CHAPTER 2

Forests and the Changing Chemical Composition of the Atmosphere

P. Kauppi

The chemical composition of the atmosphere is changing due to the trends in the fluxes of, for example, CO_2, SO_2, and NO_x that are emitted from industrial and energy combustion processes into the atmosphere. Forest ecosystems are unlikely to react in any single, universal way, but rather there may be a large variability of ecological reactions both in time and in space. This variability is partly due to the concentration patterns of the emitted compounds. Also, in conditions of a given load of pollutants the ecological response may vary according to the ecosystem characteristics. At this stage it is extremely difficult to actually quantify the possible reactions of forest ecosystems, so all quantitative scenarios should be examined cautiously because of this uncertainty. Quantitative scenarios are not useless, however, because they provide a systematic way of ranking and evaluating the different factors of uncertainty. That, in turn, improves our understanding of the phenomena.

In this chapter we highlight three issues, all dealing with the responses of forests to the trends in the chemical composition of the atmosphere. The first issue is that of forest damage currently being observed in Europe. Acid precipitation, the stress due to sulfur dioxide, ozone, and heavy metals, and the excess amount of depositing nitrogen compounds are common denominators in this phenomenon. The two remaining issues are related to CO_2 emissions. The so-called CO_2 fertilization effect is due to the obvious possibility that the rate of tree photosynthesis will generally increase as the air is given increasing amounts of one of the main substrates to photosynthesis, i.e., carbon dioxide. The greenhouse effect is related to CO_2 and other "greenhouse gases", which all have a tendency to increase

Earth surface temperatures. The possible climatic warming in the air would affect the ecology of forests.

2.1. European Forest Damage

2.1.1. Introduction

Symptoms of what has been called a "new forest decline" have increased in Central Europe since the mid-1970s. Today, many scientists share the opinion that the new symptoms are connected to air pollution, yet no single pollutant or damage mechanism is considerd as the only cause of this so-called forest dieback. Survey results compiled by the Timber Section of the ECE/FAO Agriculture and Timber Division indicate that forest dieback has been observed over a rather large area in Central Europe. Countries such as Austria, Czechoslovakia, the FRG, Luxembourg, the Netherlands, Poland, and Switzerland report widespread damage of their forest resources.

The damage was first observed on silver fir. Currently, it is reported also on Norway spruce, Scots pine, beech, and oak. The definition of damage varies from country to country and the figures estimated from various countries are only partially comparable. Some of the figures are based on expert judgment rather than on a statistical survey. By far the largest fraction of the affected forests are only slightly damaged and may well recover. Moreover, although the estimates of the damaged area are quite high in many countries, there are no indications so far of marked increases in sanitation fellings. Such information encourages hopes that the forests in Europe, indeed, would recover. Nevertheles, the situation creates serious concern.

In the early days of industrialization it was not unusual for damage symptoms to occur on trees, for instance, in the neighborhood of a smelter. The first systematic studies of such events were carried out early in the nineteenth century (Stöckhardt, 1850, 1871; von Schröder and Reuss, 1883). Although warning of possible widespread damage was expressed in the 1960s (Knabe, 1966), the problem gained wide publicity in the early 1980s as new information became available.

Air-pollution abatement has been directed, in the first place, at improvement of the quality of urban air. Constructing high stacks has assisted in reducing maximum ground concentrations of pollutants, which has certainly been a valid goal. However, similar reduction has not been realized in rural areas. On the contrary, the rural concentrations of pollutants have increased with increasing industrial activity and the consumption of fossil fuels. Only very recently has the increase of sulfur emissions reached saturation in many industrial countries. A declining trend is now anticipated in Europe for the forthcoming years, but nitrogen emissions may still continue to increase. Locally, there may be substantial deviations from these general trends.

Forest damage is a problematic concept because it does not have a standard meaning. In Section 2.1.2 we describe different indicator variables that have been applied in order to quantify forest damage. In Section 2.1.3 we give a short review of possible cause-and-effect relationships and of models for describing the damage.

2.1.2. Concepts of damage

A definition of damage requires that the limit between acceptable and unacceptable conditions is specified. Acceptable conditions are called the "norm" and unacceptable ones, "damage". Defining the limit between norm and damage is a value judgment: What people regard as acceptable depends upon their point of view, experience, and objectives. Forest hikers and the general public are responsive to the general habitus of trees and forest landscapes. The industrial timber sector will react to changes in the potential harvest of high-value tree species. Attention is here given to visible damage, to growth reduction, and to the reduction of the standing stock. Damage variables can be defined at three levels of hierarchy: tree level, stand level, and regional or forest level.

Decrease in crown density

Tree level. Visible damage occurs as leaf necrosis, immature fall of leaves and needles, death of branches, and decline of the top. A simple variable, "crown density", has been commonly used to describe these phenomena. The crown density is relatively easy to observe in regional and national surveys as it is quick to assess. At least the FRG, the UK, Sweden, and Finland apply this variable in their national surveys of forest damage.

Crown density is assessed as the fraction of needles fallen in comparison with the norm and is not determined for suppressed trees but only for dominant or codominant trees. The damage is more difficult to quantify for deciduous trees, as their appearance changes substantially over the growing season. The percentage of necrotic leaves has been used as an indicator.

Stand level. It is a natural process for some trees in any given forest stand generally lose their vigor, mainly due to self-thinning. As trees grow larger they occupy more space and, by necessity, their number will decrease (e.g., Gorham, 1979). As crown density thus varies among individual trees, the definition of damage at "stand level" requires that one specifies what proportion of trees that show the symptoms is acceptable. A stand-specific index in the FRG takes into account both the distribution of trees according to crown density and to tree size (Schöpfer *et al.*, 1984). The index puts more weight on a large tree than on a small one. The area occupied by each tree is computed and stand damage is expressed in units of land area. In mixed stands the German method computes stand damage proportionally between species.

Forest level. Any larger forest region consists of a number of forest stands. Averaging the crown density data from all the stands in the region does provide a variable for describing forest damage. However, when comparing two forest regions one must take into account the characteristics of forests in each region and ensure that the regions, indeed, are comparable. The species distribution and the distribution of stand age must be taken into account. For example, a forest region with old stands is generally especially susceptible to air-pollution damage (*Figure 2.1*).

Growth reduction

Tree level. Tree-ring analysis is an effective method for measuring growth reduction at the tree level. Tree-ring data have the advantage in that they extend several decades back. The method is intensive and it can be used in cause-and-effect studies. Hari *et al.* (1984), for example, have applied the method to detect pollutant effects.

Comparisons between damage and norm are difficult, however, because it is not easy to describe the reference tree or the norm. The growth increment of a forest tree varies as a function of many factors, such as climate, soil conditions, tree species, genotype, and position of the tree as a suppressed tree or as a dominant one. The norm must, therefore, be expressed as a function of species, site, tree age, and the position of the tree within the stand.

Stand level. Most forest operations, such as thinnings, regeneration, and possible fertilization, are organized in practice at stand level. An important variable of damage would thus be one that expresses the growth increment at stand level. Reference conditions (the norm) are available in many areas in terms of growth curves for stands of given species and sites (*Figure 2.2*).

Forest level. Arovaara *et al.* (1984) have used the data from the surveys of forest resources to detect trends in tree growth due to changes in the chemical composition of the atmosphere. Such methods cannot be used in most

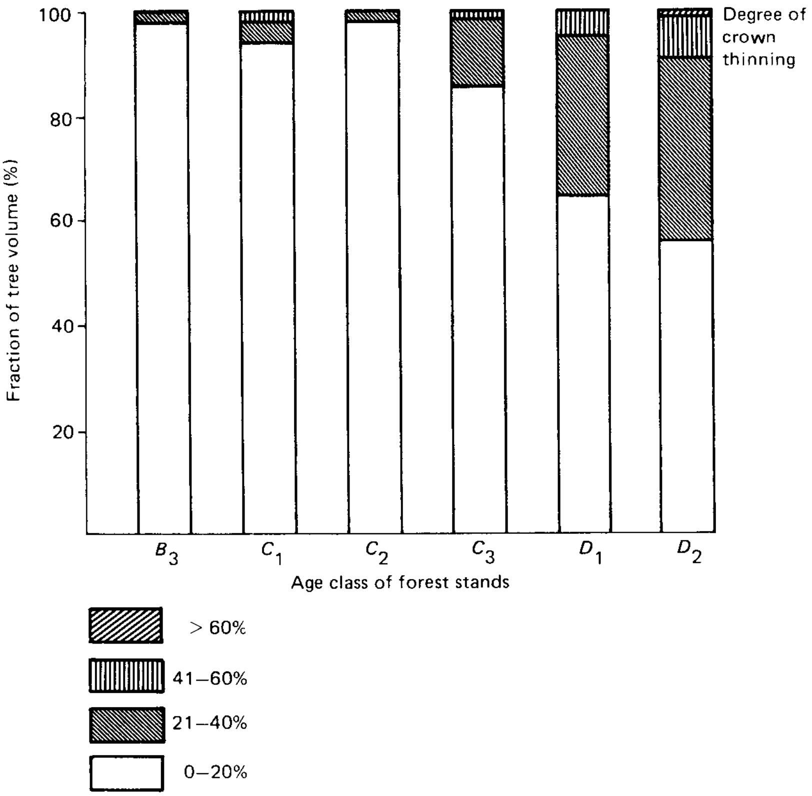

Figure 2.1 The distribution of trees, on a volume basis, into classes of crown density in different phases of stand development in Southern Sweden. Norway spruce; B_3 = young stands with average stand height > 3 m, $C_1 - C_3$ = stands at the intermediate age, $D_1 - D_2$ = old stands (Bengtsson, 1985).

parts of the world because the survey results are available only from restricted regions.

Stock reduction

Forest level. As old trees are particularly susceptible to forest damage it may sometimes be necessary in polluted areas to shorten the rotation period. This may only slightly decrease the average stand growth on a sustainable basis, but essentially reduce the volume of the standing stock.

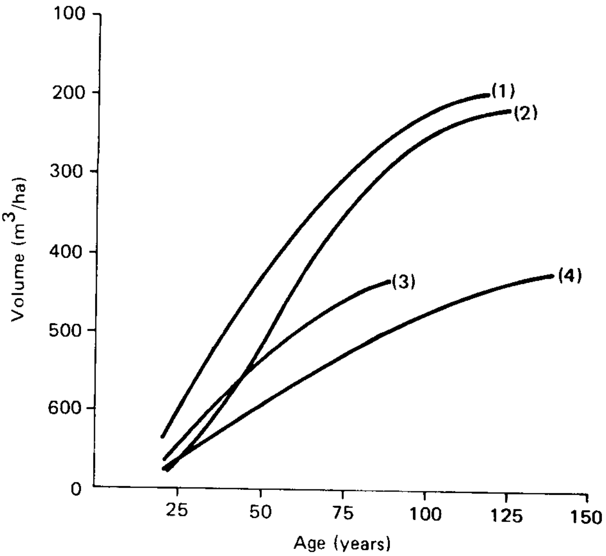

Figure 2.2 Stand volume development for some tree species and growing sites in Southern Finland (Koivisto, 1959). (1) Scots pine (*Pinus sylvestris*), *Myrtillus* site type; (2) Norway spruce (*Picea abies*), *Myrtillus* site type; (3) Silver birch (*Betula pendula*), *Myrtillus* site type; (4) Scots pine (*Pinus sylvestris*), *Cladonia* site type.

Stock reduction should hence be taken as a damage variable that is practically independent of the growth variables.

Growth of a stand typically reaches a culmination point after which it starts to decline. Standing volume, however, continues to increase. The rotation time, one of the key concepts of forest management, is selected according to economic criteria (Binkley, 1985). In most cases the rotation age is lower than that of growth culmination. Forest management maintains a control over the rotation time and, consequently, over the age distribution of forest stands.

Air pollution has the strongest effect on old stands and high pollution levels may force forest management to eliminate the oldest fraction of the stand age distribution. Shortening the rotation period by, say, 10% may decrease the standing stock of a forest region by as much as 20–30%, because old stands with the largest volumes would disappear. The average growth of the region would decrease far less because old stands do not grow very fast.

It may be, in fact, that careful attention should be given to the effects of air pollution on the standing volume of forest regions. Variables for standing stock may well be more sensitive to air pollution than growth variables. If, indeed, standing volume were strongly declining, then the timber sector should be prepared for a considerable pulse of high timber supply followed by a modest decline in the sustainable harvest.

2.1.3. Quantitative models

Wentzel (1983) has collected results from Europe concerning the relationships between damage and SO_2 concentrations. These studies are part of the Air Pollution Program of the International Union for Forest Research Organizations (IUFRO). Field observations indicate that risks of damage increase considerably as the long-time mean concentration exceeds 40–60 $\mu g\ SO_2/m^3$. Materna (1984) reports that forests at high elevations are especially sensitive to air pollution. An effect that is observed in forests 600 m above sea level within the concentration range 70–90 $\mu g/m^3$ can be observed above 1000 m in concentrations as low as 20–30 $\mu g/m^3$. IUFRO recommends that average concentrations of SO_2 in forest regions should not exceed 25 $\mu g/m^3$.

Rather close correlations have been documented between the the sulfur content of tree needles and the average age of the needle (Knabe, 1982). Nevertheless, SO_2 is no longer considered as the only major cause of pollution damage. New hypotheses about cause and effect have entered the discussion. Ozone and soil acidification, in particular, have been added to the list of potential agents of damage. Heavy metals, secondary photooxidants other than ozone, nitrogen deposition, and combinations of all these constituents also have potential damage effects.

It is illustrative to group the hypotheses on the basis of their dynamics. Such a classification has been presented by Kohlmaier *et al.* (1984), who distinguish between immediate and delayed impacts. The time scale of the delay — a week, a month, a year, or a decade — varies from one process to another and has to be specified accordingly. The delayed impacts can be further divided into delays in the physical environmental and in the biological responses.

The impact to forests can often be considered immediate if it occurs less than a year after the exposure. The acute SO_2 damage is immediate in this sense. Average sulfur concentrations in Europe have not increased for 5–10 years, so it has been argued that the new forest damage is due to ozone rather than SO_2. The concentrations of ozone still continue to increase and ozone could, therefore, explain the damage, even when assuming that the damage is acute (Prinz *et al.*, 1984).

If the damage is delayed then soil acidification is a valid hypothesis. The theory presented by Ulrich describes a gradual change in soil acidity in which several delay mechanisms are involved (Ulrich, 1983). The flow of protons into the top soil, due to sulfate and nitrate deposition, leaches calcium and magnesium ions from this soil. This process mobilizes aluminum ions that have detrimental effects on tree roots. The more protons that are deposited, the more aluminum dominates in the soil solutions. Sulfur emissions, carrying protons, gradually acidify soils through a delayed process of accumulation (van Breemen *et al.*, 1984). In the context of soil acidification the delay is of the order of years or decades. As soils acidify the trees are assumed to show damage. Reducing the emissions slows down the rate of acidification, but may not reverse it before a threshold deposition has been reached. In this way recovery is also delayed, even in the hypothetical case that all emissions are set to zero.

The recent stress hypothesis assumes that there are delay mechanisms within the tree (e.g., Schütt *et al.*, 1983) and that different stress factors can cause similar symptoms. Triggering factors include SO_2, soil acidification, and ozone. It is important to gain an insight into the processes, such as photosynthesis, respiration, and growth, that are common to all pathways of the disease.

Plant processes can, to a certain extent, cope with air pollutants and induce physiological delays that cause difficulties in identifying cause and effect. If the roots are damaged, for example, then plants allocate more photosynthates to root maintenance and less remains available for needle production. Crown density may thus react to poor soil conditions rather than to toxic effects on the needles. Such possible endogenous delays are very difficult to trace experimentally.

Dose–response models

Pollutant stresses on organisms have been analyzed using so-called dose–response models, first presented by O'Gara (1922) and further developed by, e.g., Thomas and Hill (1935) and Larsen and Heck (1976). These models are based on the idea that damage occurs after exposure to a threshold dose. The dose is not just the average concentration, but may depend on both pollutant concentration and exposure time.

In the standard form of the model, the dose is the product of the "effective" concentration and the "effective" exposure time. "Effective" concentration refers to a linear response of the strain to concentrations above a minimum threshold stress. Hence, the dose, D, is:

$$D = \sum_{i=1}^{n} (c_{ai} - c_0)$$

where c_{ai} is the ambient concentration, c_0 is the threshold concentration, and n is the duration of "effective" exposure. The model can be further simplified to compute the threshold dose as a function of exposure time. When computed in this way dose can be related to damage, for example, using a logistic function (Kauppi, 1984). As the dose–response model does not consider resistance of the plant as an explicit variable, potential differences in resistance between species and growing sites should be incorporated into the parameters of the model.

A soil-acidification model

Quantitative dose–response models for describing regional forest decline would be useful in guiding experimental research, examining the rate of expansion of forest damage, and optimizing control measures, such as emission reduction and silvicultural practices. They would also assist the timber sector to create scenarios for sanitation fellings. Such scenarios could be used in order to mitigate the possible market disturbances.

Dose–response models of regional forest damage contain much uncertainty. First, there are many variables that define damage and, moreover, those that would be of most value to the timber sector are difficult to assess at the regional level. Second, many air pollutants potentially affect trees and some of them have a number of different pathways of effect. Third, site-specific conditions — tree species, stand density, stand age, soil characteristics, climate, etc. — have a large effect on the response. Finally, quantitative dose–response models are in the early phase of development, even in applications to local and specific conditions. Efforts to develop regional models, however, generally improve our understanding of the quantitative relationships.

The IIASA Acid Rain Project maintains a model system (RAINS) that consists of several submodels, which describe processes and phenomena related to acidification in Europe (Alcamo *et al.*, 1985). The basic set of the system includes submodels on energy emissions, on the long-range transportation of air pollutants, and on ecological impacts. Using these models an analyst can select an energy pathway for European countries, compute the respective sulfur emissions, assess the transport and deposition of these emissions, and obtain a graph to describe the ecological effect. The time step of the model is one year, the time span is roughly 50 years, the spatial grid is 60 × 100 km, and the geographical coverage is Europe excluding the eastern part of European USSR. The main objective in constructing the models has been to provide policy analysts with a tool for comparing different aspects of alternative emission reduction programs in the European region. Therefore, the models operate on an interactive basis.

A model of the acidification of forest soils has been developed and incorporated into the RAINS system (Kauppi *et al.*, 1986). Input for that submodel is received as the output of upstream submodels, that is, the energy emissions model and an application of the long-range transport model of the Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe (EMEP) (for details, see Alcamo *et al.*, 1985). The output of the soil-acidification submodel is the time pattern of soil pH. The dose (stress) is defined as the annual contribution of acidity due to sulfur deposition in each grid square and in each year. The resistance of soils is defined in terms of the chemical capacity of different soil types to neutralize acids. A map on the location of soil types is used as an input file. The response is calculated on an annual basis, taking into account the acid stress each year and the efficiency of the soil to neutralize that acidity. Soil pH at any given time is obtained by deducting the annual changes from the initial conditions of each soil type. Rough estimates are obtained on forests at risk by defining and examining threshold values of the lowest soil pH permitted (*Figure 2.3*).

Sensitivity runs with the IIASA model demonstrate that a simple variable, base saturation of forest soils, is very important in the assessment of acidification. Intensive measurement programs would be needed to survey and monitor this variable. In spite of uncertainties, the model bounds regions where soil acidification due to sulfur deposition is of concern. Soil acidification due to industrial emissions is neither a local nor a global, but a regional phenomenon. Northern Scandinavia, for example, appears well protected. The main factor that bounds the affected area is the average lifetime of sulfur compounds in the atmosphere.

Sulfur is mainly deposited within 1000–2000 km from the emission source, outside which sulfur deposition cannot cause major acidification. Also, within this range there are protected areas due to the efficient buffering of certain soil types. Acidification and also the direct effects of sulfur and nitrogen emissions on vegetation can act during the rather short time scales of 10 to 30 years. An especially troublesome effect as regards the forest sector can be the impact of pollutants on old forest stands. There is a risk that this effect substantially increases sanitation fellings.

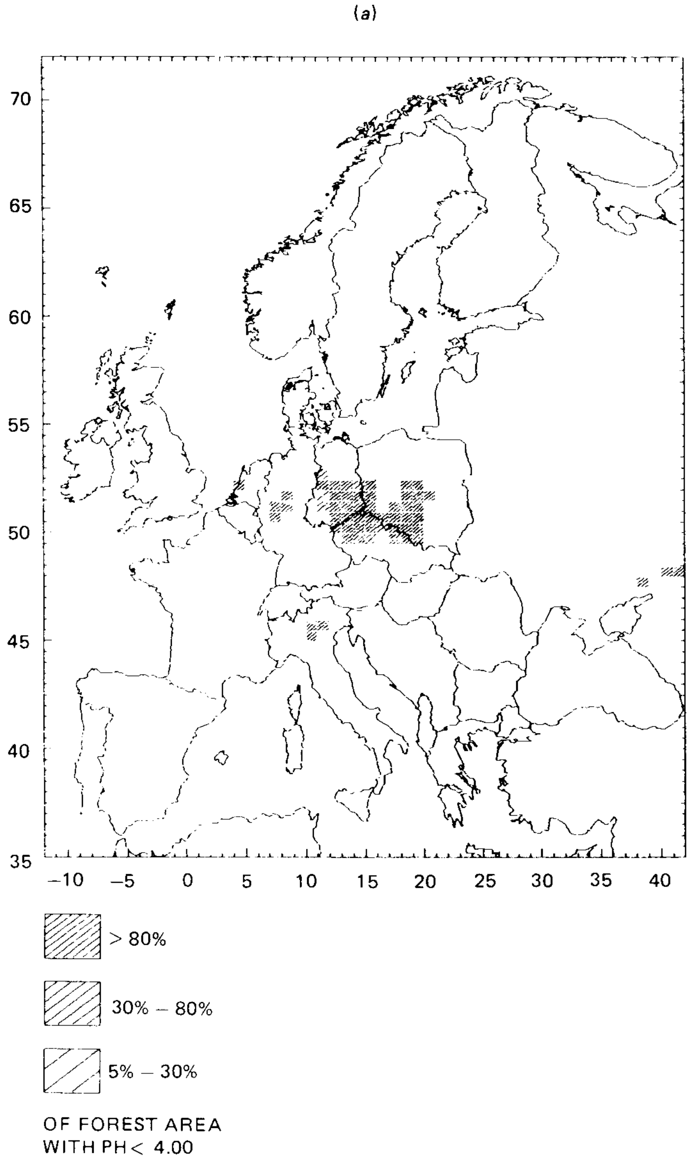

Figure 2.3 (a) The area of risk in 2010 (pH < 4.0), resulting from a low-emission scenario (from the IIASA Acid Rain Study, Alcamo *et al.*, 1985).

(*b*)

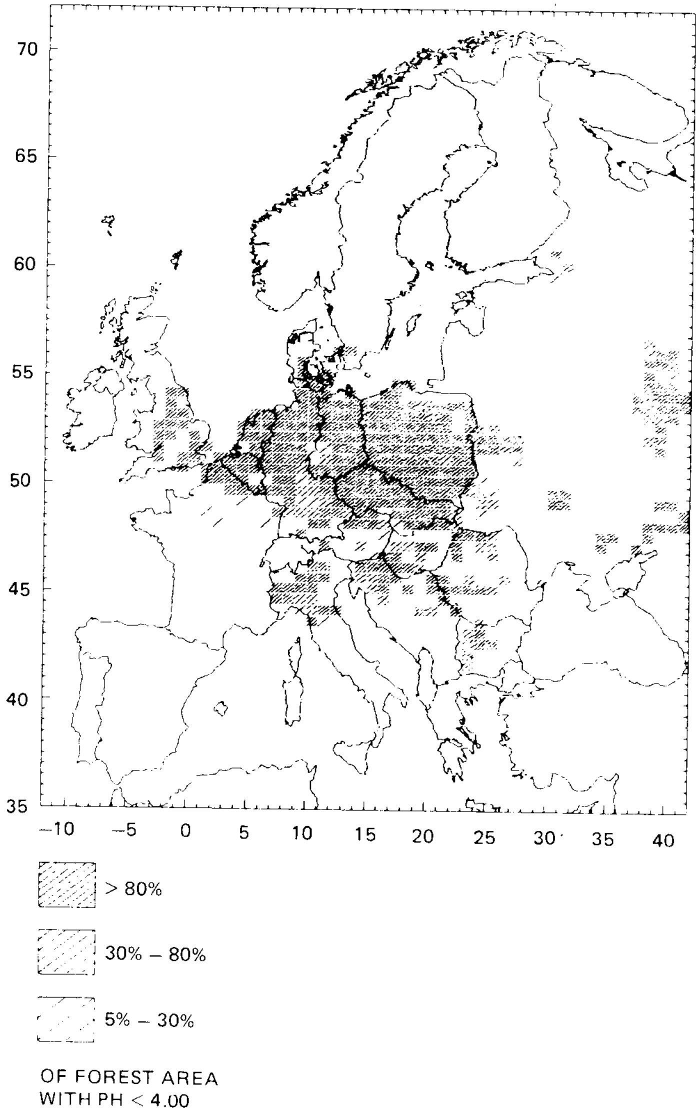

Figure 2.3 (b) The area of risk in 2010 (pH < 4.0), resulting from a high-emission scenario (from the IIASA Acid Rain Study, Alcamo *et al.*, 1985).

2.2. CO_2 Fertilization Effect

The term "CO_2 fertilization" originates from greenhouse horticulture where, quite frequently, CO_2 gas is injected into the air that surrounds the crops, since high levels of CO_2 enhance photosynthesis and yield development. There is at least one example of this practice in forestry: the Finnish Tree Breeding Foundation, a major seed producer to Finnish forest nurseries, applies CO_2 fertilization for birch seed production. Birch trees that are grown in elevated CO_2 concentrations for several growing seasons produce high seed yields. The trees also grow very fast and in this way reach a high capacity of seed production at an early stage. The application of CO_2 fertilization as a commercial practice indicates that the benefits from extra yield outweigh the costs of CO_2 injection.

A question has arisen as to whether the global increase of CO_2 in the free atmosphere would induce a CO_2 fertilization effect in natural ecosystems, including forests. This potential effect has often been called the direct effect of CO_2 on forests. The indirect effect refers to the potential climatic change associated with the increase in CO_2 levels.

From 315 p.p.m. in 1957, the average annual concentration of CO_2 in the atmosphere has increased to about 342 p.p.m. in 1984. The change has been documented with great accuracy at locations as far apart as Hawaii and the Antarctic (*Figure 2.4*). There is no doubt about the global character of this trend. The seasonal variability appears greatest in mid-latitudes, where emissions from energy production peak in winter at the time when ecosystems are dormant and do not absorb CO_2. Sea surface temperature also affects the seasonal CO_2 fluctuation.

Continuous measurements of ambient CO_2 were not available until 1957, but indirect estimates suggest that the concentration in the mid-nineteenth century was approximately 260–270 p.p.m. Analyses of air stored in glaciers and in polar ice indicate that at the end of the last glacial period, about 15 000 years ago, the atmospheric CO_2 concentration may have been as low as about 160 p.p.m. (Delmas *et al.*, 1980). There have thus been substantial changes in the atmospheric CO_2 concentration, for reasons that are largely unknown. The current rate of increase, however, is very high compared with that in prehistoric times.

2.2.1. Photosynthesis and growth

An increase in the CO_2 level in air generally accelerates photosynthesis in laboratory conditions (Koch, 1969). In other words, a high CO_2

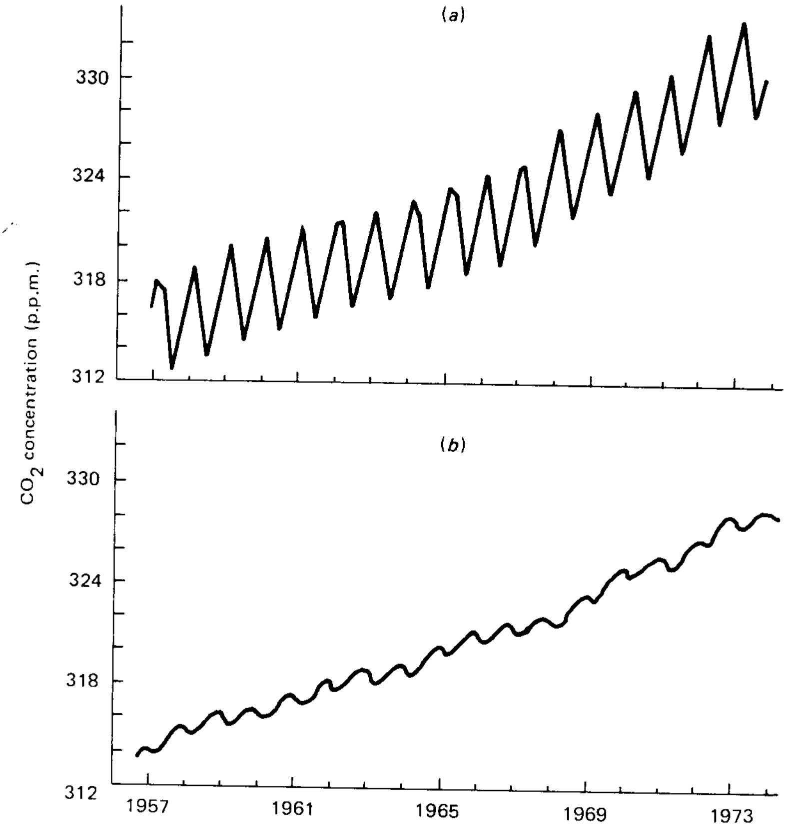

Figure 2.4 Atmospheric CO_2 concentrations (by volume, dry air) *(a)* at the Mauna Loa Observatory, Hawaii, and *(b)* at the South Pole. From measurements of Keeling and his co-workers, reproduced by Broecker *et al.* (1979). More recent data indicates that in 1984 the concentration was above 340 p.p.m.

concentration in the atmosphere provides plants with an increased flux of organic compounds to be allocated into respiratory processes and/or into the formation of plant biomass. Stomata are small openings on the leaf surface that control CO_2 uptake and plant transpiration. They are open when the plant is supplied with water and when photosynthesis is active, thus requiring CO_2 as substrate. As a rule the stomata are open by day and closed by night and have the important role of conserving water.

Based on our understanding of the functional principles of stomata, it is believed that the water-use efficiency of plants increases with increasing atmospheric CO_2 concentration. This concept is defined as milligrams of CO_2 fixed per gram of water transpired. First, owing to efficient diffusion, stomata could provide photosynthesis with an increasing flux of CO_2. Second, if photosynthesis is incapable of processing CO_2, stomata could conserve water by stomata aperture and yet fulfill the demand for CO_2 because of the high diffusion gradient. An increase in water-use efficiency with increasing CO_2 concentrations has been observed empirically (e.g., Rogers *et al.*, 1983).

Enhancement of photosynthesis has been observed on Ponderosa pine (Green and Wright, 1977) and on sweetgum (Rogers *et al.*, 1983). It is still uncertain whether this enhancement is a temporary phenomenon, since the link is tenuous between photosynthesis and growth. From a comprehensive review by Kramer (1981) it appears that many uncertainties exist, even at the plant level (tree level). All of the chemical energy bound in photosynthesis is not converted into structural biomass, but a large fraction of photosynthates are consumed in respiration (*cf.* Ågren *et al.*, 1980). Since the ratio of growth to respiration varies, there may not be a linear relationship between photosynthesis and growth. An increase in photosynthesis is a prerequisite for growth stimulation, but it does not automatically yield such a stimulation in all conditions. Physiological research has qualitatively identified the mechanisms of photosynthesis that may contribute to a CO_2 stimulation of growth. Other research disciplines are needed to quantify empirically such possible effects at stand and regional level.

Some doubt still exists as to whether the greenhouse and laboratory results are valid in natural ecosystems. In experimental or in greenhouse conditions wind is almost excluded. Goudrian and Ajtay (1979) point out that this may create a strong gradient of declining CO_2 from free air to leaf surface and to plant chloroplast. They argue that although photosynthesis responds to high CO_2 levels in laboratories and in greenhouses, the same response might be insignificant in field conditions. Wind turbulence mixes the air in the field and already assures that the leaf surface concentrations are high enough to maintain a more or less maximum photosynthesis in ambient concentrations as low as 300 p.p.m. This suggests that no essential growth stimulation would appear in natural ecosystems. The hypotheses could be tested by arranging turbulent air flows in greenhouses, but it appears that no such tests have been conducted.

A frequent argument that suggests negligible CO_2 effects on natural ecosystems refers to the "law of the limiting factors". Essentially, this maintains that plant growth is limited by one factor at a time. If this factor is, for example, water deficit then adding CO_2 is ineffective, but this is an oversimplification, as Verduin (1952) has pointed out. In fact, the reverse has been observed for wheat under drought conditions. The more severe the drought, the higher yields in high CO_2 conditions versus those in low CO_2 conditions (Gifford, 1979; Sionit *et al.*, 1980).

Doubling the CO_2 concentrations has increased the growth of tree seedlings by a factor of 1.2–2.0 (Hårdh, 1966, for Norway spruce and White spruce; and Tinus, 1972, for Ponderosa and Mountain Table pine). Tolley and Strain (1984) have reported a corresponding increase by a factor of 1.2 to 1.6 for sweetgum, although no effect for loblolly pine. These observations refer to well-watered and otherwise more or less optimal growing conditions.

There is considerable variation in experimental results on the effects of high CO_2 concentrations on plant productivity. Nonetheless, many results lend support to the view of Pearcy and Björkman (1985), who point out that the "law of the limiting factors" is sometimes misinterpreted by focusing on the absolute rather than on the relative growth effects. While CO_2 stimulation may be small in suboptimal conditions in absolute terms, it may indeed be great in relative terms. This view would have an important bearing, in particular, with respect to forests that grow in suboptimal conditions. Forestry, unlike agriculture, can operate also in conditions of low productivity because trees accumulate the wood product. If the productivity is low, one must apply long harvesting cycles, but there will, however, be sufficient amounts of yield for an economic harvest. A change of productivity, therefore, is equally important in conditions of both low and high productivity.

Field observations are necessary to examine whether long-term feedback mechanisms or the wind effect mentioned by Goudrian and Ajtay (1979) would obscure the CO_2 growth stimulation observed in laboratories and in greenhouses. Hari *et al.* (1984) conducted tree-ring investigations in low-altitude stands of Scots pine in southern Finland and provided results that are perhaps the first documentation of a possible CO_2 growth stimulation in natural ecosystems. A similar trend was also discovered using tree-ring data from two different pine species growing on high-altitude sites in the Western US (LaMarche *et al.*, 1984). Both studies report a substantial growth stimulation. A hypothesis can be formulated that a marked global CO_2 stimulation of growth has already taken place. New studies of a similar type are urgently needed from other parts of the world and from a large variety of sites.

Growth stimulation due to increasing CO_2 concentration in the atmosphere may well be a real phenomenon today. It could cover much larger forest regions than those now threatened in Europe by acid deposition and other air pollutants. CO_2 in the free atmosphere is evenly distributed in all parts of the world. Forests should theoretically differ in their responsivenes to this effect in such a way that the growth would be especially stimulated in forests that grow in arid regions. Subtropical forests could be especially responsive.

Although the effect may already exist today in large forest regions, it may have a minor impact on the global forest sector, at least in the short term. CO_2 growth stimulation might theoretically increase the sustainable harvest. There are, however, very few regions in the world where the maximum sustainable harvest directly governs the actual harvest. Forest management has several methods of increasing the sustainable harvest if so desired. These are seldom applied because the social and economic realities in most forest regions prevent it. Increasing the potential forest growth by even as much as 50% would have insignificant effects on the forest sector in many parts of the world.

CO_2 growth stimulation, unlike the European forest damage, would not have a special effect on old forest stands. It would hardly affect sanitation fellings. Whatever effect there will be, the forest sector will most likely have ample time to adapt to this change.

2.3. Possible Climatic Warming: Forest Response

Arrhenius (1896) was one of the first scientists to bring attention to the "CO_2 greenhouse effect". He computed estimates of the magnitude of the possible climatic warming on the Earth's surface, assuming that the atmospheric CO_2 concentration would increase by 100%. The physics of the "greenhouse phenomenon" are well understood. Short-wave irradiation from the Sun penetrates the atmospheric layers of CO_2 and other trace gases, but long-wave irradiation from the Earth's surface into outer space is held back. The understanding of the physics of the atmosphere has considerably improved since the time of Arrhenius and the general circulation models that are used today to quantify the "greenhouse effect" are relatively large, sophisticated ones.

A report of the US National Academy of Sciences, published in 1983, estimated that, largely depending on the future energy scenarios, the atmospheric CO_2 concentration would probably rise to 550–600 p.p.m. between the years 2020 and 2070 (Carbon Dioxide Assessment Committee, 1983; see also Clark, 1982). The concentration in 1984 was approximately

342 p.p.m. The scientific community is almost unanimously convinced that such an increase in the CO_2 level, especially as the concentrations of other trace gases, such as nitrous oxide (N_2O), are expected to rise, would cause a climatic warming. Model calculations generally propose that the Earth's surface temperature would rise by 3 (±) 1.5 °C on average. Tropical regions would experience smaller increases, whereas the boreal biome is anticipated to experience increases that are substantially larger than average. In spite of the trend in the atmospheric concentration of CO_2, a climatic warming has not yet been instrumentally recorded, because climatic fluctuations obscure the possible effects. Rainfall is also expected to change, but as this is a complicated phenomenon, mean values and spatial distribution of the change have not yet been reported generally.

A temperature increase of such a large magnitude would have very large effects, especially on boreal forests. Emanuel *et al.* (1985) have remapped world vegetation zones assuming model results for the temperature effect of CO_2 concentration increases. The present relationships were assumed between climatic variables and the large-scale biogeograpical zones (wet tropical forests, subtropical forests, temperate forests, wet and dry boreal forests, etc.). The results indicated that if the temperature increases, then large areas of boreal forests in Canada, Finland and Scandinavia, and the USSR would be replaced by temperate forests.

Precipitation, which is difficult to estimate with the current climatic models, is a comparatively insignificant ecological factor in the boreal regions. The uncertainty in estimation of precipitation is, therefore, not so crucial. The boreal coniferous forests are a particularly interesting area within the forest sector because the timber resources are of high quality and are being widely utilized for export in the world market.

Kauppi and Posch (1987) have estimated possible shifts in the productivity of the boreal forests assuming a climatic warming. Their calculation assumed temperature estimates using CO_2 concentrations expected by the mid-twenty-first century. A simple empirical regression was taken from Finland to relate forest productivity to temperature conditions (i.e., "effective temperature sum").

The results of the calculation indicated that the potential productivity would increase by as much as 100 to 300% over large regions of the boreal zone (*Figure 2.5*). These dramatic results, however, do not refer to the conditions of 50 to 70 years in the future. By that time the CO_2 concentrations may well rise to levels as high as 500 to 600 p.p.m. There will be a considerable time lag, however, in the subsequent temperature response, mainly due to the capacity of oceans to store thermal energy. An even more substantial time lag can be expected in the biological response. A typical lifetime of a tree is of the order of 100 years and the reproduction

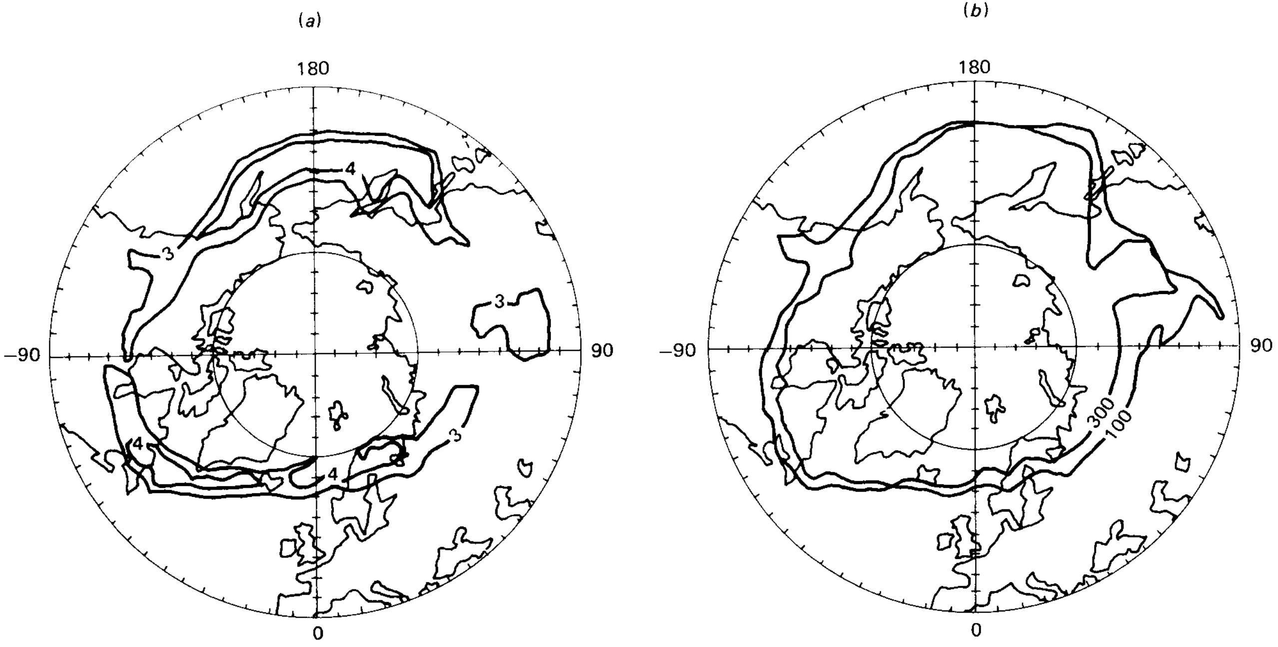

Figure 2.5 A scenario of the forestry effects of a possible climatic warning. Estimated increase in the potential productivity of the boreal forests from the baseline level of today to CO_2 conditions that are anticipated to prevail in the mid twenty-first century *(a)* in absolute units (m^3/ha/yr) and *(b)* in percentage terms (%). Note that time lags in the climatic and biological systems would, in effect, essentially postpone these kinds of forest response.

cycle in field conditions is more than 30 years. The calculation in *Figure 2.5* can be relevant to steady-state conditions very far into the future, but not to actual conditions in the twenty-first century.

A troublesome period of adaptation could be anticipated during the intermediate period of time when the climate has perhaps already changed, but the genetic properties of forests have not yet responded. The productivity of the boreal forests would, perhaps, increase in the long run, but during the time of adaptation old genetic strains would retard. This bears a risk of forest damage. Moreover, consequences of a possible climatic warming on the hot and dry margins of the mid-latitudes may more than counterbalance the possible gain anticipated in the cold forest margins. Deforestation in the tropical region often proceeds through local, unfavorable climatic changes, which should be kept in mind when constructing optimistic scenarios of a possible climatic change.

CO_2 and other trace gases that are being emitted into the atmosphere today are possibly inducing a substantial change in the global climate. Such a climatic change would particularly affect the forests that grow in the climatological margins. One possible area of a substantial change in forest vegetation is the boreal region. However, a change of the global climate is a matter for the very remote future. The time lags involved in the climatic system and the biological system will most likely prevent any major impacts in the short term.

2.4. Conclusions

A crucial factor that affects the spatial scale of the impact of pollutants is the residence time of the pollutant in the atmosphere. For CO_2 this is long enough to generate an almost even distribution of emissions in all parts of the world. The CO_2 fertilization effect and climatic effects are, therefore, global phenomena. SO_2 remains in the atmosphere for 10 to 50 hours, during which time it ascends to 2000 km in the atmosphere. The European emissions of sulfur, for example, should not induce forest damage beyond this spatial scale.

The residence time also affects the temporal variability of the compound. Compounds with relatively short residence times, such as NO_x or SO_2, occur in the atmosphere in varying concentrations. Large air masses in very remote areas are practically unaffected. Clean episodes also occur near to industrialized regions after effective scavenging by rain or, eventually, if the emissions are low. CO_2, in contrast, with a long residence time, occurs in the atmosphere in relatively stable concentrations.

The sinks of CO_2, seawater, and land biota are incapable of absorbing CO_2 at the rate that the gas is provided by the sources, energy combustion, and deforestation. Hence, CO_2 accumulates in the atmosphere. Compounds with shorter residence times do not accumulate in the atmosphere, but quite often do so in soils or in underwater sediments.

Impacts on forests of either high episodic concentrations or of the accumulated storage of emissions vary in time and in space depending on the properties of the compound and on those of the forest. Arid forests, for example, are potentially most responsive to CO_2 fertilization. Boreal forests, which grow in humid regions and are rather insensitive to the variability in precipitation, are anticipated to respond strongly to a temperature change. Mountain forests are perhaps most susceptible to the damage due to acid precipitation. In this way it is already possible to specify vulnerable forest regions where substantial changes — such as a high concentration or a possible large increase in temperature — meet with responsive reactions.

In principle, the impact of emissions on forests can, in some cases, be considered positive, especially if just the growth effect is taken into account. Adopting an optimistic view of these environmental changes, however, is quite a gamble. Ecosystems, as well as the enonomic and social structures that rely on them, are complicated. Any assessment of a possible ecological change focuses on only a few variables. What seems to be a positive change may turn out to be quite negative, especially if the new conditions fall outside the range of historical events to which all existing structures have been adapted. The consequences of such changes, which fall outside the range to which the forests have been adapted, are extremely difficult to assess.

Both similarities and differences are observed between the three issues discussed in this section as they are examined from the perspective of the forest sector. It seems possible to locate specific forest regions where one, but not all, of the issues are important. Moreover, all three issues are relevant in quite different time scales.

The issue of forest damage is being observed and anticipated, especially in continental Europe, which is a small but important area within the global forest sector. Forest damage bears the risk of rather short-term consequences because it affects not only the growth rate of the trees, but also their vitality and, consequently, the average volume of roundwood that can remain standing in the affected forests. Old trees are especially susceptible to pollutants and sanitation fellings may need to be directed at old stands. As these stands contain large amounts of timber, there is a risk of a short-term pulse of timber into the market, with subsequent adverse economic effects. “Short term” in the context of forestry would be a time span of 5–20 years. Short-term pulses, whether of high or low timber supply, are potentially troublesome as the industrial utilities and the related infrastructure have little time to adapt.

The CO_2 fertilization effect may have impacts on much larger regions than the area subjected to the European forest decline. Impacts are anticipated, especially in forests that grow in arid regions and perhaps especially in subtropical forests. Direct evidence has not been sought very effectively, but it is possible that the CO_2 fertilization effect already exists. These immediate effects, however, would be quite different from those of the European forest decline. Forests would be subject to growth enhancement rather than tree damage. Also, the possible impact to the forest sector would be very different. As there are negligible risks that old stands will lose their vigor, there is no need for a short-term adjustment of the standing volume. Infrastructures would have ample time to adapt to the new levels of productivity and to the possible shifts in species composition.

The greenhouse effect would also involve large forest regions, since the global climate, in essence, is one complicated system. Temperature and precipitation, if they change, will change in all parts of the world. Forests that grow in areas of arid climate would be susceptible, in particular, to a possible decrease in precipitation. In the boreal region over a very long time span forestry would benefit from a temperature increase as the productivity of these forests would increase. However, such scenarios are only relevant over extremely long time horizons of perhaps 500–2000 years. Within the next 50 years it is hardly realistic to anticipate any large forestry effects due to a change in the global climate. Fossil fuel combustion will possibly seed such effects within this period of time, but the actual effects are delayed because of the time lag of both the climatic and the ecological systems.

Acknowledgments

Special thanks are due to Clark Binkley, Markku Kallio, and Annikki Mäkelä for their encouragement and support. This study is part of the IIASA Forest Sector Project.

References

Ågren, G.I., Axelsson, B., Flower-Ellis, J.G.K., Linder, S., Persson, H., Staaf, H., and Troeng, E. (1980), Annual carbon budget of a young Scots pine, *Ecol. Bull.*, **32**, 307–311.

Alcamo, J., Hordijk, L., Kämäri, J., Kauppi, P., Posch, M., and Runca, E. (1985), Integrated analysis of acidification in Europe, *J. Env. Manag.* **21**, 47–61.

Arovaara, H., Hari, P., and Kuusela, K. (1984), Possible effect of changes in atmospheric composition and acid rain on tree growth. An analysis based on the results of Finnish National Forest Inventories, *Commun. Inst. For. Fenni.*, **116**.

Arrhenius, S. (1896), The influence of the carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science*, **XLI** (fifth series), 237–276.

Bengtsson, G. (1985), *Forest Damage in Sweden — A National Inventory* (in Swedish), seminar presentation, 22 May 1985.

Binkley, C. (1985), *When is the Optimal Economic Rotation Longer than the Rotation of Maximum Sustained Yield?* Working Paper WP-85-9 (International Institute for Applied Systems Analysis, Laxenburg, Austria).

van Breemen, N., Driscoll, C.T., and Mulder, J. (1984), Acidic deposition and internal proton sources in acidification of soils and waters, *Nature*, **307**, 599–604.

Broecker, W.S., Takahashi, T., Simpson, H.J., and Peng, T.H. (1979), Fate of fossil fuel carbon dioxide and the global carbon budget, *Science*, **206**, 409–418.

Carbon Dioxide Assessment Committee (1983), *Changing Climate* (National Academy of Sciences, Washington, DC).

Clark, W.C. (Ed) (1982), *Carbon Dioxide Review 1982* (Oxford University Press, New York).

Delmas, R.J., Scencio, J-M., and Legrand, M. (1980), Polar ice evidence that atmospheric CO_2 20 000 BP was 50 percent of present, *Nature*, **284**, 155–157.

Emanuel, W.R., Shugart, H.H., and Stevenson, M.P. (1985), Climatic change and the broad-scale distribution of terrestrial ecosystem complexes, *Climatic Change*, **7**, 29–43.

Gifford, R.M. (1979), Growth and yield of CO_2-enriched wheat under water-limited conditions, *Aust. J. Plant Physiol.*, **6**, 367–378.

Gorham, E. (1979), Shoot height, weight and standing crop in relation to density in monospecific plant stands, *Nature*, **279**, 148–150.

Goudrian, J. and Ajtay, G.L. (1979), The possible effect of increased CO_2 on photosynthesis, in B. Bolin, E.T. Degens, S. Kempe, and P. Ketner (Eds), *The Global Carbon Cycle*, Scope Report 13 (Wiley, New York).

Green, K. and Wright, R. (1977), Field response of photosynthesis to CO_2 enhancement in Ponderosa pine, *Ecology*, **58**, 687–692.

Hårdh, J.E. (1966), Trials with carbon dioxide, light and growth substances on forest tree plants, *Acta For. Fenn.*, **81**(1), 1–10.

Hari, P., Arovaara, H., Raunemaa, T., and Hautojärvi, A. (1984), Forest growth and the effects of energy production: a method for detecting trends in the growth potential of trees, *Can. J. For. Res.*, **14**, 437–440.

Kauppi, P. (1984), Stress, strain and injury: Scots pine transplants from lifting to acclimation on the planting site. *Acta For. Fenn.*, **185**, 1–49.

Kauppi, P. and Posch, M. (1987), A case study of the effects of CO_2-induced climatic warming on forest growth and the forest sector: A. Productivity reactions of northern boreal forests, in M.L. Parry, T.R. Carter, and N.T. Konijn (Eds), *The Impact of Climatic Variations on Agriculture. Vol. 1: Assessments In Cool Temperate and Cold Regions* (Reidel, Dortrecht, the Netherlands) (in preparation).

Kauppi, P., Kämäri, J., Posch, M., Kauppi, L., and Matzner, E. (1986), Acidification of forest soils: model development and application for analyzing acidic deposition in Europe, *Ecol. Modelling*, **33**, 231–253.

Knabe, W. (1966), Rauchschadensforschung in Nordamerika. Neue Erkentnisse und Folgerungen für deutsche Verhältnisse, *Forstarchiv*, **37**(5), 109–119.

Knabe, W. (1982), Immissionsökologische Waldzustandserfassung, *Sonderheft der Mitteilungen 1982* (Landesanstalt für Ökologie, Landschaftsentwicklung und Forstplanung Nordrhein-Westfalen).

Koch, W. (1969), Untersuchungen über die Wirkung von CO_2 auf die Photosynthese einiger Holzgewächse unter Laboratoriumsbedingungen, *Flora*, **158**, 402–428.

Kohlmaier, G.H., Sire, E.O., Bröhl, H., Kilian, W., Fischbach, U., Plöchl, U.M., Müller, T., and Yunsheng, J. (1984), Dramatic development in the dying of German spruce-fir forests: in search of possible cause–effect relationships, *Ecol. Modelling*, **22**, 45–65.

Koivisto, P. (1959), Kasvu-ja tuotostaulukoita (Growth and Yield Tables), *Commun. Inst. Forestalis Fenniae*, **51**(8), 1–49 (in Finnish).

Kramer, P.J. (1981), Carbon dioxide concentration, photosynthesis, and dry matter production, *BioScience*, **31**, 29–33.

LaMarche, V.C., Greybill, D.A., Fritts, H.C., and Rose, M.R. (1984), Increasing atmospheric carbon dioxide: Tree ring evidence for growth enhancement in natural vegetation, *Science*, **225**, 1019–1021.

Larsen, R.I. and Heck, W.W. (1976), An air quality data analysis system for interrelating effects, standards and needed source reductions: Part 3. Vegetation injury, *J. Air Pollution Control Assoc.*, **26**, 325–333.

Levitt, J. (1972), *Responses of Plants to Environmental Stresses*, Vol. I-II (Academic Press, London).

Materna, J. (1984), *Direct Forest Impacts of Deposition*, presentation given at IIASA Worshop, 13–15 June 1984.

O'Gara, P.J. (1922), Abstract of paper: Sulphur dioxide and fume problems and their solutions, *Ind. Eng. Chem.*, **14**, 744.

Pearcy, R.W. and Björkman, O. (1985), Physiological effects, in Lemon, E.R. (Ed), *CO_2 and Plants. Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*, AAAS selected symposia series (Westview Press, Colorado).

Prinz, B., Krause, G.H.M., and Jung, K.-D. (1984), Potentielle Ursachen des Waldsterbens. Landesanstalt für Immissionsschutz des Landes Nordrhein-Westfalen, Essen.

Rogers, H.H., Thomas, J.F., and Bingham, G.E. (1983), Response of agronomic and forest species to elevated atmospheric carbon dioxide, *Science*, **220**, 428–429.

Schöpfer, W., Hradetsky, J., Bösch, B., and Hannak, C. (1984), Terrestrische Waldschadeninventur Baden-Württenberg 1984 — Ergebnisse der 1. Wiederholungsinventur. Mitt. Forstl. Versuchs- u. Forschungsanstalt Baden-Württenberg.

von Schröder, J. and Reuss, C. (1883), *Die Beschädigung der Vegetation durch Rauch und die Oberharzer Hüttenrauchschäden* (P. Parey Verlag, Berlin).

Schütt, P., Blaschke, H., Hoque, E., Koch, W., Land, K.J., and Schuck, H.J. (1983), Erste Ergebnisse einer botanischen Inventur des "Fichtensterbens", *Forstw. Cbl.*, **102**, 158–166.

Sionit, N., Hellmers, H., and Strain, B.R. (1980), Growth and yield of wheat under CO_2 enrichment and water stress, *Crop Sci.*, **20**, 687–690.

Stöckhardt, J.A. (1850), Über die Einwirkung des Rauches von Silberhütten auf die benachbarte Vegetation, *Polyt. Centr. Bl*, **257**.

Stöckhardt, J.A. (1871), Untersuchungen über die schädlichen Einwirkungen des Hütten- und Steinkohlenrauches auf das Wachstum der Pflanzen, insbesondere der Fichte und Tanne, *Tharandt. Forstl. Jb.*, **21**, 218.

Tinus, R.W. (1972), CO_2 enriched atmosphere speeds growth of Ponderosa pine and blue spruce seedlings. *Tree Planter's Notes*, **23**, 12–15.

Thomas, M.D. and Hill, G.R. Jr (1935), Absorption of sulphur dioxide by alfalfa and its relation to leaf injury, *Plant Physiol.*, **10**, 291–307.

Tolley, L.C. and Strain, B.R. (1984), Effects of CO_2 enrichment on growth of *Liquidambar styraciflua* and *Pinus taeda* seedlings under different irradiance levels, *Can. J. For. Res.*, **14**, 343–350.

Ulrich, B. (1983), Soil acidity and its relations to acid deposition, in B. Ulrich and J. Pankrath (Eds), *Effects of Accumulation of Air Pollutants in Forest Ecosystems*, pp 33–45 (Reidel, Dordrecht, the Netherlands).

Verduin, J. (1952), Limiting factors, *Science*, **115**, 23.

Wentzel, K.F. (1983), IUFRO-studies on maximal SO_2 emissions standards to protect forests, in B. Ulrich and J. Pankrath (Eds), *Effects of Accumulation of Air Pollutants in Forest Ecosystems*, pp 295–302 (Reidel, Dordrecht, the Netherlands).