HEATHER ANGEL/BIOFOTOS

By Bernhard Prinz

Major hypotheses and factors

Causes of Forest Damage in Europe

This article is the second in a series on the possible relationship between forest damage and acid rain in Europe.

Forest damage has become a major topic of public and scientific discussion in recent years. Significant controversy has developed regarding the causes of this damage. This is especially true in West Germany (Federal Republic of Germany), where forests are considered in both economic and emotional terms. The mythic bonds between man and forest go back into ancient history.

This article first explains the difference between the novel character of recent forest damage and the "classic" form of smoke damage. The different forms of forest damage in Central Europe and North America are then compared, and evidence for and against several hypotheses of causation of chlorosis, or yellowing, of evergreen needles at upper elevations—the most important type of forest damage in Germany—is discussed in detail.

History of Forest Damage

With the acceleration of industrial expansion in the 19th century, damage to plants became more and more apparent. In the worst cases this resulted in plant "deserts" for the surroundings of highly industrialized British cities like Manchester and Liverpool. In Germany at the end of the 19th century, industries releasing extremely high emissions of air pollutants developed in the valleys of the Erzgebirge, mountains now situated in East Germany (German Democratic Republic). These emissions caused extensive forest devastation, which in turn stimulated much early research, especially within the forestry faculties of Tharandt and Freiberg in East Germany. The astonishingly well-developed state of knowledge at that time was summarized in 1907 by H. Wislicenus.[1]

According to his publication, acute injury could be distinguished from chronic (or "hidden") injury. In both cases sulfur dioxide was the main cause of damage, but other "classic" air pollutants were also involved. Coniferous trees proved to be more sensitive to long-lasting exposure to low pollutant concentrations (chronic effects), while deciduous trees reacted most sensitively to short-term high concentrations (acute effects). There was a close correlation between metabolic activity and sensitivity. Leaves and needles were most sensitive when just reaching full development, and whole plants suffered much more when fumigated during the day than when fumigated at night with the same concentration. Coniferous trees also proved to be much more sensitive during summer than winter. The prevailing wind determined the location and shape of the damaged area. Within stands, as well as within the crowns of single trees, clear shadow effects based on wind direction were observed. Poor soil nutrition enhanced the effect of air pollution. Most important for the severity of damage, however, was the water content of soil, especially with respect to drought conditions.

This classic type of forest decline was named *Rauchschaden* (smoke damage). Scientific proof of its causes was established through observations of the spatial and temporal relations between intensity of damage and the existence of specific sources of air pollution. A number of insightful experiments were also conducted at the time. In the case of chronic disease, clear proof was of course lacking, so the hypotheses about this type of damage had to be inferred from observations in the high range of air pollution concentrations causing acute effects.

As early as 1911 there were attempts to replace the *Rauchschaden* theory with the assumption that acute damages could appear only if previous acidification of soil by deposition of sulfuric acid (H_2SO_4) had taken place.[2] The eventual rebuttal of this view was based on the observation that damage also occurred on calcareous soils, and that this damage rather quickly disappeared when the sources of air pollution disappeared.

Another striking finding of early studies was that not all kinds of forest damage can be simply attributed to anthropogenic environmental influences. For example, in the first decades of this century, extensive damage of silver fir, a phenomenon called *Tannensterben* (fir dying), occurred at the northern border of its natural growing area. The causes of the *Tannensterben* were never unequivocally identified, but air pollution as a causal agent was never really discussed.[3] Compared with the situation of today, however, these early episodes of forest damage were neither so systematic and widespread nor on the whole so intensive. With good reason, then, the recent phenomenon of extensive forest damage is called *neuartige Waldschäden* (novel forest damage).

As a general conclusion, it can be stated that for the classic type of forest decline, especially in its chronic form, only circumstantial evidence of causation by air pollutants was provided. Nevertheless, the influence of air pollutants was never doubted where their concentrations in space and time were in agreement with the pattern of damage. Much later, in the Biersdorf field study in the 1960s,[4] the first relevant quantitative relationships on a really broad scale were produced. Disadvantageous impacts on trees resulting in growth reduction start at sulfur dioxide (SO_2) levels of roughly 50 micrograms per cubic meter as an annual arithmetic mean (see Figure 1 on this page). The sigmoidal shape of the dose-effect relationship is most striking: low dosages cause relatively little damage until a threshold is crossed. Damage then increases rapidly with further dosage increases until a dose is reached at which essentially 100 percent damage occurs. From the Biersdorf experiments, reliable data exist that can still be used today as a basis for the evaluation of sulfur dioxide–related forest damage.

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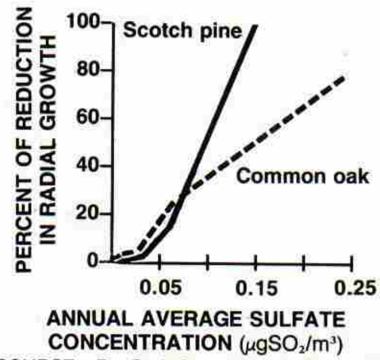
FIGURE 1. Relation between annual average sulfate concentration and radial growth reduction for two tree species.



SOURCE: R. Guderian and H. Stratmann, *Freilandversuche zur Ermittlung von Schwefeldioxidwirkungen auf die Vegetation*, vol. III (Köln-Opladen: Westdeutscher Verlag, 1968)

Recent Forest Damage

Any serious attempt to clarify the nature and causes of forest damage must address the following issues:

- Different symptoms on different tree species (and even on the same tree species) have to be clearly distinguished, if possible, and precisely described before their causes are investigated.
- It is necessary to distinguish between long-term trends and short-term fluctuations in the development of damage (see Figure 2 on page 13). Although air pollution is an example of a causal factor in long-term trends, air pollution episodes triggered by meteorological events may be a cause of short-term fluctuations. In each case, however, valid statements about trends can only be derived from appropriate time-series analyses and not—as unfortunately is done again and again—from a few single observations.
- Likewise, with respect to the spatial distribution of damage, broad-scale variation has to be distinguished from fine-scale variation (see Figure 3 on page 13).
- A most simplified but nevertheless complex causal scheme results when it is recognized that air pollutants can attack plants directly as well as indirectly via the soil (see Figure 4 on page 14).

Summing up the previous statements, it can be concluded that for the recent type of forest damage, a single, predominant cause may exist; but inspection of this cause with appropriately high resolution reveals that a complex interaction of different anthropogenic and nonanthropogenic causes really stands behind it. In addition, one must take into account that because of its specific pattern of temporal development, the recent type of forest decline reflects a chronic process. This is associated with internal dynamics as well as with accumulation of toxic matter and toxic effects, together with all other complicating factors. This is again a distinction from the classic smoke damage, where acute effects were clearly predominant.

Damage in North America

In the review attempted here, it is impossible to describe all the different facets of forest damage that have so far been observed in Central Europe and North America. It is necessary to focus on the most typical features, leaving out of course many aspects that may also be of great interest.

In 1985 a review of the facts about forest damage in North America had to begin with the statement that, unlike the situation in West Germany, precise data on the development and distribution of forest damage were missing as were data on air pollution in the most affected areas.[5] Since then impressive efforts to investigate the causes of forest decline have been undertaken. Most of these investigations are a part of the Forest Response Program, sponsored by the National Acid Precipitation Assessment Program and funded by the U.S. Environmental Protection Agency, the U.S. Forest Service, and the National Council of the Paper Industry for Air and Stream Improvement.[6]

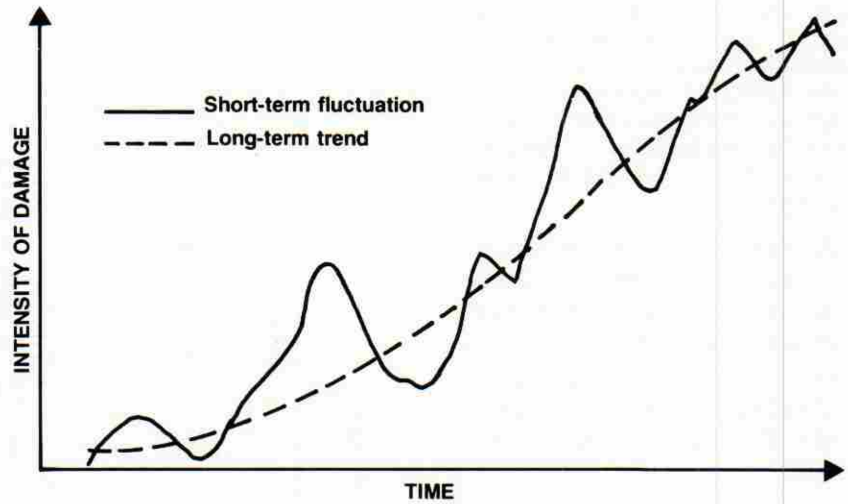
The most severe tree decline in North America involves red spruce (*Picea rubens*) growing at high-elevation sites from New York and New England to the southern Appalachian Mountains. Tree-ring analyses indicate a substantial decrease in tree growth rate during the past 20 to 25 years, as well as a strong association between severity of damage and elevation, especially in northern forests.[7] Both features are comparable to the situation in West Germany. In southern Germany, for example, the first symptoms of growth reduction can be traced back to the early 1960s.[8]

The symptoms of forest damage are rather diverse, especially if other tree species such as the balsam fir (*Abies balsamea*) and Fraser fir (*Abies fraseri*) are included. In North America the major visible foliar symptom is loss of needles starting from the tips of branches and from the apex of the crown, but, unlike the situation in West Germany, the needle loss is not accompanied by pronounced chlorosis or symptoms of nutrient deficiency.

The ideas of the German scientist Bernhard Ulrich[9] were adopted early in the 1980s to explain the occurrence of forest decline in North America as being the result of soil acidification or aluminum toxicity caused by acid deposition.[10] These assumptions were soon criticized, however, because the mechanisms of aluminum toxicity are inhibited by organic matter in soil, and organic matter is prevalent at the high elevations where forest damage is most intense.[11] Furthermore, except for the most sensitive soils, leaching of nutrients does not appear to pose a threat to soil base-cation supplies in the United States.[12]

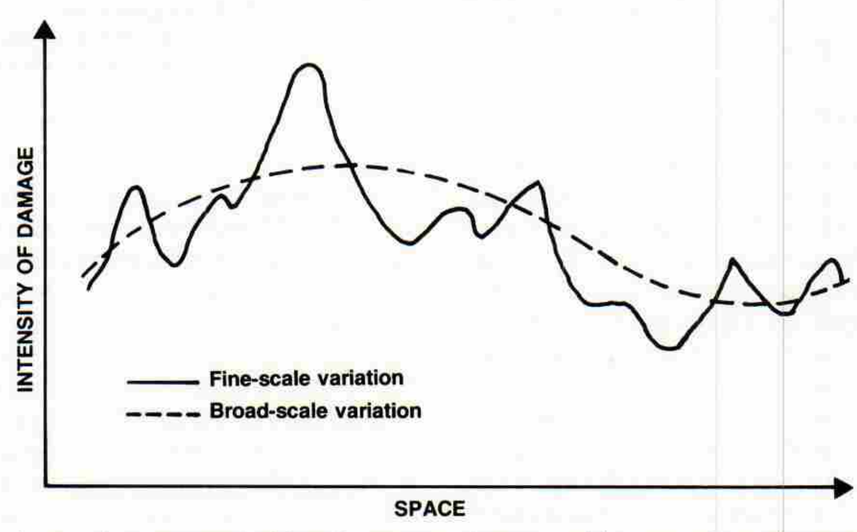
Other researchers suggested that the abnormally high frequency of drought periods in the 1960s could have caused the forest damage, or could have at least triggered it.[13] More recently the impact of ozone as a major causal factor has gained much attention.[14] Another recently discussed aspect is the suggestion that enhanced input of nitrates (NO_3) from the past may have weakened the trees' resistance to frost, so that in recent forest decline winter damage to foliage may be the crucial factor.[15] S. B. McLaughlin's authoritative review in 1985 concluded that:

FIGURE 2. Temporal development of forest decline as a result of air pollution and other environmental factors.



Over a short period of time, tree damage may appear to swing dramatically (as a result of climatic conditions, for example). Only over a sufficiently long time frame can such **short-term fluctuation** be readily distinguished from the underlying **long-term trends** (as may be induced by air pollution, for example).

FIGURE 3. Spatial variation of forest decline as a result of air pollution and other environmental factors.

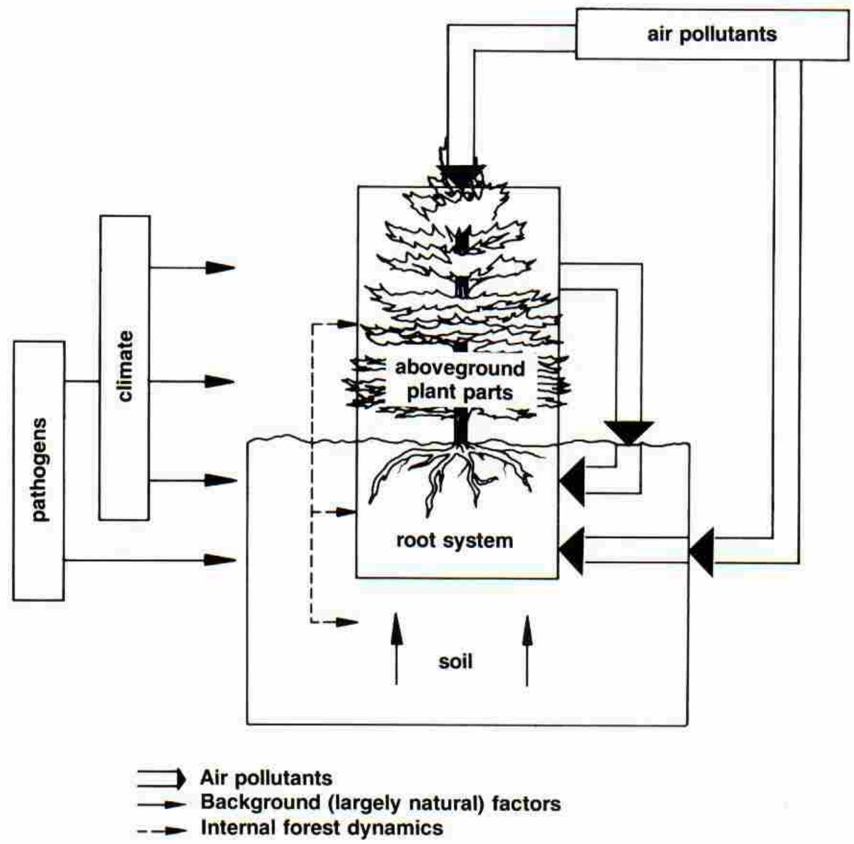


In any given segment of forest, one may observe a wide range of tree damage induced, for example, by variations in soil and exposure. Over a large enough space, this **fine-scale variation** can be distinguished from the more general pattern, or **broad-scale variation** (induced by air pollution, for example).

based on field irrigation experiments and studies of forest nutrient cycles, short-term negative effects of acid deposition on forest soils appear unlikely. Longer-term potential for negative effects . . . has not yet been adequately evaluated. . . . There are still many postulated pathways and mechanisms for the observed responses, including both direct and indirect influences of O_3, wet and dry deposited strong acids, and heavy metals, as well as climatic change. . . . However, there is still no clear evidence of a single causal agent.[16]

It should be added, however, that the encouraging and promising research now under way in the United States[17] may provide us with a much clearer picture than we have today. It seems that in these investigations ozone, in combination with other factors, will play a significant role.

FIGURE 4. Possible factors involved in the causation of forest damage and their pathways.



Damage in Europe

The extent and development of recent forest damage in Europe is reviewed in the accompanying article by S. Nilsson and P. Duinker (see page 4).[18] In addition to the broad pattern of damage, they cite several specific cases worth highlighting.

Eastern Europe

In some subalpine areas of Poland, Czechoslovakia, and East Germany (especially the Erzgebirge), the worst cases of forest damage in the world appear. The damages are solely caused by sulfur dioxide and other primary air pollutants and therefore have to be associated with the classic type of forest decline. A recent report, however, shows that in the areas of Czechoslovakia that are cleanest with respect to sulfur dioxide, a dramatic development of forest damage, especially in Norway spruce stands, took place in 1982 and 1983.[19] There are no obvious causes for this damage: the concentration of sulfur dioxide was definitely below the threshold levels of 40 to 50 micrograms per cubic meter identified in the Biersdorf field trial. The definite deficiencies of magnesium and potassium in the fir and spruce resemble the symptoms that are to be found in West German alpine and subalpine forests.

Widespread forest damage (in 1985 about 70,000 hectares) with unclear causality has also been reported recently from Slovenia, Yugoslavia.[20] According to needle analysis, "dry sulphur deposition, except in the surroundings of known local pollution sources, cannot be a significant reason" for this phenomenon. Many symptoms are similar to the so-called *neuartige Waldschäden* (novel forest damage) in West Germany, which is described later.

Nordic Countries

Inventories of forest damage in Sweden have shown that spruce trees are suffering from needle loss primarily in the most southern and western parts of south Sweden, especially on dry soil in exposed sites. Older trees are more damaged than are younger trees. Early reports speak of a "remarkable coincidence between the map of tree damage and maps showing the areas of lake acidification."[21] But five-year experiments with artificial rain,[22] as well as results from other studies conducted in Norway, suggest that acid deposition is unlikely to have rapid or major effects on soil pH in the Nordic countries.[23] Neither needle chlorosis nor apparent nutrient deficiencies occurred in damaged stands of Norway spruce in south Sweden.[24] A slight positive correlation between degree of needle loss and aluminum concentration in the needles exists and could indeed point to the toxic influence of this element. But the content of calcium, magnesium, manganese, iron, zinc, and sodium in the needles shows the same unexpected tendency—that is, positive correlation with needle loss—as does the aluminum content.

A more recent publication concludes cautiously that "no one factor can be singled out as the cause of damage" but that there are many coacting stress factors, such as drought, frost, wind, airborne pollutants (like ozone, nitrogen oxides, acid, and ammonia), nutrient deficiency, and metal poisoning caused by soil acidification, as well as nitrogen saturation.[25]

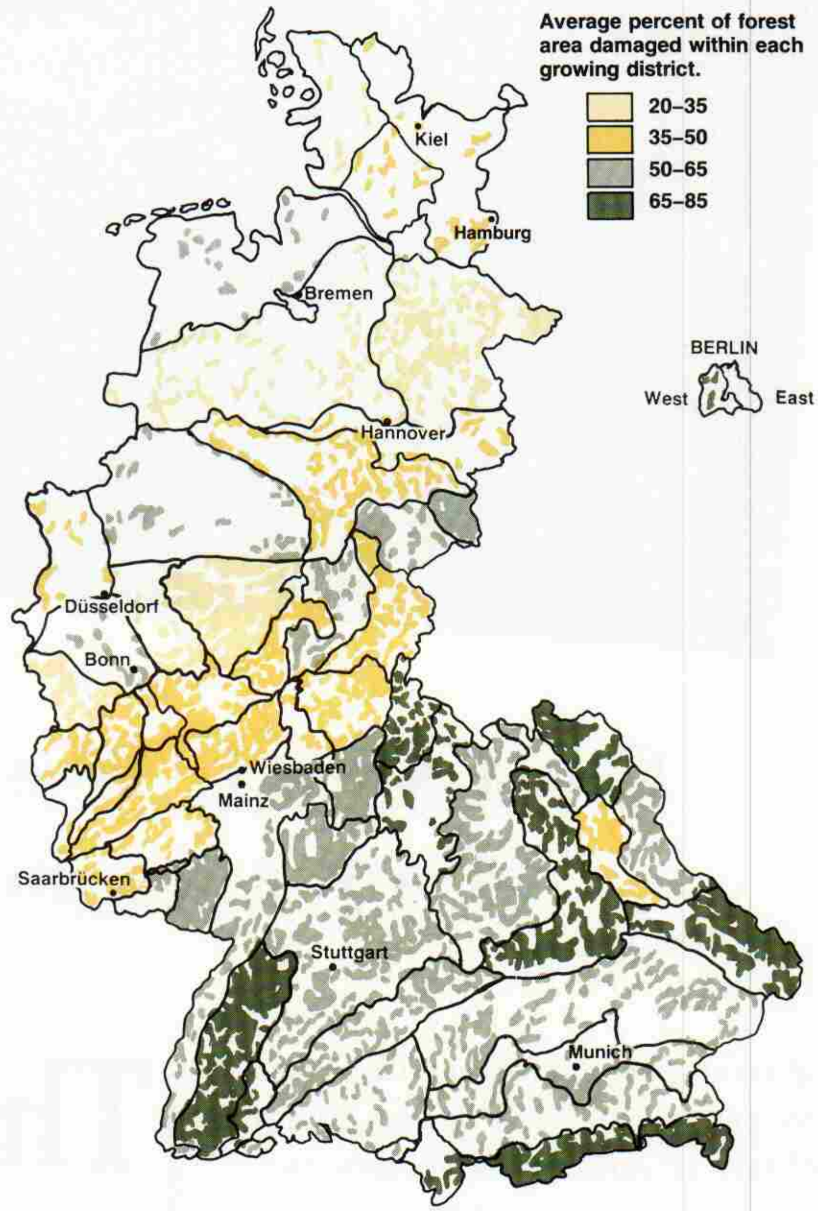
West Germany

Within Europe, West Germany is among the countries most affected in recent years by forest damage. All inventories show the damage concentrated mostly in southern Germany, south of the Main River (see Figure 5 on this page). The neighboring parts of surrounding countries, especially countries to the south like Austria, Switzerland, and France, are also damaged.

Recent forest decline in West Germany has its own politically bound history. The term *Waldsterben* (forest dying), which was first used to describe the phenomenon, caused much excitement. But this term did not reflect the complex nature of the new phenomenon or the fact that it involved more morbidity than mortality of forests. Great segments of the scientific media and political communities focused early on acid rain as the single cause. Not until 1982 and 1983 was the discussion broadened.[26] The narrow and at times rather intolerant focus on acid rain and forest death has now given way to the much more neutral term *neuartige Waldschäden*. People have again learned to have a broader and more differentiated view of the phenomenon.

Some rough generalizations about the appearance and the causal explanation of *neuartige Waldschäden* in West Germany follow.[27]

FIGURE 5. Distribution of forests and degree of forest damage in West Germany (all tree species), 1986.



Note: Growing districts are outlined in black. "Damage" is defined as more than 10 percent of leaves or needles lost.

SOURCE: Umweltbundesamt, Berlin, 1986.

• Several different species of trees (coniferous and deciduous) are involved. It appears that the silver fir (*Abies alba*) first showed apparent symptoms of decline in the mid-1970s, followed by the Norway spruce (*Picea abies*) in 1980 in southern Germany and elsewhere in 1982, and some deciduous species such as common beech (*Fagus sylvatica*) and oak (*Quercus* sp.) in 1984 and 1985. With respect to the severity of symptoms and distribution of damage, Norway spruce seems to be the most important. Although more severely damaged, silver fir stands are concentrated in relatively small areas, especially at higher altitudes of the south German subalpine mountains, so that this type appears to be less important overall.

• In Norway spruce the main symptoms are needle chlorosis, which increases with the elevation of the stand, and thinning of the crown, which occurs more at the lower altitudes and on the plain.

(continued on page 32)

Causes of Forest Damage

(continued from page 15)

• With respect to specificity, intensity, and distribution, needle chlorosis in the higher altitudes of the subalpine mountains seems to be the most important type of damage. Moreover, the greatest amount of scientific information is available for this type of damage.

• Needle chlorosis can clearly be associated with deficiencies of nutrients in the tree, especially deficiencies of magnesium, calcium, zinc, potassium, and manganese. The supply of other nutrients, especially of nitrogen and phosphorus, is on the whole sufficient. At some sites where the damage is especially severe and which are far from industrial and urban centers, even the concentration of sulfur is significantly lower in yellow needles than in green needles, reaching the range of deficiency of this essential element. This is an important observation for causality in implicating leaching rather than sulfur toxicity as a factor. Only the sun-exposed needles turn yellow.

• Older trees are more affected by chlorosis than are younger ones; stands with trees of varying ages and varying types with a rough canopy are more affected than are even-aged and uniform stands with a closed canopy.

• In relation to potential causal factors, it must be taken into account that ozone concentrations have increased over the last decades, especially at sites remote from industrial and urban centers. Moreover, the concentration of nitrite (NO_2) in rain has shown an upward trend during recent years while the concentration of sulfate (SO_4) has decreased, leaving the acidity caused by this kind of anionic substitution more or less constant. It is also important to consider that the most damaged sites at the higher altitudes are characterized by long-lasting fog exposures. There are also some indications, despite the lack of sound time-series analyses, that forest soils have undergone a loss of nutrients and a decrease in buffer capacity because of the influence of acid depositions. In relation to this assumption, aluminum concentrations in the soil solution may be higher now than in former times. Unlike the situation with ozone concentrations, however, there is no clear spatial correspondence between aluminum concentration and the intensity of damage.

The *neuartige Waldschäden* Hypothesis

Two types of damage have been distinguished in Norway spruce[28]: needle loss (Type I) and needle chlorosis (Type II). Needle loss is preceded by increased nitrate leaching from the soil and a high deposition of sulfuric acid. It results in root damage and therefore enhanced water stress, and preferentially affects suppressed (understory) trees. Needle chlorosis occurs only at moderate ranges of soil acidification and with low deposition of sulfuric acid. It results in nutrient deficiency (especially of magnesium), despite a functioning root system, and preferentially affects dominant trees.

The most probable explanation for the causes of the *neuartige Waldschäden*, especially needle chlorosis, is in the impacts of ozone and acid deposition (see Figure 6 on page 33).[29] Ozone affects the trees' energetic metabolism in a direct way and also weakens the cell membrane system so that, in combination with acid rain and fog, the leaching of essential nutrients is enhanced. As a further result, the root system is affected and the uptake of nutrients from the soil is reduced. Soil type is an important factor in explaining the microspatial damage as well as the long-term development of damage from anthropogenic influences.

Last but not least, climate has to be taken into consideration as a most important triggering factor. The more or less sudden appearance of *neuartige Waldschäden* symptoms at so many sites can only be understood if the climate has had a strong influence on the outbreak of these symptoms. The crucial question that remains to be answered is how the nutrient deficiency in general, and the magnesium deficiency in particular, can be explained. The answer to this question, and to the phenomena related to it, will be presented step by step.

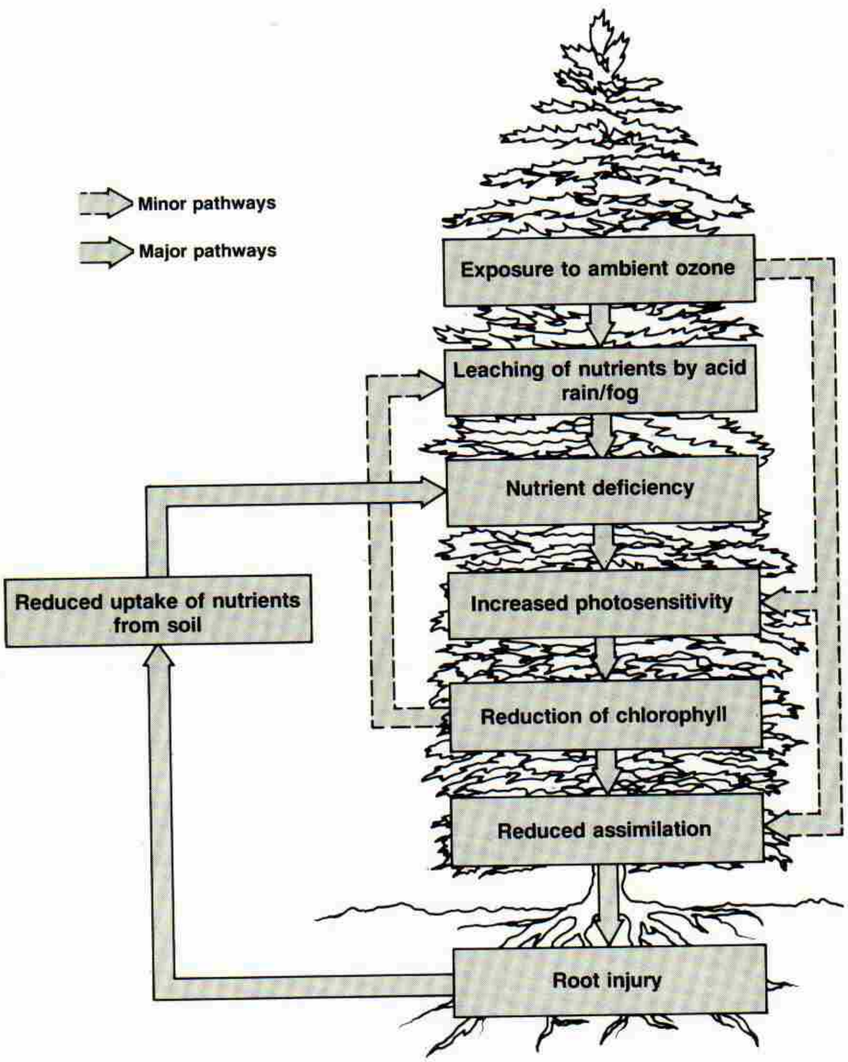
• It has been substantiated by experiments that needles suffering from nutrient deficiency lose chlorophyll if exposed to light.[30] This experimentally proven mechanism is in full agreement with the most typical symptom—chlorosis—mentioned earlier.

• Magnesium concentration is highest in youngest and oldest needles. The most pronounced deficiency occurs in the previous year's needle growth at the time of shoot budding during May and June.[31] Because of the mobility of magnesium, it is transported to the parts of the plant where it is needed most—the new shoots. This is again in agreement with observed symptoms of forest damage. The enhanced concentration in the older needles is due to accumulation during their lifetime.

• No visible acute effects occur in spruce needles fumigated with realistic concentrations of ozone.[32] On the other hand, needle chlorosis may be produced both if the needles are fumigated for longer than one year and if the fumigation is combined with soil nutrient deficiency.[33] Despite the fact that the combination of ozone and depletion of nutrients in the soil is detrimental in several aspects, the type of chlorosis it induces does not seem to be identical with the type of light-induced chlorosis observable in the stand.

• Histological investigations of damaged trees show that, in contrast to acute effects of air pollutants, the main damage in cases of chronic damage occurs in the phloem and not in the mesophyll. This type of damage can easily be reproduced by magnesium deficiency in soil alone, without further interactions with gaseous compounds.[34] By disturbing the transport of assimilates (products of photosynthesis) via the phloem, a disadvantageous feedback with regard to the root system comes into action. Essentially the same mechanism can be induced, however, by chronic exposure to ozone. In this case, the first relevant reaction is a depression of photosynthesis.[35] Subtle investigations of damaged Norway spruce trees with the symptom of chlorosis demonstrate that the membrane system is the main target of ozone.[36]

FIGURE 6. Possible impact of ozone and acid fog or rain on conifer forests.



SOURCE: B. Prinz, G. H. M. Krause, and H. Stratmann, "Waldschäden in der Bundesrepublik Deutschland," LIS-Berichte no. 28 (Essen, 1982).

• Enhanced leaching of nutrients, of cations as well as of anions, can be provoked experimentally by fumigating Norway spruce trees with ozone and then fogging them with artificial acidic fog.[37] If applied without the ozone treatment, the acidity in the fog influences only the leaching of the cations and not of the anions.

Leaching is especially high if the trees are predamaged—for example, taken from a damaged natural stand—and if the nutrient status in the soil is poor.[38] This very important mode of feedback, which accelerates the loss of nutrients, is in full agreement with observations in natural stands, as in the Fichtelgebirge.[39] On the other hand, the loss of nutrients in healthy trees treated only with artificial fog (not fumigated with ozone) can be easily compensated for with uptake of these nutrients from soil and transport within the plant.[40] In this case and in contrast to fumigation experiments with ozone, the leaching is higher on fertilized than on nonfertilized soil. Therefore, complete understanding of effective nutrient deficiency by leaching presupposes an interaction between ozone, poor nutrient status in soil, and already existing damage caused by long-lasting exposure of the trees to air pollution and/or unfavorable climatic conditions.

• With respect to the influence of soil, there are investigations that show that the ratio of calcium or magnesium to aluminum, rather than aluminum itself, affects the root system and that the presence of aluminum in the soil solution hinders the uptake of double-charged cations.[41] Results, however, are not unequivocal. It must also be considered that in some carefully executed experiments, harmful effects could only be obtained at aluminum concentrations much higher than those observable in the field.[42]

The most important point, however, is that up to now no correlation at all has been found in nature between the intensity of needle chlorosis of spruce and the aluminum content in soil or in needles, although such correlation should be expected from many experiments.[43] In natural stands it is magnesium and not calcium fertilization that has significantly improved the vitality of Norway spruce showing the symptom of chlorosis.[44] This observation speaks against the predominant influence of aluminum toxicity by acidification and in favor of magnesium deficiency in soil as the predominant predisposing factor. The most striking proof against the presumed toxicity of aluminum is the observation of a significant difference in the content of magnesium and calcium between the needles of damaged and undamaged trees in the Black Forest, but no difference at all in the roots.[45] Furthermore, no difference in the content of aluminum was found either in the needles or in the roots.

So within individually predisposed trees, some toxic agent has either prevented transport of calcium and magnesium exclusively (that is, not nitrogen, phosphorus, or potassium) from root to needle tissue, or subsequently these two elements have specifically been lost by leaching via the cuticle. Again the main question is which of these two mechanisms really exists and how it is triggered.

• The other remaining question is the influence of climate on the development of forest damage. Unfortunately, almost no experiments about this most important matter exist, but some specific observations may contribute to the discussion.

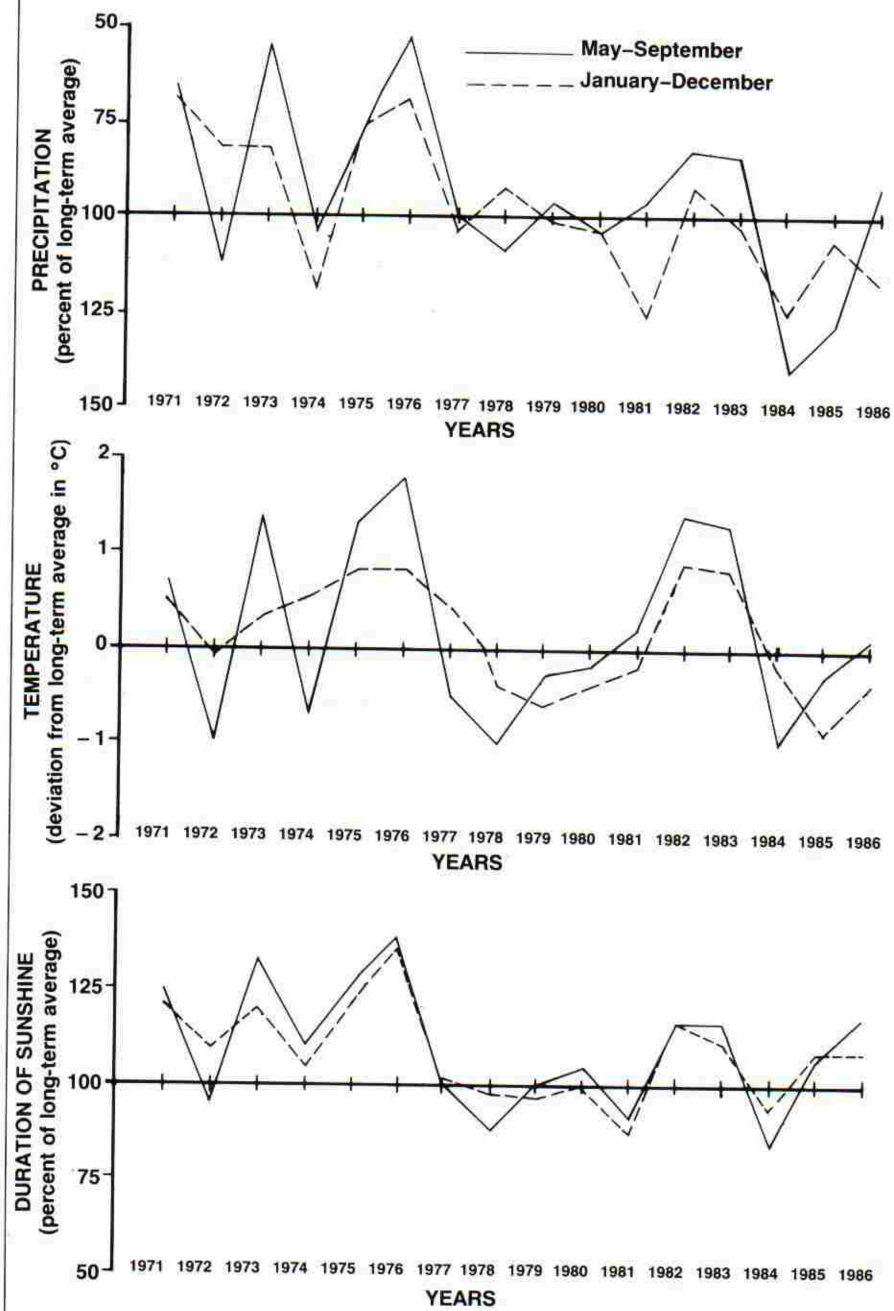
Permanent observational plots in the state of Baden-Württemberg show that observable symptoms of the decline of silver fir developed mainly between autumn 1980 and spring 1983—that is, within a relatively short period. From that time on, a more or less steady state was reached. The health of the Norway spruce worsened mainly between spring 1982 and spring 1983, with a slight improvement of the most damaged trees between spring 1986 and autumn 1986.[46]

From radial growth studies it can be shown that with both tree species an initial breaking down of radial growth appeared in the extremely dry and warm summer of 1976.[47] During this summer ozone concentrations were also extreme without, however, causing significant visible symptoms. From then on, sick trees did not recover and were further weakened, especially in 1980 and 1982, exhibiting for the first time chlorosis and needle loss. This again speaks very much in favor of a chronic, long-lasting process.

In conjunction with a fertilizer experiment, the development of damage since 1983 was very carefully observed within a specific stand of Norway spruce in the Eggemountains (east North Rhine-Westphalia), where widespread damage had occurred for the first time in autumn 1982.[48] The investigation revealed that the health status of the forest improved significantly between 1983 and 1986. This recovery was, however, more or less confined to the symptom of needle loss. In this case climate seemed to be the major factor in causing forest decline. With respect to chlorosis, within this period the health status improved considerably only in a stand fertilized with a combination of magnesium and calcium. In plots where calcium had been applied as the main fertilizer component, the situation remained unchanged. In contrast to chlorosis, needle loss was almost unaffected by fertilization.

This again provides evidence for the chronic character of the disease, modified by climatic influence; the overwhelming importance of magnesium, especially for the development of chlorosis; and the minimal influence of calcium as the most important base donor in soil.

FIGURE 7. Rainfall, temperature, and duration of sunshine at a subalpine meteorological station in North Rhine-Westphalia, 1971–1986.



Note: The selected measuring site is situated in the mountains of Sauerland (the southeast portion of the North Rhine-Westphalia province) and, consequently, is only partly representative of south Germany.

With respect to climate, the worst situation would have been expected in 1975 and 1976 (see Figure 7 on this page), assuming that drought leads to disturbance of nutrient supply by itself. (It is notable that in 1976, the highest ozone concentrations ever recorded in West Germany were also measured.) It appears, however, that even more important than the momentarily unfavorable conditions of 1976 was the fact that the plants had not had enough time to recover after 1976 and that therefore the second "climatic stress" period from 1980 to 1983, exacerbated by the influence of air pollutants, especially ozone, completed the damage.

A Complex Mode of Action

Many features of forest damage in North America and Central Europe are comparable, although some differences of symptoms also exist. Similarities in the development of the damage point to the influence of the same pollutants or the triggering effect of certain climatic factors uniformly affecting great parts of the Northern Hemisphere. For Central Europe it seems most probable that ozone, in combination with acid fog and rain, anthropogenic and natural variations in soil conditions, and specific, physiologically unfavorable climatic periods, represents the major factor in the development of the most important kind of damage: chlorosis of Norway spruce.

Summing up the evidence for and against the various hypotheses on the causes of Europe's *neuartige Waldschäden*, the most probable explanations are as follows:

- The cause of the short-term appearance (and recovery) of damage involves climate as a triggering or synchronizing factor.
- The causes for the long-term temporal development of damage involve the upward trend of ozone concentration during the last few decades and the continuous loss of nutrients in soil by acid deposition.
- The causes for the spatial distributions of damage involve the increase of ozone concentration as a daily average with increasing altitude and the natural differences in the nutrient supply from soils.

In any case the development of forest damage must be considered a long-last-

FROM EMISSION TO ACIDIFICATION: AN ACID RAIN PRIMER

Sulfur and nitrogen bound up in fossil fuels are the precipitating factors in acidification and environmental damage. How does it all come about?

Most of the sulfur leaves smokestacks in gaseous form as sulfur dioxide (SO_2). Sooner or later it is absorbed at the surface of water and land and by vegetation. This process is referred to as dry deposition because the deposition occurs in gaseous form or as small particles. Wet deposition is the result of an additional chemical change. Some of the sulfur dioxide is oxidized by atmospheric oxygen to sulfuric acid (H_2SO_4). This substance cannot exist in gaseous form; it occurs either on small particles or in solution in cloud and rain droplets. In due course the acid comes down along with precipitation—it literally rains acid.

Nitrogen is emitted as gaseous oxides (NO_x) from smokestacks and automobile exhaust pipes. Like sulfur dioxide, these oxides can be dry deposited. They may also become converted into nitric acid (HNO_3) and be wet deposited.

When sulfuric acid is dissolved in water, it appears largely in the form of sulfate ions (SO_4^{2-}) and hydrogen ions (H^+). Dissolved nitric acid consists of nitrate ions (NO_3^-) and hydrogen ions. In the last analysis, acidification is a matter of how many hydrogen ions get into circulation. (A hydrogen ion is a hydrogen atom that has lost its only electron and become positively charged—a cation. In contrast, negatively charged nitrate and sulfate ions are called anions.) The concentration of hydrogen ions in a solution is a measure of its acidity. This acidity is stated as a pH value.

Acidified soil and water systems have undergone processes in which the hydrogen ion concentration in the soil water (the moisture in the soil) and surface water (lakes and waterways) or in groundwater has progressively increased. This hydrogen ion excess touches off chemical and biological processes that affect ions of other substances. Metals that are important plant nutrients—like potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+})—are leached out of the ground, or "kicked out" by the hydrogen ions, and are thus lost to trees and field plants. Heavy metals such as cadmium and mercury and the metal aluminum begin to move, accumulating with time in excessively large and injurious quantities in water, soil, and living organisms (among them, human beings).

—*Adapted from the Swedish Ministry of Agriculture,* Acidification: A Boundless Threat to Our Environment *(Solna: National Swedish Environment Protection Board, 1983).*

ing chronic process; the resilience of the plant diminishes when reacting to environmental changes. This rather complex mode of action may be the reason that the whole chain of events leading to forest damage, including its specific symptoms, has not yet been produced in laboratories. It may be that experiments were executed over too short a time period; but it may also be that they lacked the correct, low-level mixture of nutrients, especially magnesium and calcium, perhaps combined with an oversupply of nitrogen. This last aspect of nutrient imbalance induced by nitrogen oversupply has been discussed rather intensively during recent years.[49] On the other hand, investigations have shown that even large amounts of nitrogen overfertilization appear not to be really harmful,[50] so this question remains open.

Each scientifically oriented investigation should start with observations in nature and should, as a final proof of the experimentally gained results, also end there. It is extremely important to develop and apply uniform and reliable monitoring systems to assess the type and degree of forest decline as well as for the surveillance of air pollution and other potentially influential factors like soil and climate. In particular, the symptomatology must be improved considerably. In the state of North Rhine-Westphalia, the following three stages of investigation have proved sensible:

- experiments in exposure chambers with controlled treatments with air pollutants;

- experiments in open-top chambers within a damaged stand with application of natural and filtered air as well as with natural and "purified" rain; and

- highly sophisticated observations with morphological, histological, physiological, biochemical, and gene-engineered methods in naturally exposed trees in a damaged stand.

It is hoped that through the immense effort now under way in Central Europe as well as in North America, our view on the phenomenon of *neuartige Waldschäden* will become much clearer.

NOTES

1. H. Wislicenus, ed., *Sammlung von Abhandlungen über Abgase und Rauchschäden* (Berlin: Paul Parey, 1907; reprint, Düsseldorf: VDI-Verlag, 1985).

2. A. Wieler, *Pflanzenwachstum und Kalkmangel im Boden* (Berlin: Bornträger, 1911).

3. F. W. Neger, "Das Tannensterben in den sächsischen und anderen deutschen Mittelgebirgen," *Tharandter Forstliches Jahrbuch* 58(1908):201–25.

4. R. Guderian and H. Stratmann, *Freilandversuche zur Ermittlung von Schwefeldioxidwirkungen auf die Vegetation*, vol. III (Köln-Opladen: Westdeutscher Verlag, 1968).

5. B. Prinz, "Waldschäden in den USA und in der Bundesrepublik Deutschland—Betrachtungen und Ursachen," *VGB Kraftwerkstechnik* 65(1985):930–38.

6. A. Carey, A. C. Janetos, and R. Blair, "Responses of Forests to Atmospheric Deposition: National Research Plan for the Forest Response Program" (National Acid Precipitation Assessment Program, Washington, D.C.-Corvallis, Oreg., December 1986). The statements that follow in the text are made on the basis of many sources, including personal communications, which cannot all be cited completely and properly here. A good overview of the North American situation by leading U.S. scientists is given in a recent publication resulting from a U.S.-German information exchange group on forest decline, H. E. Papke, B. Krahl-Urban, K. Peters, and Chr. Schimansky, *Waldschäden—Ursachenforschung in der Bundesrepublik Deutschland und in den Vereinigten Staaten von Amerika* (Jülich: Nuclear Research Center, 1986). Critical reviews of the state of knowledge to 1985 have been provided by among others S. B. McLaughlin, "Effects of Air Pollution on Forests: A Critical Review," *Journal of the Air Pollution Control Association* 35(1985):512–34; S. N. Linzon, "Effects of Gaseous Pollutants on Forests in Eastern North America," *Water, Air, and Soil Pollution* 31(1986): 537–50; J. R. McBride and P. R. Miller, "Responses of American Forests to Photochemical Oxidants" (Paper presented at the NATO Advanced Research Workshop on the Effects of Acidic Deposition, Toronto, 12–17 May 1985), Proceedings in press.

7. Prinz, note 5 above; McLaughlin, note 6 above.

8. G. Kenk, W. Kremer, D. Bonaventura, and M. Gallus, "Jahrring- und zuwachsanalytische Untersuchungen in erkrankten Tannenbeständen des Landes Baden-Württemberg," *Mitteilungen der FVA* 12 (1984):1–37; W. Schöpfer and J. Hradetzky, "Zuwachsrückgang in erkrankten Fichten- und Tannenbeständen—Auswertungsmethoden und Ergebnisse," *Forstwissenschaftliches Centralblatt* 105(1986): 446–70.

9. B. Ulrich, "Langzeitwirkung von Luftverunreinigungen auf Waldökosysteme," *Düsseldorfer Geobotanische Kolloquium* 1(1984):11–24.

10. G. Wetstone, "A Conversation with Acid Rain Researcher Hubert Vogelmann," *The Environmental Forum*, February 1983, 21–28.

11. A. H. Johnson and T. G. Siccama, "Acid Deposition and Forest Decline," *Environmental Science & Technology* 17(1983):294A–305A.

12. D. W. Johnson, J. M. Kelly, W. T. Swank, D. W. Cole, J. W. Hornbeck, R. S. Pierce, and D. van Lear, "A Comparative Evaluation of the Effects of Acid Precipitation, Natural Acid Production, and Harvesting on Cation Removal from Forests," ORNL-TM 9706 (Oak Ridge National Laboratory, Oak Ridge, Tenn., 1985).

13. D. W. Johnson, "Effects of Acid Deposition on Forest Soils," Proceedings, *18th IUFRO [International Union of Forestry Research Organizations] World Congress*, div. 1., vol. 2, Ljubljana, 7–21 September 1986 (Ljubljana, Yugoslavia: IUFRO World Congress Organizing Committee), 484–96.

14. Linzon, note 6 above; J. N. Woodman and E. B. Cowling, "Airborne Chemicals and Forest Health," *Environmental Science & Technology* 21(1987):120–26; McBride and Miller, note 6 above.

15. A. J. Friedland, R. A. Gregory, L. Käremlampi, and A. H. Johnson, "Winter Damage to Foliage as a Factor in Red Spruce Decline," *Canadian Journal of Forest Research* 14(1984):963–65.

16. McLaughlin, note 6 above.

17. See, for example, A. H. Johnson, "Acid Deposition: Trends, Relationships, and Effects," *Environment*, May 1986, 6; R. E. Munn, "Special Report: An Integrated Approach to Assessing Acid Deposition," *Environment*, May 1986, 12.

18. For more detail, see earlier reviews by G. H. M. Krause, U. Arndt, C. J. Brandt, J. Bucher, G. Kenk, and E. Matzner, "Forest Decline in Europe: Development and Possible Causes," *Water, Air, and Soil Pollution* 31(1986):647–68; K. Giesen, "Stand der Waldschäden und der Gegenmaßnahmen in den europäischen Ländern," *Algemeine Forst Zeitschrift* 41(1986): 1006–7.

19. J. Materna, "Luftverunreinigungen und Waldschäden," Conference proceedings, *Umweltschutz—eine internationale Aufgabe*, Prague, 13–15 March 1985 (Düsseldorf: VDI-Verlag), 19.1–19.13.

20. M. Solar, "Air Pollution and Forest Decline in Slovenia," Proceedings, *18th IUFRO World Congress*, div. 2, vol. 1, Ljubljana, 7–21 September 1986 (Ljubljana, Yugoslavia: IUFRO World Congress Organizing Committee), 368–80.

21. G. Svensson, "Forest Damage Surveyed," *Acid Magazine*, Winter 1984–85, 12–13.

22. G. Abrahamsen and A. O. Stuanes, "Lysimeter Study of Effects of Acid Deposition on Properties and Leaching of Gleyed Dystric Brunisolic Soil in Norway," *Water, Air, and Soil Pollution* 31(1986):865–78.

23. Acidification of soil was also investigated in the Tönnersjöheden Experimental Forest. A single sampling in 1927 was compared with resamplings between 1982 and 1984. In the latter sampling interval, however, warm periods caused high rates of internal acidification by sulfides as well as by nitrification. The study therefore cannot be considered as a valid substitute for a time-series analysis. See C. O. Tamm and L. Hallbäcken, "Changes in Soil pH over a 50-year Period under Different Forest Canopies in SW Sweden," *Water, Air, and Soil Pollution* 31(1986):337–41; H. Hartikainen and M. Yli-Halla, "Oxidation-induced Leaching of Sulphate and Cations from Acid Sulphate Soils," *Water, Air, and Soil Pollution* 27(1986):1–13.

24. J. Puhe and A. Aronsson, "Ernährungszustand von Fichten mit unterschiedlich starken Nadelverlüsten—Erste Ergebnisse aus südschwedischen Waldschadensuntersuchungen," *Der Forst- und Holzwirt* 17 (1986):464–70.

25. "Air Pollution and Acidification" (National Swedish Environment Protection Board, Solna).

26. B. Prinz, G. H. M. Krause, and H. Stratmann, "Waldschäden in der Bundesrepublik Deutschland," LIS-Berichte no. 28 (Essen, 1982); B. Prinz, "Säure Niederschläge—Ursachen und Wirkungen" (International Kolloquium der VDI-Kommission Reinhaltung der Luft, 7–9 June 1983, Lindau), *Staub-Reinhalt. der Lüft* 43 (1983):306–7.

27. "Forschungsbeirat Waldschäden/Luftverunreinigungen der Bundesregierung und der Länder," 2d Bericht (Kernforschungszentrum, Karlsruhe, May 1986).

28. M. Hauhs and R. F. Wright, "Regional Pattern of Acid Deposition and Forest Decline along a Cross Section through Europe," *Water, Air, and Soil Pollution* 31(1986):463–74.

29. Prinz, Krause, and Stratmann, note 26 above.

30. B. Prinz, G. H. M. Krause, and K.-D. Jung, "Untersuchungen der LIS Essen zur Problematik der Waldschäden," in *Waldschäden—Theorie und Praxis auf der Suche nach Antworten* (München-Wien: R. Oldenbourg Verlag, 1985), 143–94.

31. Ibid.; D. Stiefermann-Harms and H. Minnemann, "Auswirkungen von Schadstoffen auf die Kon-

firmation von Chlorophyll-Protein-Komplexen bei immissionsgeschädigten Waldbäumen" (Paper presented at Statuskolloquium des Projekt Europäisches Forschungszentrum für Massnahmen zur Luftreinhaltung [PEF], Karlsruhe, 10–12 March 1987), Proceedings in press.

32. Prinz, Krause, and Jung, note 30 above.

33. R. Guderian, K. Kuppers, and R. Six, "Wirkungen von Ozon, Schwefeldioxid und Stickstoffdioxid auf Fichte und Pappel bei unterschiedlicher Versorgung mit Magnesium und Kalzium sowie auf die Blattflechte Hypogymnia physodes," VDI-Berichte 560, *Waldschäden* (Düsseldorf: VDI-Verlag, 1985), 657–702.

34. S. Fink, "Anatomische und histochemische Untersuchungen zur Klärung der Beteiligung biotischer Schadensverursacher am 'Waldsterben' " (Statuskolloquium des PEF, Karlsruhe, 10–12 March 1987), Proceedings in press.

35. G. H. M. Krause and B. Prinz, "Zur Wirkung von Ozon und saurem Nebel (einzeln und in Kombination) auf phänomenologische und physiologische Parameter an Nadel- und Laubgehölzen im kombinierten Begasungsexperiment," Statusseminar "Wirkungen von Luftverunreinigungen auf Waldbäume und Waldboden," Proceedings (Kernforschungsanlage, Jülich, 1986), 208–21; U. Arndt and M. Kaufmann, "Wirkung von Ozon auf die apparente Photosynthese," *Algemeine Forst Zeitschrift* (1985):19–20; P. B. Reich, A. W. Schoettle, and R. G. Amundson, "Effects of O_3 and Acid Rain on Photosynthesis and Growth in Sugar Maple and Northern Red Oak Seedlings," *Environmental Pollution* Series A, 40(1986): 1–15.

36. A. Wild, "Licht als Streßfaktor bei Holzgewächsen," "Klima und Witterung in Zusammenhang mit den neuartigen Waldschäden," Symposium proceedings, Neuherberg, 13–14 October 1986 (GSF-Bericht, October 1987).

37. Prinz, Krause, and Jung, note 30 above; G. H. M. Krause, K.-D. Jung, and B. Prinz, "Experimentelle Untersuchungen zur Aufklärung der neuartigen Waldschäden in der Bundesrepublik Deutschland," VDI-Berichte 560, *Waldschäden* (Düsseldorf: VDI-Verlag, 1985), 627–56.

38. Ibid.

39. M. Kampenjohann, W. Zech, R. Hantschel, and R. Horn, "Ergebnisse von Düngungsversuchen mit Magnesium an vermutlich immissionsgeschädigten Fichten (*Picea abies* [L.] Karst.) im Fichtelgebirge," *Forstwissenschaftliches Centralblatt* 106(1987):78–84.

40. K. Mengel, "Einfluß von saurem Nebel auf die Auswaschung von Nährionen und Kohlehydraten junger Fichten sowie auf die Ausbildung von Schadsymptomen," Statusseminar, "Ursachenforschung zu Waldschäden," Jülich, 30 March-3 April, Proceedings in preparation.

41. K. Rost-Siebert, "Untersuchung zur H- und Al-Ionen-Toxizität an Keimpflanzen von Fichte (*Picea abies* Karst.) und Buche (*Fagus sylvatica* L.) in Lösungskultur," Berichte des Forschungszentrums Waldökosysteme Waldsterben, no. 12, 1985; A. Jorns and C. Hecht-Buchholz, "Aluminium induzierter Magnesium- und Calciummangel im Laborversuch bei Fichtensämlingen," *Algemeine Forst Zeitschrift* (1985): 1248–52.

42. G. A. Schier, "Response of Red Spruce and Balsam Fir Seedlings to Aluminum Toxicity in Nutrient Solutions," *Canadian Journal of Forest Research* 15 (1985):29–33; K. Makkonen-Spiecker, "Auswirkungen des Aluminium auf junge Fichten (*Picea abies* Karst.) verschiedener Provenienzen," Schriftenreihe des Waldbau-Inst. der Albert-Ludwigs-Univ., Freiburg im Breisgau, vol. 2 (1984).

43. See, for example, Th. C. Hutchinson, L. Bozic, and G. Munoz-Vega, "Responses of Five Species of Conifer Seedlings to Aluminum Stress," *Water, Air, and Soil Pollution* 31(1986):283–94.

44. E. Aldinger and W. L. Kremer, "Zuwachsuntersuchungen an gesunden und geschädigten Fichten und Tannen auf alten Praxiskalkungsflächen," *Forstwissenschaftliches Centralblatt* 104(1985):360–73; H. Wachter, "Beobachtungen zur Benadelung in einem Fichtenstangenholz des Eggegebirges 1983–86," *Der Forst- und Holzwirt* (1986):146–50; B. Nihlgard, "The Ammonium Hypothesis: An Additional Explanation to the Forest Dieback in Europe," *Ambio* 14(1985): 7–14.

45. H. W. Zöttl and R. F. Hüttl, "Nutrient Supply and Forest Decline in Southwest Germany," *Water, Air, and Soil Pollution* 31(1986):449–62.

46. B. Mettendorf, W. Holzapfel, and H. Schilling, "Gesundheitszustand auf der Beobachtungsfläche der FVA Baden-Würrtemberg—Stand Herbst 1986," *Algemeine Forst Zeitschrift* 15(1987):366–68.

47. Schöpfer and Hradetzky, note 8 above.

48. Wachter, note 44 above.

49. Nihlgard, note 44 above.

50. See, for example, H. G. Miller, "Long Term Effects of Application of Nitrogen Fertilizers on Forest Sites," Proceedings, *18th IUFRO World Congress*, div. 2, vol. 1, Ljubljana, 7–21 September 1986 (Ljubljana, Yugoslavia: IUFRO World Congress Organizing Committee), 368–80.