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Impacts of Air Pollution on Forests : A Summary of Current Situations[1]

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대기오염이 삼림에 미치는 영향 : 피해현황과 원인을 중심으로[1]

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요 약

세계 여러지역에서 임목생장과 활력감소가 커다란 문제점으로 대두되고 있는 바, 이 논문은 북미, 유럽 그리고 동아시아에서 대기오염으로 인한 삼림피해에 관해 현재까지 알려진 바를 요약하고 있다. 오염원 주변에서의 삼림쇠퇴는 상당히 오랫동안 인지되어 왔으나, 오염원으로부터 먼거리에 이르기까지 광범위하게 피해를 준 경우는 그리 흔치 않다. 북미지역의 경우, Los Angeles와 Mexico City 주변에서 고농도의 오존으로 인해 삼림쇠퇴가 일어나고 있고, 미국 동부의 고산지대에서는 강산성의 안개에 의한 가문비나무의 내동성 감소로 피해가 있음이 밝혀지고 있다. 유럽의 경우 독일가문비나무가 Mg 결핍과 N 과다공급이 원인이 되어 피해를 입고 있는 것으로 보이며, 지역적으로 삼림쇠퇴현상이 보이기는 하지만 전체적인 임분생장량이나 현존 biomass가 1970년에 비해 1990년에 증가되었다. 동아시아의 경우, 이에 관한 연구가 초기단계에 있는 바, 중국의 여러 공업지대에서 강산성 강우현상을 보이고 삼림쇠퇴의 주원인이 대기오염일 것으로 사료되는 예가 보고되고 있으며, 한국의 대도시와 공단주변에서 대기오염에 의한 삼림피해 현상을 보이고 있다. 전체적으로 볼 때 온대림에서 광범위한 삼림쇠퇴 현상은 보이지 않고 있으며, 지역별로 상이하게 나타나는 삼림쇠퇴의 정확한 원인을 밝혀내기 쉽지 않다. 대면적에 걸쳐 나타날 수 있는 삼림피해에 대비하는 계속적인 감시와 연구가 앞으로의 과제로 남아있다.

ABSTRACT

Issues of declining growth and vigor in forests are major concerns in many areas around the world, especially in response to predictions in the 1980s of widespread forest declines. This paper summarizes the current state of knowledge for forests in North America, Europe, and East Asia. Forest declines near point-sources of pollution(such as metal smelters) have been well recognized for a century, but evidence of widespread impacts away from point-sources remains relatively uncommon. In North America, significant forest decline has resulted from high concentrations of ozone near Los Angeles, California, and around Mexico City. Some high-elevation forests of red spruce in the eastern U.S. have declined in the past 20 years ; evidence indicates a role of low-pH fog in reducing the cold-tolerance of spruce. In Europe, most attention has focused on Norway spruce stands that developed yellow foliage, needle loss, and in some cases mortality. This syndrome appears to be related generally to an inadequate supply of magnesium, perhaps coupled with a very high supply of nitrogen. Despite localized areas that show declining trees, overall stand

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growth and standing biomass in Europe increased from 1970 to 1990. Much less information is available for East Asia. Many industrialized regions in China have a pH of rain <4.5, and some connections between pollution and forest decline have been suggested. Pollution impacts on forests near cities in Korea include needle chlorosis, reduced needle retention, and declining species diversity. Overall, temperate forests show no widespread declines, and no evidence of substantial effects of pollutants on forest growth or vigor. Small areas showing declining forests may indeed demonstrate pollution impacts, and may provide cause for concerns about future impacts on larger areas.

Key words : acid fog, air pollution, forests, nutrient deficiency, ozone, soil acidification

In the 1980's, worldwide concern developed over pollution effects on forests as stories of extensive forest decline and death emerged from western Europe and the United States. Issues of forest health now receive more attention than any time in history, and we now know much more about cases of forest decline than was possible 10 years ago. In this paper, we summarize the state of knowledge for the areas such as Mexico and southern California, Eastern and southern US, Northeastern US and Canada, Europe, and East Asia, where regional air pollution has been suggested to cause decline in forest health, expanding an earlier paper(Binkley, 1992). Thorough treatment of these subjects can be found in an excellent review book by Innes(1993).

The Nature of Forest Declines

Forests are dynamic ecosystems, involving changes in growth rates of individual trees and whole stands, competition-induced mortality, and outbreaks of pests and pathogens. The vigor of individual trees changes as the tree and stand ages ; dominant trees continue to increase in annual growth rate for decades, whereas suppressed trees decline in growth rate until they die. Overall stand growth typically increases in young stands, reaching a maximum that is sustained for some period, followed by a decline in whole-stand growth(from mortality, declining soil fertility, or other factors). These stand dynamics may provide appearances of "decline", such as dramatic reductions in the width of annual rings in trees when a stand reaches crown closure. Climate patterns also may give the appearance of declines in productivity, particularly when a decade(such as the 1980s in North America) has repeated years of unusually warm summers and cold early winters. Similarly, outbreaks of insects and diseases can depend in part on both stand condition and climate, providing periods of substantial forest decline.

Air pollution encompasses a variety of chemicals with a wide range of mechanisms of impacts on trees. Oxidants, such as ozone, directly attack the biochemistry of cells within leaves. Acid rain may directly impact leaves, or may indirectly affect trees through acidification of soils and soil solutions. The effects of air pollution on forests span a wide range, from mottling on leaf surfaces, to growth declines with no overt symptoms, to substantial decreases in canopy leaf area leading to tree death. Separating the effects of natural stand dynamics from those induced by air pollution are the key challenge in studies of forest decline in polluted regions.

Pine Forests in Mexico and Southern California

Since the 1950s, pollution damage has been evident in some forests of ponderosa pine(*Pinus ponderosa*) and Jeffrey pine(*Pinus jeffreyi*) in southern California(Miller, 1992) and in several pine species around Mexico City(Cibrian-Tovar, 1989). Evidence of pollutant impacts include mottling of needles, reduced needle retention, decreased growth, and increased mortality. The direct cause of mortality is typically bark beetles and root pathogens, which are more successful in attacking pollution-weakened trees. The key pollutant in both Mexico and California is ozone ; acid deposition does not appear to play a critical role at this point(Barnard and Lucier, 1990 ; Miller, 1992). Ozone concentrations in forests outside of Los Angeles reach maximum(24-hour average) levels of over 250 parts per billion by volume in the summer months, which is probably about 5 times above natural levels. These high concentrations lead to smaller needles, shorter retention times for needles, lower rates of growth in height and diameter, and tree death (typically through bark beetle or root pathogen attack ; Miller, 1992). Farther north in California, where ozone levels are lower (but still high enough to impact trees), some declines in needle retention and growth are evident on pine trees in some stands (Peterson and Arbaugh, 1992). The likely long-term impacts of the current levels of ozone pollution in southern California are reductions in the pine components of these forests (remaining pines will likely be ozone-resistant genotypes), with increases for the species that are more resistant to ozone [such as incense cedar (*Calocedrus decurrens*) and black oak (*Quercus kelloggii*)].

High-elevation Red Spruce Stands in the Eastern U.S.

Many red spruce (*Picea rubens*) stands at high elevation declined in growth from the 1960s to 1980s, with high rates of mortality. In some stands, 70% of the red spruce have died (Peart *et al*., 1992). Above 900 m elevation, growth rates have declined substantially, with unprecedented death of branches, terminal leaders, and roots (Johnson *et al*., 1992). Annual ring widths declined after 1960 for all age classes of trees in stands from Vermont, New Hampshire and Maine ; trends also appear to be declining farther south in red spruce stands, but the trends are less clear (Cook and Zedaker, 1992). Periods of decline appear to relate at least in part to years with cool weather in August, and above average temperature in December (which may interfere with cold-tolerance later in the winter). Precipitation in these locations is very acidic, and the pH of fog averages about 3.3. Widespread episodes of winter injury to needles and shoots appears very important. Ozone does not appear to be critical in these cases, but the decline of red spruce may relate to acid deposition in several ways. Laboratory studies have shown that treatment of seedlings with mist at pH of 3.5 or

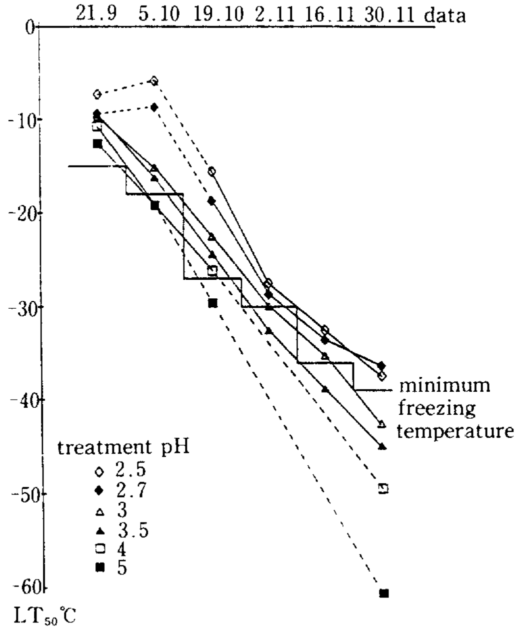

Fig. 1. Cold tolerance of red spruce seedlings in relation to pH of acid mist treatment. X-axis are dates (day.month), Y-axis is the temperature that resulted in death of half of the seedlings. Seedlings treated with pH 5 mist survived at temperatures down to -60℃ in late November, compared with only -35℃ for seedlings treated with pH 2.7 mist (from Fowler *et al*., 1989 ; DeHayes, 1992).

lower can lead to needle discoloration and cuticle damage (Scheier and Jensen, 1992). In the field, winter injury of foliage is the most widespread symptom, and this seems to relate to a reduction in the cold-hardiness of foliage after exposure to acids (Fig. 1). Misting experiments with pH 3.0 to 3.5 produce a 5-12℃ increase in the minimum tolerable temperature in winter. In the soil solution, high concentrations of aluminum (and low ratios of Ca : Al) may also indicate impaired calcium nutrition in some stands.

Pine Forests in the Southern U.S.

The U.S. Forest Service has a large network of Forest Inventory Assessment plots that are remeasured every 10 years. Between 1961 and 1972, the growth of southern pine forests that regenerated naturally (after agricultural abandonment or log-

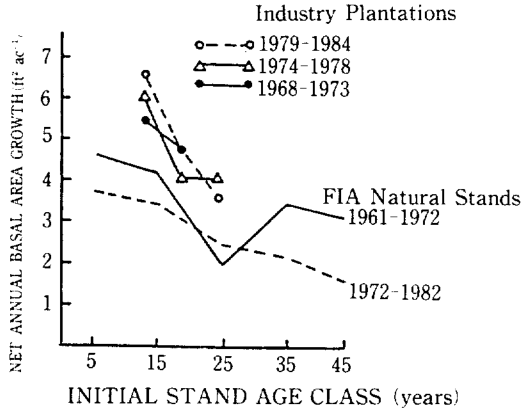

Fig. 2. Net annual basal area growth for slash pine in southern Georgia and northern Florida (1 f^2/acre = 0.23 m^2/ha). Growth of naturally established stands was much lower in the second period (lower dashed line) ; growth in industrial plantations remained high in all periods (Sheffield *et al.*, 1985 ; Barnard and Lucier, 1990).

ging) was about 20% greater than for the period of 1972 to 1982 across much of the region (Fig. 2). Intensively managed industrial plantations showed no decline in growth over a similar period. A variety of factors may account for the declining growth in naturally regenerated stands, including competition with hardwood species, declining soil fertility with time since agricultural abandonment, and regional air pollution (particularly ozone). Ambient concentrations of ozone match or exceed the doses that have reduced growth of pine seedlings in controlled experiments (Barnard and Lucier, 1990). Any role of acid deposition is not clear ; most forests in the region are N limited, and the N deposited in acid rain may have a fertilization effect. On the other hand, many soils are very low in base cations, and any accelerated leaching from acid rain could impair the base cation nutrition of trees (Binkley *et al.*, 1989). At this point, no widespread decline in forest health is apparent, and no direct evidence is available for any role of acid rain or ozone. However, concentrations of both ozone and precipitation acidity are high enough to warrant concern and continued monitoring and assessment efforts.

Sugar Maple in Northeastern U.S. and Canada

Stands of sugar maple have shown declines at various times in the 20th century, particularly in the

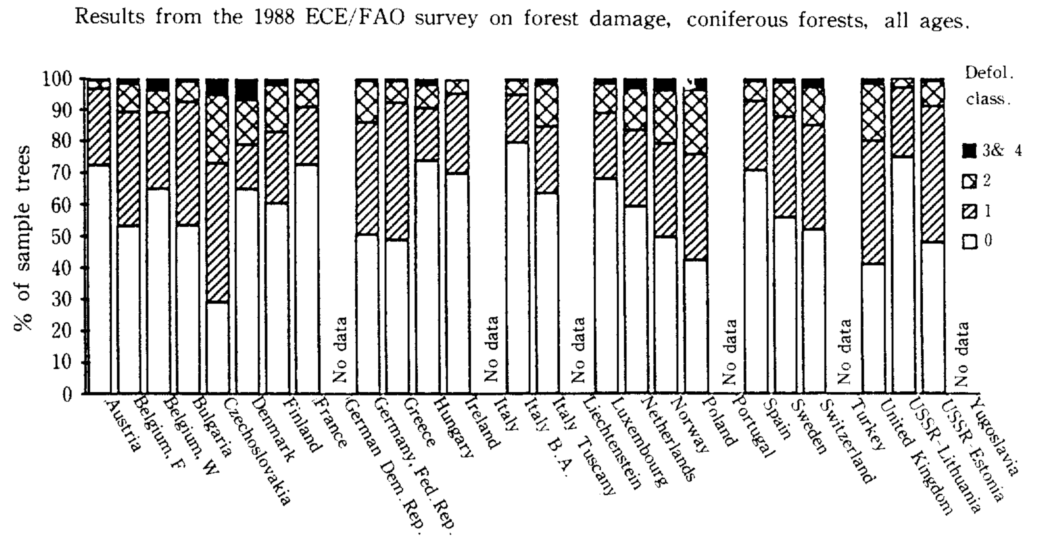

Fig. 3. Survey results for canopy thinning of forests in Europe. Class 0 means trees have full canopy present ; Class 3 and 4 represent moderate-to-severe defoliation (GEMS, 1990 ; Aamlid *et al.*, 1992).

1950s and 1960s (Millers *et al*., 1989). Concern developed in the 1980s that a major, regional decline of sugar maple may have begun, driven perhaps by acid rain. Intensive surveys (summarized in Barnard and Lucier, 1990) revealed no widespread problem, and no evidence of any impact of acid rain in the locations where declining stands were observed. Poor potassium nutrition on infertile soils appeared to be the most common cause of declining vigor in sugar maple.

European Forest Decline

Some symptoms of declining forest health were noticed in Germany in the 1970s that were thought to differ from the symptoms of known pathogens, and in the 1980s widespread concern developed among scientists and the public about forest decline and death (*Waldsterben*). Symptoms included needle yellowing or reddening, thinning of tree crowns, and tree death (Schutt and Cowling, 1985). Large scale assessments were conducted across northern Europe to determine the extent of thinning of tree crowns and overall condition of the forests. These surveys found that many forests across Europe showed moderate to high levels of crown thinning (Fig. 3). It is not clear if thin crowns represent novel stresses in the forests, or if the current state of the forests is the same as in earlier times (see below). The trend from 1984 to 1989 for forests in the former West Germany show improved canopy conditions over time (Fig. 4).

A wide variety of hypotheses have been suggested for forest decline in Europe, including toxic effects of ozone and acid deposition (Aamlid *et al*., 1992 ; Hauhs *et al*. 1989). Two mechanisms of impact of acid rain are probably receiving greatest support from scientists. In areas with very acidic soils, acid rain may have driven soil acidification to the point where concentrations of base cations are low and aluminum is high in soil solution (Ulrich, 1987). In these cases, impaired tree nutrition may result from low base cation supply, low nutrient uptake because of interference from Al^{3+} (A molar ratio of Ca^{2+}/Al^{3+} of 1 may be a critical level), or aluminum inhibition of microbial processes (especially mycorrhizae, Hartmann *et al*. 1989 ; Schneider *et al*., 1989). Not all

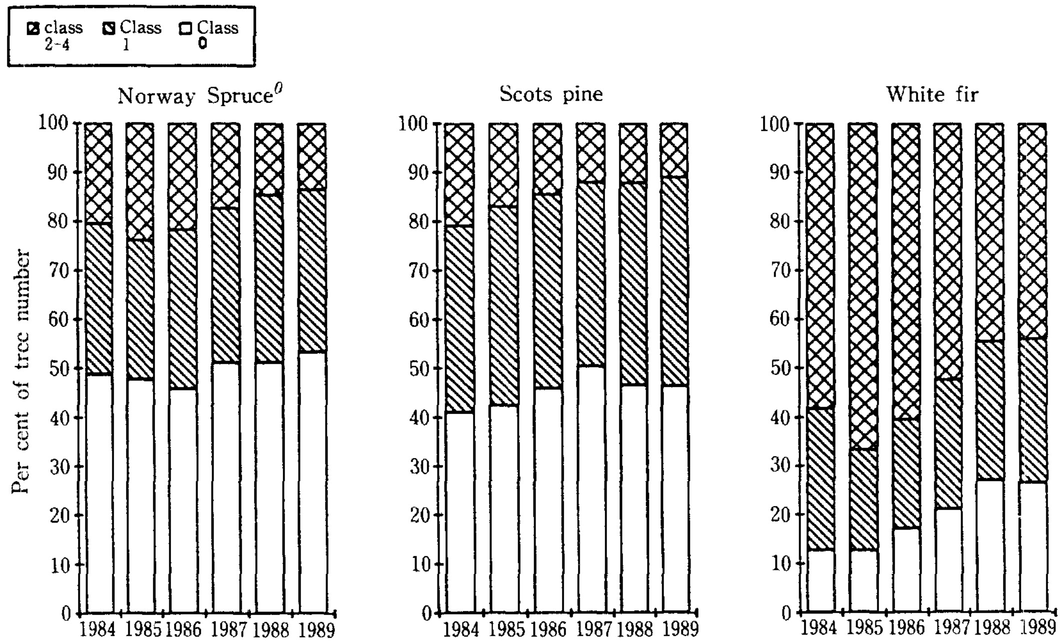

Fig. 4. Canopy thinning decreased significantly in the former West Germany from 1984 through 1989 (data in Aamlid *et al*., 1992).

research supports the primary role of Al^{3+} toxicity or interference ; some decline appears related to high concentrations of N in soil solution, or to imbalances in the supplies of nutrient cations (cf. Schneider and Czech, 1990 ; Haug and Feger, 1990). The second mechanism involves Mg^{2+} deficiency, exacerbated by excessivly high concentrations of nitrate in the soil (the "nutritional disharmony" model of Oren and Schulze 1989). Fertilization with Mg^{2+} appears to alleviate stress symptoms in foliage of Norway spruce, and increase tree growth (Zottl and Huttl, 1986 ; Kaupenjohann *et al*., 1989).

How widespread are problems of forest decline in Europe ? Kauppi *et al*. (1992) used a series of forest inventory plots from across Europe to examine the spatial extent of forest decline. They concluded that severe impacts on forests were present around point sources of pollution, such as metal smelters in Russia. Severe decline problems may cover about 8, 000 km^2 of forests in northern Europe, but this represents only about 0.5% of the forested area. In general, they concluded that stand growth rates across the entire region increased during the period of 1970 to 1990, probably as a result of N fertilization from acid rain. The forests of northern Europe had about 25% more biomass in 1990 than in 1971, because of increases in forested area, and increases in stand growth rates per hectare.

Similarly, Kandler (1992) examined historical declines of forests in Germany, noting local forest declines in area of intense sulfur dioxide emissions in the 1800s. Forests recovered after sulfur dioxide levels declined. He also examined photographs of tree canopies from the early 1900s, and determined the proportion showing various levels of crown thinning. The distribution of levels of crown thinning from the photographs roughly matched current estimates from forest health surveys, indicating no substantial change in tree crown condition in 80 years.

Air Pollution in Eastern Asia

Acid rain is becoming an issue of a concern in eastern Asia (China, Korea and Japan) as it has been in North America and Europe for more than 20 years. High economic growth and fossil fuel use result in high acid deposition levels (Bhatti *et al*., 1992). However, in general only a few studies are available on the effects of air pollution on forest ecosystems or forest decline in the region.

Air pollution study in China started in 1974 by measuring pH in rain (Zou, X., 1988, unpublished paper). Since then numerous studies measured pH and concentrations of ions in precipitation (mainly rain). Wang and Zhao (1988) reported a pH less than 5.6 in most of the southern area of Yangtze River and Quan (1991) found a very acid rain ($pH < 4.0$) in Guizhou Province. Galloway *et al*. (1987) measured precipitation pH about 4-5 in southern area and about 6.5 in northern areas. They speculated that the pH of precipitation would be much lower (about 3.5) if high base concentrations (NH_4 and Ca) were not present. Combustion of high sulfur concentration (3-5%) coal which is used as a fuel for electricity generation, heating and cooking is considered as a major source of acid rain in China (Galloway *et al*., 1987). Recently several studies have found that air pollution is causing forest dieback in southern China. Especially pollution damage seems to be evident for Armand pine (*Pinus armandii*), Masson pine (*Pinus massoniana*), and Chinese fir (*Cunninghamia laceolata*) stands (Liu *et al*., 1993 ; Feng *et al*., 1993). Low soil pH and Mg deficiency lead to needle yellowing, reduced needle size and tree growth, and finally tree death. However, dieback of Yunnan fir (*Abies fabri*) stands in high mountains is not related to pollution directly (Chen *et al*., 1993).

In Korea, many studies have examined the current levels of air pollution (FRI, 1992 ; Kang *et al*., 1991) and the influence of air pollution on the forest ecosystems (Kim, 1992 ; Kim *et al*., 1988a ; 1988b). Mean annual concentrations of SO_2 and NO_2 were high in heavily polluted areas (large cities or industrialized areas) and acidity of wet precipitation was also high in polluted areas (FRI, 1992 ; Kang *et al*., 1991 ; MST, 1987). Moderately strong acid rain ($pH < 5.0$, sometimes $< pH\ 4.5$) was recorded most of the year in industrial and urban areas. Also forest soils are being acidified and forest soil pH increases with the distance from the pollutant source (MST, 1986 ; 1987 ; 1988). Symptoms of air pollution were needle chlorosis (Kim, 1992), reduced needle retention (Kim, 1992), decreased growth rate (MST, 1986 ; 1987 ; 1988), increased insect attack (MST, 1988), and changes in species diversity (Kim *et al*., 1988a ; 1988b ; MST, 1988). Several causes were suggested to explain forest growth decrease in polluted areas ; high SO_2 concentration in the air, increased acidity and aluminum concentration in forest soils, and N, Ca, and Mg deficiencies in foliage (Kim, 1992 ; MST, 1988).

Japan has strongly enforced emission regulations compared to other nations in East Asia (Bhatti *et al*., 1992). However, higher SO_4^{2-} concentrations in rainfall were measured in large cites and industrialized areas than in residential areas (Adachi *et al*., 1990 ; Minami *et al*., 1989). It was speculated that Japanese cedar (*Chamaecyparis obtusa*) decline (mainly moderate to high level of crown thinning) in the central mountainous region (Takahashi *et al*., 1987) was caused by the increase in the deposition of NO_3^- and SO_4^{2-} (Chang *et al*., 1990). On the other hand, Inouye (1990) related Japanese cedar decline to changes in soil water conditions and acid mist in Kanto region.

Conclusions

Air pollution has clearly impacted pine forests in southern California and around Mexico City, causing substantial mortality in ozone-sensitive species. Many red spruce forests in the eastern U.S. at high elevations have declined in the past 30 years, probably resulting in part from winter injury related to acid precipitation. Concerns over declines in growth rates of southern pines and sugar maple are not supported by strong evidence linking them to air pollution ; pollution levels are high enough in the southern U.S. to warrant continued examination of forest/pollution interactions. In Europe, widespread forest decline and death has not developed as predicted in the 1980s, and at least some appearances of decline appear to be related simply to low soil fertility. Less information is available from East Asia, but high levels of pollution and the appearance of some impacts warrants greater attention in the future.

In general, air pollution impacts on forest health may not be as severe as suggested in the 1980s, but this does not necessarily indicate that pollution effects will remain minimal. One lesson from the past 10 years is that it is difficult to identify the cause of observed forest declines, even when the symptoms are very pronounced (such as in red spruce stands). More subtle problems, such as a 10% loss in productivity, may be impossible to assign to any specific cause (Bormann, 1985). These uncertainties make it difficult to decide whether potential forest impacts would justify reducing levels of air pollution. For example, should current levels of pollution be considered acceptable until scientific evidence indicates that forests are being harmed with 95% confidence? Or given available evidence, would it be wise to advocate greater controls on pollution until scientific evidence allows us to be 95% sure that current levels of pollution are safe?

The best approach for reducing the uncertainties about the effects of air pollution on forests involves 1) increased monitoring of air pollution levels (especially in East Asia), 2) greater research on pollution impacts in controlled studies, and 3) greater monitoring of the health of forest ecosystems.

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