not relevant to the objectives of this document. Although signs of health and vigor in our surroundings are of great interest, the present document is designed to examine environmental difficulties; it assesses selected concerns, and as such, does not address prosperity.

These criteria do not necessarily identify *the most important* environmental problems in Europe, but they do identify those most appropriate for our attention. The application of these criteria resulted in the analysis of six topics or issues.

Our initial analysis examined the potential changes in temperature and precipitation in Europe with increased atmospheric concentrations of greenhouse gases. The question is of obvious transboundary significance; emissions in all of Europe could be reduced without measurable effect on atmospheric concentrations. The issue is widespread, covering all regions of Europe, albeit without the same expectation of consequence. The ecological significance of the issue is great; organisms, and to a lesser extent, communities are thought to contain little plasticity in their responses to environmental limits; shifts in climatic limits to growth are likely to have a profound effect on species vigor. The potential climate changes are also of obvious political significance, as demonstrated by the recent large number of federally-sponsored meetings, programs and projects to define global climate change and its impacts. Finally, the changes are indeed thought to produce a plethora of undesirable impacts, from increased desertification and loss of marginally productive agricultural lands in southern Europe, to losses of water availability in central Europe, and the demise of the Boreal forests of Northern Europe.

The basic difficulty in projecting climate changes which follow from increasing concentrations of greenhouse gases is a lack of capability to define changes on small spatial scales. General circulation models (GCMs) of the atmosphere operate on very coarse spatial scales (a grid point every 400 to 1000 km) which omit processes responsible for regional precipitation patterns. At the same time, there is little agreement upon approaches which use projections of future weather patterns based on extant patterns provided by data from available weather stations. Therefore, in a second analysis below, we reviewed available climate change scenarios based upon GCMs and on extant weather patterns, and explored a new method for applying known spatial patterns to define expectations in the future.

The remainder of the report is devoted to environmental issues involving water, soils, and biota. One hydrological problem in Europe's future is the deterioration in water quality derived from the nutrient enrichment of surface and groundwaters. The large international rivers and watersheds of Europe define the transboundary nature of the issue. Nutrient enrichment is problematic throughout Europe, and particularly so in the vicinity of large urban populations. The ecological consequences for aquatic life are significant, as evidenced by the reduced diversity of fish species and the declining density of aquatic organisms in rivers. The social and political importance of the issue is frequently evident, as it was during summer of 1988 when the front pages of newspapers described hundreds of tons of trout and salmon dying in North Sea fishfarms from algal blooms, and television news showed dead and dying North Sea seals, which were assumed to be too weak from the stress of life in polluted waters to resist the canine distemper attacking them. Such losses of aquatic life are a very undesirable problem.

A second hydrological issue analyzed below is the question of water availability. The problem involving climate shifts translates into a redistribution of water resources in Europe and as such, is both a transboundary problem, and an issue of widespread significance. The ecological significance of the issue involves the dependence of biotic communities upon the right amount of soil moisture, delivered during critical times of the growing season. The absence or overabundance of soil moisture during these critical times can spell disaster to agricultural crops, the vegetation, and to the animals which depend upon plant life for food. The aesthetic aversion of society to dry, previously flowing rivers is only slightly less than the political importance of inadequate drinking water supplies. That these consequences of changing water availability are undesirable is self evident.

A soils problem which fits the five criteria described above is the acidification of soils from atmospheric pollutants. Atmospheric pollutants that can cause the problem easily cross European borders, and their local impacts cannot be ameliorated by efforts expended only within an affected country. According to initial analyses, soil acidification is now serious in many regions of Europe, and this soon could become the case in many others. Soil acidification can force declines in primary and net productivity of forest communities, can reduce the density and diversity of soil microorganisms required to decompose litter into its constituent plant nutrients, and can not only speed but determine the rate of lake acidification, with concomitant loss of biotic resources. The aesthetic consequences in terms of dead and dying trees, and the reduction in the recreational uses of forestland and lakes, translates into political concern, which is also an undesirable consequence of the acidification issue.

Forest decline is the most pressing of issues which involve biotic interactions with environmental change in Europe. This is so for many of the same reasons that make soil acidification a significant transboundary problem of great political and aesthetic importance. The specter of now forested landscapes becoming permanently treeless generates strong negative feelings among citizens and decision makers. The ecological consequences of accelerated tree mortality coupled with retarded tree establishment and growth would be severe at best and catastrophic at worst. The presence of forest declines in many countries of Europe attest to its wide distribution.

Where possible, we have attempted to use similar formats in each analysis of these issues. Each assessment begins with an introduction which defines the nature of the issue in general terms. The definition includes an examination of the environmental or resource values at stake, the degree of concern, the source of concern, and the reasons for concern. Next, the spatial distribution of the issue within Europe is described, followed by an assessment of the past temporal patterns, i.e., the nature of the trend of change.

Next, we delved into causal agents and response indicators related to the issue. We have attempted to define the factors which are thought to be responsible for each issue, and to examine the evidence for that belief. Insofar as was possible, the spatial and temporal patterns produced by the causal agents were documented as one form of evidence. Then we looked at the quantifiable features of the system in question which could be used in judging the future behavior of the system, and the temporal and spatial patterns which emerge from mapping these factors.

The potential future characteristics of the issue were determined, based on our knowledge of the causal agents, and the scenarios of change provided by the climate analysis, or on decisions already taken by governments to ameliorate the problems. In a few cases, we also discussed adaptation and mitigation possibilities: the magnitude and geography of actions which could be undertaken to favorably alter the future intensity or presence of the issue. As a result of these considerations, we have defined research recommendations to quantify the importance or critical features of the issue, which now is obscured by a lack of information. In particular, we have tried to define the models which need to be developed and exercised in order to examine the relevant, sensitive system responses to changes in causal agents. The data needed to support such modelling, and thus, the kinds of supporting field and laboratory studies required, are then defined.

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CHAPTER 1

Climate: Approaches to Projecting Temperature and Moisture Changes

Jill Jäger

1.1. Introduction

Climate scenarios are detailed descriptions of the way in which climate would behave in the future, if the knowledge on which the scenarios are based is also the only information needed to predict the climate. Since this knowledge is not adequate to the purpose, scenarios cannot be construed as predictions. Rather, they constitute "projections" of unknown predictive value.

In recent years, climate scenarios have mainly been developed for use in assessments of the effects of climatic changes on environment and society. There are basically two ways of deriving climate scenarios: using computer models of the global climate systems (referred to as general circulation models or GCMs) or using past climate data to provide analogues for the future. Both of these approaches have shortcomings. While GCMs can provide some guidance to possible future globally-averaged temperature changes, they cannot produce reliable predictions of climatic changes on the regional scale. Reliable climate data which can characterize regions, are only available for the past hundred years for most of the globe. The magnitude of the climatic changes during this period has been small compared with the expected anthropogenic changes in the next fifty years so that analogues based on past data cannot be taken as reliable predictions.

A further difficulty in the development of scenarios results from incomplete knowledge of the causes and nature of climatic change. On a time scale of many thousands of years global climatic changes have been forced by changes in the earth's orbital parameters. On shorter time scales volcanic eruptions and variations of solar activity are known to be climatic forcing factors. However, it is not possible to conclude with any reliability what the causes of, say, the observed changes of global and regional climate were during the last hundred years. Both natural and, probably to a lesser extent, anthropogenic factors played a role in this period. During the next fifty years, on the other hand, it appears that anthropogenic factors will play a large role and it is impossible to predict how natural factors, such as volcanic activity or large-scale changes in ocean circulation, will affect climate.

Given the uncertainties both in the methodology of developing scenarios and in the understanding of the nature of climatic change, it is clear that scenarios for climate cannot be taken as predictions of future changes. Since the scenarios do provide internally consistent descriptions of climate, they can, however, be used for "sensitivity analyses" to look at the effects of different magnitudes and distributions of climatic change on environment (e.g., forest growth, lake levels) and society (e.g., agriculture, coastal engineering).

The following sections contain discussion of scenarios for the climate of Europe, within limits imposed by the caveats expressed above. Sections 1.2 and 1.3 include empirical and modelling approaches, respectively, and discuss their advantages and disadvantages in more detail. This is followed by a consideration of the implications of unanticipated (surprise) climatic changes. The paper concludes with a discussion of the present state of the art of climate scenario development and some ideas for future study.

1.2. Empirical Scenarios

The approaches used to derive climate scenarios based on observed climate data have been discussed in detail recently by Wigley *et al.* (1986). There are in fact three different approaches to deriving empirical climate scenarios for a warmer world (Pittock and Salinger, 1982):

- Using a chosen set of warm years from the recent instrumental record and comparing this with the long term mean or a similarly defined cold-year ensemble.
- Using regional reconstructions of paleoclimate during past warm periods.
- Using atmospheric dynamical arguments and empirical climate relationships to develop an educated guess.

The majority of scenarios have used the first approach.

The underlying assumption in the development of empirical scenarios has been that the main factor that will influence future climate is the global warming that results from the increasing atmospheric concentrations of greenhouse gases. Thus the scenarios are demonstrating the kinds of climate patterns that existed at other times when the earth was at least relatively warm, although the causes for this warmth are not necessarily the same as those that will prevail during the next fifty years.

1.2.1. Instrumental records

Figure 1.1, from Williams (1980) shows the difference in temperature between the average of the 10 winters in which the Arctic was warmest and the the long-term average of the 1900–1969 period. In the years when the winters were warm in the Arctic, northern and Central Europe were also warmer than the long-term average, while southern Europe including all of the Mediterranean area was colder. The sea-level pressure data showed that the lower temperatures in the Mediterranean area were a result of increased northerly flow over that area, while the warmth in the Arctic was a result of increased cyclonic flow from the North Atlantic into the Eurasian sector of the Arctic.

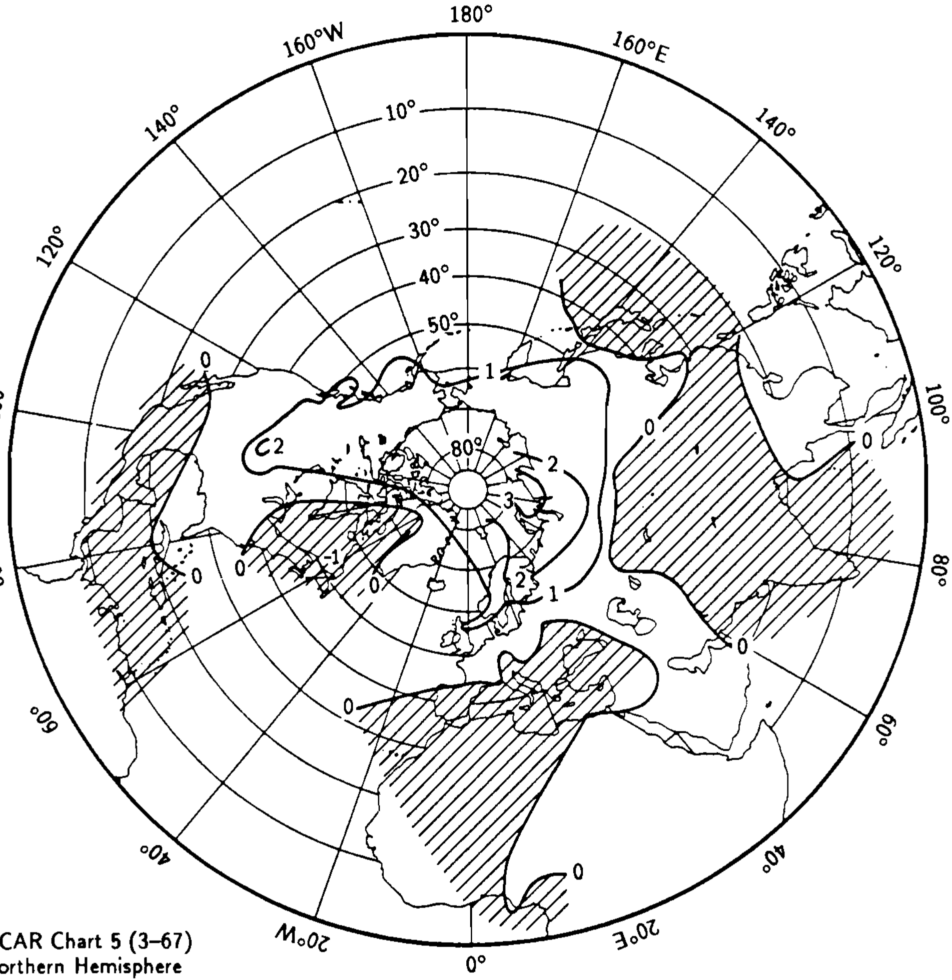
For the summer season, the differences in temperature between the 10 warmest Arctic summers and the long-term average are smaller than in the winter season (*Figure 1.2*) but there is again an area of lower temperatures in southern Europe over the western half of the Mediterranean. Following on the discussion in Section 1.1 above, such "scenarios" cannot be taken as predictions of future climate but provide information that must be borne in mind in the assessment of the effects of climatic change on environment and society:

- Even when the hemisphere as a whole is warmer than average, changes in the atmospheric circulation will mean that some areas will be cooler than average.
- Magnitude and distribution of changes differ according to season and region.

Wigley *et al.* (1980) made a similar analysis for the northern hemisphere by comparing a composite of the five warmest years in the period 1925–1974 with a composite of the five coldest years. The warmest and coldest years were defined using the temperature observations of stations in the zone between 65° N and 80° N.

Kellogg and Schware (1981) compared the results of Williams (1980) and Wigley *et al.* (1980). Some similarities were found in the results of Williams for the winter season and Wigley *et al.*, for the annual averages which basically reflects the fact that the winter seasonal anomalies are usually the largest and dominate within the annual anomalies.

Jäger and Kellogg (1983) extended the work of Williams (1980) by considering all seasons, not only winter and summer, and by looking at runs of five consecutive years in addition to the composites of 10 individual years. *Figure 1.3*, from Jäger and Kellogg, (1983), illustrates the differences between average winter temperatures during the five warmest consecutive seasons and the five coldest consecutive Arctic seasons. As in *Figure 1.1*, a positive temperature anomaly appears in the Arctic and northern and Central Europe and a negative temperature anomaly in the areas of southern Europe and the Mediterranean. *Figure 1.4* shows the differences between average winter precipitation during the five warmest consecutive Arctic seasons and the five coldest consecutive Arctic seasons. While the stippled areas in Northern Europe and over much of the



NCAR Chart 5 (3–67)
Northern Hemisphere
Polar projection: $15\frac{3}{8}''$ dia.

Figure 1.1. Surface temperature anomalies for the 10 warmest Arctic winters. Areas of cooling are shaded. (Source: Williams, 1980.)

Mediterranean had more rainfall during the warm Arctic years, much of Spain, France, and Central Europe had reduced precipitation.

Lough *et al.* (1983) looked at the differences in mean temperature, precipitation and pressure patterns between the periods 1901–1920 and 1934–1953. These are the coolest and warmest 20-year periods in this century based on Northern Hemisphere annual mean surface air temperature data. The scenarios derived contained marked subregional scale differences from season to season and individual season scenarios often had little similarity to the annual mean scenario.

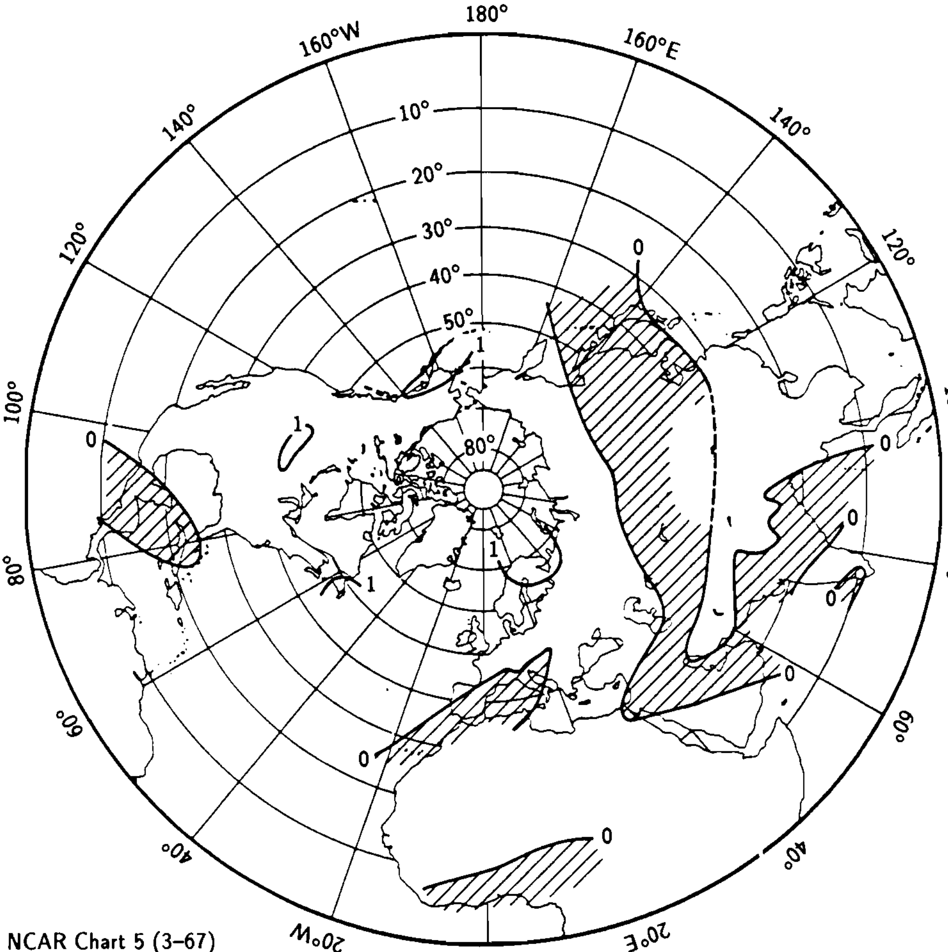


Figure 1.2. Surface temperature anomalies for the 10 warmest Arctic summers. Areas of cooling are shaded. (Source: Williams, 1980.)

The temperature differences for each season and the annual mean are illustrated in *Figure 1.5.* In spring, summer, and autumn European temperatures were warmer during the warm Arctic years. In winter, however, a belt of negative values is located at about 50° N and extends for about 10 degrees to the north and south. Lough *et al.* found by examining the sea-level pressure data that this area of lower temperatures was associated with higher pressure and, by implication, with an increase in the number and/or intensity of European blocking anticyclones in warm periods, forcing travelling depressions to pass either to the north or south.

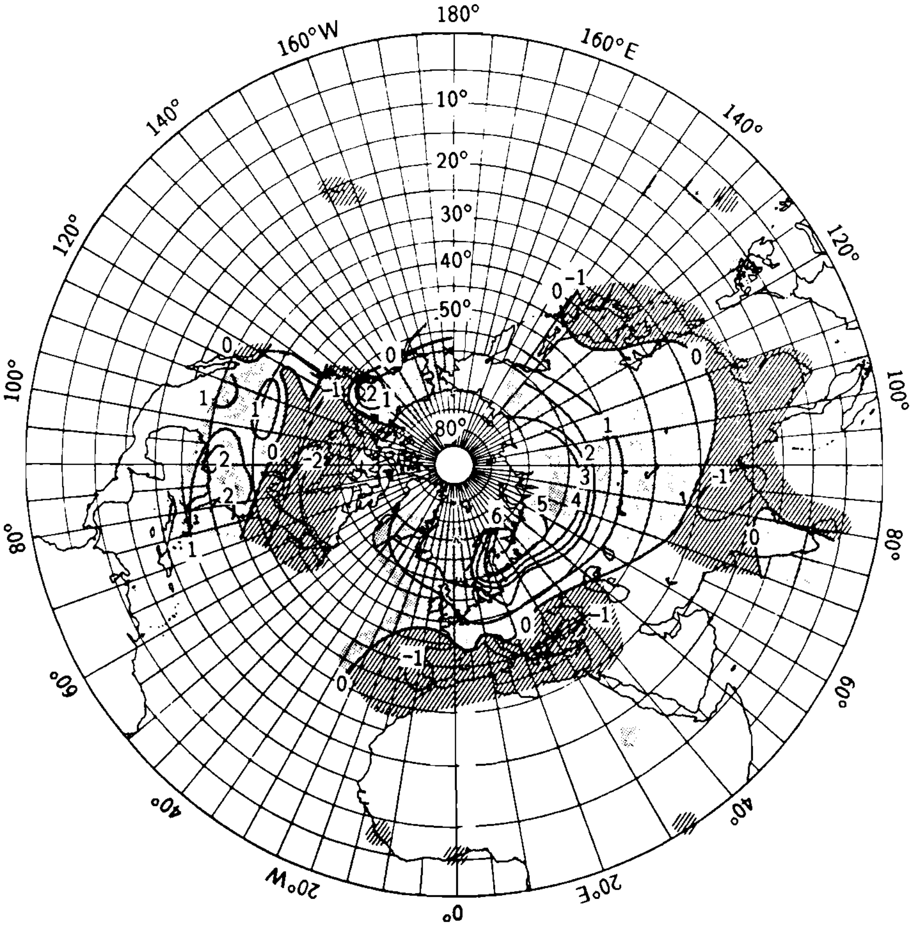


Figure 1.3. The differences between average winter temperatures during the five warmest consecutive Arctic seasons and the five coldest consecutive Arctic seasons. Areas of warming are indicated by dotted shading and areas of cooling by lined shading. (Source: Jäger and Kellogg, 1983.)

The differences in precipitation found by Lough *et al.* are shown in *Figure 1.6*. For most of Europe spring was drier in the warm period, whereas in autumn and winter the warm period was generally wetter. *Figure 1.7* shows the changes in the interannual variability of precipitation between the cold period and the warm period. In spring, autumn, and winter Lough *et al.* found that the warm period was associated with increases of interannual variability over considerable areas.

Another empirical approach to scenario development has been used by Budyko *et al.* (1978), Groisman (1981), and Kovyneva and Vinnikov (1983). In this approach linear relationships are derived between local, seasonally specific

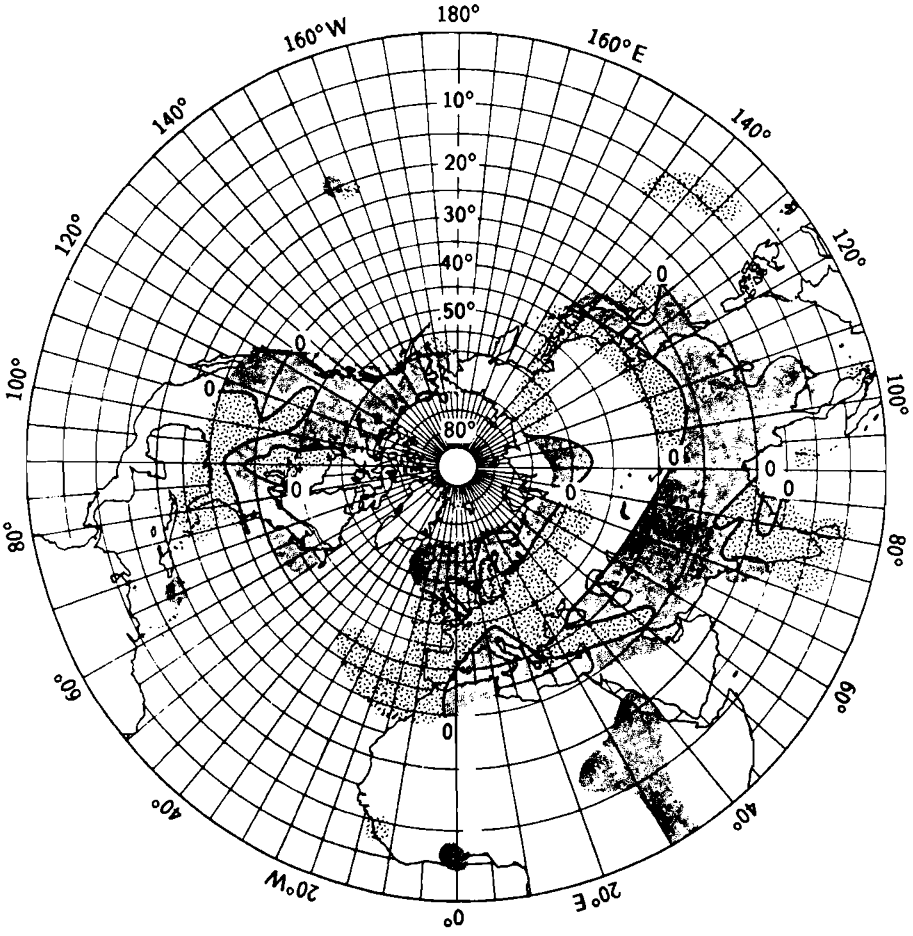


Figure 1.4. Differences between average winter precipitation during the five warmest consecutive Arctic seasons and the five coldest consecutive Arctic seasons. Stippled areas had more precipitation, hen-tracked areas were drier. (Source: Jäger and Kellogg, 1983.)

climate data, and the Northern Hemisphere surface air temperature record (17.5–87.5° N) of Borzenkova *et al.* (1976) and Vinnikov *et al.* (1980). Wigley *et al.* (1986) point out that the results of this approach depend on the period over which the regression equations are developed and that the correlation coefficient between local temperature and the Northern Hemisphere temperature will vary according to the time period chosen, thus casting some doubt on the validity of the correlation coefficient as a forecasting tool. However, the use of linear relationships derived from data from defined periods could be useful in scenario development – bearing in mind the distinction between climate scenarios and forecasts.

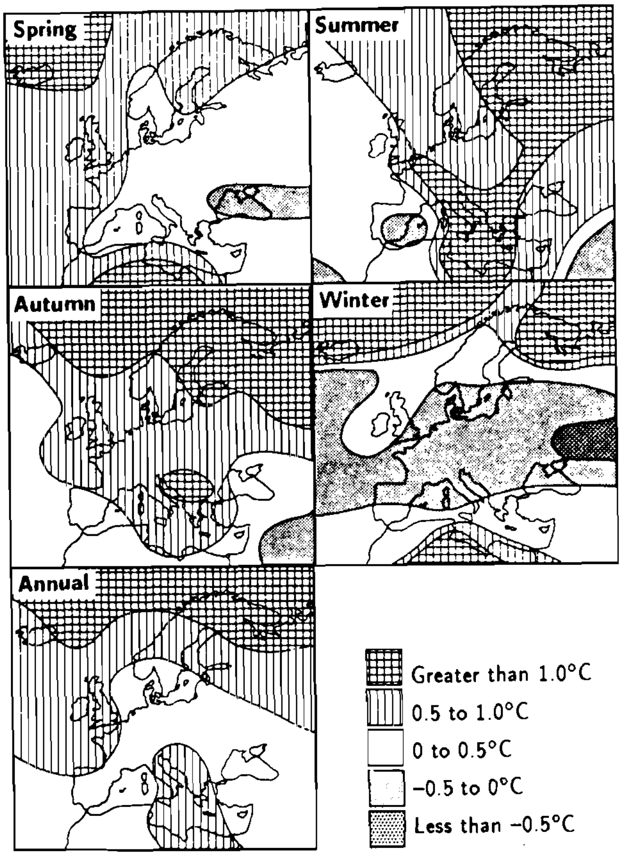


Figure 1.5. Temperature differences, warm period minus cold period. (Source: Lough *et al.*, 1983.)

Namias (1980) looked at anomalies in the 1,000 to 700 (mb) thickness data from the Northern Hemisphere for the period 1951–1978, suggesting that these data can be used as reliable indicators of hemispheric temperature variations and that thickness values may be more appropriate for large-scale circulation studies than surface temperature.

1.2.2. Paleoclimatic records

As discussed in the introduction, climate scenarios have also been based on reconstructions of past climate. Flohn (1977) suggested a number of periods that had a warmer climate than now could be used as "analogues": the Medieval Warm Epoch, the time of maximum Holocene warmth, and the last (Eemian) interglacial.

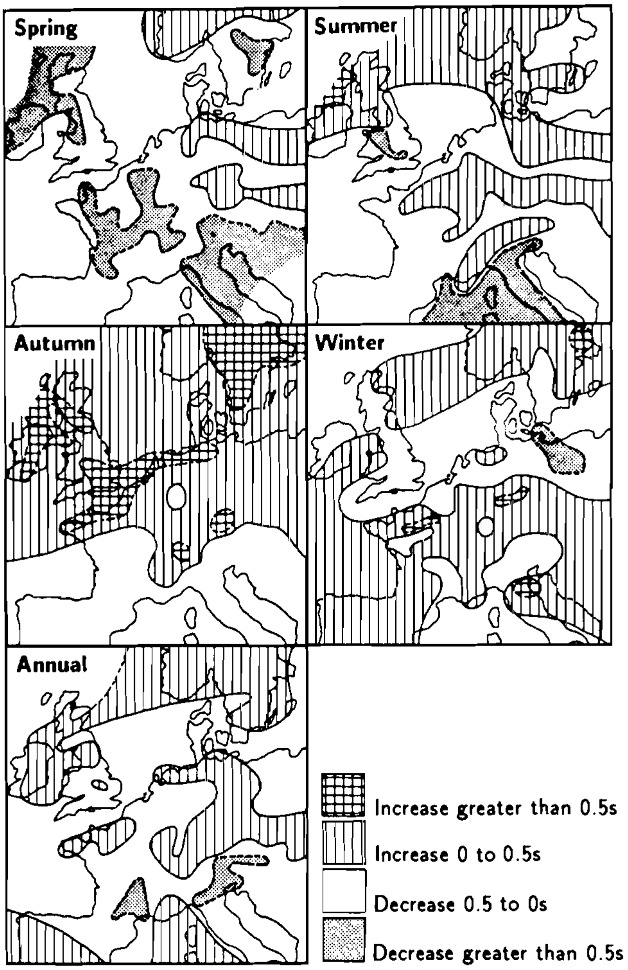


Figure 1.6. Differences in precipitation (warm period minus cold period) as multiples of the standard deviation. (Source: Lough *et al.*, 1983.)

Kellogg (1977 and 1978), Kellogg and Schware (1981), and Butzer (1980) looked at the climate of the early Holocene. This period is thought to have been a globally warmer time with temperatures up to 2° C warmer in many regions of the globe. However, as Wigley *et al.* (1986) and Webb and Wigley (1985) have pointed out, the data are incomplete and dating uncertainties have not been taken into account sufficiently in existing studies. *Figure 1.8* shows the reconstruction of the climate of the early Holocene warm period made by Kellogg (1977), illustrating the lack of data and in particular the lack of regional detail required for further studies of the effects of climatic change on environment and society.

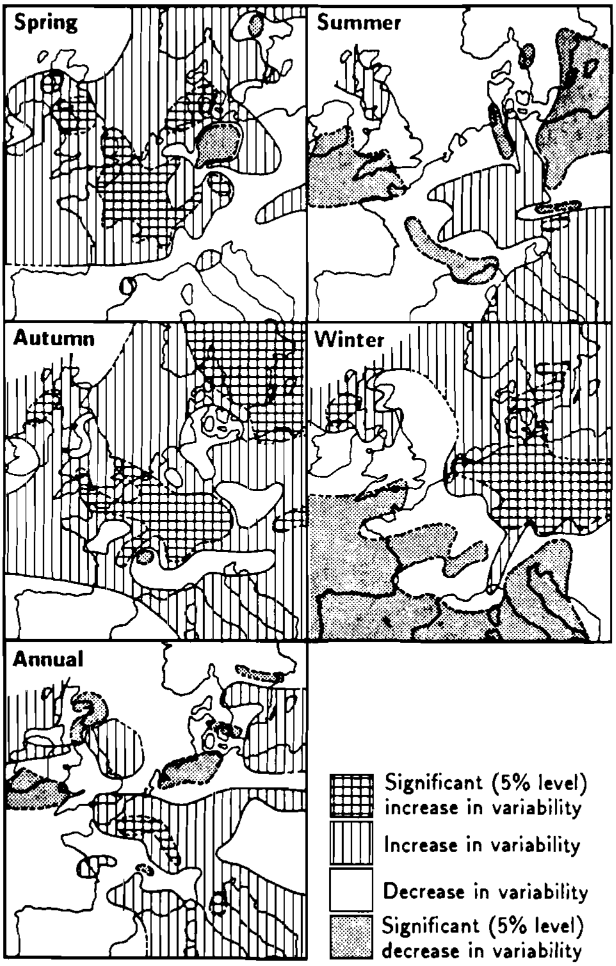


Figure 1.7. Differences in the interannual variability of precipitation from the cold period to the warm period. (Source: Lough *et al.*, 1983.)

Figure 1.9 shows a much more regionally valid reconstruction, this one describing July temperatures in Europe 6,000 years before present, based on pollen data (Huntley and Prentice, 1988). The reconstruction shows that July temperatures were higher than those of today over most of Europe but cooler than at present around the Mediterranean. Huntley and Prentice interpret this pattern to reflect the combined effects of altered summer insolation and the differential heating of the landmass.

The Medieval Warm Epoch (*ca.* A.D. 800 to 1200) and the Eemian interglacial have not been discussed in detail in the literature. Flohn (1980) looked at the Eemian period and at periods in the more distant geological past when the Arctic pack ice did not exist. The latter scenario illustrates possible conditions if

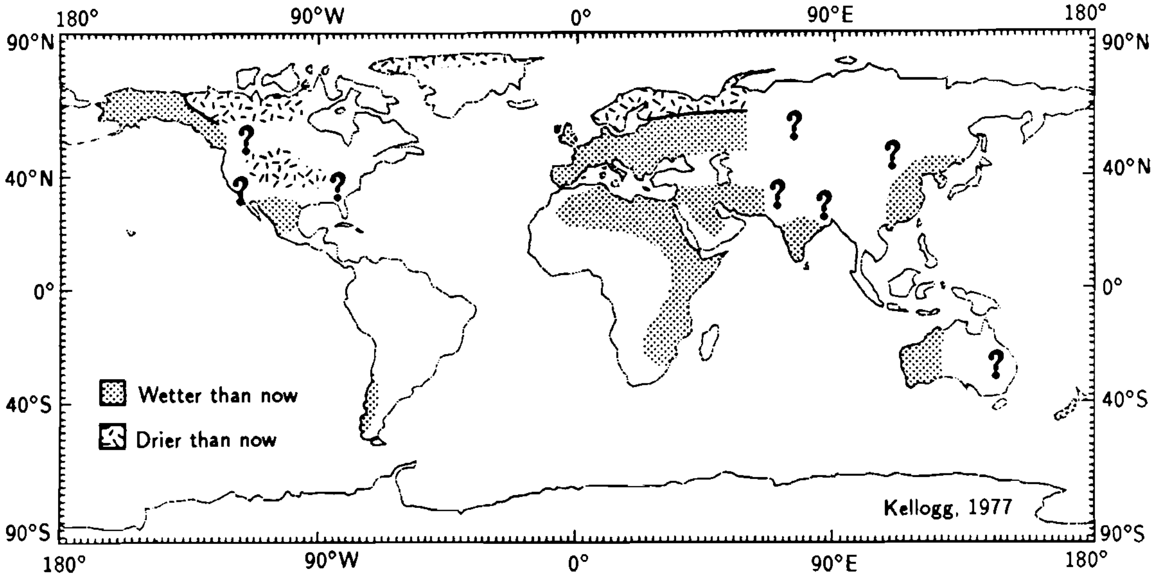


Figure 1.8. A reconstruction of moisture during the Altithermal period of about 4,500 to 8,000 years ago showing the areas where the conditions were wetter or drier than now. The blank areas are not necessarily regions where no change occurred, since the information is also incomplete. (Source: Kellogg, 1977.)

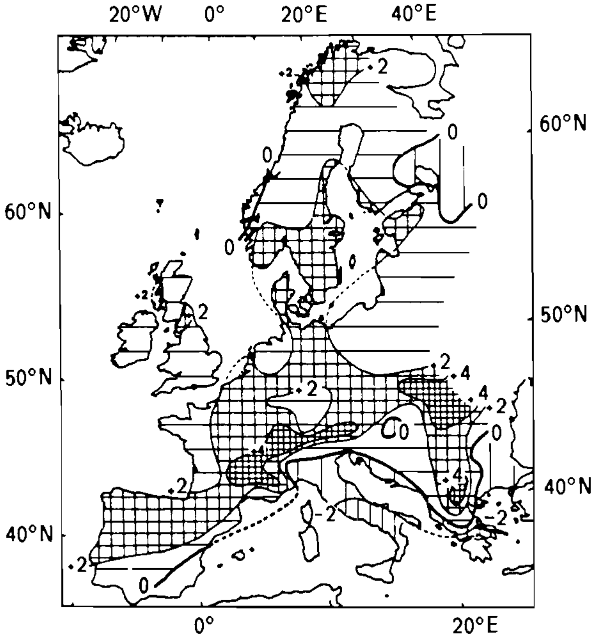


Figure 1.9. Reconstruction of the July mean temperature anomaly pattern at 6,000 BP. The contours show temperature at 6,000 BP minus the present temperatures. (Source: Huntley and Prentice, 1988.)

the global warming were to lead to a complete melting of the Arctic ice. Lamb (1982) studied anecdotal evidence (cultivation limits, crop failures, montane tree-lines, norse settlements, etc.) of medieval warmth, inferring increases from today's climate in fair weather and warmth, growing season length, alpine drought, and Mediterranean moistness, and so on. However, the Medieval Warm Epoch may well have been restricted to the North Atlantic Basin region, and, even over this large area, reconstructed changes in different locations show large differences in timing on century and shorter time scales (Williams and Wigley, 1983). It is, therefore, difficult to use this period for deriving a plausible scenario for future European climate.

1.3. GCM Scenarios

The use of GCMs to derive climate scenarios has been described in a number of recent studies, including Dickinson (1986) and Schlesinger and Mitchell (1985). Several scenarios have been based on model runs looking at the effects of a doubling or quadrupling of the atmospheric CO_2 concentration. As indicated in the introduction, the available models have a number of shortcomings so that it is not possible at present to make reliable predictions of regional climatic changes that would result from changes in the greenhouse gas concentration of the atmosphere.

A major shortcoming is the treatment of the oceans. Models of the atmospheric circulation have been coupled to two types of simplified model of the ocean. In the "swamp ocean" the heat capacity of the ocean is neglected so that the ocean is always in equilibrium with the atmosphere. However, such a formulation cannot simulate the seasonal cycle, since the ocean cannot store heat in the summer and release it in the winter. The results of model experiments with a swamp ocean are useful, nevertheless, for demonstrating some of the mechanisms of climatic change. To simulate seasonal effects atmospheric circulation models have either been run with prescribed changes of sea surface temperature or have been coupled to models of the mixed layer of the ocean in which the depth and horizontal heat transport are generally prescribed as a constant or zero.

Schlesinger and Mitchell (1985) have summarized the present state of the art of global climate modelling as follows:

> GCMs simulate the present climate imperfectly, although some of the models do reasonably well, at least for the limited climatic quantities considered in this chapter ... Yet these models frequently employ treatments of dubious merit, including prescribing the oceanic heat flux, ignoring the oceanic heat flux, and using incorrect values of the solar constant. Such approximations indicate that the models are physically incomplete and/or have errors in the included physics. Furthermore, the state of the art is that the CO_2-induced climate changes simulated by different GCMs show many quantitative and even qualitative differences; thus, we know that not all of these simulations can be correct, and perhaps all could be wrong.

Schlesinger and Mitchell suggest that it is necessary now to try to understand the differences and similarities of the most recent simulations and to develop more comprehensive models of the climate system.

There are basically two ways in which global climate models can be used to derive climate scenarios:

- To look at the response of the model climate to a perturbation, e.g., a prescribed increase of the atmospheric CO_2 concentration (called an equilibrium response experiment).
- To look at the response of the model climate to a time-dependent continual increase in CO_2 and/or other greenhouse gas concentration in the atmosphere (called a transient response experiment).

Since in the real world the concentrations of greenhouse gases are not increasing as a step function but continually, the validity of the results of equilibrium response experiments has been questioned (Schneider and Thompson, 1981; Thompson and Schneider, 1982). However, the development of models of the coupled atmospheric-oceanic system that could be used for such transient response studies will not be completed in the near future both because of the computational requirements and the need for scientific understanding and data.

In the process of examining the results of GCMs for their utility in impact assessments, Bach (1988) suggested that in order to be useful the models should:

- Be based on realistic geography and topography.
- Have a high spatial resolution.
- Have an adequate temporal resolution.
- Incorporate a coupled model of the atmosphere-ocean circulation.
- Simulate realistically the patterns of the observed climate.

Bach concluded that none of the existing GCMs meets all of these requirements. However, it was decided that the Goddard Institute for Space Studies (GISS) model (Hansen *et al.*, 1984) would be the best choice for developing climate scenarios for the IIASA project on assessment of the impact of climatic variations on agriculture. At the same time Bach emphasized that there are still model shortcomings in the treatment of hydrological processes at the surface, moist convection, clouds, and boundary layer transport processes.

Figure 1.10 shows a comparison of observed data with a simulation of the present day climate for the area of Europe and North Africa. In the western half of this area the differences between the observed and modelled temperature data are minimal. In the eastern half, on the other hand, the model underestimates the temperatures by as much as 2° C. The simulated annual mean precipitation rate shows considerable overestimates over large areas. Bach (1988) points out that the discrepancies between observed and simulated data mean that the model results must be interpreted with caution. Nevertheless, Bach concludes that the model results give at least a general idea of the changes that are possible in a greenhouse gas-warmed earth, even though details of changes at any given location cannot be reliably predicted by any GCM at the present.

Figure 1.11 shows the changes of surface air temperature that were simulated by the GISS GCM for a doubling of the atmospheric CO_2 content. Temperature increases of between 3 and 7° C were projected in all seasons in Europe. Bach found that these changes were all statistically significant at the 5% level over the whole area in all seasons. The changes of precipitation rate are shown in *Figure 1.12*. The scenarios suggest a precipitation reduction in the southwest and an increase in northern regions in all but the autumn season. However, since precipitation is inherently more variable than, say, temperature, the areas over which the precipitation changes are statistically significant are smaller than in the case of temperature.

The Max Planck Institute for Meteorology in Hamburg is presently testing a coupled global ocean-atmosphere GCM and plans to use this model in the near future for climate studies (Hasselman, personal communication 1988). In particular, the coupled model will be used to look at the effects of a step-function doubling of the atmospheric CO_2 concentration and subsequently for different time-dependent CO_2 input scenarios. The results of these model experiments would provide climate scenarios for Europe that avoid some of the shortcomings of previous uncoupled GCM experiments.

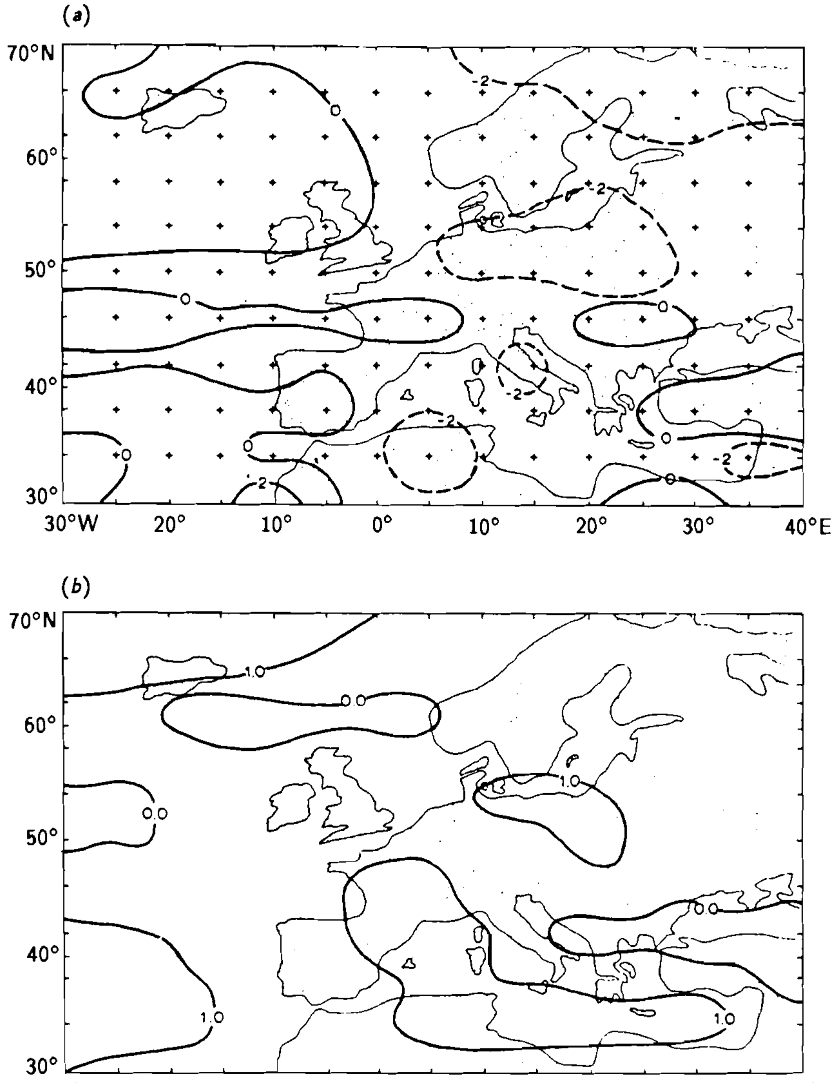
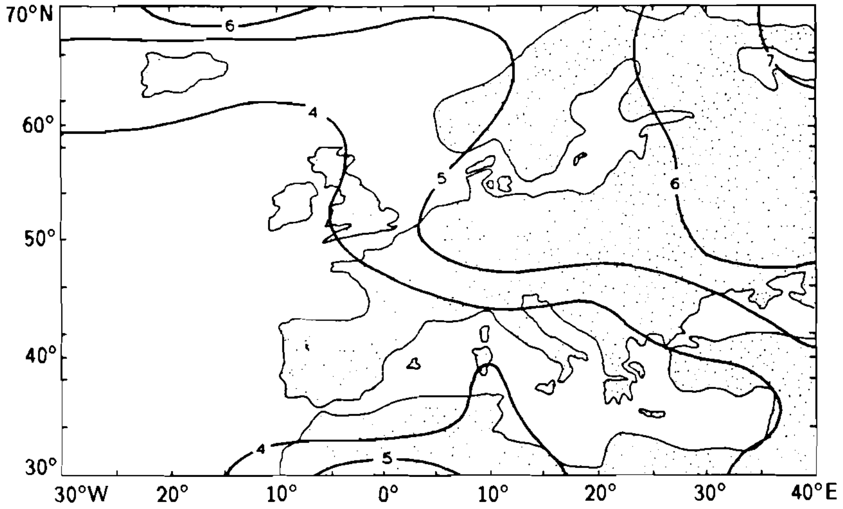


Figure 1.10. Model validation for the European region in terms of the difference between the "control" climate generated by the GISS GCM and the observed climate for: (*a*) mean annual temperature (K), and (*b*) mean annual precipitation rate (mm/day). (Source: Bach, 1988.)

(*a*) Winter



(*b*) Spring

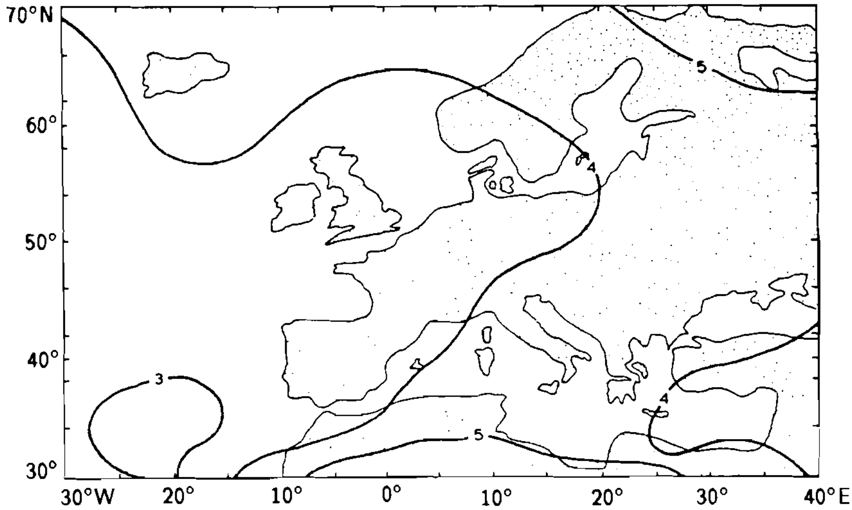
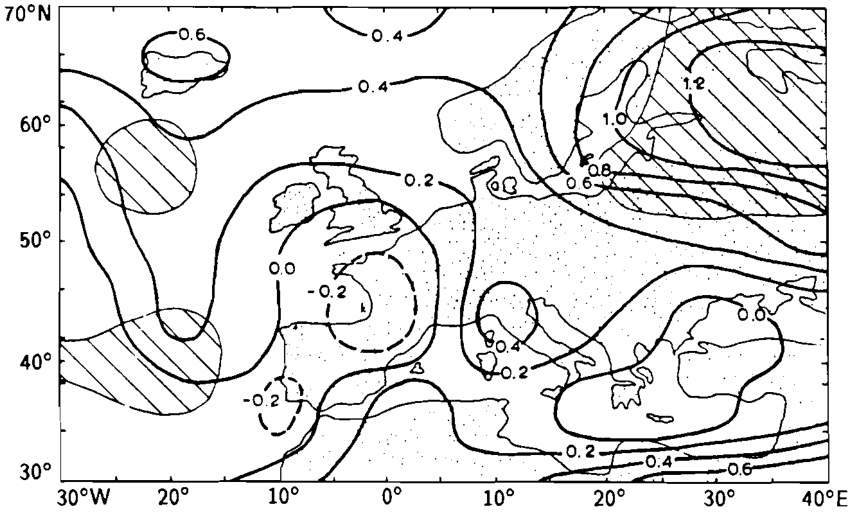


Figure 1.11. Regional distribution of the average surface temperature change (K) between the GISS model control case and the CO_2-doubling experiment in the European region by season. Shading indicates changes that are significant at the 5% level. (Source: Bach, 1988.)

(*c*) Summer



(*d*) Autumn

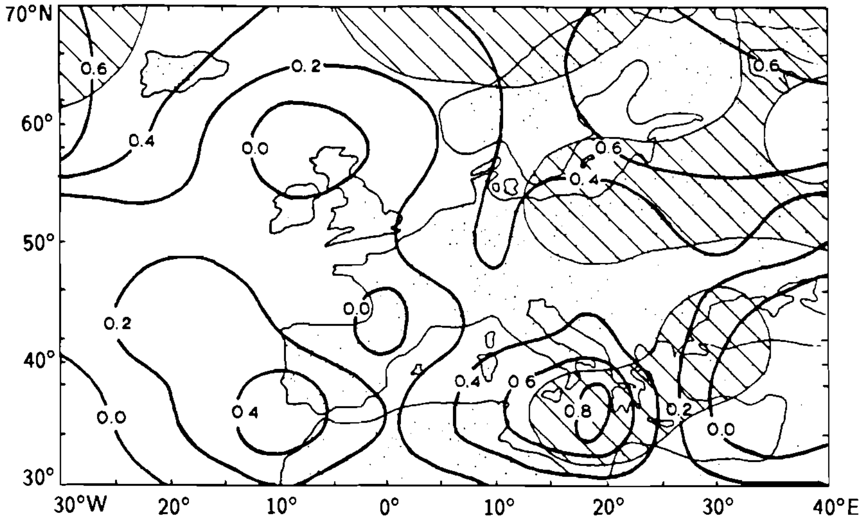
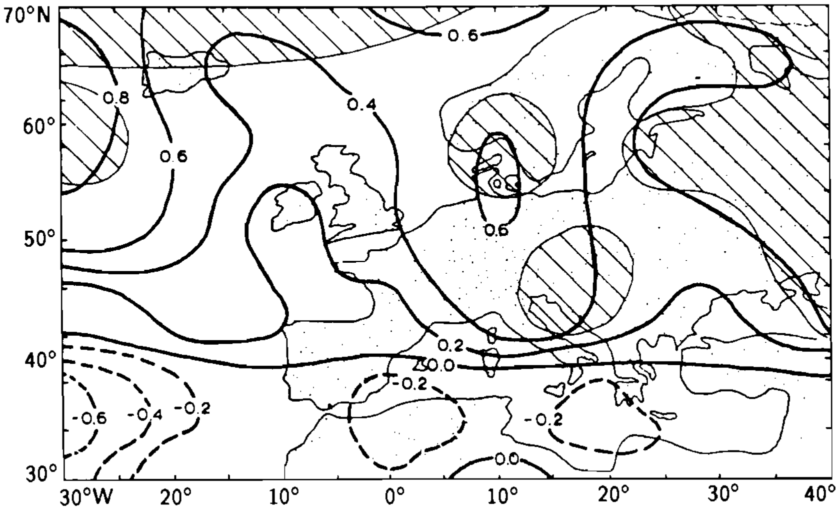


Figure 1.11. Continued.

(*a*) Winter



(*b*) Spring

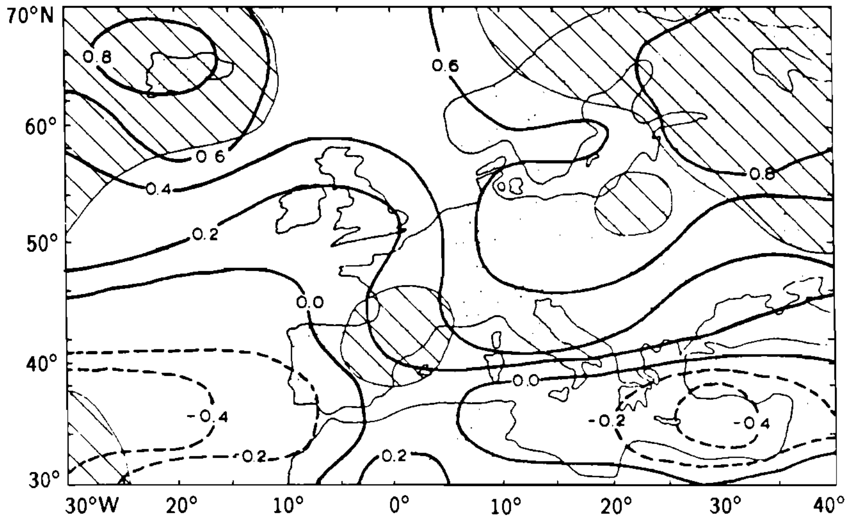
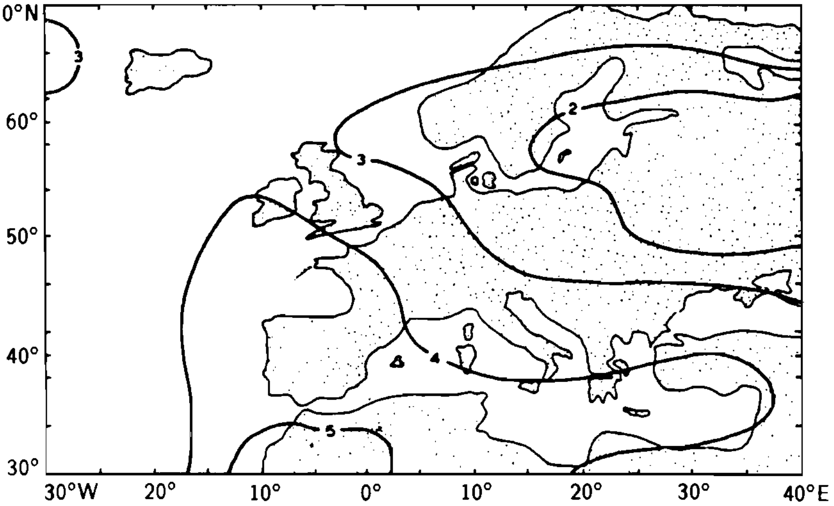


Figure 1.12. Regional distribution of the change in average precipitation rate (mm/day) between the GISS model control case and the CO_2-doubling experiments in the European region by season. Shading indicates changes that are significant at the 5% level. (Source: Bach, 1988.)

(c) Summer



(d) Autumn

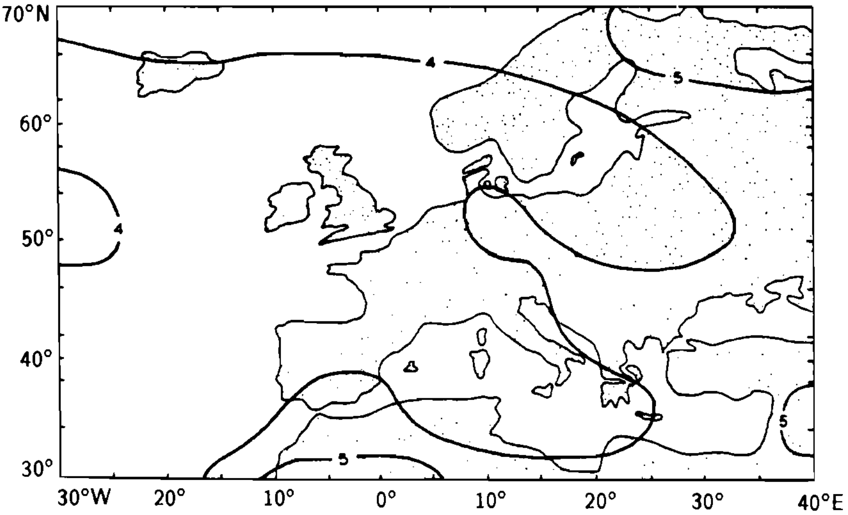


Figure 1.12. Continued.

1.4. "Surprise" scenarios

Although the scientific understanding of the physical basis of climate and climatic change has increased considerably in the past two decades, there are still large areas of uncertainty which mean that there is a possibility of unexpected environmental changes occurring. This was pointed out recently by Broecker (1987), who emphasized that the oceans are a major source of uncertainty. For example, at a workshop in 1984 (Bennett *et al.*, 1985) scientists considered the process of North Atlantic Deep Water Formation. They pointed out that large increases of temperature and precipitation at high latitudes as a result of the increasing concentrations of greenhouse gases could shut off or reduce deep water formation. If this were to happen, the North Atlantic and European regions could become colder while the global climate warms. Further, it was emphasized that climatic changes can take place more suddenly than is often anticipated and that the geographical distribution of climatic changes may be much more complex than suggested by current climate models, which generally assume that the oceans will continue to operate in the future in the same way as at present.

1.5. Transient Changes

Most climate models have examined the so-called equilibrium response to the changes of the atmospheric concentration of CO_2. That is, the model is run first of all with the present CO_2 concentration and a second simulation is made with a doubled (or quadrupled) CO_2 concentration and the model is allowed to reach equilibrium, i.e., the modelled climate can adjust fully to the changed atmospheric composition. In reality such a step change in the atmospheric composition is not taking place; the concentrations of greenhouse gases are increasing steadily as a function of time. Moreover, the large heat capacity of the oceans slows down the surface warming so that the surface climate lags behind the equilibrium climate for the present greenhouse gas concentration in the atmosphere by several or many decades. Schneider and Thompson (1981) and Thompson and Schneider (1982) used a simpler climate model to look at the implications of transient effects. Their results suggested that storage of heat in the oceans may significantly modify the geographical distribution of climatic change.

The Goddard Institute for Space Studies (GISS) has made transient runs with a GCM. These runs start in 1958 with the atmospheric concentrations of greenhouse gases at that time and the concentrations and equivalent radiative forcing are increased from 1958 according to assumptions about rates of growth of emissions. Scenarios for impacts studies have been created by combining the GCM transient output with a historic time series of climatic data.

Wigley *et al.* (1986) concluded that on the global scale the transient warming to date due to CO_2 and other greenhouse gases should be in the range 0.3–1.1° C given all model uncertainties. The observed global-scale warming experienced over the past hundred years is compatible with these estimates, but

Wigley *et al.* concluded that unequivocal, statistically convincing detection of the effects of greenhouse gases was not possible.

1.6. Frequency of Extreme Events

In addition to considering changes in mean temperature and rainfall, it is necessary to look at changes in the frequency of extreme events. Mearns *et al.* (1984) have shown that there can be shifts in the probability of extreme high temperature events with seemingly small changes of mean maximum temperature. For example, they calculated that the likelihood of five or more consecutive days with maximum temperatures exceeding 35° C with a 1.7° C increase in the mean temperature (holding the variance and autocorrelation constant), is about three times greater than that under the current climate at Des Moines, Iowa. Such changes in the probabilities of extreme high temperature events could have important implications for crop yields, energy demand, and animal and human morbidity and mortality. Scenarios based on climate model results have not considered possible changes in the probabilities of extreme events (droughts, floods, heat waves, etc.). Some empirical scenarios have included changes of interannual variability (Lough *et al.*, 1983) and empirical data could be used to look at the potential magnitude of change in the probabilities of extreme events in individual seasons and in particular regions.

1.7. Discussion

Both climate models and empirical methods can be used to produce scenarios of future climate. Both approaches have the advantage of providing a plausible, internally consistent description of climate but the scenarios cannot be taken as predictions of future climate because of acknowledged shortcomings in both approaches. Although it is possible to produce scenarios of such variables as temperature and precipitation in map form, impact assessments often require detailed information on a very local scale and therefore interpolation is required. It is easier to derive this kind of detail from model results.

The major shortcomings of the modelling approach include poor treatment of the oceans, cloud formation, hydrological processes and small-scale phenomena. In addition, the applicability of "equilibrium" scenarios has been questioned. The empirical scenarios are based on climate data from the past hundred years, during which the climatic changes were relatively small compared with those that are expected as a result of human activities during the coming fifty years. Therefore, it has been suggested that the empirical scenarios based on recent observed data are applicable only to the next 10–20 years and not on a longer term. Empirical scenarios based on data from the earth's past are generally sparser and sometimes poorly dated, so that detailed regional scenarios cannot be derived.

Given the shortcomings of the present methods of scenario derivation, studies of the effects of climatic change on environment and society will have to continue to be based on scenarios for future climate that are hypothetical but, at the same time, plausible on the basis of model and empirical studies. That is, "impact studies" will continue to be conducted as "sensitivity analyses", investigating, for example, the effect on agriculture, water resources or coastal defenses of a temperature change of x° C and a precipitation change of y%.

Most of the scenarios that have been derived to date have been based on the assumption that the main factor that will influence climate during the next half century will be the global warming caused by the increased atmospheric concentrations of greenhouse gases. While there is scientific consensus about the importance of the greenhouse effect, scenarios should also look at the possible effects of other natural and anthropogenic factors that could influence climate.

Since there has been a tendency towards a preoccupation with the globally averaged climatic changes resulting from the greenhouse effect, the magnitude and nature of regional climatic changes has often been neglected. Clearly, one of the main reasons for this neglect is that models can not produce reliable simulations of regional climatic change. Empirical studies emphasize the point that regional changes can have a different magnitude and even the opposite direction to the global changes.

Scenarios of possible future climate in Europe are needed in order to ensure that necessary steps can be taken to prepare for or avoid climatic change. For this reason, further scenarios should be developed and new approaches tested. One approach that could be used for developing climate scenarios for Europe has been developed by Pitovranov (1986). The approach is based on an empirical relationship between large-scale weather patterns (*Grosswetterlagen*) in Europe and the Northern Hemisphere temperature or the Northern Hemisphere equator-to-pole temperature gradient. Scenarios could therefore be derived from the changes in weather patterns (and, thus in temperature and rainfall patterns) as a result of hypothesized changes of the Northern Hemisphere temperature. This approach has the advantage of combining empirical data with information on the synoptic climatology of Europe.

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CHAPTER 2

Climate: Grosswetterlagen Approaches

Sergei Pitovranov and *Jill Jäger*

2.1. Introduction

An empirical approach to scenario development has been analyzed recently by Pitovranov (1987 and 1988). The approach is based on the relationship between the average temperature of the Northern Hemisphere and the positions of the large-scale weather patterns in Europe. These weather patterns are commonly referred to by the German word *Grosswetterlagen*. A *Grosswetterlage* identifies the major trends in atmospheric events over the region during several days of essentially similar weather character in the various parts of the region. For example, the *Grosswetterlagen* type HN (see Hess and Brezowsky, 1952) defines a situation in which there is a closed anticyclone over the North Sea, which means that much of Europe is under a northerly airstream. In contrast, the *Grosswetterlagen* type TB defines a situation when there is a closed depression over the British Isles and southerly airflow over Central Europe. The concept of *Grosswetterlagen* was developed over a period of 30 years in Germany by Bauer (1947). The original Bauer classification of 21 types of *Grosswetterlagen* was modified by Hess and Brezowsky (1952) in the light of increased upper air information. Hess and Brezowsky (1952) also combined similar *Grosswetterlagen* (GWL) into 12 *Grosswettertypen* (GWT) and 3 main circulation regimes (GWR).

They subsequently prepared a daily reclassification for the period 1881–1950. The daily *Grosswetterlage* classification has been tabulated since 1952 by the German Weather Service. A daily classification of GWL for the region extending from 30–70° N and 40° W–40° E for the period 1891–1980 was supplied to IIASA by the Koninklijk Nederlands Meteorologisch Instituut.

2.2. The Relationship Between Hemispheric Temperature and Circulation in Europe

We used a statistical approach to determine the relationship between the frequencies of *Grosswetterlagen* (GWL), *Grosswettertypen* (GWT), and circulation regimes (GWR) and the Northern Hemisphere average temperature. Like Vinnikov *et al.* (1980), we calculated a linear relationship between seasonal frequency of GWLs, GWTs, and GWRs and the mean annual surface temperature.

$$\nu_i = \alpha_i \Delta T + \bar{\nu}_i + \xi_i(t) \tag{2.1}$$

where ΔT is the deviation from a five-year running average of the mean annual Northern Hemisphere temperatures, $\bar{\nu}_i$ is a 90-year mean of circulation frequency, α_i is the coefficient of linear correlation, and ξ_i is an error term.

The correlation coefficient was estimated by least squares, and the significance of the coefficient was tested using the students' T-test. The analysis showed that for some GWLs, GWTs and GWRs the "null hypothesis" that there is no linear relationship is rejected at the 95% probability level. The results are shown in *Table 2.1.*

In the first two columns of *Table 2.1* values of 90-year (1891–1980) means and standard deviations of the frequency of GWTs and GWRs are presented. The coefficient of linear correlation between the hemispheric temperature and GWT and GWR frequencies are presented in the third column. The sign and value of the coefficient represent the direction and amount that GWT and GWR frequencies change, when the hemispheric temperature increases by 1° C. From *Table 2.1* it follows that at the 95% probability level, relationships between changes in hemispheric temperatures and frequency of some GWTs and GWRs are significant in some seasons.

There is a negative correlation between the average Northern Hemisphere temperatures and the zonal circulation regime in the winter season. This type of circulation represents the normal eastward progression of Rossby waves in the upper westerlies at middle latitudes. Hemispheric warming is associated with a decreasing frequency of this normal progression of Rossby waves.

Temperature is directly related to the frequency of meridional/blocked circulation and to the frequency of Easterly GWT in winter. This result is supported by the results of Lough *et al.* (1983), who showed that the number of European blocking anticyclones increases in a warm period.

In summer, variations in hemispheric temperatures are positively correlated with mixed circulation frequencies. Therefore, an increase in hemispheric temperatures accompanies a decrease of blocking high pressure ridges in Europe during summer months. It should be mentioned, however, that the blocking GWL (characterized by a zonal circulation type, a southerly flow in Eastern Europe and a blocking anticyclone in the European part of the USSR) has a tendency to increase in frequency during warm periods in the Northern Hemisphere, though the strength of this relationship is not sufficient to reject the null hypothesis at the 95% level.

Table 2.1. Results of linear regression of frequencies of GWT and GWR [see equation (2.1)].

Circulation type	Mean	Standard deviation	α	t value	Probability (two-tailed)
Winter					
Zonal	22.6	10.7	-10.5	-2.04	0.04
Meridional/blocked	39.1	13.4	12.6	1.96	0.06
Easterly	7.4	7.2	7.1	2.03	0.05
Spring					
Transient	1.0	1.4	-1.0	1.96	0.06
Northerly	14.8	8.4	13.8	3.55	0.00
Summer					
Mixed	27.6	10.3	14.0	2.9	0.01
High CE	14.3	7.5	8.4	2.35	0.03
Northerly	12.9	7.2	-12.9	-3.9	0.00
Easterly	5.7	5.7	-5.7	-2.1	0.05

Hemispheric temperatures in summer are also positively related to the frequency of the GWT "High C.E.", characterized by ridges of high pressure or anticyclonic conditions over Central Europe. The frequency of easterly airstreams decreases in summer months when the hemisphere is warmer. Finally, there is a strong relationship between an increase of hemispheric temperature and decreasing frequencies of northerly airstreams in the summer months in Europe.

In spring, in contrast to summer, the frequency of the GWT "Northerly" is positively correlated to hemispheric temperature. High correlation with the temperature is also observed for transient circulation types in spring. There is no significant relationship between variations in hemispheric temperatures and frequencies of circulation-types in the autumn months.

2.3. Scenario Development

The results from the regression analysis were used to develop a climate scenario by deriving GWL frequencies which produced an increase of 1° C in hemispheric temperatures. The approach follows. For each season the year was selected from the period 1891–1980 for which the GWT frequencies are as close as possible to the calculated frequencies in a warmer climate. Obviously, it is almost impossible to find such seasons with *exactly* the same distributions. Furthermore, statistically significant regression parameters could be established only for some GWTs and GWRs (*Table 2.1*). Therefore, in the search for an analogue season in the past, a weighted least squares procedure was applied, in which the weights are proportional to the t-values of the regression analysis performed in *Table 2.1*.

Table 2.2. Frequency distributions of GWT and GWR for a warmer world.

	Winter		Spring		Summer		Autumn	
	Sc.	An.	Sc.	An.	Sc.	An.	Sc.	An.
Zonal	12.1	12	18.8	19	22.0	22	22.4	14
Mixed	26.1	29	22.9	33	41.6	45	23.4	23
Merid./blocked	51.7	48	49.4	36	28.1	25	43.8	54
High C.E.	13.9	16	14.2	16	22.7	19	12.9	12
SW-ly	5.2	0	4.4	1	3.2	7	3.5	10
NW-ly	7.0	13	4.5	21	15.7	19	7.0	1
Northerly	10.5	14	28.6	30	0.0	0	10.5	19
Low C.E.	6.5	0	3.8	0	6.2	6	7.0	9
Southerly	6.5	0	3.8	0	6.2	6	7.0	9
SE-ly	6.6	6	4.5	0	9.6	11	8.8	1
Easterly	14.5	13	4.6	0	0.8	0	6.9	12
NE-ly	3.7	11	2.2	6	9.0	4	3.0	6
Ww	3.4	0	0.2	0	3.1	0	4.1	1

Sc. – calculated frequencies, using equation (2.1) and assuming a 1° C temperature increase.
An. – frequency distribution in the analogue season.

Results of the weighted procedure are presented in *Table 2.2.* It was found that winter 1938, spring 1939, summer 1952, and autumn 1939 had GWTs and GWRs most closely resembling a year in a warmer climate. It can be seen from *Table 2.2* that the frequencies of all GWT and GWR which are significantly correlated with the hemispheric temperature are in good agreement with the frequencies of their season-analogues.

The results of the statistical analysis shows that the "artificial year" which consists of winter 1938, summer 1952, and spring and autumn 1939 has a circulation frequency distribution similar to the distribution derived from a regression analysis of the relationships between frequency distribution of GWT and GWR, and the hemispheric temperatures over the 90-year period from 1891 to 1980. All seasons of the "artificial year" belong to the warmest 20-year period of the century. The mean annual air surface temperatures of the Northern Hemisphere in the zone 30–87.5° N for the years 1938, 1952, and 1939 are 8.0° C, 7.5° C, and 7.8° C, respectively.

The differences in seasonal temperatures and precipitation between the "artificial" year-analogue and climatic mean data for the "climatic normal" period 1951–1980, gives a scenario for climatic changes in Europe for a +1° C warmer world.

The temperature differences for each season are shown in *Figure 2.1* and precipitation differences for the annual mean and each season in *Figure 2.2.* Using the Thornthwaite formula (Willmoth *et al.*, 1985) and the precipitation and temperature data from the analogue seasons, the changes in potential evaporation were calculated. The results are given in *Figure 2.3.* The main conclusions from *Figures 2.1* to *2.3* are:

(1) In all four seasons there are areas in Europe with lower temperatures than the 30-year average. The same conclusion has been reached in other

studies using empirical methods to derive climate scenarios (e.g., Lough *et al.* 1983; Jäger and Kellogg 1983).

(2) The most significant positive temperature differences are observed in the winter months in high latitude land areas of Europe. This result has also been found in model and empirical studies looking at the effects of hemispheric warming on European climate.

(3) In the winter season a negative temperature anomaly is observed in southern Europe and the Mediterranean area. Again, this has also been noted in other empirical studies and is shown in *Figures 2.1* and *2.3* of this chapter.

(4) A positive temperature anomaly is found in central and southern Europe in the summer season. This was also found, for example, in the empirical study of Jäger and Kellogg (1983).

(5) Mean annual precipitation changes show a tendency for a decrease in central and southern Europe, the Mediterranean and the belt between 50–55° N. The opposite tendency is observed in the western and northern parts of Europe.

(6) Summer precipitation decreases over Spain, the Balkan, Nordic, and central European countries. Precipitation increases over France and the British Isles.

(7) Greater evapotranspiration during winter occurs along coastal areas alone. Greater evapotranspiration in summer is widespread over continental areas of central and southern Europe, which would probably greatly increase agricultural problems induced by precipitation decreases in these regions.

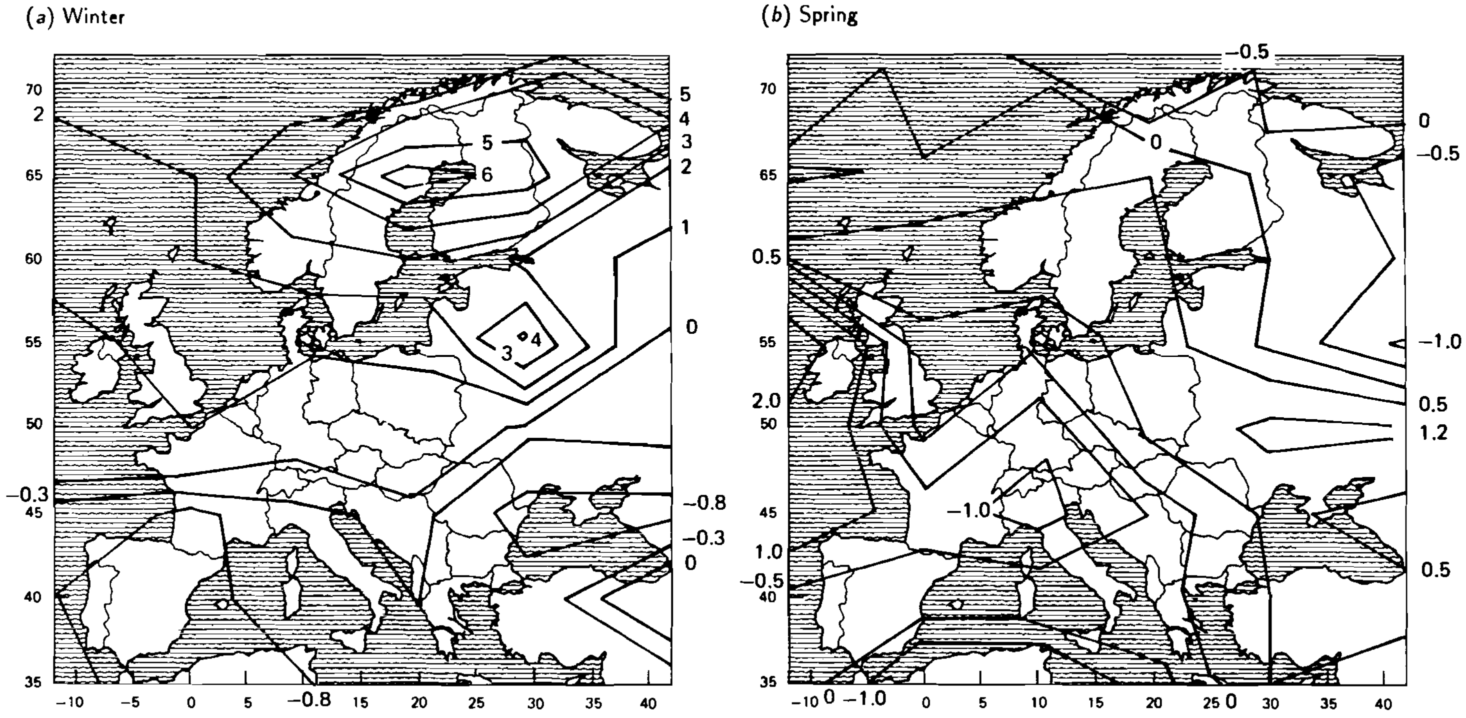
It can be seen that the changes in potential evaporation also have different tendencies in different seasons and regions of Europe.

2.4. Discussion

Statistical analysis has shown that there are significant relationships between the annual average Northern Hemisphere temperature and the frequencies of some of the main types of atmospheric circulation over Europe. This result is not unexpected, since earlier studies have shown relationships between changes in hemispheric temperature and changes in surface and upper air pressure distributions (e.g., van Loon and Williams, 1976).

On the basis of the empirical relationship, it is possible to calculate the changes of the frequencies of circulation types assuming a 1° C increase in hemispheric temperature. The circulation types corresponding to the assumed 1° C increase of hemispheric temperature resemble the circulation types that occurred in seasons during the past 50 years that are known to have been warm – particularly the end of the 1930s.

This empirical approach to scenario development has the advantage of producing internally consistent and physically plausible scenarios. The chain of reasoning from hemispheric temperature change to change in the frequency of atmospheric circulation types, to changes in the distribution of temperature and



(a) Winter

(b) Spring

Figure 2.1. The differences in temperature (° C) between the analogue season and the 1951–1980 mean for (*a*) winter, (*b*) spring, (*c*) summer, and (*d*) autumn.

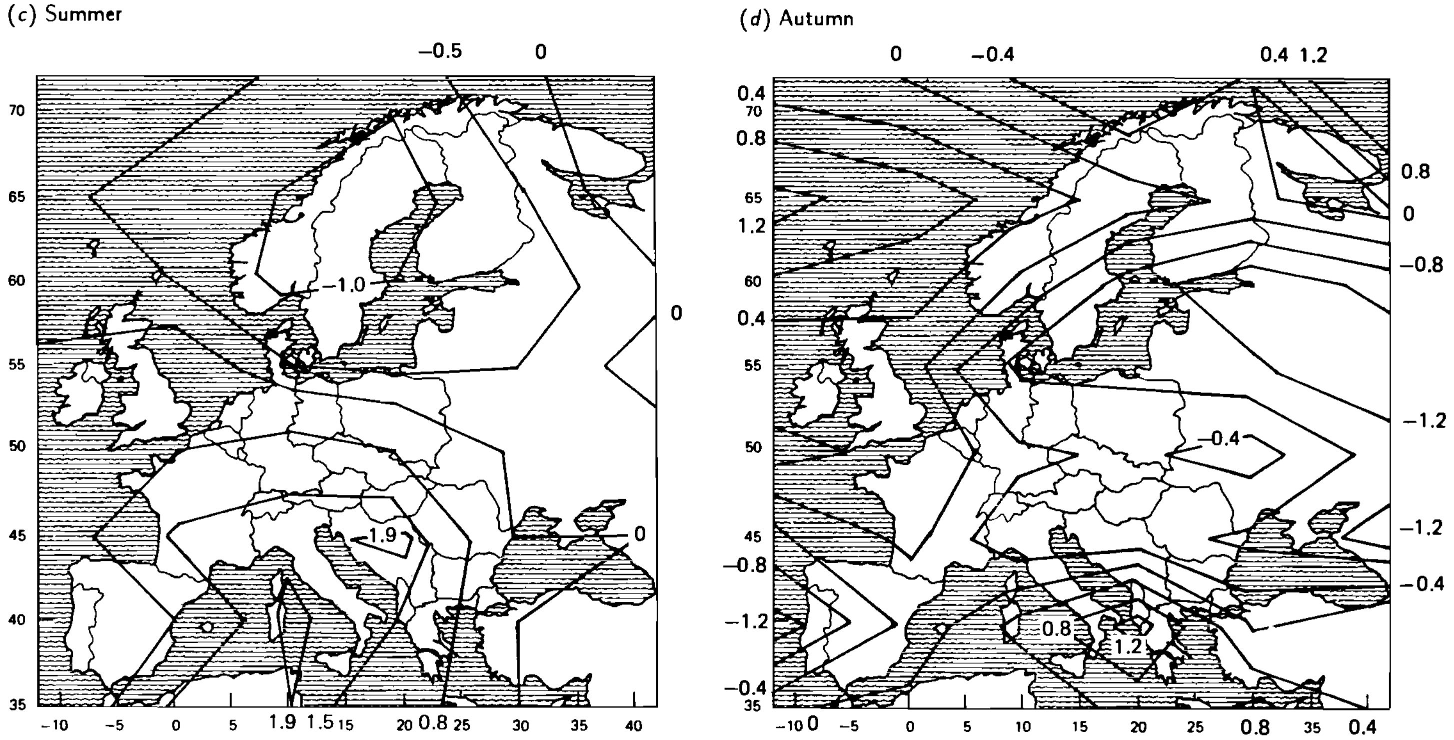
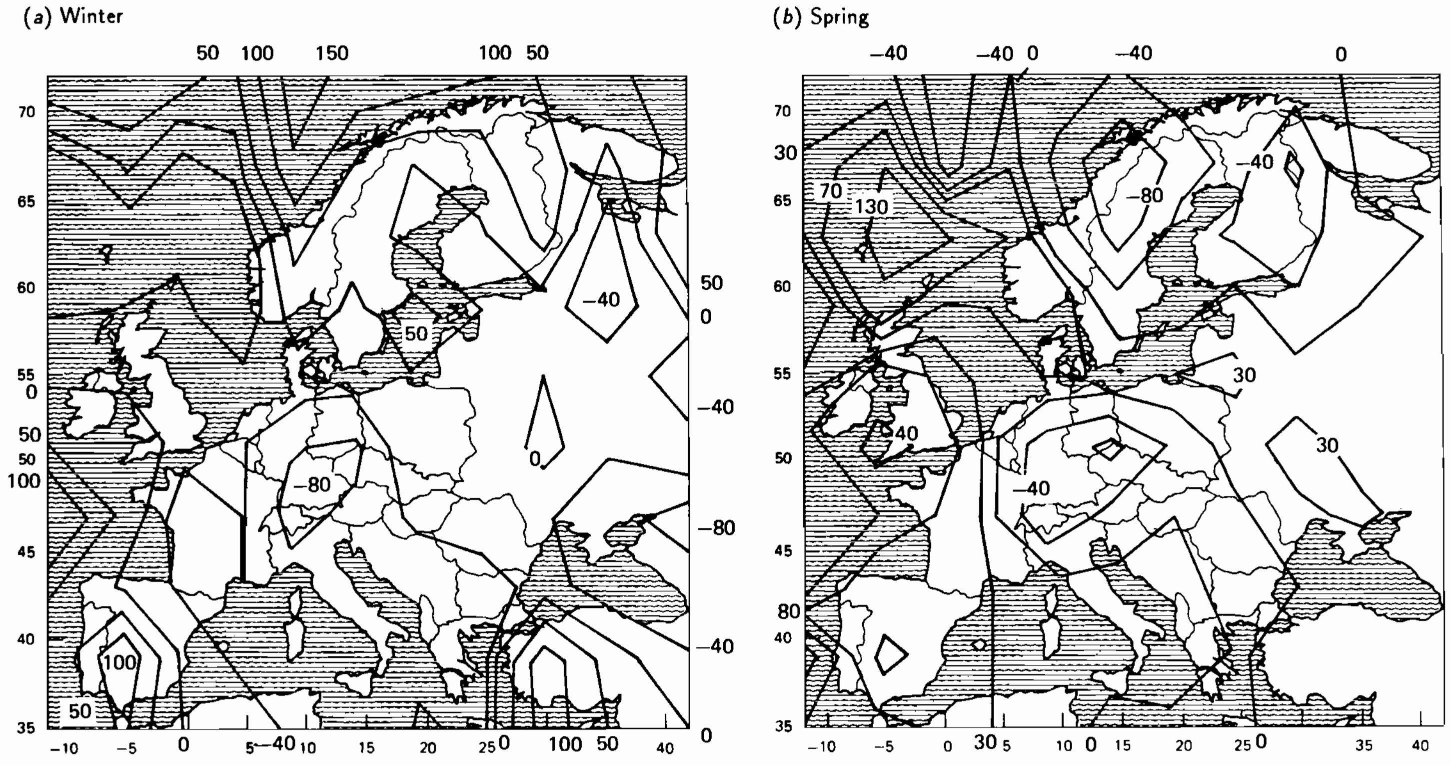


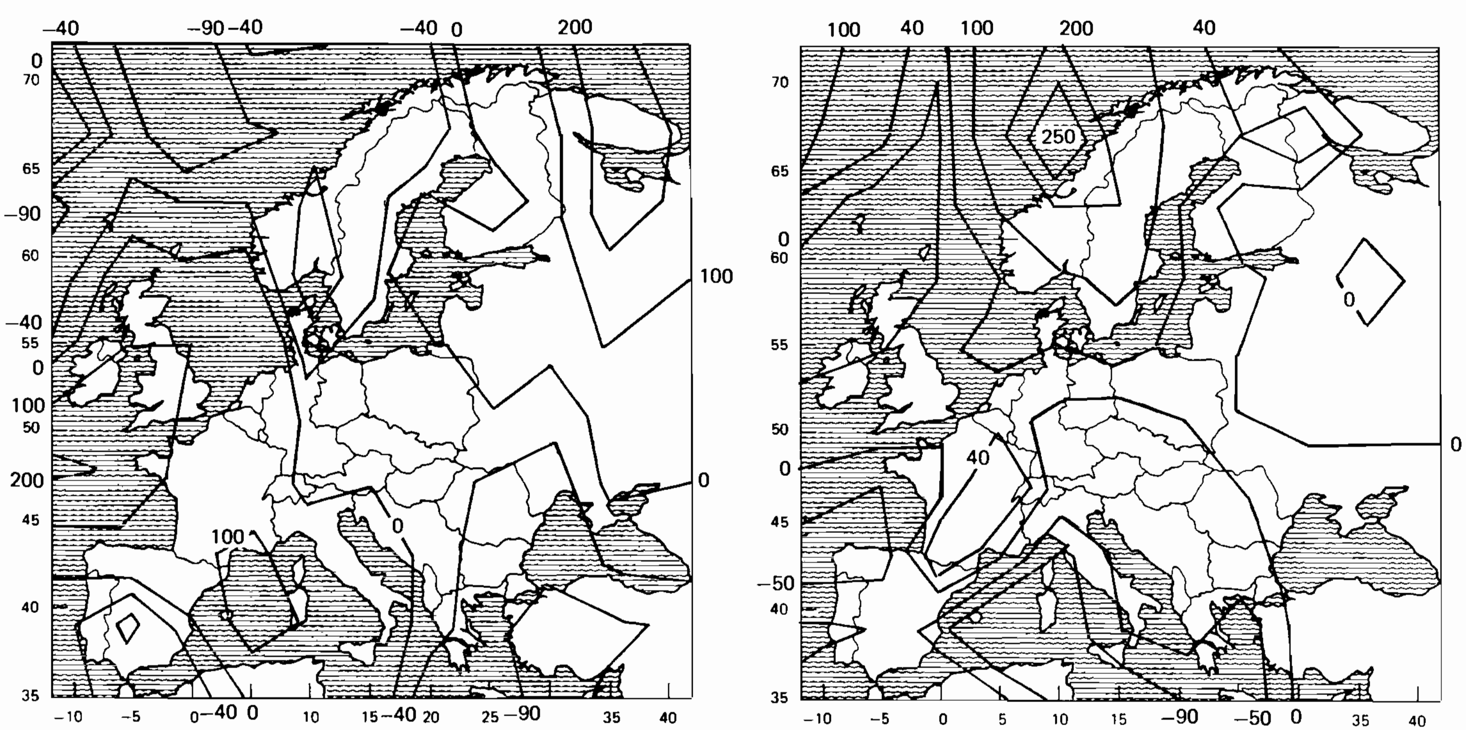
Figure 2.1. Continued.



(a) Winter

(b) Spring

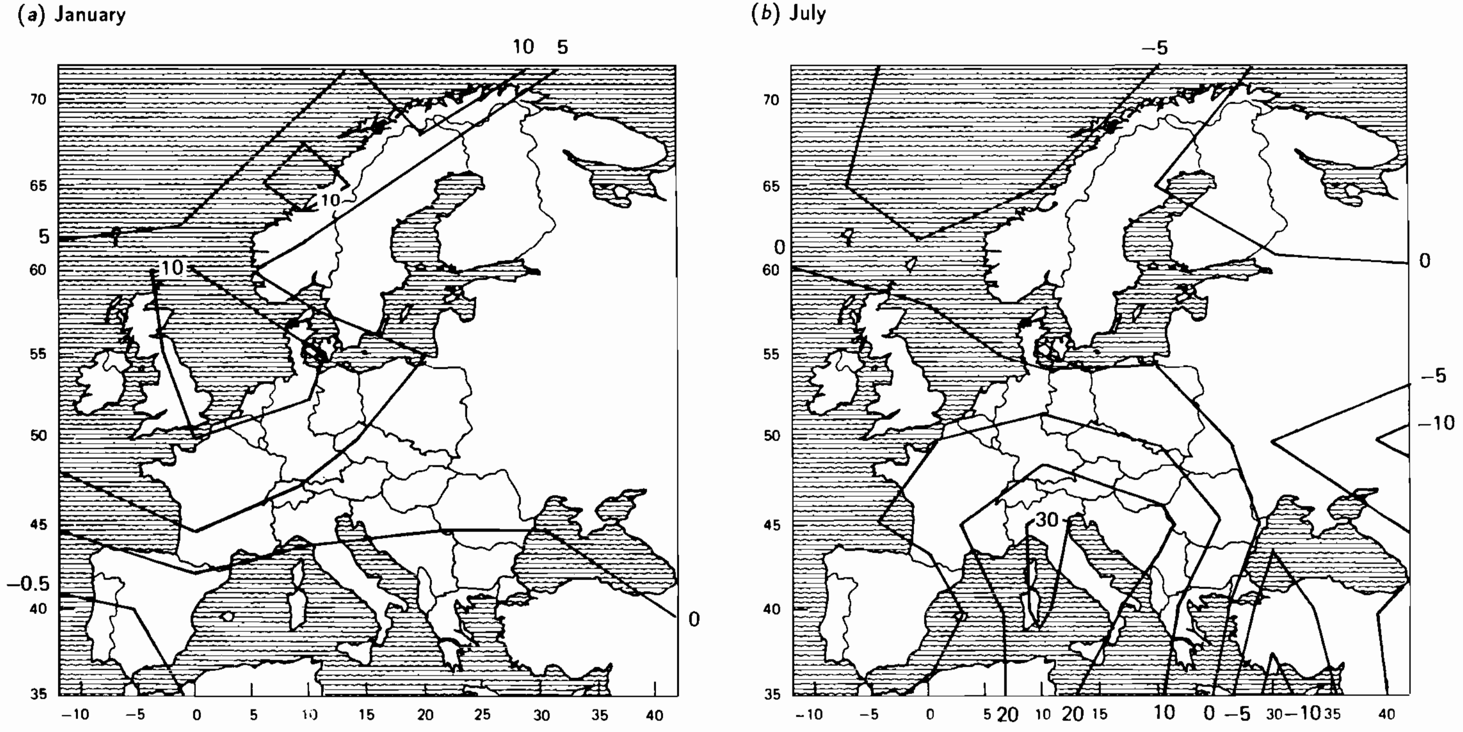
Figure 2.2. The differences in precipitation (mm) between the analogue season and the 1951–1980 mean for (*a*) winter, (*b*) spring, (*c*) summer, and (*d*) autumn.



(*c*) Summer

(*d*) Autumn

Figure 2.2 Continued.



(*a*) January

(*b*) July

Figure 2.3. The differences in computed potential evaporation (mm/month) between the analogue values and the 1951–1980 mean in (*a*) January, and (*b*) July.

precipitation in Europe, provides a solid basis for climate scenario development. As always, of course, care should be taken that the derived scenarios are not interpreted as predictions.

This pilot study of the approach has demonstrated its feasibility. Further steps include: the use of seasonally averaged Northern Hemisphere temperatures instead of annually averaged values; the investigation of the effects of other hemispheric temperature changes (e.g., +2° C, +3° C, -2° C); detailed comparison with the results of other empirical and model studies. In addition, the present test of the approach was based on a 5° by 5° latitude-longitude grid, which is about the same frequency of "samples" as one could derive from GCM runs. Future assessment work could use a much finer grid of stations, permitting examination of much more localized effects of climate change.

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CHAPTER 3

Hydrology: Water Quality Changes

Lea Kauppi

3.1. Introduction

3.1.1. The problematic nature of eutrophication of surface waters

Eutrophication has been defined as an increase in productivity of the aquatic ecosystem. Very pure waters are very poor in nutrients and microorganism populations and are defined as oligotrophic. In natural conditions evolution should lead from oligotrophy to eutrophy as a result of the gradual downslope movement of components from terrestrial systems. This evolution is, however, very slow without human intervention. Anthropogenic eutrophication began when man started clearing land for cultivation. The problems resulting from nutrient enrichment first appeared in *fresh surface waters.* Paleolimnological studies show that the present trophic state of many eutrophic lakes was achieved before industrialization. However, the most serious eutrophication appeared after the 1940s.

The eutrophication level is the expression of the physicochemical complexes of the catchment system. It is also a function of the internal physicochemical and biological dynamics of the separate compartments of the lake itself (OECD, 1982). Thus eutrophication due to increased nutrient input is only a special aspect of normal lake productivity. More critical is the rate and the level of eutrophication that the lake reaches. Problems arise when fertility increases to the point of producing algal blooms, heavy growth of aquatic plants, algal mats, deoxygenation, and bad taste and odors. These affect the uses of water for water supply, recreation, and fisheries. Expensive purification methods may be needed to produce potable water but sometimes even this does not help, which means that new water sources must be found.

Recreation activities suffer from eutrophication because, for example, bathing has to be forbidden due to toxic algal blooms. A *hypertrophic lake* (or river or sea) having a high phytoplankton production (see *Figure 3.1*) is aesthetically unpleasant.

Recent development on the western coast of Scandinavia provides a pessimistic picture of the future of fisheries in that area: at least 500 tons of salmon and rainbow trout died in the fish farms on the southern coast of Norway in spring 1988 because of the toxic algal bloom. Furthermore, numerous fish farmers had to move their farms into the fjords in order to save the fish. The economic losses were obviously important. The events of 1988 resulted from continuous eutrophication over a long period. However, detrimental changes in the aquatic ecosystems also occur in the early phases of eutrophication. For example, economically less valuable fish species often replace the original fish stock.

Considerable research was conducted on eutrophication in the late 1960s and 1970s. The influential report *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication* (Vollenweider, 1968) was funded by the OECD. In many European countries special research programs were established such as the Swedish RR-study (*Reningsverk-Recipient*) (Forsberg *et al.*, 1975). In the early 1970s, the OECD started the Cooperative Programme on Eutrophication, aimed at a better understanding of the quantitative relationships between nutrient supply and the trophic response of lakes, and of the relative significance of nitrogen and phosphorus in eutrophication (OECD, 1982). The main conclusion was that phosphorus plays a crucial role in eutrophication and thus, the emphasis in sewage treatment should be on phosphorus removal.

In the past the public was less concerned about eutrophication. Today, however, as leisure time and recreation have increased, people appreciate environmental benefits. More information is also available on environmental issues. As a result, general environmental awareness has increased and people observe their environment more carefully than before. Particularly in regions which are still relatively unpolluted, like Scandinavia, accumulation of slime on nets or the occurrence of even a small algal bloom makes people contact water authorities and call for pollution reduction. Thousands of people took part in demonstrations against the pollution of the North Sea in summer 1988 after the mass killing of fish and seals.

3.1.2. Historical development and current spatial extent of eutrophication in Europe

Different countries define oligotrophic and eutrophic waters somewhat differently. The OECD (1982) proposed trophic categories based on total phosphorus concentration, *chlorophyll a*, and Secchi disc transparency (*Table 3.1*). These categories can be described in the form of probability distributions (*Figure 3.1*).

Table 3.1. Proposed boundary values for trophic categories (fixed boundary system).

	mg/m^3			m	
Tropic category	$[\bar{P}]_\lambda$	$[\overline{chl}]$	$\begin{bmatrix}\max\\ \text{chl}\end{bmatrix}$	$[\overline{\text{Sec}}]^y$	$\begin{bmatrix}\min\\ \text{Sec}\end{bmatrix}^y$
Ultra-oligotrophic	≤ 4.0	≤ 1.0	≤ 2.5	≥ 12.0	≥ 6.0
Oligotrophic	≤ 10.0	≤ 2.5	≤ 8.0	≥ 6.0	≥ 3.0
Mesotrophic	10–35	2.5–8	8–25	6–3	3.0–1.5
Eutrophic	35–100	8.0–25	25–75	3–1.5	1.5–0.7
Hypertrophic	≥ 100	≥ 25	≥ 75	≤ 1.5	≤ 0.7

(Source: OECD, 1982.)

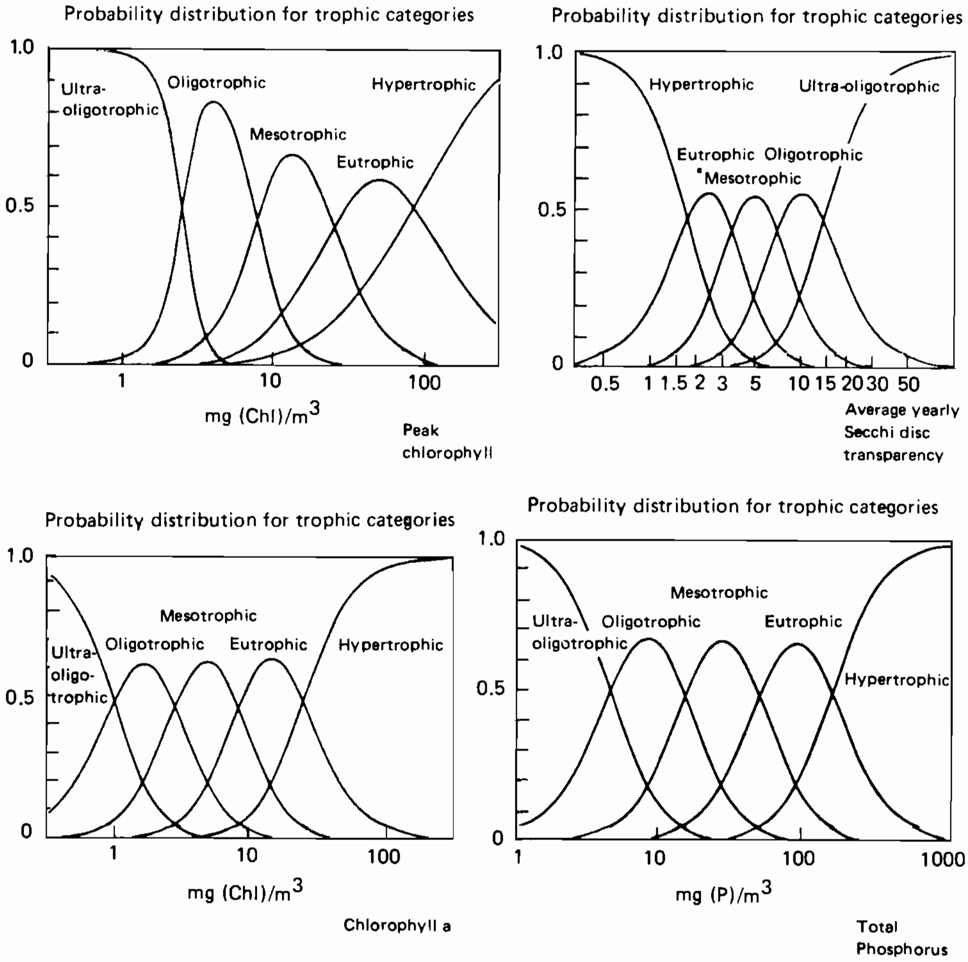

Figure 3.1. Trophic categories of lakes according to OECD (1982).

Traditionally, eutrophication has been a problem in waters which receive domestic or industrial effluents. Lakes and some closed coastal waters have suffered most, while eutrophication has not normally been a serious problem in rivers because of the high flushing rate which restricts the efficient utilization of nutrients.

Paleolimnological studies on cultural eutrophication provide useful information about long-term changes in the trophic status of lakes. Alhonen (1989) reviewed paleolimnological studies on some European lakes. Most of the lakes included in the review have been loaded by industrial and/or municipal wastewaters. In some cases, like the Esthwaite Water in the English Lake District and the Grosser Plõner See in the Federal Republic of Germany (FRG), cultural eutrophication dates back to hundreds and even thousands of years. More often, however, signs of accelerated eutrophication are observed at the end of the 19th century. Over the last twenty years, water protection measures have resulted in the improvement of the state of some lakes.

The spatial distribution of man-made eutrophication thus used to follow the urbanization pattern. Eutrophic lakes occur when the soil and parent material in the watershed are naturally nutrient-rich. These are normally on sedimentary rocks, especially limestones and dolomites. Limestones are most prevalent beneath European soils south of the Alps. However, these naturally rich lakes are difficult to distinguish from those affected by agriculture. In fact these two affecting factors, nutrient-rich soils and agriculture, generally go hand in hand. Agriculture is practiced on the most fertile soils, which also naturally would supply waters with plenty of nutrients.

There is no overall systematic survey on the extent of eutrophication in European waters. According to the OECD report on the state of the environment (OECD, 1985) eutrophication has decreased from what it was in the early 1970s in Finland, Sweden, Norway, and Switzerland. This mainly refers to the recovery of some water areas polluted earlier. Several examples can be given, like Lake Constance (Austria, FRG, Switzerland), Lake Mjøsa (Norway), Lake Mälaren and Lake Vättern (Sweden), and Lake Tuusulanjärvi (Finland).

However, at the same time an increase in nutrient concentrations has been observed in many water systems. In the majority of observation sites in Hungary, an increase in nitrate and phosphate concentrations occurred between the years 1976 and 1985 (Hock and Somlyody, 1990). Eighty-seven per cent of all the sites showed an increasing trend in nitrate concentrations. A continuous increase in nitrate concentrations is found also in the river Danube as well in the river Rhine (*Figure 3.2*).

The most detrimental consequences of increased nutrient concentrations in river waters are often in the coastal areas into which the rivers discharge. Alarming eutrophication of European coastal waters has been observed almost everywhere. The recent fish and seal kills in the North Sea have been strongly connected to the nutrient loads discharged by the river Elbe as well as by the coastal cities. The continuously increasing nutrient input to the sea has gradually changed the structure of the ecosystem. At certain points an alga

Figure 3.2. Development of nitrate concentrations in the rivers Danube and Rhine. (Source: Hock and Somlyody, 1990.)

(*Chrysochromulina polylepsis*) which has always been found in the area, but in small amounts, assumed dominance (Rosenberg, 1988). The consequences were dramatic because this species produces toxin.

In addition to the toxin from the algal bloom the seals were suffering from a rabies-type virus. The occurrence of all these events shows that the ecosystem of the North Sea cannot sustain the present pollution. The estuary of the river Rhine accumulates, among other substances, tens of thousands of tons of phosphorus annually (Santema, 1980). Most of the phosphorus input into the Baltic Sea comes as river discharge (Melvasalo *et al.*, 1981). Diverting effluents from a lake to a river only relocates and maybe postpones the problem.

At the same time that eutrophication accelerates in coastal waters, indications of a new wave of lake eutrophication are also to be seen, particularly in Scandinavia. In this case the lakes experiencing detrimental changes are generally located in rural areas without any major point source pollution. A typical phenomenon has been blooms of blue green algae capable of fixing atmospheric nitrogen, indicating an excess supply of phosphorus over nitrogen. This phenomenon is assumed to be connected mainly to agriculture.

Eutrophication has been one of the main water problems in Europe for decades. Appearing first mainly in lakes receiving domestic or industrial effluents, it is now attacking coastal areas and lakes in rural areas without identified point sources of pollution (Fleischer *et al.*, 1987; Kauppi *et al.*, 1989). Some lakes which became eutrophic some decades ago have instead partially recovered due to measures taken to reduce pollution (e.g., Olsen and Willen 1980; Willen, 1987).

3.1.3. Nitrate in groundwaters

Groundwaters were previously thought to be well protected against pollution by the overlying soil layers. However, in the early 1970s elevated concentrations of nitrate nitrogen and other pollutants were measured (Zwirnmann, 1982; Overgaard, 1984; OECD, 1986). As a result more systematic surveys of groundwater quality were initiated in the European countries. They clearly revealed that in intensively cultivated areas, the risk for nitrate pollution is real. The delay in the response of groundwater, which depends on depth and other characteristics of the soil, makes the problem more complex. It may be that the cases which are known so far are only the first signs of more widespread problems in the future.

The concern in case of high nitrate concentrations in groundwaters is related to domestic water supply. High intake of nitrates by bottle-fed infants is known to cause methemoglobinemia (reduced oxygen carrying capacity of the blood). Nitrites (and indirectly nitrates) can also form nitrosamines and nitrosamides when reacting with amines and amides. Many of these N-nitroso compounds are carcinogenic, mutagenic and teratogenic to animals.

As a result of the health risks, WHO (World Health Organization) set drinking water standards for Europe (WHO, 1970). According to these standards, nitrate concentrations should be below 50 mg NO_3/l (11.3 mg N/l) but concentrations of up to 100 mg/l (22.6 mg N/l) are acceptable. The EEC Directive on the quality of *Water for Human Consumption*, effective from 1985 (EEC, 1980) makes 50 mg NO_3/l the maximum admissible concentration, and gives a guide level of 25 mg NO_3/l. During the last ten or fifteen years nitrate concentrations exceeding these limits have been observed in groundwaters more and more frequently (Zwirnmann, 1982; Overgaard, 1984; OECD, 1986; Umweltbundesamt, 1986).

In Denmark drinking water in 18% of the public water works had nitrate concentration above 25 mg NO_3/l and 8% exceeded the upper limit set by the EEC (Overgaard, 1984). The western part of the country, where sandy soils are common, is more affected than the eastern part. Agriculture has been proven to be the most important source of nitrate.

In the FRG 8% of the public waterworks use water with a nitrate concentration of above 50 mg NO_3/l (Umweltbundesamt, 1986). All these waterworks use ground or spring water. The private water supply systems are much more affected, according to the Umweltbundesamt (1986) up to 50% exceed the upper limit of the EEC Directive. Investigations in other countries, like the Netherlands, France, and the UK show the same increasing trend in nitrate concentrations over time (OECD, 1986).

3.2. Causal Agents and Response Indicators

3.2.1. Causes of nutrient enrichment of water resources

Nutrient enrichment of different water systems is caused by discharges of nutrients from different human activities. Earlier, municipal and industrial wastewaters discharged into the watercourses were considered to be the main contributor. Recently, however, the nutrient runoff from agricultural areas has gained significance, as wastewater treatment has improved while the increased use of fertilizers in agriculture has increased losses as well.

The majority of the population in most western and eastern European countries is served by public water supply and sewage (*Figure 3.3*). However, only about half is served by sewage treatment works, most of which are mechanical or biological (EWPCA, 1984). This implies that the sewage facilities mainly reduce suspended matter and the oxygen consuming load, while nutrient removal is not very efficient. Only a few countries, such as Sweden, Finland, and Switzerland have widely adopted tertiary wastewater treatment, which also removes phosphorus by chemical precipitation.

The total municipal wastewater nutrient load in Europe can thus be roughly estimated on the basis of population. In 1985 the total population in Europe, excluding the USSR, was 492 million (FAO, 1985b). Assuming that a person produces 0.90 kg phosphorous (P)/yr and 4.0 kg nitrogen (N)/yr (National Board of Waters, Finland, 1986) the total amount would be almost 450,000 tonnes of phosphorus and 2,900,000 tonnes of nitrogen annually. Treatment plants without chemical precipitation remove perhaps 25–30% of both nutrients. Thus the annual load discharged to the waters would be around 300,000 tn P and 1,500,000 tn N. The population of those countries having significantly better wastewater treatment is small. On the other hand, several countries in Europe have no treatment at all for a significant part of their wastewater. These two factors could compensate for each other so that the load estimates above could be more or less correct. The spatial distribution of municipal wastewater loads follows the population distribution.

Industrial nutrient loads are even more difficult to estimate. Only a few countries provide this information. Based on the few data available, industry apparently contributes less to nutrient loads than municipal wastewaters. For example, in Finland, industrial phosphorus is about equal to the municipal sewage load, but the nitrogen load from industry is only half of the load from municipal treatment plants. In Norway, the industrial nutrient load is clearly less than the municipal load. The phosphorus load to the Skagerrak and Kattegat from Swedish industry is equal to the municipal discharges, but the

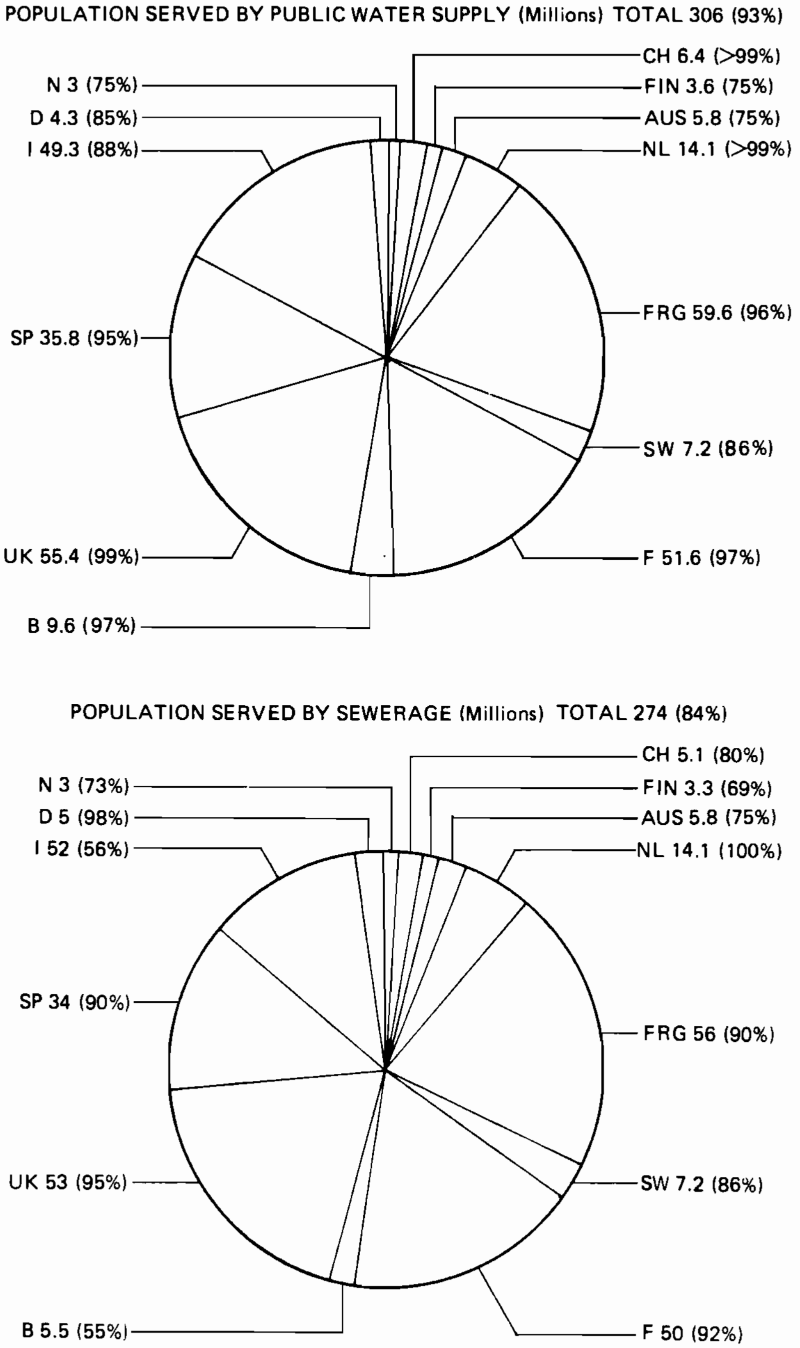

Figure 3.3. Population served by public water supply and sewerage in EWPCA countries. (Source: EWPCA, 1984.)

Table 3.2. Specific annual amounts of nutrients excreted by different animals.

	Phosphorus kg/yr	Nitrogen kg/yr
Cattle	12.2	46.0
Pigs	2.3	10.8
Sheep and goats	1.1	8.9
Poultry	0.23	0.22
Horses	9.0	34.0

Source: Paasonen-Kivekäs, 1989.

industrial nitrogen load is less than one-tenth of the municipal N load (Oslo and Paris Commissions, 1984).

The amounts of phosphorus and nitrogen used in agriculture in Europe are an order of magnitude higher than the amounts produced by the population. The use of mineral fertilizers alone accounts for over 3.5 million tons of phosphorus and 15 million tons of nitrogen annually in Europe, excluding the USSR. The manure produced by the livestock contributes an additional 2.5 million tons of P and 10 million tons of N annually, i.e., the total input into agricultural soils is 6 million tons P and 25 million tons N assuming the specific nutrient contents listed in *Table 3.2* (Paasonen-Kivekäs, 1989). Plants take up part of these nutrients, but the use of fertilizers and manure clearly exceeds the uptake.

As the trend in almost all European countries is toward more efficient wastewater treatment, it is obvious that the significance of agricultural nutrient inputs will increase in the future. Technical methods also exist for solving the wastewater problem. For these reasons our work will concentrate on nutrient enrichment caused by agriculture.

3.2.2. Agricultural nutrient balances in various countries

In the 1950s the input and uptake of phosphorus and nitrogen were more or less in balance. Since then the inputs have increased manyfold. The yields have also increased, but at a slower rate. This implies that the excess nutrients have either accumulated in the soil or have been discharged into adjacent ecosystems. In fact the increase in the phosphorus content of agricultural soils has been observed in several countries (e.g., Breeuwsma and Schoumans, 1987; Sillanpää, 1986). The increase of nitrate concentrations in ground and surface waters in agricultural areas is a clear indication of excess nitrogen leaching from the soil.

In order to be able to describe the spatial and temporal distribution of the overfertilization in more detail one must know the fertilization rate, livestock density, plants cultivated, and their yields. This kind of information is readily available on a country basis in international statistics, published by FAO (also available on tape). These data were used in our nutrient balance calculations.

The input–output analysis of nitrogen and phosphorus was made for 24 European countries (excluding the USSR) for the years 1961, 1965, 1970, 1975, 1980, and 1985. All the values were calculated as kg/ha/yr on agricultural land. The fertilizer and land use data were collected from the FAO statistical

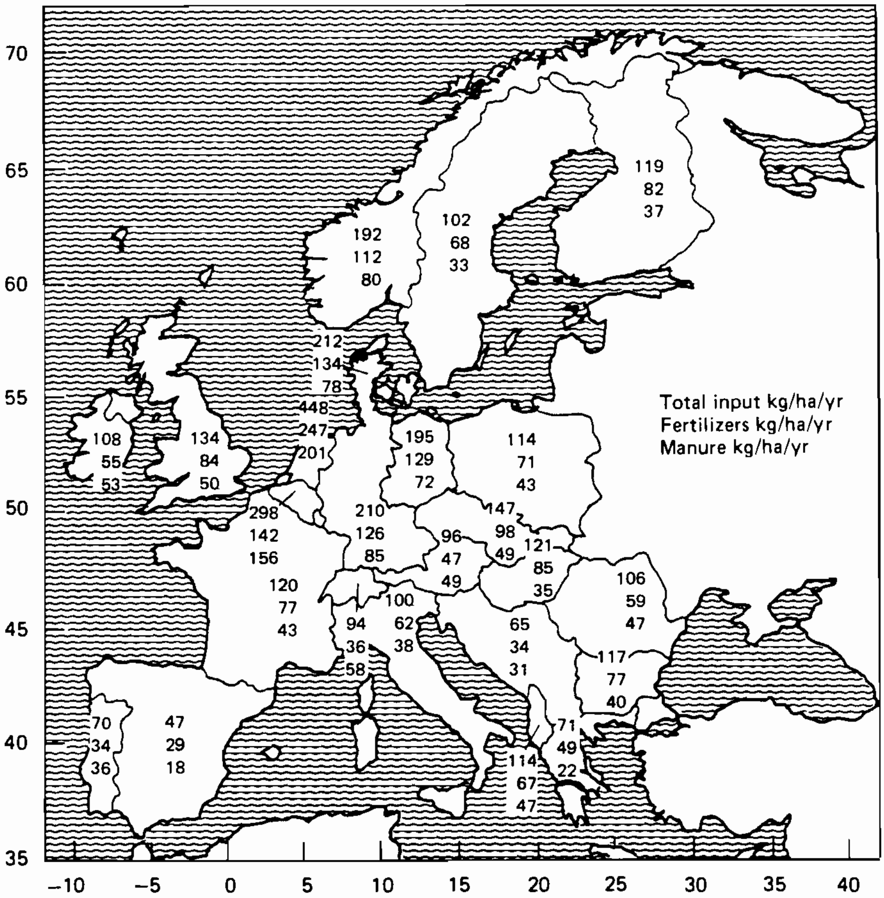

Figure 3.4. Total input of nitrogen per ha of agricultural land and year. (Source: Paasonen-Kivekäs, 1989.)

yearbooks (FAO 1961a, 1961b, 1965a, 1965b, 1970a, 1970b, 1975a, 1975b, 1980a, 1980b, 1985a, 1985b). Information on agricultural production and number of livestock was mainly derived from the FAP/FAO database at IIASA. A more detailed description of the data sources used can be found in Paasonen-Kivekäs (1989).

The main feature of the fertilizer use was the increasing trend during the whole period in all countries and the significant variation between different countries. The nitrogen-phosphorus ratio in fertilizers has also increased.

Manure applications increased during the period 1961–1985, particularly in Central European countries. The highest nutrient input values due to manure application were in the Netherlands, B.g.,um-Luxembourg, Denmark, the FRG, and the GDR, the lowest ones in Spain and Greece. The proportion of manure in the total nutrient input has steadily decreased. In 1985 total nutrient inputs

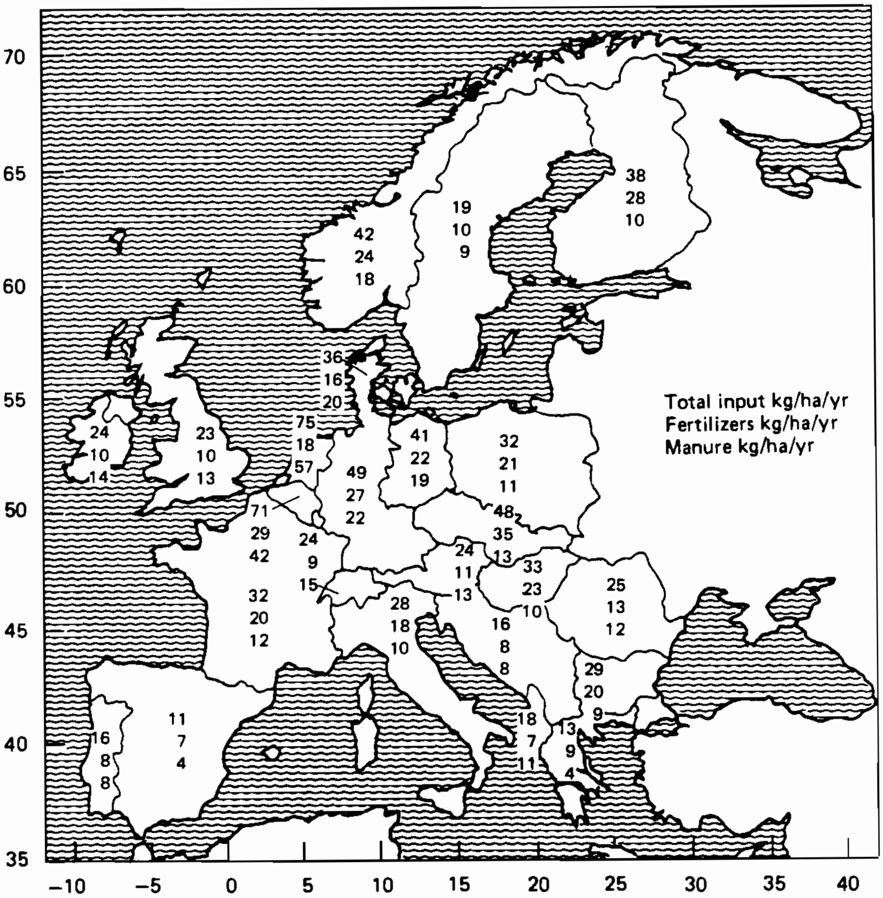

Figure 3.5. Total input of phosphorus per ha of agricultural land and year. (Source: Paasonen-Kivekäs, 1989.)

per ha of agricultural land varied from 47 kg N/ha/yr and 11 kg P/ha/yr in Spain to 450 kg N/ha/yr and 75 kg P/ha/yr in the Netherlands (*Figures 3.4* and *3.5*). As these are country averages, the actual variation in the fields is much larger.

Nutrient outputs are far more difficult to estimate than inputs, because the production data needed are not reported in a homogeneous way in different countries. For some crops, like cereals, reliable yield estimates are available, while for forage, silage, and fruits the statistics are very heterogeneous. Therefore, in the following analysis the latter were excluded.

The Netherlands again had the highest yields: 217 kg N/ha/yr and 36 kg P/ha/yr in 1985. The lowest output values were calculated for southern Europe, Portugal having the minimum with 36 kg N/ha/yr and 6 kg P/ha/yr (*Figure 3.6*). Throughout the whole observation period the yields have increased,

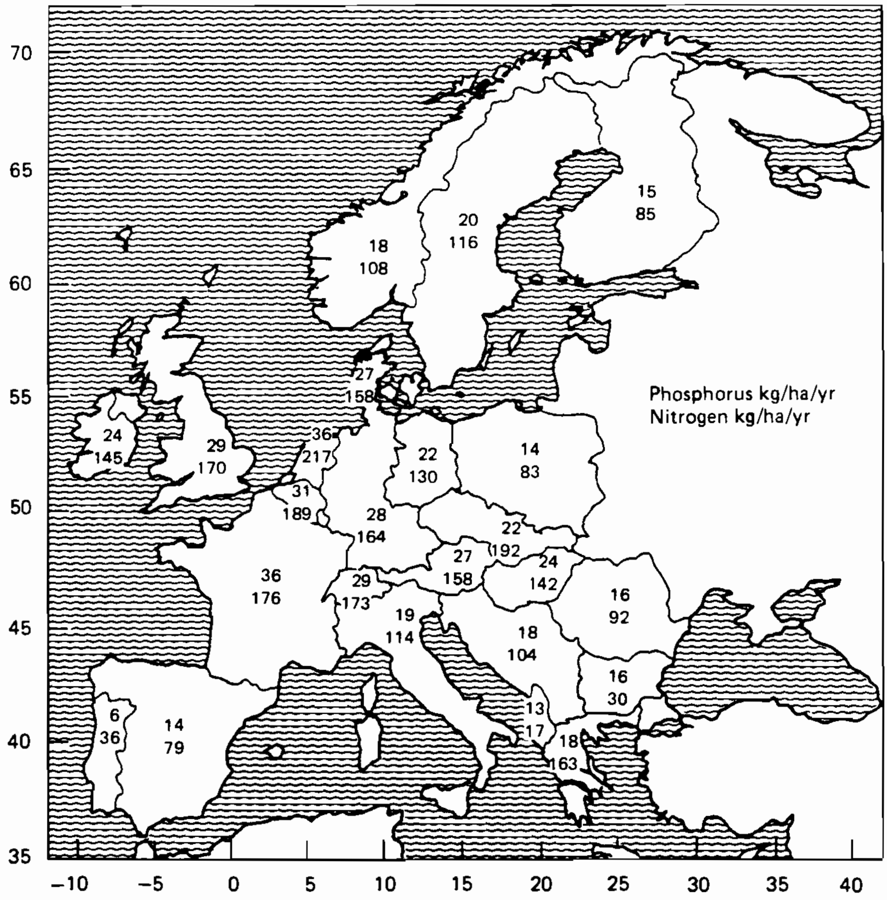

Figure 3.6. Output of phosphorus and nitrogen by plant uptake per ha of agricultural land and year excluding forage, silage, and fruit production. (Source: Paasonen-Kivekäs, 1989.)

resulting in increasing nutrient output values.

From the environmental point of view the most important figure is the input–output difference. These figures vary remarkably from country to country (*Figure 3.7*). In general, the higher the inputs, the more that remains unused, i.e., the utilization rate decreases as inputs increase. There are considerable uncertainties in all the data used and the estimates should be considered relative rather than absolute. However, they clearly point out that in some countries, agriculture uses much more nutrients than the plants can utilize. At the same time some countries are still consuming the natural nutrient storage in the soil, or in the case of nitrogen, the difference is balanced by fixation of atmospheric nitrogen.

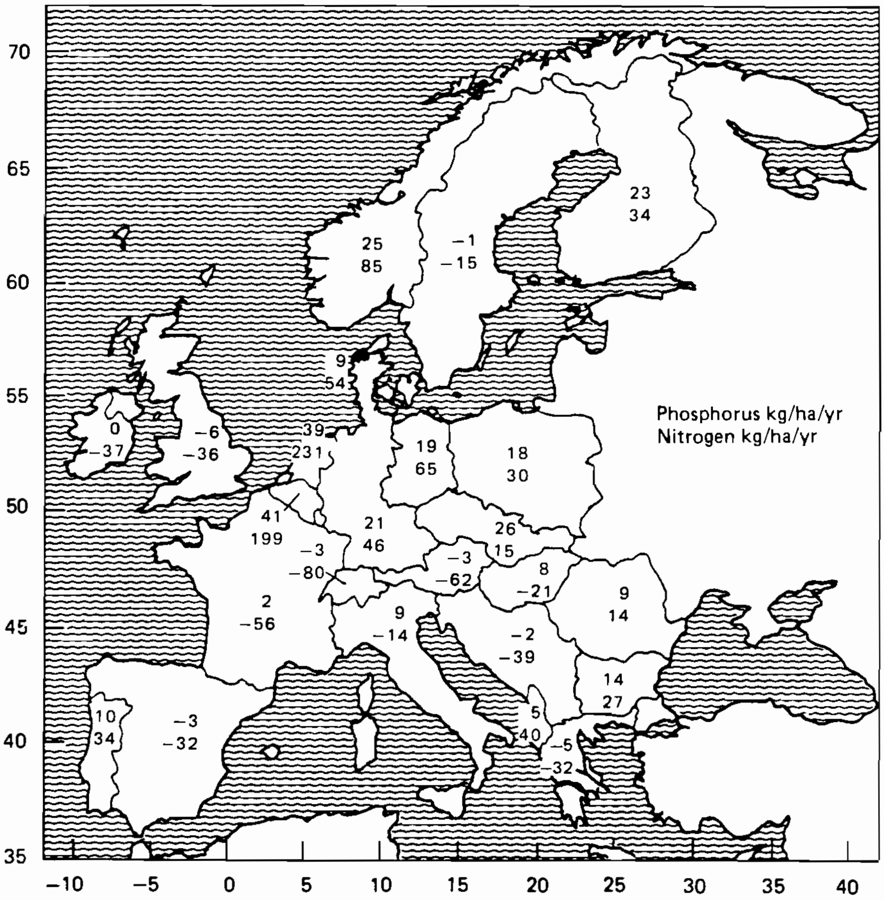

Figure 3.7. Input–output values of phosphorus and nitrogen per ha of agricultural land and year excluding forage, silage, and fruit production. (Source: Paasonen-Kivekäs, 1989.)

Atmospheric deposition was excluded from the calculations. It would, in some countries, change the balance to a positive one. The highest nitrogen deposition values have been observed in the Benelux countries, with about 30 kg N/ha/yr. In northern and southern Europe the deposition is much lower, being around 10 kg/ha/yr (Zwirnmann, 1982).

3.2.3. Reactions in the soil

In the absence of any major point sources, the state of a water body is a reflection of its watershed. Therefore the best indicators to judge the systems' future behavior are to be found in the watershed. In the case of nutrient enrichment the critical factors are the characteristics of the soil which describe its capacity to retain nutrients. Phosphorus sorption capacity is strongly dependent on the aluminum and iron oxide content of the soil. Topography affects erosion and the nutrients carried by the eroded material. The fate of nitrogen is determined by the infiltration characteristics of the soil, which in turn can be estimated on the basis of the texture.

The water table level also affects the time needed before the phosphate concentration of surface and ground waters increases significantly. Today phosphorus saturation is only observed in areas where the water table is high, but soil samples taken from different soil layers suggest that the phosphorus front is gradually penetrating deeper in many areas. This problem is discussed in greater detail in the next Section.

3.2.4. Relationships between causal agents and response indicators

Modelling the Consumption of the Phosphorus Sorption Capacity of European Agricultural Soils

The relationship between overfertilization and phosphorus enrichment of water resources can be studied by comparing the excess amount of phosphorus used in agriculture with the phosphorus sorption capacity of the soil. The difference expresses the rate of the consumption of phosphorous sorption capacity.

As the input–output calculations showed (*Figure 3.7*) the use of phosphorus fertilizers (mineral and manure) has exceeded the uptake of plants in many European countries since the 1950s (see e.g., Behrendt, 1988; Sillanpää, 1986). This is especially true in the Netherlands where intensive animal husbandry produces surpluses of manure. As a result, very high amounts of manure are spread mainly on fields of maize, a crop which is not adversely affected by high amounts of manure. Also in many other countries the phosphorus content of agricultural soils has increased remarkably. For example in Finland and in Norway, where the soils are acid, it has been a policy to raise the content of phosphorus available for plants by fertilization. This policy can easily be seen from the fertilization rates (*Figure 3.5*).

The result of overfertilization has been an accumulation of phosphorus into the uppermost soil layers. The soil, however, has a limited capacity to adsorb phosphorus, the magnitude depending mainly on the content of amorphous aluminum and iron. In some areas in the Netherlands this capacity has already been exhausted leading to leaching of phosphorus to ground and surface waters (Breeuwsma and Schoumans, 1987). Even before the total adsorption capacity is filled, the phosphorous content of eroding soil material increases, thus causing a risk for eutrophication of rivers and lakes.

Modelling the consumption of phosphorous sorption capacity on a European scale requires simplified models in order to minimize the data requirements. The RETRAM model developed by Breeuwsma and Schoumans (1987) may be the only existing model suitable for this purpose. It has been designed for regional applications, i.e., the input data needed can be obtained from regional soil surveys and agricultural statistics. In each soil layer considered, the model compares the annual effective phosphorus load (= the amount of P applied – the uptake by the crops + the amount dissolved from supersaturated layers) to the total phosphate sorption capacity of that layer. Thus the average rate of penetration of the phosphate front (V_p) can be calculated as follows:

$$V_p = \frac{\text{annual effective phosphate load (kg P/ha/yr)}}{\text{total phosphate sorption capacity (kg P/ha/cm)}} \tag{3.1}$$

The maximum load is defined by:

$$EPL_{max} = NN \text{ x } c_{sat} , \tag{3.2}$$

where

EPL_{max} = maximum, annual, effective load of phosphate (kg P/yr)
NN = annual net precipitation, P-E (m^3/yr)
c_{sat} = phosphate concentration in a saturated solution (kg P/m^3)

The important feature of the model is that it is soil-survey oriented, i.e., the soil parameters of the model can be related to soil survey data. As mentioned earlier the phosphate sorption capacity correlates quite well with oxalate-extractable iron and aluminum (e.g., Kaila, 1963; Hartikainen, 1979; Schoumans *et al.*, 1987), which, in turn, correlate well with soil type and horizon. This means that using transfer functions it is possible to use data from soil maps for estimation of phosphorus sorption capacity. Based on Dutch soil survey data Schoumans *et al.* (1987) have calculated the regression between total phosphorus sorption capacity and oxalate-extractable aluminum (Al) and iron (Fe):

$$PSC_{total} = 3.6 + 0.30 \ (Al_{ox} + Fe_{ox}) \tag{3.3}$$

in which all variables are expressed in mmol/kg.

Data Requirements

In order to estimate the annual effective phosphate load we need data on the amount of phosphate applied as well as on the plant uptake. At the moment the only data base easily accessible and covering the whole of Europe is the FAO statistics on fertilizers and agricultural production. They are, however, on a country basis and the only way to give values for the specific locations where the soil samples have been taken, is to assume the same rate of use of mineral fertilizers as well as an even distribution of animal husbandry in the agricultural area of the whole country. This does not mean that we should be satisfied with this and we could, however, make test runs with the already existing data. For estimating the input of phosphorus in manure, the number of animals in a country can be combined with the amount of phosphorus excreted by different animals (see e.g., Behrendt, 1988). The plant uptake would be estimated on the basis of yields and specific nutrient content of different agricultural plants, respectively.

There is no soil data base available which contains direct information on the soil variables mentioned above (Al and Fe content and texture). However, a rough estimate for aluminum and iron content as well as for texture can be obtained by using the FAO-UNESCO Soil Map of Europe (1974). The map, which is in digital form at IIASA (see chapter on soil acidification), gives the distribution of soil types and texture (3 texture classes). In order to use these data one would need information on the typical values of oxalate-extractable aluminum and iron content for each soil type in combination with different texture classes. This information is not readily available from publications, but must be collected from various sources. Most of it could be found in the International Soil Reference and Information Centre (and the Soil Survey Institute) in Wageningen, the Netherlands. This task would require 3–4 months' work by a soil scientist familiar with soil classification. Because other soil maps being prepared or recently accomplished use the same classification as the FAO-UNESCO Soil Map, the specific values would be directly applicable to them as well. This refers mainly to the Soil Map of European Communities (1:1,000,000), which should become available for IIASA in a digital form in the near future.

In contrast to the soil data, available information on European topography is fairly detailed. IIASA has a data base which describes the altitude distribution by grids of 10' by 10'. The data was originally extracted from the US Department of Defense Operational Navigation Charts (scale 1:1,000,000), Jet Navigation Charts and World Aeronautical Charts by the US Navy Fleet Numerical Oceanography Center.

Modelling the Nitrate Leaching Risk in Agricultural Soils

As part of our study, Paasonen-Kivekäs (1989) has described the state of the art of nitrate leaching modelling. The following text is based on her work. Two principal groups of mathematical models are used for evaluating nitrate leaching risk: chemical transport models and planning and management models. Chemical transport models estimate chemical losses from cropland to water bodies. Planning and management models are used to evaluate trade-offs between environmental and agricultural production (economic) objectives.

Three types of *chemical transport models* have been distinguished. Continuous simulation models describe the system of nitrogen and water on the basis of physical, chemical, and biological theories. These models have generally been applied to estimation of chemical losses in percolation or groundwater in one or more dimensions. The model applications need a multitude of parameter values and other input data, which makes testing and calibration of the models difficult.

A second model type, the discrete simulation model, is the most common type of chemical transport model. These models are based on water and chemical mass balances. They have been applied to estimate percolation losses or the complete hydrologic budget in a field or watershed. Several of these models are operational tools for water quality planning since they are computationally efficient, do not require extensive data, and have been tested in applications. For example, the CREAMS model developed by the US Department of Agriculture (Knisel, 1980) has been applied in many countries for nitrogen leaching applications.

The third and simplest kind of transport models are classified as functional models (Haith, 1982). Usually they do not simulate actual transport or chemical and biological processes. Rather, these models are simple equations based on empirical or intuitive information. Since these models do not attempt to simulate the fundamental transformation and transport phenomena, their use is limited to analyzing and predicting the system behavior in conditions for which they have been developed.

Planning and management models are in principle the most useful models for policy making since they provide estimates of economic and water pollution impacts of different management practices. However, the economic components of these models are usually much better developed than components for prediction of pollution.

At the Netherlands Soil Survey Institute a process-oriented simulation model, RENLEMA (Regional Nitrate Leaching Model), has been developed to estimate large-scale water quality response to nitrogen applications (de Vries *et al.*, 1987). The model has been designed to generalize process descriptions based on regional data. The model utilizes relatively simple descriptions for all relevant nitrogen transformation reactions and transport. The processes incorporated are volatilization of NH_3, mineralization, nitrification, denitrification and plant uptake. In a preliminary study for a pilot area, information on soil type and land use was derived from the soil map and the topographical map of the region to produce a map of groundwater vulnerability to nitrate pollution.

The data required by the model are as follows:

- Nitrogen fluxes: atmospheric deposition, fertilizers, animal manure, crop residues, plant uptake.
- Water flux.
- Initial nitrate concentration in each soil layer.
- Process parameters: mineralization, volatilization, denitrification.
- Land characteristics: mean highest water table, mean lowest water table, soil type, land use.
- Soil characteristics per layer: transmissivity, moisture content.

Nitrogen pollution on a regional scale has also been evaluated in a qualitative sense based on information on land use, soils, and hydrology. In these studies by de Vries *et al.* (1987), the soil features used were texture and organic carbon content (indicating soil water retention), porosity (permeability), and wetness (indicating soil water regime and influence of drainage). Aquifers were classified on the basis of thickness and lithology of the soil layers above. Vulnerability categories were determined by combining the two classifications. The combination of this natural vulnerability with the nitrate load describes the actual risk for pollution.

A similar approach has been applied in a study at IIASA to assess the impact of acid deposition on groundwater in the whole of Europe (Holmberg *et al.*, 1987). As the factors which determine the vulnerability of groundwaters to acidification and nitrate pollution are to a large extent the same, the soil and aquifer data base created for the acidification study could be utilized in the assessment of nitrate pollution risk. Due to the more local and regional nature of nitrate pollution sources more detailed information might be needed on the spatial distribution of land use and aquifers. However, this kind of an assessment would be a good basis for further modelling work, which could then focus on areas under risk.

3.3. The Potential Future of Nutrient Enrichment of Water Resources

3.3.1. Development of agriculture

Agriculture in western Europe has been in great difficulty for many years. Farmers try to improve their income and try to increase yields as much as possible. At the same time overproduction is the main problem in agricultural policy making. Various measures have been proposed to decrease overproduction. The main proposal has been to withdraw some land from cultivation. This would very probably imply more intense cultivation of the remaining agricultural fields, while marginal land would be taken out of production. The result would be the concentration and intensification of environmental problems in isolated areas.

The overall loads into the watercourses might also increase, if the absolute amounts of fertilizers used do not decrease. Normally, above the optimum dose, the efficiency of plant uptake decreases with increasing fertilization. The optimum dose naturally depends on many factors. With nitrogen fertilization above 100 kg/ha in Sweden, losses increase relatively more than the uptake (Jonsson, 1975). In more favorable climate conditions this optimum might, of course, be higher. Behrendt (1988) estimated that if one third of a basin is converted to forest and at the same time cultivation of the remaining two thirds is intensified by increased use of fertilizers in order to obtain the same total yield from the basin, the total nutrient losses would increase by 20–30%.

Another method to solve the problem of overproduction would be the shift to more extensive agriculture, i.e., the area of agricultural land would remain at the present level, but the inputs used would be lower. The yields per hectare would decrease thus decreasing the overall production. When operating at this optimum fertilization level (maximum uptake) the environmental losses would be smaller than at present.

3.3.2. Effect of climate change on nutrient losses

Most scientists agree that climate change will be a reality in the near future. Although there is uncertainty in the estimates of the magnitude of the change, in most parts of Europe the temperature will increase, the increase being most pronounced in northern parts. The precipitation may also increase in northern Europe, but decrease in southern Europe, the change being only minor in Central Europe (see Chapter 1).

Climate change could affect the question of nutrient enrichment and its consequences in many ways. Firstly, the transport of nutrients in the soil strongly depends on water movements. In areas where temperature increase would be accompanied by decreased precipitation and increased evapotranspiration (southern Europe) the leaching of nutrients into groundwaters would become less important as the downward movement of water would be insignificant. On the other hand, in areas where the climate would become more humid (northern Europe), the risk of nutrient leaching would increase. Increasing temperature would also enhance processes involved in nitrogen cycling.

Climate change could also affect nutrient losses from agriculture by changing the growing conditions. Plant uptake determines the amount of nutrients left for leaching. If increased temperature and precipitation improve growing conditions in northern Europe, the losses might decrease in spite of the increased runoff and infiltration. It is very probable, however, that the increased variability of climate (increased probability of extremes) determines the overall effect of climate change (Parry *et al.*, 1988). The annual nutrient losses under the present climate mainly occur during relatively short periods (Knisel, 1980; Kauppi, 1979; Kohonen, 1982). If climate change increases the intensity of rainfall then nutrient losses would become higher. The significance of the snow-melting period – today more than half of the annual nitrogen and phosphorus runoff in Finland occurs during this period (Kohonen, 1982) – on the other hand, would diminish in Nordic countries.

Simulation models are available which describe the transport of nutrients from agricultural areas. They describe hydrology as a function of climate and thus, they can be used for estimating the impact of climate change on nutrient losses. Haith (1982) has reviewed these models. More recently Kallio (1987) reviewed models with special reference to Nordic conditions. He described three field-scale models and four watershed models which are in use and were developed from fertilizer application experiences. In principle any of these models could be used to estimate nutrient losses under a new climate. Kallio (1987) concluded that of the watershed models available, the Norwegian SI/GEFO model (Kalgraf and Seip, 1986) would be the most suitable one for northern conditions because of its ability to describe the frost and snow conditions. In other parts of Europe the CREAMS model has been widely applied (Svetlosanov and Knisel, 1982). On a regional scale models described earlier, i.e., the RENLEMA and RETRAM models, could also be applied.

3.3.3. Effect of climate change on the response of water ecosystems

Climate change not only affects the transport of nutrients into watercourses, but changes the characteristics of recipients as well. The ice-cover period would shorten significantly as the temperature increases in winter (see Chapter 1). In Central Europe the lakes might remain unfrozen the whole winter. In Nordic countries the seasonal rhythm would change dramatically. Kuusisto (1987) has estimated from long ice observation series that if the winter temperature rises by 6° C large lakes in southern Finland would remain unfrozen once every 2 to 5 years depending on the hydrography of the lake. This would, of course, affect the water temperature. Circulation would continue longer and thus the water mass would get colder than in present conditions. In fact, today the winter temperatures of Central European lakes are lower than in the lakes of Northern Europe. Oxygen conditions in winter would also improve due to better circulation thus partly mitigating the detrimental effects of increased nutrient input.

Although the most prominent changes might occur in winter, the increased air temperature would also affect stratification in summer as well as the length of the growing season. The increased volume of the epilimnion implies a thicker productive layer and improved nutrient utilization.

The analysis of the impacts of climate change on the aquatic ecosystems should start from the changes in physical processes. Changes in the length of the ice-cover period could perhaps best be estimated by the historical approach, i.e., by analyzing long ice observation series and comparing warm and cold years and periods. These long observation series are available from several European countries. By selecting data sets from different latitudes, for example from the FRG, Poland, Sweden, and Finland one could get a good picture of the past and present variability of the phenomenon.

There are also several lake stratification models available, which can be used for analyzing the changes due to climate change, for example the MITEMP model developed in the Massachusetts Institute of Technology. This model is already available at IIASA. Once the physics of the lake in a new climate can be described reliably enough it can be used as an input to an ecological model to estimate the changes in the productivity of the ecosystem. This should, however, be done at a later stage.

3.4. Adaptation and Mitigation Possibilities

There are certain possibilities of adapting to enriched water resources. In China, nutrient-rich waste waters are often discharged to ponds used for intensive fish cultivation. In Europe, however, there is no similar tradition of utilizing waste. Therefore strong resistance is to be expected if this kind of measure were to be implemented. The main focus of mitigation activities should clearly be in preventing an increase of nutrient inputs into water systems. As concluded earlier, the technology for treating the waste waters effectively is available, the main problem being cost.

In the agricultural sector, the strategy has to be the improved utilization of nutrients in agriculture itself. However, as long as fertilizers are so cheap then there is no cost incentive for farmers to use less fertilizer and thus there is likely to be no change. Some countries, like Sweden, have in fact already introduced an environment tax for fertilizers. The main purpose of this tax is to reduce fertilizer use. In order to solve the overproduction problem of animal products, the number of livestock has to decrease markedly in Europe. This would, at the same time, largely solve the manure problem as well.

3.5. Research Recommendations

The pollution of groundwaters by nitrate has been the main topic in the foregoing discussions about the effects of agriculture on water resources in Europe. The nature of the problem is in fact well-known, as is its present geographical extent. Due to the time delay known to be inherent in the phenomenon, it is also important to assess the extent of the risk in the future. The assessment should take into account the possible climate change.

Recently, it was recognized that excess agricultural phosphorus could be transported to surface waters in amounts that have caused detrimental effects. The late recognition of the potential problem was due to soil processes which counteracted the problem for some time, i.e., sorption onto soil particles. However, as there are already indications of the exhaustion of this sorption capacity in some heavily loaded areas, it would be important to analyze the future development of the problem. This could best be done by a modelling approach.

With regard to ecosystem impacts in lakes it would be important to establish a study on the effects of climate change. In the first phase the study should focus on the changes in lake physics, because it forms the basis for the biological system.

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CHAPTER 4

Hydrology: Water Availability Changes

Florinus Brouwer and Malin Falkenmark

4.1. Introduction

Man lives in the natural environment, which provides him with food to eat, fodder for his cattle, timber for his houses, fuel for heating, water for drinking and washing, and other beneficial resources. Water is a main determinant of life, its ubiquitous presence distinguishing Planet Earth from other planets. It is one of the key resources: (i) it is essential for crop growth and wood production; (ii) numerous species live in water, and (iii) the hydrological cycle of evaporation, precipitation, and runoff plays a central role in the biogeochemical cycles of, among others, carbon, nitrogen, and phosphorus. Disturbances in the water chemistry and/or water flows, caused by pollutants or by the intervention of soil and vegetation, therefore tend to produce many secondary effects on flora, fauna, and human health.

Water is continuously circulating through the biosphere, where life is based on myriads of water flows through plants, animals, and human bodies. The amount of water that circulates annually between oceans, the atmosphere, and continents is only a minor part of the overall global water volume which amounts to about 1,400 million km^3 (UNESCO, 1978). Roughly 98% exists either as water in the oceans (about 96.5%), or as ice/snow in ice caps and permanent snow cover (about 1.5%). These two major components of the global water cycle have a very long residence time, amounting to between a few thousand and several hundreds of thousand years, for example, continental ice caps contain ice that is 100,000s of years old. The remaining 2% of global water volume is available either as groundwater (about 1.5%), soil moisture, in rivers and lakes, or as water vapor in the atmosphere. Those parts of the global water cycle have residence times of between a week and a few centuries.

The atmosphere wets the land through precipitation, but gains water back by evapotranspiration from vegetation and wet surfaces. As seen from an overall perspective, water reaching the ground is partitioned into two main water flows: the upward return flow, which is part of the plant production process, and the recharge of terrestrial waters, producing the flow in aquifers and rivers. Apart from the air temperature, the recharge in the root zone in relation to the water attraction capacity of the atmosphere determines the length of the growing season.

The water in the terrestrial water systems can be used while passing through a country. The amount locally accessible can be increased by the development of water resources (e.g., wells, storage reservoirs, distribution channels and networks, etc.).

From a human perspective, water has a number of functions:

- It is necessary to sustain life. Crop production is operated by water flowing in through the roots and out through the leaves. Plant production may be very vulnerable to lack of water in the root zone. When the soil moisture goes below a certain threshold (wilting point), plant production stops altogether. This vulnerability is reflected by the fact that 80% of the fresh water consumed globally is used for irrigated agriculture (Pimentel, 1986). In Europe, about 40% of the consumed water is used for agriculture, and irrigated agricultural land covered over 15 million ha during the 1980s (not including the USSR).
- It is used to supply households and for a multitude of other (mainly socioeconomic) purposes, such as in industry and for energy production. Between 40% and 50% of the total European water use is for industrial purposes (Chernogaeva, 1971).

In addition to the above mentioned functions that water may have from a human perspective, water systems may also be affected by environmental pollution (e.g., eutrophication, toxification) which degrades the aquatic ecosystems. A large amount of nitrogen and phosphorus fertilizers may enter surface waters by runoff, especially in areas of intensive agricultural practice (see Chapter 3).

These different functions and processes must be balanced into a well-functioning, and preferably well-integrated, land and water management system. Experience, however, indicates that a "water barrier" exists (Falkenmark, 1986), limiting the size of the population that can be supported from each flow unit of water. That limit depends on water demand patterns (including water for irrigation in agriculture, and other activities), access to technology (for storage, redistribution, recycling of wastewater), administrative capacity (to coordinate all sectors related to water), and the geographical scale of a country (possibility to organize sequential, multi-purpose recycling of water). On the whole, water management problems tend to increase in complexity with an increase in the level of water competition (in terms of the number of people that need to be supported from a flow unit of water), an increase in aridity (agricultural demands for irrigation), and an increase in the size of a country.

This paper focuses on the issue of *water availability in Europe*, i.e., on the amount of water that is moving through the landscape, as seen from the perspective of climate change. We shall distinguish between its two main components: the root zone water availability, i.e., the watering of terrestrial ecosystems on the one hand, and the availability in terrestrial freshwater systems on the other.

The large-scale climatic change that results from the accumulation of greenhouse gases in the atmosphere will affect humankind primarily through the water cycle (e.g., through changes in soil moisture levels), as well as through numerous phenomena that are closely related to the water cycle and related processes (such as the occurrence of flooding or droughts). The issue of water availability might become more important in Europe over the next decades, especially in those regions that will be affected by a decrease in precipitation levels and/or an increase in temperature.

4.2. Present Hydrology of Europe

4.2.1. Introduction

The water cycle is a crucial system within the biosphere. Three important reasons are:

- It circulates water between the atmosphere, lithosphere, and world oceans.
- It provides water for the soils and feeds terrestrial ecosystems.
- It feeds the terrestrial freshwater systems (with runoff being the difference between precipitation and evaporation).

The water cycle is also one of the major determinants of regional climatic conditions, exchanging heat and water vapor from tropical latitudes to middle and high latitudes. This phenomenon is a critical factor in the climatic conditions of Europe. In addition, Northern Europe is warmed by the ocean circulation system through heat that is released from the surface waters of the North Atlantic (Broecker, 1987).

The water balance for each of the continents is summarized in *Table 4.1* and is based on average values with a considerable variation both in space and time. Thus, in Africa for example, a considerable surplus occurs at the continent level, although we are all aware that water availability reaches minimum levels in the Sahara and Kalahari deserts. The total amount of available runoff is critical to meet the water requirements for society in large areas of the world, while the extremes in runoff (as seasonal temporal variation not shown in *Table 4.1*) are critical for floods and droughts. This table also includes the availability of water resources on a per capita basis, showing the already limited amount of water available in Europe compared to other continents (WHO/UNEP, 1987).

Table 4.1. Water balance (precipitation, evaporation, and runoff in mm/year) and water availability (in m^3 per capita) at the continent level.

Continent	Precipitation	Evaporation	Runoff	Availability
South America	1,648	1,065	583	54,400
Europe	734	415	319	4,800
Asia	726	433	293	6,550
North America	670	383	287	19,000
Africa	686	547	139	12,000
Australia	440	393	47	n.a.

(Source: Lvovich, 1979.)

In response to the hydroclimate, European land has developed its present pattern of soil wetness, of returning evaporated water to the atmosphere, and of recharging groundwater and river systems. Basically, there are five main types of water balances in Europe (Chernogaeva, 1971), distinguished by differences in hydroclimate* as well as differences in topography and soil permeability.

(1) Heavily moistened mountain regions of the Alps, Pyrenees, and the mountain regions of northern Europe (aridity index between 3 and 4).
(2) Normally moistened lower mountain regions of Great Britain, the Apennines, the Carpathians, and the lower mountains of Central Europe (aridity index between 2 and 3).
(3) Mountain-plain complexes of Central Europe and heavily moistened plains of Great Britain, France, the FRG, the Netherlands, and Denmark (aridity index between 1 and 2).
(4) Moderately moistened plains in the lowlands of Poland, the GDR, and Czechoslovakia (aridity index around 1).
(5) Arid plains in major parts of the Mediterranean region, southern part of the USSR, and the coastal lowlands of the Danube catchment (aridity index less than 1).

We have no map of such indices, but runoff (the difference between precipitation and evaporation) is closely related. *Figure 4.1* shows the regional overall patterns of runoff in Europe, based on long-term mean annual values. Annual runoff values are in the range of between over 1,000 mm in the mountain regions, and about 10 mm in parts of the Mediterranean area and the borders of the Black Sea.

The river flow discharge (and similarly, the amount of water that is moving through the landscape) is also characterized by large interannual and interseasonal variations. *Figure 4.2* for example, shows the distribution of the monthly average discharge values (in m^3 per second) for the catchment areas of five rivers in several parts of Europe. The figure shows the range of monthly average discharge values for approximately a 50-year period, in Finland, Romania, Spain,

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* In terms of an aridity index, with annual precipitation expressed as a multiple of the water attraction capacity of the atmosphere (potential evapotranspiration).

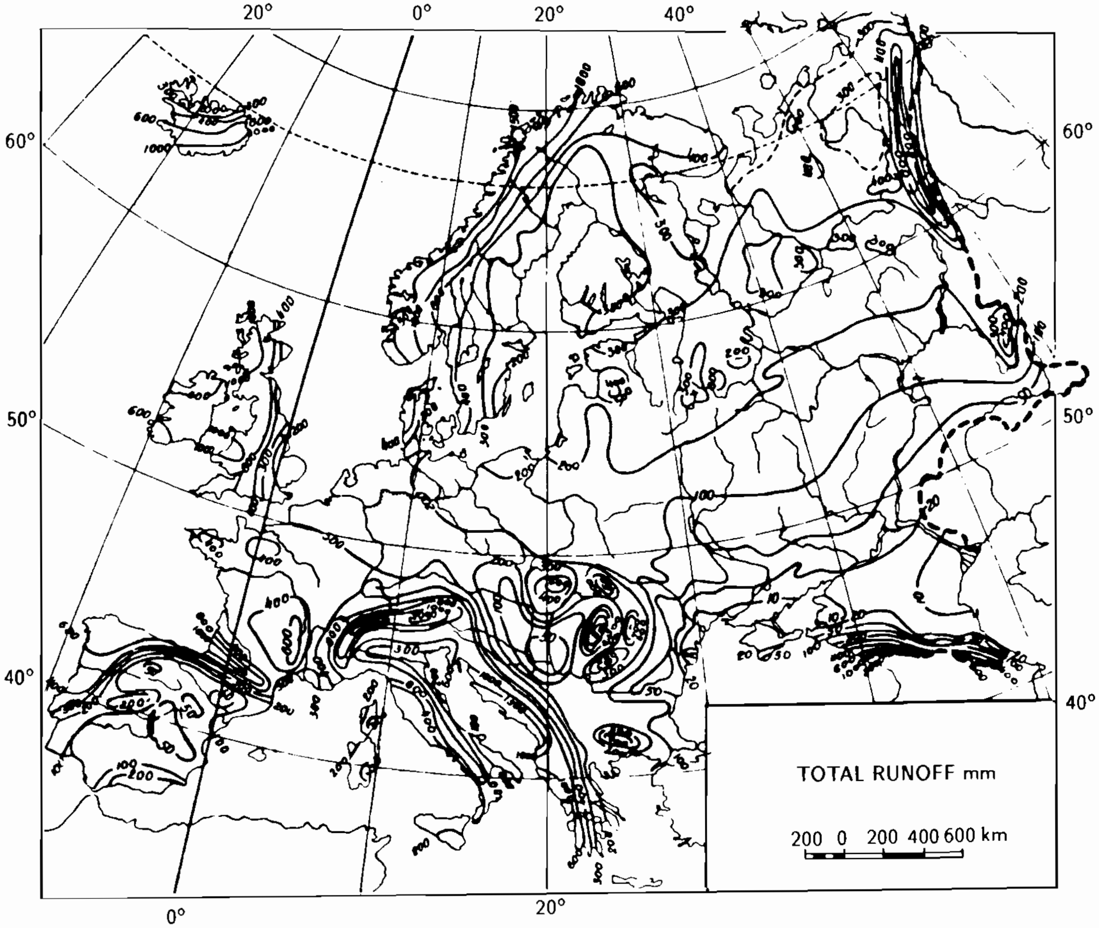

Figure 4.1. Runoff generation in Europe. (Source: Chernogaeva, 1971.)

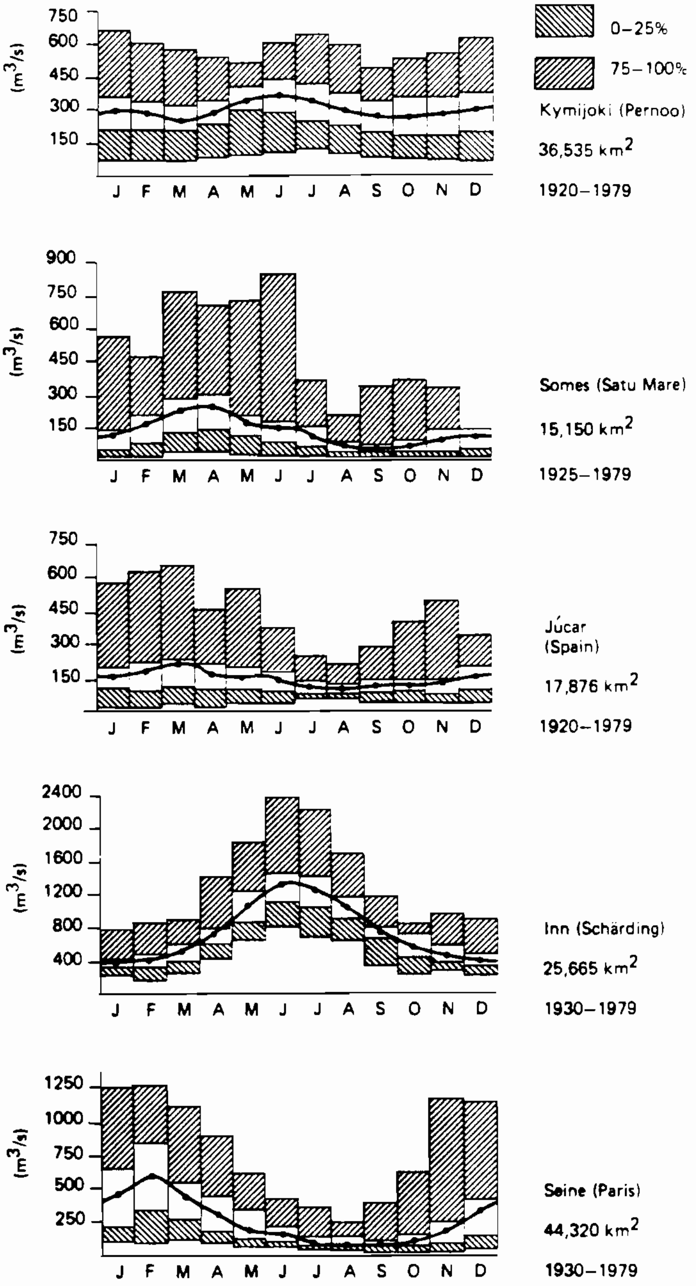

Figure 4.2. Range of monthly average discharge (in m^3 per second) for five river basins in Europe (Finland, Romania, Spain, Austria, and France) over a fifty year period, approximately.

Austria, and France respectively. The line drawn for each of the catchment areas represents the long-term mean monthly discharge. The figure also shows the first and fourth quartiles of the monthly average discharge values, and this statistic already indicates the large variation during the observed period, with maximum values sometimes being several orders of magnitude larger than the minimum values.

4.2.2. Water availability in terrestrial freshwater systems

This is the total amount of runoff that is moving in aquifers and rivers, produced either from local precipitation over the country itself, or by water that enters rivers and regional aquifers. The per capita amount of water available is declining towards critical levels in semi-arid countries, with limited amounts of water available from the global water cycle, and increasing water needs for the growing population, and for the irrigation of agricultural land. As indicated earlier, the number of people that a society can support on a certain flow unit of water depends on a number of supply and demand factors. Under optimal conditions in a well-organized, small, and advanced country like Israel, for example, sophisticated water management and demand control policies, may enable 2,000 individuals to be supported on one million m^3 per year (a per capita level of 500 m^3). This may in fact be close to the barrier of what a modern society is able to manage with advanced technology and an advanced administrative capacity (Falkenmark, 1986; Falkenmark *et al.*, 1987). Larger countries with less advanced water management would be expected to have massive water-related problems at considerably lower levels of the water competition index.* On the whole, water management problems tend to increase with an increase in the water competition index, increasing aridity, and an increase in the geographical scale.

The water balance components also have a wide spatial variation over Europe, and this will be further explored in terms of the amount of water that is available in each country from the natural flows. *Table 4.2* shows the amount of water (in km^3/year), in relation to the population (in millions), that is available in Europe for each country for household supply, agriculture, and other socioeconomic activities. It also shows the number of people that need to be supported from a unit of one million m^3 of water.

Table 4.3 relates the total water demand in the different countries to the per capita availability. It is clear when combining both tables that the most water-stressed countries under present climatic conditions are Belgium, the GDR, and Poland. These countries have a per capita water availability in the range from 1,200 to 1,600 m^3, which means that about 600–800 individuals need to be supported from each flow unit per million m^3 of water.

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* The number of individuals supported by 1 million m^3 of water annually.

Table 4.2. Water availability for human use in Europe.

Country	Population (million)	Available water: national (km^3)	Available water: per capita (m^3)	Number of people per flow unit
Albania	2.7	27.5	10,200	100
Austria	7.5	90.0	12,000	85
Belgium	10.2	12.5	1,200	835
Bulgaria	8.9	197.0	22,100	45
Czechoslovakia	15.3	90.0	5,900	170
Denmark	5.1	12.9	2,500	400
Finland	4.8	104.0	21,700	45
France	53.7	180.0	3,400	295
Germany, F.R.	61.6	160.0	2,600	385
GDR	16.7	26.2	1,600	625
Greece	9.6	55.0	5,700	175
Hungary	10.7	120.0	11,200	90
Ireland	3.4	43.7	12,900	80
Italy	57.1	167.0	2,900	345
The Netherlands	14.1	90.5	6,400	155
Norway	4.1	388.0	94,600	10
Poland	35.6	58.8	1,700	590
Portugal	9.9	87.5	8,800	115
Romania	22.2	192.0	8,600	115
Spain	37.4	110.0	2,900	345
Sweden	8.3	183.0	22,000	45
Switzerland	6.3	50.0	7,900	125
United Kingdom	55.9	162.7	2,900	345
Yugoslavia	22.3	244.0	10,900	90

(Source: Forkasiewicz and Margat, 1980; Population data for 1980, United Nations, 1986.)

Table 4.3. Per capita water demand (including demand by industry, agriculture, etc.) and water availability for human use in the mid 1970s (in m^3 per year).

	Water demand per capita				
Water availability per capita	<100	100-300	300-500	500-800	>800
1,000-2,000			GDR, Poland		Belgium
2,000-3,000		Denmark	UK	FRG, Italy, Spain	
3,000-5,000				France	
5,000-10,000			CSFR, Greece, Switzerland	Portugal	Netherlands
10,000-50,000			Austria, Yugoslavia	Hungary, Ireland, Sweden	Finland
>50,000			Norway		

(Source: Forkasiewicz and Margat, 1980.)

4.2.3. Water availability for plant growth

Here we focus on the moisturization of the soils and the storage of soil moisture in the European environment. The terrestrial ecosystems are primarily driven by energy and water, and controlled by soil conditions and the management of cultivated land. Soil moisture in summer is a critical factor for crop growth, because it has to supply enough water to the plants to compensate for their water loss through evapotranspiration. The major climatic factors that influence crop growth are based on temperature and moisture conditions.

Figure 4.3 shows the period of the year (in number of days) that the average temperature is over 5° C (the figure is based on data from weather stations with monthly averages for a 30-year period from 1931–1960, and they originate from Müller, 1982).* The threshold of 5° C is considered to be a critical level for crop growth. Winter wheat for example, requires a period of some 180–210 days with an average temperature of at least 5° C (Verheye, 1988), and rainfall during the growing period of some 600–800 mm. Limitations in production are otherwise expected to occur.

The growing period (*Figure 4.4*) is also controlled by the availability of soil moisture, and is defined as the period of the year (in months) that the long-term mean temperature is above 5° C and the period during which long-term mean precipitation exceeds half of the potential evapotranspiration (Verheye, 1986).

A comparison of *Figures 4.3* and *4.4* shows that soil moisture is a major critical factor for crop growth in the southern part of Europe, since the growing period is largely limited by soil moisture conditions. This is particularly true from May to August since this part of Europe is characterized by a Mediterranean climate with maximum rainfall in the autumn or winter periods, and minimum amounts during the summer period. Although soil moisture deficits are recharged during winter and soil moisture storage can meet moisture demand during short periods when evapotranspiration exceeds precipitation, soil moisture deficits soon restrict transpiration and the rate of dry weight increment is reduced. The average January temperature in this part of Europe is over 5° C with only occasional occurrences of frost, while the monthly average July temperature is over 20° C. The critical climatic factor for growing crops in the northern part of the continent is, however, temperature and the growing period in this part of Europe is between three and six months. The limitation to plant growth is not affected by lack of soil moisture in a major way.

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* The maps of Europe in this report are all based on grids of 0.5° latitude × 1° longitude, which corresponds to grids of about 60 km in the North-South direction and 90 to 40 km in the East-West direction.

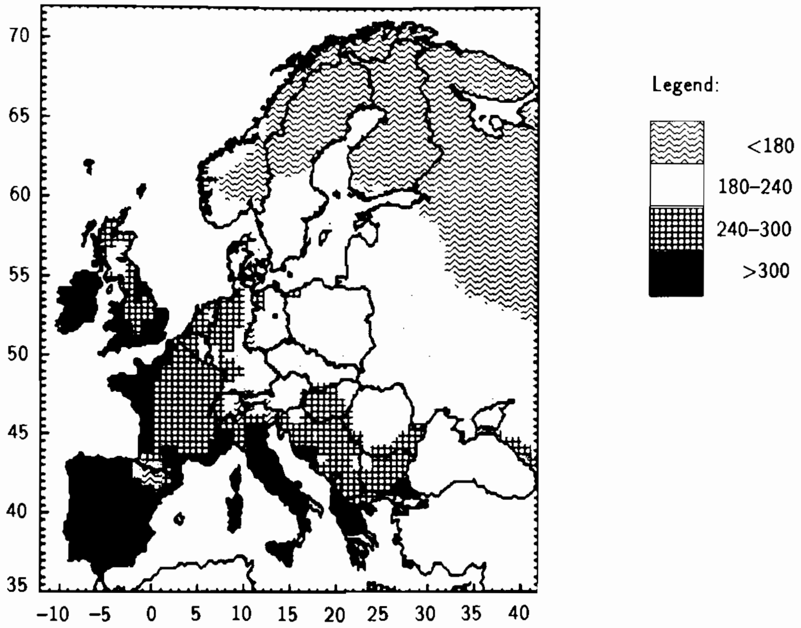

Figure 4.3. Number of days in Europe with mean monthly temperature over 5° C.

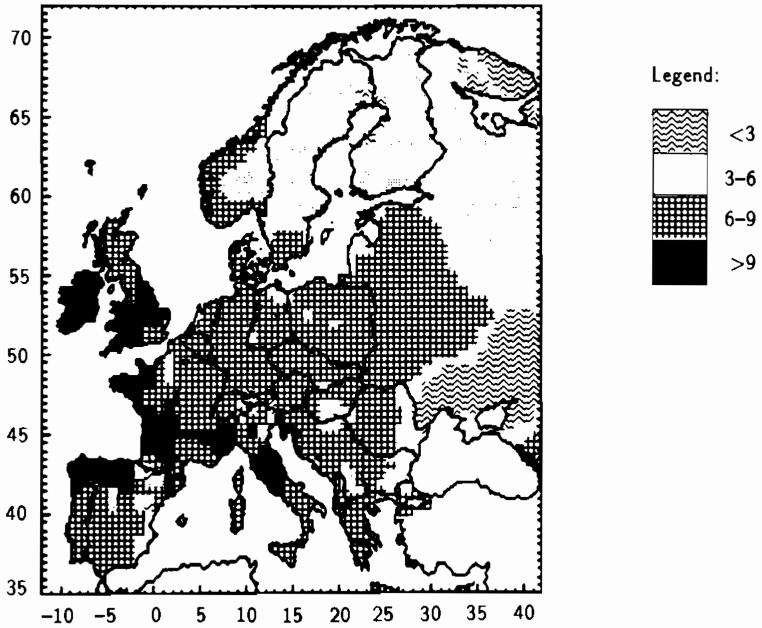

Figure 4.4. Growing period in Europe (in months).

4.3. Climatic Changes in Europe

Climate is expected to change on a global scale due to increasing concentrations of atmospheric greenhouse gases (carbon dioxide, chlorofluorocarbons, nitrous oxide, methane, and ozone). The last hundred years have already seen an increase in global mean temperature of between 0.3° C and 0.7° C. Although a direct relationship between changes in the concentrations of greenhouse gases and temperature is complicated by numerous factors (such as the atmospheric blocking phenomena, and the effects of oceanic thermal inertia on atmospheric circulation), this rise in global temperature is consistent with the observed increasing concentrations of carbon dioxide and the other greenhouse gases.

Recent estimates, based on general circulation models (GCMs) with a doubling of atmospheric CO_2 concentrations, suggest an annual global warming of between 1.5° C and 4.5° C (Jäger 1988). A doubling of carbon dioxide could occur before the middle of the next century. This scenario of increasing CO_2 depends on (uncertain) long-term projections of fossil fuel consumption. However, the magnitude and order of variation of the climatic change as well as the changes over the seasons will vary with latitude. The largest increases in temperature are expected to occur in high latitude regions (above 60° latitude).

Several climate scenarios for Europe are described in Chapters 1 and 2. These were not available for performing the present analyses. Therefore, we used the climate scenario from the GCM of the United Kingdom Meteorological Office which is based on a doubling of atmospheric carbon dioxide compared to pre-industrial levels (hereinafter referred to as the UKMO), and an equilibrium response in climate (see also Mitchell, 1983). *Figure 4.5* shows the changes in mean annual temperature and precipitation in this scenario, compared to present climatic conditions. The increase in mean annual temperature is between 2° C and 4° C for most of Europe, with the largest increases in the southern part of Sweden. The mean annual precipitation roughly shows an increase in the north at around the 50° latitude level and a decrease to the south at the same level. The largest decreases in mean annual precipitation are projected in the southeastern part of Europe.

The summer and winter scenarios project warmer temperatures all over Europe (*Figure 4.6*) as a result of a doubling of carbon dioxide, with the largest increases in the winter period. Summer temperatures increase by less than 2° C for most of Europe, while an increase of more than 4° C is projected during the winter period over Scandinavia and in the north of the USSR. The increase in winter temperature could be as much as over 6° C in parts of northern Europe. The summer and winter scenarios (*Figure 4.7*) project increased precipitation over the northern half of Europe, and less precipitation over much of southern Europe. The largest decreases in summer precipitation (more than 0.8 mm/day) are projected in the region bordering the Black Sea, and an increase in winter precipitation (more than 0.8 mm/day) is projected in large areas of Great Britain, Norway, Sweden, Denmark, Poland, and the USSR.

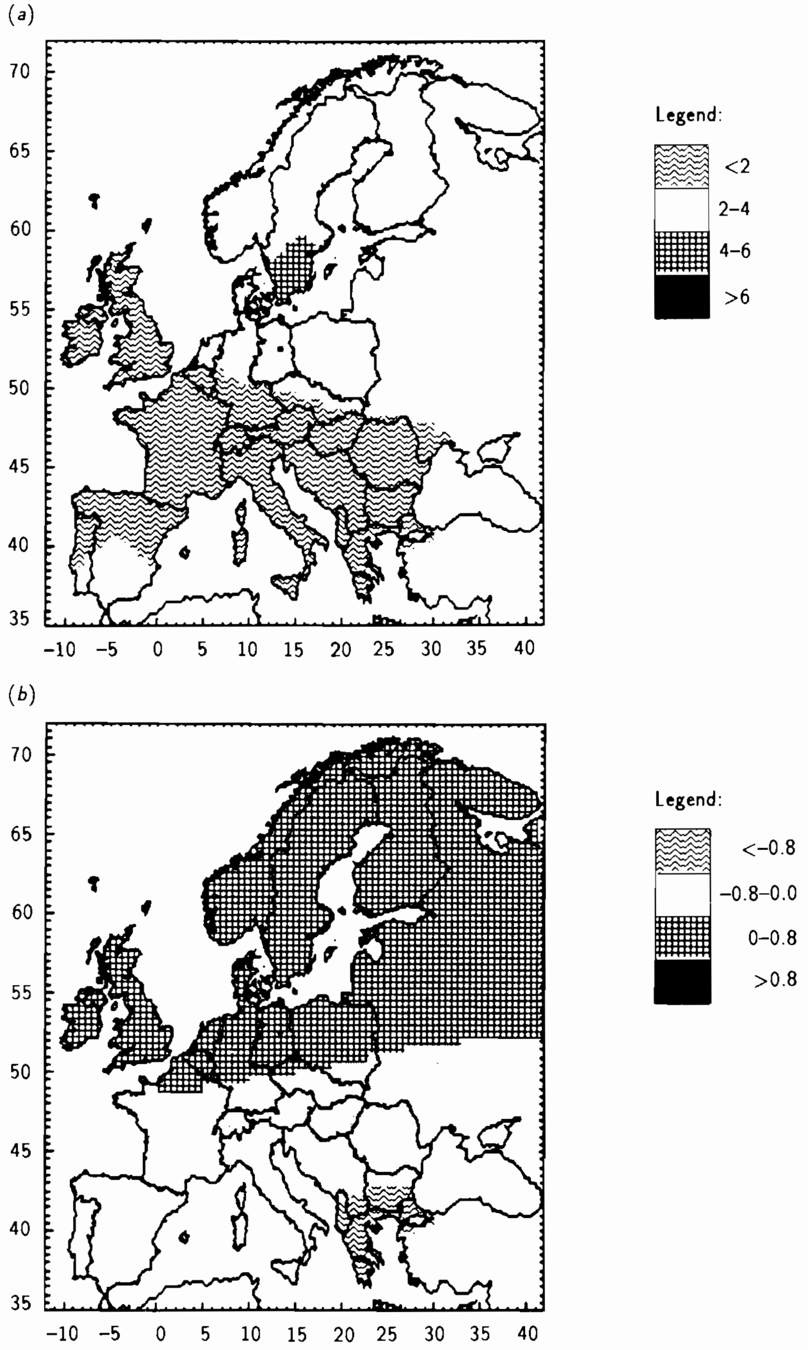

Figure 4.5. (*a*) Changes in mean annual temperature (in °C); (*b*) Changes in mean annual precipitation (in mm/day). (Source: UKMO scenario.)

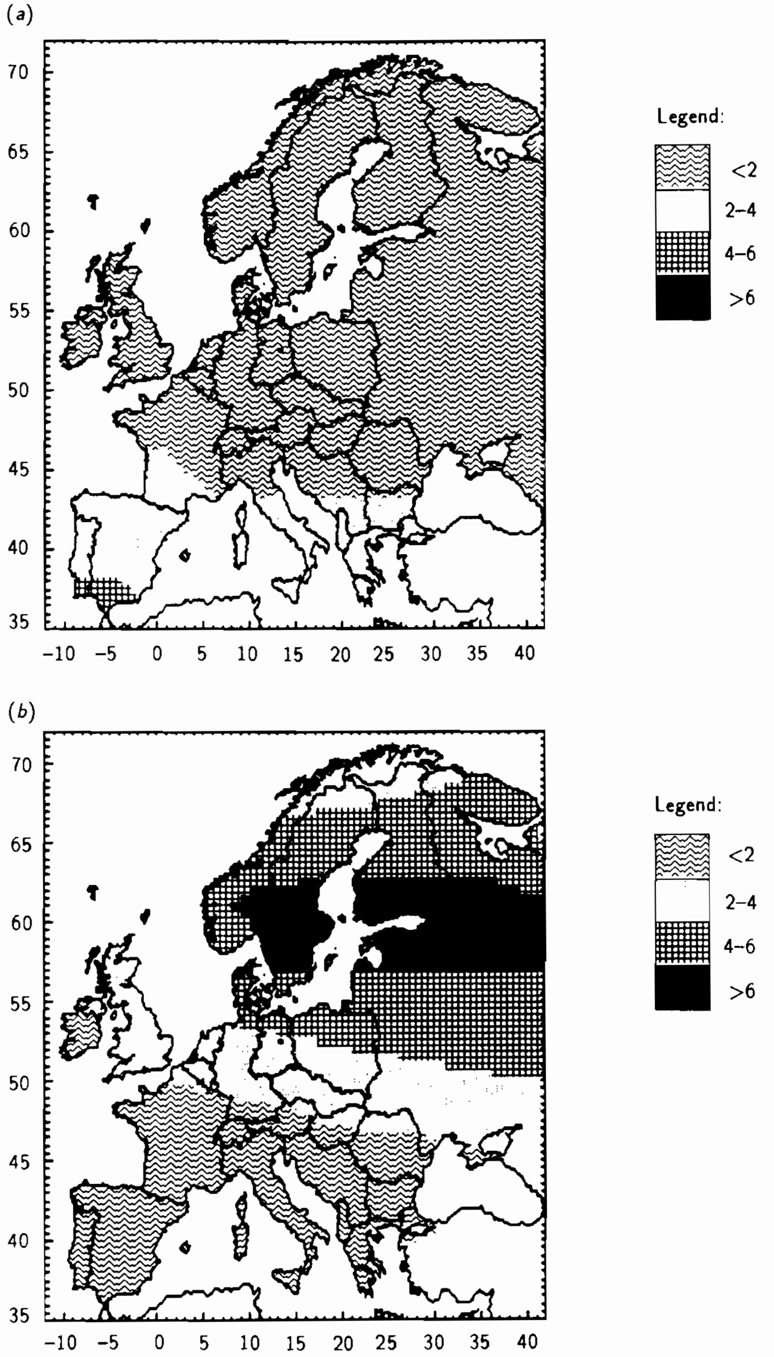

Figure 4.6. Temperature increases in (*a*) summer and (*b*) winter (in °C). (Source: UKMO scenario.)

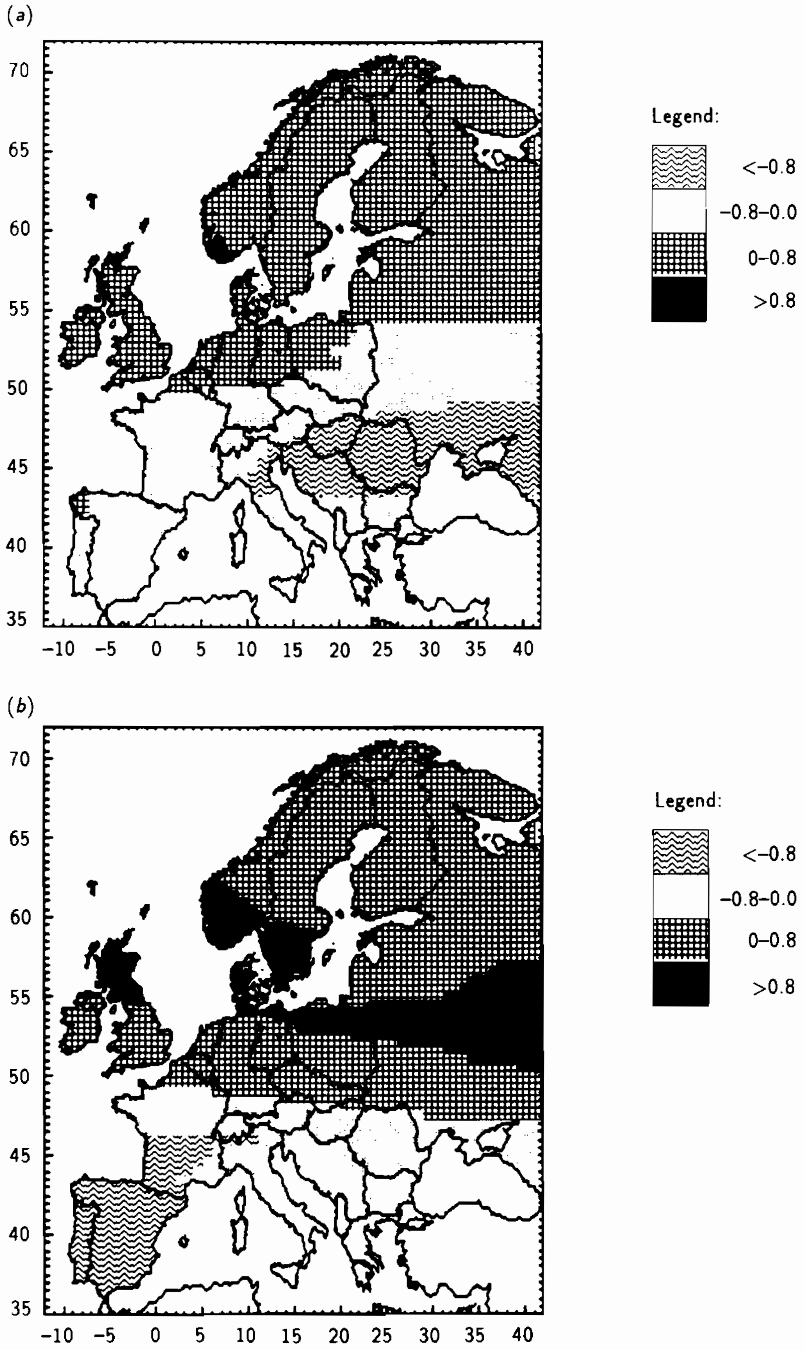

Figure 4.7. Precipitation changes in (*a*) summer and (*b*) winter (in mm/day). (Source: UKMO scenario.)

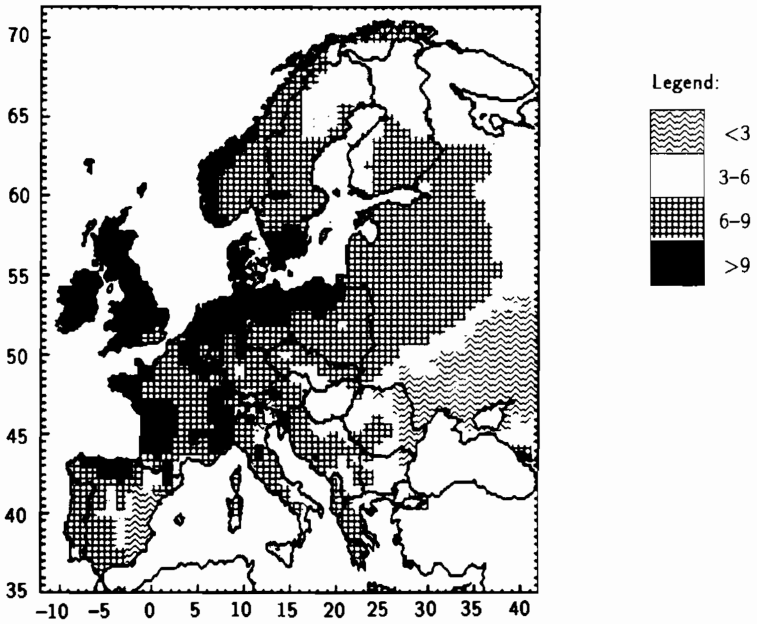

Figure 4.8. Growing period (in months). (Source: UKMO scenario.)

4.4. Hydrological Shifts in Europe due to a Changing Climate

A climatic change will have a major impact on the availability of water, in terms of feeding the terrestrial ecosystems as well as the freshwater systems (the available methods and models to assess the impacts of climatic change on water resources have been surveyed by Beran, 1986). In the following, we suggest some of the major hydrological shifts in Europe which would follow from a changing climate in terms of its consequences for terrestrial and freshwater systems.

Figure 4.8 indicates the length of the growing period based on the UKMO scenario. Comparing *Figures 4.4* and *4.8* shows that the greatest increases are projected in northern Europe (due to an overall rise in mean seasonal temperature) and the largest decreases are projected in southern Europe where increasing soil moisture deficit would limit crop production. Water consumption for the irrigation of cultivated land might increase accordingly in this part of the continent.

A more detailed seasonal analysis of changes in the growing period is shown in *Figure 4.9* for a few climate stations in Europe. *Figure 4.9(a)* shows the present and projected conditions of precipitation and potential evapotranspiration (mean monthly values represented by bars) and temperature (mean

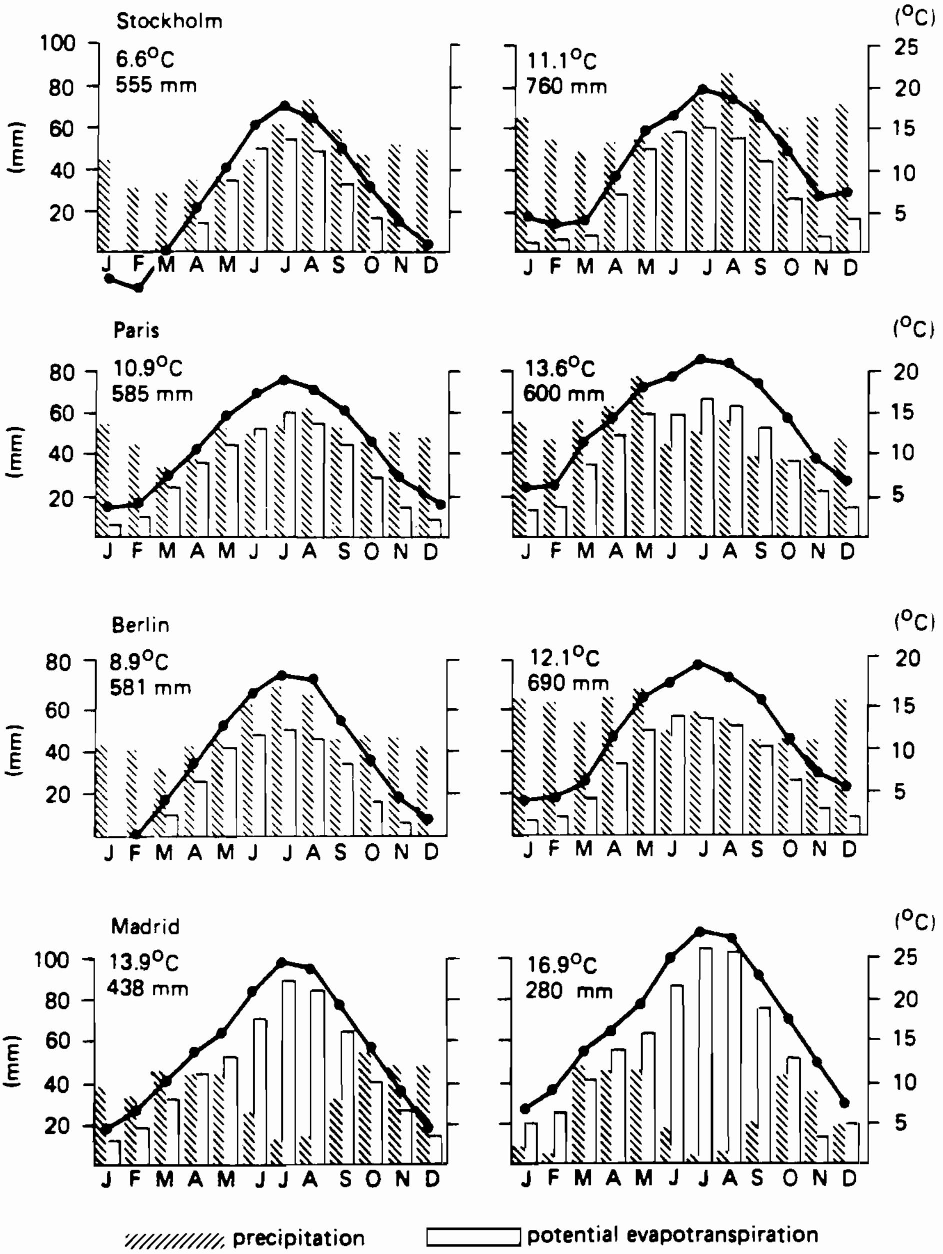

Figure 4.9(*a*). Mean monthly temperature (solid lines), precipitation (hatched bar) and potential evapotranspiration (empty bar) for four weather stations under the present (left) and a projected (right) climate.

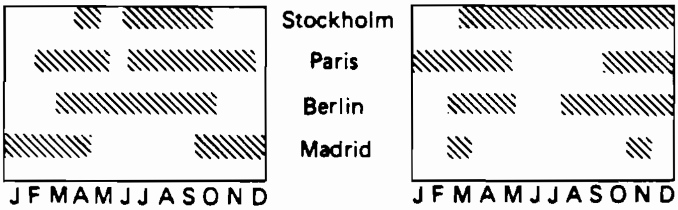

Figure 4.9(*b*). The resulting growing period (in months) under the present (left) and a projected (right) climate.

monthly values represented by a line). The left side of the figure shows the present conditions, and the projected ones under a climate change are depicted on the right side. The resulting growing period [*Figure 4.9(b)*] indicates the period of the year that climatic conditions are not critical to crop growth. The figure shows that the climatic conditions such as those around Stockholm, are affected by a short period of soil moisture deficit during early summer. This is projected to change due to an increase in precipitation. The growing period during spring and summer is projected to decrease in the remaining climate stations considered because of an increase in soil moisture deficit, as a result of the increase in temperature and changing precipitation patterns.

The climate change scenario can also consider a rise in sea level over the next 70 years of between 40 and 160 cm (UNEP/WMO/ICSU, 1988). This is particularly important for the coastal lowlands of Western Europe (France, Belgium, and the Netherlands), and part of the Mediterranean coastal areas (Italy). Salt intrusion of groundwater and surface water may affect agriculture and the quality of drinking water as a result of a rise in sea level in these areas.

Various kinds of soil degradation factors may be aggravated over the next several decades due to changes in hydroclimatic factors. The expected increase in soil moisture deficit in the Mediterranean area, already mentioned, might result in changing fertilization patterns, and more fertilizers might be added to the soils to maintain land productivity, which again may result in a decrease of nutrients from leaching. In addition, the depletion of nutrients and organic matter may accelerate in areas of increased precipitation due to leaching (particularly in northern Europe).

Figure 4.10 shows the direction of changes in water availability in relation to population for the European countries, compared to the actual levels shown in *Table 4.2*. The figure has been divided into four areas, in order of increasing water scarcity: water surpluses (less than 100 people/unit); water management problems (between 100 and 500 people/unit); water stress (between 500 and 1,000 people/unit); and absolute water scarcity (more than 1,000 people/unit). The changes in water availability should be considered as a first approximation only. The water availability was based on the climate scenario discussed above and determined simply by subtracting future evapotranspiration from future

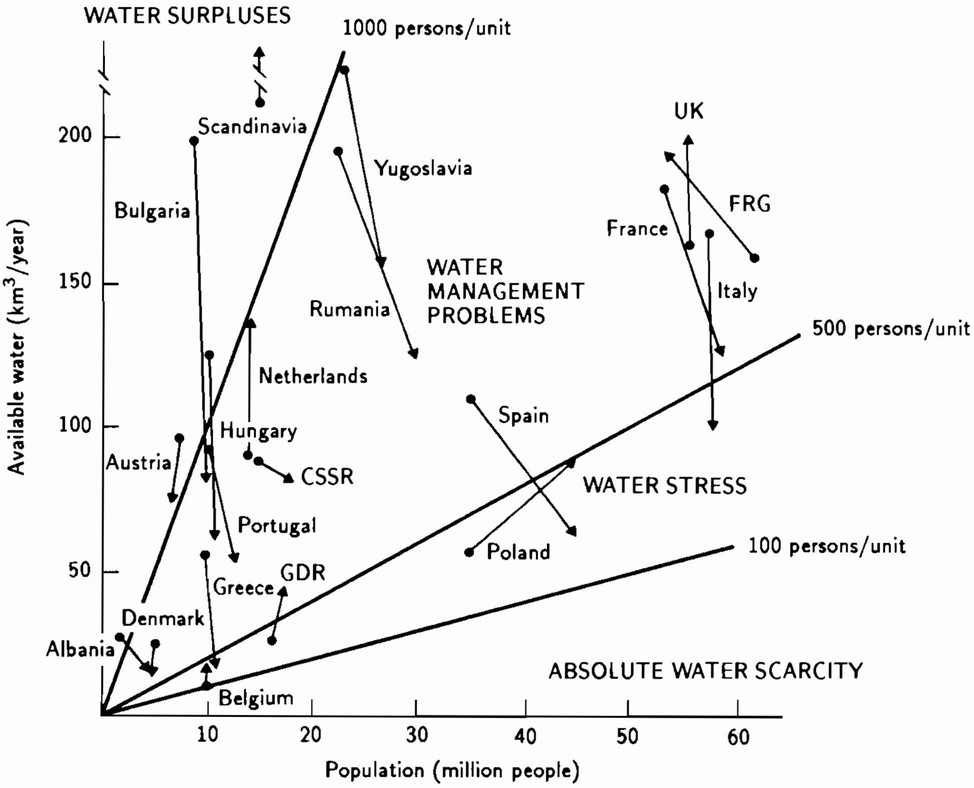

Figure 4.10. Indicative hydrological shifts due to a changing climate for the European countries based on the UKMO (1 unit corresponds to a flow of 1 million m^3 water per year).

precipitation (Kovacs, 1987; Olejnik, 1988). The population trend is from the United Nations medium projections (United Nations, 1986).

The total amount of available water may decrease in 13 European countries: Albania, Austria, Bulgaria, Czechoslovakia, France, Greece, Hungary, Italy, Portugal, Romania, Spain, Switzerland, and Yugoslavia. Large decreases in water supply may be experienced in Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, Spain, and Yugoslavia. The amount of water that is available in Belgium, the GDR, and Poland, which are water-stressed under the current climatic conditions, increases because of an increase in future precipitation. The total runoff may also increase in these countries (Olejnik, 1988). This analysis on water availability is based on annual flows. The variation over the seasons and the years is also of considerable importance (*Figure 4.2*); this wide seasonal and interannual variation indicates one of the major difficulties in projecting changes in water availability due to a climatic change.

A water shortage would be most serious in the Mediterranean region, because of the drier and warmer summers. Soil moisture during summer in southern Europe may decrease by between 20 and 50%, whereas soil wetness may increase over large regions of Europe, particularly in middle and high latitudes (Manabe and Wetherald, 1986). Gleick (1987) assessed the effects of climatic change on seasonal runoff for the Mediterranean-style climate of the Sacramento river in California. He concluded that changes in seasonal temperature and precipitation of the magnitude of the UKMO might result in large changes in regional water availability. An increase of 4° C in summer temperature and a 20% reduction in precipitation resulted in a reduction of runoff of nearly 75%. An increase of 4° C in winter temperature with a 20% increase in precipitation would result in a 75% increase in runoff.

4.5. Research Recommendations

Changes in water conditions as described in this paper will affect society in a major way. The major implications are exemplified in *Table 4.4*, which lists the main problems to be expected and engineering measures needed to mitigate the effects of such changes. The table lists the multitude of societal sectors that will be concerned. The water-related disturbances have been structured into two main groups: disturbance of land-based water uses, and disturbance of river-based water uses, respectively. The table also distinguishes different functional uses of river water: flow-related uses, use as a carrier of effluents, use of water bodies as such, and use for activities related to water depth.

Based on the discussions on the major hydrological trends, we recommend three important issues for future research and monitoring activities in the area of linkages between water availability and its fluctuations in time and space to vegetation, soil fertility, land use, and societal activities in general. In Section 4.5.1, we shall describe the importance of variability changes of climatic and hydrological factors. An environmental assessment to link hydrological shifts to changes in land use patterns will be described in Section 4.5.2, to be followed by a proposed comparative historical study on the factors determining changes in water availability (Section 4.5.3).

4.5.1. Changes in climatic variability and the impacts on hydrological shifts

Climatic factors such as temperature and precipitation are characterized by large interannual variations. During the summer of 1976 Western Europe was affected by extreme droughts, which resulted in a large soil moisture deficit, and a reduction of yields of as much as 30% in Belgium and France with widespread problems over Europe in general: rural wells ran dry, there were problems with the municipal and industrial water supply due to exhausted water reservoirs, high levels of pollution in overloaded water courses, etc.

Table 4.4. Implications of water-related disturbances.

		Land				Rivers and lakes		
	Wetter (+) Drier (−)	Soil moisture	Ground-water	Surface water	Flow-related uses	Carrier of effluents	Use of water bodies	Use related to water depth
Societal activities concerned		• agriculture • forests • buildings • roads	• rural water supply • local irrigation	• urban activities	• water supply • hydropower • irrigation	• sanitation • industrial waste water disposal	• fishing • recreation	• navigation
Problems encountered	+	• reduced fertility	• water logging • building damages	• urban storm runoff • erosion	• failing flow control • floodings		• erosion/ sedimentation • increasing currents • flushing of lake phosph.	• floodings, inundations
	−	• droughts • crop failures	• drying wells • pumping costs • foundation problems • subsidence		• water deficiencies • reduced hydropower production	• reduced dilution • aeration problems • unsafe for bathing	• changing fish population • reduced water removal	• collapsing navigation systems • reduced traffic
Engineering measures to mitigate	+	• drainage	• drainage	• urban drainage	• flow control		• river training	• increased levee height • reservoirs
	−	• irrigation	• deeper wells		• water transfer schemes	• flow control • waste treatment • aeration	• dredging	• flow control • barrages • sluices • dredging

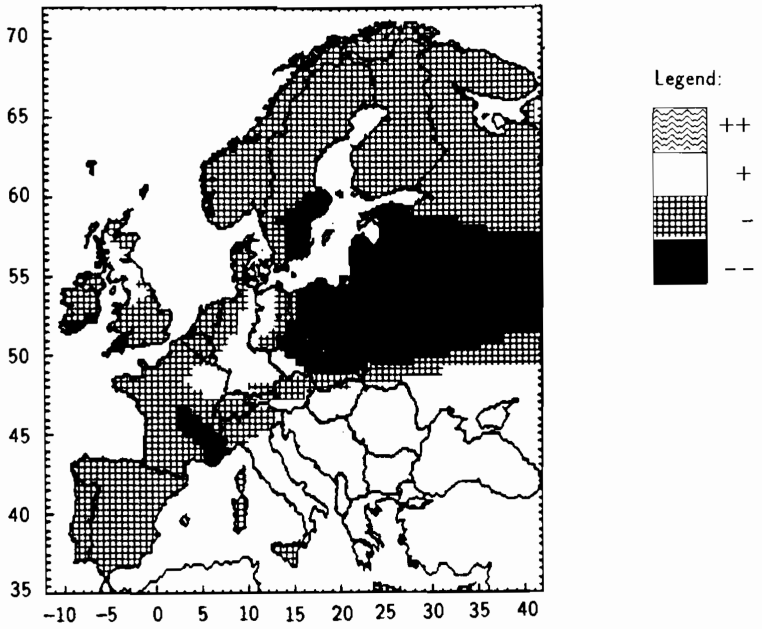

Figure 4.11. Changes in the interannual variability of precipitation in summer due to a climatic change (++ = significant (5% level) increase in variability; + = increase in variability; - = decrease in variability; -- = significant (5% level) decrease in variability). (Source: Lough *et al.*, 1983.)

The frequency of extreme climatic events is expected to increase with climatic change (see for example Lough *et al.*, 1983). An important characteristic of the occurrence of extreme climatic events is the interannual variability of precipitation and temperature, which is expected to change in Europe. *Figure 4.11* shows a scenario for changes in the interannual variability of precipitation in summer due to climatic change.

The interannual variability of precipitation in summer might decrease in large areas of Europe with the exception of the south-eastern part of Europe, and parts of Central Europe. The largest increases in the interannual variability of precipitation are expected to occur during the spring and autumn season (Lough *et al.*, 1983).

The variability in climate components is reflected in the hydrological components, such as river flow, which is characterized by large interannual and interseasonal variations as was illustrated in *Figure 4.2* for some river basins in Europe. The present rainfall/runoff models are not sufficient to incorporate interannual variability of runoff and (potential) evapotranspiration at the continent level. In addition, the relationship between climatic factors and water balance components would most probably also change under a changing climate.

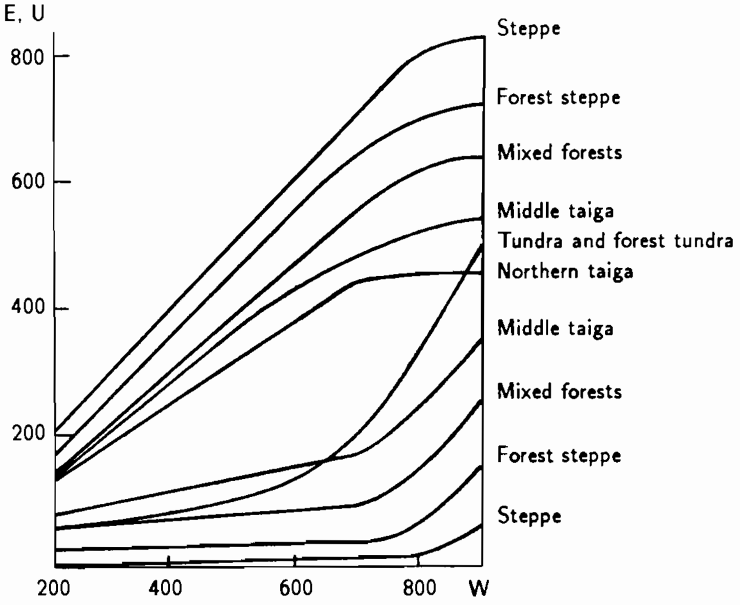

Figure 4.12. Zonal regularities of the water balance elements in Eastern Europe according to Chernogaeva (1971). Diagram shows relation between evapotranspiration (E), upper 5 curves; and groundwater recharge (U), lower 5 curves; with infiltration (W in mm).

For example, changes in soil surface conditions as well as in vegetation will alter these functions (RIVM, 1988).

4.5.2. Hydrological shifts and changes in land use due to a climatic change

Hydrological shifts are expected to produce major effects on both terrestrial ecosystems and water-related phenomena. Developing methods to assess these shifts will be an important task for future research. One rather crude way of addressing this issue might be to use empirical relationships between water balance elements and terrestrial ecosystems in ecological zones of Europe (*Figure 4.12*). From a long-term perspective, the relations would, of course, change as a result of new ecosystems developing in response to changed soil wettening, and changes in potential evapotranspiration. Early changes, however, could possibly be seen as perturbations in the present zonality pattern, i.e., a move along the curves for specific ecosystems. Higher precipitation would, in other words, produce more groundwater. Subsequent changes would probably cause shifts to neighboring ecosystems. In the former example, persistently increased groundwater would favor the development of ecosystems adapted to wetter conditions.

A climatic change and a fluctuation in the availability of water will have a major effect on the use of European land over the next decades, as well as on degradation factors (such as erosion, leaching of soluble components, depletion of nutrients and organic matter, and salinization) that relate to changes in the use of cultivated land and hydroclimatic conditions.

A proper assessment to link changes in soil moisture deficit with land degradation factors at the continent level is still missing. This assessment is complicated by the occurrence of threshold conditions in the soils. This means that soil conditions that can be characterized as being stable could suddenly switch to a state that would allow erosion in various forms to take place.

4.5.3. A comparative historical assessment of changes in water availability

A proper assessment of interannual variability of water balance components in relation to a change in climate would require the collection of long-term historical data for a representative set of countries. Such a comparative historical assessment of hydrological shifts would require information on temperature and precipitation at a monthly level, soil and vegetation types, surface runoff, and geophysical information on the watersheds. The European areas that are projected to be most vulnerable to a change in climate and consequential changes in hydrological phenomena are the Mediterranean region (with an increase in soil moisture deficit in summer) and northern Europe (with enhancement of soil wetness because of the increase in precipitation).

4.6. Concluding Remarks

The issue of water availability is already important in some parts of Europe which suffer from seasonal soil moisture deficits and societal water stress. However, this issue could become even more important, as demonstrated by the analysis of changes in hydrological shifts due to a change in climate. The following items ought to be taken into account in further explorations on future trends in water availability and their socio-economical consequences at a European level.

(1) Water authorities in areas suffering increasing shortages require methods for the conservation and recycling of water, including water storage alternatives and parsimonious irrigation. The total amount of available water that can be made accessible from different sources (groundwater, aquifers, and rivers) has to be matched, in time and space, with water demand for different purposes. It is likely that the need for a national water authority with broad responsibilities will increase in water-stressed regions, where it will also play an increasingly important role in obtaining an integrated view on the conservation and management of land and water.

(2) Stimulation of research in the field of biotechnology to grow more drought resistant crops could provide varieties adapted to poor local climatic conditions. This can be incorporated in a land-use policy to improve the marginal land and to maintain the socio-economic structure of rural areas, but it would further aggravate the current problems of agricultural surpluses.

(3) Water shortage for growing crops (as defined by soil moisture deficit) could be characterized by large interannual variations, as the frequency of extreme climatic events is expected to increase over the next decades. The occurrence of extreme climatic events (e.g., frequency of very dry years) could become more important in southern Europe, which means that the number of years with extreme levels of soil moisture deficit will increase.

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CHAPTER 5

Soil: Acidification Changes

Lea Kauppi and Maximilian Posch

5.1. Introduction

In recent decades, acid rain and its consequences for terrestrial and aquatic ecosystems have been of serious concern, particularly in Europe, but also in North America. The first signs of acidity effects were seen in vulnerable lake ecosystems in Scandinavia (Oden, 1968). About ten years later, soil scientists in Central Europe reported detrimental changes in the chemistry of forest soils (Ulrich *et al.*, 1980). The central role of soils as a link between acid rain and lake and groundwater acidification as well as between acid rain and forest damage was recognized quite early (see e.g., the Norwegian SNSF-project, Overrein *et al.*, 1981).

Soil acidification is significant in lake acidification since all the water entering the lakes has been in contact with the soil, except direct precipitation onto the lake surface. If the soil loses its buffering ability, the acid load reaches the waters. Depending on the retention time of the lake, as well as its internal alkalinity production, there is a time lag before the lake becomes acidified. Linkages between soil acidification and lake and groundwater acidification, have been described by physico-chemical models (e.g., Kämäri *et al.*, 1985).

In the case of forest damage, the link to soil acidification is not very well understood. A decrease in the buffering capacity of soil implies changes in nutrient ratios which might affect plant growth due to an imbalance in the supply of different elements. When acidification proceeds far enough, dissolution of aluminum (Al) results in Al concentrations that can be toxic to plants. However, the present understanding of the forest decline phenomenon is that there are several contributing factors, of which soil acidification is only one (see Chapter 6).

In the following discussion only *forest* soils are considered. Agricultural soils managed intensively with lime, fertilizers, and other chemicals, are not discussed. These practices dominate the soil processes and, thus, they can be easily used to counteract acidification.

5.1.1. The concept of soil acidification

Soil acidification has been defined as a decrease in the acid-neutralizing capacity (ANC) of the inorganic fraction of the soil including the solution phase (van Breemen *et al.*, 1984):

$$\mathrm{ANC_m} = \mathrm{B_m} - \mathrm{A_m} \ , \tag{5.1}$$

where B = basic components (the contributing cations depend on the reference pH chosen), A = strongly acidic components (anions of strong acids), and m = mineral soil.

De Vries and Breeuwsma (1987) redefined the concept of van Breemen *et al.* (1984) by distinguishing between actual and potential soil acidification. They differentiated between the acid-neutralizing capacity (ANC) and the base-neutralizing capacity (BNC). ANC was defined as the sum of the basic components and BNC as the sum of the acidic components of the soil:

$$\mathrm{ANC_s} = \mathrm{B_m} + \mathrm{B_o} \ , \tag{5.2}$$

$$\mathrm{BNC_s} = \mathrm{A_m} + \mathrm{A_o} \ , \tag{5.3}$$

where A = strongly and weakly acidic components, s = solid and solution phase (total soil), and o = organic phase. Actual soil acidification was then defined as a decrease in $\mathrm{ANC_s}$ and potential soil acidification as an increase in $\mathrm{BNC_s}$. Thus, actual acidification is manifested by leaching of cations from the soil, regulated by the mobility of major anions. Potential acidification is primarily due to the accumulation of the atmospherically derived nitrogen and sulfur (de Vries and Breeuwsma, 1987). The weakly organic acids are also included in the definition of $\mathrm{BNC_s}$. An increase in exchange acidity caused by the accumulation of acid organic matter increases the BNC of the soil, and should thus be considered as potential soil acidification. The potential acid threat is realized by mineralization processes after the removal of vegetation.

5.1.2. The Historical Development and Current Spatial Extent of Forest Soil Acidification in Europe

There are at present no systematic surveys on the extent of forest soil acidification in Europe. However, a rough estimate of the areas where acidification proceeds can be obtained by comparing the acid stress due to air

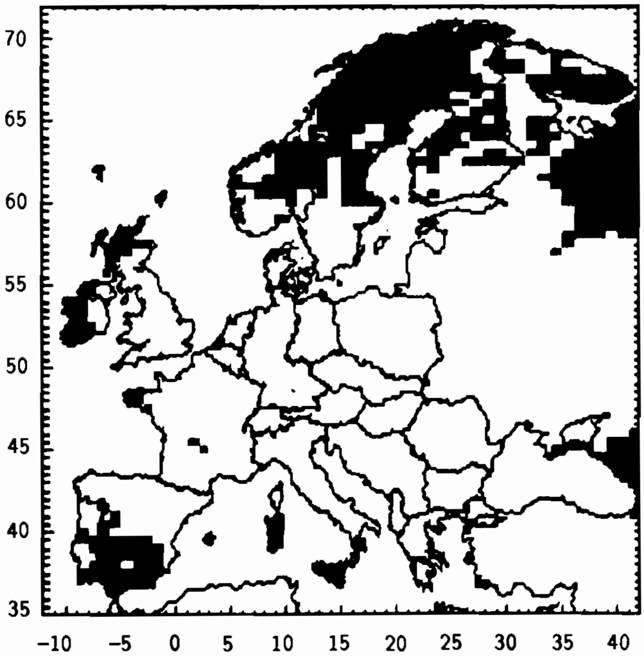

Figure 5.1. The distribution of areas in Europe where the weathering rate of silicates can counteract the acid stress due to sulfur deposition in 1985. (Source: Alcamo *et al.*, 1990.)

pollutants with the weathering rate; this is the only natural process to neutralize acid stress. Based on this comparison, most of Europe is experiencing soil acidification (*Figure 5.1*). Only areas remote from emission sources, like parts of the Nordic countries, parts of the southern countries, and parts of the British Isles, receive such a low acid deposition that weathering could counteract it. However, this does not mean that soil acidification does not occur, because factors other than deposition – biomass accumulation, forestry practices – may contribute to acid stress as well.

Soil studies from some European countries confirm the overview above. Berdén *et al.* (1987) synthesized literature on the observed changes in pH or exchangeable cations from the Federal Republic of Germany (FRG), Sweden, Austria, Czechoslovakia, and the United Kingdom (UK). Most of the studies showed an acidification trend, the only exceptions were those where calcareous dust or liming occurred. The degree of acidification, however, varied remarkably in different sites.

Only a few observations on the acidity of forest soils in the past exist. In southern Sweden the acidity of forest soils was first measured in the 1920s and the same sites were resampled in the period 1982–1984 (Hallbäcken and Tamm, 1986). A pH decrease of about 0.9, 0.2 and 0.1 units was found in A_0-, A_2- and

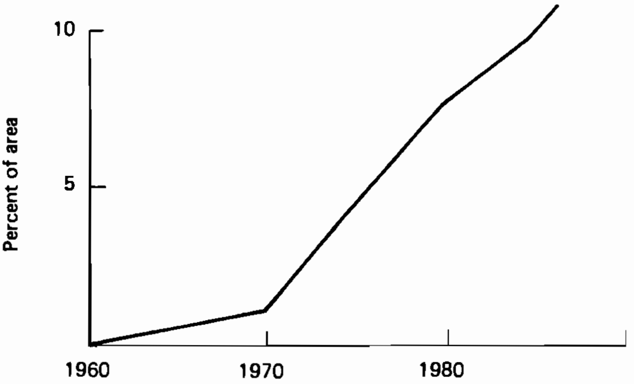

Figure 5.2. The change of the total forest area containing strongly acidified soils (pH less than 4.2) for 1960–1985. (Source: Kauppi *et al.*, 1985.)

B-horizons, respectively. Falkengren-Grerup (1987) also observed increasing acidity in the forest topsoils in southern Sweden in 1984 compared to earlier measurements from the period 1949–1970. The pH change was 0.5–1.0 unit.

The time periods covered in studies from other European countries are much shorter. Generally, the earliest observations date back to the 1950s or 1960s. Recent measurements normally show increased acidity compared to acidity at that time (Berdén *et al.* 1987). Today most of the forest soils investigated in the above-mentioned studies had already lost their cation exchange capacity, i.e., their pH was below 4.0.

Using a modelling approach adopted in the IIASA Acid Rain Project, Kauppi *et al.* (1986) estimated that the area of forest soils without any cation exchange capacity has increased over the last 25 years and is today over 10% of the total forest area (*Figure 5.2*). These areas are mostly located in Central Europe (*Figure 5.3*).

Posch *et al.* (1988) tested the ability of the model used by Kauppi *et al.* (1986) as well as a new improved soil acidification model to simulate the historical development of soil acidification. The model outputs were compared to acidity and base saturation on soil samples taken first in 1949/50 and then from the same sites in 1984/85 in six forest stands in southern Sweden (Falkengren-Grerup *et al.*, 1987). Measurements suggested declining base saturation and pH on all sites between 1949 and 1985. The changes in the amount of exchangeable base cations were predicted fairly well by both models. The order of magnitude of the pH changes was predicted reasonably well by the new model, while it was underestimated by the earlier model (Posch *et al.*, 1988). This implies that the estimate of the area of strongly acidified forest soils in Europe given by Kauppi *et al.* (1986) might well be too low. On the other hand Posch *et al.* (1988) pointed out that the models tested are best suited for estimating soil acidity on non-calcareous mineral soils, subject to relatively high deposition loads. It might well be that in Central Europe with high deposition loads the models could

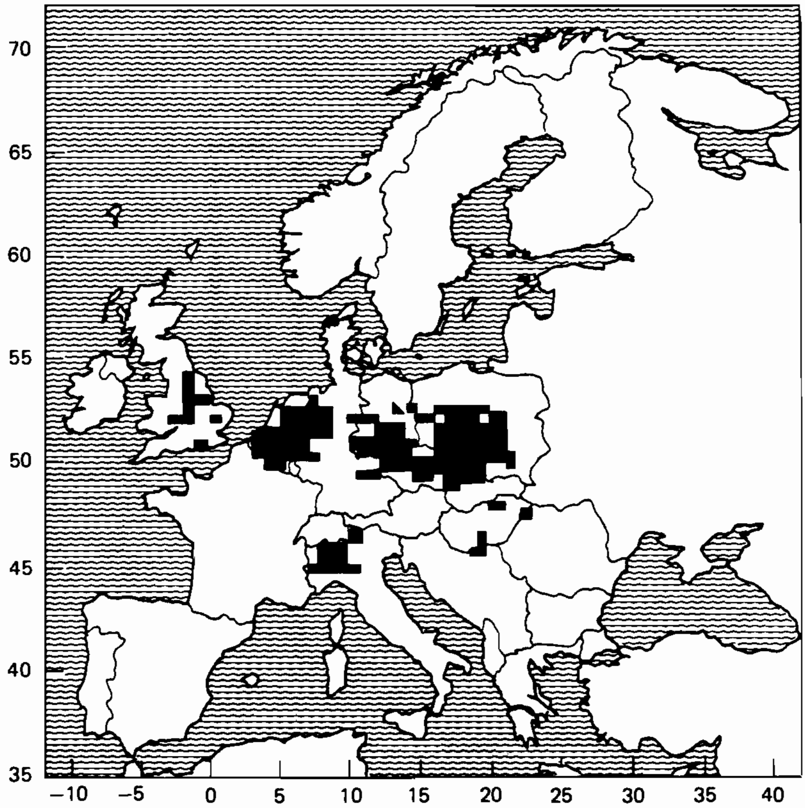

Figure 5.3. The distribution of European forest soils with pH values lower than 4.2 in 1985. (Source: Alcamo *et al.*, 1990.)

better simulate the historical development than in southern Sweden, where the deposition is quite low and the uppermost organic soil layer is important.

5.2. Causes of Soil Acidification

Soil acidification can result from several ecosystem and soil processes. Berdén *et al.* (1987) mentioned the following:

- Increased deposition of acid or potentially acidifying compounds.
- Decreased deposition of acid-neutralizing compounds.
- Increased primary productivity (and/or biomass harvest).
- Increased rate of nitrification or sulfur oxidation.
- Changes in land use, e.g., afforestation, introduction of acidifying species, and changes in forest management.

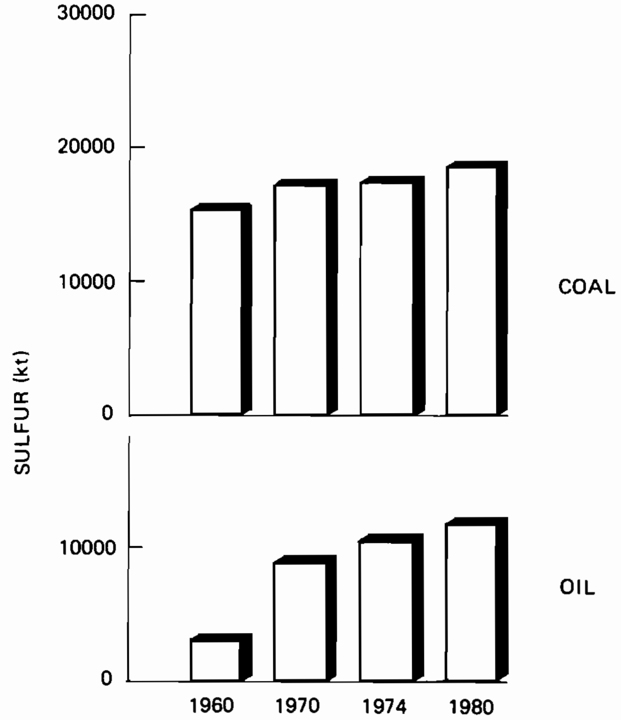

Figure 5.4. The change of sulfur emissions in Europe between 1960 and 1980. (Source: Alcamo *et al.*, 1987.)

- Reduced decomposition rate of litter and soil organic matter.
- Increased production and vertical movement of organic acids.

The most intensively studied of these causes is anthropogenic sulfur emissions. Annual sulfur (S) emissions in Europe increased from *ca.* 10 million tonnes in 1900 to *ca.* 30 million tonnes in 1980, most of the increase occurring after 1950. The emissions of nitrogen oxides have increased continuously, while sulfur emissions have levelled off and even decreased during the 1980s (*Figure 5.4*). In some areas (e.g., the Netherlands) ammonia emissions from agriculture are also important (Alcamo and Bartnicki, 1988).

The spatial distribution of sulfur deposition is very uneven. The highest deposition rates (>10 g $S/m^2/yr$) are observed in the heavily industrialized regions of Central Europe (*Figure 5.5*). Most of Central Europe as well as parts of the UK and the USSR receive more than 4 $g/m^2/yr$ sulfur deposition.

Present nitrogen deposition in the Benelux countries and in a large part of the FRG and GDR is greater than 3.0 $g/m^2/yr$ (*Figure 5.6*). Nearly all of Europe south of the Nordic countries and the northern part of the USSR, and

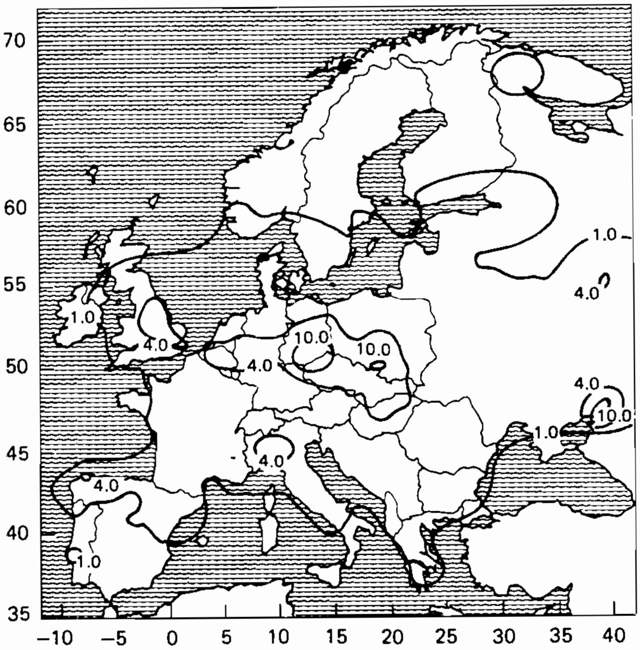

Figure 5.5. Sulfur deposition (g S/m^2/yr) in Europe in 1985. (Source: Alcamo *et al.*, 1990.)

north of Spain, Greece and Turkey receive more than 1.0 g/m^2/yr of nitrogen (Alcamo and Bartnicki, 1988).

Atmospheric deposition of these potentially acidifying substances leads to actual soil acidification if they are not taken up by vegetation or immobilized into soil organic matter. In contrast, potential acidification is manifested by the accumulation of organic N and S in the vegetation and soil.

Most northern forest ecosystems are nitrogen-limited (Cole and Rapp, 1981; Ågren, 1983). As long as these conditions prevail no actual soil acidification occurs. Eventually, however, forest ecosystems might get saturated by nitrogen. According to Ågren and Kauppi (1983) the system can be defined as nitrogen saturated when the nitrogen concentration in the leaf biomass is the maximal attainable without tissue injury. This concentration is around 2% of dry weight for conifers (Ingestad, 1979), whereas deciduous species permit higher nitrogen concentrations, at least up to 4% of dry weight (Ingestad, 1981). At this point the nutrient cycle operates at the maximum level and the excess nitrogen acidifies the soil.

Ågren and Kauppi (1983), using the model developed by Ågren (1983), estimated the time scales for nitrogen saturation in European forests. They assumed that the geographical distribution of nitrogen deposition is equal to

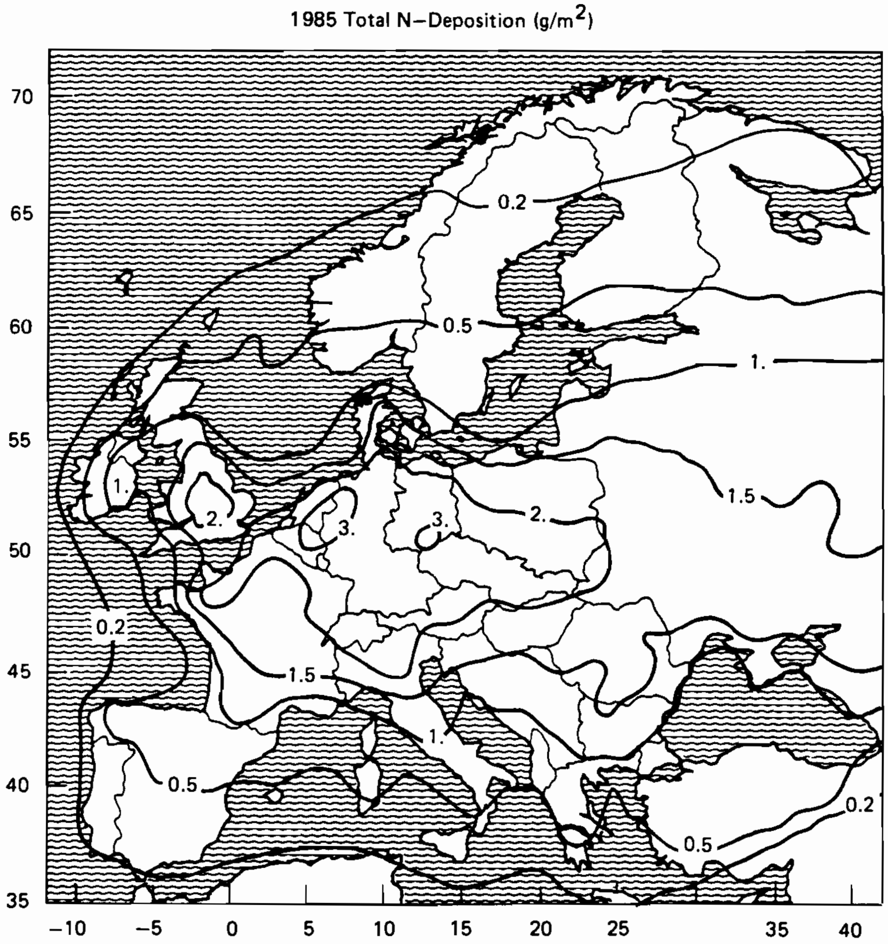

Figure 5.6. Nitrogen deposition (g N/m^2/yr) in Europe in 1985. (Source: Alcamo *et al.*, 1990.)

one-third of the level of sulfur deposition in 1974, and that the deposition rate of nitrogen increases by 4% a year. In Central Europe, according to their calculations, the amount of time typically required to saturate a pine forest on medium soils with nitrogen is of the order of thirty years, whereas in northern Scandinavia it takes over one hundred years. Spruce forests typically require 50% longer to reach saturation. When actual acidification would occur depends on the balance between the input versus the output of NH_4^+ (ammonium) and NO_3^- (nitrate) on an annual basis (van Breemen *et al.*, 1984):

$$H^+ \text{ production} = (NH_{4in}^+ - NH_{4out}^+) - (NO_{3in}^- - NO_{3out}^-) \ . \qquad (5.4)$$

Also, if the vegetation is removed, mineralization is no longer balanced by uptake, leading to a realization of the potential acidification. According to de Vries and Breeuwsma (1987), this effect is not usually important in forest soils because clearing is not frequent and vegetation generally regrows rapidly.

The uptake of sulfur by vegetation is quite low compared with that of nitrogen since much of the sulfur enters the soil. Therefore, the acidifying effect of sulfur deposition is usually high compared with that of nitrogen deposition (van Breemen *et al.*, 1984). The mobility of sulfate can also be affected by soil adsorption or by precipitation. The annual rate of actual acidification caused by S transformations is equal to the difference between the input and output of sulfate (SO_4):

$$H^+ \text{ production} = -(SO^{2-}_{4\mathrm{in}} - SO^{2-}_{4\mathrm{out}}) \ . \tag{5.5}$$

Potential acidification occurs in the case of S retention.

Mineralization, weathering, and desorption of cations neutralizes the acid production induced by the production of anions in mineralization and oxidation processes. Loss of cations thus reflects the acid production in the soil. In northern Europe, intensified forestry contributes to the loss of cations from the soil via increased biomass growth and harvest.

The relative significance of the different factors in actual soil acidification varies depending on the region. Berdén *et al.* (1987) concluded, based on numerous studies, that acid deposition is of great importance in many cases, and definitely so in southern Scandinavia and Central Europe. In northernmost Europe where low temperatures retard biomass decomposition, the natural accumulation of biomass contributes to acidification by removing cations from the mineral soil.

Based on the synthesis of major element cycles (C, N, S, and cations), de Vries and Breeuwsma (1987) concluded that natural soil acidification, i.e., dissociation of weak acids (carbonic and organic) is most important in calcareous soils. Acidification rates measured in these soils vary between 7 to 13 kmol/ha/yr, whereas in podzolic soils the rate is only 0.1 to 0.7 kmol/ha/yr. In non-calcareous agricultural soils, land use, i.e., removal of vegetation, largely determines acidification intensity, the rate being about 8 kmol/ha/yr. Finally, in non-calcareous forest soils acid precipitation is the most important cause of acidification, the rate varying between 1 and 6 kmol/ha/yr (de Vries and Breeuwsma, 1987).

5.3. Buffering Reactions in the Soil

Acid stress can be defined as the input of hydrogen ions into the top soil. Equally, the buffering properties of the soil imply consumption of hydrogen ions within the soil profile. Buffering can be described by using two kinds of variables, the buffering capacity and the buffering rate. Both kinds of variables refer to the intrinsic properties of the soil and can be quantified for any volume of the reacting soil. They are defined as:

- *Buffer capacity* [or acid neutralization capacity (ANC)]: the total reservoir of the buffering compounds in the soil (mmol/ha).
- *Buffer rate*: the maximum potential rate of the buffering process (mmol/ha/yr).

5.3.1. Buffer ranges

The dominant buffer reaction varies with the soil pH. Ulrich (1981 and 1983) has systematically described these reactions and introduced categories called *buffer ranges*. The name of each buffer range refers to the dominant buffer reaction.

Carbonate Buffer Range

Soils containing $CaCO_3$ in their fine earth fraction (calcareous soils) are classified into the *carbonate buffer range* (pH $\geq$ 6.2). The buffer capacity of soils in this range is proportional to the content of $CaCO_3$ in the soil. When $CaCO_3$ is evenly distributed in the soil, the dissolution rate of $CaCO_3$ is high enough to buffer any reasonable level of acid load, i.e., the reaction rate is not a limiting factor.

Silicate Buffer Range

Soils in the *silicate buffer range* (pH 5.0–6.2) have no $CaCO_3$ in their fine earth fraction. The only acid being produced in the soil is carbonic acid and the only buffer process taking place in the soil is the weathering of silicates and the associated release of base cations. The buffer rate is often quite low. The buffer capacity, in turn, is high because rocks contain large amounts of silicate material. The weathering of silicates occurs throughout all buffer ranges. The switch to the lower buffer range implies that the weathering rate of silicates is not sufficient to buffer the acid stress completely.

Cation Exchange Range

Soils are classified as being in the *cation exchange range* (pH 4.2–5.0) when the cation exchange reactions play the major role in acid buffering. This implies that the weathering of silicates is not capable of buffering the acid stress completely. The remaining acid stress is adsorbed in the form of H^+ - or Al -ions at the exchange sites, thus displacing the base cations. These exchange reactions are fast and the buffer rate of this range effectively counteracts any of the acid stress that might occur. The total buffer capacity (= cation exchange capacity, CEC_{tot}) is generally rather low depending mainly on the soil texture. The remaining buffer capacity at any given time is quantified by base saturation, i.e., the percentage of base cations of the total CEC. As long as exchangeable base cations are available the excess stress is buffered by the cation exchange reactions and the value of the soil pH is between 5.0 and 4.2, the actual value depending on the base saturation.

Aluminum Buffer Range

If base saturation declines to between 5% and 10%, hydrogen ions are mainly consumed in the release of aluminum from clay minerals. These reactions merely change the form of acidity from H^+ to Al^{3+}, the basic reaction being (Ulrich 1983):

$$AlOOH + 3H^+ \rightarrow Al^{3+} + 2H_2O \ . \tag{5.6}$$

The leachate has the potential of acidifying the adjacent ecosystems. Since aluminum compounds are abundant in soils, the buffering capacity hardly ever restricts the reaction in the *aluminum buffer range* ($pH < 4.2$). As the base cation concentrations decrease and also their ratios in the soil change due to selective exchange reactions, plants may suffer from a deficiency of some nutrients.

5.3.2. Reversibility of soil acidification

The ability to reverse changes in the soil caused by acidification depends on how far the acidification has proceeded. Weathering is the process that increases the acid neutralization capacity. It proceeds from minerals with a high weathering rate to minerals with low weathering rates. Exhaustion of minerals of the former type will prevent soil recovery to the original base saturation level. Other processes, like the dissociation of organic acids, are reversible. Thus the inability of the soil to reach its former pH value is mainly due to irreversible changes of the solid soil matrix (Berdén *et al.*, 1987).

5.3.3. Indicator variables in the soil

The most commonly used measure of soil acidity is the pH. However, acidification, defined as a decrease in the acid-neutralizing capacity, does not necessarily cause a decline in the pH of a soil. The functional relationship between the pH and the acid-neutralizing capacity depends on the dominating buffer system under given circumstances, because the pH is an intensity factor. Therefore, other indicators, like base saturation and the Ca/Al ratio in the soil solution, are also needed in order to estimate the state of soil acidification. In order to estimate the subsequent risk for water acidification, the soil thickness variable has to be considered since it determines the reacting volume in the soil. The watersheds of those lakes and rivers already acidified, typically have very thin soils (if any).

5.3.4. Spatial and temporal patterns of indicator variables

No systematic soil surveys cover the whole or even a large part of Europe. Therefore, spatial and temporal patterns of the indicator variables based on empirical data cannot be described. This clearly points to the need for coordinated soil surveys.

Currently the only way to describe the temporal and spatial patterns of indicator variables is to model the processes, starting the simulation when the deposition load is too low to cause acidification. This approach will be described in Section 5.4. However, there is still a need for soil surveys because the data is needed for verification of the model.

5.3.5. Relationships between causal factors and response indicators

The relationships between acid stress and indicators of soil acidity are quite well described based on the understanding of the processes involved. However, testing these descriptions by temporal and spatial overlay is not possible because of the lack of data on indicator variables. The description of the relationships adopted into the IIASA RAINS soil model is given in the next section.

5.4. Modelling Forest Soil Acidification by the IIASA RAINS Soil Model

Although there are at present several soil acidification models developed on the basis of experimental studies, the only one that has been applied to the whole of Europe is the one developed within the IIASA Acid Rain Project (Kauppi *et al.*, 1985 and 1986). The forest soil acidification model is part of the RAINS (Regional Acidification INformation and Simulation) model system which links together pollution generation, atmospheric pollution transport and transformation processes, and environmental impacts (Alcamo *et al.*, 1987). Each of these subjects is described by submodels. Due to large spatial and temporal scales each submodel is as simple as possible. The time step of the calculations is a year, and the spatial aggregation is 0.5° latitude × 1.0° longitude for the soil model.

5.4.1. Structure of the model

The soil submodel is a description of the sequence of the buffer ranges introduced by Ulrich (1981 and 1983). It deals with the uppermost 50 cm of the soil which is assumed to be homogeneously mixed. Due to lack of information, the effect of organic matter was neglected. As the focus is on year-to-year changes in soils, redox processes as well as sulfate adsorption processes have been omitted. The weathering rate was assumed to be independent of the soil pH.

The main driving variable is annual acid load which is obtained from the other RAINS submodels for any location in Europe for any particular year. The basic ideas of the model are: (1) the weathering rate of silicate minerals (wr) is subtracted from the corresponding annual acid load (ac), and (2) the difference is then subtracted from the buffer capacity of the dominating buffer range (BC) to estimate the depletion of the acid-neutralizing capacity of the soil:

$$\mathrm{BC}_t = \mathrm{BC}_{t-1} - (\mathrm{ac}_t - \mathrm{wr}) \ . \tag{5.7}$$

In the case of calcareous soils, ac is subtracted directly from the buffer capacity of the carbonate buffer range until this capacity is depleted. The calculation is repeated in yearly steps throughout the simulation period. Time patterns of soil variables like base saturation and pH are computed on the basis of these comparisons, and pH is computed as a function of base saturation. After all base cations are depleted, an equilibrium between solid phase aluminum and soil H^+ is assumed. If the acid load decreases below the weathering rate, a recovery of the acid-neutralizing capacity occurs.

5.4.2. Estimation of model parameters

The model can be used to describe soil acidification on a small scale, i.e., on a certain site, using measured values for the input variables and parameters. However, its main use has been and will be in regional applications, where direct measurements of the buffering properties are not available. Thus, model parameters must be estimated indirectly.

The buffering properties of different soils vary depending on their parent material and texture. The buffer capacity of the carbonate range is proportional to the lime content of the soil; the buffer rate of the silicate range is related to the chemical weathering rate of the silicate minerals; the buffer capacity of the cation exchange range depends on the clay content and on the base saturation of the soil; and the buffer rate of the aluminum range depends on the accessibility of aluminum compounds. Values for the buffer capacities and buffer rates of European soils have been calculated based on the *International Geological Map of Europe and the Mediterranean Region* (Bundesanstalt für Bodenforschung Hannover, 1972) and the FAO-UNESCO *Soil Map of the World* (1974). The depth of the reacting soil was assumed to be 50 cm throughout the study area and 1960 was selected as the base year.

All information regarding soils was stored in a computerized grid-based format. Each square in the grid was of 1° longitude × 0.5° latitude. The size of a grid was fixed at 56 km in the north-south direction, and from 38 km to 91 km, in the east-west direction depending on latitude.

Detailed soil chemistry information regarding the soil variables other than the buffer rate of the silicate range was available from the *Soil Map*. The fraction of each soil type within the grid square was computerized to an accuracy of 5%. The resolution of the map was such that the standard grid square was

Table 5.1. Buffer capacities of the carbonate and cation exchange buffer ranges estimated for the year 1960 for soil types of the *FAO-UNESCO Soil Map of the World* (1974). Soil thickness of 50 cm is assumed.

Soil type	BC_{Ca}	BC_{CE} kmol/ha	Soil type	BC_{Ca}	BC_{CE} kmol/ha	Soil type	BC_{Ca}	BC_{CE} kmol/ha
Ao	200	910.0	Kk	8000	1170.0	Vc	32000	1170.0
Bc	500	1225.0	Lc	3000	170.7	Vp	9000	3640.0
Bd	0	165.8	Lf	0	138.8	Wd	0	47.3
Be	500	1824.0	Lg	0	146.3	We	500	1410.5
Bg	500	180.0	Lo	0	107.3	Xk	43000	1170.0
Bh	0	136.5	Lv	3000	1225.0	Xy	40000	1225.0
Bk	25000	1470.0	Mo	0	1495.0	Zg	15000	1225.0
Bv	0	2210.0	Od	0	72.0	Bc-Lc	3000	685.6
Ch	0	390.0	Oe	0	168.8	I-Bc	200	1050.0
Ck	19000	2535.0	Pg	0	180.0	I-Bc-Lc	1500	469.1
Cl	0	419.3	Ph	0	49.0	I-Bd	0	151.2
Dd	0	136.5	Pl	0	68.3	I-Be	0	765.6
De	0	136.5	Po	0	78.0	I-Be-Lc	1500	533.9
Dg	0	468.0	Pp	0	239.2	I-Bh-U	0	136.5
E	20000	2600.0	Qc	100	227.5	I-C	500	910.0
Gd	0	126.8	Ql	0	117.0	I-E	10000	1750.0
Ge	0	302.3	Rca	0	47.3	I-L	0	149.3
Gh	0	146.3	Rcb	0	136.5	I-Lc	1500	153.6
Gm	0	183.8	Rcc	500	857.5	I-Lo-Bc	0	408.5
Hc	7000	1170.0	Re	0	136.5	I-Lc-E	10000	1500.0
Hg	500	1820.0	So	500	1183.0	I-Po	0	126.8
Hh	1000	321.8	Sm	0	236.3	I-Po-Od	0	108.5
Hl	0	312.0	Th	0	127.5	I-Rc-Xk	20000	1500.0
I	0	136.5	Tm	0	136.5	I-Re-Rx	0	106.8
Hc	8000	315.0	To	0	183.3	I-U	0	136.5
Je	200	1008.0	Tv	0	120.0	Lo-Lc	1500	139.1
Kh	0	136.5	U	0	136.5			

(Source: Kauppi *et al.*, 1985.)

composed of one to seven soil types. The number of different soil types was 80. The soil data base consists of 5212 units, the mean number of soil types per grid square being 2.2.

Initial values for the soil variables were provided for every soil type (*Table 5.1*). The *FAO-UNESCO Soil Map* (1974), however, could not provide the information regarding the buffer rate of the silicate buffer range which is equal to the weathering rate of the parent material. This variable was estimated from other sources. Ulrich (1983) reports a range of variation in weathering rates of European soils from 0.2 to 2.0 kmol/ha/yr/m. Four classes for the reacting 50 cm soil layer were introduced with the following buffer rates (in kmol/ha/yr):

Class	1	2	3	4
Buffer rate	0.25	0.50	0.75	1.00

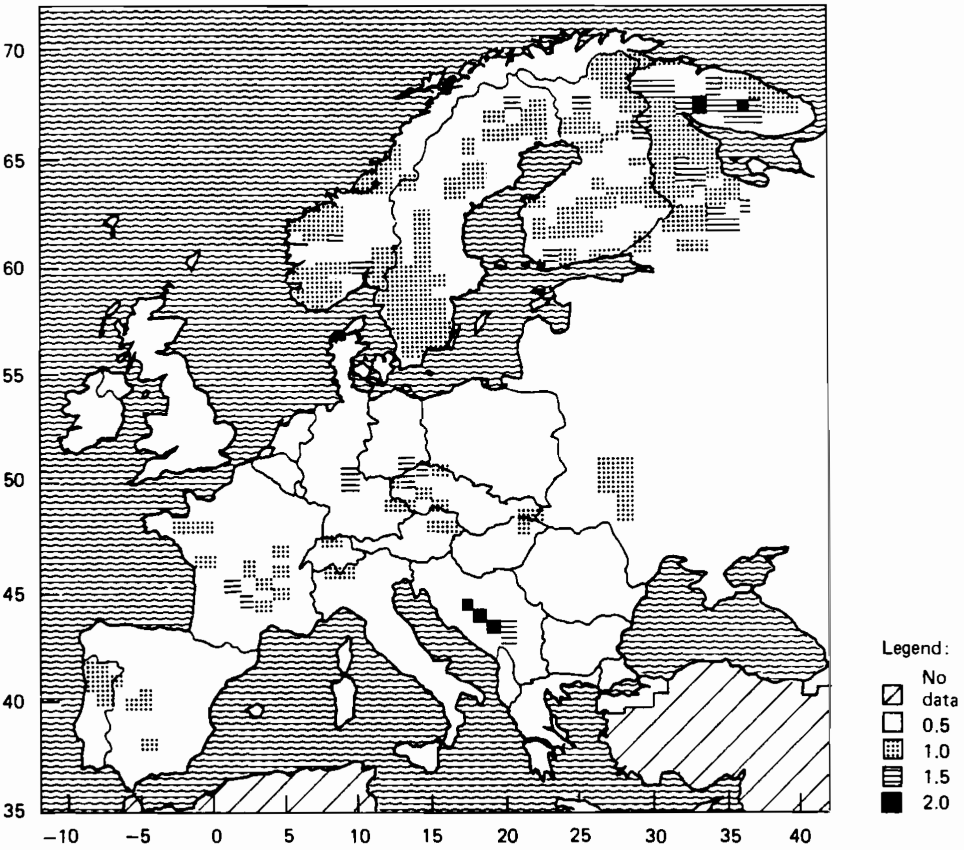

Figure 5.7. The dominant weathering rate (in kmol/ha/yr/m) in different grids estimated on the basis of the parent material. (Source: Alcamo *et al.*, 1990.)

The *Geological Map* (Bundesanstalt für Bodenforschung Hannover, 1972) was used to determine parent materials of soils in each grid square. Depending on the dominant parent material the soil of each grid square was classified into one of the above categories (*Figure 5.7*).

For determining the location of forest soils the *Weltforstatlas* (1975, 1:10 000 000) was used, which gave the percentage of forest cover in each grid. The fact that forests are known to grow on less fertile soils than agricultural crops was taken into account by allocating the forests in a given grid square starting from soil types with the lowest weathering rates and cation exchange capacity values and continuing until all forests were distributed.

The soil data base of the IIASA Acid Rain Project was created in 1983. Since then more recent and accurate information has appeared. For example the Commission of the European Communities has recently published a soil map of

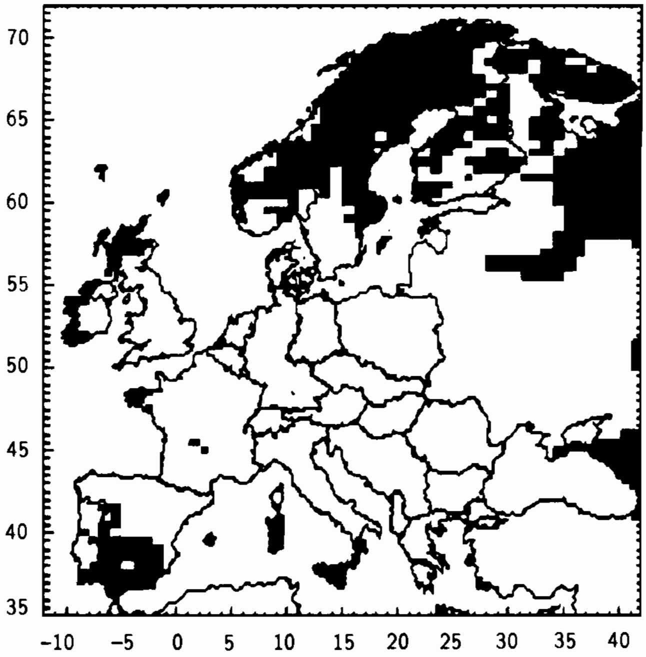

Figure 5.8. The distribution of areas in Europe where the weathering rate can counteract the acid stress due to sulfur deposition in the year 2000 assuming the current reduction plans in all European countries. (Source: Alcamo *et al.*, 1990.)

its region (1:1 000 000) which follows the same principles as the *FAO-UNESCO Soil Map.*

5.5. Potential Future Patterns of Soil Acidification

5.5.1. Scenarios for acid stress

The future acidification/recovery strongly depends on future emission patterns. The IIASA Acid Rain Project uses several scenarios for future emissions. The *current reduction plans* scenario is based on information that the countries which have joined the Convention on Long-range Transboundary Air Pollution have given their plans regarding air pollution abatement to the ECE (ECE, 1987). According to this scenario, emissions of sulfur dioxide would decrease by 15% by the year 2000. This would improve the situation in southern Europe, Scandinavia, and the USSR (*Figure 5.8*). In these areas a slow recovery should be seen. However, the current reduction plans would not reverse the acidification trend in Central Europe.

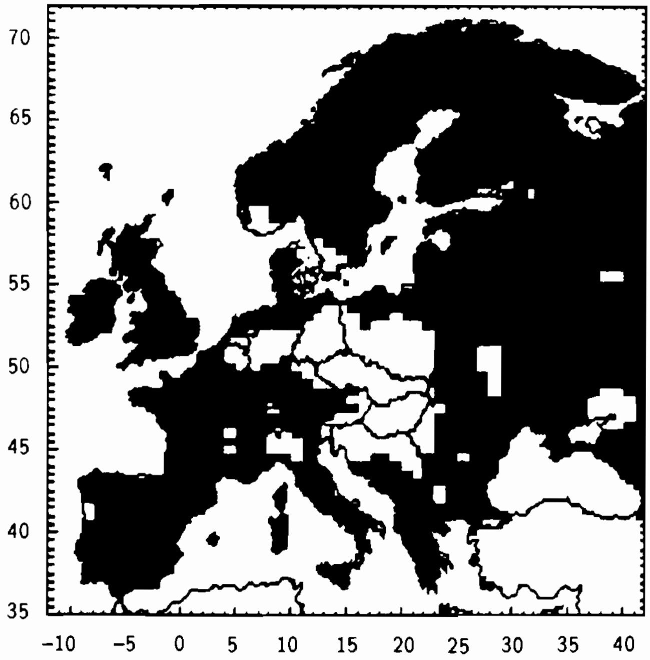

Figure 5.9. The distribution of areas in Europe where the weathering rate can counteract the acid stress due to sulfur deposition in the year 2000 assuming the maximum feasible reduction of sulfur emissions. (Source: Alcamo *et al.*, 1990.)

Assuming that all countries introduce the *maximum technically feasible reductions* (see e.g., Amann and Kornai, 1987) the SO_2 emissions would decrease by 80% to the year 2000 compared to the emissions in 1985. Even with this assumption there would be areas in Central Europe where soil acidification would continue (*Figure 5.9*). In most of Europe a recovery would then be observed.

5.5.2. Effect of climate change on soil acidification

At present there is no clear understanding on how climate change might affect soil acidification. For example, in the IIASA Acid Rain Soil model, temperature plays no role and also precipitation only enters the model when the soil is already in the aluminum buffer range. In such a case the soil pH is slightly dependent on precipitation. Posch *et al.* (1985) tested the sensitivity of the model to changing net precipitation (P-E) with three common forest soil types. According to their results for the same stress rate, the soil pH in the aluminum buffer range stays higher in humid areas than in areas with a drier climate (*Figure 5.10*). This implies that in Northern Europe, where precipitation will

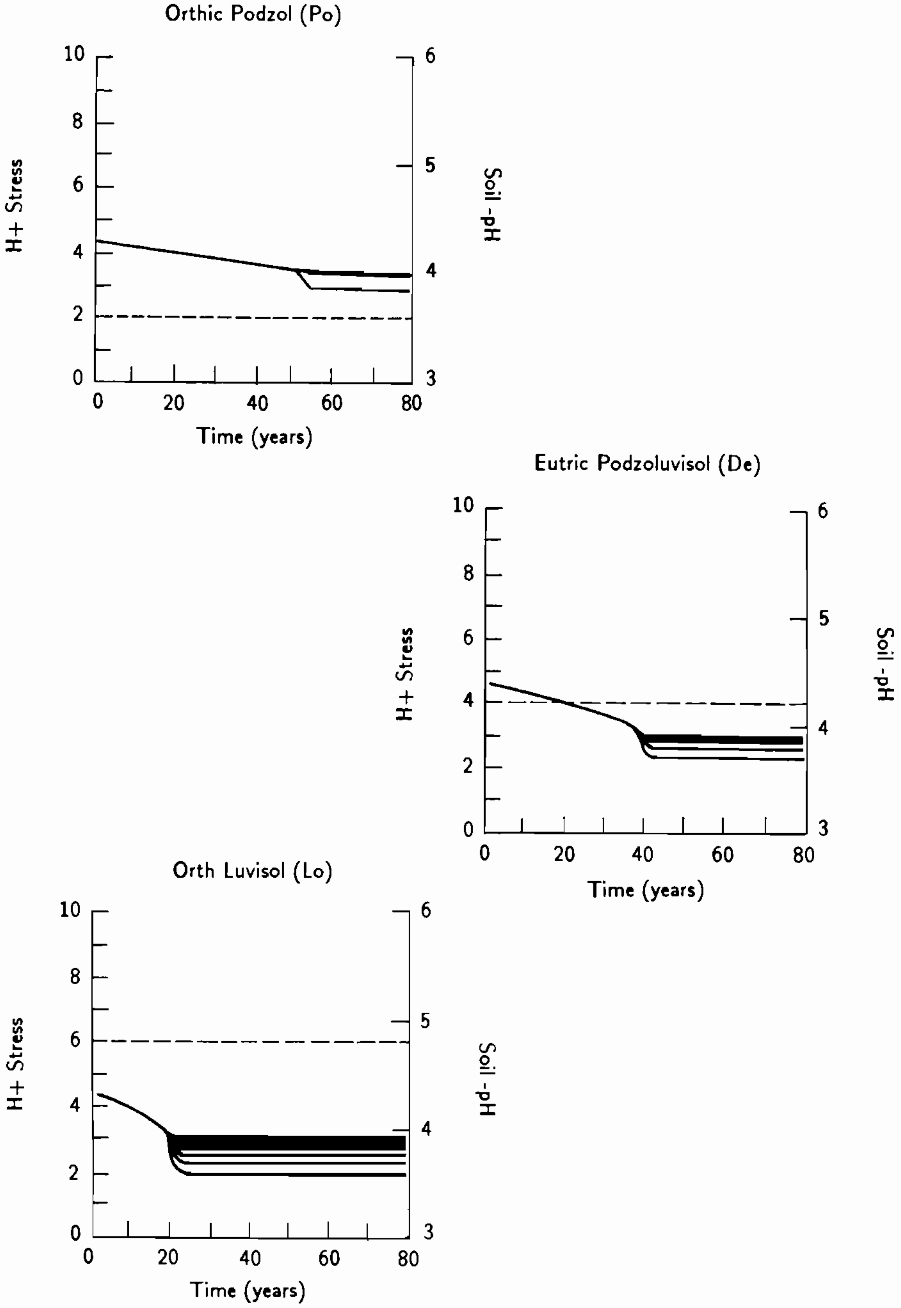

Figure 5.10. Effect of net precipitation (precipitation minus evaporation) on the soil pH in different soils with a constant acid stress rate. (*a*) Orthic Podzol, (*b*) Eutric Podzoluvisol, and (*c*) Orthic Luvisol. (Source: Posch *et al.*, 1985.)

probably increase, the lowest pH values might ameliorate. This would improve the growing conditions for trees, since a pH increase by 0.1 units in the range pH < 4.5 decreases the soil water concentration of aluminum by at least a factor of 2 (Berdén *et al.*, 1987). In contrast, the situation in Central Europe would worsen due to decreased soil moisture.

In northern parts of the continent, climate change might contribute to the recovery of soils via the increase in temperature. Biomass decomposition would be faster thus causing less internal proton production, which today may be the most important source of acid stress in the north.

Soils play an important role in water acidification. Climate change might also affect this relationship by changing the hydrological cycle and thus the reaction time in the soil. In Scandinavia, where the problem of water acidification is most urgent, the seasonal distribution of precipitation would become more constant (less snow accumulation as well) and thus the reactions in the soil would be more complete. This implies less acid stress to aquatic ecosystems as long as some buffer capacity remains in watersheds.

5.6. Adaptation and Mitigation Possibilities

The main strategy to mitigate soil acidification should be the reduction of emissions. The technology exists to reduce at least sulfur emissions dramatically. The main problem is cost. Several West European countries have already agreed to reduce emissions by above the 30% agreed in the Convention on Long-Range Transboundary Air Pollution. For example, Austria, the FRG, and Sweden are reducing emissions by almost 70%, and Denmark, Finland, the Netherlands, and Norway, by about 50% (ECE, 1987). However, there are also several countries that will probably have difficulties in achieving the 30% reduction. So far the reductions have only been discussed on a country basis. From the point of view of minimizing environmental impacts, it might be useful to study the optimization of emission reductions by further reducing those sources which contribute most to the acid stress in vulnerable areas. For example, it might be more beneficial for the forests in the FRG if at least part of the pollution control investments of the FRG were allocated to Czechoslovakia. To some extent this is in fact already being practiced.

Even when one assumes maximum feasible emission reductions, some areas in Central Europe will continue to undergo soil acidification. This implies that additional mitigation techniques are needed. Liming of soils is already being attempted in Sweden and to some extent in the FRG. However, in some earlier experiments, the results were not very promising as regards the effect on forest growth.

In some European countries, experiments are underway to test tree species that would better tolerate air pollution. The planting of these trees would not solve the problem of soil acidification, but would help in adapting to the situation. However, the tree species now being tested (e.g., some *Sorbus* species) have a low economic value. The main function of these new forests would be to protect the soil from erosion.

5.7. Research Recommendations

The present RAINS soil submodel is very simple and ignores some important processes. However, a new version is being developed, which takes additional factors into account, e.g., natural soil acidification due to the dissociation of CO_2 and the impact of NO_x- and NH_3-deposition. Nitrogen emission and transport models have recently been implemented in the model system, thus making N-deposition calculations possible. Furthermore, the new soil model version predicts the major components of the soil solution rather than projecting only pH or base saturation. This is a major advance since the ratios of aluminum and/or ammonium to calcium and other base cations are more important indicators of the risk of forest decline.

However, if only the model structure is improved the understanding of the problem has not really improved. To date the application of the IIASA soil model has been based on data obtainable from the *FAO-UNESCO Soil Map of Europe* and the *International Geological Map of Europe and the Mediterranean Region.* These maps were not originally prepared for displaying the variables relevant for soil acidification (lime content, weathering rate of silicates, cation exchange capacity, base saturation). Therefore, indirect transfer functions and best guesses had to be used to estimate buffer capacities and buffer rates from soil types and bedrock. In the future, it would be highly desirable to conduct forest soil surveys aimed at collecting direct and statistically valid information on variables relevant to soil acidification. These surveys should be internationally coordinated and conducted in order to better utilize general soil maps, i.e., the surveys should always include the determination of the soil type according to the FAO classification. More research would be needed on the weathering rate of silicates from different minerals shown in geological maps.

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CHAPTER 6

Biota: Forest Decline

Peter N. Duinker

6.1. Introduction

Forest decline (or, as it is known in German, *Waldsterben*) has been a serious issue on the European continent for almost ten years. Society was first alerted to the problem in the late 1970s when foresters noted unusual disease symptoms in coniferous tree species in southern parts of the Federal Republic of Germany (FRG) (Schütt and Cowling, 1985). Since then, an explosion of awareness, discussion, research, and on-the-ground mitigative action has occurred. The issue still is receiving much coverage in the press (e.g., Tifft, 1985), attention in international organizations (e.g., the United Nations Economic Council for Europe – see, e.g., ECE/FAO, 1986), and study by academics and practitioners (see, e.g., Kairiukstis *et al.*, 1987). Indeed, Kairiukstis *et al.*, among others, indicate that the forest-decline phenomenon is by no means limited to Europe, being found all over the globe and receiving special attention in North America (see, e.g., Johnson and Siccama, 1983; Federal LRTAP Liaison Office, 1986; Hakkarinen and Allan, 1986).

The nature of forest decline in Europe in the 1980s is such that trees and stands all over the continent, of all species, of all ages, on all site qualities, at all elevations, managed and unmanaged, are displaying a shared, complex set of symptoms (see Schütt and Cowling, 1985 for a list of symptoms), thus setting this disease phenomenon apart from any yet seen. Moreover, the suspected causes of the disease seem equally if not more complex (for discussions on hypotheses of possible causes, see Krause *et al.*, 1986; Last, 1987; McLaughlin, 1985; Prinz, 1987). There is a great cloud of uncertainty surrounding causes and effects in forest decline, especially when the phenomenon is viewed on a scale of regional forests, nations, and a continent.

Forest decline is occurring in all countries in Europe. Each country that takes its forest resources seriously must make substantial investments in research, monitoring, assessment, and mitigative action over the next decades. Despite current uncertainty, we know enough about forest decline today to say that it is unlikely to cease by itself (notwithstanding evidence that some European forest stands reported in decline in the early 1980s, have actually improved in condition over the last few years).

This paper examines the forest-decline issue as one of several environment-development issues in Europe (others being, e.g., soil acidification, long-term climatic change, degradation of water quality and quantity) that need to be examined on a wide scope and large spatial scale before they can be understood in terms meaningful to the international community. The paper is not an exhaustive literature review on forest decline; such work covering the whole European continent would require a team effort with working capabilities in many languages. Rather, my selective review leads ultimately to a sketch of the kinds of research and monitoring I feel should be pursued to guide action in dealing with forest decline in the future. Not much can be done now about past decline – society's focus must be on how to cope with possible continued forest decline and its diverse consequences.

My focus will be largely biophysical (see Metz, 1988, for a review of the economic effects of forest decline). I begin with a discussion of the concept of forest decline, and of the environmental and socio-economic values at stake. I then review the main indicators that can be (and in some cases are) used in international monitoring programs designed to gauge the extent and severity of forest decline. Subsequently I summarize the best data available on the patterns of forest decline across Europe, indicating how serious the situation apparently is. I review two main sets of causes I feel are *most responsible* for forest decline, namely, air pollution and silvicultural practices. I then present some possible futures for the two sets of causes, and for the courses forest decline might take. I conclude by reviewing possibilities for adapting to and mitigating forest decline, and by outlining the kinds of models and data sets that should be developed to build defensible quantified scenarios for forest decline and its effects.

6.2. Concept and Meaning of Forest Decline

What is actually meant by the term *forest decline* and related terms? A tree as defined here is an individual of a large woody-plant species, a stand is a group of populations of trees sufficiently homogeneous according to some set of criteria that it is distinguished from neighboring groups of populations of trees, and a forest is a set of stands, often defined according to economic or political boundaries. The spatial extents of a tree, a stand, and a forest can vary widely depending on, among other things, the region in which they are located, local environmental conditions, and the criteria used to distinguish individual stands and forests. Trees may occupy from 1–2 m^2 each up to tens of square meters each; stands may range from, say, 0.5 ha to hundreds of hectares; forests can be as small as privately owned woodlots (e.g., order of tens of hectares), or as large as the largest management units (e.g., hundreds of thousands of hectares).

Although *decline* usually is preceded by *forest*, sometimes one encounters "tree decline". Cowling (1984) referred to tree decline as an appropriate label for declines affecting single tree species.

Because the decline phenomenon described in this report is widespread throughout Europe, across a multitude of species, ages, site qualities, and climatic zones, we might more carefully refer to each instance in which a decline is observed in a "closed forest" as a stand decline. While there is considerable health variation among trees within a stand, there is at least as much variation among stands. All the relevant factors that could contribute to a stand decline should be taken into account in reckoning potential causes, with the expectation that stands in the same forest may be declining for very different reasons. Thus, what we are calling a general phenomenon of forest decline is really a large set of stand declines (each of which, in turn, could be considered as a set of tree declines). However, for the purposes of this paper, the descriptor *forest* will be retained because of its connotations and popularity.

Among the terms *decline*, *dieback*, and *damage*, I argue strongly for the general use of the term *decline*. Manion (1981) defined forest decline as a complex disease caused by the interaction of a number of interchangeable, specifically ordered abiotic and biotic factors to produce a gradual deterioration, often ending in the death of trees. According to Cowling (1984), forest decline is a widespread disease in the health and vigor of forests, frequently leading to the death of many individual trees over a large region. Both of these definitions seem appropriate. In contrast, *dieback* is often used to denote a *dying back* of tree crowns where the extremities of branches lose foliage and twigs die. These symptoms are by no means the most ubiquitous in the declines seen throughout Europe in the 1980s. The term *damage* implies that some natural or anthropogenic agent or set of agents is known to be *causing* the symptoms observed. In the case, for example, of tree defoliation by insects, this is clearly legitimate because the damaging agent can often be seen in action, and the symptoms observed are easily attributed to a specific damaging agent. But in the case of needle loss, especially older age-classes of needles for instance, we do not have a clear case where causal agents are known for sure. In such a case, it is hardly a careful use of terms to refer to the phenomenon as damage – if the defoliation could be attributed mainly to excessive competition and age in a stand, would we call this forest damage due to silviculture?

6.3. Environmental and Socio-Economic Values at Stake

Forest stands in Europe may have the following functions, or provide the following benefits (either by design or by default):

- Timber.
- Environmental protection (e.g., protection from erosion, avalanches, and

floods; noise and pollutant absorption; water quantity and quality; nature conservation).

- Recreation (e.g., hiking, riding, skiing, hunting, fishing, landscape amenity, and scenery).
- Non-wood products (e.g., foods, wool and skins, tannins, Christmas trees and other decorative materials, cork) (ECE/FAO, 1986).

Continued forest decline could threaten the first three of these forest functions in the ways described below.

6.3.1. Timber

There is sufficient concern over the possible effects of forest decline on timber supply that the ECE Timber Committee recently established a team of specialists to investigate the "implications of air pollution damage to forests for roundwood supply and forest products markets". There are also large international research efforts now underway to elucidate the possible repercussions of continued forest decline on future wood supplies throughout Europe (e.g., the Forest Study of IIASA's Biosphere Project).

Sanitation fellings are harvests of diseased and dying trees and stands considered necessary to maintain acceptable health conditions of forests. The two specific concerns with respect to timber supply are the degree to which sanitation fellings may disrupt either the temporal and spatial patterns of planned fellings, or the amount and quality of roundwood brought to market. With regard to the former concern, attempts are likely to be made to keep total annual fellings constant (ECE/FAO, 1986), so any increases in sanitation harvests necessitated by decline conditions would delay planned harvests, with detrimental disruptions of proper silvicultural schedules in stands where planned fellings were postponed. In the latter case, a higher proportion of wood from declining stands [with possible quality reductions (Splawa-Neyman *et al.*, 1988)] in the total wood supply would be an undesirable consequence, as would be any significant increase (or decrease) in the total amount of roundwood marketed annually (Kornai, 1988). Although it is reported that there have not yet been any market disturbances of a regional or national scope in Europe, there have been some local effects (ECE/FAO, 1986). But the potential for regional effects certainly exists. For example, an examination of recent data for Czechoslovakia (*Figure 6.1*; Stoklasa and Duinker, 1988) suggests that the volume of necessary sanitation fellings is rapidly climbing towards the level of planned annual fellings (Samek, 1985). Unfortunately, very poor records are kept in most countries about the degree to which sanitation fellings, both clearcut final harvests and thinnings, take place.

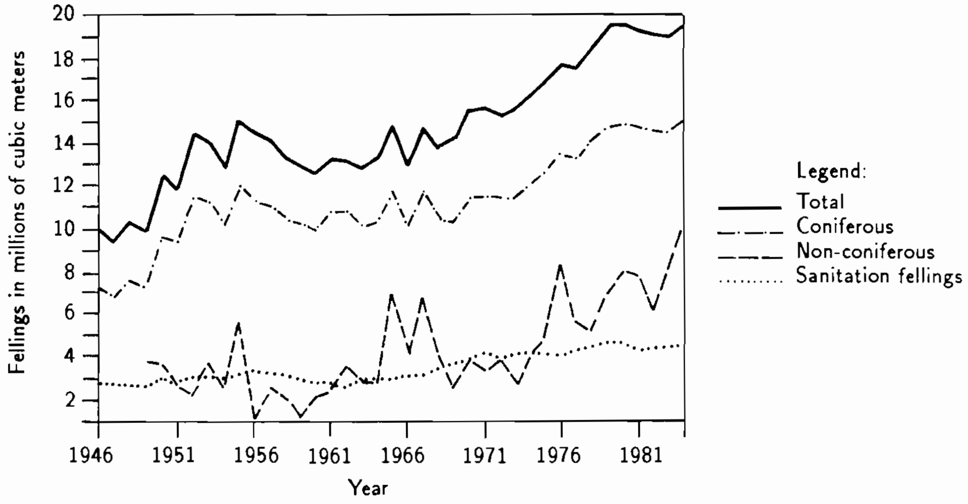

Figure 6.1. Annual fellings in Czechoslovakia during the period 1946 to 1984. (Source: Stoklasa and Duinker, 1988.)

6.3.2. Environmental protection

The environmental functions of European forests, as listed above, are rather important to European society. Some 25% of European forests are dedicated to environmental protection functions, with the highest regional percentages found in the Mediterranean area (around 55%), and the lowest in the Nordic countries (around 7.5%) (ECE/FAO, 1986). Reductions may already be evident in the ability of forests to perform these functions under declining conditions (ECE/FAO, 1986). For example, the runoff-controlling functions of mountain forests in Czechoslovakia have already been seriously diminished by forest decline (Stoklasa and Duinker, 1988).

6.3.3. Recreation

The recreational functions of European forests have also been important for a very long time, and are increasingly demanded (Florio, 1987). Significant proportions of the total forest resource in Eastern Europe are apparently dedicated to recreation i.e., some 8.2%, compared to a European total of some 2.2%, (see ECE/FAO, 1986), yet recreational use of a multitude of types of forests is strong throughout the continent. Forest decline can be viewed as a threat to the recreational value of forests, especially in cases where decline necessitates clearcut sanitation felling of mature stands that are particularly highly appreciated by recreationists. It is not clear, however, whether forest decline in general will lead to a decrease in recreational visits to forests, or additionally whether forest decline will lead to special silvicultural measures taken solely to maintain forests for recreational purposes. Evidence of this is very sparse. Stoklasa and Duinker (1988) concluded that recreational use of mountain forest landscapes in Czechoslovakia continues to increase despite widespread forest decline. However, it is probably safe to say that, overall, the quality of recreational experiences, and the value of forests for recreational purposes, are reduced when forests exhibit symptoms of decline.

6.4. Indicators of Forest Decline

A range of forest variables that are being used, and could be used, to quantify the extent and severity of forest decline will now be examined. For each variable, its use at the tree, stand, and forest levels will be discussed.

6.4.1. Defoliation

The most common variable used in internationally developed forest-decline surveys (e.g., Programme Coordinating Centres, 1986) is the percentage of foliage a tree has lost, compared to a so-called normal, fully foliated tree. The measurements are in most cases tree-level ocular estimates made by trained observers, and trees are assigned to percentage defoliation classes with a width of 10 percentage points, or a standard scheme of classes of 0–10%, 10–20 (or 25)%, 20(25)–60%, and more than 60% (Programme Coordinating Centres, 1986; Wright and de Meyer, 1986). Most countries apply elaborate sampling procedures to selected trees (in stands in which sample plots are located) for observation in specific regions of their territories, or preferably across their entire forested territories.

There are significant problems associated with the foliage-loss variable. While the measurements are made on sample trees, it is usually desirable to aggregate the tree-level data. What is an appropriate method of aggregation? Simple tree counts in various foliage-loss classes, as a percentage of the total number of trees of that species and social class sampled, is a frequent method used to represent the forest level, even national-level forests. But this assumes that the sampled trees adequately represent the entire population of such trees in the forest, and this is hardly the case in most national forest-decline surveys.

Another problem has to do with the nature of the foliage-loss estimate being ocular. While some countries try to remove as much observer bias as possible, it nevertheless remains an issue (Wright and de Meyer, 1986). There are difficulties in making ocular estimates on tall trees in fully dense stands – how can one judge accurately by eye what the defoliation status of a tree is, especially when the reference trees come from photos in a book (e.g., Bosshard, 1986) where the trees all are sufficiently free standing that one can get a good view through the crown, horizontally, with blue sky in the background!

A third problem is that this response indicator of tree decline is not cause-specific, which means that a number of factors, singly or interacting, can lead to the same apparent foliage losses. For many reasons, there is considerable variation among trees with respect to their foliage status – it is even quite natural, due to normal competition among trees in a stand, for some trees to be in a state of decline while the stand overall is considered to be quite vigorous. Thus, the variable is not by itself useful in assessments of forest decline due to air pollution, a factor blamed for much forest decline and the main reason the internationally coordinated annual forest-decline surveys were started in the first place. Despite these and other problems, this variable remains the most common measure of forest decline throughout Europe.

6.4.2. Foliage discoloration

The degree to which foliage changes color abnormally (i.e., wrong color for the season) is another popular but somewhat less widely used decline variable. In Europe, there is an internationally adopted scheme for combining the two variables of foliage loss and discoloration into one set of decline classes (Programme Coordinating Centres, 1986), but measurement of discoloration is still considered optional.

As a forest-decline indicator, discoloration suffers from the same problems as foliage loss because it is measured ocularly on individual trees. Thus, there are difficulties with observer bias, making observations on tall trees in closed canopies, determination of the specific cause of discoloration (although this symptom is probably a better indicator for this purpose than foliage loss), and translating the tree-level results beyond the sample plot in which they were taken.

6.4.3. Wood increment

The rate of annual increase of wood, often referred to as growth, is also used as an indicator of tree, stand, and forest decline. Measurements are usually taken non-destructively with stem cores. At the tree level, growth is normally a fast variable, with large variations from year to year. At the stand level, it is a fast to medium-pace variable, because some of the factors influencing growth are distributed across the entire stand at roughly the same level (e.g., climatic factors), but other factors, such as genotypic and microsite factors, are tree-specific. At the forest level, however, increment is a slow variable, because it is rare that any strong growth-controlling factor can simultaneously influence all stands throughout a large forest.

While increment measurements can be rather accurately and precisely made, this indicator is, like the crown indicators, controlled by a wide range of factors. Particularly relevant is the fact that annual increment rarely correlates well with tree vigor (F. Schweingruber, personal communication), perhaps because annual increment depends on factors other than available photosynthate. Therefore, it is also not directly useful by itself to indicate what factor has caused fluctuations, although some claim it can be used in cause-effect studies (e.g., Kauppi, 1987). A major advantage of tree-ring data for indicating changes in tree, stand, and forest growth is the historical record that extends back to the early years in the lives of the sample trees.

6.4.4. Wood volume

Wood volume is always a calculated indicator based on measurements of tree diameter and height (and perhaps a form factor). At all levels, wood volume is, harvesting activities aside, a rather slow variable, except at the tree level in the case where a tree dies (its volume goes to zero rather quickly). However, if we take timber harvesting into account, wood volume can be a rapidly changing variable, especially at the tree and stand levels where it is virtually instantaneous, but also at the forest level if many high-volume stands are taken in rapid succession. Interestingly, there are cases where the impact of forest harvesting (in either planned or sanitation harvests) on the growing stock (wood volume) of a forest, can be much greater than the impact on increment (Kauppi, 1987). This occurs when harvesting is concentrated primarily on old stands in which increment is already much lower than the forest average but which contain very significant amounts of the growing stock. The effect of forest decline on forest growing stock is only meaningfully examined along with the potentially strong effect of forest decline on harvest patterns.

6.4.5. Mortality

Sometimes the general term *forest decline* is misinterpreted as a phenomenon sure to lead to forest *death.* However, it is meaningful to speak of mortality only in terms of individual trees. When it comes to the species level, we normally speak of extinction, at a variety of spatial scales. At the stand level, it hardly seems appropriate to speak of stand death, except when all trees in the stand die (as in clearcut harvesting, or severe cases of air-pollution damage). Perhaps stand disappearance is a more fitting descriptor, especially when a new stand of trees would probably not regenerate naturally (as in the case of severely polluted ecosystems). The number of tree deaths per unit area, per unit of time is a very relevant measure of forest decline.

6.4.6. Sanitation fellings

Harvests of damaged or diseased (declining) trees are normally referred to as sanitation fellings, since they are made to improve the sanitary condition of the stands in which they occur. One could consider the magnitude of sanitation fellings in a forest to be an indicator of the extent and severity of forest decline. Of course, the indicator would only be comparable among time periods as long as the criteria by which foresters and forest managers make sanitation fellings are stable. Because sanitation fellings are undertaken after such diverse calamities as blow-down, insect and disease infestations, fires, and others such as air-pollution damage, it is important to know in the sanitation-fellings data what the damaging agents (if known) were.

Unfortunately, few records are widely available as yet about the degree to which sanitation fellings occur across Europe. Some countries such as Czechoslovakia (see, Samek, 1985; Stoklasa and Duinker, 1988) publish the extent of sanitation fellings in their forests, but most do not. Since the degree of sanitation fellings may strongly influence whether planned harvests are carried out (and thus whether planned silviculture is carried out), or conversely whether the roundwood market will undergo an overabundance of product, it seems very important that sanitation fellings be monitored and reported annually.

6.4.7. Conclusions

All of the above indicators can be considered as meaningful symptoms of forest decline. None of these indicators can be used alone or together to identify unambiguously what is causing a particular decline. The main problem is that there are many factors which can singly or in concert, simultaneously or sequentially, influence the performance of the indicators. Thus, while the indicators may give clues as to the extent and severity of forest decline, and thus can be used to suggest where, when, and approximately what types of action might be taken to mitigate the decline, they do not lend themselves directly to clear assignment of cause. This limitation is recognized (e.g., Programme Coordinating Centres, 1986; Wright and de Meyer, 1986), and has already led to many suggestions (e.g., Programme Coordinating Centres, 1986) for establishing networks of intensively investigated permanent plots in which a wide variety of measurements on site factors and vegetation characteristics are taken. The main purpose of course is to help elucidate more convincingly what could be the causes of specific instances of stand and forest declines.

6.5. Patterns of Forest Decline in Europe

Despite the existence of the UN-ECE international cooperative forest-decline monitoring protocol (Programme Coordinating Centres, 1986) for several years, there is still no consistent data set across all countries of Europe showing the extent and severity of forest decline. On the other hand, some countries have had forest-decline monitoring programs underway annually for a longer period (e.g., the FRG and Poland since 1983; Austria, Luxembourg, the Netherlands, Sweden, Switzerland, and the UK since 1984). The most complete analysis of the patterns of forest decline across Europe have been undertaken by Nilsson

(1986, 1987, and 1988) on behalf of the ECE Timber Committee, using data collected mainly under the ECE monitoring protocol. Nilsson and Duinker (1987) recently summarized these data for a broad audience. The data reported below have all been taken from or derived from Nilsson's latest (1988) report. Nilsson's source data are more detailed than those he presented, and they are the best available for European countries at the present time.

6.5.1. Decline in terms of number of trees

Nilsson's (1988) information to examine each country's data in a common structure was retabulated. The tables (not shown) illustrated the consistency of the data from country to country with respect to species, age classes, periods covered, and classes of decline reported. *Table 6.1* defines the classes of decline in the summarized data from each country which follows:

Austria – high percentages (26% to 49%) of trees display slight decline; only silver fir and oak display high percentages of moderate decline (about 15% each); low percentages of severe decline are reported.

Belgium – high percentages (more than 25%) of trees display slight decline for all species; high percentages of beech and oak (38% and 19% respectively) display moderate decline; beech displays significant severe decline in 8% of trees sampled.

Bulgaria – high percentages of pine and oak trees display light decline (oak under 60 years of age at 44% of sampled trees); only young pines display relatively high proportions of trees in moderate decline (almost 20%).

Czechoslovakia – both species reported (pine and spruce) display relatively high proportions of trees in all three decline classes.

Denmark – coniferous trees display significant proportions in all decline classes; non-coniferous trees display very high incidence of slight decline (more than 60%) and significant incidence of moderate decline (19%).

Finland – relatively high proportions of older spruce and pine trees display slight and moderate decline.

France – significant proportions of trees of all species show slight and moderate decline; severe decline notable in suppressed trees of oak, spruce, and pine.

Germany, F.R. – significant proportions of trees of all species surveyed show slight and moderate decline; only silver fir has a relatively high proportion (8% of trees sampled) of trees in severe decline.

Table 6.1. Decline classification scheme within the international protocol adopted under the UN-ECE International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests.

	Levels of discoloration		
Levels of defoliation	<25%	26–60%	>60%
0 to 10%	0	I	II
10 to 20–25%	I	II	II
20–25 to 60%	II	II	III
>60%	III	III	III
Dead	IV	IV	IV

Decline class 0 indicates healthy trees.
Decline class I indicates slight damage.
Decline class II indicates moderate damage.
Decline class III indicates severe damage.
Decline class IV indicates dead trees.
(Source: Programme Coordinating Centres, 1986.)

GDR – significant total declines appear in all species sampled, especially conifers (data by area of forest, not number of trees).

Hungary – relatively high proportions of oak and coniferous trees display light decline; significant proportions of oak, beech, soft non-coniferous (e.g., poplar), and conifers display moderate decline; relatively significant proportions of oak and soft non-coniferous trees are in severe decline.

Italy – notably high proportions of oaks and most pines show light and moderate decline in the Sardegna region; in the Bosen region, silver fir stands out with nearly 16% of trees in moderate decline.

Liechtenstein – decline of all classes is relatively high in pine; high levels of slight decline occur in all species.

Luxembourg – relatively high proportions of slight and moderate decline occur in all non-conifers; especially high levels of slight decline exist in older conifers.

Netherlands – there are double-digit percentages for slight and moderate decline in all species, up to 47% of oaks in slight decline, and 40% of Douglas fir in moderate decline; significant severe decline occurs in some pines, fir, spruce, beech, and oak.

Norway – relatively high slight and moderate decline in pine of all ages and in older spruce is occurring.

Poland – significant proportions of all conifer species show decline in a class of moderate and severe combined.

Sweden – there is a relatively high level of moderate decline in pine (i.e., 11% of trees).

Switzerland – consistently high proportions of trees of all species sampled show slight decline; proportions of moderately declining trees of spruce, pine, fir, larch, beech, and oak range from 11% to 17%; severe decline is relatively high in pine.

United Kingdom – very high proportions of slight and moderate decline are reported for all species (24% to 41%, and 28% to 63%, respectively).

Lithuania – significant slight decline (more than 40% of trees) is reported for all species sampled; there is significant moderate decline (more than 10%) for pine and older spruce.

Yugoslavia – combining all decline classes, there are relatively high levels for all species sampled (from 25% for beech to 59% for silver fir).

Clearly, all reporting countries in Europe are experiencing significant forest decline. For some countries, the problem is more serious for certain species groups (e.g., conifers in the GDR and Poland) age classes (e.g., older trees in Finland), and decline classes (light decline in Austria and Liechtenstein, moderate decline in UK). For other countries, there seems to be consistently serious decline (at the level of nationally aggregated data) across most species and decline classes (e.g., Czechoslovakia, France, the FRG, the Netherlands, and the UK).

After analyzing forest decline by species across Europe, the result was not particularly revealing as far as strong spatial patterns are concerned. There are many factors that tend to hide clear spatial patterns, even if they do exist:

- Some countries have not reported the full extent of their declines.
- Some countries do not have significant amounts of some species.
- The countries reporting vary widely in size.
- Most countries are too large and geographically diverse to allow causal patterns to be inferred (e.g., one cannot distinguish the Ruhr or Saar valleys, or the Black Forest of the FRG).
- Decline data are reported at the genus level rather than at the species level.
- Management regimes for each species across the continent are variable, as are the qualities of sites on which they grow, and thus the susceptibility of any one species to natural and anthropogenic decline factors will vary greatly across space.

Unfortunately, while the data displayed in this fashion may appear interesting, they do not seem to lend themselves to rigorous spatial analysis.

Table 6.2. Extent of moderate and severe decline in coniferous forests in selected European countries in 1987. Volumes are reported in millions of cubic meters.

Country	Volume in declining stands	Decline/ growing stock %	Decline/ fellings
Austria	23.6	3.5	1.9
Belgium	3.0	7.5	1.7
Bulgaria	3.8	3.8	2.6
Czechoslovakia	107.0	15.6	6.5
Denmark	6.2	21.4	4.8
France	72.6	12.0	3.9
Germany, F.R.	118.3	11.1	4.7
Hungary	2.1	7.2	4.2
Italy	31.5	15.7	16.6
Luxembourg	0.1	0.8	0.7
Netherlands	2.9	13.8	3.8
Norway	81.7	10.9	5.1
Spain	30.0	10.7	3.3
Sweden	206.9	11.0	4.1
Switzerland	29.4	14.0	8.7
United Kingdom	25.5	23.0	7.1
Yugoslavia	54.5	17.5	9.4

6.5.2. Decline in terms of relations with growing stock and fellings

The decline data was aggregated into coniferous and non-coniferous classes and the aggregated data was related to rough estimates of the growing stocks and fellings in each country in these two forest types (*Tables 6.2* and *6.3*). The reader must interpret these relations very cautiously. There are numerous sources of potential error in collecting and synthesizing these data (see Nilsson and Duinker, 1987 for a discussion). They represent only the relative order of magnitude of forest decline in various European countries. For example, the ratio of volumes in stands showing moderate and severe decline, to annual fellings of that class of stands, indicates the relative risk of planned fellings being disrupted by the need to undertake sanitation fellings should the declining stands get worse. Obviously, a country for which this ratio is near 5 or 10 should be much more anxious about possible future wood-supply disruptions than a country where the ratio is near unity. However, the difference between unity and e.g., two may not be measurable on the ground.

If we examine the performance of countries with respect to moderate and severe decline combined for coniferous species, the ratio of volumes in declining stands to growing stocks exceeds the average (for all countries represented) in Czechoslovakia, Denmark, France, Italy, the Netherlands, Poland, Switzerland, the UK, and Yugoslavia. The average for all countries represented is exceeded in the ratio of volumes in declining stands to annual fellings in Czechoslovakia, Denmark, France, FRG, Italy, Norway, Poland, Switzerland, the UK, and Yugoslavia.

Table 6.3. Extent of slight, moderate, and severe decline in non-coniferous forests in various European countries. Volumes are reported in millions of cubic meters.

Country	Volumes in declining stands 1983	1984	1985	1986	1987	Non-coniferous growing stock	Non-coniferous fellings	Decline/ g. stock %	Decline/ fellings
Austria			48.0	52.0	65.8	124.0	2.7	53.1	24.4
Belgium			0.5		15.3	33.0	1.0	46.4	15.3
Bulgaria				23.6	36.3	197.0	4.6	18.4	8.0
Czechoslovakia				9.1		237.0	5.0	3.8	1.8
Denmark					16.2	18.0	0.8	90.0	20.2
France			137.0	183.3	202.2	945.0	22.6	21.4	8.9
Germany, FR	65.5	136.7	147.9	174.3	189.5	435.0	11.9	43.6	15.9
Hungary			22.1	51.6	35.7	224.0	7.0	15.9	5.1
Italy			5.3	7.8	87.9	356.0	6.1	24.7	14.4
Luxembourg		2.4	2.6	3.3	4.7	10.8	0.2	43.5	22.0
Netherlands		1.6	2.3	3.8	5.4	8.0	0.4	67.5	12.9
Poland	25.1		17.3			265.0	4.9	6.5	3.5
Spain				7.3	72.7	173.0	4.2	42.0	17.5
Switzerland		25.4	29.5	45.9	58.1	102.0	1.4	57.0	40.9
United Kingdom			14.7	13.6	50.6	92.0	1.0	55.0	51.9
Yugoslavia					205.2	824.0	14.2	24.9	14.5
Total	90.6	166.1	427.2	576.4	1045.6	4043.8	87.9	26.5	12.2

All classes of decline combined for non-coniferous species are greater than average in terms of the ratio of volumes in declining stands to growing stocks in Austria, Belgium, Denmark, the FRG, Luxembourg, the Netherlands, Spain, Switzerland, and the UK. For the ratio of volumes in declining stands to annual fellings, Austria, Belgium, Denmark, the FRG, Italy, Luxembourg, the Netherlands, Spain, Switzerland, the UK, and Yugoslavia are above average. Interestingly, Denmark, Switzerland, and the UK are above average in all four categories discussed above. The FRG, Italy, the Netherlands, and Yugoslavia are above average in three of the four categories. Thus, forest decline in Europe seems most serious, in terms of these "importance" indicators, in the central countries.

6.5.3. Conclusions

Despite the numerous possibilities for serious errors in the data presented above, and the known inconsistencies among them, it seems clear that forest decline is, at one level or another, for one species or another, a fairly widespread and serious problem across Europe. Spatial variation is great; some countries obviously have more to worry about than others. Much improvement remains to be made in terms of expanding the range of species and decline classes reported, and the consistency of collection and reporting of all forest-decline data.

6.6. Causes of Forest Decline

There are immense difficulties and complications in identifying which factors (both anthropogenic and natural) are contributing to which symptoms of decline, in which particular manner, in a specific stand (Woodman and Cowling, 1987). Several authors have recently reviewed the major hypotheses advanced by researchers to account for the new forest decline (e.g., Schütt and Cowling, 1985; Krause *et al.*, 1986; Last, 1987; Prinz, 1987). From these reviews and other sources, the following list of factors has been summarized:

- *Increases in Air Pollution* – among the many substances of anthropogenic origin emitted into the atmosphere (or created there as products of reactions involving emitted substances) that are implicated in forest decline are: (*a*) sulphur, through both direct (i.e., gaseous fumigation into leaf stomates, e.g., see Mäkelä, 1987) and indirect (i.e., as a solute in acid rain, e.g., see Morrison, 1984; Hakkarinen and Allan, 1986) pathways; (*b*) nitrogen, both as nitrate and as ammonium (e.g., see Nihlgard, 1985); (*c*) ozone (e.g., see Ashmore *et al.*, 1985; Krause *et al.*, 1986; Prinz, 1987); (*d*) heavy metals (e.g., see McLaughlin, 1985; Klein, 1986); (*e*) organic photooxidation products (e.g., see Grossmann, 1987); and (*f*) various dusts (e.g., see Greysta, 1988).

- *Climatic Change* – the main climatic factors may be changing frequency of episodes of frost and drought, but some theories also implicate long-term climatic change (e.g., see Auclair, 1987).
- *Increasing Nutrient Deficiencies* – these may be related to imbalances created by high atmospheric inputs of nitrogen (e.g., see Nihlgard, 1985), or they may be longer-term site deficiencies of such elements as Magnesium (Mg), Calcium (Ca), and Zinc (Zn) (e.g., see Zöttl and Hüttl, 1986).
- *Increasing Attacks by Pests and Diseases* – insect pests and fungal diseases have been and are responsible for much forest decline throughout the world, and are usually associated with the major contemporary forest declines mainly as factors that infect already weakened trees (Lachance, 1986).
- *Inadequate Silvicultural Practices* – these include mainly rotation regimes (controlling stand age), thinning regimes (controlling stand density), and choice of species for regeneration; in general, old dense plantations of conifers on sites where non-conifers would normally dominate are most prone to decline (e.g., see Krause *et al.*, 1986; Kuusela, 1987).

Among these causes of forest decline in Europe, the most important are probably air pollution and silvicultural practices, which are detailed below.

6.6.1. Air pollution

Most investigators reporting on forest decline suggest that in one way or another, air pollutants play the most significant role in contemporary forest declines occurring in Europe and North America. What makes generalization dangerous is that, in the particular decline conditions of any one forest stand, a variety of air pollutants may actually be contributing to the decline, and a variety of the other causal factors listed above may also be contributing. Therefore, each case of stand decline needs to be examined carefully in terms of the possible contribution of each causal factor, with consideration for stand history and other site factors such as exposure, elevation, and the soil-moisture regime. Some decline cases can be attributed fairly confidently to an overwhelming influence of one or another factor (e.g., stand age and density in some spruce plantations in the FRG, or sulphur dioxide in the industrial centers of southern Poland). But in many cases, it is impossible to attribute cause readily and simply, because great uncertainty prevails about, for example, the pollution history of the site.

Significant reviews of air pollution as a causal agent in forest decline have been undertaken already (e.g., McLaughlin, 1985; Kozlowski and Constantinidou, 1986a and 1986b). Below the potential roles of the major pollutants implicated in forest decline are summarized.

Table 6.4. National emissions of sulfur dioxide and nitrogen oxides in Europe (in 1,000 metric tons per year).

	Sulfur dioxide		Nitrogen oxides	
	1980	1984/5	1980	1984/5
Austria	354	181	216	216
Belgium	799	467	442	385
Bulgaria	1034	1140[a]	–	150
Czechoslovakia	3100	3150	1204	1127
Denmark	438	326	251	238
Finland	584	370	280	250[a]
France	3558	1845	1867	1693
GDR	4000	4000[a]	–	–
Germany, FR	3200	2400	3100	2900
Greece	800	720[a]	127	150[a]
Hungary	1633	1420	–	270
Iceland	6	6	13	12
Ireland	219	138	67	68
Italy	3800	3150[a]	1480	1460[a]
Liechtenstein	0.4	0.2	0.5	0.4
Luxembourg	23	13	23	22
Netherlands	487	315[a]	535	522
Norway	141	100	–	215
Poland	4100	4300	–	840
Portugal	266	305[a]	166	192[a]
Romania	200	–	–	–
Spain	3250	3250[a]	–	950
Sweden	483	272	328	305
Switzerland	126	95	196	214
Turkey	–	321	–	–
USSR[b]	12800	11100	2790	2930
United Kingdom	4670	3540	1916	1690
Yugoslavia	1175	1800	–	–

[a] 1983 figures.
[b] European part only.
(Source: Dovland, 1987.)

Sulphur

Sulphur dioxide has been emitted in major quantities in Europe during this century. During the period between 1950 and 1970, emissions doubled, but are now beginning to subside, especially in Western Europe (Dovland, 1987; *Table 6.4*). Sulphur dioxide in the atmosphere can affect trees directly (e.g., Mäkelä, 1987), or through its contributions to increased soil acidity (e.g., Kauppi *et al.*, 1986).

It has been possible to estimate quite readily the sulphur emissions of European countries, and an extensive monitoring network for sulphur concentrations and deposition has been in place in Europe for some ten years (Dovland, 1987). In addition, there are several atmospheric-transport modelling efforts underway for sulphur dioxide, and even simulation studies on the Europe-wide ecological effects of acid rain (e.g., Alcamo *et al.*, 1987).

Work at IIASA is currently underway to combine a Europe-wide forest database with a model of sulphur-dioxide transport and deposition, permitting estimates to be made of how much of the forests of Europe, in area and volume terms, are currently subject to critical concentrations/depositions of sulphur dioxide. Also using the RAINS modelling framework at IIASA (Alcamo *et al.*, 1987), it is possible to show the degree to which soils throughout Europe are at risk of acidification due to current sulphur-dioxide deposition. Preliminary trials of this nature will be undertaken soon as well.

Nitrogen

The major pathway by which emissions of nitrogenous substances (mainly nitrates and ammonium substances) put forest trees at risk is considered to be through nutrient imbalance, wherein there is so much nitrogen in the forest ecosystem that some mineral nutrients, and perhaps even water, may become severely limiting (Nihlgard, 1985). In addition, nitrates also contribute to acidification of precipitation, and thus like sulphur can put forests at risk in this manner.

Emissions of nitrogen oxides have increased considerably over recent decades, even more rapidly than emissions of sulphur compounds (Dovland, 1987). However, at present, nitrogen-oxide emissions appear roughly stable (Dovland, 1987). Sources of ammonium compounds in the atmosphere include mainly the manufacture of commercial fertilizers, and application of commercial and natural fertilizers to agricultural fields (Nihlgard, 1985).

Some suggest that increased nitrogen emissions are beneficial to forests in which nitrogen is the major limiting nutrient (e.g., especially the Nordic countries). This is probably not the case where nitrogen is not growth-limiting, and where nitrogen emissions are highest. Thus, nitrogen emissions in much of Europe probably contribute in some measure to forest decline. To examine the extent to which this might be possible, one could use the RAINS model at IIASA (Alcamo *et al.*, 1987) to indicate spatial patterns of deposition of nitrogenous compounds from the atmosphere, and to estimate the forest areas and volumes thus placed at risk. Preliminary trials of this nature are in progress at the time of writing.

Ozone

Ozone in the troposphere is mainly a product of photooxidation reactions which are enhanced by nitrogen oxides, or NOX (Crutzen and Graedel, 1986). Across much of Europe, ozone occurs frequently at phytotoxic concentrations (McLaughlin, 1985) and in concentrations exceeding ambient air-quality standards (Dovland, 1987). Ozone concentrations have increased over the past several decades in specific European localities (Ashmore *et al.*, 1985). In addition, ozone *episodes* (defined by Dovland (1987) as a day with ozone concentrations above 120 $\mu g/m^3$ measured simultaneously at several stations, or above 200

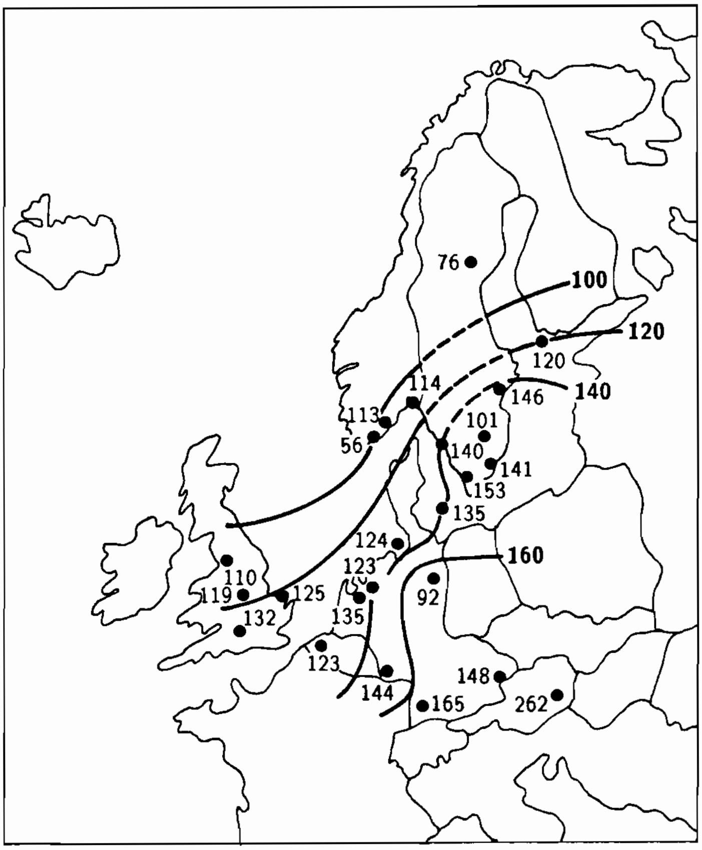

Figure 6.2. Concentrations of ozone in Europe from April to September 1985 (in micrograms per cubic meter). (Source: Dovland, 1987.)

$\mu g/m^3$ at one station) are frequent in Europe, with frequencies being highly variable from year to year depending on meteorological conditions (Dovland, 1987).

McLaughlin (1985) suggested that ozone occurs regionally in Europe at high enough concentrations to be in the range of phytotoxicity. Last (1987) reported that some areas of Europe experience potentially phytotoxic concentrations of ozone more than 40 days per year. Although some suspect ozone to be a major contributing factor in forest decline (e.g., Krause *et al.*, 1986; Prinz, 1987), others feel that not enough is known about the role of ozone in forest decline to permit more than mere speculation (e.g., Ashmore *et al.*, 1985), and some feel that the hypothesis is not supportable (e.g., Tomlinson, 1986).

Unfortunately, coordinated data on ozone concentrations in Europe are still not available (Dovland, 1987). Measurements from 1985 (Grennfeldt *et al.*, 1987, cited in Dovland, 1987; see also *Figure 6.2*) support McLaughlin's (1985) contention above. Based on the literature, and discussions with many forest-decline researchers (e.g., see Kairiukstis *et al.*, 1987), I feel that ozone is a very likely culprit in many forest declines throughout Europe.

6.6.2. Silvicultural Practices

Very little has been written about the role of silviculture as a contributing factor in the current declining state of European forests. The following description reviews recent trends in management regimes, focusing especially on species-site matches, rotations, and stand density to determine whether these silvicultural factors may be contributing to forest decline in the region. In interpreting this analysis, we must recognize the great variety of forest types in Europe, and consequently the great variation in silvicultural regimes under which they are managed. Kuusela (1988) provided most of the information for this discussion.

Management regimes and silvicultural treatments acting as potential decline factors can be divided into the following groups:

- Selection of genotypes and tree-species composition.
- Methods of stand establishment.
- Thinning regimes.
- Selection of rotation periods.
- Management of even-aged and uneven-aged stands.

Genotype qualities define the tree species, their geographical provenances and genetic qualities created by breeding hybrids. According to general experience, the stability of stands and forests is greatest if stands are composed of tree species adapted to local environmental factors. A mixed stand of many species corresponding to the local environment is more stable than a one-species stand. However, to fulfill the functions assigned to the forest, stand types are often required which are not the most stable ones. The aim to produce the greatest amount of high-quality timber for forest industries and other users by profitable management has led to stand types which deviate significantly from stands of greatest stability. Reasonable risk has to be taken, however, while keeping in mind the risk and the measures required to reduce it if needed.

The central European coniferous forests are the best example of artificial but economically valuable stands in growing conditions where broadleaved trees are climax species. They fulfill the timber function well, but with considerable risk of instability. On the other hand, mixed broadleaved stands and coppice forests in large areas are obviously more stable but of much less timber value. Broadleaved mixed stands serve well as recreational and scenery forest. Heavy coniferous timber stands may best serve as protection from avalanches in the mountains.

The glacial-interglacial climate oscillations reduced the number of tree species, especially conifers, in Europe compared to North America and Asia. Therefore, tree species from other continents were thought to grow as well as or better than the few tree species indigenous to Europe today. Sitka spruce and lodgepole pine, and to a minor extent Douglas fir, have been widely planted in Europe and grow better than the native conifers in continental Europe, as does lodgepole pine in Scandinavia. Their tolerance to windthrows, insects, and fungus diseases cannot be determined yet. Southern provenances of spruce and pine are less tolerant to decline factors than the local provenances in northern Europe.

Eucalyptus, poplars, and their hybrids, and *Robinia pseudoacacia* are new tree species in European plantation forests. Because of their short rotation, their possible sensitivity to decline factors is different from the long-rotation species. Growing them is nearer to agriculture than to traditional forestry and their tolerance to environmental hazards can be monitored better than the tolerance of the long-rotation trees.

On the basis of Europe's planted areas and age class-structure, one may conclude that planting is the major method of establishing new stands. Some silvicultural systems are based on natural seeding, but the need for fast establishment, control of tree species composition, and decreasing logging costs more often justifies planting. However, if the genotype of planted seedlings fits to the site, the tolerance of the planted stand to decline factors does not differ significantly from the stand established by natural seeding.

Prescribed thinning regimes are aimed at harvesting the trees that would otherwise die in self-thinning, to control tree-species composition, and to keep up the crown size and growth of the final crop trees. Rising labor costs, shortage of skilled labor capable of forest work, and small demand and low price for small-sized wood have decreased the profitability of thinnings and postponed them in all industrialized countries. Consequently, stand densities have increased over the prescribed growing densities. Over-density decreases average crown size and also the vitality of the dominant and co-dominant trees and their tolerance to decline factors.

Prescribed rotations for the same tree species on similar site qualities differ greatly from one country to another. Rotations for spruce vary from 50 to 120 years, for oaks from 90 to 300 years. Prescribed rotations are shorter and followed better in those countries where the investments to build up forest resources continue, than in those countries with long-established forest resources. In the latter there are strong tendencies to increase continuously the rotation length. It is often said that protective, social, and cultural functions require longer rotations. The decreased need for wood production in affluent societies which can supply their needs by imports, and the inefficiency of forestry organizations to fulfill the timber functions, may be the real causes of lengthened rotations. Whatever the reasons, stand ages in large areas are so great that the stands are reaching or have already reached senescence. If stands collapse in over-maturity, they will lose all their functional values.

In considering the stability of current forests, the great variation in the length of the senescence age of different tree species on different site qualities has been overlooked. Little notice has been given to the fact that never before in Europe have there been such heavily stocked and such old stands of planted trees of various species than at present. Even-aged stands produce more wood with better profitability than uneven-aged ones, but the latter are appropriate especially in scenery and recreational forests. On the other hand, an even-aged stand with an even crown storey is considered to be more tolerant to air pollutants than an uneven-aged stand with an uneven crown storey, mainly because an even-aged stand catches less emission downfall than an uneven-aged one.

6.7. Potential Futures for Causes and Indicators

Changes in air pollution and silvicultural practices over the next few decades will affect the future behaviors of the forest-decline indicators. Below, a few fairly plausible future paths of development are presented.

6.7.1. Causes – Air pollution

Sulphur Compounds

The main source of sulphur emissions in Europe is energy production (Alcamo *et al.*, 1987). There has already been concerted action at the political and applied levels to reduce these emissions (Sand, 1987). Alcamo *et al.* (1987) presented four scenarios for sulphur deposition across Europe in the year 2000, based on a combination of energy-use and sulphur-emission-control scenarios. An example of one of their scenarios is presented in ***Figure 6.3.*** If European countries are successful in implementing a broad program of control of sulphur emissions, the prospects are good for significantly reducing the land areas receiving high sulphur deposition.

Nitrogen Compounds

Alcamo and Bartnicki (1988) reported that automobiles produce about half of the total nitrogen oxides emitted into the European atmosphere, the other half arising from power plants and industrial installations. Ammonia nitrogen comes mainly from livestock wastes, but also from applications of ammonia fertilizers and industrial installations (Nihlgard, 1985). Sand (1987) reported that NOX emission trends for various European countries up to 1995 vary. The range includes increases over 1980 levels of up to 50% and decreases down to 50%. Alcamo and Bartnicki (1988) presented scenarios for future total nitrogen deposition in Europe based on five emission-reduction scenarios, and concluded that while the most extreme emission-reduction plan for NOX would cut NOX emissions and deposition significantly, it would alter the deposition pattern of total nitrogen only very little.

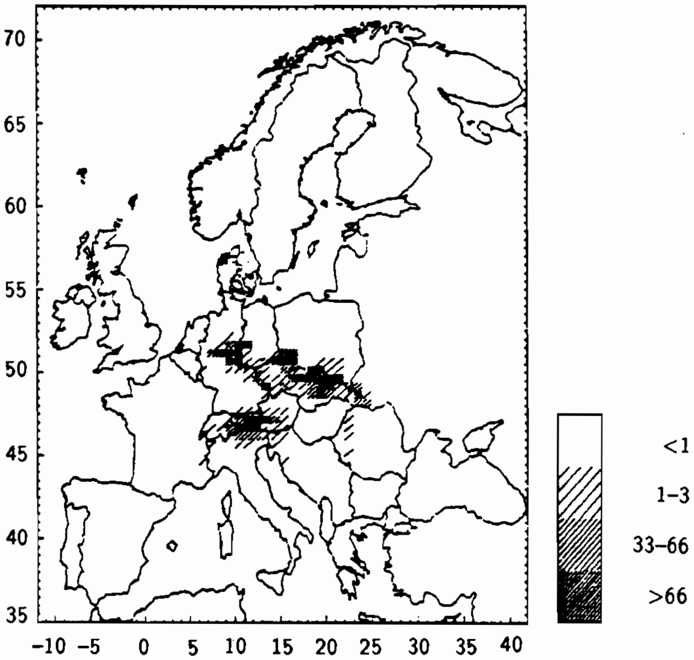

Figure 6.3. Forests under risk of direct impacts of SO_2 for all altitude classes, assuming the 30% reduction scenario (year 2000). Percent of forest area under risk. (Source: Alcamo *et al.*, 1987.)

Ozone

Ozone precursors include mainly NOX and hydrocarbons. Thus, future ozone levels will depend largely on the emissions of these precursors. The above mentioned NOX emission controls will help reduce ozone levels, but preliminary modelling results show that the response is complex, with ozone concentrations increasing in urban and industrial areas and decreasing in downwind rural areas (Dovland, 1987). At the present time, it is not possible to generate defensible quantified scenarios for future ozone concentrations in Europe. Perhaps it can safely be said that for the next few decades, until NOX emissions are actually significantly reduced, the average atmospheric concentrations of ozone, and the incidence of ozone episodes, will not decrease.

6.7.2. Causes – silvicultural practices

Kuusela's (1988) examination of forest management in nine regions of Europe guides this assessment of the future potential of silviculture as a decline agent.

Northern Europe (Finland, Norway, Sweden)

Removals and losses may be about 20% smaller than the increment of the growing stock. Consequently, the prescribed thinning regimes and rotations cannot be followed in all forests. For example, the current thinning areas should be at least doubled to keep up a satisfactory silvicultural condition in the growing stands. Profitability of the first commercial thinning is continuously decreasing. Mature and overmature stands, as well as stand density, will increase. Thus, the sensitivity of the stands to decline factors, and the need for sanitation cuttings, will increase.

The required thinning of juvenile stands cannot all be realized. The share of low-value broadleaved trees will thus increase in coniferous stands. This may increase the biological stability of the stands but it decreases the value of the wood crop per unit area.

Fertilization to ameliorate decline factors will probably increase, but not in commercial forests. Investment in fertilized areas will be rather small compared to the obvious benefits to be gained in increasing wood increment and the tolerance of stands to decline agents. Efforts to improve the stability of future stands by genetic measures may increase, but results will be reached only after several decades because of the slow growth of trees in this region. Genetic improvements of fast-growing growing birch (*Betula pendula*) may be an exception to this rule. The role of exotics is negligible except for lodgepole pine in Sweden.

Middle Europe (Denmark, FRG, GDR, Poland, Czechoslovakia)

The increase in logging costs continuously restrict commercial thinnings. Removals and fellings will be much smaller than they should be according to the prescribed thinning regimes and rotations. Consequently, stand densities and ages will increasingly make stands less stable. Therefore, the tree-species selection policy applied so far may change to a certain extent. We may see fewer conifers planted because mixed forests are supposed to be more tolerant to decline factors, and more valuable for scenic and recreation purposes. Rapid changes in overall species composition would require significant additional silvicultural costs. On the other hand, coniferous wood will be the major raw material of forest industries. In afforestations of agricultural land, conifers, supplemented with poplars, will play a major role. The proportion of coppice stands will decrease, although many of them may be kept for environmental purposes.

Experiments with exotic species and genetic structures will increase in the search for genotypes more resistant to decline factors. Except for liming, fertilization will retain a minor role in silviculture.

Atlantic Europe (Ireland, UK)

Great afforestation investments will continue to dominate the treatment of forests. To reach the expected return on investments, the prescribed thinning regimes and rotations will be followed. On the other hand, there may be factors like insufficient domestic industrial-wood demand or increasing logging costs which may restrict thinnings. The density of many stands is already greater than prescribed by management tables. Afforestation will likely continue with Sitka spruce and lodgepole pine as the major species. On soils covered by peat, ploughing and fertilizing will continue as site preparation for planting.

Sub-Atlantic Europe (Belgium, France, Luxembourg, Netherlands)

In the spruce and fir forests of eastern France, managed in the middle-Europe tradition, new industrial facilities may activate timber production. In other parts of France, attempts at wood production for industrial purposes will be frustrated by the wide array of species (especially broadleaved), the variable stand structures, and the small size of forest properties owned by private concerns. There are good chances that prescribed management regimes will be followed in new plantations. In the Benelux countries, there are efforts to increase stand stability using genetic improvements and suitable exotic species.

Alpine Europe (Austria, Switzerland)

In Austria, where forestry and industries concerned with forest-products are of major economic importance, there are better chances that prescribed management regimes will be followed than in Switzerland. In mountainous coniferous forests throughout the region, where high stand densities and ages are obvious serious decline factors, no significant management changes are expected.

Pannonian-Pontic Europe (Hungary, Romania)

Current management regimes are likely to continue in Hungary. The greatest decline risk probably comes from the species grown in production plantations. In the mountainous coniferous forests of this region, no changes from the traditional middle-European management regimes are foreseen.

Mediterranean (Albania, Bulgaria, Cyprus, Greece, Italy, Portugal,
Spain, Turkey, Yugoslavia)

No changes in current management regimes in either fast-growing plantations or in original high forests are expected.

6.7.3. Forest Indicators

To date, there are few published scenarios on the future possible outcomes of forest decline across Europe. I have found qualitative scenarios (e.g., ECE/FAO, 1986), and quantitative scenarios for countries or parts of countries (e.g., Anonymous, 1988), or even for regions of Europe such as Western Europe (e.g., Dykstra and Kallio, 1986), but I know of only one published and one unpublished set of scenarios for the future consequences of forest decline for all of Europe. Some of these scenarios are presented below.

Qualitative Scenarios – European Timber Trends

The Fourth European Timber-Trends Study (ECE/FAO, 1986) included a qualitative analysis of the potential consequences of continued pollution-induced forest decline on several forest variables. Three scenario variants were presented, differing mainly in the relationships between increment and fellings. The common basis for the three variants is that:

- Loads of relevant pollutants continue for a time to increase.
- Forest response is at first independent, or even enhanced, but later, increment is decreased.
- Sanitation fellings occur whenever stands are classed as dying or dead, with the cumulative area of sanitation fellings growing steadily.
- Planned fellings are reduced.
- Decisions are made to reduce pollutant emissions, but there are lag effects in the implementation of measures and in forest response.
- During the lag period, decline responses of the forests continue.

Variant 1 is illustrated in *Figure 6.4*. Increment and fellings are in balance before decline is evident, but the great need for sanitation fellings eventually forces total harvest to increase. In addition to a declining increment, growing stock then decreases. Eventually, no new forest areas are classified as dying or dead, so sanitation fellings cease. Increment is low because of low growing stock, so fellings are kept even lower to permit growing stock to recuperate during a forest-reconstruction period.

In **Variant 2** (not shown), increment and fellings are also equivalent to start with, but total fellings are maintained despite the same levels of new decline. This means that growing stock is reduced somewhat less than in variant 1, and increment is also not as low. The problem with this variant is that planned harvests are severely reduced for some time, leading to over-maturity of unharvested stands and disruption of recommended silvicultural programs.

In **Variant 3** (not shown), increment exceeds fellings at first, and total fellings takes a path initially as in variant 1. However, the increased fellings do not reduce growing stock initially, but rather halt its increase. Later, growing stock is brought in line with its size prior to the decline phenomenon.

It is stressed in ECE/FAO (1986) that these variant scenarios are by no means the only possible ones, but are simply examples of the kinds of interactions that could take place.

Europe-Wide Scenarios – Forest Study of the Biosphere Project

One of the main objectives of the Forest Study in IIASA's project on Biosphere Dynamics is to generate scenarios of the potential future courses of forest decline

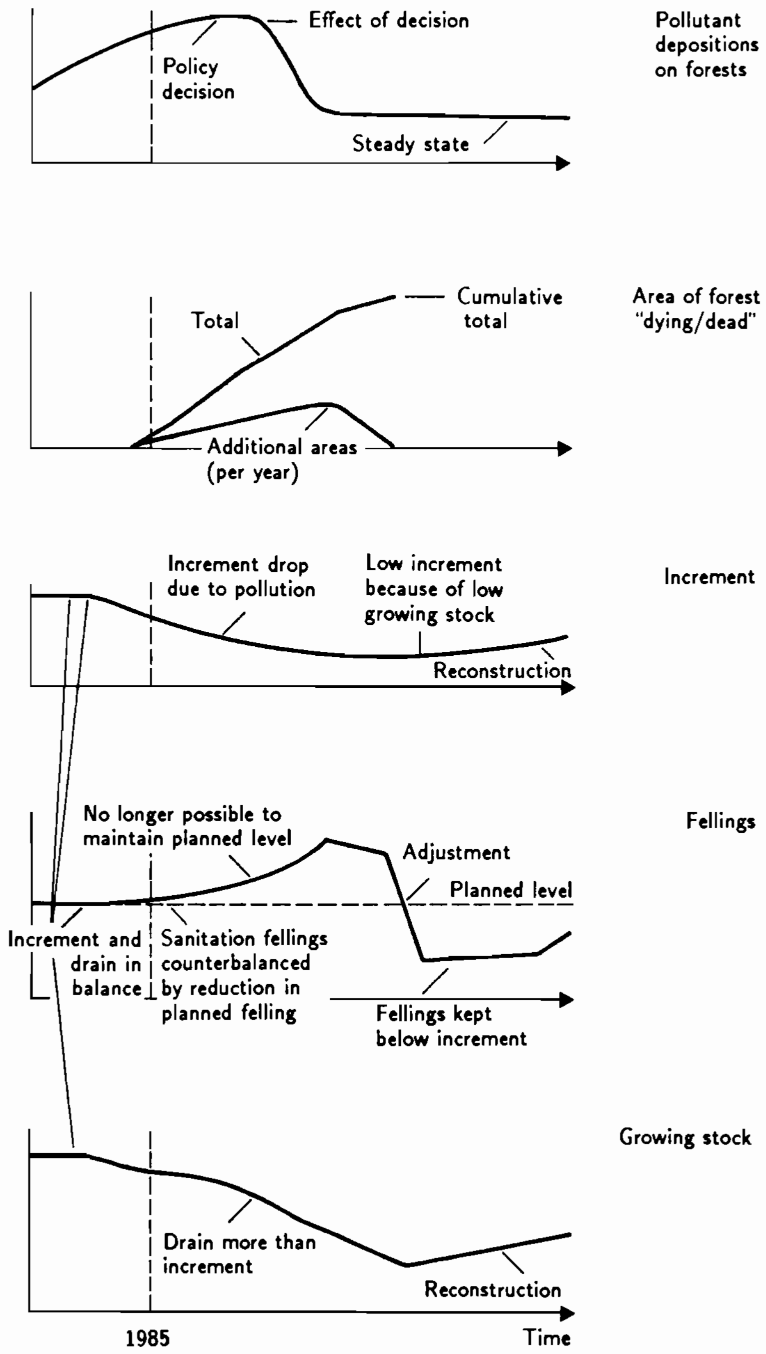

Figure 6.4. Effects of forest decline in Europe, **Variant 1.** (Source: ECE/FAO, 1986.)

in Europe and its environmental and socio-economic consequences (Duinker *et al.*, 1987). The scenarios are used in "policy exercises" in which policy people respond to the projections with policies that attempt to improve the potential course of events.

In one such policy exercise, we used our experience and general knowledge about the forest-decline situation across the continent to develop a set of factors representing the potential increase in total fellings and the potential decrease in increment in ten-year intervals up to 2020 for the ECE country groupings (*Table 6.5*). We suggested no significant differences between responses of coniferous and non-coniferous species, but significant differences among regions. The regions EEC (9), Central Europe, and Eastern Europe (see *Table 6.5*) are projected to experience continually increasing total fellings and increment losses through 2020, with Eastern Europe suffering the most. On the other hand, decline would have the least effect in Nordic and Southern Europe, stabilizing from 2010 on. These scenario trends mimic the first parts of variant 1 in ECE/FAO (1986), suggesting that the rising part of the fellings curve (*Figure 6.4*) continues to at least 2020.

Europe-Wide Scenarios – Wood-Supply Futures for Trade Analyses

On behalf of the Forest Study of the Biosphere Project, Kornai (1988) performed an analysis of the potential trade and industrial-investment patterns following from alternative forest-decline scenarios. In using a modified version of the IIASA Global Trade Model for Forest Products (GTM), it was necessary to construct wood-supply series based on assumptions about future decline. Three forest-decline scenarios were constructed, along with a "base" scenario. The base scenario was developed by using the GTM to calculate "normal" market-driven removals. The first forest-decline scenario (FDS1) assumes that due to forest decline, sanitation fellings must increase, and there is no possibility to reduce planned harvests so as to maintain a total harvest level as in the base scenario. This occurs only from 1990 to 2010. In the second forest-decline scenario (FDS2), the increased sanitation harvests of FDS1 are incorporated, but additionally there is an annual 1% decrease in harvest level because of lower increment due to decline. Finally, in the last forest-decline scenario (FDS3), preliminary results of the timber assessment of the Forest Study were adjusted to match the framework of the GTM.

Kornai's (1988) harvest-level assumptions for the GTM analysis may appear to be rather drastic. Perhaps most disturbing is the base scenario which represents market-driven fellings – what is not known is the degree of sustainability of the higher harvest levels at the end of the scenario period. However, despite the wide fluctuations in harvest levels over a 40 year period shown in the Kornai (1988) scenarios, they are, to our knowledge, the only published, quantified forest-decline scenarios covering all of Europe, and thus could serve as a fruitful basis for discussion.

Table 6.5. Projected percentage increases in fellings and decreases in increment due to forest decline attributed to air pollutants. The figures are to be applied to scenarios that have not taken decline into account.

	1990		2000		2010		2020	
Country group Forest types	Increase fellings	Decrease increment	Increase fellings	Decrease increment	Increase fellings	Decrease increment	Increase fellings	Decrease increment
Nordic								
Coniferous			5	2	10	5	10	5
Non-Conif.			10	5	10	5	10	5
EEC (9)								
Coniferous	10	7	20	12	25	15	30	20
Non-Conif.	10	7	20	12	25	15	30	20
Central								
Coniferous	10	7	20	12	25	15	30	20
Non-Conif.	10	7	20	12	25	15	30	20
Southern								
Coniferous			5		10	5	10	5
Non-Conif.			5		10	5	10	5
Eastern								
Coniferous	20	10	30	15	40	20	50	30
Non-Conif.	20	10	30	15	40	20	50	30

(Source: Forest Study of the Biosphere Project, unpublished data.)

6.8. Possibilities for Adaptation and Mitigation

Forest decline is both a real phenomenon, describable in terms that clearly demonstrate it is greater in extent and more severe in nature than any forest decline in recorded European history, and an ill-perceived issue in which concern is justified but basic information is lacking, misleading, or distorted. With respect to forest decline as a real phenomenon, much can be done to reduce the stresses to which European forests are exposed, especially stresses from air pollution and inappropriate silvicultural regimes. Much can also be done, with respect to forest decline as a broadly perceived issue, to improve our basic perceptions, even with the woefully inadequate data now in hand.

6.8.1. Reduced air pollution

No matter what perspective one takes, air pollution has been and may continue to be a growing threat to European forests. On the one hand, some pollutant emissions are decreasing at national and multinational scales (e.g., sulphur). On the other, some "pollutants" are said to be beneficial to some forests when depositions are within specific ranges (e.g., nitrogenous compounds). However, trees do not respond to each pollutant separately, but rather must live within whatever pollutant "soup" or mixture prevails in its environment. The chemical atmospheric environment of European forests clearly contains more potentially detrimental substances nowadays than early this century or before (at least sulphur dioxide, nitrogen compounds, various hydrocarbons, heavy metals, hydrogen fluoride, ozone and other oxidants – the list is much longer).

Progress is being made in the European continent to bring major pollutants under control (Sand, 1987). However, atmospheric concentrations and ground deposition of the various substances that are potentially harmful to trees should be reduced to acceptable levels. The forestry community, in concert with other sectors whose basic biophysical support systems are under threat or are actually eroding (e.g., agriculture, water resources, conservation resources, monuments), should continue to work toward reducing emissions of the major pollutants threatening forests (e.g., Duinker, 1987).

6.8.2. Improved silviculture

Mitigation of forest decline through silvicultural measures may be seen in two different categories:

- The practice of normal "good" silviculture so that no stands suffer from competitive stress, age-related senescence, and maladaptation to site conditions.
- The practice of remedial silviculture to rehabilitate stands under the influence of air-pollution stress.

Normal "Good" Silviculture

To restate the obvious: foresters need to (*a*) follow prescribed rotations to avoid growth losses and tree mortality due to senescence, (*b*) follow prescribed combinations of planting densities and thinning regimes to avoid growth losses and tree mortality due to competition, and (*c*) regenerate provenances well-adapted to local site conditions to avoid growth losses and tree mortality due to harsh site conditions. In many cases throughout Europe, foresters are in a position of having to catch up because many of the stands in timber-production forests can be considered as overmature, overdense, and/or ill-suited to site conditions. The most powerful tools to correct these problems are harvesting tools. Such good silviculture is often difficult enough to justify even when markets for the harvested wood assortments do exist; but these days there are serious marketing bottlenecks in Europe for pulpwood (an undercapacity of pulp processing in many countries), sawlogs (low prices for sawn products), and fuelwood (low oil prices). This does not imply, of course, that the European markets for forest products are already saturated from local raw materials; continental Europe (excluding the Nordic countries) remains a huge net importer of most such products. Moreover, many forest managers face the problems of finding affordable skilled labor for their harvesting and regeneration tasks. These obstacles of poor markets and high harvest costs will have to be overcome before the backlog of areas requiring catch-up silviculture, let alone the current normal schedule of silvicultural measures, will ever receive the attention they need.

Remedial Silviculture for Pollution-Damaged Stands

In many areas of Europe, the evidence is either very strong or incontrovertible that stands are declining primarily because of stress from air pollutants. In such cases, foresters need to reconsider their standard silvicultural regimes in favor of new regimes that increase the resistance, or lower the susceptibility, of stands to air pollutants. Depending on the conditions of the individual stand and environment under consideration, changes may be required in, for example: (*a*) species (and provenances) chosen for regeneration (e.g., Colorado spruce has been demonstrated to be more resistant to pollutants in Czechoslovakia than most other conifers; Stoklasa and Duinker, 1988); (*b*) fertilization including the addition of specific cations, such as magnesium (Mg) which may alleviate symptoms of needle yellowing precipitated by air pollutants (e.g., Zöttl and Hüttl, 1986); (*c*) lime application to retard or reverse soil acidification; (*d*) sanitation thinnings to remove sick and dead trees; and (*e*) total reconstruction of species composition and structure of forest stands (e.g., Greysta and Maczynski, 1989).

6.8.3. Changed attitudes

There are often statements in the popular media like "half of Germany's forests are either dead or on the brink of dying". However, throughout most of Europe, the casually observing traveller usually has great difficulty in finding any so-called declining forests! Can we be sure that the forest declines recorded in this decade, especially declining forests remote from strong point sources of air pollution, are both real and unique (as expressed in the German label for the phenomenon, ***neuartiges Waldsterben***)? Numerous writers caution that forests have always displayed, at one time or another, foliage losses and discoloration and growth decrements under natural conditions. Others have even gone to the trouble of finding turn-of-the-century photos of forest landscapes in their countries, showing that the forests then seemed to show as much crown thinning as they do now (e.g., F. Schweingruber, personal communication, July 1988). Do we really then have a set of novel forest declines? What is surely novel is the way in which almost the entire European continent is now monitored systematically for foliage loss and discoloration. Perhaps we did not find so much forest decline previously because we were not looking for it, primarily because we did not have such a widespread perceived threat to forests as air pollution. On the one hand, one could argue that, while we have what seems to be an unusually high incidence of tree-foliage loss across Europe in most major species in this decade, such forest declines have always existed and are quite normal (although perhaps to a somewhat lesser degree). On the other hand, one might suggest that, if indeed we have new forest declines with air pollution as a major contributing factor, perhaps they existed well before the 1980s when systematic monitoring programs were established. I conclude that similar forest declines have probably occurred in the past throughout Europe, but also that there is sufficient evidence from and concurrence among European scientists to show that the current extent and severity of forest decline on this continent are really larger than anything experienced before.

Individual trees can and do decline in overall "healthy" stands, and individual stands can and do decline in overall "healthy" (read sustainable) forests. Therefore, incidences of tree decline, or even stand decline, do not necessarily indicate a general forest-level decline. Whether we interpret the term forest decline loosely (i.e., decline *in* the forest) or narrowly (i.e., decline *of* the forest), we must always be careful to explain exactly what measures, and at what time and space scales, we are using to indicate decline.

Many are quick to blame air pollutants as the primary, if not the only, culprit behind the current forest declines in Europe. Indeed, some even blame them all on *acid rain*. While air pollution is a likely *major* factor in many forest declines throughout Europe, as a general interpretation of the cause(s) for all such decline, it is a deceptive path. Many stress factors can bring on the same symptoms of foliage loss and discoloration in trees, including air pollution, climatic stress, competition and others. For a reasonable assessment of the state of a stand and the causes of any decline, qualified professionals in stand pathology, mensuration and ecology need to study the field conditions and examine the relative roles of all potential decline factors. Such assessments are hardly useful at the level of the individual tree, and are not possible to make at the level of the forest.

6.9. Research Needs

There are a few, very basic questions that should be pursued for a better understanding of the forest-decline issue in Europe.

(1) What are the potential causes of stand-level decline in terms of foliage loss, discoloration, and other symptoms seen widely in Europe's current declines?
(2) What is the true nature, severity, and extent of forest declines across Europe today?
(3) What are the current and especially the potential future environmental, social, and economic consequences of forest decline across Europe?

These research questions each require rather different methodological approaches, as discussed below.

6.9.1. Stand-level causes of forest decline

The causes of decline should be examined at the stand level. Documenting causes of decline is best approached through a combination of simulation modelling and intensive field measurement. Simulation models permit experimentation with cause-effect hypotheses for which direct field experimentation is impossible. Direct experimentation with stands and the causes of decline is impractical because controls and treatments are impossible to construct, and stand response to stressors often requires many years before it can be measured.

Features that should be included in any simulation model for the purpose of elucidating stand response to the main suspected causes of decline are:

- A dynamic representations of ecological processes governing tree establishment, growth, reproduction, and mortality.
- Representation of competition processes.
- Explicit relationships between levels of suspected decline agents and levels of response at the physiological level in trees.

To my knowledge, there are few if any simulation models existing that are ready to be exercised for all stand types throughout Europe, for all site conditions and all major decline agents. The Jabowa-Foret family of forest-succession models (Shugart, 1984) would appear at first glance to be appropriate, but there are several shortcomings with these models in their current form:

- They can currently handle silviculture and climate as decline agents, but not air pollution (although algorithms could be added).
- They were designed for long-term successional analyses, and not specifically rotation-length responses to decline agents.
- They do not have sufficiently detailed tree physiological mechanisms to mimic realistically the various ways in which the decline agents can affect trees (R. Leemans, personal communication, 1988).

I know of other groups in Europe that have built, or are building, tree-level and stand-level simulation models (e.g., Bossel *et al.*, 1987; Hari *et al.*, 1988; teams led by Professor W. Haber at the Technical University of Munich, and by Dr. W.-D. Grossmann at the University of Vienna), but the structures of these models are either not yet fully published, or do not have all the desirable features listed above.

Development is needed of a stand simulator that has a sufficiently broad structure that it can be parameterized for any stand/site combination in Europe, and in which stand performance is responsive to any combination of specific levels of air pollution, climatic regime, and silvicultural regime (and any other decline agents considered worthy of inclusion). A wide range of stand-response indicators should be built into the model, including crown condition, wood increment, reproduction, and mortality. The model would be used to help reject alternative hypotheses about why specific forest stands throughout the European continent are showing decline symptoms. Of course, a rather detailed stand-wise dataset would be needed for each application of the model to a real case of stand decline. Therefore, a major part of this research would be the acquisition of such data, either from field measurement programs already in place (in which case appropriate quality control and complementation of the data might be required), or from field programs specially designed for this study. The study would provide two very valuable sets of results:

(*a*) It could yield the most definitive exploration yet, across all Europe, of the numerous hypotheses advanced to explain current patterns of forest decline.
(*b*) It could provide the stand-wise performance data required by forest simulators used in developing scenarios of possible future forest-decline situations and their many effects (see below).

6.9.2. Improved images of the extent and severity of forest decline

Despite the large potential for error in the data describing forest decline in various countries of Europe, and the risks in transforming the measurements into other, more meaningful data, these are the only data that can be used to obtain a picture of the extent and severity of forest decline across the continent. Therefore, those responsible for monitoring the state of forest resources in each country should at least follow the international cooperative monitoring protocol, and supplement the regularly collected data under the protocol with stand mensurational and ecological data that can be used to make detailed stand-wise analyses of the nature and causes of decline in each sampled plot. Countries should expand the range of species monitored (with data reporting at the species level), as well as the range of decline classes. Indeed, such complete data sets for each stand monitored would become the information needed for analyses using the above-mentioned stand simulator.

Additionally, countries should make their decline data sets available on a more spatially disaggregated basis. National-level reporting, or even state- or county-level reporting for large countries, of decline data does not contain sufficient spatial resolution for analysis of cause and effect. The finer the spatial resolution of the decline data, the less uncertain will be the analyses of the relationships among air-pollutant depositions and forest condition.

6.9.3. Scenarios of possible consequences of future forest decline

The forest declines we perceive in Europe today are generally seen as a phenomenon of this decade, even though the major decline agents (silviculture, air pollution, climatic extremes) have been significant for much longer. However, the important questions from policy and management points of view are rather about the future, e.g., given recent trends and the current situation with respect to forest decline, how might it evolve, and what might be the repercussions of such evolution?

Such future explorations require construction and use of simulation models. In this case, a model framework is needed at the forest level, forest here being defined as desired on the basis of, for example, ecological characteristics, political jurisdiction, or administrative boundaries. The first such study of this kind performed on a Europe-wide scale is now underway in the Biosphere Project at IIASA. Here, the simulation-modelling emphasis is on (*a*) forest-resources responses to continued forest decline, and (*b*) industrial structure and investments and trade patterns in response to changing forest resources due to forest decline. This study could be expanded to include a quantitative simulation of changes in the abilities of forests to provide environmental functions such as control of regional water cycles, erosion, avalanches, and wildlife habitat, as a result of continued forest decline. Furthermore, the stand-performance results from the use of the stand simulation models should be incorporated into the forest-resources simulator (Attebring *et al.*, 1987) to obtain the responses of stands to the several major decline agents. This would result in a model structure in which causes (the decline agents) are linked quantitatively to the basic intermediary component (the forests), which then is linked quantitatively to the several response components (soils, water, industry, trade). Such model structures are already known to be powerful tools for scenario building and policy analysis [e.g., the RAINS model at IIASA (Alcamo *et al.*, 1987 and 1990)]; here, the causes are energy systems that are quantitatively linked through emissions to the intermediary component, i.e., the atmosphere, which through depositions is quantitatively linked to the response components of groundwater, soils, surface waters, and forests.

6.10. Conclusions

(1) Forest decline (and tree and stand decline) can be an entirely natural phenomenon. Trees decline and die in healthy stands, and stands decline in "healthy" forests. Current scientific evidence and consensus suggest that the present set of forest declines in Europe are more extensive and severe than any seen before, and that air pollution is generally a major causal factor.

(2) Continued and expanded forest decline could threaten all the functions that forests fulfill, especially wood supply, environmental protection (including providing wildlife habitat), and recreation.

(3) Forest decline can be expressed quantitatively in terms of several indicators, including foliage loss, foliage discoloration, wood increment and volume, and the extent of sanitation fellings. Several variables should be reported for each case of stand decline. Use of the term *death* and its associated terms should be avoided except in the case of individual trees.

(4) While available data are grossly inadequate, we can see from them that forest declines are occurring throughout Europe, and all major species of trees are afflicted. In some countries, all species are affected to such an extent that natural-resources agencies should begin to explore appropriate mitigative actions.

(5) In addition to air pollution as a major cause of forest decline, inappropriate silvicultural practices have created conditions in many European forests where trees are dying and stands declining due to old age, competition, and maladaptation to site factors.

(6) While emissions of specific air pollutants may be reduced, trees must cope with an atmosphere polluted with a wide range of substances. The array of phytotoxic substances in the atmosphere is unlikely to subside in the near future. Therefore, air pollution will remain as a strongly implicated culprit in future forest declines in Europe. Silvicultural practices in many countries are responsible for many tree deaths and stand declines, as well as making trees more susceptible to other stressors like air pollution. It appears likely that silvicultural practices will continue to be a prominent culprit in forest decline.

(7) Much of the forest decline in Europe today could be eliminated if air pollution were drastically reduced, and the silvicultural condition of stands put in order. We (impact analysts) also need to be careful about how we express our numbers about forest decline, so that the attitudes of the layman toward it might be more fully informed and carefully formulated.

(8) Research is needed to elucidate the causes of stand-wise declines, spatial patterns of the extent and severity of forest decline across Europe, and possible future developments in forest decline and its potential effects.

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Conclusions

The study of specific scientific problems concerning future ecological sustainability in Europe has yielded a set of conclusions regarding the nature and magnitude of each problem, and a clear set of requirements for reducing the uncertainties inherent in each problem. Based on five criteria, we selected from among the plethora of potential issues of concern involving European climate, water, soils, and biota. The first criterion was a transboundary one; the problem must have international causes which cannot be alleviated by individual governments acting independently. The second criterion was that the problems be of widespread geographic distribution. Third, problems must change the way in which ecosystems function, i.e., they must have ecological significance. Fourth, the problems must be of obvious political or social consequence, which would generate pressure upon decision makers to take action. Finally, the problems must have negative connotations, although this is quite likely in any case, based upon the fourth criterion.

These criteria led to the selection of five problems for analysis. The first problem is climatic, that is, the nature of global greenhouse warming in Europe, and particularly, the methods available to predict its patterns in space and time (Jäger), and what those methods tell us about future climate changes in Europe (Pitovranov and Jäger). The second problem involves hydrology; what is the nature of future changes in European water quality, especially high-quality water for municipal purposes which may be drawn from polluted international rivers and lakes (Kauppi)? The third problem also concerns hydrology, focusing on the effects of greenhouse, gas-induced climate changes on the distribution of European water supplies (Brouwer and Falkenmark). The fourth problem is a soils dilemma; how will the magnitude and geography of acidification of European soils change in the future (Kauppi and Posch)? The fifth problem is a biotic issue related to three of the other four; how is the magnitude and geography of European forest decline, which may be affected by changes in temperature, water availability, and soil acidification, likely to change in the future (Duinker)? Finally, we sift through the analyses, finding one region at greatest risk in the future decades in Europe: the plains of Central Europe.

1. Climate: Approaches to Projecting Temperature and Moisture Changes

Jill Jäger's analysis reveals that two basic methods are available to estimate future climate patterns; projecting climate from past climate records (proxy paleoclimate records in tree rings, fossil pollen, and ice cores; instrumental records of past warm and cold periods), and general circulation models of the atmosphere (GCMs) which are designed to mimic the processes which control weather and climate at the global scale. The great advantage of using climate records is that they produce patterns which we are assured the atmosphere can produce, because they have been present before. This also provides an important disadvantage of the techniques; it seems likely that greenhouse gases will generate some climate patterns unlike those known to have occurred in the past, rendering the past an imperfect analog for the future. Proxy paleoclimatic records cover long time periods and include climate changes of great magnitude. However, they are unreliable estimators of temperature and precipitation values, their temporal resolution is too poor to allow defining rates of climate change, and their spatial resolution is irregular or too sparse to allow a description of regional, as opposed to global, patterns. Instrumental records have the advantage of supplying precise values and regionally-distributed records, but the magnitude of temperature shifts in the 100 or so years of globally-available records is minor, compared to that expected from greenhouse gases during the next century.

On the other hand, GCMs can be run in unique climate configurations and can mimic atmospheric behavior under warming of great magnitude. Yet, they possess three general disadvantages which limit their use in climate effects assessments: first, their spatial resolution is too coarse to allow projection of local and regional distributions of temperature and precipitation; second, their treatment of certain processes that control climate is so weak that they cannot correctly describe those aspects of the earth's climate today; and, third, they assume equilibrium climate, rather than the perturbed transitional climates which are expected to dominate the next century, and which are likely to be quite different from equilibrium states.

Jäger's examination of the published climate change projections derived from these methods, provides the following conclusions:

- All methods suggest that European winters will warm to a much greater extent than will summers, and that warming will be greatest in northern Europe, and least in southern Europe.
- The use of past weather records (paleoclimate; instrumental records using warming in the arctic or in Europe) suggests that during summer, northern Europe could become somewhat warmer, central Europe less so, and the western Mediterranean would actually be cooler.
- Winter instrumental weather records (no paleoclimate records are available for winter) suggest that northern Europe would become much warmer (about three times the warming increment of summer), southern Europe,

colder in winter. In addition, winter precipitation would decrease in central Europe, increasing in northern and southern Europe.

- Use of GCM results is more ambiguous than the use of past weather records. The GISS model favored in previous IIASA research suggests summer warming in most places, except in western Europe. It projects much greater warming in winter, particularly in the north, although all of Europe is simulated to have a warmer winter climate. Similar to that in instrumental records, winter precipitation in the GISS GCM increases in the north, less so in the center, and decreases only in southwestern Europe.
- The British Met Office GCM, used by Brouwer and Falkenmark in this volume, produces a similar temperature pattern. However, in contrast to both the GISS model, and the different pattern which emerges from instrumental records, the Met Office GCM indicates that winter precipitation would increase greatly in central areas, less so in northern regions, and would decrease in southern and Mediterranean regions.
- Based on this analysis, it is clear that no predictive scheme to define magnitudes and regions of greenhouse gas-induced climate change for Europe can be made at present. Instrumental records are probably not accurate estimators over 10–20 years into the future, while models do not contain important processes which induce change and stability. Therefore, climate futures must continue to be studied as impact and sensitivity analyses, rather than as predictions of future events.

2. Climate: Grosswetterlagen Approaches

Pitovranov and Jäger evaluate an empirical method for projecting climate changes which minimizes some of the problems associated with use of the instrumental record of climate. The approach is based on the numerical relationship between hemisphere-wide temperature or temperature gradients, and large-scale weather patterns (*Grosswetterlagen*) in Europe alone. The resulting climate scenarios, derived from change in weather patterns (and thus, also, from temperature and precipitation patterns), have the advantage of combining empirical data with that from synoptic climatology. A *Grosswetterlage* identifies the major trends in atmospheric events over a region during several days of essentially similar weather. In the example produced here, Pitovranov and Jäger identified the most appropriate historically-recorded *Grosswetterlagen* for each season, and mapped the difference between its temperature and precipitation and the temperature and precipitation of the region as a whole. Thus, they chose the *Grosswetterlage* from spring 1939, summer 1952, fall 1939 and winter 1938 as warm weather analogs. The differences between this artificial year and climatic mean data (1951–1980) provides a scenario for climatic changes of a one-degree centigrade warmer world. The major conclusions which emerge from this scenario are as follows:

- Like in the other empirical scenarios, winter temperature increases are greatest to the north, less so in central Europe, and actually decline in southwestern Europe.

- Again, as from other methods, the *Grosswetterlagen* approach suggests that the summer increase in temperature is less than winter temperature increases, with little geographic differentiation of temperature differences.
- In all four seasons, there are some areas that undergo temperature decreases, even though the trend is to warmer temperatures in most areas.
- Mean annual precipitation decreases somewhat in central and southern Europe and the Mediterranean, with increases in western and northern Europe.
- Evapotranspiration increases over continental areas of central and southern Europe, greatly increasing the already high plant water stress in these areas.
- The method itself is a sound way to proceed in climate scenario production, in that it links hemispheric temperature change to atmospheric circulation types, and in turn, links atmospheric circulation types to the distribution of temperature and precipitation values within local areas.

3. Hydrology: Water Quality Changes

The water quality problem of concern involves eutrophication, i.e., increases in nutrients in both standing water and in rivers, causing great increases in the frequency of algal blooms (population explosions) which rapidly take up oxygen when decomposing, in turn, producing fish kills and turbid, malodorous waters. Where eutrophic rivers reach the sea, marine fish and mammal mortality can increase dramatically.

Kauppi demonstrates convincingly that eutrophication of surface waters is directly related to the intensity of agriculture; as a result of overfertilization, excess nutrients are washed into surface waters. In addition the contamination of ground water drinking supplies with health-threatening nitrates occurs where agriculture is particularly intense. Thus, changing patterns of agricultural land use will determine lake, river, and ground water eutrophication. At this time, marginal farming in northern Europe is being reduced, but central and western European agriculture is becoming more mechanized and intense. In fact, Kauppi shows that agriculture in central and northern Europe currently provides tens to hundreds of kg per hectare of excess nutrients as runoff to lakes and streams, in contrast to the absence of excess nutrients in southern regions. The problem may become more acute in the north if greenhouse gas-induced climate change causes increased agriculture intensity in northern Europe, because of the expected increase in growing season length and warmth, and the increased moisture during growing seasons. Other conclusions from Kauppi's analysis include the following:

- Unless reductions are made in the rates at which agricultural fertilizers are applied per unit area, or the total area of land used for agriculture is decreased, the future contamination of ground water and surface water supplies is likely to increase, particularly in central Europe.

- At this point, the direction of changing contamination is ambiguous; climate warming and increasing human populations should induce increases in the amount of European land which undergoes intensive agriculture; on the other hand, most fertilizers are derived from petroleum products, which may become too expensive for routine agricultural use during the next several decades, forcing the use of alternate, and probably, less nutrient-wasteful technologies.
- The problem surrounding eutrophication of surface waters is one which can be solved by simple changes in agricultural policy. However, those changes have to be coordinated by several countries in order to avoid economical difficulties.

4. Hydrology: Water Availability Changes

Brouwer and Falkenmark have assessed the role of future climate change in the hydrologic cycle of Europe. They demonstrated how geographic changes in the distribution of water supplies, in combination with increasing water needs by humans, may generate potential large-scale difficulties for drinking water and industrial water supplies. After defining the nature of the hydrologic system, they applied the output of a general circulation model of the atmosphere to calculate the hydrological consequences of the climate scenario to both human and agricultural systems.

They note that a certain minimum amount of water is required for each person and they determine that the amount may be as little as 500 m^3/yr under optimal conditions, in a well-organized and advanced country which practices sophisticated water management and demand-control policies. In Europe, Belgium (1200 m^3/yr per person), the GDR (1600 m^3/yr per person), and Poland (1700 m^3/yr per person) already approach the per capita water "barrier"; while the GDR and Poland have an annual per capita water demand under 500 m^3, Belgium's water demand exceeds 800 m^3, leaving little room for population growth or declines in water supplies in Belgium. In addition, they noted that the critical water limits to agriculture are currently in southern Europe and the Mediterranean, where little moisture occurs during the summer growing season. They reached the following conclusions with regard to moisture supply vulnerabilities in Europe:

- Under greenhouse gas-induced warming, the vulnerability of current water supplies in Belgium, the GDR and Poland could be lessened but several Mediterranean countries (Greece, Spain, Italy, France) would come perilously close to water scarcity.
- An increase in the length of the season during which evapotranspiration occurs, combined with enhanced summer drought could reduce agricultural yields in central and western Europe, as well as increasing water demand significantly for irrigation there.

- Agricultural yields in northern Europe are presently limited by lack of warmth during growing seasons, and thus, vulnerability to moisture deficits would be unlikely to occur there; indeed, waterlogging of soils due to potential increases in precipitation could decrease yields.

5. Soils: Acidification Changes

Kauppi and Posch define the problem of soil acidification in Europe. The problem involves increasing the concentration of anions in soils from atmospheric pollutants, with resulting damage to the growth of trees, a decline in populations of organisms in lakes and streams, and changes in ground water chemistry. Because agricultural soil processes are dominated by management practices, including maintenance of ion concentrations, Kauppi and Posch focused the review upon acidification of forest soils.

After defining the nature of soil acidification, and ways in which it can be described, they used IIASA data bases to determine the current geographic pattern of soil acidification, and then to examine potential changes in that pattern under differing circumstances of pollution abatement strategies, as well as under changing climate. The conclusions which were derived from this analysis include the following:

- Based on current plans by European countries to reduce emissions through the year 2000, acidification would continue in central Europe, although it would lessen in southern Europe, Scandinavia and the USSR.
- Based on the maximum technically feasible reductions in emissions, most European forest soils would undergo a slow recovery, with the exception of small parts of central Europe, which would continue to undergo soil acidification in any case.
- In northern Europe, changing climate due to greenhouse gas increases seems likely to improve soil acidification conditions, first, because precipitation increases would decrease the aluminum concentrations in the soil, and second, because warming-induced increases in biomass decomposition would reduce internal proton production.
- In central Europe, soil acidification conditions would worsen if climate changes as suggested by future climate scenarios, due primarily to increases in evapotranspiration, and consequent increases in aluminum concentrations in the soil.

6. Biota: Forest Decline

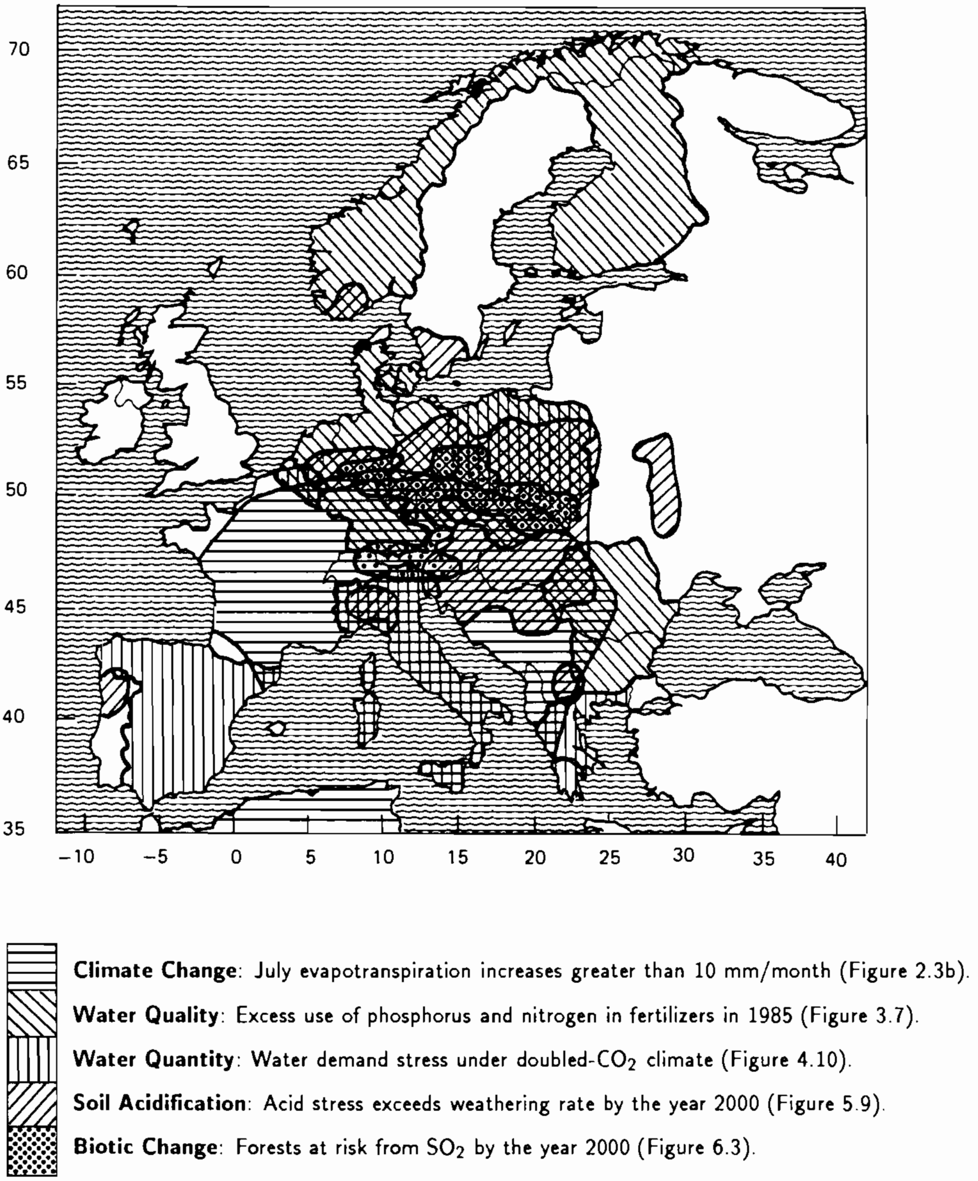
The most visible problem in European biotic response to environmental change has been the decline of whole forest stands. As Duinker points out, a shared and complex set of symptoms is evident in trees and stands in all parts of the continent, occurring in all species, at all ages, at all elevations, at all site qualities and in all management treatments. Duinker discusses the complex concept of forest decline and the important values which are threatened by forest decline (i.e., timber supply, supply of other products, environmental protection, and recreation). He then draws upon the literature to illustrate the variables, which are or could be, used to measure forest decline in the field, the patterns of forest decline which have been measured in Europe, and the probable causes of forest decline. He provides evidence to suggest that the most important causes for decline are increases in air pollution, and inadequate silvicultural practices, although he also includes long-term climatic change, increasing nutrient deficiencies, and increasing attacks by pests and diseases.

Duinker then uses the remainder of the paper to analyze the present and future effects of air pollutants and silvicultural practices on European forest vigor and decline. The major conclusions to be derived from these analyses include the following:

- Assuming a 30% reduction of atmospheric sulfur compounds by the year 2000, forests will continue to be at risk to air pollutants, at least in central Europe and the Alps.
- Silvicultural practices which have produced overpopulated stands and overaged trees with little capability to withstand additional stresses, will probably continue because of the increasing costs of forest-stand maintenance and harvesting in northern and central Europe.
- Because many stress factors (air pollution, climate change and variation, competition, etc.) bring about the same symptoms of forest decline, it seems unlikely that simple changes in forest-management policies can alleviate forest declines.

7. European Ecological Sustainability: Collective Problems

Examination of the foregoing information allows one to identify geographic patterns of environmental deterioration, both as individual and as collective risks. We have attempted to illustrate the geographical relationships of these problems in *Figure 7.1*, which presents a single "indicator" of each of the issues we have discussed. Thus, for the climate change issue, summer evapotranspiration is used to integrate effects of changes in temperature and precipitation, with large increases suggesting either great warming or enhanced drought, or both, and implying negative water balances for use by natural vegetation, crops, and humans. In this case, we used July evapotranspiration as shown in *Figure 2.3b*. Water quality problems are suggested from expected overuses of agricultural fertilizers. The indicator we possess of this problem at the present time is the list of countries in which phosphorus and nitrogen inputs exceed their outputs in food products (*Figure 3.7*). Future water quantity difficulties are indicated by our list of countries in which water demand reaches critical levels (e.g., 500 or more persons per million cubic meters of water per year) under climate simulated for a doubling of atmospheric CO_2, as shown in *Figure 4.10*. Soil



▤ **Climate Change**: July evapotranspiration increases greater than 10 mm/month (Figure 2.3b).

▧ **Water Quality**: Excess use of phosphorus and nitrogen in fertilizers in 1985 (Figure 3.7).

▥ **Water Quantity**: Water demand stress under doubled-CO_2 climate (Figure 4.10).

▨ **Soil Acidification**: Acid stress exceeds weathering rate by the year 2000 (Figure 5.9).

░ **Biotic Change**: Forests at risk from SO_2 by the year 2000 (Figure 6.3).

Figure 7.1. Geographic distribution of five indicators of future environmental degradation in Europe. Each of the five phenomena are described and illustrated in the figures indicated.

acidification is represented by the regional distribution of soils in which acid stress exceeds weathering rates by the year 2000, even with the maximum reduction of sulfur emissions which is technologically feasible (*Figure 5.9*). The potential for forest decline due to atmospheric sulfur by the year 2000, from *Figure 6.3*, is used to illustrate the forest decline issue. Obviously, additional stress on forests will be likely from local differences in silvicultural practices, and the changes mapped in *Figure 7.1* in soil acidification, water demand stress, and evapotranspiration.

An overall geographic conclusion, which is evident from the figure, is that the greatest risk of declining environmental quality, and increasing complexity of linkages among deterioration causes and consequences is to be found in central Europe. Here, warming and drying from increasing greenhouse gas concentrations is suggested by instrumental records of climate, and by climate modelling experiments in the analyses of Jäger and of Pitovranov and Jäger. The increasing evapotranspiration is likely to increase stress on central Europe's biotic and agricultural systems, and on municipal water supplies, as noted by Brouwer and Falkenmark. Water quality, particularly eutrophication of surface and ground water supplies, is also quite vulnerable in central Europe, where Kauppi notes that fertilizers are used in excess and that longer growing seasons may increase the intensity of agricultural activities. No matter how drastic the air pollution control strategies implemented by governmental decision makers will be, Kauppi and Posch determined that central Europe will continue to undergo soil acidification. Soil acidification could be enhanced by climate change and by forest decline. Forest decline, in turn, is most likely in central Europe because of atmospheric pollutant concentrations, according to the analysis by Duinker. Soil acidification there would further enhance forest decline.

Figure 7.1 indicates that each of the other regions of Europe are likely to encounter one or more of these individual ecological problems in the future, in greater intensity, or in different ways than in central Europe. However, only the region of central Europe, as defined in these investigations, has the potential to undergo all the problems we have discussed, and to do so simultaneously, with unpredictable, but exceedingly negative consequences.

The timing of deterioration can be of greater importance than the amount of change, but our assessment of rates of change is much more uncertain. Clearly, the more slowly these declines in environmental quality take place, the more likely it is that mitigating activities can be implemented. Some problems, such as the potential die-back of forests under warming induced by increasing greenhouse gases, may actually be caused by rapid rates of change, rather than by the magnitude of change, and hence, may also be lessened by slow rates of change. Also, the linked and synergistic effects of the individual environmental problems will be greatly enhanced if they co-occur in time, rather than as a series of changes in which each increases then decreases in intensity in a sequential manner.

There is no obvious means to determine rates of change in the environmental characteristics that we have discussed. Qualitative estimates of points in time at which certain conditions could be reached may be made: at current rates of change, the scenarios of seasonal temperature and precipitation changes shown by Pitovranov and Jãger may be in place in one to four decades; thus, municipal water supplies and agricultural yields may be expected to be threatened within the same time period, and a new wave of forest decline could follow the climate change by a decade (i.e., in two to five decades from now). At current rates of pollutant emissions, central European forest soils may become too acid for tree growth in five to ten decades, producing a doubled stress on forests (acid soils, climate change) as early as five decades from now. At this point, however, there is no means to link these events or methodology to define the limits to their rates of change.

Recommendations for Further Research

1. Climate: Approaches to Projecting Temperature and Moisture Changes

- The most prominent recommendation is for research to determine the potential nature and magnitude of regional, rather than globally-averaged, changes in climate.
- A second recommendation involves continuing to refine scenarios of possible future climate in Europe; a recommended approach to attain both this and the first recommendation is the use of *Grosswetterlagen* methods described by Pitovranov and Jäger in this volume.
- Finally, Jäger recommends that future research should examine possible climatic effects of changes in natural and anthropogenic forcing variables in addition to the research on greenhouse gases, which currently provides the great majority of climate change studies.

2. Climate: Grosswetterlagen Approaches

- Like Jäger, Pitovranov and Jäger recommend further development of the *Grosswetterlage* approach for the construction of climate scenarios, because of the need by society for suggestions of the potential local changes climate could undergo during a global-scale warming, and due to the nature of this approach in combining empirical relationships and data with synoptic processes.
- The next step for this approach, is to move from the 5° × 5° latitude and longitude grid used in the current study, and approximating the spatial scales of GCMs, down to the finer-resolution spatial scales represented by weather station data in Europe.

3. Hydrology: Water Quality Changes

- Although the nature of the current pollution of groundwater by nitrates is relatively well known, its future magnitude and geographic distribution badly needs assessment, particularly as it would be affected by climate change. This would require fine-scale data on agricultural land use, soil nitrogen applications, and natural soil nitrogen contents.
- Similarly, the potential for phosphorus saturation of soils, and subsequent losses of phosphorus into lakes and streams, requires quantification of the process. The development of mathematical models of this phenomenon is critical for testing in the field and for subsequent assessments of future phosphorus transport. This will require data on typical values of oxalate-extractable aluminum and the iron content of each soil type and data on texture classes in the available FAO soil data sets.
- Effects of climate change on lake physics and water quality, especially in terms of the seasonality of ice and the increased growing season productivity, are badly needed in northern European regions.

4. Hydrology: Water Availability Changes

- The interannual variability of precipitation in summer is likely to have great impact upon water supplies for both municipal and agricultural uses. Present rainfall-runoff models need to be modified to incorporate interannual variability of runoff and evapotranspiration at the level of regions and subcontinents.
- Hydrological linkages are critical in the future, and are presently hardly studied. Modelling is required to examine the relationship between changing availability of water as determined by climate shifts, and changing agricultural use of the land as determined by soil degradation, climate change, and product demands. Additional effects to be considered include the way in which changes in land cover by ecosystems change the storage of water in soils, and water movement back to the atmosphere and into ground reservoirs and surface waters.
- Hydrological data time-series analysis could be the basis for studies of inter-annual variability, and of linkages among water-affected sectors. Statistical evaluations could include long-term historical data sets describing monthly temperature, precipitation, surface runoff, geographic data on vegetation and soils, and geophysical information on watersheds in several European countries, chosen for their data availability and geographic representativeness.

5. Soil: Acidification Changes

- The data must be collected to define important soil acidification processes that are not now part of IIASA's RAINS pollution model, except as parameterized variables from empirical data.
- Forest soil surveys need to be conducted to collect those data directly related to soil acidification predictions: lime content, weathering rate of silicates, cation exchange capacity, and base saturation.
- The forest soil surveys should be internationally conducted and coordinated to better utilize general soil maps by FAO.

6. Biota: Forest Decline

- Because direct experimental manipulation of forest stands is too time consuming and expensive to be a practical method for quantifying forest decline causes and effects, the causes of forest decline must be analyzed at the stand-level through mathematical simulation models. These models can mimic the interactions of decline processes, and allow testing of hypotheses. The development of a mathematical simulation model which includes responses to air pollutants is a critical need.
- The symptoms and empirical relationships of outside variables to forest decline itself cannot be defined for lack of standard measures in all regions. The data collected to measure and describe forest decline in Europe must be standardized, improved, and updated.
- The political questions on forest decline must be approached: given recent trends and the current situation with respect to forest decline, how might the decline problem evolve and what might the economic repercussions be of such an evolution? The most likely path to answers will involve improved data collections, mathematical modelling, and scenario building through policy analysis, all aimed at linking decline agents through the forests and into responses by the forest industry and trade organizations.

7. European Ecological Sustainability: Collective Problems

The study of the collective properties of environmental deterioration requires the generation of mathematical models which contain realistic geography and can treat the chronic changes in environmental forcing and ecological responses over long time periods. The modelling is only possible on the basis of European-wide data bases, developed in order to define relationships between cause and effect, and to apply the cause-effect relationships in the real world. The greatest uncertainty and vulnerability rests in the central European plains where the most difficult transboundary environmental problems will co-occur, and probably, will amplify the effects of one another through linkages and synergisms among ecological processes.