JOURNAL OF
ARBORICULTURE

February 1986
Vol. 12, No. 2

THE IMPACT OF ENVIRONMENTAL POLLUTION ON SHADE TREES[1]

by T. T. Kozlowski

Abstract. Protecting shade trees from toxic chemicals will be increasingly important to arborists because phytotoxic air pollutants are heavily concentrated in urban areas and the amounts of some of these pollutants are likely to increase. When incorrectly applied, deicing salts, herbicides, fungicides, insecticides, and antitranspirants may also be variously phytotoxic. Arborists should give high priority to selecting trees for planting that are tolerant to the air pollutants present in a given area and to supporting research on developing pollution-tolerant trees. Injury to shade trees by deicing salts can be reduced by using less salt, planting salt-tolerant trees, leaching of salts with fresh water, and adding gypsum to soils containing salt. To avoid injury to shade trees from herbicides, fungicides, insecticides, and antitranspirants strict adherence is advised to directions on the label of each chemical with respect to appropriate dosage, plant species and cultivar, manner of application, and weather conditions.

One of the most serious challenges that arborists will face in the future is how to cope with shade tree problems that are caused by toxic chemicals. Not only are phytotoxic pollutants highly concentrated in urban areas but the amounts of some of the most toxic pollutants are likely to increase.

Environmental pollutants may be localized in the air, or soil, or both. Because normal growth of trees requires substances supplied by roots (water, mineral nutrients, and certain hormonal growth regulators) to shoots, any adverse effect on roots of polluting chemicals in the soil will lead to reduced growth of the tree crown. Direct harmful effects of air pollutants on tree crowns may be expressed in foliar injury as well as reduction in the amounts of shoot-produced compounds (carbohydrates, certain hormonal growth regulators) that are necessary for root growth. A simultaneous pollution stress on the roots and the crown may be expected to adversely affect trees faster and more drastically than a pollution stress that is exerted only on the roots or on the crown (43).

A wide variety of naturally occurring and man-made toxic chemicals may adversely affect shade trees. These include gaseous air pollutants and particulates as well as improperly used deicing salts, herbicides, fungicides, insecticides, and antitranspirants.

Air Pollutants

The important air pollutants affecting shade trees include sulfur dioxide (SO_2), acid rain, ozone (O_3), fluorides (F), nitrogen oxides (NO_X), and such particulates as cement kiln dust, soot, lead particles, magnesium oxide, iron oxide, foundry dusts, and sulfuric acid aerosols. Most of the adverse effects of air pollutants on trees are associated with sulfur and nitrogen oxides produced by burning of fossil fuels and smelting of metallic ores (45).

In the United States about half of the total amount of SO_2 is released in Indiana, Ohio, and Pennsylvania. In Canada SO_2 concentrations are highest in the major cities of Ontario and Quebec and industrialized parts of the St. Lawrence Seaway. The concentrations of such phytotoxic pollutants as ozone (O) and nitrogen oxides (NO_X) also are high in densely populated areas (45). In England the amount of S laid down by wet deposition averaged two to three times as much in urban areas as in rural areas (51).

Although some effort has been exerted to reduce emission of air pollutants, the amounts of certain pollutants that are toxic to trees will in-

[1] Paper presented at the Annual Meeting of the International Society of Arboriculture, Milwaukee, Wisconsin, August, 1985.

crease because of greater use of fossil fuels with a high sulfur content. For example, the demand for coal by the year 2,000 probably will be at least doubled in the industrial countries of North America and Europe (67). The Environmental Protection Agency (25, 26) estimated that emissions of SO_2 by 1990 will be about 10% higher than in 1975. Lincoln and Rubin (52) estimated that release of SO_2 in the northeastern states in 1990 might be as much as 60% higher than in 1975 (based on emission regulations in 1978). Postel (64) estimated that by the year 2,000 nitrogen oxides will increase by 25% in the United States.

Responses of shade trees to air pollution. The specific effects of environmental pollution on shade trees vary greatly with the type or types of pollutants present, dosage, tree species, age of tree, environmental conditions, and response parameters. Pollutants may cause injury (Fig. 1), mortality, reduction in growth and yield (Fig. 2), and changes in physiological processes of shade trees (9, 10, 11).

Injury. Air polluting chemicals, alone and in combination, injure leaves by causing blotchiness, discoloration, necrotic mottling, and lesions. For example, after high concentrations of SO_2 are absorbed by leaves through the stomatal-pores, necrotic lesions form but the area around the leaf veins remains green (41). Such acute injury has been reported for many species of trees. Absorption of low amounts of an air pollutant over a long time induces chronic injury characterized by chlorosis and early leaf senescence. Necrotic markings may or may not be associated with chronic injury. Chlorosis and necrosis of leaves often are followed by leaf shedding (45). Air pollution may also injure fruits. For example, exposure to fluorides resulted in lesions on apricots, peaches, and pears as well as deformation of pears (5).

Figure 1. Sulfur dioxide injury on sumac characterized by dead patches of leaf tissue located between the healthy tissue and the veins.

Figure 2. Ozone-affected pine needles (left) and healthy needles (right). The pollutant prevented needle expansion and induced tip injury.

Growth. Air pollution reduces leaf growth, height growth, stem diameter growth, root growth, and reproductive growth (41, 42, 45, 46, 57, 62, 76). Such growth inhibition may or may not be associated with visible leaf injury.

Physiological Processes. Reduction in growth of trees by air pollution is preceded by changes in physiological processes. Air pollutants inhibit chlorophyll synthesis and photosynthesis (10, 55, 74), and alter stomatal aperture (58, 59), permeability of cell membranes (4, 33), amounts of stored carbohydrates and proteins (10), and activity of enzymes (32, 36).

The rate of photosynthesis of shade trees is reduced by a variety of air pollutants (37, 49). One or more mechanisms may be involved in early reduction of photosynthesis, including closing of stomatal pores as well as changes in metabolic rates and in the capacity of plant cells to tolerate pollutants. In the longer term the inhibition of photosynthesis is also the result of decreased formation and expansion of leaves as well as leaf injury and leaf shedding (45).

Effects of air pollutants on diseases and insects. Air pollutants may increase or decrease the effect of diseases and insects on shade trees, depending on the specific pathogen and pollution dosage. By weakening trees air pollutants often predispose them to some diseases. For example, injury by *Armillaria mellea* and wood rotting fungi may increase following exposure of trees to SO_2 (46). Costonis and Sinclair (12) reported that injury of *Pinus strobus* needles, caused by fungi, was increased by exposure of host trees to O_3, and James *et al.* (35) noted that *Fomes annosus* killed trees that had been injured by O_3. Pollutants can also act directly on disease-causing organisms and reduce the severity of some diseases because of greater toxicity of the pollutant to the pathogen than to the host tree. For example, blister rust symptoms were reduced near an SO-producing smelter (53, 54). By comparison, low dosages of SO_2 can stimulate certain disease-causing fungi. In *Pinus sylvestris* seedlings, for example, production of lesions on needles by *Scirrhia acicola* was favored by exposure to low SO_2 dosages (78).

Air pollutants may also influence tree-insect interactions. For example, heavy infestations of secondary pests such as bark insects may occur on trees weakened by air pollutants (50). Increased infestations of primary insect pests on trees exposed to air pollution have also been reported. Such attacks may be associated with suppression of insect predators of parasites (80) or increased emission by trees of insect-attracting terpenes (65).

Deicing Salts and Salt Spray

Large amounts of sodium chloride and calcium chloride are used to deice roads and pavements. For example, in 1969 alone some six million tons of salt were so used in the northern states (81), with up to a ton of salt applied to a mile of road during a single storm (70).

Deicing salts may have direct toxic effects on leaf tissues or roots. Salts sprayed on trees dehydrate the shoots, usually leading to tip or marginal scorching and, sometimes, death of trees. Salts that enter the soil in runoff decrease the capacity of roots to absorb water and mineral nutrients. Injury, decreased growth, and death of trees often follow. Salt injury to shade trees may also predispose them to other environmental stresses such as drought and low temperature (23, 31, 34, 73).

Trees often are injured by salt spray near oceans and only a few species of trees can survive seacoast conditions. Shade trees may also be injured by spray drift from cooling towers of power stations that use seawater (28).

Agricultural Chemicals

A number of chemicals which are indispensable in the practice of arboriculture may, under certain conditions, injure shade trees. Such chemicals include herbicides, fungicides, insecticides, and antitranspirants.

Herbicides. Because of their effectiveness and ease of application many herbicides have been very useful for weed control, brush control, utility line maintenance, and elimination of undesirable trees. However, when improperly used, herbicides may be extremely toxic to shade trees. For example, hormone-type herbicides such as 2,4-D and 2,4,5-T sometimes cause abnormal growth of trees, including curling of leaves, twisting of petioles, distortion of shoots (Fig. 3), and inhibition of leaf expansion. Some nonhormone type herbicides such as aminotriazole cause bleaching of foliage.

The arborist should also be aware that some herbicides are transported from one tree to another through root grafts. In a *Pinus strobus* plantation more than 40% of untreated plantation trees were killed by "backflash" (movement of ammonium sulfamate from treated to untreated trees) (6). Backflash of 2,4,5-T also occurred in *Liquidambar styraciflua* trees (27).

Contact herbicides such as sodium arsenite, paraquat, and cacodylic acid, although usually not applied near shade trees, sometimes cause necrotic spots on leaves as a result of spray drift. Some herbicides, including simazine, atrazine, monuron, 2,4-D, and 2,4,5-T reduce the rate of photosynthesis (68, 69).

Fungicides. As a general rule fungicides have been less toxic than some other chemicals when applied to trees. Nevertheless, both phytotoxicity and growth reduction following application of certain fungicides to trees have been reported. Worf (personal communication) cited the following examples: 1) Phaltan (folpet), widely used as fungicide on cherry, severely burned the foliage of closely related hawthorn species, 2) Difolaton controlled scab on flowering crabs but injured the leaves of a few varieties, 3) systemic fungicides, including Benlate, Lignasan, and Arbotect, widely used on elms for control of Dutch elm disease, were toxic to red and black oaks when applied at concentrations effective against the pathogen causing oak wilt. Injury to elm leaves has sometimes occurred following application of these fungicides, particularly on rock elm (*Ulmus thomasii*). Andersen *et al.* (1) cautioned that although benzimidazole compounds are very effective in control of Dutch elm disease they should be used with care. They reported that arbotect injected into elms induced stem bleeding and cracking as well as death of parenchyma cells in the sapwood.

Captan is registered for use on a wide variety of fruit trees but, as the label states, it should not be used on D'Anjeau pear. Captan has been reported to injure both leaves (13) and roots (8). Captan applied to the soil surface at concentrations as low as 0.2% reduced shoot and root growth of 5-week-old *Picea sitchensis*, *Pinus sylvestris*, and *Tsuga heterophylla* seedlings (22). Hence, several sequential applications of captan at very low concentrations may be advisable to control pathogens without injuring seedlings.

Some fungicides lower the rate of photosynthesis by reducing the light intensity reaching the leaf, plugging stomatal pores, or affecting metabolism. For example, sulphur fungicides and copper oxychloride reduced photosynthesis appreciably but the organic fungicides Ziram, Zineb, Captan, and Phaltan did not (49).

Insecticides. As emphasized on the label injury to shade trees may occur when certain insecticides are applied to some species of shade trees. For example, malathion may cause injury to *Carya* spp, *Acer* spp., and *Pinus strobus*. Crop (spray) oils may cause leaf scorch in *Fagus sylvatica*, *Juglans nigra*, *J. cinerea*, *Carya* spp., and *Acer saccharum*. Flower buds of *Pseudotsuga menziesii* may also be injured. The label for Omite lists 49 species and varieties of ornamentals that have shown slight necrosis and 24 species and varieties exhibiting moderate to severe necrosis. The labels for acephate indicated that phytotoxicity varied for two different formulations of this material.

Some insecticides may appreciably lower the rate of photosynthesis. These include petroleum oils, lindane, phosphate insecticides, Sevin, Acaralate, Dikar, Karathane, Parathion Superior oil, Zolone, Morestan, and wettable sulfurs (2, 49).

Many insects can be controlled by systemic chemicals without causing appreciable injury to shade trees. However, this usually requires closer regulation of dosage per tree than does use of conventional insecticides. When systemic chemicals are applied to the soil around tree roots, adsorption of the chemical on soil particles, degradation of the chemical, and capacity of roots for selective adsorption of the chemical reduce the possibility of phytotoxicity from errors in dosage. However, when chemicals are injected directly into trees, the only buffers between the

Figure 3. Distortion of young red pine seedlings by tordon (right). Healthy seedlings are on the left.

chemical and living tissues are layers of dead phloem and periderm. Hence, the chances for high dosages causing injury are greater. Norris (60) cited many examples of phytotoxicity of systemics injected into trees and no attempt will be made to review those here.

Antitranspirants. The antitranspirants (antidesiccants) are of two main types: 1) film antitranspirants which coat leaves and prevent water loss from plants (e.g., waxes, silicones, higher alcohols, plastics, latex, and resins), and 2) metabolic antitranspirants which chemically induce stomatal pores of leaves to close (e.g., abscisic acid (ABA), succinic acids, phenylmercuric acetate (PMA), sodium azide, and the herbicides karsil and atrazine).

Both film type and metabolic antitranspirants have been successfully used to prevent water loss by trees. Besides conserving water in the soil and in plants antitranspirants sometimes also reduce injury from insects, fungi, smog, and salt spray.

Film type antitranspirants reduced transpiration and desiccation injury of holly (63). Film antitranspirants also improved water balance in transplanted citrus trees and increased fruit production in transplanted olive and peach trees (15, 18). In California antitranspirant films applied to ornamental oleanders (*Nerium oleander*) along highways reduced transpiration by about 35% and delayed the need for irrigation by at least two weeks, thereby reducing maintenance cost appreciably (16). A film-forming antitranspirant sprayed on bing cherry trees 10 days before harvest improved the water balance of trees, resulting in an increase of 15% in the size of cherry fruits (14). Wax emulsions applied 3 weeks before harvest also increased the size and reduced shrivel of olive fruits (18).

Cracking of cherry fruits is a serious problem in areas where rains occur near the time of harvest. In some seasons crop losses of crack-susceptible cultivars have been over 50% and sometimes as high as 75%. Absorption of external water, the cause of cracking of cherry fruits, occurs through the entire fruit surface. Antitranspirant film applied to sweet cherry fruits reduced water uptake and decreased cracking of fruits of crack-susceptible cultivars (17).

The metabolic antitranspirant ABA closed stomata of *Acer saccharum*, *Fraxinus americana*, and reduced transpiration of Calamondin orange seedlings by as much as 60%, with some reduction apparent three weeks after application. No toxic effects were apparent (19).

In contrast to the foregoing reports, various investigators have noted that some antitranspirants induced leaf lesions, chlorosis and browning of leaves, leaf shedding, and tree mortality. Phytotoxicity varied with the antitranspirant used, its dosage, species to which applied, manner of application, and prevailing environmental conditions (20, 44, 47, 61, 77). Whereas some film antitranspirants reduced water loss of conifers by as much as 90% they also greatly lowered the rate of photosynthesis for many weeks. The reduction in both transpiration and photosynthesis was the result of the antitranspirant combining with natural waxes in the stomatal pores and forming plugs that prevented both outward diffusion of water from the leaf and inward diffusion of CO_2 into the leaf (20).

Phytotoxicity of metabolic antitranspirants varies with the compound used. As mentioned, ABA was an effective, non-toxic antitranspirant. However, succinic acids applied to *Pinus resinosa* trees injured the needles and suppressed bud development, with the result that shoot growth in the following year was reduced and some of the treated trees died (44).

Conclusions

Careful planning by arborists is needed to prevent possible short-term and long-term adverse effects of naturally occurring and applied environmental chemicals on shade trees.

Air pollutants. To alleviate the effects of air pollutants on shade trees arborists should work toward reducing pollution at the source. At the present time only a few countries require power plants to effectively control emission of air pollutants. Although some steps have been taken to require polluting industries to install scrubbers to lower the amounts of SO_2 released to the atmosphere, emission of other phytotoxic pollutants has not been effectively regulated (64).

Because air pollution will continue to be a serious problem in urban areas much more attention should be given by arborists to plant only those trees that exhibit high tolerance to the air pollutants present in a given area. Sometimes it will be important to give a higher priority to the pollution tolerance of a species or cultivar than to its aesthetic attributes.

Rankings of tolerance of trees to the major air pollutants are readily available (21, 46, 72, 79). Pollution tolerance not only varies widely among species but also within species. For example, clonal variation in tolerance has been confirmed for *Pinus sylvestris* (29), *Pinus strobus* (66), and *Populus* species (39). Such within-species differences in pollution tolerance usually are related to variations in size and number of stomata. However, variations among some plants in biochemical tolerance of pollutants may also contribute to the mechanism of pollution tolerance (42, 46).

Pollution tolerance of species or genetic materials may be ranked somewhat differently by various individuals. This is largely because the criteria for deriving the rankings, and experimental conditions under which they were obtained, have varied appreciably (21, 46). Nevertheless, arborists can use the available lists of pollution tolerance of shade trees to good advantage.

Arborists should also support greatly expanded research on producing pollution tolerant trees. Such trees can be obtained through selection of tolerant individuals, families, or populations; mating selected individuals; and mass producing tolerant varieties sexually or vegetatively (21). Among the methods used to verify pollution tolerance of trees selected in polluted areas are use of grafted clones, exposing attached or excised branches of trees to pollutants, and exposing seedlings in nursery beds or chambers to air pollutants (30). Research is also needed on selecting pollution tolerant trees and by selective breeding combining pollution tolerance with other desirable characteristics such as tolerance of disease, frost, and drought.

Additionally arborists should support needed research on the use of applied chemicals to prevent uptake of pollutants or detoxifying them. There is some evidence that calcium sprays can counteract the effects of fluorides on trees (62). Benomyl (Benlate) applied as a spray reduced oxidant injury to grapevines (38) and when applied as a soil drench decreased oxidant injury to azaleas (56). EDU(N-[2-(2-oxo-1-imidazolidinyl)ethyl]-N-phenylurea) applied as a spray or soil drench either reduced or prevented O_3-induced leaf necrosis and premature senescence of leaves of several species of shade trees (7). Some antitranspirants also prevented uptake of air pollutants.

Deicing salts. Salt injury to shade trees can be minimized by reducing the amount of salt applied around shade trees, and planting only salt tolerant species in areas likely to be affected by salt. For example, *Eleagnus angustifolia*, *Gleditsia triacanthos inermis*, *Quercus rubra*, *Q. alba*, *Robinia pseudoacacia*, *Aesculus hippocastanum*, *Pinus thunbergii*, *P. nigra*, *P. banksiana*, *Taxus* spp., *Picea glauca*, and *Picea pungens* are rated as salt tolerant species. By comparison, *Acer saccharum*, *Acer negundo*, *Fagus sylvatica*, F. grandifolia, *Carpinus caroliniana*, *Pinus resinosa*, *P. strobus*, *Abies balsamea*, and *Tsuga canadensis* are not (23, 24, 75).

If the leaves or soil have been affected by salt both washing of the foliage and leaching of the soil with large amounts of fresh water may be helpful. Alternatively, gypsum can be added to the soil so as to replace sodium with calcium (3). Trees showing salt injury can also be pruned, fertilized, and irrigated with fresh water (23).

Agricultural chemicals. The arborist should be ever mindful that chemicals that prevent or arrest disease will, at some dosage, be toxic to the host plant. Much injury from application of agricultural chemicals is the result of improper use, including overdosage, application to the wrong species or cultivar, and improper application.

Higher than recommended dosages of pesticides should be carefully avoided. Dosage recommendations are based on tree trunk diameter and do not take into account differences in tree vigor or leaf volume (60). Hence a specific dosage of a pesticide may have a different effect on several trees of the same stem diameter. Nevertheless, the arborist runs a serious risk of phytotoxicity if he increases the dosage over that given on the label.

Applying herbicides that might contribute to injury of non-target plants by spray drift should be avoided on windy days. If possible sprayers and spreaders used for applying herbicides (especially hormone-type herbicides) should not be used for applying other chemicals. If injury from persistent herbicides in the soil occurs, the soil can be detoxified by working activated charcoal into the soil (71). Application of fertilizers in the spring and periodic watering to stimulate root growth may also accelerate recovery from herbicide injury.

The use of soil sterilants around shade trees requires particular caution. Such herbicides usually control weeds effectively when applied to the soil surface. Some do not leach readily into the deeper soil layers and hence shade trees avoid uptake of such compounds through the roots (48). However, when mixed into the soil such herbicides can be very toxic, especially in tree nurseries. Persistent herbicides such as simazine that are applied to the soil surface may be mixed into the soil much later and the toxic residues may injure or kill trees (82). While some herbicides kill seedlings, others cause abnormal growth of cotyledons, primary needles, and secondary needles of conifer seedlings (69), leading to production of low-quality nursery stock or eventual death of seedlings (40).

The manner of application of pesticides is particularly important. Injury from Dexon (Lesan) was reported by a nurseryman who had sprayed the fungicide on the foliage. Yet this chemical is recommended only as a soil drench. Caution is also advised in combining adjuvants with fungicides. The waxy cuticle of leaves prevents many fungicides from entering the leaf interior. Hence fungicides operate as protectants on the leaf surface. However, some adjuvants increase penetration of leaves by fungicides, often with severe phototoxicity resulting. For example, Cyprex (dodine) when mixed with an adjuvant may injure trees (G. Worf, personal communication).

Weather conditions may increase or decrease toxicity of some pesticides. When properly applied such materials generally are effective and safe over a wide temperature range but they may be phytotoxic at very high or very low temperatures. When some fungicides are applied at temperatures above 90°F (33°C) leaves may be injured. At temperatures below freezing some fungicides break down and the decomposition products may then injure trees. Some pesticides maintained in solution on tree foliage when the air humidity is very high may break down and the decomposition products may cause injury. Hence, trees should be sprayed only when temperature extremes are not anticipated and when the biocides in solution will dry rather quickly (75).

Labels for some of the new pesticides have disclaimers, stating that not all species and varieties have been tested. Hence, before treating a large number of trees of a particular variety it is advisable to treat a few plants and observe the results before a full scale application is made. Similar precautions are advisable in use of antitranspirants (47).

Consultation with Dr. G. Worf and Dr. D. Mahr on the use of pesticides on shade trees is gratefully acknowledged.

Literature Cited

1. Andersen, J. L., R. J. Campana, A. L. Shigo, and W. C. Shortle. 1985. *Wound response of Ulmus americana. 1: Results of chemical injection in attempts to control Dutch elm disease.* J. Arboric. 11:137-142.
2. Ayers, J. C. and J. A. Barden. 1975. *Net photosynthesis and dark respiration of apple leaves as affected by pesticides.* J. Am. Soc. Hort. Sci. 100:24-28.
3. Ayoub, A. T. 1975. *Effect of some soil amendments on sodium uptake and translocation in dry beans (P. vulgaris L.) in relation to sodium toxicity.* J. Agric. Sci. 84:537-541.
4. Beckerson, D. W., and G. Hofstra. 1980. *Effects of sulfur dioxide and ozone, singly or in combination, on membrane permeability.* Can. J. Bot. 58:451-457.
5. Bonte, J. 1982. Effects of air pollutants on flowering and fruiting. P. 207-233. **In** M. H. Unsworth and D. P. Ormrod (eds.), Gaseous Air Pollutants and Plant Metabolism. Butterworth, London.
6. Bormann, F. H. and B. F. Graham. 1960. *Translocation of silvicides through root grafts.* J. For. 58:402-403.
7. Cathey, H. M. and H. E. Heggestad. 1982. *Ozone sensitivity of woody plants: Modification by ethelenediurea.* J. Am. Soc. Hort. Sci. 107:243-253.
8. Cayford, J. H. and R. M. Waldron. 1967. *Effect of captan on the germination of white spruce, jack, and red pine seed.* For. Chron. 43:381-384.
9. Constantinidou, H. A. and T. T. Kozlowski. 1979a. *Effects of sulfur dioxide and ozone on Ulmus americana seedlings. I. Visible injury and growth.* Can. J. Bot. 47:170-175.
10. Constantinidou, H. A. and T. T. Kozlowski. 1979b. *Effects of sulfur dioxide and ozone on Ulmus americana seedlings. II. Carbohydrates, proteins, and lipids.* Can. J. Bot. 57:176-184.
11. Constantinidou, H. A., T. T. Kozlowski, and K. Jensen. 1976. *Effects of sulfur dioxide on Pinus resinosa seedlings in the cotyledon stage.* J. Environ. Qual. 5:141-144.
12. Costonis, A. C. and W. A. Sinclair. 1972. *Susceptibility of healthy and ozone-injured needles of Pinus strobus to invasion by Lophodermium pinastri and Aureobasidium pullulans.* Eur. J. For. Path. 2:65-73.

13. Daines, R. H., R. J. Lukens, E. Brennan, and I. A. Leone. 1957. *Phytotoxicity of captan as influenced by formulation, environment, and plant factors.* Phytopathology 47:567-572.
14. Davenport, D. C., R. M. Hagan, and K. Uriu. 1972a. *Sizing cherry fruit with antitranspirant sprays.* Calif. Agr. 26:(8)9-10.
15. Davenport, D. C., P. E. Martin, and R. M. Hagan. 1972b. *Antitranspirants for conservation of leaf water potential of transplanted citrus trees.* HortScience 7:511-512.
16. Davenport, D. C., P. E. Mullin, and R. M. Hagan. 1973. *Effects of an antitranspirant on water use by highway oleander (Nerium oleander L.) plantings.* J. Amer. Soc. Hort. Sci. 98:421-425.
17. Davenport, D. C., K. Uriu, and R. M. Hagan. 1972c. *Antitranspirant film: Curtailing intake of external water by cherry fruit to reduce cracking.* HortScience 75:507-508.
18. Davenport, D. C., P. E. Martin, and K. Uriu. 1972d. *Antitranspirants increase size, reduce shrivel of olive fruit.* Calif. Agr. 26(7):6-8.
19. Davies, W. J. and T. T. Kozlowski. 1975. *Effect of applied abscisic acid and plant water stress on transpiration of woody angiosperms.* For Sci. 22:191-195.
20. Davies, W. J., T. T. Kozlowski, and K. J. Lee. 1974. *Stomatal characteristics of Pinus resinosa and Pinus strobus in relation to transpiration and antitranspirant efficiency.* Can. J. For. Res. 4:571-574.
21. Davis. D. D., and H. D. Gerhold. 1976. Selection of trees for tolerance to air pollutants. P. 61-66. **In** Better Trees for Metropolitan Landscapes (F. S. Santamour, H. D. Gerhold, and S. Little, eds.). U.S. Forest Service, General Tech. Rept. NE-22.
22. Denne, M. P. and L. D. Atkinson. 1973. *A phytotoxic effect of captan on the growth of conifer seedlings.* Forestry 46:49-53.
23. Dirr, M. A. 1976. *Selection of trees for tolerance to salt injury.* J. Arboric. 2:209-216.
24. Dirr, M. A. 1978. *Tolerance of seven woody ornamentals to soil-applied sodium chloride.* J. Arboric. 4:162-165.
25. Environmental Protection Agency. 1978a. Diagnosis of vegetation injury caused by air pollution. EPA 450/378005.
26. Environmental Protection Agency. 1978b. Research outlook. EPA-600/9-78-001.
27. Fenton, R. H. 1965. *Root grafts and translocation of 2,4,5-T in young sweet-gum stands.* J. For. 63:16-18.
28. Francis, B. A. and C. R. Curtis. 1979. *Effect of simulated saline cooling tower drift on tree foliage.* Phytopathology 69:349-353.
29. Genys, J. B. and H. E. Heggestad. 1978. *Susceptibility of different species, clones, and strains of pines to acute injury caused by ozone and sulfur dioxide.* Plant Disease Reporter 62:687-691.
30. Gerhold, H. D., E. H. Palpant, W. M. Chang, and M. E. Demeritt, Jr. 1972. *Tubing fumigation method for selection of pines resistant to air pollutants.* Mitt. Forstl. Bundes-Versuchsanst. 97:511-520.
31. Gibbs, J. N. and D. A. Burdekin. 1980. *De-icing salts and crown damage to London plane.* Arboric J. 6:227-237.
32. Hallgren, J. E. and K. Gezelius. 1982. *Effects of SO_2 on photosynthesis and ribulose bisphosphate carboxylase in pine tree seedlings.* Physiol. Plant 54:153-161.
33. Heath, R. L. 1980. *Initial events in injury to plants by air pollutants.* Ann. Rev. Plant Physiol. 31:395-431.
34. Holmes, F. W. 1961. *Salt injury to trees.* Phytopathology 51:712-718.
35. James, R. L., F. W. Cobb, Jr., P. R. Miller, and J. R. Parmeter, Jr. 1980. *Effects of oxidant air pollution on susceptibility of pine roots to Fomes annosus.* Phytopathology 70:560-563.
36. Keller, T. 1974. *The use of peroxidase activity for monitoring and mapping air pollution areas.* Eur. J. For. Path. 4:11-19.
37. Keller, T. 1983. Air pollutant deposition and effects on plants. P. 285-294. **In** B. Ulrich and J. Pankrath (eds.) Effects of Accumulation of Air Pollutants in Forest Ecosystems. Reide Publishing Co., Dodrech, Holland.
38. Kender, W. J., E. F. Taschenberg, and N. J. Shaulis. 1973. *Benomyl protection of grapevines from air pollution injury.* HortScience 8:396-398.
39. Kimmerer, T. W., and T. T. Kozlowski. 1981. *Stomatal conductance and sulfur uptake of five clones of Populus tremuloides exposed to sulfur dioxide.* Plant Physiol. 67:990-995.
40. Kozlowski, T. T. 1976. *Susceptibility of young tree seedlings to environmental stresses.* Am. Nurseryman 144:13,55-59.
41. Kozlowski, T. T. 1980a. *Impacts of air pollution on forest ecosystems.* BioScience 30:88-93.
42. Kozlowski, T. T. 1980b. *Responses of shade trees to pollution.* J. Arboric. 6:29-41.
43. Kozlowski, T. T. 1985. *Tree growth in response to environmental stresses.* J. Arboric. 11:97-111.
44. Kozlowski, T. T. and J. J. Clausen. 1970. *Effect of decenylsuccinic acid on needle moisture content and shoot growth of Pinus resinosa.* Can. J. Plant Sci. 50:355-356.
45. Kozlowski, T. T. and H. A. Constantinidou. 1986a. *Environmental pollution and tree growth. Part I. Sources and types of pollutants and plant responses.* For. Abstr. (in press).
46. Kozlowski, T. T., and H. A. Constantinidou. 1986b. *Environmental pollution and tree growth. Part II. Factors affecting responses to pollution and alleviation of pollution effects.* For. Abstr. (in press).
47. Kozlowski, T. T., and W. J. Davies. 1975. *Control of water balance in transplanted trees.* J. Arboric. 1:1-10.
48. Kozlowski, T. T., and J. H. Torrie. 1965. *Effect of soil incorporation of herbicides on seed germination and growth of pine seedlings.* Soil Sci. 100:139-146.
49. Kramer, P. J., and T. T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, New York.
50. Larsson, S., R. Oren, R. H. Waring, and J. W. Barnett. 1983. *Attacks of mountain pine beetle as related to tree vigor of ponderosa pine.* For. Sci. 29:395-402.
51. Last, F. T. 1982. *Effects of atmospheric sulphur compounds on natural and man-made terrestrial and aquatic ecosystems.* Agric. and Environ. 7:299-387.
52. Lincoln, D. R. and E. S. Rubin. 1980. *Air pollution emissions from increased industrial coal use in the northeastern United States.* J. Air Pollut. Contr. Assoc. 20:1310-1315.
53. Linzon, S. N. 1958. The influence of smelter fumes on the growth of white pine in the Sudbury region. Ontario Dept. Lands and Forests. Canada Dept. Agric. Publ. 1-45.
54. Linzon, S. N. 1966. *Damage to eastern white pine by sulfur dioxide, semi-mature tissue needle blight and ozone.* J. Air Pollut. Contr. Assoc. 16:140-144.
55. Lorenc-Plucinska, G. 1982. *Effects of sulphur dioxide on*

CO_2 exchange in SO_2-tolerant and SO_2-susceptible Scots pine seedlings. Photosynthetica 16:140-144.
56. Moyer, J. W., H. Cole, Jr., and N. L. Lacasse. 1974. *Suppression of naturally occurring oxidant injury on Azalea plants by drench or foliar spray treatments with benzimidazole or oxathin compounds.* Plant Disease Reporter 58:136-138.
57. Norby, R. J. and T. T. Kozlowski. 1981a. *Response of SO_2-fumigated Pinus resinosa seedlings to post fumigation temperature.* Can. J. Bot. 59:470-475.
58. Norby, R. J. and T. T. Kozlowski. 1981b. *Relative sensibility of three species of woody plants to SO_2 at high or low exposure temperature.* Oecologia 51:33-36.
59. Norby, R. J. and T. T. Kozlowski. 1982. *The role of stomata in sensitivity of Betula papyrifera Marsh. seedlings to SO_1 at different humidities.* Oecologia 53:34-39.
60. Norris, D. M. 1967. *Systemic insecticides in trees.* Ann. Rev. Entomol. 12:127-148.
61. Olofinboba, M. O., T. T. Kozlowski, and P. E. Marshall. 1974. *Effects of antitranspirants on distribution and utilization of photosynthate in Pinus resinosa seedlings.* Plant and Soil 40:619-635.
62. Ormrod, D. P. and N. O. Adedipe. 1974. *Protecting horticultural plants from atmospheric pollutants.* HortScience 9:108-111.
63. Pair, J. C. and S. M. Still. 1982. *Antitranspirant effects on leaf water potential and winter injury of holly.* J. Amer. Soc. Hort. Sci. 107:9-13.
64. Postel, S. 1984. Air pollution, acid rain, and the future of forests. Worldwatch Paper 58: Worldwatch Institute, Washington, D.C.
65. Renwick, J.A.A. and J. Potter. 1981. *Effects of sulfur dioxide on volatile terpene emission from balsam fir.* J. Air Pollut. Contr. Assoc. 31:65-66.
66. Roberts, B. R. 1976. *The response of field grown white pine seedlings to different sulphur dioxide environments.* Env. Pollution 11:175-180.
67. Rubin, S. 1981. *Air pollution constraints on increased coal use by industry.* J. Air Pollut. Contr. Assoc. 31:349-360.
68. Sasaki, S. and T. T. Kozlowski. 1967. *Effects of herbicides on carbon dioxide uptake of pine seedlings.* Can. J. Bot. 45:961-971.
69. Sasaki, S. and T. T. Kozlowski. 1968. *Effects of herbicides on seed germination and early seedling development of Pinus resinosa.* Bot. Gaz. 129:238-246.
70. Smith, E. M. 1975. *Tree stress from salts and herbicides.* J. Arboric. 1:201-205.
71. Smith, F. M. and T. A. Fretz. 1975. Chemical weed control in nursery and landscape plantings. Ohio Co-op. Ext. Serv. Bull. MM-297.
72. Smith, W. H. 1981. Air Pollution and Forests. Springer-Verlag, New York.
73. Sucoff, E. 1975. Effects of deicing salts on woody vegetation along Minnesota roads. Minn. Agr. Expt. Sta. Tech. Bull. 303.
74. Suwannapinunt, W. and T. T. Kozlowski. 1980. *Effect of SO_2 on transpiration, chlorophyll content, growth, and injury in young seedlings of woody angiosperms.* Can. J. For. Res. 10:78-81.
75. Tattar, T. A. 1978. Diseases of Shade Trees. Academic Press, New York.
76. Thompson, M. A. 1981. *Tree rings and air pollution. A case study of Pinus monophylla growing in east-central Nevada.* Environ. Pollut. (Series A) 26:251-256.
77. Waisel, Y., G. A. Borger, and T. T. Kozlowski. 1969. *Effects of phenylmercuric acetate on stomatal movement and transpiration of excised Betula papyrifera Marsh. leaves.* Plant Physiol. 44:685-690.
78. Weidensaul, T. C. and S. L. Darling. 1979. *Effects of ozone and sulfur dioxide on the host-pathogen relationship of Scotch pine and Scirrhia acicola.* Phytopathology 69:939-994.
79. Weinstein, L. H. 1977. *Fluoride and plant life.* J. Occupational Medicine 19:49-78.
80. Wentzel, K. F. and B. Ohnesorge. 1961. *Zum Auftreten von Schadinsekten bei Luftverunreinigung.* Forestarchiv 32:177-186.
81. Westing, A. H. 1969. *Plants and salt in the roadside environment.* Phytopathology 59:1174-1181.
82. Winget, C. H., T. T. Kozlowski, and J. E. Kuntz. 1963. *Effects of herbicides on red pine nursery stock.* Weeds 11:87-90.

Department of Forestry
University of Wisconsin
Madison, Wisconsin 53706