The Effects of Air Pollution on Forests

Gordon L. Brown

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Gordon L. Brown
Institute of Animal Resource Ecology
University of British Columbia

The term "decline" in forestry, refers to a widespread decrease in the health and vigour of forests. This paper reviews existing literature searching for possible causes of major forest declines, with a focus on the potential involvement of air pollutants including gaseous pollutants, acid deposition, heavy metals and organic compounds.

The author describes the major declines which have occurred or are occurring in the world and outlines the potential causes of decline including natural causes. The response of forests to various pollutants: ozone, sulphur dioxide and nitrogen dioxide, acid deposition, heavy metals and pollutant mixtures is discussed and hypotheses of pollutant-related forest declines are developed.

Currently, most of the information linking air pollution to forest decline is circumstantial. A successful explanation of a decline must fulfill the following conditions:

- It must be possible to connect all the specific symptoms of the decline to the causal factor in question.
- The temporal development of the decline must match the temporal development of the causal factor.
- The spatial distribution of the decline must coincide with the spatial distribution of the causal factor.

Condition number one is the most difficult to satisfy.

The ozone hypothesis is presently the most popular hypothesis of air-pollutant related forest decline. The second most popular hypothesis is that excessive nitrogen compounds are predisposing conifers to winter injury. Scientific opinion is generally moving to the view that different factors are responsible for declines at different locations and that pollutant mixtures are likely of significance.

In the absence of conclusive scientific evidence of the risks of air pollution to Canadian forests, expert opinion on the likelihood of such effects is a logical alternative. The final chapter of this paper evaluates the potential use of the opinions of experts in characterizing the risk of damage to forests from air pollution.

Les effets de la pollution de l'air sur les forêts.

Résumé

Le terme déclin, en foresterie, réfère à une importante décroissance de la santé et de la vigueur des forêts. Ce rapport fai. la revue de littérature existante sur les causes possibles des déclins de certaines forêts importantes. Une attention particulière est portée sur l'implication des polluants atmosphériques, incluant les polluants gazeux, la déposition acide, les métaux lourds ainsi que les composés organiques.

L'auteur décrit les déclins majeurs passés et présents encore dans le monde. Il souligne de plus, les causes potentielles de ces déclins incluant les causes naturelles. La réponse des forêts aux divers polluants: ozone, dioxide de sulfure, d&position acide, métaux lourds, ainsi que les polluants mixtes, est discutée.

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THE EFFECTS OF AIR POLLUTION ON FORESTS: CURRENT UNDERSTANDING, UNCERTAINTY ANALYSIS AND ELICITATION OF EXPERT OPINION

by
Gordon L. Brown
Resource Management Science
University of British Columbia

for

Dr. M. H. Sadar
Canadian Environmental Assessment Research Council

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Abstract

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submitted by Gordon L. Brown
University of British Columbia

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Currently, most of the information linking air pollution to forest decline is circumstantial. A successful explanation of a decline must fulfil1 the following conditions:

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CONTENTS

1. INTRODUCTION

The term decline is used in forestry to refer to a widespread decrease in the health and vigor of forests, frequently leading to death of many individual trees over a large geographical region. McLaughlin (1985) defines declines as complex diseases resulting in progressive weakening of trees and leading to dieback, which is the death of portions of the foliated canopy. Gradual loss of vigor involving reduced growth rate and increased susceptibility to secondary biotic and abiotic stresses typically ensues.

Except in the cases of ozone damaging various pine species in eastern U.S., California, and Mexico, present evidence is not adequate to definitively link air pollution to any particular decline of forests in either Europe or North America. However, a consensus of scientific opinion is developing that air pollutants. are among the primary causal factors in several major forest declines in central Europe and eastern North America.

The first objective of this paper was to review of the existing literature on the possible causes of the major forest declines, with a focus on the potential involvement of air pollutants including gaseous pollutants, acid deposition, heavy metals and organic compounds. Chapters 2 through 6 review the present status of scientific knowledge related to the physical and physiological mechanisms of injury related to specific pollutants, community level responses and uncertainties, and evidence to support or refute various proposed hypotheses which strive to link anthropogenic air pollutants to forest decline.

Although a consensus of scientific opinion seems to be emerging that long range transported air pollutants are contributing to observed forest decline, a scientifically documented link has not yet been established. Thus, there exists a certain unkown risk that Canadian forests are or will be affected by air pollutants, in which case stringent pollution controls may be immediately warranted. On the other hand, there is the risk that implementation of contol programs, with certain negative socio-economic effects, may prove to be unnecessary with respect to forest effects, if air pollution is not a factor in forest decline in Canada. In the absence of conclusive scientific evidence of the risk to Canadian forests from air pollution, expert opinions on the likelihood of such effects seem to be the logical second best alternative. A second objective of this paper was to evaluate the potential use of the opinions of experts in forest air pollution effects, in characterizing the risk of damage to forests from air pollution. This material is presented in Chapter 7.

. OBSERVED FOREST DECLINE

Although tree declines are not new, major regional forest declines have not been observed until recently. Less extensive declines have been observed in Europe over the last 200 years and in North America over the last 100 years (Cowling 1985b).

2.1 West Germany and Europe

2.1.1 Waldsterben

Recent forest declines in Germany ("Waldsterben") have been **summarized** by Blank **(1985)**, **Bruck** (1985) and Schutt and Cowling (1985). In the **1970's** the first reports of forest damage were confined to silver fir damage, which increased dramatically during the hot and dry summer of 1976 and is now affecting nearly all stands. Since the late 1970's symptoms have also been noticed on Norway spruce, **Scots** pine and common beech, which together account for 77% of the total forest area (silver fir covers 2% of the forest area).

This new type of forest decline, called "Neuartige Waldschaden", **is** unprecedented in severity and geographical extent, and cannot be attributed to a known cause of previous **dieback** events. There has been a drastic increase in the total forest area affected, from 8% damage in 1982 to 34% in 1983 and 50% in 1984. However, the majority of this damage is "slight", and the scientific community in Germany is apparently unhappy about the crude inventory methods being used and the fact that all types of damage are reported, even that which clearly is attributable to climatic and biotic factors. Rehfuess has emphasized that, in the case of Norway spruce and silver fir, only decline of high elevation forests should be attributed to the potential effects of air pollution. Other equally widely distributed damage in forests is quite definitely due to climatic factors or fungus infection (air pollution levels in most of these areas are insignificant) (Prinz, 1985).

Forest damage in Germany first appeared at higher altitudes, usually above 600 to 800 meters; the amount of damage still tends to be higher at higher elevations (**Ashmore** et al, 1985). Trees growing on fertile and infertile soils, both basic and acidic, are affected; most severe damage is on northwest facing slopes in northwest Germany, and on west facing slopes in the Black Forest (**Bruck**, 1985).

The "new type" of decline is not confined to West Germany. Recent reports of loss of vigor and increased mortality of deciduous and coniferous forest species has also been reported in East Germany, Austria, Poland, France, England, Yugoslavia, Czechoslovakia, Switzerland, and Italy (McLaughlin, 1985; Cowling 1984b; Postel 1984).

Of the various declines observed in Europe and North America, Waldsterben is by far the most important (Cowling 1985b). It is he first multiple species decline; in **fact nearly all** native and xotic tree species are affected, as well as-some shrubs and herbs. It is also important because of the large geographical area affected, the remarkable diversity of physical, chemical, climatic, soil, site, and forest management conditions in which damage has been observed; the unique symptoms shown by the trees (Table 1), some of which have never been seen before (Schutt and Cowling 1985) and the very great aesthetic and commercial value of the forests to the people of Europe. A survey in the summer of 1983 showed that West Germans were more concerned about the fate of their forests than about the Pershing missiles to be placed on their land (Postel, 1984).

2.1.2 Other Declines in Europe

In addition to Waldsterben, the following declines have occurred in Europe in the twentieth century (Cowling 1984b):

- Tannensterben (white fir decline) in West Germany, since the middle 1700's.

- Kiefersterben (Scots pine decline) in East Germany and European Russia during the early 1970's.

- Oak decline in Germany and France since the early 1900's.

- Pine decline on the Atlantic coast of France since the early 1980's.

2.2 North America

Regional-scale forest decline symptoms in North America are neither as diverse nor as well developed as those in West Germany. Of interest, however, is that at least two of the declines examined provided direct evidence that air pollution (ozone) was the primary causal factor (Cowling 1985b).

In the first of these, Miller et al (1983) attributed injury and growth reductions of ponderosa pine and other species in the San Bernadino Mountains in California to ozone originating in the Los Angeles area, approximately 100 km east.

In the second decline, that of eastern white pine and other species in the Green Mountains of Virginia, a research project by Skelly et al (1983) demonstrated that long range transport of ozone was the primary causal factor.

Other studies of forest decline in North America have failed to establish unequivocally that air pollution was involved in the decline. Possible reasons for pitch and shortleaf pine declines in New Jersey were evaluated, and it was concluded that acid precipitation might have been a factor on the basis of a strong orrelation between annual variation in stream pH (a surrogate or acid rain) and growth rates (Johnson et al 1981).

Table 1

The Common Symptoms of Waldsterben

Growth decreasing (hypoplastic) symptoms:

- Discoloration and loss of foliar biomass
- Loss of feeder root biomass
- Decreased annual increment
- Premature senescence of older needles in conifers
- Increased susceptibility to secondary root and foliar pathogens
- Death of affected trees
- Death of herbaceous vegetation

Abnormal-growth (hyperplastic) symptoms:

- Active casting (abscission) of green leaves and green shoots
- "Stork's nest" formation in white fir
- Altered branching habit and greater than normal production of adventitious shoots
- Altered morphology of leaves
- Altered allocation of photosynthate
- Excessive seed and cone production

Water-stress symptoms:

- Altered water balance

Source: Schutt and Cowling (1985)

In New York Puckett (1982) used multivariate regression in dendroclimatology to show that changes in the relation of tree growth to climate have occurred since 1945. By elimination of other sources of decline such as disease and insects it was concluded that acid rain and/or air pollution alone or in combination with other growth limiting factors may be responsible.

Since the early 1980's there has been increased observation and documentation of red spruce decline throughout the Appalachian Mountains. The present decline is unprecedented in its synchrony and consistency, affecting spruce and fir of all age classes, site conditions, soil type and aspect. On the basis of tree ring cores, this decline was found to have begun in the early 1960's (McLaughlin 1985, Bruck 1985).

Since 1964-1966, red spruce were found to have declined by 40-60% in basal area in low elevation forests (less than 900 m) and by 60-70 % above 900 m (Scott et al 1984). At Mt. Mitchell in North Carolina red spruce and Fraser fir above 1935 m are in a severe state of decline. Trees of 45-85 years exhibited some form of growth reduction beginning in the early 1960's. Spruce stands below 1935 m are healthy and vigorous (Bruck 1984, Bruck 1985).

Decline of red spruce at high elevation forests is characteristic of a stress' related disease ie (Johnson and Siccama 1983a):

- lack of an obvious cause,
- dieback and loss of foliage in the crown and branch tips and progressing downward and inward over time,
- subsequent invasion by secondary organisms that normally do not cause substantial damage to vigorous trees.

In addition to the above, the following regional declines, each with no obvious cause, have been observed (Cowling 1985b):

- Birch dieback in the northeastern U.S.A. and southeastern Canada in the early 1940's through 1970's.
- Oak decline in the southeast U.S.A. since the mid 1960's.
- Maple declines in northeast U.S.A. and southeast Canada since the 1950's.
- Decline in growth in loblolly, shortleaf and slash pines in southeast U.S.A. since the mid 1960's.
- Ash dieback in southeast Canada and northeast U.S.A. since the 1950's.

'he cause of several additional forest declines in North America as determined to have been due to natural causes as follows (Cowling 1985b):

- Beech bark disease in northeast U.S.A. and southeast Canada since the early 1940's.
- Littleleaf disease of shortleaf and loblolly pines in the southeast U.S.A. since the early 1920's.
- Pole blight of western white pine in the Rocky Mountains of western U.S.A. since the early 1950's.
- Sweetgum blight in the southeastern U.S.A. in the 1950's and 1960's.

2.3 Mexico

Pine trees are declining and dying at elevations of 3000-3500 meters in the mountains around Mexico City (deBauer et al 1985). Ozone injury symptoms were observed on mature needles. A pollution gradient effect was also observed; trees were more extensively damaged near Mexico City, with damage decreasing as the altitude decreased and distance from Mexico City increased. The authors attributed the decline, which resembles the ponderosa pine decline in California, to ozone.

2.4 Australia

"New England Dieback" is a particular group of symptoms including crown defoliation, secondary shoot development, death of primary and secondary shoots, and premature death of eucalyptus trees in Australia. Dieback was independent of most site, land use and stand characteristics. The cause was not obvious until several stands of trees were treated with insecticide, leading to significant recovery of the treated stands. Insects were implicated as the primary cause of the decline (Mackay et al 1984).

2.5 Pacific Rim

Evidence of the role of natural processes in forest decline is also found in Pacific Rim forests (McLaughlin 1985). Declines observed in the Pacific Rim are very far from pollution sources, where the air may generally be considered "pristine". Several forest declines have been documented in the past and are considered normal; they occur in a wide variety of site, soil and climatic conditions. There are five principal theories of causation as follows (McLaughlin 1985):

- diseases and insect damage,
- climate change or perturbation,
- nutrient limitation,

- stand succession, and
- physiological stress in areas where trees are narrowly adapted.

The stand succession (cohort senescence) theory of Mueller - Dombois seems to fit many of these situations. This theory suggests that concomitant senescence of even-aged cohorts of trees occurs in patterns determined by previous catastophic disturbances such as tropical storms, lava flows, ash blankets, or landslides. These patterns may be repeated but occur with decreasing continuity in successive generations as large numbers of trees reach senescence simultaneously in patches of ever decreasing spatial integrity (McLaughlin 1985).

2.6 Common Decline Factors in Europe and North America

Appendix 1 contains a comparison of the major symptoms observed in the declines of forests in Europe and North America. Some of the most important conclusions of this comparison are as follows (Cowling 1985b):

- The symptoms of decline in forests are diverse and often specific to a particular tree species.
- Although there are similarities, there are many differences among the symptoms of decline observed, attributed primarily to different species.
- Norway spruce (ornamental in North America) is showing almost identical symptoms of stress on both continents.
- Oldest tissues tend to be affected first.
- Decreases in diameter growth of conifers have been observed on both continents, although these are more gradual in Europe and more synchronous in North America.
- Some of the most important differences in symptoms include:
  - greater frequency of dying back from the top (youngest tissues affected first) in North America than in Europe,
  - greater frequency of abnormal growth symptoms in Europe than in North America (symptoms 9 to 15 Appendix 1),
  - substantial number of symptoms observed in Europe (symptoms 8,9,10,11,14) are reported only rarely or not at all in North America, and
  - greater frequency of decrease in growth without other visible symptoms of damage in North America than in Europe.

. POTENTIAL CAUSES OF FOREST DECLINE

3.1 Analysis of Regional Declines

Airborne chemicals have been positively identified as an important causal factor in only two of the 18 European and North American regional declines listed in the previous section. These include the decline of ponderosa and Jeffrey pine in California, and the white pine decline in eastern U.S.A.. In these cases (Cowling 1985c):

- Geographical gradients in damage are correlated with gegraphical gradients in ozone concentration;
- The major symptoms (yellowing and necrosis of foliage, decline in rate of growth, and death of trees) can be reproduced by exposure to ozone; and
- Genetic variation in susceptibilty and resistance to damage in the field is correlated with genetic variation in susceptibility and resistance to ozone in controlled exposures.

In the case of Waldsterben, geographical gradients in damage are not well correlated with geographical gradients in concentration and deposition of any known air pollutants. But in at least one region, Baden-Wurttemberg, the amount of damage to trees was greater on trees of greatest exposure to moving air masses. This was shown with regard to predominant wind direction, altitude, position within a stand (edge vs center), and position within the canopy (dominant vs non-dominant trees). Also no known biotic, physical, or soil chemical factors were well correlated with damage. Finally, controlled exposure to ozone and to ozone plus acid mist has reproduced one of the symptoms (yellowing of spruce foliage) observed in the forest (Cowling 1985c).

In the case of red spruce and Fraser fir declines, evidence for air pollution involvement is weakest of all. Here the amount of damage (decrease in diameter growth, loss of foliage and root biomass, and mortality of the trees) is greater at high than at low elevation. This is consistent with altitudinal gradients in concentration of ozone and other pollutants, time of exposure to nutrient-rich and acidic cloud water, and accumulation of lead and other toxic metals. Neither controlled exposure tests nor genetic tests with resistant and susceptible genotypes have been done with red spruce or Fraser fir (Cowling 1985c).

In addition to the above, declines of forests where air pollution is a primary causal factor may be ocurring unnoticed, for two reasons:

- Hidden injury: growth and productivity can be declining in trees subjected to low-level and long-term exposures to air pollution that show no visible signs of injury (Postel, 1985).

- Extensive areas of low elevation, spruce-fir forests in eastern North America have been studied little with respect to dieback and decline (Bruck, 1985).

3.2 Natural Causes of Forest Decline

Widespread mortality of selected forest species have been observed before at times, and in places where air pollution was not a factor (Bruck 1985). There are several potential natural causes of forest growth decline, which are summarized in Table 2.

3.2.1 Role of Natural Causes in Forest Decline in Germany

Waldsterben cannot be attributed to a known cause of natural dieback factors, although it is possible that a series of hot and dry years experienced during the last decade has affected tree vitality and resistance to pollutant and/or pathogen attack. Hot summers have often been followed by harsh winters; these drastic and sudden changes may be important. The number of trees affected by fungal infections has markedly increased over the past few years suggesting pathogens play an important role, probably as a secondary cause of decline following a lowering of the resistance by pollution or climatic factors (Blank, 1985).

The following natural factors have been suggested as possibly contributing to German forest declines (Environmental Resources Ltd. 1984):

- Many of the ecosystems of central and southern Germany, where extensive damage has been observed, are naturally fragile with respect to their ability to sustain permanent and robust tree growth (eg altitudes over 800 m, acidic soils, underthinned trees over 50 years old).

- Stands with even aged trees may lead to a fragile ecology for firs and the likelihood of disease susceptibility.

- Unhealthy forests in Bavaria may be partially explained by their location in areas experiencing storms and snow, and to the use of forests for grazing.

- Climate, particularly drought and wind, could be a factor. Dry years may lead to fine root damage, and this is a major cause of fir mortality. The long dry summer of 1976 may have been particularly damaging - the death of fine roots predisposed the root system to increased attack by pathogens and fungi.

Another open question is the possibility of the quality of received radiation being involved. It cannot be ruled out that the higher proportion of ultraviolet radiation received by trees at higher altitudes may be involved in the degradation of chlorophyll in damaged needles (Blank 1985).

Table 2

Possible Natural Causes of Forest Decline

Stand age:	• distribution of trees shifting to older stands • higher proportion of smaller trees in competition with larger trees
Stand density:	• higher average basal area • increased competition in overstory
Hardwood competition:	• in overstory • in understory • improved fire protection favors hardwoods and shrubs
Stand structure:	• uneven stands with more intermediate trees • less uniform spacing with clumps and holes
Species competition:	• some hardwood species may negatively influence pine growth • hardwoods may be more competitive than pines
Insects & disease:	• damaging agents may cause stress without actually damaging trees • pathogens may be unidentified as causal
Genetic stock:	• poorer through natural selection
Climate:	• Precipitation: amount, form, distribution • Temperature extremes summer and winter • Other weather elements eg early or late freeze
Site	• Naturally acid soils • Naturally "borderline" fertility, etc.

Adapted from Cowling 1984b

.2.2 Role of Natural Causes of Decline in North America

Bruck (1985) feels that the possibility that the eastern North America red spruce decline could be the result of natural factors should not be ruled out.

Southern Appalachians

On Mt. Mitchell in North Carolina red spruce and Fraser fir growing at altitudes above 1935 m averaged 75-90% defoliation, characterized by a shedding of the oldest needles. Precipitation data from 1930 to 1983 showed that at no time during these 53 years was there a drought near the summit of Mt. Mitchell, nor were abnormally high or low seasonal temperatures of significance (Bruck, 1984).

Pine Barrens

In the Pine Barrens region of southern New Jersey, abnormal growth over the past 25 years was correlated with natural environmental factors including winter moisture, winter temperature, spring and summer insolation and summer drought, and stream pH (a surrogate for precipitation pH) (Johnson et al, 1981).

Northern Appalachians

Although several studies have been conducted of the red spruce declines in the high elevation forests in the northern Appalachians, the cause has not been unequivocally determined. There is reasonable evidence that the dry period of the early 1960's triggered the decline, but it is not clear whether drought alone was sufficient to cause the initiation of the decline, or whether other stresses were involved (Johnson and Siccama, 1983a; Johnson 1983).

In the 1950's and 1960's substantial areas of red spruce were observed in Vermont and New Hampshire. Fungal pathogens whose invasion is triggered by stress were found in high numbers. Recent spruce decline in southern Vermont is heavily infected with Armillaria fungus, but no fungal pathogens are present in declining trees in northern Vermont (Johnson and Siccama, 1983a).

3.3 Human Causes Of Forest Decline Other Than Air Pollution

The following possible human causes other than air pollution of forest decline have been suggested (Cowling, 1984b):

- Loss of site quality, by clearcutting, heavy cutting on better sites, and erosion of top soil.

- Loss of "old field" site conditions, due to cultivated soils, competing vegetation, and residual fertilizers.

- Harvesting, due to selective cutting of better, faster growing trees, and soil compaction by heavy equipment.

- Poorer genetic stock, as a result of selective cutting.

In addition it has been suggested that regional declines may be apparent only now through new and improved field measurement procedures and computation methods, when in fact the regional declines now observed may be part of the natural course of events (Cowling, 1984b).

3.4 Multiple Stress Concept

Regional declines of forests in Europe and North America are believed to result from the combined action of several different competitional, biological, physical and chemical stress factors that act togerther simultaneously or sequentially to induce the symptoms of damage (Cowling 1985c). One of the most widely accepted concepts of causality was introduced by **Manion** (1981). Stresses are **categorized** into three classes as follows:

- Predisposing factors, resulting in chronic weakening, due to changes in climate, soil moisture, genotype of host, soil nutrients, air pollutants, or competition. These factors may make the tree more susceptible to the shorter term inciting factors.

- Inducing or inciting factors, resulting in short term acute stresses which may act as "triggering mechanisms", due to insect defoliation, frost, drought, salt, air pollutants, or mechanical injury. Sudden physiological shocks may alter the tree's physiological condition and make it more susceptible to secondary biotic stresses (either in the form of increased attractiveness as a host, or decreased capacity to recover from the stress). Carbohydrate and nutrient supply may play an important role in these changes.

- Contributing factors, resulting in acceleration of decline once a tree has begun to decline, due to bark beetles, canker fungi, viruses, root-decay fungi, and competition. These factors are often blamed for the tree's condition when they have in fact exerted their role as secondary or tertiary stresses.

In well stocked forest stands, competition may have significant influence as either a predisposing or contributing factor in tree responses to anthropogenic stresses (McLaughlin, 1985).

Air pollutants may act as both predisposing and inciting stresses in influencing declines of forest trees. The potential interactions of pollutant and natural stresses in both of these categories suggest that multiple stress hypotheses for these declines may be particularly appropriate (McLaughlin 1985).

lthough the concept of multiple causality has gained wide acceptance in both North America and Europe, there is much less agreement on which factors are predisposing, inducing or inciting, and contributing in any given decline of forests (Cowling, 1985b). Additionally it should be remembered that airborne chemicals of importance to forests include beneficial as well as injurious substances.

4. FOREST RESPONSE TO AIR POLLUTION: POLLUTANT MECHANISMS

Except in the cases of ozone damaging various pine species in eastern U.S., California, and Mexico, present evidence is not adequate to definitively link air pollution to any particular decline of forests in either Europe or North America. However, on the basis of general knowledge of the responses of forests to stress, some circumstantial evidence, and a very few controlled-exposure experiments, a consensus of informed judgement is developing that the air pollutants of greatest probable relevance to the decline of forest include the following in approximate order of decreasing importance (Cowling, 1984b):

- Ozone
- Total biologically available nitrogen compounds, including wet and dry deposition of all biologically available gaseous, aerosol, and dissolved or suspended forms of nitrate (including HNO_3 vapor), ammonia and ammonium-nitrogen.
- Other phytotoxic gases, including nitrogen oxides, sulfur dioxide, fluorine, peroxacetyl nitrate (PAN) and peroxyproprionyl nitrate (PPN).
- Toxic metals especially lead and cadmium, and possibly also zinc and copper.
- Nutrient and acidity-determining cations and anions in wet and dry deposition, ie acid deposition.
- Growth altering organic chemicals such as ethylene and aniline.

The physical and/or physiological mechanisms by which the above air pollutants are thought to impact forest trees are described in this section. Evidence to support or refute the various air pollution-related hypotheses of forest injury presently believed to be plausible is given in Section 6.

4.1 Ozone

4.1.1 Loss of Foliar Nutrients

Exposure to elevated ozone levels damages plant cell membranes, thereby altering their permeability and the integrity of cellular organization (McLaughlin, 1985). Cell membrane damage causes the cells to become "leaky", resulting in increased leaching of ions, a process which may be exacerbated by acid fog and acid rain. Ozone also damages the photosynthetic apparatus, resulting in diminished carbohydrate reserves which reduce the ability of the affected trees to replace the leached nutrients (Skeffington and Roberts, 1985). In addition to the negative effects on growth resulting from nutrient deficiencies, changes in foliar nutrient status may enhance foliar susceptibility to frost injury (Ashmore et al 1985).

.1.2 Reduced Biomass of Fine Roots

Altered plant-water relations (decreased water uptake) can result from a reduction in biomass of fine roots, due to reduced translocation of photosynthate from pollution damaged shoots. In general, stresses that reduce the capacity of aboveground plant systems to produce photosynthate at a rate required for growth and development of these tissues will result in reduced allocation to root systems and a consequent decline in root vigor. Gaseous air pollutants, particularly ozone, can alter partitioning of biomass between plant parts and interfere with translocation of photosynthate to these systems (McLaughlin 1935).

4.1.3 Altered Resistance to Secondary Stresses

Both natural and anthropogenic stresses can alter the allocation of resources to various plant organs and among various biochemical compartments. These influences may exert significant control over a tree's ability to resist disease (McLaughlin 1985). Forest trees may become more susceptible to secondary stresses as a consequence of exposure to air pollution. In both the white pine decline in Virginia and the ponderosa/Jeffrey decline in California, forest decline was furthered by secondary stresses including bark beetle attack and root disease (Skelly et al, 1983; Miller et al, 1983).

4.2 Excess Nutrient (Nitrogen Compounds)

Although nitrogen is one of the most important nutrients required by forest trees for normal growth and development, and is the element which is most often limiting to forest growth and productivity, it is also known to have certain detrimental effects on forest plants when deposited in greater than normal amounts and/or concentrations, as follows (Cowling, 1985b):

- Stimulation of increased growth leading to increased demand for all other essential nutrients and thus to deficiencies of other nutrient elements.

- Increased susceptibility to frost end to winter desiccation due to delay in conversion of starches to sugars and/or in formation of protective cuticle on leaf surfaces. An oversupply of N deposited as ammonium or nitrate ions carried by windblown dust, rain or snow, may exacerbate frost damage. Plant cells continue to grow late into the autumn, and excess nitrogen delays differentiation of cuticularized epidermis. If cuticle thickening is not completed, the plants are more susceptible to damage from winter desiccation or early frost.

- Inhibition of necrosis of mycorrhizae, which are beneficial associations of fine feeder roots with certain soil fungi which assist in uptake of nutrients and water and afford protection against feeder-root pathogens of forest trees.

- Predisposition to increased attack by foliage and root-disease fungi, and by insects.

- Changes in the relative amounts of shoot growth with respect to root growth. Increasing the shoot:root ratio of trees, whether induced nutritionally from atmospheric inputs or from reduced translocation of photosynthate from pollutant-stressed shoots, would be anticipated to enhance susceptibility of trees to moisture stress. Potential transpiration is higher due to larger leaf area, and water uptake from the soil is reduced due to a smaller root system (McLaughlin, 1985; Watt Committee, 1984).

- Alterations in patterns of nitrogen transformations in forest soils including nitrification, denitrification, and possibly biological fixation of nitrogen.

An alternate mechanism of potential excess nitrogen/ammonium was proposed by Nihlgaard (1985). Since most plants are well adapted to live with very low levels of N, they are capable of taking it up in various forms including gaseous atmospheric ammonium, a major source of which is volatilization of agricultural fertilizers. When forests are N-saturated (eg after exposure to 30 kg N/ha for 30 years), trees taking up gaseous ammonium may accumulate it and other non-protein N in the leaves. This is enhanced when protein synthesis is blocked in the leaves due to Mg, K or P deficiencies. The result can be excess hydrogen ion and other toxic material buildup from ammonium oxidation; secondary effects include decreased frost hardiness, increased fungal disease, increased insect attack and algal growth, and early fall of green leaves.

4.3 Sulfur Dioxide and Nitrogen Dioxide

Both sulfur dioxide and nitrogen dioxide are sufficiently soluble to dissolve readily in the extracellular water once they have entered a leaf. Although S and N are essential mineral nutrients, they can cause physical and biochemical disturbances because the cells are exposed to higher levels of some chemical species (sulfite and nitrite) than occurs in normal metabolism (Watt Committee, 1984).

4.3.1 Effects on Stomata

The primary response of plants to sulfur dioxide is on stomatal functioning, with stomata of some species opening at concentrations as low as 50 ug/m3. This is the result of damage to the epidermal and subsidiary cells. Sulfur dioxide has also been shown to result in stomatal closure, especially at higher concentrations (1430 ug/m3) or when the relative humidity was low. Strong interactions with humidity have been noted; 100 ug/m3 caused stomatal opening at high humidity and closure at low humidity in bean, sunflower and tobacco. Effects of nitrogen dioxide on stomata have not been investigated in detail, although there is evidence that in bean it may cause a temporary stimulation of opening similar to the effect of sulfur dioxide (Watt Committee, 1984).

Even a small disturbance of the normal functioning of stomata is likely to impair the physiological efficiency of a leaf, and a major disturbance will lead either to water-deficit stress or to a severely restricted supply of carbon dioxide for photosynthesis. Water-deficit stress may be particularly important for the upper branches of trees whose supply of water is strictly limited by the resistance of the xylem conduits. In cases where pollutants cause stomata1 closure, the interference with carbon dioxide supply must limit growth and may also be associated with premature senescence of leaves (Watt Committee, 1984).

4.3.2 Effects on Photosynthesis

Although pollutant-induced stomata1 closure must directly affect photosynthesis, there is evidence also of direct metabolic effects of sulfur dioxide and its products in plant cells. Structural changes within chloroplasts seen under the electron microscope are the first visible signs of perturbation and are thought to indicate ionic disturbances or pH changes. These are reversible after short fumigations, but recovery time increases after longer treatments or exposure to higher concentrations. However, because of the complex nature of the effects of sulfur dioxide on various plant processes, and due to strong interactions with local environmental conditions including light intensity, relative humidity and temperature, it has so far proved impossible to describe a precise dose-response relationship (Watt Committee, 1984).

The results of experiments of nitrogen dioxide effects on net photosynthesis are even more variable. Inhibition of photosynthesis seems to begin in many species at gas concentrations between 200 and 500 ug/m3, and at lower concentrations may result in growth stimulation (Watt Committee, 1984).

4.4 Acid Deposition

Claims were made in the early 1970's that acid rain (wet deposition) was causing a decline in forest productivity in Scandinavia. Fifteen years later these claims have not been substantiated, but the major research effort that followed the claims revealed several potential pathways of injury to plants from acid deposition. These include both direct or contact effects, and indirect effects.

4.4.1 Direct (Contact) Effects

Potential direct effects of acid deposition on plants include foliar damage; effects on reproductive processes, seedling emergence and early growth; and effects on canopy nutrients. Direct effects of acid deposition on plants have so far only been observed under very acidic simulated rain solutions. The effects escribed below have rarely if ever been observed in the field.

Foliar Damage

Potential effects of acid deposition include direct foliar damage due to excess acidity, cuticular damage, interference with normal functioning of guard cells and poisoning of plant cells after diffusion of acidic substances through the stomata or cuticle. Potential results include changes in photosynthetic efficiency and altered plant water relations. The majority of these mechanisms have been observed in experiments, although the dose applied was in general significantly more acidic than ambient conditions (Morrison 1984). Very few if any of these effects have been observed in the field.

Effects on Reproduction and Growth

Potential effects of excess acidity include reduced pollen germination, seedling germination and emergence, and reduced early growth, including alterations in morphology and autogeny of very young seedlings. These effects are generally only observed in very acid conditions, for example in experiments with simulated rain at or below pH 3.0-3.5.

Effects on Canopy Nutrients

Canopy nutrient enrichment can occur due to trapping, filtering, or absorption of particulates and gases (dry deposition) as well as substances in solution (wet deposition). On the other hand, crown nutrient depletion can occur due to crown leaching, whereby cations adsorbed onto exchange sites on the foliar cuticle are displaced by hydrogen ions from precipitation. Replenishment cations move directly from the transpiration stream within the plant into the leaching solution by diffusion and mass flow. Increasing displacement of adsorbed cations should accompany increasing acidity of rain pH (Morrison, 1984).

Canopy exchange processes vary among both chemical elements and between species. For example, hardwood canopies generally gain nitrogen, while conifer species generally experience minor losses. Leaching losses of sulfate, calcium and magnesium occur to varying degrees with both forest types. Among the nutrients lost from foliage are carbohydrates, which are the major constituents leached from foliage (McLaughlin 1985).

The significance of these losses will depend upon the rates of replenishment from the soil, as well as on the overall nutritional adequacy of initial plant tissue levels. The combination of cation losses from foliage and reduced cation availability and/or uptake from soil (see Section 4.4.2) could potentially result in a nutrient deficiency stress on forest trees (McLaughlin, 1985).

hroughfall (precipitation below the canopy) is altered chemically from ambient precipitation due to interaction with the canopy. Assuming precipitation and deposition components are not absorbed into the canopy, throughfall will consist of ambient precipitation, crown leachates and crown wash-down, which represents materials dry deposited on leaves and washed off. If it is assumed that absorption and leaching losses are insignificant, total content in throughfall less that in ambient rainfall (ie washdown) is an estimate of dry deposition.

4.4.2 Indirect Effects

Potential indirect mechanisms whereby acid deposition could have a negative impact on plants include: changes in site fertility, aluminum toxicity, increased incidence of tree diseases or insect attack, and effects on mycchorizae.

<u>Changes</u> in Site <u>Fertility</u>

The potential negative effect of acid rain on forest soils is considered to be related to displacement of calcium and magnesium from the upper soil horizon, or from reduced microbial decomposition and release of nutrients from soil organic matter. On the other hand, positive effects may potentially result from rainfall nitrogen inputs where available nitrogen in soil is limited. If soil acidification is going to occur, levels of exchangeable ydrogen and aluminum must increase at the expense of either dsorbed basic cations or by occupying new exchange sites. In the former case there is a loss of available nutrients from the soil. Whether this will occur depends on the following (Watt Committee, 1984):

- the equilibrium between cations in solution and those on the exchange surface, which controls the nature of the exchange,

- the presence of a mobile ion, such as sulfate, to transport the resulting cation out of the soil, thereby achieving electroneutrality. In strong sulfate adsorbing soils, nutrients will not be leached.

The potential losses of nutrients from soils must be considered in relation to the following (McLaughlin, 1985):

- available pools of nutrients in soils and vegetation,

- natural leaching losses from internal acid production by trees and microorganisms,

- rates of resupply of nutrients from mineralization of soil organic matter and weathering of minerals, and

- nutrient uptake and incorporation into woody biomass

The significance of nutrient losses from soils to growth and physiological processes of forest trees has not been well quantified, and there are significant differences in nutrient requirements between tree species. Other acidification-related soil processes that could be affected include availability of phoshorous, which is pH-dependent, and changes in mineral weathering.

Aluminum Toxicity

Based on long-term studies of forest soils in the Solling Plateau in West Germany, Ulrich predicted that decreased plant water uptake could be the result of a reduction in biomass of fine roots induced by aluminum toxicity. (The mechanism is described in more detail in Section 6.)

Disease and Insect Attack

In general, trees weakened by any primary stresses that reduce below ground vigor are likely to experience increased susceptibility to root pathogens. In declining red spruce stands in New England, an increasing incidence of the root decay fungus *Armarillea* was found in all locations examined. Root decay was considered a contributing secondary agent on the basis of its being least developed on the most heavily damaged stands at high elevation (McLaughlin, 1985).

It has been demonstrated that acid rain at pH 3-4 can reduce the incidence of pathogens in some situations, due presumably to the debilitating effect of acid on the pathogen. In other cases infection can be enhanced, as a result of plant injury caused by acid deposition (Bruck and Shafer 1982).

Effects on Myccorhizae

It has been demonstrated that simulated rainfall at a near ambient pH level can reduce the vigor of myccorhizae of loblolly pine seedlings (Shafer and Bruck 1985). This could potentially result in decreased uptake of nutrients and water and reduced capacity for growth.

4.5 Heavy Metals

In addition to aluminum (described above) potentially toxic metals include lead, cadmium, zinc and copper.

The interaction of factors controlling chemical and biological availability of heavy metals, and ultimately biological effects, is poorly understood. Individual and combined trace element concentration thresholds for toxicity to forest trees have generally not been determined. Because of the uncertainties of influences of elemental ratios and rhizosphere reactions in soil solutions, the levels of trace elements in tissues may be a more realistic indicator of toxic threshold (McLaughlin, 1985).

4.6 Growth Altering Organic Substances

It has been suggested that, among the thousands of synthetic organic compounds produced, some might, by means of release to the atmosphere as fugitive emissions, contribute to the systems of forest decline. It is known for example that ethylene can affect plant growth, and very low concentrations of atmospheric aniline from a chemical plant have resulted in dieback and decline of trees in the vicinity (Shutt and Cowling 1985).

4.7 Pollutant Mixtures

It is now well established that the effects of an air pollutant may be altered substantially by the presence of other air pollutants (Ashmore et al 1985). Effects of pollutant mixtures on plants may be additive, antagonistic (less than additive) or synergistic (more than additive).

As described in Section 4.1.1, leaching of magnesium and calcium by acid rain or acid mist may be enhanced by ozone damaging the cell membranes. Other potentially significant interactions include O3/SO2, SO2/NO2, SO2/NO2/O3, acid deposition plus any combination of gaseous pollutants etc.

Peterson (1985) suggested a possible ozone-N-acid deposition interaction. Foliar cells may be more sensitive to ozone damage as a result of excessive N fertilization, allowing more rapid leaching of nutrients by acid deposition.

Nihlgaard (1985) proposed a possible excess nitrogen/ammonia-acid deposition interaction, leading to accumulation of toxic hydrogen ions within foliage.

5. FOREST COMMUNITY LEVEL RESPONSES

Forest response to air pollution and other stresses will ultimately result from physical, chemical and biological integration of many processes. Because of the perennial nature of trees, this integration may occur over a long timeframe and hence involve strong interactions with forest community dynamics. Stresses resulting from anthropogenic air pollutants may be either obscured or accentuated by natural processes. Air pollutants are known to affect vegetation at various levels of organization, from the cell to the ecosystem. Best understood are the responses of tissues, organs and individual plants; much remains to be learned about pollutant effects on forest communities and ecosystems.

5.1 Stress in Ecosystems

It is important that a stress at one level of organization may be beneficial at a higher level. For example, periodic fire is a stress to the many organisms that are hurt or killed, but it is not necessarily a stress at the ecosystem level; the absence of fire at this level may be a stress (Odum, 1985). Furthermore disturbance at the same level may sometimes have a positive effect or produce both positive and negative responses (the "subsidy-stress" syndrome).

Some ecosystems have become more productive under moderate stress, possibly because their evolution occurred under the influence of these stresses. And since each ecosystem has developed under a different set of external variables, ecosystems have different capacities to resist or recover from stresses. As ecosystems suffer stress, they respond on various time scales, from the almost immediate, to the delayed for decades (Risser 1985).

Defining what constitutes stress to an ecosystem has been difficult, because ecosystems are constantly subjected to external conditions that cause stress, such as drought, air pollution and insect outbreaks. Some of these external influences are natural, others are caused or intensified by human activities (Risser 1985). Air pollution stress should be thought of as an unusual external disturbance, a stressor of (historically) low probability to which a community of organisms is not preadapted (Odum 1985).

5.2 Forest Response Stages

Disturbance from air pollutants is dose related and dose-response thesholds for a specific pollutant are very different among the various organisms of an ecosystem. Thus ecosystem response is a very complex process (Smith 1985b).

he effects of pollutant dose consists of four stages of response (Bormann 1985) corresponding to four dose classes (Smith, 1981). These response stages are given in Table 3.

Table 3

Forest Community Level Response Stages

- Stage 0. Insignificant pollution, pristine systems.
- Stage I. Low dose. Ecosystems serve as a sink for some pollutants, but species and ecosystem functions are relatively unaffected or may be slightly stimulated.
- Stage IIa. Intermediate dose. Levels of pollutants are inimical to some aspect of the life cycle of sensitive species or individuals, which are therefore subtly affected eg reduced photosynthesis or reproductive capacity, change in predisposition to insect or fungus attack.
- Stage IIb. With increased pollution stress, populations of sensitive species decline, and their effectiveness as functional members of the ecosysytem diminishes.
- Stage IIIa. High dose. Size becomes important to survival, and large plants, trees and shrubs of all species die. The basic structure of the forest ecosystem changes, and biotic regulation is affected. The ecosystem becomes dominated by small scattered shrubs and herbs, including weedy species not previously present. Productivity drops as the ability of the ecosystem to repair itself by substituting tolerant for intolerant species is exceeded. Masses of highly flammable dead wood are left behind, increasing the probability that fire will occur. The capacity to regulate energy flow and biogeochemical cycles is severely diminished. Runoff increases, the loss of nutrients previously held and recycled accelerates, erosion increases, and soil and nutrients are exported to interconnected aquatic systems, which may be severely affected.
- Stage IIIb. Ecosystem collapse. Even if the perturbing force is removed, the system may never return to its predisturbance levels of structure and function.

Source: Bormann, 1985

5.2.1 Response to High Pollution Dose

Studies conducted in the vicinity of strong point sources have in the past provided many opportunities for observing Stage III responses in various forest types. Although different studies have involved different species and ecosystems, there were certain similarities in community response (McLenahen 1983). Retrogression, or reverse succession, is a typical process observed under high gaseous pollutant dose conditions. Reduced diversification is followed by successive structural stripping from the tallest vegetative layer downward, with an accompanying dominance of a few pollutant-tolerant species.

In the early 1970's H.T. Odum proposed that pollutant stress increases the energy demand for survival within the organism, diverting power away from central organization and specialization within the ecosystem. If the stress is sufficient, the system loses specialists and disintegrates, leaving generalists to start succession once again (McLenahen 1983).

All ecosystems undergo various natural or human-made recurring disturbances, such as wildfires, windstorms, insect outbreaks, or forest cutting. Usually ecosystems have a built in capacity to recover from these disturbances. The difference between such classic disturbances and Stage III stress resulting from air pollution is the long term nature of air pollution stress and the degree of degradation, which drive the ecosystem over the resilience threhold where the properties of the system may seek new steady-state levels instead of returning to original conditions.

5.2.2 Response to Intermediate and Low Pollutant Dose

Since ecosystems are essentially unaffected by low pollutant dose (to our knowledge) this discussion will focus on Stage II responses of forests, ie to Smith's (1981) intermediate dose.

Stage II and especially Stage I responses to air pollution arc difficult to separate from other factors that control tree growth, such as age, competition, moisture, temperature, nutrients, insects, and pathogens; as well as from other factors that induce symptoms of dieback and decline, such as drought or other climatic stresses, insects or pathogens (Smith 1985a).

In addition species composition and succession patterns are regulated by numerous determinants, including site alterations, species interactions, activities of insects and pathogens, windstorms, fires, and human cultural activities. Forest ecosystem production is influenced by several variables, including system age, competition, species composition, moisture, temperature, nutrients, insects and pathogens (Smith 1985a).

ormann (1985) believes that Stage II responses may be occurring over large areas of the United States, and that the subtle and cumulative effects that are occurring may be damaging over extensive areas in the long term.

otential implications include (Bormann 1985):

- Direct reductions in productivity with or without visible symptoms of damage. Tree ring analyses in eastern U.S. and California show declines in productivity are associated with ozone damage. Productivity losses in crops have been demonstrated without visible symptoms of damage. Ambient ozone concentrations have been shown to result in 15-20 % reductions in aspen, eastern cottonwood, and hybrid poplar productivity, without visible symptoms of ozone damage.

- Significant changes in gene pools, with natural selection favoring resistance to air pollution. Obvious costs include economic losses if pollution sensitive species are of commercial recreational or aesthetic value. Hidden costs may include lowered productivity and loss of fitness, due to loss of competitive ability, reproductive capacity, or resistance to drought, insects or disease.

As mentioned previously, it is possible that due to "hidden injury", air pollution stresses are now causing significant but largely unmeasurable declines in forest ecosystems. Such declines may not now be experiencing loss of biotic regulation: as populations of sensitive plant species decline under air pollution stress, their role in ecosystem function may be taken over by tolerant species in the same or different layers of the forest. This situation suggests there may exist a threshold below which pollution effects on individual species may not perturb biotic regulation by the ecosystem. On the other hand, there may not be a threshold as such - small but continuous reductions in energy flow through ecosystems may be linked to subtle declines in biotic capacity to regulate energy flow and biogeochemical cycles (Bormann 1985).

5.3 Redundancy and Response in Ecosystems

"Redundancy" is an important property of some ecosystems which allows them to carry out critical functions in more than one way, or have a reserve capacity to perform these functions beyond current needs (Bormann 1985). Thus if one pathway to carry out vital functions such as photosynthesis, decomposition, nutrient uptake, nutrient storage or water routing is impaired, due for example to air pollution, another pathway may take over with little long-term change in the ecosystems's capacity to fix energy and to carry out biotic regulation. Redundancy is based on variations among genotypes, populations and species, such that more than one pathway is available for carrying out each process, ie it allows the ecosystem flexibility in adapting to stress. Thus a forest ecosystem might be much more capable of withstanding airborne chemical stress than might be inferred from controlled exposure tests with a few genotypes {Cowling 1985c).

However, redundancy can diminish loss of biotic regulation, such that Stage II responses may not be maintained in perpetuity. As redundancy is used up, the ecosystem becomes increasingly vulnerable to added stress and to a Stage III response (Bormann 1985).

Smith (1985b) states that not all ecosystems respond in the same way to disturbance. Each has distinctive characteristics of inertia and resilience with regard to particular disturbances. Inertia is the resistance of the ecosystem to disturbance. Resilience is the degree, manner and pace of restoration of initial structure and function in an ecosystem following disturbance.

5.4 Surprise in Stressed Ecosystems

Both natural and anthropogenic sources of stress can produce unanticipated and unprecedented ecosystem responses, such as a new equilibrium with long-term effects (Loucks 1985).

Natural events such as recurring fires and destruction by storms are part of the normal renewal process for disturbance-dependent ecosystems. Prevention of such disturbances (thus allowing dominance by climax-adapted species) can itself be a stressor that can produce an unprecedented as well as an unpredictable response. Our incomplete knowledge of the systems involved and the stochastic nature of certain processes imply that surprise will be a continuing part of resource management (Loucks 1985).

New anthropogenic stresses make it more difficult to anticipate the secondary consequences of stress management. Thus although management of stressed systems may involve a lot of educated guesses, some stressed ecosystems (for example the Great Lakes) have responded to management. Quantitative examination of responses around a supposed equilibrium can be insightful and will assist in evaluating stress management strategies (Loucks 1985).

5.5 Trends Expected in Stressed Ecosystems

When ecosystems are not suffering from unusual external perturbations, certain developmental trends may be observed. Disturbance to which a community is not adapted tends to arrest, or even reverse these autogenic developments, resulting in some ecosystem responses to stress which may be anticipated. These have been suggested by (Odum 1985) under the categories of trends expected on energetics, nutrient cycling, and community structure; and expected general system-level trends (Table 4). Early warning of **stress will be more easily seen at the species level. When stress is detectable at the ecosystem level, there** is real cause for alarm, for it may signal a breakdown in homeostasis (Odum 1985).

5.6 Major Sources of Uncertainty in Predicting Community Level Stress

There are significant deficiencies in our understanding of eco**systems that seriously restrict prediction of responses to stress (Smith** 1985b), as **summarized in Table 5.**

Table 4

Trends Expected In Stressed Ecosystems

Trends expected on energetics

- Increase in community respiration, which should be the first early warning sign of stress, since repairing damage caused by disturbance requires diverting energy from growth and production to maintenance.

- Production/respiration ratio becomes unbalanced, because it is affected by any change in the partitioning of energy between production and maintenance. (The P/R ratio tends toward balance in undisturbed ecosystems).

- Maintenance/biomass structure ratios increase (production/biomass and respiration/biomass) ie a decreased ratio of biomass to energy flow, or a low efficiency of converting organic energy to organic structure.

- Importance of auxiliary energy increases, due to the drain of productive energy in dissipating entropy.

- Exported or unused primary production increases, since the altered metabolism may result in an increase in unused resources.

Trends expected on nutrient supply (1)

- Nutrient turnover increases

- Horizontal transport (one way flow) increases and cycling index increases.

- Nutrient loss increases ie systems become more "leaky"

Trends expected on community structure

- Communities are favored by opportunistic, rapidly reproducing, hardy species.

- Size of organisms decreases.

- Lifespans of organisms or parts (such as leaves) decreases.

- Food chains shorten because of reduced energy flow at higher trophic levels and/or greater sensitivity of predators to stress.

- Species dominance decreases decreases and dominance increases; if initial diversity is low, the reverse may occur; at the ecosystem level, redundancy of parallel processes is theoretically possible.(2)

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continued

Table 4 continued

Trends expected at the ecosystem level

- The system becomes more open (ie input and output environments become more important as internal cycling is reduced).
- Autogenic successional trends reverse (succession reverts to earlier stages)
- Parasitism and other negative reactions increase, and mutualism and other positive interactions decrease.(3)
- Functional properties such as community metabolism are more robust (homeostatic-resistant to stressors) than are species composition and other structural properties.(3),(4)

Source: Odum 1985

Note (1): These three expected trends are interdependent. Increased turnover and decreased cycling frequently appear in stressed ecosystems. Together they result in accumulation of nutrients which may be lost from the system.

Note (2): It should be noted that a decrease in species diversity is not a reliable index of stress in general because of a disturbance affecting the structure of the system (eg patch cutting in a forest) often increases the diversity of species of both plants and animals.

Note (3). The last two properties are hypothetical. In the first of these, cooperation and mutualism seem to develop when resources become scarce eg in mature ecosystems such as large biomass forests, or in nutrient-poor conditions. A disordering input should disrupt thes intricate homeostatic positive interactions and increase the likelihood that parasitism overgrazing, and other negative interactions will develop.

Note (4) Whole lake acidification studies in Ontario supported this hypothesis. Primary productivity and other aspects of community metabolism were homeostatic, but species composition of plankton were greatly altered. Species replacement and other adjustments keep the overall function of the system steady.

Table 5

Major Sources of Uncertainty in Predicting the Response of Ecosystems to Stress

Inherent:(1)

- Deficiency of information on effects of long-term, low level effluents
- Difficulty of performing controlled, replicable experiments that provide in situ information about ecosystems
- Lack of models allowing the use of measurable data to predict detailed ecological responses to stress

Rectifiable:(Z)

- Energy and nutrient needs of organisms (ie limiting factors)
- Overconfidence in untested ecological dogma
- Effects of acute stresses on ecosystems (especially synergistic effects)
- Critical stability indicators and correlates of stability
- Populations fluctuations
- Environmental fluctuations
- Ecological-meteorological interactions
- Microbial ecology and nutrient chemistry
- Sources of stress (both gross effluent levels and pollution levels in the microenvironment of organisms)
- Genetic parameters governing ecosystem dynamics and responses to stress
- Cumulative effects on populations of successive small habitat losses

Source: Smith 1985b, who adapted the above from National Research Council, Committee on Nuclear and Alternative Energy Systems (1980).

Note 1: It would be difficult to design a research project to reduce uncertainty.

ote 2: It should be possible to plan a research project to educe uncertainty.

. AIR POLLUTION/FOREST DECLINE HYPOTHESES

6.1 Hypotheses to Explain Waldsterben

40 The order in which the hypotheses are presented in this and the next section (North American hypotheses) are arbitrary ie they are not listed in order of preference to the author or in order of acceptance by the scientific community.

158
- Acidification-Aluminum Toxicity (or "Below-Ground") Hypothesis: This hypothesis was developed by B. Ulrich who predicted a general decline of forest ecosystems in central Europe prior to the widespread development of Waldsterben. It is based on Ulrich's long term studies of nutrient cycling on the Solling plateau in Germany, and proposes that the natural acidification of forest soils (due to humus disintegration, nitrification, and greater uptake of cations than of anions from the soil) is accelerated as a result of deposition of acid from the atmosphere. Increased acidity in the soil leads to increased concentrations of soluble aluminum ions. Aluminum toxicity results in necrosis of fine roots, which leads to increased moisture and or nutrient stress and eventually to "drying out" and death of the trees, particularly during drought periods. Ulrich believes that gradual acidification of the soil is a predisposing factor and that periodic "acid pushes" are a primary inducing factor in Waldsterben (Schütt and Coping 1985).

35
- Ozone (or "Above-Ground") Hypothesis: This hypothesis, proposed by Rehfuess and Prinz, is based on findings taken from field studies and supported in part by experiments. It may be stated in two parts (Prinz 1985):

19 (i) some tree species, especially pine a& be&h, are probably sensitive enough to be damaged directly by ozone alone.

104 (ii) for other species gaseous pollutants, mainly ozone, in combination with acid rain and fog, plays a key triggering role. The feedback mechanism is believed to be decay of fine roots, and possibly myccorhiza, caused by an insufficient supply of assimilates. It is believed that tree decline will increase even if the level of air pollution remains constant, because the change of some biological factor within the system is the important influence. It is also believed that the soil is an important contributing factor but not a primary factor, because nutrient deficiency in soil alone has never caused such a widely distributed forest dieback.

70
- General Stress Hypothesis: This hypothesis, de&loped at the University of Munich, is based on field and laboratory observations of symptoms in various tree species, especially spruce and' beech. The observations include changes in gas exchange rates and formation of plant growth hormones and secondary metabolites during symptom developnt. Air pollution (in general) has led in recent years to a decrease in net photosynthesis and associated diversion of photosynthate from mobile

carbohydrates to less mobile and potentially toxic secondary metabolites. This in turn leads to a poorer energy status in roots and to accumulation of toxic substances in shoots, leading to poor development of fine roots and myccorhizae and to foliar decline symptoms. Reduced energy status reduces the susceptibility of trees to other stress factors, such as drought, nutrient deficiency, and the usual secondary or contributing biotic pathogens.

- Excess Nutrient (Excess Nitrogen) Hypothesis: This was based on a synthesis of widely scattered observations and theoretical considerations of how the nutrient status of forests can be related to recent increases in nitrogen emissions. It is postulated that one or more detrimental effects (see Section 4.2) could be induced by nitrogen thus leading to the present decline of forests in central Europe (Schutt and Cowling 1985).

- Organic Substances Hypothesis: This hypothesis, considered to be very speculative, suggests that one or more of the many synthetic organic compounds that is produced in central Europe may be transported in the atmosphere and contribute to the symptoms of Waldsterben (Schutt and Cowling 1985).

6.2 Hypotheses Presently Popular in the U.S.

The following presently popular U.S. hypotheses were generally proposed to explain potential atmosphere-related forest dieback in both North America and Europe (U.S. NAPAP 1983; Lefohn 1984; Bruck 1985). Hypotheses different from those presented in the last section (proposed to explain Waldsterben) are marked with an asterisk (*).

- Ozone is causing damage to tree foliage and either alone or in combination with acid deposition is affecting tree growth.

- (*) Deposition of metals either alone or interactively with acid deposition is directly or indirectly affecting tree growth.

- (*) Acid deposition is directly or indirectly increasing the leaching of nutrients from foliage, especially calcium and magnesium.

- (*) Sulfur dioxide or gaseous pollutants other than ozone have reached toxic levels.

- Uptake of excess nitrogen can result in abnormally succulent crowns and shoots, decreasing the resistance of coniferous trees to frost, wind desiccation, fungal pathogens and insect parasites.

- (*) Excess acidity leads to reduction of ectomyccorhizal short roots.

3 Evidence to Support or Refute Individual Hypotheses

The order in which the following hypotheses are analyzed is not completely arbitrary. Ozone is presented first, because it is considered by various authors to be the most popular hypothesis explaining forest decline in both Europe and North America, and because of all potential pollutants, the evidence is strongest that ozone is a causal factor in observed forest decline.

Excess nitrogen compounds are considered to be the second most important atmospheric compound in the present forest decline. The evidence here is very circumstantial -- winter injury is a major component of the red spruce decline in the Appalachians.

The potential applicability of the remaining hypotheses are essentially open questions at this time. Cowling (1984b) suggested that the order of importance for the remaining atmospheric compounds of concern is heavy metals, acid deposition, and organic chemicals, with essentially no evidence to infer any of these are involved in the present decline.

6.3.1 Ozone

Ozone is considered to be the airborne chemical of "greatest probable relevance" to the current declines of U.S. southern commercial forests, high and low elevation spruce forests in the U.S., and high and low elevation forests in Europe (Cowling 1985a). The ozone hypothesis is currently the most widely accepted explanation of Waldsterben (Blank 1985). Ozone effects appear highly likely across large areas of both North America and central Europe because of the regional distribution of this ubiquitous pollutant in phytotoxic concentrations (McLaughlin 1985).

Ozone is considered to be of "greatest probable relevance" on the basis of the following (Cowling 1985a):

- Gases have a greater potential for detrimental effects on plants than other physical forms of airborne chemicals, because gases enter directly through stomata on the leaves and shoots.

- Toxic substances are more likely to cause detrimental effects than nutrients, acidic or acidifying substances.

- Ozone is toxic to many plants which commonly occur in the forests of eastern U.S.. Toxic levels of NO_x and SO_2 occur relatively infrequently in forests remote from point sources of pollutants.

- Ozone accumulates in phytotoxic concentrations in industrial regions of the world even at substantial distances from major sources of air pollution.

  Ozone has been shown to interact synergistically with other air pollutants in certain crop plants in the U.S.

In addition to the above circumstantial factors, there exists direct evidence of ambient long range transported ozone having caused the decline and mortality of eastern white pine and other species in the eastern U.S. (Skelly et al 1983) and of ponderosa pine and other species in California (Miller et al 1983).

On the basis of field observations in California, visible injury threshold for current season needles is equivalent to a mean ozone concentration of 95 ug/m3, a level which is exceeded in large areas of North America and central Europe. In the Black Forest and Bavarian Forest in Germany, mean summertime ozone concentrations are about 100 ug/m3 (50 ppb) while concentrations above 200 ug/m3 (100 ppb) occur in 3-5 % of summer hours. These concentrations are equivalent to those experienced in the U.S. where ozone has resulted in forest damage (Ashmore et al 1985).

Three long term monitoring sites in Europe show that ambient ozone levels have been steadily increasing. Near Munich annual average levels have increased from approximately 50 to 65 ug/m3 since 1970. Ozone concentrations in East Germany have approximately doubled since 1956 to 50 ug/m3 annual average (Ashmore et al 1985).

Ozone long term trends have recently been compiled for Texas and California (Walker 1985). In Texas between 1973 and 1982, average ozone at various sites increased about 2.5% annually, average daily maximum increased 2.1-2.6% annually, and hours greater than 120 ppb increased by 5.7-10% annually. For California the respective numbers for the same period were -1.8 to 1.596, -1.3 to 1.5%, and -0.5 to -11.3%.

Stem analysis of trees in West Germany suggests that growth has been progressively reduced over the last 20-30 years. During this period NOx emissions have increased by approximately 50 % while SO2 emissions have remained relatively constant (Ashmore et al 1985).

Forest damage in both North America and Europe first appeared at higher altitudes and still tends to be higher at higher elevations. Ozone appears to increase in concentration with increasing elevation and the classic diurnal cycle flattens out. Unfortunately there does not appear to be much monitored ozone data for high elevation forests. In Whiteface Mountain N.Y. typical summer levels are in the range 80-110 ug/m3 (ie slightly higher than ambient background levels) with peaks in the range of 160 ug/m3 (Bruck 1985). Average daily ozone levels at an alpine site near San Diego have decreased from approximately 220 ug/m3 in 1978 to 180 ug/m3 in 1982 (Walker 1985).

Ozone levels recorded at various locations in the U.S. and in the Black and Bavarian forests of Germany are in the range of levels which caused visible damage to several tree species in various locations. Trees sensitive to ozone include eastern white pine, ponderosa pine, Jeffry pine, loblolly pine, hybrid poplar, tulip ree, sweetgum, green ash, silver birch, European ash and white ash. It is significant, however, that the major-tree species that are damaged in West Germany (Norway spruce, Scots pine, and beech) are considered "not sensitive" to ozone (Ashmore et al 1985). Additionally, experimental work in Germany using or exceeding these concentrations has so far failed to produce the chlorosis which is so characteristic of the decline in Norway spruce (Blank 1985).

In assessing whether or not ozone is involved in the decline of red spruce in the Appalachians, it may be of significance that symptoms observed in the northern Appalachians appear to be substantially different from those in Germany, while those in the southern Appalachians are more similar to those observed in Germany (Bruck 1985).

In North America and in West Germany, diseased trees are typically randomly scattered throughout the stand. The existence of substantial intra-specific variability in sensitivity to ozone has been confirmed for many species and this could be responsible for the random scattering.

An apparent inconsistency exists between the symptoms of damaged trees in West Germany compared to trees that were definitely injured by ozone in the U.S.. The chlorotic German needles often contain low (deficient) concentrations of certain cations (especially Mg) and it has been claimed that the addition of Mg can reverse the progress of chlorosis and decline. In contrast there are no reports of ozone-damaged trees in the U.S. being deficient in cations (Ashmore et al 1985). This could be to to the involvement of acid mist interacting with ozone in Germany but not in the U.S. ie trees were injured by ozone alone in the U.S., while trees in West Germany were injured by the pollutant interaction.

A high incidence of fog is characteristic for higher altitudes in some of the major damaged areas in Germany, with an annual mean of up to 226 days with periods of fog reported in the Bavarian Forest (Blank 1985). However, high fog incidence has also been observed at certain high elevation sites exhibiting major forest decline in North America. At very high elevation locations such as Whiteface Mountain in New York and Mt. Mitchell in North Carolina, spruce-fir forests are bathed in cloud water more than 50% of the time. Also, because of the high speed with which clouds are driven through the mountains, and the high concentration of airborne chemicals in cloud water, the total amount of pollutant chemicals deposited in high elevation forests is substantially greater than at low elevation (Cowling 1985c).

Whether this high pollutant deposition is contributing to forest injury is not known at this time. Since both ozone and acidity deposited both increase with elevation, both are strongly suspeced to be involved with forest damage, which increases with elevation.

Iditionally, there is a possibility that ozone and/or acid deposition predisposes forest trees to damage by frost and/or drought. This potential mechanism is consistent with reports of major increases in damage coinciding with severe winter weather and with dry summers; furthermore Mg-deficient leaves are known to be less frost-resistant (Ashmore et al 1985).

German work has attempted to determine the potential role of ozone and acid precipitation in leaching magnesium from Norway spruce. A preliminary investigation showed-that leaching from shoots was increased by a factor of 2.5 when plants subjected to pH 3.0 artificial rain were previously fumigated with 300 ug/m3 ozone for 28 days. More detailed subsequent experiments have confirmed these earlier experiments and also shown that intermittent exposure to 200 ug/m3 ozone was sufficient to increase Mg leaching caused by artificial rain by 22 %. However, because no analyses were carried out on the foliage, it is not known whether the treatments actually induced Mg deficiency. Recent experiments with Scots pine did not show any reduction in Mg or Ca content with either ozone or acid rain (Ashmore et al 1985).

A major inconsistency in the ozone hypothesis is that ozone cannot account for the primary symptoms of chlorosis and loss of older needles. Fumigation experiments produce chlorotic flecking on recently formed needles (Manion 1985).

5.3.2 Excess Nitrogen Compounds

There is little published direct evidence to support or refute whether excess nitrogen leads to reduced forest growth due to deficiencies of other nutrient elements, or due to altered shoot-root growth. However, repeated winter damage appears to be a component of the red spruce decline in the northern Appalachians. Evidence that this may be exacerbated by excess N includes the following (Bruck 1985):

- Foliar N, dieback and mortality all increase with elevation (demonstrated by Johnson and Siccama 1983).

- N-deposition is greater at higher elevation than at lower sites. In New England, high elevation N-deposition estimates are about six times the wet deposition measured at Hubbard Brook (which was about 6.5 kg N/ha/yr).

- The high elevation deposition rates could be significant considering that fertilization rates of 100 to 200 kg N/ha/yr, applied at 500 to 1000 kg/ha at 5 yr intervals, were sufficient to promote frost damage to Norway spruce and Scots pine in Finland. Additionally, Weetman and Fournier (1984) showed over-fertilization of jackpine in Quebec (495 kg N/ha applied in six equal quantities over a ten year period) caused mortality.

  Abnormalities in mesophyll cells of red spruce foliage at Camel's Hump Vt. were similar to abnormalities observed in frost-damaged conifers in northern Finland.

vidence that excess N may be deleterious to myccorhizal associations is weak at this time, but studies are being conducted on red spruce to determine if ambient levels of N can adversely affect myccorhizal development (Bruck 1985).

6.3.3 Gaseous Pollutants other than Ozone

Sulfur Dioxide

In West Germany, concentrations of SO_2 in or adjacent to major areas of forest damage are in the range of 7 to 21 ug/m3, well below any values at which direct damage to foliage has been observed (Tomlinson 1983). Additionally, rich growth of sulfur dioxide sensitive lichens has been noted in severely damaged areas (Prinz 1985).

Roberts (1984) suggests an approximate long-term concentration threshold for effects of SO_2 on growth and physiological parameters lies in the range of 260 ug/m3 (0.1 ppm) for several weeks to 130 ug/m3 (.05 ppm)for several years, the concentration being lower in multi-year fumigations because of the cumulative effect of reduced growth rates on yield. The thesholds may be lower in regions where climatic conditions are marginal for tree growth.

The International Union of Forestry Research Organizations concluded that the average SO_2 concentration should be 50 ug/m3 (.019 ppm) to protect normal spruce stands and 25 ug/m3 (.009 ppm) for stands at the extreme of their climatic range. However, these studies were all carried out around point sources so the effects should be related to the peak concentrations rather than the annual averages (Roberts 1984).

McLaughlin (1985) reviewed concentration thresholds and data on ambient pollutant concentrations and concluded that direct effects of SO_2 would be expected in industrial but not rural areas of Germany, and that in the U.S. effects would only be expected in the vicinity of large urban complexes or near point sources.

The effects of gaseous pollutants on stomatal function is well documented. In general high levels of either SO_2 or NO_2 will cause stomatal closure thereby protecting plants from further pollutant injury and from water vapor loss. However under low levels of SO_2 (26 ug/m3) and low relative humidities (less than 40%) stomatal opening was enhanced (in bean), particularly when plants were previously drought-stressed, a factor which could intensify plant-water stress under these conditions (McLaughlin 1985).

Nitrogen Dioxide

Annual average NO_2 values in rural areas of both Germany and .S.A are very low (2-20 ug/m3); maximum hourly values range from 28-73 ug/m3. These values are well below the injury threshold for plants, for both individual and combined effects (McLaughlin 1985).

Fluoride

Fluoride gas is a highly phytotoxic air pollutant which can cause injury to susceptible plant species at very low concentrations. Fluoride emissions from the aluminum smelter at Kitimat B.C. have been shown to reduce the growth of western hemlock adjacent to the smelter by up to 28%, at average concentrations of about 1 ug/m3. Growth stimulation has also been observed adjacent to the damaged area. Increases in growth of 3-14% were observed in an area where the average Fl concentration was 0.3-0.8 ug/m3 (Bunce 1985).

6.3.4 Heavy Metals

The potential impact of heavy metals is considered in two parts:

- aluminum toxicity

- other heavy mtals

Aluminum Toxicity

This hypothesis has been given a great deal of attention because it is one of the potentially significant "acid rain" hypotheses. However, doubts about its plausibility, first expressed by Prinz in 1982, are now widespread (Blank 1985). This is because it cannot explain the damage observed on all soil types, especially calcareous soils not susceptible to acidification. Additionally long term field experiments in Norway using very high rates of acid applications did not have any effects on Norway spruce growth, and the trees tolerated Al very well (Bruck 1985). It has recently been pointed out that damage in West Germany is concentrated on soils with poor nutrient status but apparently with variable buffering capacity, ie there is no relation between damage and soil acidification potential (Prinz 1985).

The significance of acid pulses and associated increases in trace elements, as proposed by Ulrich, was also questioned by Rehfuess, who pointed out that some tree species have adapted to survive on acid soils in the presence of high levels of Al, Mn, and other heavy metals (McLaughlin 1985).

In terms of soil acidification, of key importance is whether or not atmospheric additions have overwhelmed the natural acid sinks, either as a result of short term imbalances (ie sometime during the growing season) or as the result of long term acidification. Bruck (1985) feels it is probable that acid deposition accelerates the acidification of some soils in the long term, but whether or not it happens to the extent that acid pulses during the growing season result in stress to trees is an open question. Additionally it is not known whether decades of acid deposition have created unfavorable conditions for the existing vegetation, even on sites susceptible to acidification. The complexity of assessing this possibility stems from a lack of data needed to nstruct detailed H+ budgets (Bruck 1985).

At present there is no direct evidence that aluminum toxicity induced by soil acidification is a factor in forest decline. As a matter of fact Johnson and Siccama (1983) observed that for the Appalachians Al content of damaged red spruce foliage and root tissue decreases with increasing elevation, while decline increases with elevation.

On the other hand, Prinz (1985) states that free aluminum ions may cause some root decay in highly acid soils in Solling/Lower Saxony West Germany. However, in his opinion, from an evolutionary point of view it seems illogical that conifers should react most sensitively to aluminum, because they tend to produce their own acidic rhizosphere by breakdown of litter to humic and fulvic acids.

It should be considered that in instances where the Ca:Al ratio may appear to be a factor in forest decline, effects on root growth may result from a lack of calcium rather than from the presence of aluminum (Prinz 1985).

Other Heavy Metals

The potential significance of heavy metals other than aluminum is ased on regional increases in availability in rainfall, recent ccumulations in soil and litter, long residence times in soil systems and inherent toxicity to plant growth processes (McLaughlin 1985).

Most studies of the toxicology of lead have focussed on human beings, and there is little data relevant to forest impacts. Besides the direct metabolic effects of heavy metals on plant, animal and microorganism cells, heavy metals can affect many subtle microbial activities and interactions. For example, a concentration of 1040 ug of lead per gram of soil completely inhibited nitrogen mineralization. Various fungi are inhibited in cultures with 50 to 100 ug per mil of lead added to their media. Microbiota of soils and of leaf surfaces of plants from sites heavily contaminated with lead and other,heavy metals had a significantly lower species diversity than did soils and plants from uncontaminated sites (Bruck 1985).

The accumulation of lead in soils has been documented, and the forest floor is an important sink for lead, accumulating nearly all lead falling on it. Accumulation of lead and copper, and to a lesser extent zinc and copper, in the forest floor is especially pronounced in high elevation boreal forests. Between 1965 and 1980, metal concentrations have markedly increased in the soils on Camel's Hump in Virginia's Green Mountains, a site of massive spruce dieback. Lead concentration doubled, while that of copper ose by 40% and zinc by 70% (Postel 1984).

in North America, lead levels in forest floors of some high elevation stands in Vermont and North Carolina are often in xcess of 2 g of total lead per square meter of forest floor, with average concentrations of approximately 200 ug Pb/ g soil in spruce/fir forests, and occasional concentrations of greater than 300 ug in the organic horizon. However, at present it is an open question whether or not metals which have accumulated in the boreal soils of North America have altered ecosystem or plant processes to a sufficient degree to have participated in conifer mortality (Bruck 1985).

In West Germany, heavy metals can be excluded as a major cause (Prinz 1985). This is because heavy metal levels are insignificant in needles exhibiting typical symptoms of decline. Additionally it has been observed that no damage is occurring in the vicinity of heavy metal-emitting smelters and refineries, even though deposition of metals to the surrounding forest and metal concentration in soils is several orders of magnitude higher than in typically damaged stands.

6.3.5 Acid Deposition Effects on Forest Nutrient Status

The discussion on potential effects of acid deposition is divided into the following topics:

- Effects on Nutrient Cycling
- Effects on Myccorhizal Associations

Effects on Nutrient Cycling

The observation that damaged spruce in Germany appear to be losing excessive quantities of magnesium and calcium has led to the widespread belief that acid deposition may be involved. The fact that most of the damage has occurred on infertile soils (Prinz 1985), suggesting that the nutrients leached from foliage cannot be readily repaced, lends support to this hypothesis.

Several experiments have investigated the effects of simulated acid rain on foliar nutrient leaching, demonstrating that cation losses increase with increasing acidity. However, significant effects are only observed with simulated rainfall ten or more times more acidic than ambient rainfall events, and foliar losses are generally not accompanied by a reduction in foliar content (Amthor 1984, Morrison 1984, Watt Committee 1984).

Ulrich has suggested that roots respond to and regulate calcium levels in foliage. Since foliage and roots are connected along an electrolytic continuum, the neutralization of rainfall in the canopy may be accompanied by acidification in the rhizosphere as roots take up base cations and release hydrogen to the soil solution (McLaughlin 1985).

Johnson (1982) discussed the importance of soil factors in determining and sustaining plant nutrient uptake. The mechanisms and speed with which trees compensate for canopy-level nutrient change are still not well quantified, however (McLaughlin 985). Whether forest trees can readily replace leached foliage elements, especially on infertile sites, has yet to be determined Morrison 1984). Due to differences in site characteristics and volumes and types of acid rain inputs, generalizations about potential impacts have little meaning. The impacts at any one site can be positive, negative or both in terms of counteracting forces. Thus potential changes must be evaluated in an ecosystem context (Johnson 1982).

At this time any predictions of potential long-term nutrient deficiencies in forest ecosystems being induced by acid rain are speculative. Short-term negative effects of acid rain on forest nutrients appear unlikely (McLaughlin 1985).

No long term studies have so far demonstrated a reduction in forest site quality due to acid rain (Bockheim 1983), although it is very difficult to quantify the impact of acid rain relative to natural acicity. In one recent study comparing cation losses in several forest ecosystems, atmospheric acidity was important at only one site, while natural organic, carbonic and nitric acids dominated in cation leaching at the other sites. Relative to exchangeable cation capital, cation losses due to atmospheric acidity at the one site "were not alarming" (Johnson et al 1983).

In a second study, Johnson et al (Ref. 123 in McLaughlin 1985) stimated that anthropogenic inputs of acidity have approximately doubled internal acid production in the soil, and available soil cation reserves are adequate for 50-70 years in the absence of weathering.

Effects on Mycchorizal Associations

Bruck (1984) suggested ambient acid deposition could be contributing to the reduction of ectomycchorizae of damaged red spruce and Fraser fir on Mt. Mitchell, N.C.. Damaged trees growing at high elevation averaged 35% myccorhizal incidence, while those at lower elevation averaged 72% myccorhizal incidence. A highly significant correlation was observed between myccorhizal incidence and degree of decline. Recent experiments with loblolly pine seedlings (Shafer et al 1985) showed that treatment effects of simulated acid rain resulted in a quadratic relationship with greatest myccorhizal incidence (62%) at pH 2.4. Rains of intermediate acidity (pH 4.0 and 3.2) inhibited ectomycchorizal formation. Increased soil acidity or other factors induced by acid rain at pH 2.4 enhanced ectomycchorizal associations.

6.3.6 Organic Substances

The only direct evidence that appears to be available to support the hypothesis that airborne synthetic organic compounds are involved in forest damage is described by Schutt and Cowling 1985). Loblolly pines in the vicinity of two chemical plants in orth Carolina were changed in growth habit and later killed. As with Waldsterben spruce and beech, the trees showed changes in hapes of leaves (twisted needles) and dropping of leaves while till green. These observations suggest that the normal balance of growth regulators was altered. Controlled exposures of pine seedlings to 0.4 ppm of aniline could induce the symptoms.

Indirect evidence that airborne synthetic compounds may affect trees includes the observation that atmospheric ethylene can affect plant growth and development.

6.3.7 General Stress

Because of its general nature, this hypothesis is probably applicable to most decline symptoms observed in North America and Europe. It fits well with the increasingly popular view that there is no single simple cause of forest decline, but that atmospheric pollutants are among the primary causal factors (Ashmore et al 1985; Schutt and Cowling 1985). Unfortunately this hypothesis is not very helpful in defining which pollutants are of most probable importance in the decline of forests.

Support for the general stress hypothesis is given by the divergence of symptoms and characteristics of Waldsterben that have been observed. These include increased susceptibility to insects, foliage and root pathogens, drought, frost and other stress factors, although Waldsterben is distinct from the diseases induced by the familiar biotic forest pathogens. Waldsterben is also distinct from the typical injuries to forest induced by drought and frost or by the toxic gaseous air pollutants (Schutt and Cowling 1985).

7. UNCERTAINTY ANALYSIS AND ELICITATION OF EXPERT OPINION

Although a consensus of scientific judgement seems to be developing that long range transported air pollutants are contributing to observed forest decline, a scientifically documented link has not yet been established. Because our understanding of complex forest ecosystem/air pollution interactions is very incomplete, we are very uncertain about the potential impact to forests. As a result of this uncertainty, a certain risk of damage to our forests is associated with inaction regarding control programs.

On the other hand, there is the risk that implementation of control programs, with certain negative socio-economic effects, may prove to be unnecessary, if air pollutants are not a factor in forest decline.

It is widely appreciated that there is no substitute for scientific research, and that science will eventually give us the answers to our questions regarding air pollution effects on forests. Unfortunately, however, there is significant risk in waiting for science to provide answers. Under these circumstances subjective judgements will be necessary in the evaluation of the need for air pollution control programs related to protection of forests. There are two alternatives: (i) The decisionmakers themselves can perform implicit guesses, based on their review of largely contradictory experimental results and divergent conclusions, or (ii) forest ecology experts can assist decisionmakers by providing informed judgement and opinion, based on existing scientific knowledge.

The first and fairly obvious consideration in using experts to provide judgements regarding the potential risks to forests from air pollution, as pointed out by Fraser et al (1985), is that caution should be exercised, as the results represent opinion and not proven fact.

A second precaution is that subjective probability estimates are subject to systematic biases due to human cognitive limitations, for example humans experience shortcomings in acting as "intuitive statisticians". However, considerable psychological and decision analysis research has been conducted in the area of subjective probability elicitation, and techniques have been designed to elicit probabilistic assessments while counteracting these biases (Wallsten and Budescu, 1983).

Cognitive limitations of humans are reviewed in the next section, followed by a description of approaches of incorporating probabilistic judgements into forest/air pollution risk assessments, the use of Bayesian methods, and aggregation of opinions of different experts.

7.1 Cognitive Limitations of Humans

Psychological research has demonstrated that humans encounter a variety of cognitive limitations as they attempt to make judgements under uncertainty. People are prone to biases in processing and in interpreting the information they receive; they are ill-equipped to access and interpret probabilistic information, so that uncertainty is often ignored. When humans deal with uncertainty, the complexity of the task is reduced due to the use of cognitive simplification mechanisms and intuitive heuristics in making judgements (Hogarth, 1975; Tversky and Kahneman, 1974).

Although these heuristics are quite useful on a day to day basis, they can introduce significant cognitive errors. The three primary decision-making heuristics that are employed are repre-entativeness, availability, and adjustment and anchoring. Examples of errors in human judgment related to these three heuristics are summarized below (Tversky and Kahneman 1974):

(a) Representativeness: people order events by probability and by similarity (representativeness) in exactly the same way. Similarity is not influenced by several factors that should affect judgements of probability, such as:

o prior probabilities - people consistently ignore base information, in direct contradiction of Bayes Law.

0 sample size - people are insensitive to sample size.

o misconception of chance: people expect that the essential characteristics of a process will be represented eg. gamblers fallacy - after observing a long run of red on the roulette wheel, most people erroneously pick black, so it will result in a more representative sequence.

o insensitivity to predictabilty: people show little consideration for factors (such as future events) which can affect predictability.

o illusion of validity: people have unwarranted confidence in their judgements, which is produced by a "good fit" between the predicted outcome, and input information.

0 misconceptions of regression: people do not develop correct intuitions about regressions to the eg the 10 best students in the midterm will probably not be the 10 best in the final.

(b) Availability: instances of large classes are usually recalled better than less frequent classes; likely occurrences are easier to imagine than unlikely ones, associative connections between events are strengthened when they frequently co-occur. Reliance on availability leads to systematic errors.

(c) Adjustment and anchoring: *different starting points yield different estimates, as initial values are usually "anchored", and adjustments are usually insufficient.

In addition to the employment of the above simplification mechanisms, the use of "expertise" may introduce biases to the risk assessment. This is because people tend to pay more attention to information that is consistent with their own way of thinking and preferences, and to ignore or reinterpret information that is inconsistent with their own views (Smart et al 1984). In the assessment of risks, conflicts between knowledge (data) and values results in a reconciliation process, known as dissonance reduction, where either attitudes or held knowledge are modified to achieve consistency (Smart et al 1984).

Hogarth (1975) argued that since humans are selective, sequential-information processing systems with limited capacity, they are ill-equipped to assess probability distributions. He suggets that people are only capable of comprehending a small part of their environment, and that anticipation of a specific perception often leads to a specific perception. He concurs with other researchers that people do not have the intuitive capacity to make optimal calculations mentally, and that they cannot simultaneously integrate information.

Hogarth (1975) and Smart et al (1984) point out that our culture encourages confident statements, even when we are not so confident, and that not very strong opinions are considered worthless. It is felt this attitude has introduced another form of systematic bias into subjective probability estimates.

In spite of the rather negative aspects related to human cognitive limitations, research has demonstrated that humans can be good to excellent probability assessors (Wallsten and Budescu 1983). For example weather forecaster predictions are nearly perfectly calibrated** with observed outcomes, and significantly outperform predictive models based on historical data.

It is felt that by making experts aware of the biases and heuristics described above, they may be avoided to a certain extent during the elicitation process. Thus Whitfield and **Wallsten** (1984) and Morgan et al (1984, 1985) summarized information pertaining to these cognitive limitations and provided it to air quality experts (meteorologists and health experts) before the elicitation session. They also discussed the psychological aspects of elicitation in some detail before the session.

** "Calibration" is a measure of the relationship between a subject's assessed probabilities and the actual occurrence or frequency of the associated events.

Of relevance to predictions of forest impacts from air pollution is that people tend toward assigning probability distributions to adverse events that are too high, and possibly also to other events which catch attention (Wallsten and Budescu 1983). In evaluation of forest impacts, for which no evidence exists at present that would allow comparisons of expert judgements with actual outcomes, it is not possible to "calibrate" forest expert probability distributions. Thus the best we can hope for are probability assessments that reflect the true belief of the expert, given the available information.

There are two main theories on subjective probability (Wallsten and Budescu 1983) that may be applicable to elicitation of expert judgements from forest impact specialists. The first states that within each individual there is a single, well-defined distribution of uncertainty (a true score), but different elicitation methods introduce both systematic and random errors that are sources of observed inconsistencies. The second definition, which is becoming increasingly popular, is that subjective probability is not precisely determined internally; it has some vagueness, representation of which depends on the encoding method. If this latter view is correct, it would suggest that forcing additive coherence (a requirement of the first approach) might distort judgement. Thus, as Wallsten and Budescu (1983) suggest, development of non-additive probability theory might be more suitable for representing actual beliefs and opinions.

Elicitation of useful and valid subjective probabilistic expert judgements is as much an art as it is a science. Comprehensive descriptions of the method may be found in Spetzler and von Holstein (1975) and in Morgan et al (1979).

7.2 Use of Experts in Predicting Forest Impacts

The traditional approach to consideration of uncertainty in environmental policy assessment is to select best estimates of state parameter values, and to proceed as if these were the true values. Uncertainties are usually addressed qualitatively in the text, This approach frequently does not help decisionmakers determine the degree of confidence associated with the conclusions. When risk assessments related to regulatory decisions are subject to considerable uncertainty, and decision--makers are aware of the magnitude of the uncertainty, they are generally more hesitant to implement expensive regulatory programs.

When uncertainty is directly incorporated into a policy analysis, two approaches may be used:

(i) If estimates of the effects of air pollution are derived statistically from historical data, then confidence intervals around the estimated parameters are used as a measure of uncertainty. Confidence intervals are based on a number of underlying statistical assumptions that may or may not be true

(Peterson and Violette 1985). For example confidence intervals arc not the correct measure of uncertainty when extrapolating dose-response relations from specific experiments to other regions or species.

(ii) Where direct scientific data is not available, subjective probability distributions may be elicited from experts.

It is this second method of addressing uncertainty that is relevant to the assessment of forest impacts, due to the lack of present knowledge regarding forest ecosystem/air pollutant interactions.

In using expert judgements Morgan et al (1984) suggest that subjective probability distributions should only be elicited if uncertainties are not too large. They suggest that, if uncertainties are large, only upper and lower bounds of uncertain parameters or values should be elicited.

In forest ecosystem/air pollution policy analysis, it seems that upper and lower bounds to damage estimates are about the best estimates of uncertainty that may be achieved at this time. If scientific research were to establish a definite link between observed forest decline and air pollution, then it may become feasible to define probabilistic dose-response functions in terms of subjective probability distributions. In the case that such a relationship is established, the observed functional relationship will apply to the specific system in which the response was observed, and expert judgements may help to dimension the uncertainty around extrapolations to other ecosystems and pollutant conditions.

Experts have been used to define probabilistic upper and lower bounds to forest injury from air pollution in at least two studies. In one study, Fraser et al (1985) used the Delphi method and 39 forest experts to define the risk to Canadian forests from present and future levels of pollution. An iterative questionnaire process was used, which stopped after it was judged that a reasonable level of consensus had been reached, and further shifts in opinion were unlikely. In this project respondents were not brought together, as the analysts believed anonymity is useful given the limited information available and the need for speculation. Reasonable consensus was achieved by feeding combined results back to the experts after each iteration, and asking them if they would like to revise their opinions. This required three iterations.

In a second study the analysts used several experts in a decision analysis framework to analyze air pollution control strategies for the State of Wisconsin. Choices evaluated included imposition of additional controls now, or to wait for further information which could reduce uncertainty. Unfortunately the method of elicitation of expert judgements (probability of injury to forests under existing and alternate air quality scenarios) was not specified. The analysts concluded that risks to forest from

present air pollution levels were minimal, and the preferred strategy is to undertake a vigorous research program to resolve existing scientific uncertainty before making a commitment to additional emission controls (North, **D.W.** et al 1985).

7.3 The Use of Bayesian Methods

Funtowicz and Ravetz (1984) state that traditional meanings of probability, based either on **replicable** large sets of simple events, **or** on analyzable symmetries in a configuration, do not extend to cover modern environmental and social effects related to technological development. This is due to the sparseness of data and the complexity of the structures and systems involved. They point out that policy analysts **recognized** this limitation some time ago, and turned to the subjective approach to probability, based on Bayes theorem.

Bayesian methods in general rely upon being able to express a degree of belief in the true values, before a measurement is made, **by** using a prior probability distribution. This degree of belief can be changed by making a measurement, thereby changing the prior distribution to a posterior distribution. A description of the Bayesian approach and an example of its implementation may be found in Morris (1974).

Due to some subjectivity in specifying the prior distributions, Bayesian methods are often rejected as controversial (Suggs 1980). **If** a set of estimates can be obtained that are essentially independent (which is hard to do with experts of similar backgrounds), then a classical estimate of uncertainty can be obtained by combining the numbers into one estimate of the damage function (Morgan and Morris 1978).

Bayesian methods, in theory, allow analysts to incorporate an expert's initial state of ignorance (lack of confidence) within a probability estimate, then learn by experience, using Bayes rule, to update the estimate as objective data becomes available. The method thus combines objective frequency distributions with degree of confidence uncertainties (Tompson 1983).

Funtowicz and Ravatz (1984) are not **optimisitic** about the applicability of Bayesian methods in environmental risk assessment where considerable uncertainty (ignorance) is present, as is evident from their comments below.

> "Bayesian statistics... can be seen in historical context as the last hope for an effective claim to a traditionally scientific solution to the environmental and societal problems of **science**-based technology. (Unfortunately) the Bayesian approach does not solve the problems of using experts' judgements under normal conditions where disagreement and ignorance are evident... Unless using Bayesian statistics is to be merely a

> **euphanism for** trusting some **experts, certain** conditions must be met... including application of probability distributions in the light of relevant new (information)... Also, the outcome of the exercise must display some degree of consensus, enabling the use of this expert information in a decision process."

Funtowicz and Ravatz (1984) conclude that traditional probabilistic approaches cannot compensate for major lack of information (ignorance) in risk assessment.

1.4 Aggregation of Opinion

Morgan et al (1985) suggest that **if** experts disagree, their probability distributions should not be combined, unless their divergent views lend to roughly the same policy conclusions. They suggest that the analyst should focus on the reasons for the divergence.

Hogarth (1975) suggested there are three means of approaching consensus when using experts. The first involves using a weighted average of individual opinions, although it is difficult to determine the weights that should be applied to each expert's distribution. Secondly, experts may be asked to revise their probability distributions, based on a review of the distributions of other experts. Thirdly, group interaction or the Delphi approach can be used, although these methods frequently do not permit for exchange of reasons for opinions.

In addition, various mathematical approaches to consensus have been suggested for the aggregation of experts' probability distributions, ranging from a simple average of the distributions to a formal Bayesian revision process (Winkler, 1981).

8. SUMMARY AND CONCLUSIONS

8.1 Current Understanding

As pointed out by Cowling (1985c), it is ironic that the arena of greatest present public interest, air pollution effects on forests, is the arena of greatest scientific uncertainty. Much more is known about the public health effects, materials damage effects, aquatic and other effects than is known about the effects of air pollution on forests.

At present essentially all of the evidence linking regional air pollution to forest decline is circumstantial. The exceptions are the documented declines of pine trees due to ozone in California and Virginia (section 2.2).

Although a consensus of scientific judgement seems to be emerging that air pollutants are primary causal factors in the present decline, this consensus is running ahead of the documented status of knowledge (Cowling, in Manion 1985). A successful explanation of the decline must fulfill the following conditions (Prinz 1985):

- It must be possible to connect all the specific symptoms of the decline to the causal factor in question.
- The temporal development of the decline must go along with the temporal development of the causal factor in question, including consideration of accumulation effects.
- The spatial distribution of the decline must largely coincide with the spatial distribution of the causal factor in question.

The most difficult aspect of solving the forest decline problem involves satisfying the first item above. Forest trees suffer from many different causes of stress, including competition, physical climatic stress, biotic pathogen stresses and chemical stresses including air pollution. Distinguishing the effects of air pollution from the combined or individual effects of these other forms of stress is an extremely difficult scientific challenge (Cowling 1985c). So far, it has not been possible to characterize pollution stresses among the collection of other stress agents (Manion 1985).

Existence of the second relationship above has also been difficult to prove. McLaughlin (1985) suggested the timing of a shift to slower growth rates in red spruce and Fraser fir in the U.S., and limited studies showing similar relationships in Norway spruce and silver fir in Europe, generally coincide with a period of rapidly increasing emissions of SO2. The relevance of this rather loose circumstantial evidence has been questioned. Prinz (1985) points out that the really relevant symptoms of forest decline appeared when emissions of SO2 were already on the downward trend. More importantly, as pointed out by Prinz, the concentration of air pollutants in the typically damaged areas scarcely reflects the emission trends of distant pollutant source areas.

Additionally, the assumption of any of the air pollutants as primary causal factors does not solve the problem of the more or less sudden appearance of the apparent symptoms in the early 1980'9, suggesting climatic episodes are involved as a triggering or synchronizing factor (Prinz 1985).

Some progress seems to have been made on the third item above. For example ozone concentrations, acid loading, nitrogen loading, and amount of rain and fog exposure are all known to increase with elevation. The same trend (increasing with elevation) has been observed for severity of tree injury and forest damage.

It has also been observed that primary pollutant (sulfur and nitrogen oxide) concentrations, and precipitation and soil pH values do not coincide spatially with the forest damage areas. Thus these latter factors, by themselves, may essentially be removed from the list of plausible causal factors. As more of these relevant. relationships are examined, the number of potential causal factors may be reduced. More intensive air quality monitoring in remote forests exhibiting decline symptoms is required to establish whether the relationships required by Items 2 and 3 above can be satisfied.

Manion (1985) does not believe there is sufficient evidence to consider air pollution a potential contributor to forest decline. He points out that there is little evidence for the claim that regional changes in forest vitality are due to stresses beyond those expected from natural factors. In Germany for example, the majority of documented foliage loss in the slight damage category (10% - 20% loss) is well within the limits of normal healthy tree variation.

The ozone hypothesis is presently the most popular of several air pollutant-related hypotheses of forest decline. Emission levels of the primary precursor pollutant, nitrogen oxides, have been steadily increasing for over two decades in both central Europe and in North America. Long term ozone concentrations have been increasing at most of the few isolated longterm monitoring stations that exist, and are often high enough in rural areas to damage sensitive tree species. Ozone concentrations increase with elevation, and have been observed to "flatten out" at several high elevation sites. These factors all support the ozone hypothesis. However, since experimentation with ozone and associated pollutants such as acid mist have so far failed in producing the symptoms observed in the damaged forests (chlorosis and loss of older needles), this hypothesis remains unproven for Waldsterben and the unexplained North American declines.

The second most popular hypothesis is that excessive nitrogen compounds are predisposing conifers to winter injury, a major symptom in the red spruce decline in the Northern Appalachians. However, only weak circumstantial evidence of a possible link between excess nitrogen compounds in air pollution and the observed damage is available (Section 6.3.2).

Whether or not any or all of the remaining hypotheses represent valid models of air pollution/forest damage relationships remain an open question at this time. Although short-term negative effects of "acid rain" on forest nutrients appears unlikely, longer term potential effects based on influences of balances of weathering, leaching and microbial mineralizations have not been adequately evaluated (McLaughlin 1985).

Scientific opinion is generally moving to the view that no single factor or pollutant is responsible for the present forest declines, and that different factors (natural and anthropogenic) are responsible for the decline at different locations.

The fact that no single hypothesis can explain the observed symptoms suggests that, if air pollutants are among the primary stresses responsible, then pollutant mixtures (both co-occurrences and sequences) are likely of significance. This is an important research area, because while several synergistic reactions have been observed using relatively high pollutant concentrations, little data is available on effects of pollutant mixtures at conditions which forest trees are exposed to in the real world.

8.2 Use of Experts

Until some scientific evidence of a link between air pollution and forest ecosystem decline is established, the use of subjective probabilty distributions in evaluating risks to forest ecosystems is probably quite limited. Until dose-response functions can be established experimentally, there is little point in attempting to judge risk to forests from air pollution in finer detail than that attained by Fraser et al (1985).

When and if functional relationships are established scientifically, it would appear that the use of subjective probability distributions will be a major asset to ecological policy analysis of forest-air pollution interactions. Should a definite link be established, Bayesian methods could be used to predict posterior distributions combining subjective and objective data. Experts could be asked to define probabilistic dose-response or damage functions for ecosystems and conditions that differ from the experimental conditions. These probabilistic damage functions could be used in computer models that simulate forest ecosystems, such as Forcyte 11, which is being developed in the Faculty of Forestry, University of British Columbia.

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Appendix 1

Comparison of Symptoms of Decline in Forests of Europe and North America

Source: Cowling 1985b