# Changes in forests and their relationship to air quality

**Alan A. Lucier and Benjamin B. Stout**

*Recent changes in European and North American forests do not conclusively demonstrate the existence of forest health problems resulting from regional air quality. For each reported change, there are unconfirmed but plausible explanations that do not rely on air pollution.*

Forests, like all plant communities, are constantly changing (*1*). Change occurs through natural and man-made disturbance and through the processes of evolution, succession, and biomass accumulation (*2*). Tree and stand growth rates, mortality rates, and all other forest attributes are subject to change.

Changes in forests resulting from natural abiotic and biotic stresses occur every year in the United States and result in substantial losses in productivity. **Table I** lists some of the major natural stresses and their effects on U.S. forests in 1985. Some natural stress agents, such as fire and fusiform rust, have such devastating impacts that detailed records are kept. Other agents, such as frost, flood, and most insects and diseases, have subtler impacts that are difficult to quantify and are thus less well documented.

Changes in forests frequently are caused by several interacting factors. Recent catastrophic mortality of pines in Texas and Louisiana is attributable not only to the bark beetles that killed the trees but also to the overcrowded stand conditions that weakened the trees and predisposed them to bark beetle attack (*3*).

Scientific investigations cannot always determine the cause for a particular change in a forest. German scientists have studied the episodic mortality of the silver-fir since the early 1800s, but they have failed to discover the principal cause or causes for the decline (*4*). In this case, as in many others, scientists often attribute decline to complex interactions of numerous biotic and abiotic factors.

## Recent changes in forests

Several recent changes in European and North American forests have received considerable attention during the ongoing debate on the ecological effects of acid rain and other regional air-quality problems. Several of the most thoroughly investigated changes are briefly described here. In each case, the available information is inadequate to define the contributions of air quality and other factors to observed change.

Lucier is the northern regional manager and Stout is the national manager of the Air Quality/Forest Health Program, National Council for Air and Stream Improvement, 260 Madison Ave., New York, N.Y. 10016.

### West German forests

The incidence of premature foliage loss and other stress symptoms in West German forests increased in the 1970s (*5–7*). Annual surveys of damage were initiated in 1982 (*8*). The estimated percentage of damaged trees was 8% in 1982, 34% in 1983, and about 50% in 1984, 1985, and 1986. These figures have been widely reported but are somewhat misleading. Changes in survey procedures in 1983 and 1984 may account for much of the increase in estimated damage. Moreover, nearly two-thirds of the trees classified as damaged are in "stage 1" (slight damage), defined as 10–25% foliage loss. Many foresters consider trees in stage 1 to be normal, since not every tree in a forest is expected to have perfect form and 100% of maximum potential foliage area. Less than 5% of the trees surveyed are in stage 3 (severe damage) or stage 4 (dead).

Air pollutants are among the possible causes of forest damage in the Federal Republic of Germany. Sulfur dioxide concentrations reach harmful levels in forests near emissions sources across the German Democratic Republic and Czechoslovakian borders. However, the area affected is a small percentage of the total West German forest (*5*). In contrast, large areas are exposed to potentially harmful ozone concentrations and high rates of acidic deposition (*6*).

Nonpollutant causes of forest damage in Germany have clearly not been ruled out. Possible nonpollutant causes include unusually dry, hot summers in 1976, 1980, 1982, and 1983 (*6*); planting of species on sites to which they are not well adapted (*6*); and soil fertility depletion attributable to the long history of unusually intensive biomass utilization in German forests.

### Spruce-fir forests in the eastern United States

Surveys conducted throughout the Appalachians indicate that many high-elevation spruce-fir stands are exhibiting high rates of mortality, excessive foliage loss, and slow growth (*9–11*). Damage to red spruce increases with increasing elevation and does not appear to be correlated with stand basal area or tree age (*10*). Tree seedlings, especially fir, are usually abundant and apparently healthy

I. Some major natural stresses in U.S. forests and their effects in 1985*

| Stress | Extent of effect, million acres | Nature of impact |
|---|---|---|
| Wildfire | 4.3 | $750 million damage to timber resources |
| Gypsy moth | 1.7 | Tree defoliation concentrated in southern New England and Mid-Atlantic states |
| Mountain pine beetle; southern pine beetle | >4.0 | Mortality often severe in infested stands |
| Spruce budworm | 5.2 | Tree defoliation and mortality concentrated in Maine |
| Western spruce budworm | 12.8 | Tree defoliation and mortality, primarily in the Rockies, Intermountain region, and the Pacific Northwest |
| Fusiform rust | 15.3 | Annual timber value loss of $35 million from volume and quality reductions in southern pines |
| Dwarf mistletoe | 22.4 | Annual timber volume loss of 383 million $ft^3$ in the West |
| Root diseases | >15.0 | Annual timber volume loss of 239 million $ft^3$ in the West; substantial but unknown impact in other regions |

*All data provided by USDA Forest Service (58,59). Data on wildfire based on published (58) and unpublished information provided by the Forest Service.

wherever mortality in the overstory allows direct sunlight to penetrate to the forest floor. Undocumented concerns that spruce seedlings and saplings are abnormally scarce or unhealthy are sometimes expressed at scientific meetings.

No single factor accounts for recent changes in spruce-fir forests at high elevations. Data gathered while monitoring air quality and cloud chemistry suggest that ozone and cloud-water acidity sometimes reach potentially harmful levels (*12, 13*), but their impact on forests is undetermined. Analyses of tree rings, forest history, and weather records show that widespread episodic mortality of spruce has occurred before and that water and temperature stress may be responsible (*10, 11*). In the southern Appalachians, the balsam wooly aphid has killed many fir trees, thus altering the environment of associated spruce (*9*). In the northern Appalachians, insects and wind damage may be important factors contributing to observed damage (*11*).

At low elevations in upstate New York and northern New England, radial growth rates of red spruce and balsam fir trees have declined during recent decades. The declines, however, are largely attributable to historical land use patterns, insect outbreaks, and normal processes of stand development (*14*). Growth rates of eastern white pine, northern red oak, sugar maple, and eastern hemlock are increasing (*15*).

**Natural pine stands in the southeastern United States**

The U.S. Dept. of Agriculture Forest Service has reported reductions in tree and stand growth rates for naturally regenerated pine in Georgia, North Carolina, and South Carolina (*16*). These reductions, which began in the 1950s and 1960s, are at least partially attributable to historical land use patterns, increases in age and competition, and other natural factors. Growth-rate reductions have not been found on intensively managed forest industry lands (*17*). Whether ozone or other air-quality factors are influencing southern pine growth rates remains to be determined (*18*).

**Sugar maple in the northern United States and southern Canada**

Unexplained declines of individual sugar maple trees and stands have been reported periodically since 1913. Drought and/or defoliation by insects have frequently preceded the appearance of decline symptoms. Other factors such as low soil fertility, improper stand management, road salts, and root pathogens have also been involved in some instances. Whether acidic deposition and other air-quality factors play a role in these instances of decline remains to be determined (*19–21*).

The extent and severity of these instances of decline have not been sufficient to reduce the overall growth and abundance of maples in the areas that have been examined thus far. Hornbeck *et al.* (*15*) found no evidence of a decline in average radial growth rate in increment cores taken from sugar maple and red maple trees throughout the northeastern United States. Statistics from the Forest Service show that the volume of growing stock for both sugar maple and red maple has been increasing in recent years in New York and Maine (*22, 23*).

## Air-quality impact mechanisms

Scientists have proposed many mechanisms by which air pollutants might affect forests in areas remote from emissions sources. The most plausible mechanisms are those involving ozone stress to above-ground tree tissues (*6, 24–26*). Emissions of nitrogen oxides (precursors of ozone) have increased sharply since the 1960s in the Federal Republic of Germany and in the United States (*27, 28*), and there is evidence of increased ozone concentration in the Federal Republic of Germany (*29*). Moreover, controlled-exposure experiments have demonstrated adverse effects of ambient ozone levels on many food and forage crops (*30*) and on seedlings of several tree species (*31–33*). Estimated crop losses in the United States from exposure to ozone are on the order of $2 billion per year (*34, 35*). Whether or not ozone is having significant effects on forest health and productivity remains to be determined.

Realistic levels of acidity in simulated rainfall have generally not injured foliage or reduced growth in short-term studies with crops and trees (*36*). However, acidic deposition might affect vegetation in other ways:

1. Fog and cloud water are sometimes much more acidic than rainfall (*12, 13, 37, 38*). Do acidic fog and cloud water injure foliage at high elevations and along coastal sites?

2. Nitrogen fertilization at excessive rates or during autumn can impair the ability of perennial plants to withstand cold temperatures (*39*). Does the nitrogen component of acidic deposition predispose trees to damage by low temperatures (*40, 41*)?

3. Dry acidic deposition can accumulate on foliage and other plant surfaces (*42*). Could foliage or reproductive structures be injured by accumulated acids dissolved by dew, fog, or mist?

4. Mechanisms exist by which acidic deposition might accelerate nutrient leaching and acidification in some types of forest soil (*43*). Could acidic deposition over a period of decades reduce the fertility of important forest-soil types?

Impact mechanisms involving direct action of gaseous sulfur and nitrogen oxides are quite speculative except near emission sources. At the Electric Power Research Institute/Sulfate Regional Experiment (EPRI/SURE) air-quality monitoring sites in the eastern United States (nonurban, nonindustrial locations), about 95% of the one-hour-average values for $SO_2$ concentration were less than 20 ppb, with few values greater than 100 ppb (*44*). For (NO + $NO_2$), the 95th-percentile one-hour-average concentration was about 40 ppb, again with few values greater than 100 ppb. Dose-response studies (*45, 46*) have not shown that such exposure regimes are harmful to tree species.

Other pollutants sometimes mentioned in discussions of long-range transport and forest effects include trace metals, peroxides, and volatile organics. Atmospherically deposited metals are accumulating in forest soils (*9, 47*). However, current levels in remote areas do not appear high enough to disrupt the activity of soil organisms or the decomposition of organic matter (*47*). Some measurements of peroxides (*12*) and organics (*48*) are available, but the implications for forest health are unknown.

## Research status

Substantial research programs on air quality and forests have been initiated since 1980 in Europe and North America. Annual expenditures in the United States are now greater than $20 million. Research in the United States is organized and funded by the National Acid Precipitation Assessment Program, EPRI, National Council of the Paper Industry for Air and Stream Improvement, California Air Resources Board, and a variety of other organizations in the public and private sectors.

Most current investigations on air quality and forests can be classified as either epidemiological or mechanistic. Both types of investigation provide information that is useful in developing risk assessments.

### Epidemiological surveys

Epidemiological surveys can help determine whether air pollutants are important factors in unexplained forest health problems. However, such surveys probably cannot provide quantitative estimates of pollutant impact on forest productivity.

In some surveys, investigators seek nonpollutant causes of unexplained forest health problems by measuring forest health and natural stress factors at many different sites. A strong correlation between a natural stress factor and a forest health problem is evidence that air pollution is not involved in the problem. However, the possible influence of pollution on a forest's ability to resist natural stress may still be a valid matter of consideration.

In other surveys, investigators seek evidence of pollution effects by measuring tree growth and foliage appearance at points along a gradient of pollutant concentration or deposition. This kind of survey has documented pollutant impacts along well-defined gradients near point sources and urban areas (*26*). Unfortunately, regional pollutant gradients are not well defined over most areas of interest. Moreover, regional pollutant gradients are confounded by parallel gradients for rainfall, temperature, soil type, and other factors that can directly influence tree growth and appearance and alter tree resistance to pollutants. Consequently, regional gradient surveys of tree growth and appearance could easily fail to detect real pollutant effects, or they could indicate effects where none exist.

Application of the gradient-survey approach to regional pollution questions requires more precise definition of gradients and development of procedures that distinguish pollutant effects from effects of other stresses. Potential diagnostic indicators of pollutant-induced stress include foliage sulfur concentration (*49*), surface wax structure (*50*), cell ultrastructure (*51*), biochemical assays (*52*), and foliage spectral characteristics (*53*). Intensive monitoring of climatic variables, air quality, and potential diagnostic indicators at a limited number of sites will be needed to distinguish pollutant effects from effects of season, foliage age, and natural stresses.

### Mechanistic studies

Studies of pollutant impact mechanisms are essential complements to epidemiological surveys in efforts to define air pollution's role in unexplained forest health problems. In addition, mechanistic studies are useful in estimating possible effects on productivity in forests without obvious symptoms.

Investigations of hypothesized pollutant impact mechanisms take many forms. Some involve exposing seedlings to known pollutant concentrations in the laboratory. Others involve measuring rates of geochemical processes in forest ecosystems. The unifying concept is that forest responses to pollutants are determined by pollutant exposure levels *and* by the capacity of ecosystem components to exclude, buffer, and detoxify pollutants (*54, 55*). With sufficient information about ecosystem components, responses to measured pollutant inputs can be predicted.

The simplest form of mechanistic study is the dose-response experiment. Typically, the response of seedling growth to various levels of pollutant exposure are determined using controlled-environment techniques. Such studies can identify potentially harmful levels of pollutant exposure for important species. This information, in combination with data obtained by monitoring air quality, can be used to identify regions where a particular species may be exposed to potentially harmful levels of a particular pollutant.

U.S. and European research programs are relying heavily on dose-response studies to support risk assessment. Initial assessments (i.e., those to be completed in 1987 and 1988) will be qualitative and will have a high level of uncertainty associated with them. Development of more reliable and quantitative assessments will require (a) projection of pollutant effects over a tree's entire life cycle and (b) consideration of interactions among genetic, ontogenetic, and environmental factors (*54, 56, 57*). These tasks involve assembling and interpreting large amounts of data about soil, plant, and atmospheric processes. An integrated systems analysis approach to research such as that described by Chen and Goldstein (*54*) is clearly essential. In such an approach, mathematical models are used to summarize empirical observations, suggest critical experiments, and eventually to estimate impacts on forest growth. With effective research management, the gaps in mechanistic understanding will be filled by the synergistic interaction between modeling and experimental research components.

The most important information gaps are in the areas of forest–atmosphere interactions and tree response to pollutants. Key topics include the within-canopy variabilities in microclimate and pollutant deposition; mechanisms of pollutant absorption, metabolism, and damage repair; and effects of pollutants on tree carbon budgets, reproduction, and stress resistance. Important information gaps also exist in our understanding of response at the stand level. We do not yet understand the within-stand variability in pollutant sensitivity and its effect on competitive relationships and total biomass productivity.

Clearly, both tree and stand-level models are needed. Tree models will integrate results of dose-response studies with current knowledge of forest air quality and tree physiology to estimate pollutant impacts on the growth and hardiness of individual trees throughout their life cycles. Stand-level models will combine impact estimates from tree models with knowledge of forest-stand dynamics to estimate the effects of pollutants on stand growth and yield.

## Conclusions

Recent changes in European and North American forests do not demonstrate the existence of forest health problems resulting from regional air quality. For each reported change, there are unconfirmed but plausible explanations that do not rely on air pollution as a mechanism.

The possibility of forest health problems caused by regional air quality cannot be ruled out, however. Mechanisms of impact involving ozone may be operative in some commercial forest regions of the United States and West Germany. Whether ozone is affecting forest productivity remains to be determined. Impact mechanisms involving acidic deposition are plausible but may be of no practical significance in many forests. Significant impacts of acid inputs are most plausible for high-elevation forests receiving high rates of acidic deposition.

Substantial new research programs on air quality and forests are underway in Europe and North America. Dose-response studies and epidemiological surveys are receiving considerable support. These activities are providing data that will support qualitative near-term risk assessments. However, more effort should be directed toward development of (a) diagnostic indicators of pollutant stress and (b) mechanistic models of tree and stand responses to ozone and acidic deposition.

## Literature cited


1. Cooper, W. S., Ecol. 7(3): 391(1926).
2. Raup, H. M., J. Ecol. 52(supplement): 19(1964).
3. Sharpe, P.J.H. *et al.*, in "Integrated Pest Management Research Symposium, the Proceedings" (S.J. Branham and R.C. Thatcher, Eds.), USDA Forest Service Gen. Tech. Rept. SO-56, New Orleans, 1985.
4. Wachter, A., Z. Pflanzenkrankheiten und Pflanzenschutz 85(6): 361(1978). Translation by Central Electricity Generating Board, London.
5. Blank, L.W., Nature 314: 311(1985).
6. Prinz, B., Krause, G.M.H., and Jung, K.-D., paper presented at "NATO advanced research workshop on Effects of Acidic Deposition and Air Pollution on Forests, Wetlands, and Agricultural Ecosystems," May 13–17, 1985, Toronto.
7. Schutt, P. and Cowling, E.B., Plant Disease 69: 548(1985).
8. "1986 Forest Damage Inventory," Federal Ministry of Food, Agriculture, and Forestry, West Germany, 1986.
9. Bruck, R.I., in "Air Pollutant Effects on Forest Ecosystems," The Acid Rain Foundation, St. Paul, Minn., 1985.
10. Johnson, A.H. and McLaughlin, S.B., in "Acid Deposition: Long-term Trends," National Academy Press, Washington, D.C., 1986.
11. Weiss, M.J. *et al.*, Forest Pest Mgmt. Rept. NA-TP-11, USDA Forest Service, Broomall, Pa., 1985.
12. Kadlacek, J.A. *et al.*, in "Transactions of APCA specialty conference on Meteorology of Acidic Deposition," Air Pollution Control Assoc., Pittsburgh, 1987.
13. Lovett, G.M., Reiners, W.A., and Olson, R.K., Science 218: 1013(1982).
14. Hornbeck, J.W., Smith, R.B., and Federer, C.A., Water Air Soil Poll. 31: 425(1986).
15. Hornbeck, J.W., Smith, R.B., and Federer, C.A., in "Proceedings of the international symposium on Ecological Aspects of Tree Ring Analysis," U.S. Department of Energy CONF-8608144, 1987.
16. Sheffield, R.M. *et al.*, USDA Forest Service Resource Bull. SE-83, 1985.
17. Lucier, A.A., NCASI Tech. Bull. 508, National Council for Air and Stream Improvement, New York, 1986.
18. Pinkerton, J.E. and Lefohn, A.S., Tappi J. 69(4): 58(1986).
19. Bernier, B. and Brazeau, M., in "Maple Producers Information Session: Maple Decline," Ministere de l'Agriculture, Quebec, 1986.
20. Gagnon, G. *et al.*, paper presented at "NATO advanced research workshop on Effects of Acidic Deposition and Air Pollution on Forests, Wetlands, and Agricultural Ecosystems," May 13–17, 1985, Toronto.
21. McIlveen, W.D., Rutherford, S.T., and Linzon, S.N., ARB-141-86 Phyto, Ontario Ministry of the Environment, Toronto, 1986.
22. USDA Forest Service, Resource Bull. NE-71, Broomall, Pa., 1982.
23. USDA Forest Service, Resource Bull. NE-81, Broomall, Pa., 1984.
24. Evans, L.S. and Ting, I.P., Am. J. Bot. 60(2): 155(1973).
25. "Air Pollution by Photochemical Oxidants" (R. Guderian, Ed.), Springer-Verlag, New York, 1985.
26. Smith, W.H., "Air Pollution and Forests," Springer-Verlag, New York, 1981.
27. Husar, R.B., in "Acid Deposition: Long-term Trends," National Academy Press, Washington, D.C., 1986.
28. Van Osten, W., in "Air Pollution Effects on Forest Ecosystems," The Acid Rain Foundation, St. Paul, Minn., 1985.
29. Lefohn, A.S. and Mohnen, V.A., J. Air Poll. Cont. Assoc. 36: 1329(1986).
30. Heck, W.W. *et al.*, Env. Sci. Technol. 17: 537A(1983).
31. Chappelka III, A.H. and Chevone, B.I., Can. J. For. Res. 16: 786(1986).
32. Hogsett, W.E. *et al.*, Can. J. Bot. 63: 2369(1985).
33. Reich, P.B. and Amundson, R.J., Science 230: 566(1985).
34. Adams, R.M. and Crocker, T.D., in "The Economics of Acid Deposition" (T.C. Crocker, Ed.), Ann Arbor Science Press, 1982.

35. Shriner, D.C. *et al.*, Oak Ridge National Lab Rept. No. 5910, Oak Ridge, Tenn., 1982.
36. "The Acidic Deposition Phenomenon and Its Effects," Vol. 2, "Effects Sciences," U.S. Environmental Protection Agency, EPA 600/8-83-016BF, 1984.
37. Deal, W.J., J. Air Poll. Cont. Assoc. 33: 691(1983).
38. Weathers, K.C. *et al.*, Nature 319: 657(1986).
39. Soikkeli, S. and Karenlampi, L., Eur. J. For. Path. 14:(2) 129(1984).
40. Friedland, A.J. *et al.*, Can. J. For. Res. 14: 963(1984).
41. Nihlgard, B., Ambio 14:(1) 2(1985).
42. Lindberg, S.E. *et al.*, Science 231: 141(1986).
43. Ruess, J.O. and Johnson, D.W., Ecological Studies 59, Springer-Verlag, New York, 1986.
44. "The Sulfate Regional Experiment: Report of Findings," Vol. 2, Electric Power Research Institute, EPRI EA-1901, Palo Alto, Cal., 1983.
45. "Air Quality Criteria for Oxides of Nitrogen," U.S. Environmental Protection Agency, EPA-600/8-82-026, 1982.
46. "Air Quality Criteria for Particulate Matter and Sulfur Oxides," U.S. Environmental Protection Agency, EPA-600/8-82-029, 1982.
47. Friedland, A.J., Johnson, A.H., and Siccama, T.G., Can. J. Bot. 64: 1349(1986).
48. Ligocki, M.P., Leuenberger, C., and Pankow, J.F., Atmos. Env. 19: 1609(1985).
49. Huttunen, S., in "Monitoring of Air Pollutants by Plants" (L. Steubing and H.J. Jager, Eds.), Dr. W. Junk Publishers, the Hague, 1982.
50. Huttunen, S. and Laine, K., Ann. Bot. Fennici 20:(1) 79(1983).
51. Soikkeli, S. and Tuovinen, T., Ann. Bot. Fennici 16:(1) 50(1979).
52. Darral, N.M. and Jager, H.J., in "Gaseous Air Pollutants and Plant Metabolism" (M.J. Koziol and F.R. Whatley, Eds.), Butterworth, London, 1984.
53. Rock, B.N., Williams, D.L., and Vogelmann, J.E., in "Proceedings: Machine Processing of Remotely Sensed Data," Purdue University, Lab. for Applic. of Remote Sensing, West Lafayette, Ind., 1985.
54. Chen, C.W. and Goldstein, R.A., in "Air Pollutants and Their Effects on the Terrestrial Ecosystem" (A.H. Legge and S.V. Krupa, Eds.), John Wiley, New York, 1986.
55. Tingey, D.T. and Taylor, G.E.,Jr., in "Effects of Gaseous Air Pollution in Agriculture and Horticulture" (H.H. Unsworth and D.P. Ormrod, Eds.), Butterworth, London, 1982.
56. Horn, N.M., "Effects of Air Pollution and Acid Rain on Fungal and Bacterial Diseases of Trees," Dorschkamp Research Institute for Forestry and Landscape Planning, Wageningen, The Netherlands, 1985.
57. Miller, P.R., in "Proceedings of Workshop on Controlled Exposure Techniques and Evaluation of Tree Responses to Airborne Chemicals" (A.A. Lucier, Ed.), NCASI Tech. Bull. 500, National Council for Air and Stream Improvement, New York, 1986.
58. "National Forest Fire Report 1985," USDA Forest Service, Washington, D.C., 1986.
59. "Forest Insect and Disease Conditions in the United States 1985, Forest Pest Management," USDA Forest Service, Washington, D.C., 1986.



Received for review Sept. 1, 1987.

Accepted Sept. 23, 1987.