COAL COMBUSTION AND FOREST ECOSYSTEM HEALTH

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Abstract

Historically, the combustion of fossil fuels has directly or indirectly been the source of air contaminants at three levels; local, regional, and global. Pollutants of importance at the local level have included sulfur dioxide and trace metals. Local forest damage is confined to a zone of a few km immediately surrounding a facility and for a distance of several to tens of km downwind. Regional air pollutants may be deposited over expansive forest areas because they are transported tens or hundreds of km from point of release due to small size or snythesis in the atmosphere from precursors introduced into the troposphere. Regional air pollutants of potential influence for forests include; oxidants, trace metals, and acid deposition. Global pollutants influence the entire atmosphere of the earth, e.g. halocarbons and carbon dioxide. The latter is important because of the potential it has to influence global climate. Risks associated with regional and global air pollution and forest health are high. The evidence available to describe the total boundaries of the problem for all pollutants is incomplete.

Introduction

A challenge of developed nations throughout the temperate zone is air quality policies that protect natural resources as well as human health. Throughout Europe and North America, the decade of the Eighties will be recorded as a period of profound decisions regarding atmospheric contamination and natural resource quality. The central issues for those interested in forest health are as follows. Is air pollution influencing the growth of forests or individual species, changing the species composition of forest communities or destroying certain tree species, associated plants or animals over significant forest areas? In an effort to answer this question, I shall discuss the spatial scales of air pollution stress and what we know about the response of trees to pollutants at these scales.

Local, regional and global-scale air pollutants

Local-

During the first two thirds of the twentieth century, research and regulatory efforts were focused on local air pollutants and acute vegetative effects. Pollutants of primary concern were sulfur dioxide, particulate and gaseous fluoride compounds and numerous heavy metals such as lead, copper, and zinc. Occasional interest was expressed in other inorganic gases including ammonia, hydrogen sulfide and chloride, and chlorine. The sources of these pollutants were and are typically discrete and stationary facilities for: energy production, for example, fossil-fuel electric generating plants, gas purification plants; metal related industries, for example, copper, nickel, lead, zinc or iron smelters, aluminum production plants; and diverse other industries, for example, cement plants, chemical and fertilizer plants and pulp mills.

It is appropriate for us to consider the above pollutants local-scale because forest areas directly affected by these facilities are typically confined to a zone of a few km immediately surrounding the plant and for a distance of several to tens of km downwind. The dimensions of the surrounding and downwind zones of influence are variable and primarily controlled by source strength of the effluent, local meteorology, regional topography and susceptibility of vegetation. In any case, the forest influence is confined to a region generally less than a thousand hectares.

Regional-

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, cobalt, copper, lead, mercury, molybdenum, nickel, vanadium, zinc; and acid deposition, most importantly 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 the fossil fuels coal, oil, gas release some hydrocarbons and sulfur dioxide. The heat of combustion causes nitrogen and oxygen to react and form nitrogen oxides. Many activities generate small particles (approximately 0.1 - 5 μm diameter). Those activities associated with 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 may occur 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 (3). In a study of rural ozone episodes in the upper-midwest, Pratt et al. (18) 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 particle air pollution (23). Murozumi et al. (13) 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 266 g per hectare. This caused lead contamination of the forest floor 5-10 times greater than the estimated pre-industrial concentration (20).

Evidence is available, satellites, surface deposition of aerosol sulfate and reduced visibility (2, 22, 28), 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 (24).

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.

Global-

In the past 25 years, we have become concerned with a third 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 two 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 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 ($5.2x10^4$ $\mu g\ m^{-3}$) 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 about one ppm (1.8×10^3 $\mu g\ m^3$) per year. In 1977-78 it increased 1.5 ppm (2.7×10^3 $\mu g\ m^{-3}$). In the year 2020, if the increasing rate continues, the carbon dioxide amount in the global atmosphere may be nearly two times the present value (5).

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 can deplete the natural ozone layer surrounding the earth. In summary, halocarbon molecules, especially chlorofluoromethanes, released by various human activities, are 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 (14). In 1982, the National Academy revised its previous estimate and suggested a depletion from 5 to 9 percent (17).

Affect of local-scale, regional-scale and global-scale air pollution on forest ecosystems

Local-

High deposition of local air pollutants has caused documented forest destruction. High sulfur dioxide or fluoride doses, severely injure or kill forest trees. The ecosystems, of which the trees are a part, are simplified, lose nutrients, sustain soil erosion, have microclimates and hydrologic patterns altered and ultimately they are destroyed or converted to more resistant seral stages. Miller and McBride (12) reviewed the forests destroyed by local air pollution. Early in this century, it was clearly documented in numerous locations throughout North America that sulfur dioxide and trace metal pollution destroyed forests surrounding metal smelting facilities. Smelting centered in Ducktown, Tennessee devastated the southern hardwood forest over 27 km^2 (10.5

mi^2) surrounding the plant, coverted an additional 68 km^2 (17,000A) to grassland and created a 120 km^2 (30,000A) transition zone with altered species composition. Smelters in the Sudbury, Ontario, Canada area have caused simplification of the surrounding mixed boreal forest and have caused eastern white pine mortality in a 1865 km^2 (720 mi^2) zone to the northeast.

Aluminum reduction plants have also caused local forest destruction. In Montana, fluoride pollution killed or severely injured ponderosa pine and lodgepole pine on 8 km^2 (2000A) surrounding a plant. In Washington, ponderosa pine mortality and morbidity resulted over a 130 km^2 (50 mi^2) area in the vicinity of an aluminum plant.

Local pollution has caused extensive forest destruction throughout Europe. Examples are in Austria, Germany, Hungary, Norway, Poland and Sweden. Industrial operations along the northern border of Czechoslovakia have caused extensive forest destruction.

Regional-

Deposition of regional pollutants subject forests to different perturbations then local- pollutants because the doses are less. Rather than severe tree morbidity or mortality with dramatic symptoms, regional pollutants subtly change tree metabolism and ecosystem processes. Smith (19) 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 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, and biomass production. In the instance of high-dose local-scale pollution, the symptoms are typically acute, dramatic and obvious (severe disease, mortality, forest simplification). In the case of lower-dose regional-scale pollution, the symptoms are typically not visible (at least initially), undramatic and not easily measured. The integration of regional pollutant stresses is slower growth, altered competitive abilities and changed susceptibility to pests. Ecosystem symptoms may include altered rates of succession, changed species composition and biomass production. Symptom development is, of course, much slower at the regional scale. 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 60 years, of ozone approximately 25 years and of acid deposition approximately 10 years.

Table 1 suggests the relative strength of evidence for forest responses to regional pollutants. A review of the column totals suggests we know most about the regional effects of oxidants, less about regional effects of trace metals and least about regional effects of acid deposition. A review of the row totals suggests tree and ecosystem processes especially vulnerable to air pollution stress. The processes with a total of five or more include: litter decomposition, seedling survival, photosynthesis, foliar necrosis, tree growth, microbial pathogen activity, and ecosystem succession plus species composition. These are the tree and ecosystem processes at particular risk from regional air pollution. Fig. 1 provides an overview of regional air pollution influence on forest trees and ecosystems.

Global-

Increasing carbon dioxide concentration and decreasing stratospheric ozone concentration of the atmosphere may alter global radiation fluxes. Presumably a primary result of more carbon dioxide in the air will be warming. While incoming solar radiation is not absorbed by carbon dioxide, 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 project 0.7 to 9.6°C. 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 ± 1.5°C appears reasonable (National Academy of Sciences 1982 a, b).

The consequences of a warmer global climate, with even a very modest temperature increase, on the development of forest ecosystems, could be profound. Warming, with increased carbon dioxide in the atmosphere, might enhance forest growth. Manabe and Stouffer (8) have estimated that a doubling of atmospheric carbon dioxide would cause a 3°C warming at the U.S.-Canadian border, while Kellogg (6) has suggested that a rise of 1°C in mean summer temperature extends the growing season by approximately 10 days. Other changes associated with global warming, however, may restrict forest growth. Physiological processes of plants, especially photosynthesis, transpiration, respiration and reproduction are sensitive to temperature. With warming, respiration and decompositon 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. Precipitation changes are associated with global warming, and certain areas will receive more and others less. Those areas receiving less precipitation will also experience increased evaporation and transpiration. Waggoner (26) has estimated that the projected change in weather by the year 2000 caused by increased atmospheric carbon dioxide, will cause moderate decreases of 2-12 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 termed dieback/decline disease. Drought is the most common and important initiator of forest tree decline. Forest stresses caused by other air pollutants and other agents must be evaluated against this background of forest change caused by climatic warming.

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. 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 (9). Chlorofluorocarbons can also contribute to global warming in a manner similar to carbon dioxide.

__Regional air pollutants are the most important concern of forest managers.__

The effects of local air contaminants on forests have stabilized in the vicinity of existing point-sources of air pollutants. In numerous cases improvements have been achieved. In the case of sulfur dioxide, increasing stack heights and use of scrubbers have reduced ground level concentrations of sulfur dioxide. New industries and electrical plants in the U.S. can employ the best available air quality technology.

On the global-scale, the destruotion of ozone by halocarbons was addressed in the U.S. by banning chlorofluorocarbons in aerosol products. The release of carbon dioxide to the atmosphere from fossil fuel combustion will continue well into or through the twenty-first century. Energy requirements of nations of the temperate zone will require combustion of gas, oil and coal and the atmospheric burden of carbon dioxide will continue to increase with uncertain consequences.

Regional-scale air pollutants, on the other hand, exhibit both increasiug 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 (Fig. 1). Documentations of decreased tree growth and increased decline symptoms 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, 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 Smith (19). The comprehensive study of oxidant pollution in portions of the San Bernardino National Forest, California demonstrated air pollution effects on forest growth and succession (11). Additional evidence of reduced forest growth imposed by oxidant pollution in the west, mid-west and east has been provided (23). For various forest ecosytems 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 (U.S.E.P.A. 1983). Although adverse effects on forest ecosystems from acid deposition have not been conclusively proven by existing 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 (7, 21). 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 growth reductions and decline symptoms of the forests of the Federal Republic of Germany are dramatic and should warn all nations that the resiliency of forest ecosystems has limitations. Until the cause of this decline is more clearly understood, prudent natural resource science should not reject nor indict any single stress.

Conclusion

A sensitive and convenient forest parameter must be found to monitor the extent and intensity of stress on expansive forest systems. Waring (27) suggested that monitoring 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. Baes and McLaughlin (1) have proposed that trace metal analyses of tree rings can provide information on temporal changes in air pollutant deposition and tree health.

Implimentation 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—age, competition, environment (moisture, temperature, nutrition), insect and pathogen activity. 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 (4, 10, 27). The second challenge is to convince foresters 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 air pollutants.

Air pollution has been killing trees locally for centuries. We have been keenly aware of this in the United States for over 100 years. We now realize that in addition to mortality, regional air pollutants may be capable of causing alterations in species composition and growth-rate reductions in certain forest ecosystems over large areas and across national boundaries.

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 air pollutants, or any other environmental stress, are presently rarely available. Dendrochronological or other tree-ring analytical techniques 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 to 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 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. We do know, however, that coal combustion will provide more than 50 percent of America's electricity by 1990. We further know that without management or control, coal combustion is a source of numerous regional and global pollutants identified as important, or potentially important, to the health of forest ecosystems. Natural ecosystem health, along with human health, must be recognized in assessments, economic and otherwise, of pollution abatement strategies.

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Table 1. Relative strength of evidence (quantity/quality)* available to support forest ecosystem interaction with regional[+] air pollutants.

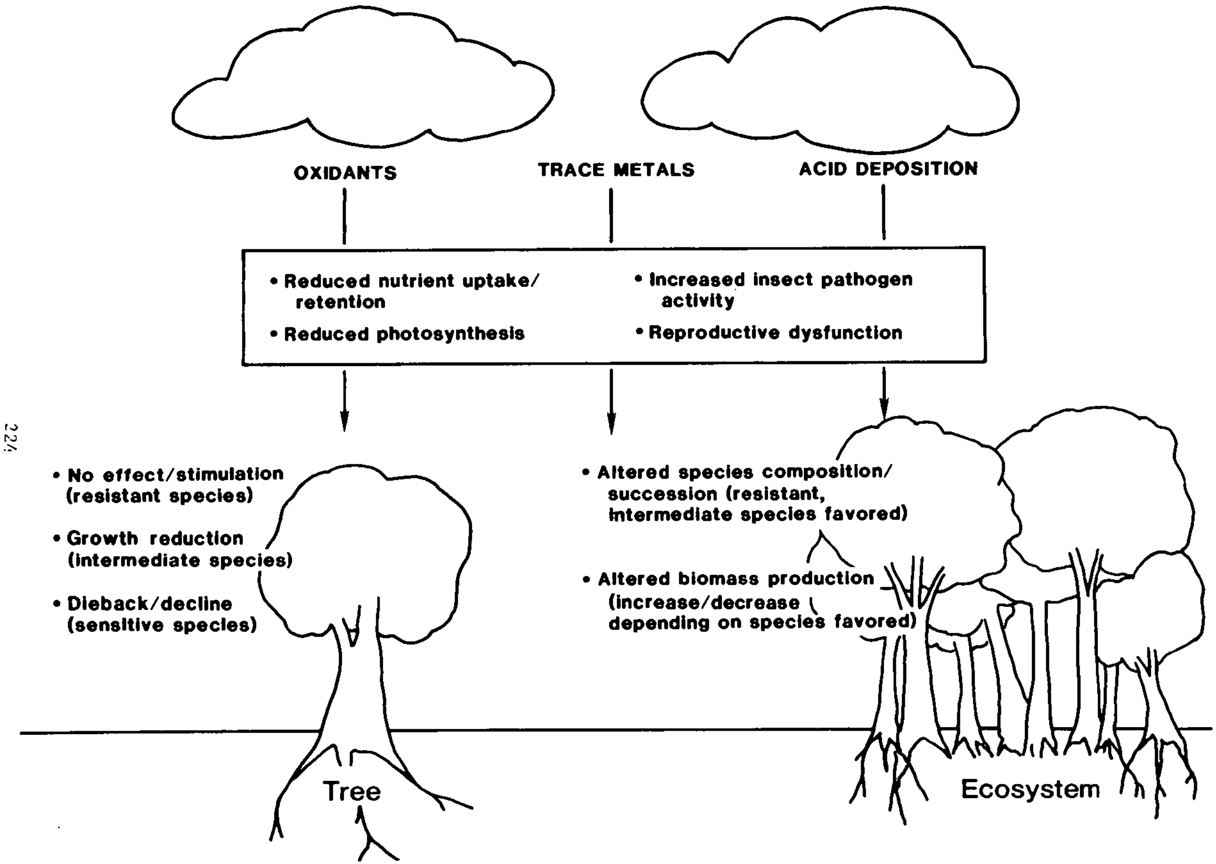
ecosystem process/component perturbation	air contaminants: oxidants	trace metals	acid deposition	TOTAL
I. <u>nutrient cycling</u>				
1. increase nutrient availability				
a. increase input (fertilization)	0	1	2	3
b. increase soil weathering	0	0	1	1
2. decrease nutrient availability				
a. reduce litter decomposition	0	4	1	5
b. increase soil acidification	0	0	2	2
c. increase soil (cation) leaching	0	0	2	2
d. decrease microbial symbioses	0	3	1	4
II. <u>primary producers</u> (trees)				
1. reproductive physiology				
a. reduce flowering	1	1	0	2
b. reduce pollen production/metabolism	2	1	1	4
c. reduce cone/seed set	2	0	0	2
d. reduce seedling survival	3	3	1	7
2. foliar physiology				
a. reduce photosynthesis	4	1	0	5
b. increase (cation) leaching	0	0	2	2
c. increase necrosis	4	2	0	6
3. root physiology				
a. decrease water/nutrient uptake	0	1	1	2
b. increase necrosis	0	1	2	3
4. reduce tree growth	4	1	1	5

III. consumers				
1. arthropod pest activity				
a. increase	4	0	0	4
b. decrease	0	0	0	0
2. microbial pathogen activity				
a. increase	4	1	1	6
b. decrease	1	2	0	3
3. other pest activity (viruses, bacteria, nematodes, mistletoes, weeds)				
a. increase	0	0	0	0
b. decrease	0	0	0	0
4. wildlife (bird/mammal) activity				
a. reduce food	2	0	0	2
b. reduce habitat	2	0	0	2
c. increase morbidity/mortality	0	2	0	2
IV. ecosystem succession/species composition (cause alteration)	4	1	0	5
V. ecosystem productivity (increase/decrease biomass accumulation)	4	0	0	4
TOTAL	41	25	18	

*evidence scale

0 – extremely limited evidence or hypotheses only
1 – slight evidence
2 – more evidence
3 – greater evidence
4 – considerable evidence including field evidence

+exclusive of local air pollution effects within several km of point sources



OXIDANTS
TRACE METALS
ACID DEPOSITION
• Reduced nutrient uptake/ retention
• Reduced photosynthesis
• Increased insect pathogen activity
• Reproductive dysfunction
• No effect/stimulation (resistant species)
• Growth reduction (intermediate species)
• Dieback/decline (sensitive species)
• Altered species composition/ succession (resistant, intermediate species favored)
• Altered biomass production (increase/decrease depending on species favored)
Tree
Ecosystem