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RESPONSES OF SHADE TREES TO POLLUTION[1]

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The concern for effects of air pollution is not new. As early as 1306 the pollution of air in England by coal fumes was serious enough to prompt Edward I to appoint a commission to punish "with great fines and ransomes" those responsible for air pollution. The Royal concern with air pollution was even greater during the reign of Edward II, as shown by the record of a man being put to the torture for releasing a "pestilential odor" from burning of coal. The major pollutants at that time were sulfur dioxide and particulates.

What is different about the pollution problem now is that it is far more complex and involves a large array of polluting substances in the air, soil, and water. These pollutants include gases, particulates, and sometimes even agricultural chemicals. Arborists must be particularly concerned because the accumulation of pollutants is greatest in areas where there is the highest concentration of people and industrial activity. Urban America is a depository for some three-fifths of the pollutants in the air. These include sulfur dioxide (SO_2), ozone (O_3), fluorides, peroxyacyl nitrates (PAN), oxides of nitrogen, and various particulates, such as cement kiln dusts, soot, lead particles, magnesium oxide, iron oxide, foundry dusts, and sulfuric acid aerosols (Mudd and Kozlowski, 1975).

This paper will deal primarily with the problem of air pollution as it affects shade trees. It will also allude briefly to the consequences of excessive use of applied chemicals.

Types and Sources of Air Pollutants

Air pollutants are often classified as primary or secondary. Primary pollutants originate at the source in a toxic form. Examples are sulfur dioxide and hydrogen fluoride. Secondary pollutants develop as a result of interactions between pollutants that originate from a source. Examples are the photochemical oxidants, ozone and peroxyacyl nitrate, which are formed by sunlight acting on products of fuel combustion, especially nitrogen dioxide and hydrocarbons that are emitted by motor vehicles.

Industry, motor vehicles, and electric generating plants are the major sources of pollutants that injure plants (Table 1). The major component of pollution by motor vehicles is carbon monoxide, whereas the primary pollutants of industry, power generation, and space heating are sulfur oxides (Mudd and Kozlowski, 1975). Most air pollution injury to woody plants is traceable to sulfur dioxide and ozone. These two compounds cause more injury to plants than all other air pollutants combined. However, in the immediate vicinity of large point sources of pollution, such as aluminum plants and smelters, extensive damage is often caused by fluorides, dusts, and heavy metals, pollutants that are considered of minor importance in terms of the proportional damage they do throughout the country.

Table 1. Sources of general air pollutants and phytotoxic air pollutants[a]

Source	*All major pollutants*	*Phytotoxic pollutants*
	Percent	Percent
Transportation	60	28
Industry	18	30
Generation of electricity	14	26
Space heating	5	9
Refuse disposal	3	7

[a] From David and Gerhold (1976).

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[1] Presented at the 55th Annual Meeting of the International Society of Arboriculture in San Diego, California on August 13, 1979.

The major sources and trends of air pollution in the United States are shown in Figs. 1 and 2. Vigorous efforts are being made to decrease the emission of air pollutants at the source. Air quality standards have been legislated, primarily to safeguard the health of humans rather than to protect pollution-sensitive plants. Much effort has been exerted to minimize accumulation of air pollutants in urban areas by planning for sources of relatively clean energy, using scrubbers on stacks of new power plants, developing mass transportation systems, and moving industrial sites. Despite all of these very commendable efforts, the effects of air pollution on shade trees will regrettably be with us for a very long time indeed because increases in population and increasing use of technology will tend to prevent reduction of the amount of some of the most phytotoxic air pollutants. The Environmental Protection Agency (1978) has estimated that emission of carbon monoxide, hydrocarbons, and particles will decrease in the next decade but sulfur oxides and nitrogen oxides will increase appreciably (Fig. 2). Hence, nurserymen and arborists should realize that prospects for attaining a really clean atmosphere in the foreseeable future are unrealistic.

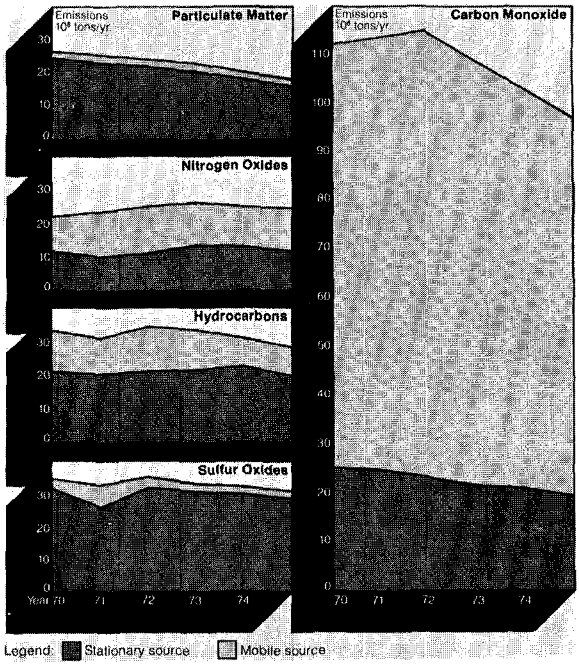

Figure 1. Air pollution emission trends. From Environmental Protection Agency (1978).

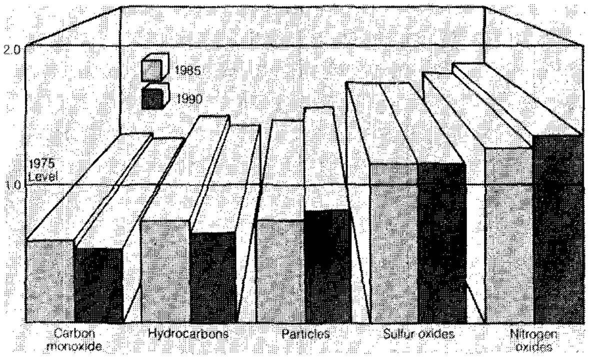

Figure 2. Estimates of emission of various air pollutants in 1985 and 1990. From Environmental Protection Agency (1978).

Effects of Air Pollution

Air pollution affects trees by injuring and killing them and by adversely affecting physiological processes so as to decrease growth without necessarily causing visible symptoms of injury. Conifers are generally injured more than broadleaved trees by air pollutants, but there are wide variations in pollution tolerance within both groups (Tables 2 and 3).

Injury. For the most part gaseous air pollutants injure trees through effects on leaves after being absorbed through stomatal pores. Hence the most obvious effects of air pollution are injuries to the foliage such as those shown in Figures 3 to 7. Visible pollution injury is classified as acute or chronic. Acute injury is severe and is traceable to rather sudden absorption of enough air pollutant within a few hours to kill tissues. During or soon after exposure, collapse of cells occurs with subsequent development of necrotic patterns. Chronic injury is caused by rapid absorption of an amount of pollutant that does not kill tissues or by absorption over a long period of time of sublethal amounts of air pollutants. Chronic injury is characterized by leaf yellowing which progresses slowly and causes early senescence of leaves. In some instances chronic injury is associated with necrotic markings.

Sulfur dioxide injury to tree leaves. U.S. Dept. of Agriculture photos.

Fig. 3. Poplar.

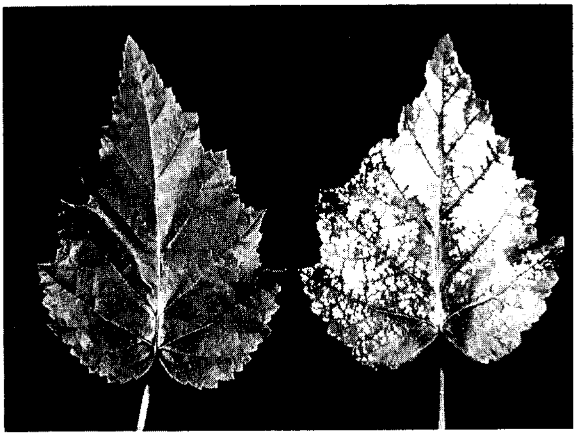

Fig. 4. Birch

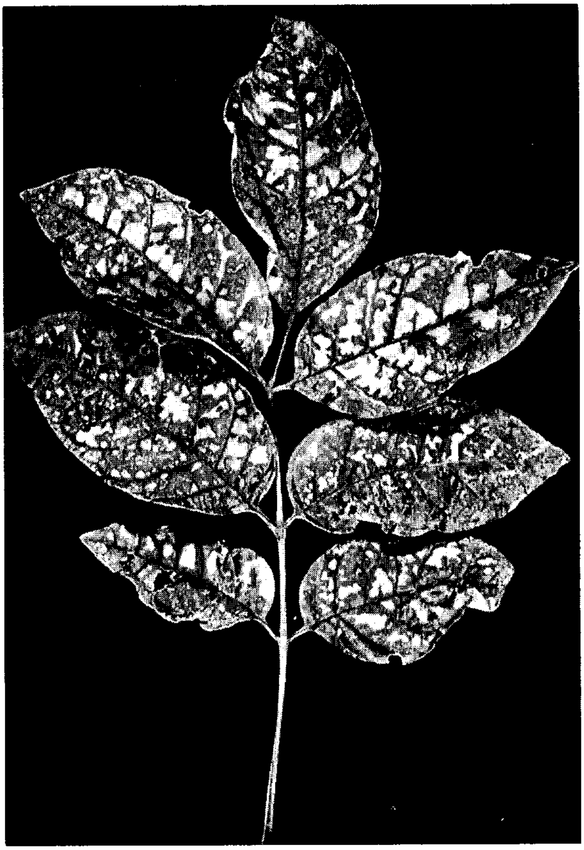

Fig. 5. Ash.

Fig. 6. Maple.

Symptoms of pollution injury vary with the polluting substance. Sulfur dioxide injury on broadleaved trees is characterized by areas of injured leaf tissue located between the healthy tissue and the veins (Figs. 3-6). Tissues adjacent to veins remain alive. Ozone symptoms appear as flecks or stipples of dead tissues, usually only on the upper leaf surface (Fig. 7). With severe ozone injury the flecks coalesce into larger lesions that are visible on both leaf surfaces. Hydrogen fluoride causes distinct marginal necrosis of leaves of broadleaved trees.

In conifers large doses of sulfur dioxide cause brown tipburn of needles, with the color change moving downward as fumigation continues. Chronic injury is expressed by chlorosis, especially in older needles which often are shed prematurely. Acute ozone injury is expressed in discoloration of needle tips or whole needles. Eventually all except the current-year needles may be shed, giving the branches a tufted appearance. Mild ozone injury, seen only shortly after fumigation, is expressed in chlorotic mottling of needles. In the field where conifers are exposed to more than one pollutant it often is very difficult to ascertain which pollutant is exerting the greatest effect. Symptoms on conifers are not distinct for any one pollutant. Several pollutants, including sulfur dioxide, ozone, and fluoride cause tipburn depending on the dosage and species of conifer. Tipburn of conifers is also caused by some herbicides, deicing salts, and excess fer-

Table 2. Relative susceptibility of trees to sulfur dioxide.[a]

Sensitive	*Intermediate*	*Tolerant*
Acer negundo var. interius	Abies balsamea	Abies amabilis
Amelanchier alnifolia	Abies grandis	Abies concolor
Betula alleghaniensis	Acer glabrum	Acer platanoides
Betula papyrifera	Acer negundo	Acer saccharinum
Betula pendula	Acer rubrum	Acer saccharum
Betula populifolia	Alnus tenuifolia	
		Crataegus douglasii
Fraxinus pennsylvanica	Betula occidentalis	Ginkgo biloba
Larix occidentalis	Picea engelmannii	Juniperus occidentalis
Pinus banksiana	Picea glauca	Juniperus osteosperma
Pinus resinosa	Pinus contorta	Juniperus scopulorum
Pinus strobus	Pinus monticola	
Populus grandidentata	Pinus nigra	Picea pungens
	Pinus ponderosa	Pinus edulis
Populus nigra 'Italica'		Pinus flexilis
Populus tremuloides	Populus angustifolia	Platanus × acerifolia
Rhus typhina	Populus balsamifera	Populus × canadensis
Salix nigra	Populus deltoides	
Sorbus sitchensis	Populus trichocarpa	Quercus gambelii
Ulmus parvifolia	Prunus armeniaca	Quercus palustris
	Prunus virginiana	Quercus rubra
	Pseudotsuga menziesii	Rhus glabra
		Thuja occidentalis
	Quercus alba	Thuja plicata
	Sorbus aucuparia	Tilia cordata
	Syringa vulgaris	
	Tilia americana	
	Tsuga heterophylla	
	Ulmus americana	

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[a] From David and Gerhold (1976).

tilizers. In fact tipburn of conifers is common and to pinpoint the causal agent may require a process of elimination of various causal agents, comparison with symptoms on other plants, and making a chemical analysis of the needles.

The adverse effects of air pollution on trees are perhaps most dramatically demonstrated by responses of forest ecosystems at various distances from point sources of heavy pollution, such as smelters, refineries, and power

Table 3. Relative susceptibility of trees to ozone.[a]

Sensitive	Intermediate	Tolerant
Ailanthus altissima	Acer negundo	Abies balsamea
Amelanchier alnifolia	Cercis canadensis	Abies concolor
		Acer grandidentatum
Fraxinus americana	Larix leptolepis	Acer platanoides
Fraxinus pennsylvanica	Libocedrus decurrens	Acer rubrum
		Acer saccharum
Gleditsia triacanthos	Liquidambar styraciflua	
Juglans nigra	Pinus attenuata	Betula pendula
		Cornus florida
Larix decidua	Pinus contorta	Fagus sylvatica
Liriodendron tulipifera	Pinus echinata	Ilex opaca
		Juglans nigra
Pinus banksiana	Pinus elliottii	Juniperus occidentalis
Pinus coulteri	Pinus lambertiana	
Pinus jeffreyi	Pinus rigida	Nyssa sylvatica
Pinus nigra	Pinus strobus	Persea americana
Pinus ponderosa	Pinus sylvestris	Picea abies
Pinus radiata	Pinus torreyana	Picea glauca
Pinus taeda		Picea pungens
Pinus virginiana	Quercus coccinea	
	Quercus palustris	Pinus resinosa
Platanus occidentalis	Quercus velutina	Pinus sabiniana
Popolus maximowiczii × trichocarpa		Pesudotsuga menziesii
	Syringa vulgaris	Pyrus communis
Populus tremuloides		Quercus imbricaria
	Ulmus parvifolia	Quercus macrocarpa
Quercus alba		Quercus robur
Quercus gambelii		Quercus rubra
Sorbus aucuparia		Robinia pseudoacacia
Syringa × chinensis		Sequoia sempervirens
		Sequoiadendron giganteum
		Thuja occidentalis
		Tilia americana
		Tilia cordata
		Tsuga canadensis

[a] From David and Gerhold (1976).

generating plants. Trees are eliminated first, followed in order by lower shrubs, herbs, mosses, and lichens (Woodwell, 1970).

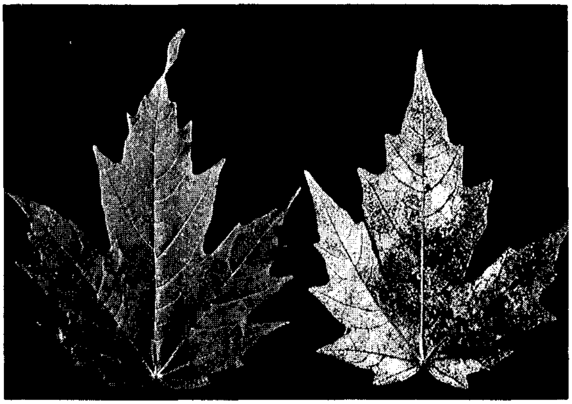

Figure 7. Ozone injury to maple leaf. U.S. Dept. of Agriculture photo.

Miller and McBride (1975) presented a comprehensive review of effects of pollutants from industrial sources in North America and Europe. They described injury to forest ecosystems at various distances from sources of emission. Symptoms included chlorosis, necrotic lesions on leaves, leaf abscission, twisting of needles, growth retardation, dieback of branches, and death of trees. Trees were affected for up to 20 miles by a copper smelter at Anaconda, Montana; for 30 miles by an iron sintering plant near Wawa, Ontario; and for 52 miles by a smelter at Trail, British Columbia. Other effects of air pollution on forest ecosystems included lowering of soil pH, reduction in number of plants of the understory and herb layer, and soil erosion leading to windthrow of some trees. Miller and McBride (1975) also described severe damage to ponderosa pine trees by photochemical oxidants transported from urban centers of coastal California to inland valleys and across forested mountains. Symptoms included chlorosis, progressive reduction in numbers of all except current-year needles, reduced growth of the remaining needles, and deterioration of roots. Tree mortality, usually caused by attacks of Dendroctonus beetles on pines weakened by ozone, approached 10% over a 4-year period.

It should not be assumed that all injury to trees occurs close to the source of pollution. There is growing concern with the fact that atmospheric pollutants are dispersed by wind and adversely affect trees very far from the source of emission. Oxidants formed over the Los Angeles basin injure pines in the San Bernardino mountains, 60 to 70 miles from the city center as the polluted air mass moves eastward. Similar injury to ponderosa pine and other tree species has been found in the lower-elevation forests of the southern Sierra Nevada mountain range of California (Williams *et al.*, 1977).

There is considerable evidence that pollution from midwestern states moves eastward with westerly winds and augments the pollution generated in eastern states. Recent studies also show that the rains in relatively pollution-free areas may be very acid. Rain formed in an atmosphere that is free of pollution would be expected to have a pH of about 5.8. However, some rains in New Hampshire, hundreds of miles from major pollution sources, had pH values as low as 3.0. Such "acid rains" developed as a result of release of pollutants into the atmosphere following burning of fossil fuels.

It has been estimated that more than three fourths of the sulfur in rain that falls in Norway and Sweden originates in the industrialized parts of England and central Europe (Braekke, 1976), further emphasizing long-distance transport of pollutants. We do not as yet have much good data on the harmful effects of acid rains on growth of trees in the United States but data for Sweden show that acid rains decrease growth of forest trees. Simulated rain acidified with sulfuric acid has been shown to injure leaves, accelerate leaching of nutrients from leaves, and increase erosion of leaf waxes. Much more research is needed on identifying the specific effects of acid rain on shade trees.

There is a great deal of interest in establishing threshold concentrations of individual pollutants that will injure different species of plants. Such values are difficult to establish because plant responses to a given concentration of pollutant are appreciably modified by a variety of factors such as duration of exposure, age of plants, age of leaf, and prevailing environmental conditions.

The younger, fully expanded leaves and those near full expansion are most sensitive to sulfur dioxide; old leaves are less sensitive, and small expanding leaves are least sensitive. Young trees are much more susceptible than old trees to a given dosage (concentration × duration of exposure) of an air pollutant. Other experiments showed that leaves of 4-month-old American elm seedlings were injured within a day by mixtures of sulfur dioxide and ozone (2 ppm sulfur dioxide and 0.9 ppm ozone for 5 hours, followed by sulfur dioxide for one hour) (Constantinidou and Kozlowski, 1979a).

Seedlings in the cotyledon stage of development are especially sensitive to air pollutants. When red pine seedlings in the cotyledon stage were fumigated with 4 concentrations of sulfur dioxide (0.5, 1, 3, or 4 ppm) at 4 exposure times (15, 30, 60, or 120 min.), the harmful effects were evident early. The fumigations caused chlorophyll breakdown, inhibited expansion of primary needles and dry weight increase of seedlings, and caused death of needle tips. The sensitivity of these very young seedlings to sulfur dioxide was emphasized by chlorosis following exposure to sulfur dioxide for only 15 minutes (Constantinidou *et al.,* 1976).

In general, environmental conditions that favor growth of trees tend to increase their sensitivity to air pollutants. The critical dosages of pollutants that injure various tree species and cultivars are appreciably modified by light intensity, water supply, relative humidity, and temperature, factors that influence opening and closing of stomatal pores. Leaves absorb more pollutants and are injured more at high light intensities (open stomata) than at low light intensities (stomata more closed). Moisture stress before or during fumigation reduces injury because it causes closure of stomatal pores, thereby inhibiting absorption of gaseous pollutants by leaves (Noland and Kozlowski, 1979).

Growth. Several investigators have shown that both vegetative and reproductive growth of trees is inhibited by exposure to pollutants at dosages below the threshold for inducing visible injury. For example, Pollenschuetz (1970) found that growth of several species of forest trees was reduced by exposure to sulfur dioxide before any visible injury symptoms developed. Similarly, Phillips *et al.* (1977a, 1977b) reported that growth of loblolly pine and eastern white pine trees was appreciably reduced by sulfur dioxide. "Chlorotic dwarf" or stunting of eastern white pine trees has been traced to effects of sulfur dioxide and ozone emitted at low concentrations for long periods of time (Dochinger and Heck, 1969). Houston and Dochinger (1977) noted reduction in seed production by red and white pine trees exposed to ambient levels of sulfur dioxide. There was no evidence of visible injury. In California ozone greatly reduced yields of citrus fruit even when leaves of ozonated trees were free of visible injury (Heggestad *et al.,* 1972). Treshow *et al.* (1967) found that cambial growth of Douglas-fir trees was reduced by about half near a source of atmospheric fluorides. The reduction in growth occurred even when there was no evidence of visible injury.

Physiological Processes. Reduction in growth of trees following exposure to air pollutants reflects adverse effects on several physiological processes including chlorophyll synthesis, photosynthesis, and enzymatic activity. Particular interest has been shown in the inhibitory effects of air pollution on photosynthesis as a prelude to reducing growth. Reduction in photosynthesis would be expected when tissues are injured or leaves are shed, but the rate often is reduced long before visible injury or growth inhibition occur. For example, photosynthesis of eastern white pine and loblolly pine seedlings was reduced by ozone at concentrations much too low to induce needle injury (Barnes, 1972). Ozone at 0.15 ppm for 30 days reduced photosynthesis of ponderosa pine by 10%; 0.45 ppm ozone reduced it by 85% (Miller *et al.,* 1969). Reductions in photosynthesis were accompanied by decreases in sugars in needles. Some studies show that photosynthesis may be reduced by extremely low concentrations of ozone. For example, photosynthesis of lime seedlings was reduced within 4 to 5 minutes after fumigation with 60 parts per hundred million (pphm) of ozone (Taylor *et al.,* 1961). Significant inhibition of photosynthesis of eastern white pine and loblolly pine seedlings was recorded following exposure to as little at 10 pphm of ozone for 10 minutes (Wilkinson and Barnes, 1973). Sometimes the inhibition of photosynthesis by air pollutants reflects the induction of stomatal closure by the polluting substance.

Air pollutants affect plant metabolism very rapidly. Our experiments showed, for example, that exposure of 4-month-old American elm seedlings to sulfur dioxide (2 ppm for 6 hours), to ozone (0.9 ppm for 5 hours), or to sulfur dioxide-ozone mixtures (2 ppm sulfur dioxide and 0.9 ppm ozone for 5 hours, followed by sulfur dioxide for one hour) led to a rapid reduction of carbohydrates and proteins in leaves, stems, and roots (Table 4). The effects of a combination of sulfur dioxide and ozone were much more severe than those of either pollutant alone. Much evidence indicates that growth of trees is reduced by air pollutants because of lowered availability of metabolites. Usually decrease in growth does not occur until considerable time after metabolism of leaves has been inhibited by pollutants. In our experiments with elm seedlings, decreases in carbohydrates and proteins were detected within a day after fumigation with pollutants; reduction in leaf expansion did not occur until a week later; and reduction in the rate of dry weight increase of stems and roots was not evident until 5 weeks after fumigation (Constatinidou and Kozlowski, 1979a, 1979b).

Reduction of Pollution Damage

There are several possible approaches to alleviation of the pollution problem. These include reducing the amount of pollution at the source, planting only trees that are already known to be resistant to pollution, using chemicals to alleviate pollution effects, and selecting and breeding pollution-resistant varieties.

Use of Pollution-Resistant Trees. Recognizing that pollution is here to stay, perhaps the best way of dealing with the problem is to select trees known to be resistant to pollution. This is not always a simple matter, however, and should be done with caution. A number of published lists of resistance of different species to individual air pollutants are available but these often have some limitations. The ranking of species often depends on the criteria that are used for ranking, with the same species sometimes rated differently by various individuals.

The ranking of species for pollution resistance may depend on physiological responses, leaf injury, or change in species composition. Forest trees and fruit trees sometimes are ranked on the

Table 4. Effects of sulfur dioxide, ozone, and sulfur dioxide mixtures on carbohydrates, proteins, and lipids of actively growing and quiescent American elm seedlings 24 hours and 1 week after fumigation. Data are given as % of value for unfumigated control seedlings.[a]

	Sulfur dioxide		*Ozone*		*Sulfur dioxide-ozone mixture*	
	24 h	*Week 1*	*24 h*	*Week 1*	*24 h*	*Week 1*
Carbohydrates						
Active	66	77	78	80	63	69
Quiescent	71	73	78	81	50	49
Proteins						
Active	67	77	79	81	65	63
Quiescent	74	70	85	80	50	55
Lipids						
Active	98	96	96	95	96	95
Quiescent	95	90	96	91	92	83

[a] From Constantinidou and Kozlowski (1979b).

basis of wood production or fruit yield. Trees used as ornamentals and Christmas trees are generally ranked on leaf discoloration. Most rankings, however, are based on the degree of leaf injury that is caused by a polluting substance.

A major problem with rankings of pollution resistance of tree species is that much variation in resistance has been found for different clones and cultivars of the same species. Another practical limitation of lists of resistance to air pollutants is that they may have been derived from different plant growing situations such as field observations of injury to native trees, to trees transplanted into an area, to trees exposed to a pollutant in a chamber, or to trees exposed to a pollutant in the field. This can lead to different rankings. For example, field observations near a source of heavy pollution may indicate the susceptibility of a tolerant population of trees because the susceptible individuals or species were eliminated early.

Despite the limitations of listing of variations among species in resistance to air pollutants, the arborist very often can make good use of them. Rankings of species at the extremes (very sensitive or very tolerant to a pollutant) are generally more useful than those for species in an intermediate class. As Davis and Gerhold (1976) emphasized, species found to be very tolerant or very sensitive when exposed to a pollutant in a chamber usually also are tolerant or sensitive, respectively, to the same air pollutant in the field. By comparison, sensitivity of species listed as intermediate in pollution tolerance may vary widely among clones and cultivars as well as with environmental conditions.

Chemicals. Another approach to coping with the air pollution problem is to treat leaves with chemicals that will either prevent uptake of a pollutant or detoxify it. For example, calcium sprays have been used on fruit trees to counteract the effects of fluorides. This technique has had only limited success because of its high cost and the undesirable effects of spray residues.

Developing Pollution-Resistant Varieties. Perhaps the best long-term solution to the pollution problem is to select and breed trees for resistance to pollution. Such a course is enormously important and nurserymen and arborists will need to work closely with geneticists and tree breeders in order to develop resistant varieties for different parts of the country. Much expanded research and enthusiastic support by organized arborists are urgently needed.

In approaching the problem of developing pollution resistant trees two very important questions need to be considered: 1) what are the specific mechanisms of pollution resistance between and within species? and 2) what procedures should tree breeders follow to develop pollution resistant trees?

Pollution Resistance Mechanisms. In the long term success in developing pollution resistant shade trees will depend on a clear understanding of the specific mechanisms of resistance. Pollution resistance in different trees may be the result of: 1) avoidance of uptake of pollutants, 2) biochemical tolerance (resistance to the toxic effect), 3) incorporation of pollutants into less toxic substances, and 4) dilution of pollutants by their rapid redistribution within a tree.

Variations in avoidance of uptake of pollutants generally are associated with differences in stomatal characteristics. We found, for example, that leaves of white ash seedlings (with large stomata) absorbed more sulfur dioxide than leaves of sugar maple (with small stomata) (Jensen and Kozlowski, 1975). Braun (1977a) found that certain pollution-resistant clones of Norway spruce took up less sulfur dioxide than susceptible clones, and stomata of the former were more sensitive to environmental stresses.

There is also considerable evidence that biochemical tolerance of pollutants is largely responsible for the pollution resistance of certain trees. For example, some pollution-resistant Norway spruce clones fixed more sulfur in organic fractions following fumigation with sulfur dioxide than susceptible clones did (Braun, 1977b, 1977c). Roberts (1976) reported that more sulfur dioxide was absorbed by grafted clones of sulfur dioxide-resistant eastern white pine trees than by grafted clones of susceptible trees, suggesting the importance of biochemical differences in tolerance of sulfur dioxide rather than in avoidance of uptake of sulfur dioxide.

Methods of Selection and Breeding. Pollution resistant shade trees can be obtained by selecting resistant individuals, families, or populations; mating selected individuals; and mass producing resistant varieties either sexually or by vegetative means. Berry (1973) described clones of eastern white pine that were selected for tolerance and susceptibility to sulfur dioxide, ozone, and fluorides. The selections were used as foundation stock for a breeding program to produce progeny more tolerant to each pollutant. Because the upper limit of genetic control is rather high in some species, selection and vegetative propagation often are very effective (Smith and Dochinger, 1975).

Information on genetic variation in pollution resistance has accumulated largely from controlled experiments in fumigation chambers and from comparisons of plants in the field that were exposed to uncontrolled fumigations. Within-species variation of individual plants has been confirmed in red maple, Norway spruce, red pine, white pine, ponderosa pine, and Douglas-fir. Clonal variations in pollution resistance of poplars are particularly well known (Karnosky, 1976, 1977).

Several methods have been used to verify the pollution resistance of trees selected in polluted areas. These include use of grafted clones, exposing attached or exised branches to various pollutants, and exposing large numbers of seedlings in nursery beds or chambers to pollutants (Gerhold *et al.*, 1972). Some investigators have used indirect methods of selection by seeking anatomical characteristics that are associated with pollution resistance. For example, small stomata and low stomatal frequency have been shown to inhibit entrance of pollutants into leaves (Jensen and Kozlowski, 1975).

Gerhold (1975) posed some thoughtful procedural questions on how to go about developing pollution-resistant trees. He suggested that researchers in different regions should attempt to answer the following questions:

1. *Which of the commercially available species and cultivars should be recommended for planting in polluted areas?* Answering this question will involve classifying specific planting sites on the basis of phytotoxic risks and ranking many species, clones, and cultivars on the basis of their resistance to specified levels of pollutants. Observations of pollution resistance of trees in urban areas should be coordinated with fumigation experiments.
2. *In which species or genera should genetic improvement projects be initiated?* Among the species deserving attention are those sensitive to pollutants (for example, eastern white pine), those resistant to one or more pollutants and which could be improved in other desirable characteristics (for example, red oak), and those whose pollution resistance is not adequately understood (for example, sugar maple, basswood, and many others). Emphasis in producing pollution-resistant varieties should initially involve a few conifers and deciduous genera. Examples are species of pine, spruce, maple, ash, and basswood.
3. *Which methods are best in selecting for pollution resistance?* Important subsidiary questions include: Can leaf injuries be used as criteria for selection? Can resistant plants be selected at an early age? If so, what is the best age? How is pollution resistance influenced by environmental factors such as light intensity, water supply, air, humidity, and temperature, etc.?
4. *What is the best method for seeking resistant genotypes?*
5. *Which breeding methods and mating designs are best for creating improved varieties?* This question should be closely integrated with question 4.
6. *Which propagation methods are best for mass producing new varieties?* A decision about whether to mass produce pollution resistant trees by sexual or by vegetative propagation should be made early.

Answers to these questions will not necessarily be the same for all urban areas. Selecting pollution-resistant trees and combining air pollution resistance with other desirable traits, such as disease resistance, frost resistance, drought resistance, and tree form are possible by selective breeding. Hence, excellent opportunities exist for nurserymen and arborists to identify their regional requirements to geneticists and tree breeders and to support research dedicated to increasing pollution resistance of shade trees. The improved trees from such research will enhance our homes and cities for a very long time.

Applied Chemicals

Shade trees most often are the beneficiaries of various applied chemicals. Sometimes, however, arborists have found that excessive use of chemicals such as road salts, herbicides, insecticides, fungicides, and antitranspirants not only causes direct injury to trees but also adversely affects physiological processes to such an extent that growth of trees is reduced. The harmful effects of excessive use of certain chemicals may be variously caused by blocking of stomatal pores, reducing the light intensity reaching the leaves, and inducing abnormal metabolism (Kramer and Kozlowski, 1979).

For a good review of the effects of roadside salts on shade trees the reader is referred to the recent paper by Hofstra *et al.* (1979). A number of herbicides, when properly applied, have been very useful in weed control in nurseries, fire and utility line maintenance, and roadside maintenance. However, when improperly used, certain herbicides can be dangerous. Herbicide toxicity takes many forms and includes arrested growth, injury, and killing of trees (Kramer and Kozlowski 1979). It should be remembered that some herbicides are readily translocated from one tree to another through root grafts. Injections of ammonium sulfamate to kill individual trees often kill several trees by "backflash" (translocation of the herbicide through root grafts to adjacent trees).

Herbicides are particularly toxic to seedlings in the cotyledon stage and cause curling, shrivelling, and fusion of cotyledons, as well as chlorosis, distortion, and growth inhibition of cotyledons and foliage leaves. The harmful effects of herbicides vary greatly with the chemical used; the rate and method of application; time of year; tree species and variety; age of trees; soil type; and weather. Persistence of certain herbicides and their accumulation in nursery beds often pose serious problems. Some herbicides, such as the triazines, may persist for several years in soils. However, the longevity of different herbicides in soils varies greatly.

Much interest has been shown in the inhibitory effects of agricultural chemicals on photosynthesis as a prelude to reducing tree growth. Many herbicides decrease photosynthesis, with the inhibitory effect varying greatly not only among structurally different chemicals but also among structurally related ones. For example, photosynthesis was depressed much more by the triazine herbicides, atrazine and simazine, than by the closely related propazine and ipazine (Sasaki and Kozlowski, 1968).

Oil-based insecticides decrease photosynthesis for a long time. Ayers and Barden (1975) reported that 10 out of 33 insecticides tested appreciably reduced photosynthesis of young apple trees. Similarly various fungicides, particularly those containing sulfur, reduce photosynthesis. Lime-sulfur, for example, reduced photosynthesis of apple treesby about half (Heinicke, 1937).

Film-type antitranspirants, used to control water loss from leaves, are more permeable to water vapor than to CO_2. Therefore, thorough coverage of leaves with such compounds may be expected to reduce CO_2 absorption more than water loss by transpiration (Kramer and Kozlowski, 1979). Our experiments showed that single applications of a variety of antitranspirants reduced photosynthesis for many weeks in both pines and broadleaved trees. Sometimes the rate of photosynthesis was reduced by up to 90% when the antitranspirants combined with leaf waxes in stomatal pores, thereby plugging them. Such plugging was followed by chlorosis, leaf injury, and growth reduction (Davies and Kozlowski, 1974). Another set of experiments showed that carbohydrate metabolism was greatly altered in red pine trees that had been treated with film-type antitranspirants (Olofinboba *et al.,* 1974).

Literature Cîted

Ayers, J.C. and V.A. Barden. 1975. *Net photosynthesis and dark respiration of apple leaves as affected by pesticides.* J. Amer. Soc. Hort. Sci. 100: 24-28.

Barnes, R.L. 1972. *Effects of chronic exposure to ozone on photosynthesis and respiration of pines.* Environ. Pollut.

3:133-138.

Berry, C.R. 1973. *The differential sensitivity of eastern white pine to three types of air pollution.* Can. J. Forest Res. 3: 543-547.

Braekke, F.H. 1976. Impact of acid precitation on forest and freshwater ecosystems in Norway. Res. Rept. FR6/76 Forest Res. Inst. As, Norway.

Braun, G. 1977a. *Causes and criteria of resistance to air pollution in Norway spruce. II. Reflexive resistance.* Eur.J. For. Path. 7: 129-152.

Braun, G. 1977b. *Causes and criteria of resistance to air pollution in Norway spruce. II. Tolerance of toxic material ("internal" resistance).* Eur. J. For. Path. 7: 236-249.

Braun, G. 1977c. *Causes of resistance against air pollution in Norway spruce and conclusions in respect of resistance breeding.* Forstwiss. Centralbl.96: 62-66.

Constantinidou, H.A., T.T. Kozlowski and K. Hensen. 1976. *Effect of sulfur dioxide on Pinus resinosa seedlings in the cotyledon stage.* J. Environ. Qual. 5: 141-144.

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. 57: 170-175.

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.

Davis, D.D. and H.D. Gerhold. 1976. Selection of trees for tolerance of air pollutants. **In** Better Trees for Metropolitan Landscapes (F.S. Santamour, H.D. Gerhold, and S. Little, eds.), pp. 61-66. U.S. Forst Service, General Tech. Rept. NE-22.

Davies, W.J. and T.T. Kozlowski. 1974. *Short- and long-term effects of antitranspirants on water relations and photosynthesis of woody plants.* J. Amer. Soc. Hort. Sci. 99: 297-304.

Dochinger, L.S. and W.W. Heck. 1969. *An ozone-sulfur dioxide synergism produces symptoms of chlorotic dwarf disease of eastern white pine.* Phytopathology 59: 399.

Environmental Protection Agency. 1978. Research Outlook. 1978. EPA 600/9 78-001. Washington, D.C.

Gerhold, H.D. 1975. Resistant varieties. **In** Air Pollution and Metropolitan Woody Vegetation. (W.H. Smith and L.S. Dochinger, eds.). Pinchot Inst. Consortium for Environmental Forestry Studies. pp. 45-48.

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-Versuchanst. 97: 511-520.

Heggestad, H.E., F.S. Santamour, Jr., and L. Bernstein. 1972. Plants that will withstand pollution and reduce it. pp. 16-22. **In** Landscape for Living, Yearbook of Agriculture, U.S.D.A., Washington, D.C.

Heinicke, A.J. 1937. *How lime surfur affects the photosynthesis of an entire ten year old apple tree.* Proc. Amer. Soc. Hort. Sci. 35: 256-259.

Hofstra, G., R. Hall, and G.P. Lumis. 1979. *Studies of salt-induced damage to roadside plants in Ontario.* J. Arboriculture 5: 25-31.

Houston, D.B. and L.S. Dochinger. 1977. *Effects of ambient air pollution on cone, seed and pollen characteristics in eastern white and red pines.* Environ. Pollut. 12: 1-5.

Jensen, K.F. and T.T. Kozlowski. 1975. *Absorption and transporation of sulfur dioxide by seedlings of four forest tree species.* J. Environ. Qual. 4: 379-381.

Karnosky, D.F. 1976. *Threshold levels for foliar injury to Populus tremuloides by sulfur dioxide and ozone.* Can. J. For. Res. 6: 166-169.

Karnosky, D.F. 1977. *Evidence for genetic control of response to sulfur dioxide and ozone in Populus tremuloides.* Can. J. For. Res. 6: 437-440.

Kozlowski, T.T. and J.B. Mudd. 1975. Introduction. **In** Responses of Plants to Air Pollution (J.B. Mudd and T.T. Kozlowski, eds.). pp. 1-8. Academic Press, New York.

Kramer, P.J. and T.T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, New York.

Miller, P.R. and J.R. McBride. 1975. Effects of air pollution in forests. **In** Responses of Plants to Air Pollution (J.B. Mudd and T.T. Kozlowski, eds.), pp. 196-235. Academic Press, New York.

Miller, P.R., J.R. Parmeter, Jr., B.H. Flick, and C.W. Martinez. 1969. *Ozone dosage response of ponderosa pine seedlings.* J. Air Pollut. Cont. Assoc. 19: 435-438.

Mudd, J.B. and T.T. Kozlowski, eds. 1975. Responses of Plants to Air Pollution. Academic Press, New York.

Noland, T.L. and T.T. Kozlowski. 1979. *Effect of SO_2 on stomatal aperture and sulfur uptake of woody angiosperm seedlings.* Can. J. For. Res. 9: 57-62.

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.

Phillips, S.O., J.M. Skelly, and H.E. Burkhart. 1977a. *Growth fluctuations of loblolly pine to periodic air pollution levels. Interaction of rainfall and age.* Phytopathology 67: 716-720.

Phillips, S.O., J.M. Skelly, and H.E. Burkhart. 1977b. *Eastern white pine exhibits growth retardation by fluctuating air pollution levels: Interaction of rainfall, age, and symptom expression.* Phytopathology 67: 721-725.

Pollenscheutz, J. 1970. Observations about the susceptibility of various kinds of trees with respect to emission of SO_2, HF and magnetic dust. pp. 371-377. **In** Proc. First European Congr. on Influences of Air Pollution on Plants and Animals. Wageningen, The Netherlands.

Roberts, B.R. 1976. The response of field grown white pine seedlings to different sulphur dioxide environments. Environ. Pollut. 11: 175-180.

Sasaki, S. and T.T. Kozlowski. 1968. *The role of cotyledons in early development of pine seedlings.* Can. J. Bot. 46: 1173-1183.

Smith, W.H. and L.S. Dochinger. 1975. Capability of metropolitan trees to reduce atmospheric contaminants. **In** Better Trees for Metropolitan Landscapes (F.S. Santamour, H.D. Gerhold, and S. Little, eds.), pp. 49-59. U.S. Forest Service, General Tech. Rept. NE-22.

Taylor, O.C., W.M. Dugger, Jr., M.D. Thomas, and C.R. Thompson. 1961. *Effect of atmospheric oxidants and apparent photosynthesis in citrus trees.* Plant Physiol. 36 (Suppl.): XXVI-XXVII.

Treshow,M., F.K. Anderson, and F. Harner. 1967. *Responses of Douglas-fir to elevated atmospheric fluorides.* For. Sci. 13: 114-120.

Wilkinson, T.G. and R.L. Barnes. 1973. *Effects of ozone on $^{14}CO_2$ fixation patterns in pine.* Can. J. Bot. 51: 1573-1578.

Williams, W.T., M. Brady, and S.C. Willison. 1977. *Air pollution damage to the forests of the Sierra Nevada mountains of California.* APCA J. 27: 230-234.

Woodwell, G.M. 1970. *Effects of air pollution on the structure and physiology of ecosystems.* Science 168: 429-433.

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ABSTRACTS

Peterson, G.W. and J.D. Olta. 1979. **Controlling phomopsis blight of junipers.** Am. Nurseryman 149(5): 15, 75, 78, 80-82.

Phomopsis blight (cedar blight) is common in the Great Plains from South Dakota to Texas and eastward to the Atlantic coast. Losses have been especially severe in seedling beds of *Juniperus virginiana* and *J. scopulorum.* Phomopsis initially infects foliage, then spreads to and kills stem tissues. Damage from drought can be confused with Phomopsis blight. In both cases, tips of branches may be killed. Fungicides are needed for effective control in seedling beds. Removing infected seedlings from beds (roguing) can reduce the amount of infection. Poorly drained areas should be avoided because losses are often greater where water tends to stand. Some nurseries have abandoned production of highly susceptible cultivars. Phomopsis can cause unsightly junipers in landscapes but seldom kills established trees.

Shurtleff, Malcolm. 1978. **The myth of pesticide-induced injuries.** Grounds Maintenance 13(9): 1.

There are many myths that need to see the light of day. In the 16-year period from 1960 to 1975, there were 35 deaths in Illinois caused by accidental ingestion of pesticides. Interestingly, only one death resulted from a pesticide used for an agricultural purpose. The remaining 34 deaths resulted from household pesticides. Sixteen casualties were the result of improper pesticide storage; 15 deaths occurred while the pesticide was in use. Even more startling is that 19 of the victims were three years old or younger. Seventy-four percent of the deaths were children 12 years of age or younger. Sodium arsenite, a weed killer, was involved in more accidental deaths (8) than any other pesticide, with sodium fluoride (6) and phosphorus paste baits (5) in second and third places. Several deaths occurred because sodium arsenite was poured into pop bottles and stored in refrigerators. There have been no deaths reported in Illinois from accidental exposure or ingestion of pesticides since 1973. The facts should explode some myths fostered by the mass media. The data point out where pesticide accidents occur and how. Hopefully, we can learn from past mistakes and can concentrate now on correcting the deficiencies that allow accidental poisonings to occur.

Smith, Ronald C. 1978. **Tree staking and guying.** Grounds Maintenance 13(9): 50, 52.

There are variations in staking methods. These and the standard staking methods are discussed, plus data on what research shows goes on with staked and unstaked trees. The need for tree staking arises from the desire to keep trees in their upright position until their root systems penetrate the soil to provide sufficient anchorage against high winds. Not all trees require staking. If the ball size is up to par, the top properly thinned at planting and the backfill is according to specifications, many larger deciduous, nursery-grown trees will flex but not lean under normal prevailing wind and rain conditions. Any wild or native-grown trees should be staked. This is because the root systems of such trees are shallow and have had a significant portion of their surface area removed from transplanting. The staking should remain for no more than two years, with frequent checks on the wires to be sure no girdling takes place.