KEYNOTE

FUTURE OF THE HARDWOOD FOREST: SOME PROBLEMS WITH DECLINES AND AIR QUALITY [1/]

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Abstract.--One of the most important phenomena of temperate zone forests are extended-term stresses termed dieback-decline diseases. Generally declines result from sequential influence of multiple stress factors. A variety of hypotheses have been identified that would allow atmospheric deposition to function as an initial stress, contributing stress or final stress in decline phenomena. Air pollution stresses are discussed on a regional and global scale. The importance of long-term air quality monitoring and forest health assessment is emphasized.

Keywords: air pollution, forest dieback/decline, atmospheric deposition, forest health

INTRODUCTION

The vast hardwood forests of the eastern United States are a diversified natural resource of extraordinary value. They represent a continuum of management strategies that range from the natural forest to the urban-suburban forest.

The eastern hardwood forest can be conveniently divided into three major types, northern, central and southern. The northern forest is dominated by yellow birch, American beech and sugar maple. This forest covers approximately 14 million ha (35 million A) primarily on upland sites in the New England, Middle Atlantic and Lake States regions. It is located from sea-level to 800 m (2500 ft) in the north and between 800 and 1400 m (4500 ft) in the southern Appalachians.

The central forest is dominated by various species of oak and hickory with yellow poplar an important associate in various portions of the distribution. This forest is characterized by a favorable climate, extended growing season and relatively high species diversity and productivity. The forest covers approximately 46.5 million ha (115 million A) from southern New England across the United States to the prairie. This is the largest hardwood forest of the United States and occurs on dry and moist sites from sea-level to approximately 1400 m (4600 ft).

The southern hardwood forest is appropriately designated an oak-pine forest and it covers approximately 14 million ha (35 million A) where pines represent 25-50 percent of the stands.

One of the very most important phenomena of temperate zone forests are extended-term stresses termed dieback-decline diseases or more simply declines. The importance of dieback-decline stress in long-term forest ecosystem development may be very great. The shorter-term influence on forest management objectives is appreciated to be very severe in selected cases. Presently decline stress is especially important in portions of the northern forest on sugar maple (McLaughlin et al. 1985, McIlveen et al. 1986, Parker and Houston 1971, Wargo and Houston 1974) and on American beech (Houston 1975, Houston et al. 1979, Lacki 1985). Very widespread decline and mortality of yellow birch occurred throughout New England, New York and southeastern Canada from 1940 to 1965 (Greenidge 1953, Hansbrough et al. 1950, Hawboldt 1952). An important decline of white ash was most severe in the Northeast during the 1950-1960's (Brandt 1961, Hibben and Silverborg 1978, Sinclair 1965) and may again be significant (Castello et al. 1985).

The most widespread and serious declines over the past several decades in the central forest have been associated with members of the

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red oak group (scarlet, pin, red and black oak) (Nichols 1968, Skelly 1974, Staley 1965). The present distribution of oak decline is highly variable, but mortality can vary from 20 to 50 percent in severely impacted areas. Significant mortality has occurred in the George Washington and Jefferson National forests in Virginia (Shriner 1986). There is evidence that similar declines occurred during earlier periods in this century in the southern Appalachians (Balch 1927). Declines of lesser importance that have occurred in the central and southern hardwood forests include sweetgum decline (Miller and Gravatt 1952), yellow-poplar decline (Toole and Huckenpahler 1954) and magnolia decline (McCracken 1985).

DECLINE STRESS

The decline stress is highly variable in distribution, discontinuous and recurrent in time and the result of multiple individual stress agents. Never-the-less, these phenomena have sufficient common characteristics in various forest tree species to allow some generalization and synthesis of concept.

Decline stress is more characteristic of mature forests than immature forests. Generally declines result from sequential influence of multiple stress factors. Stress factors are both abiotic and biotic in nature. Abiotic stress factors common to numerous declines include drought and low and high temperature stress. Biotic agents of particular importance include defoliating insects, borers and bark beetles along with root infecting and canker inducing fungi. Typically declines are initiated by an abiotic stress with mortality ultimately caused by a biotic stress agent. Quite commonly the abiotic stress responsible for decline initiation is the direct or indirect influence of change in some climatic parameter, for example, less than normal precipitation. Decline stress is characterized by a common progression of symptoms (Table 1). Excellent reviews of the decline phenomenon have been provided by Houston (1974, 1981) and Manion (1981). Examples of decline stresses of significance over the past century in the United States, with a suggestion of primary stress factors involved, are presented in Table 2.

AIR QUALITY AND DECLINE STRESS

In view of recent evidence documenting forest tree growth decline (Hari et al. 1986, Lucier 1986, McClenahen and Dochinger 1985, Sheffield et al. 1985) and visibly symptomatic tree dieback/decline (Friedland et al. 1984, Johnson and Siccama 1983, Siccama et al. 1982, Weiss et al. 1985), it is appropriate and necessary to critically examine the role that regional and global atmospheric contaminants may play in these wide area forest stresses. A variety of mechanisms have been identified (Smith 1981, 1984, 1985) that would allow atmospheric deposition to function as an initial stress, contributing stress or final stress in decline phenomena.

Regional-scale air pollution

During the past three decades we have become increasingly aware of regional-scale air pollutants. The regional designation is applied because these contaminants may affect forests tens, hundreds, or even thousands of kilometers from their site of origin. The regional air pollutants of greatest documented or potential influence for forests include: oxidants, most importantly ozone; trace metals, most importantly heavy metals - e.g. cadmium, iron, copper, lead, manganese, chromium, mercury, molybdenum, nickel, thallium, vanadium, zinc; and acid deposition, most importantly the wet and dry deposition of sulfuric and nitric acids. Ozone, sulfuric and nitric acids are termed secondary air pollutants because they are synthesized in the atmosphere rather than released directly into the atmosphere. The precursor chemicals, released directly into the atmosphere and causing secondary pollutant formation, include hydrocarbons and nitrogen oxides in the case of ozone, and sulfur dioxide and nitrogen oxides in the case of sulfuric and nitric acid. The combustion of fossil fuels for energy production releases hydrocarbons and sulfur dioxide. The heat of combustion causes nitrogen and oxygen to react and form nitrogen oxides. Many combustion activities generate small particles (approximately 0.1 - 5 μm diameter). Those activities associated with energy combustion (particularly coal burning) can preferentially contaminate these small particles with trace metals. Because the formation of secondary air pollutants may occur over tens or hundreds of km from the site of precursor release, and because small particles may remain airborne for days or weeks, these pollutants may be transported 100 to more than 1000 km from their origin. Eventual wet and dry deposition of the pollutants onto lakes, fields, or forests occurs over large rather than small areas.

The U.S. Environmental Protection Agency and the U.S. Department of Agriculture, Forest Service established a network of air monitoring stations to measure ozone concentrations in remote areas of National Forests. Analysis of selected high ozone events during 1979 suggested that long-range transport of air masses contaminated by urban centers contributed to peak concentrations at remote sites (Evans et al. 1983). In a study of rural ozone episodes in the upper-midwest, Pratt et al. (1983) presented evidence that ozone and precursors were transported 275 km from Minneapolis-St. Paul. Studies of trace metal concentrations, in the atmosphere in remote northern and southern hemispheric sites revealed that the natural sources include the oceans and the weathering of the earth's crust, while the major anthropogenic source is particu

Table 1.--Symptoms characteristic of decline stress of forest trees. [3]

1. reduced growth - reduced shoot elongation and diameter increment
2. shorter internodes - tufted foliage
3. fine root and mycorrhizal root destruction
4. reduced food storage in roots
5. premature development of foliar color in late summer/early fall
6. reduced size of foliage and yellowing
7. twig and branch dieback typically caused by weakly parasitic fungi
8. outer crown dieback
9. stimulation of stem and branch adventitious buds
10. root infection by decay fungi, notably Armillaria mellea

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[3] Manion 1981.

late air pollution (USEPA 1983a). Murozumi et al. (1969) showed that long range transport of lead particles from automobiles significantly polluted polar glaciers. We estimated the annual lead deposition on a remote northern hardwood forest in New Hampshire to be as high as 266 g per hectare in 1978. This caused lead contamination of the forest floor 5-10 times greater than the estimated pre-industrial concentration (Smith and Siccama 1981).

Evidence is available; satellites, surface deposition of aerosol sulfate and reduced visibility (Chung 1978, Tong et al. 1976, Wolff et al. 1981), for long-range transport of acidifying pollutants from numerous sources. During the winter, approximately 20 percent of the emissions from tall power plant stacks in northeastern United States may remain elevated and relatively coherent for more than a day and 500 km (USEPA 1983b).

The long distance transport of regional pollutants means they may have interstate, international and even intercontinental significance. It means further that the forests subject to their deposition exceed tens of thousands of km^2.

Rather than severe tree morbidity or mortality with dramatic symptoms, regional pollutants subtly change tree metabolism and ecosystem processes. Smith (1981) has provided a comprehensive review of subtle air pollution forest stress.

Regional air contaminants may influence reproductive processes, nutrient uptake or retention, metabolic rates (especially photosynthesis and respiration), and insect pest and pathogen interactions of individual trees. At the ecosystem level, regional air pollutants may influence nutrient cycling, population dynamics of arthropod or microbial species, succession, species composition, and biomass production. In the case of low dose regional- scale pollution, symptoms are typically not visible (at least initially), undramatic and not easily measured. The integration of regional pollutant stresses can be slower growth, altered competitive abilities and changed susceptibility to pests. Ecosystem symptoms may include altered rates of succession, changed species composition and biomass production. Visible symptom expression is not a useful assessment strategy. Evidence of the relative importance of regional pollutants is variable, caused in part by the length of time that has been devoted to the study of individual pollutants and in part by the subtleness and complexity of the pollutant interactions. The toxicity of trace metals has been studied for approximately 65 years, of ozone approximately 30 years and of acid deposition approximately 15 years.

Global-scale air pollution

In the past 25 years, we have become concerned with a new scale of air pollution--global. Global pollutants affect the entire atmosphere of the earth. Two global air pollutants of special note include carbon dioxide and halocarbons.

Careful monitoring of carbon dioxide during the past three decades in Hawaii, Alaska, New York, Sweden, Austria and the South Pole has firmly established that carbon dioxide is steadily increasing in the global atmosphere. This increase is due to anthropogenic activities including fossil fuel combustion. It may also be

Table 2. Important forest tree declines of the past century in the United States.

species	initial stress	contributing stress	final stress
yellow and white birch	warm summer temperatures, drought	foliage feeding insects	bronze birch borer, *Armillaria mellea* (root disease)
white ash	drought		*Cytophoma pruinosa* and *Fusicoccum* spp. (canker disease)
sugar maple	drought	insect defoliation, harvesting, nutrient deficiency	*Armillaria mellea* (root disease) *Verticillium dahliae* (vascular disease)
American beech	beech scale *Cryptococcus fagisuga*	?	*Nectria* spp. canker fungi
oak	drought, low temperatures spring	gypsy moth or oak leaf roller defoliation (insect)	*Armillaria mellea* (root disease), *Agrilus bilineatus* (insect borer)
sweetgum	drought	nutrient stress	??
western white pine	drought		*Armillaria mellea*, *Leptographium* spp. (root disease), *Europhium trinacriforme* (canker disease)
shortleaf pine	drought and excessive soil moisture	nutrient stress, *Phytophthora annamomi* (root disease)	*Armillaria mellea*, *Pythum* spp. (root disease) ??
balsam fir	drought	eastern spruce budworm	*Armillaria mellea* (root disease)
white spruce	drought (?)	western spruce budworm (bud mortality)	*Aureobasidum pullulans* (twig, branch disease)
red spruce (high elevation)	?	?	?

Table 3. Forest Ecosystem Stress Indicators [4/]

Indication	Examples
Canopy limitation	Maximum leaf area index
	Duration of leaf display
Production limitation	Diameter growth and cell division
	Growth efficiency per unit leaf area
Susceptibility to insect and disease attack	Starch content of twigs and large roots
	Tannin and terpene content of tissues
	Growth efficiency per unit leaf area
Moisture limitations	Predawn water stress
	Noon leaf turgor
	Sapwood relative water content
	Stomatal closure
Nutrient limitations	Foliar nutrient content
	Foliar nutrient ratios
	Nutrient retranslocations
	Mineralization indices
Physical stress	Sapwood/diameter index
	Bole taper
	Symmetry of wood growth
	Leaf-edge tatter

4/ Waring and Schlesinger 1985.

caused by altered land use management, such as, forest destruction in the tropics. The atmospheric carbon dioxide concentration has been estimated to have been approximately 290 ppm (5.2×10^4 $\mu g\ m^{-3}$) in the middle of the nineteenth century. Today, the carbon dioxide concentration approximates 340 ppm (6.1×10^5 $\mu g\ m^{-3}$) and is increasing very approximately two ppm ($3.6\mu \times 10^3$ $\mu g\ m^{-3}$) per year. In the year 2030, if the increasing rate continues, the carbon dioxide amount in the global atmosphere may be nearly two times the present value (Hansen 1987, Holdgate et al. 1982).

Naturally occurring stratospheric ozone is important because it screens the earth from biologically damaging ultraviolet radiation -- light with wavelengths between 290 and 320 nanometers -- released by the sun. Halocarbons released by humans may be capable of reducing the natural ozone layer surrounding the earth. In summary, halocarbon molecules, for example chlorofluoromethanes, released by various human activities, are slowly transported through the troposphere. They pass through the tropopause and lower stratosphere and are decomposed in the mid- to upper-atmosphere. Free chlorine, resulting from decomposition, causes a rapid, catalytic destruction of ozone. In 1979, the National Academy of Sciences estimated that release of halocarbons to the atmosphere, at rates inferred for 1977, would eventually deplete stratospheric ozone 5 to 28 percent, most probably 17 percent (NAS 1979). In 1982, the National Academy revised its previous estimate and suggested a depletion of from 5 to 9 percent (NAS 1982c).

Increasing carbon dioxide and halocarbon concentrations and decreasing stratospheric ozone concentration of the atmosphere may alter global radiation fluxes. Presumably a primary result of more carbon dioxide, halocarbon and other trace gases in the atmosphere will be warming. While incoming solar radiation is not absorbed by carbon dioxide, and certain other trace gases, portions of infrared radiation from earth to space are. Over time, the earth would become warmer. While the forces controlling global temperature are varied and complex, the increase of 0.5°C since the mid-1800s is generally agreed to be at least partially caused by increased carbon dioxide. By 2000 it may increase an additional 0.5°C. Numerous models advanced to estimate the average global warming per doubling of carbon dioxide and related climatic feedbacks predict an increase of 1.0 to 5.0°C (Hansen 1987). Natural impacts on climate, such as solar variability, remain important and of unclear relationship to anthropogenic causes. A mean global average surface warming, however, of 3 $\pm$ 1.5°C in the next century appears possible (National Academy of Sciences 1982 a, b).

This amount of warming is far from trivial. The difference in average global temperature between the last glacial period and the present (interglacial period) is approximately 5°C (Broecker 1987). In thirty years, New York City could have the same annual temperature mean that Washington, D.C. presently has. In thirty years, the global mean temperature of the earth could be higher than it has been in the last several hundred thousand years (Hansen 1987).

The consequences of a warmer global climate, with even a very modest temperature increase, on the development of forest ecosystems, will be profound. Warming, with increased carbon dioxide in the atmosphere, might enhance forest growth. Manabe and Stouffer (1980) have estimated that a doubling of atmospheric carbon dioxide would cause a 3°C warming at the U.S.-Canadian border, while Kellogg (1977) has suggested that a rise of 1°C in mean summer temperature extends the growing season by approximately 10 days.

It is important to realize, however, that carbon dioxide is probably not the most important limiting factor to the growth of forest trees. Limitations imposed by nitrogen availability or other nutrients obtained from the soil may be much more important. Other changes associated with global warming may restrict forest growth. Physiological processes of plants, especially photosynthesis, transpiration, respiration and reproduction are sensitive to temperature. With warming, respiration and decomposition may increase faster than photosynthesis. Transpiration and evaporation increases may enhance stress on drier sites. Reproduction may be altered by changes in dynamics of pollinating insects, changes in flower, fruit or seed set, or changes in seedling production and survival. The geographic or host ranges of exotic microbial pathogens or insect pests may expand. Previously innocuous endemic microbes or insects may be elevated to important pest status following climatic warming. Certain insects, for example, defoliators may need to consume greater foliar biomass to obtain nitrogen requirements due to the increase in the carbon:nitrogen ratio of the foliage resulting from carbon dioxide enrichment.

One of the biggest uncertainties of the influence of global warming on forests is the inadequate understanding of the influence on precipitation patterns. There is general agreement that the hydrologic cycle will be intensified with warming, but present climate models cannot suggest which areas will receive more and which areas will receive less precipitation. Precipitation changes are critical to the prediction of forest responses. Those areas receiving less precipitation will also experience increased evaporation and transpiration. Waggoner (1984) has estimated that the projected change in weather by the year 2000, caused by increased atmospheric carbon dioxide, will cause moderate decreases of 1-12 percent in yield of wheat, corn and soybeans in the American grain belt due to increased dryness. While agriculturists may be able to adopt new crop varieties to a drier climate, forests cannot be similarly manipulated. Increased drought stress over widespread forest areas would be expected to

initiate new rounds of progressive tree deterioration or dieback/decline disease. Drought is the most common and important initiator of general forest tree decline. It is possible, as we approach doubling of atmospheric carbon dioxide, that climatic warming may be quite rapid. It is possible that a 3.5°C increase in global average could be achieved in approximately 60 years. Such a rapid change could cause large numbers of tree species to be out-of-phase with their climate. Decline stress could be widespread under such circumstance.

A serious consequence of anthropogenic release of halocarbons to the atmosphere is the depletion of naturally occurring stratospheric ozone. Some reduction in halocarbon release has been achieved in the United States and a few other countries. Immediate termination of all release worldwide, however, would still leave the world with important stratospheric ozone reductions during the next decade. Reduced upper-air ozone would increase ultraviolet radiation reaching the surface of the earth. Current understanding does not allow an inventory of the impacts of increased ultraviolet radiation on forests. Vegetation can acclimatize to changes in ultraviolet radiation. Higher plants also vary substantially in resistance to ultraviolet radiation. Because some plants are sensitive, however, reductions in biomass production and/or competitive strengths may be altered by changes in short-wave radiation flux at the surface of the earth (Caldwell 1981). Studies of more than 100 agricultural species showed that increased ultraviolet exposure reduces plant dry weight and changes the proportion of root, shoot and leaf tissue. Studies of more than 60 aquatic organisms showed that many were quite sensitive to current levels of ultraviolet radiation at the water surface (Maugh 1980). Chloro-fluorocarbons can also contribute to global warming in a manner similar to carbon dioxide as previously indicated.

Global- and regional-scale air pollutants exhibit both increasing trends and known and probable effects on forest ecosystems over large portions of the temperate region. The integration of stresses imposed by regional pollutants has the potential to cause growth reductions in some forest species and, ultimately, dieback-/decline symptoms in susceptible tree species at ambient levels. At the ecosystem level this has or will cause changes in species composition and increases or decreases in biomass production depending on the specific ecosystem. Documentations of decreased tree growth and increased decline symptoms solely or primarily due to air quality in the field are very limited because the changes are subtle, not continuous but patchwork in character, and extremely difficult to separate from other factors that control tree growth (eg. age, stand structure, competition, moisture, temperature, nutrients, insects, pathogens) and that induce dieback/decline symptoms (eg. drought, other climatic stresses, insects, pathogens). In addition, species composition and patterns of forest succession are regulated by numerous determinants (eg. vegetative site alterations, plant species interactions, insect/pathogen activities, windstorms, fires and human cultural activities) and forest ecosystem production is influenced by several variables (system age, competition, species composition, moisture, temperature, nutrients, insects, pathogens).

A review of the current evidence available, to support the importance of air pollution induced forest change, has been provided by Fraser et al. (1985), Kozlowski and Constantinidou (1986), McLaughlin (1985) and Smith (1981). The comprehensive study of oxidant pollution in portions of the San Bernardino National Forest, California demonstrated air pollution effects on forest growth and succession (Miller et al. 1982). Additional evidence of reduced forest growth imposed by oxidant pollution in the west, mid-west and east has been provided (USEPA 1983a). For various forest ecosystems we are at, or near, the threshold of trace metal impact on nutrient cycling processes. Lead will continue to accumulate in forest floors as long as it is released into the atmosphere (USEPA 1984). Although adverse effects on forest ecosystems from acid deposition have not been conclusively proven by existing field evidence, we cannot conclude that adverse effects are not occurring. Presently, tree mortality and tree morbidity and growth rate reductions in European and North American regions do occur where regional air pollution, including acid deposition, is generally high. Temporal and spatial correlations between wet acidic deposition and forest tree growth rates has been provided. Numerous hypotheses for adverse forest effects from acid deposition, worthy of testing, have been proposed (Linthurst 1984, SAF 1984). Under natural conditions, forest ecosystems are exposed to multiple air pollutants simultaneously or sequentially and interactive and accumulative influences are important. It is inappropriate to consider the effects of any regional pollutant on forests in isolation.

The potential stresses imposed by regional-scale air pollutants must be viewed against the background of uncertainty associated with the changes in radiation balances associated with global scale air contaminants. If global warming does accelerate in the near term, and especially if expansive forest regions are subjected to reduced moisture availability, the expansion of forest tree decline could be very great. Such an occurrence would pale the impact of regional-scale pollutant deposition.

CONCLUSION

Assessment of the subtle influences of regional and global air pollutants cannot be based on visible symptom expression. It must be based on systematic monitoring of forest health and growth indices. Waring and Schlesinger

(1985) have provided an excellent list of potentially useful forest ecosystem stress indicators (Table 3). Canopy leaf area and its duration of display is a very appropriate general index of forest ecosystem stress. Canopy quantity and quality is an indicator of productivity. Inventory techniques from the air (multispectral scanning, microwave transmission, radar, laser) and ground (correlations with stem diameter, sapwood cross-sectional area) for canopy leaf area are available. At a given site, detection of an increase in leaf area would suggest an improving environment, a decrease in leaf area would infer the system is under stress (Waring 1983, 1985). Baes and McLaughlin (1984) have proposed that trace metal analyses of tree rings can provide information on temporal changes in air pollutant deposition and tree health.

In addition to forest health assessment, systematic determinations must be made of the doses of air pollutants received by forests. This requires a rural air-quality monitoring network capable of measuring all important phytotoxic pollutants deposited by both wet and dry mechanisms.

Assessment of both forest health and atmospheric deposition would be most appropriately implemented by establishing a permanent plot network not unlike the Continuous Forest Inventory plots of the USDA Forest Service. Trends over time in both health and deposition would be regularly and continuously recorded.

A final component of the assessment program is research directed to understanding the mechanisms of low-dose influence on vegetative health imposed by air contaminants, the influence of enhanced carbon dioxide and warming, and the influence of increased short wave radiation on trees. This research program must be simultaneously conducted in managed environments (eg. laboratory and greenhouse chambers, open-top chambers, and other regulated environment facilities) and in natural environments (eg. field studies conducted in association with long-term ecosystem research areas, experimental forests of the USDA, national laboratory facilities or other sites presenting unique characteristics, ancillary data, security and long-term perspective). Permanent assessment plots could be used to validate models developed in seedling/sapling studies. Stand-level models could be verified with permanent plot data.

Forests are variable in species, topography, elevation, soils and management. Air pollution deposition and influences are also variable and poorly documented in the field. Monitoring of species dynamics and productivity, necessary to detect effects of regional and global air pollutants, or any other environmental stress, are presently rarely available. Dendrochronological or other tree-ring analytical techniques alone are subject to enormous difficulty when they attempt to partition the relative importance of forces that may influence tree growth. Growth is regulated by precipitation, temperature, length of growing season, frost, drought, by developmental processes such as succession and competition, and by stochastic events such as insect outbreaks, disease epidemics, fire, windstorms and anthropogenic activities such as thinning, fertilization, harvesting and finally air quality.

For a long time, dieback and decline of specific forest species, somewhere in the temperate zone, has been common. Age, climate, or biotic stress factors have frequently been judged to be the principal causes for declines. Again, however, it is difficult to assign responsibility for specific cause and effect. Trees are large and long-lived and their health integrates all the stresses to which they are exposed over time.

The risks associated with regional and global air pollution stress and temperate zone forest ecosystem health are high. The evidence available to describe the total boundaries of the problem for all pollutants is incomplete. There is enormous uncertainty about specific effects on forests of regional and global air pollutants.

Individual forest tree processes at greatest risk from wide area air pollutant stress include foliar metabolism (especially photosynthesis and respiration), root metabolism, reproductive physiology, pest (arthropod and microbial) interactions and growth. At the ecosystem level, processes at greatest risk from wide area air pollutant deposition include nutrient cycling (especially mineralization and nutrient uptake processes), biomass production, and population dynamics of insect and microbial pests. Major structural changes may be caused in impacted forests over the long term due to alteration of species composition and patterns of succession.

The primary needs to enable a more complete understanding and assessment of air quality and forest decline include the following:

1. Complete monitoring of gas and particulate, wet and dry pollutant deposition in forest ecosystems.

2. Systematic monitoring of forest growth and health parameters on permanent plots over extended time.

3. Coordinated field, controlled environment and laboratory studies directed toward tree and ecosystem processes identified at risk using single pollutant and pollutant mixtures in realistic (ambient) dose patterns and in association with varying climatic scenarios.

4. Modelling and systems analysis studies to assist with experimental designs and to extend experimental conclusions to larger forest areas.

Implementation of wide-area forest monitoring of any nature involves two challenges.

First, detection of stress does not suggest cause. We are keenly aware that tree and forest health are controlled by many factors in addition to air quality. We desperately need procedures to partition the relative importance of influencing variables for a given site. Fortunately we are making research progress toward this resolution (Fritts and Stokes 1975, Waring 1985). The second challenge is to convince natural resource managers that the time and cost of systematic forest health monitoring is justified. I feel it is not only justified, but essential for intelligent decisions regarding regulation of regional and global air pollutants, for understanding the health and productivity of our forests over the next century and for deliberations on National energy policy.

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