Ecological Research Series

EFFECT OF AIR POLLUTION ON *Pinus strobus* L. AND GENETIC RESISTANCE

A Literature Review

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EFFECT OF AIR POLLUTION ON *PINUS STROBUS* L. AND GENETIC RESISTANCE

A Literature Review

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report summarizes knowledge which may be used in providing protection to white pine, a valuable timber and ornamental tree species.

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ABSTRACT

Effects of the main phytotoxic gases that injure eastern white pine (*Pinus strobus* L.) and the possibilities of breeding resistant trees are discussed in a comprehensive literature review. The main purpose of the report is to summarize knowledge which may be used in providing protection to a valuable species. Implicitly related topics are reviewed briefly, including sorption and emission of gases by plants, air quality standards, bioindicators for monitoring air quality, and silvicultural measures for protecting trees against injuries. Extensive studies in growth chambers and in nature indicate that widespread and in places very serious damage has been caused by ozone, sulfur dioxide, and nitrogen oxides. There is good reason to be concerned about not only acute injuries, but also chronic effects that probably reduce the growth of this species and other trees. Air pollutants may also disrupt forest ecosystems less perceptibly, though over vast areas. A large body of existing knowledge apparently has been utilized very little for protecting trees exposed to this hazard. It appears doubtful that current emission abatement efforts will improve air quality enough to adequately protect the more sensitive species and individuals. Recommendations are made for shifting research emphasis toward developing and implementing strategies that will provide greater protection in forest ecosystems and among landscape trees.

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SECTION I

INTRODUCTION

PERSPECTIVES ON THE PROBLEM

Eastern white pine, *Pinus strobus L.*, probably is injured by air pollutants more than any other tree species in eastern North America. It certainly is one of the most sensitive. Estimates of damage to trees and economic values have been made for only a few cases of the most obvious or extensive injuries. Among the best known examples is the elimination of the species from large areas in Ontario, Canada, by fumes from smelters (Gordon and Gorham 1963, Gorham and Gordon 1960). Damage in several localities has occurred on thousands of acres and losses may involve millions of dollars. An aerial survey of two counties in North Carolina showed that white pine foliage was injured in an area estimated to be 112,640 acres, with 100 trees affected per square mile (Landgraf *et al.* 1969). Many large trees lost all their needles and died, some of them in residential areas where they had high aesthetic values; insect attacks on weakened trees posed a continuing threat. Ten percent of the white pines throughout Pennsylvania were estimated to have been injured by one air pollution episode in 1972 (Nichols 1972). In a 1966 survey of white pine plantations in Wisconsin, needle blight symptoms were found in almost every plantation (Prey 1968). An out-of-court settlement of $450,000 was paid to Christmas tree growers for alleged damage caused by air pollutants from a power generating station. It represents about one-fourth of the claimed damage to 500,000 trees of several species, including white pine (Edwards 1972). Litigation has been brought in additional cases. Other examples of injuries are cited elsewhere in this report, and experts are aware of many others which have not been recorded. The true extent of this damage cannot be estimated accurately from available data, but it must be extremely large.

The damage caused by air pollutants to eastern white pine is only a small part of a global problem, affecting countless individual trees and entire forest ecosystems. The literature contains numerous published accounts of air pollutant injuries, either proven or probable, to sensitive trees in various industrial regions of several continents. Some of the best substantiated cases have been described in various literature reviews (Hansbrough 1967, Hepting 1964, Hepting 1968, Horntvedt 1970, Keller 1968, Kisser 1966, Knabe 1966, Knabe 1972, Materna 1969, Wentzel 1967). One of the earliest reports of damage to forests by industrial fumes in the United States appeared some 50 years ago (Toumey 1921). Scientists have been cognizant of the phytotoxic effects of industrial fumes for more than 100 years (Grouven 1855, Stöckhardt 1871), but a preponderance of the research on the subject has been conducted during the past 20 or even 10 years.

The cause of a recently discovered hazard to forests, termed "acid rain", also may be traceable to air pollutants. In both North America (Likens et al. 1972) and Europe (Oden 1968), a trend of increasingly acidic rainfall has been linked to sulfur and nitrogen oxides given off when fossil fuels are burned. Potentially serious effects on forest ecosystems are anticipated, though some experts have expressed dissenting views. Forest measurements in Sweden do indicate that a decline in forest productivity has occurred (Jonsson and Sundberg, 1972). Small reductions may be involved, but over vast areas, so that economic losses could be very great.

When dramatic or less obvious effects of air pollutants on eastern white pine are under consideration, one should be aware also of possible side effects. The species occurs not in isolation but as a member of an ecosystem. Ulrich (1972) has outlined relationships of air pollutants with forest ecosystems which may cause disturbances in a steady state. The situation in temperate regions has been reviewed by Smith (1974). He classified relationships ranging from vegetation functioning as a sink for pollutants, to subtle or severe effects which can cause various kinds of stresses or mortality. These in turn may have varying impacts on ecosystems.

In reviewing interactions between air pollutants and plant parasites, Heagle (1973) found indications that pollution stress may decrease obligate parasitism but increase facultative parasitism. For example, infection by Cronartium ribicola on white pine was less severe close to a smelter that emitted SO_2; white pine weevil incidence was higher on trees injured by SO_2, but the insects caused less damage. Plant reactions are highly dependent on environmental conditions and on genetic characteristics. Data on the latter are quite limited, and less well understood, especially in nature.

PURPOSE OF THE REPORT

It has been shown that eastern white pine, a species having considerable commercial and ornamental importance, has been damaged extensively by air pollutants. The general purpose of reviewing research results, therefore, is to summarize existing knowledge so it may be used in providing protection to this valuable tree. What has been learned about eastern white pine might apply also to other species which have received less attention. Furthermore, gaps in knowledge may be identified to indicate further research needs.

There are different ways of providing protection, and these require various kinds of information. The main body of the report is organized according to the two main topics: effects of specific air pollutants and the methodology of producing resistant varieties. How-

ever, the information contained therein may be applied also to the following subjects, which are considered to be implicitly related to the purpose of this report.

1. sorption of pollutants by plants

2. emission of gases from plants

3. air quality standards for pollution abatement

4. bioindicators for monitoring air quality

5. silvicultural measures for protecting against injuries

6. uses of trees for improving human environments

These topics are discussed briefly here to amplify how they are related to the overall purpose.

The sorption of pollutants by trees (Roberts 1971) is of interest in understanding how injuries occur, and also in defining the ability of vegetation to improve air quality. Experiments in specially designed chambers with alfalfa (Bennett and Hill 1973, Hill 1971) indicated that vegetation may be effective in removing large quantities of pollutants from the air. HF, SO_2, and NO_2 were removed efficiently; O_3 was readily deposited on surface tissues; very little NO or CO absorption was detected Uptake rates increased linearly with concentration, and were influenced also by wind velocity, light intensity, and depth of the leafy canopy. Waggoner (1971) described a method for calculating uptake rates based on resistances of leaves to gas exchange, and for transfer in the atmosphere based on meteorological conditions. Ozone sorption studies (Hanson and Thorne 1970, Thorne and Hanson 1972) showed that rates of herbaceous species were four to seven times as great as those of woody species of Quercus, Ginkgo, Camellia, and Bougainvillea. They were higher for actively growing tissues than dormant tissues. A strong positive correlation was found between sorption rate and transpirational water loss. In some species uptake fell off as fumigations continued. Variation in concentrations of 0.17 to 1.04 ppm O_3 had little effect on sorption rates. In another series of ozone experiments (Townsend 1974), deciduous tree species differed significantly in uptake rates at concentrations of 0.2 to 0.8 ppm. White oak and white birch leaves removed the largest quantities, while red maple and white ash were the least efficient. Uptake by white birch was linear over the range 0.1 to 0.8 ppm, and decreased very little during eight hours of exposure. Uptake by red maple populations differed significantly. Similar studies with sulfur dioxide (Roberts 1974) also revealed large species differences. Sorption rates of red maple, white birch, and sweetgum (0.26 to 0.27 mg $SO_2 - h^{-1} \cdot g^{-1}$) were much greater than rhododendron and azalea (0.07 to

0.08), while firethorn, privet, and white ash were intermediate. The capacity to remove SO_2 was influenced little by a range of concentrations from 0.2 to 1.0 ppm or by exposure periods of one to six hours.

The contribution of trees toward improving air quality is still a controversial subject despite the convincing and compatible results of several carefully controlled experiments. Mooi (1974) concluded that the amounts of hydrogen fluoride removed by trees during long exposures contributes little to air purification; uptake rates were estimated from fluorine contents of leaves. Extensive measurements by Lampadius (1966, 1968) within and outside forests did not support the expected filtering capability. He concluded that forests have little if any effect in lowering SO_2 concentrations. The data were quite variable, and seemed to be influenced mainly by exchange of air masses. Though the author did not mention it, the possibility remains that a more careful analysis of turbulence effects and gradients in vertical and horizontal directions may be required to detect beneficial effects of trees. Brunig (1971) believes that oxygen emissions from forests are too small to effectively improve man's environment, but that increased turbulence caused by aerodynamic roughness may cause pollutants to be diffused rapidly. He regards increased air mixing as one of the most important nonproductive functions of forests, besides providing recreational locales, local noise abatement, dust absorption, and protection of soil and water quality. Additional literature on this subject has been reviewed by Keller (1971).

Little is known about the effect on humans of many substances given off by plants. Vigorov (1966) has discussed possible beneficial or detrimental influences. Rasmussen (1972) estimated that plant species, including Pinus strobus, release six times as much volatile organic substances as come from manmade sources. The fate of these gaseous hydrocarbons in the atmosphere is unknown.

The relationship of air quality standards to pollutant injuries to forests has been discussed by Knabe (1971). He pointed out that emission standards in Germany permit slight to severe injuries to several tree species, principally the most important timber species, Norway spruce and Scotch pine. It has long been recognized that the most desirable way of alleviating such damage is by controlling pollutants at their sources (Wentzel 1967). This has not proven to be a feasible solution, however, for technical, economic, and social-political reasons. The possibility of controls at emission sources that would be adequate for protecting sensitive trees was considered remote, so other alternatives for providing protection are being pursued. Heggestad (1969) reviewed air quality standards for vegetation with respect to ozone. He concluded that a total oxidant level of 0.15 ppm for one hour, which had been selected as a standard for ambient air quality, will not be adequate to protect sensitive vegetation in eastern United States. Ozone is re-

garded as the most damaging of all air pollutants affecting vegetation. More adequate air quality criteria for oxidants are urgently needed, and more background information is required for the setting of standards.

The use of sensitive plants as bioindicators to monitor air pollutants has been explored by Berry (1964, 1973). Eastern white pine clones were selected that will detect low levels of oxidants, sulfur dioxide, or fluorides. Pollutants may be identified by using clones that are sensitive to only one type. Out of 1428 seedlings that survived from an original population, 53 were sensitive only to oxidants, 8 to sulfur dioxide, and 14 to fluorides. Only 64 (4.5%) were tolerant to all three types of pollutant regimes to which they were exposed. The feasibility of selecting and propagating sensitive clones has been clearly demonstrated. Plant indicators have several advantages over instruments, the chief of which may be low costs and automatic integration of all pollutant and environmental variables which influence injuries to vegetation. There may be operational difficulties in establishing a bioindicator network, as Baer (1967) reported. However, systems using several kinds of plants have been operating successfully in Germany (Guderian and Stratmann 1968, Schönbeck _et al_. 1970).

The adoption and implementation of air quality standards, monitoring systems and enforcement procedures probably will not provide adequate protection to all forest and landscape trees. Wood (1968) predicted, even before the onset of current energy problems, that the most damaging phytotoxic air pollutants would worsen until 2000 A.D. despite abatement procedures, and that serious problems would remain for some time afterwards. Silvicultural measures which may be taken to protect forests against air pollutants have been reviewed by Keller (1964, 1968) and Kisser (1966). These include principally site improvement (e.g., fertilizing), changing species by selection during natural or artificial regeneration, and breeding more resistant varieties. Existing knowledge is inadequate, in many respects, for implementing such measures.

In justifying the protection of trees against air pollutants, it should be recognized that their usefulness goes beyond the commercial products derived from them. Baumgartner (1971) discussed the importance of forests to the biosphere in regard to air pollution uptake, noise absorption, and energy exchange. Urban planners are interested in trees not only for their beauty, but also for their capacity to influence noise, air pollution, microclimate, and the water supply (Smith 1970). The most important contribution in ameliorating urban microclimates is the interception of solar radiation by trees on hot summer days (Heisler 1974). Cooling by transpiration could be important, but little is known about availability of water which is needed if trees are to function as nature's air conditioners. Human comfort may be improved by a lowering of wind speeds in the winter, but summer breezes may also be reduced. Trees can play a significant role in noise control in suburban and rural

areas, especially when used in combination with land forms and structures (Herrington 1974). A belt of trees can reduce noise by three to eight decibels per 100 feet of depth, depending on its density (Reethof 1973). A 200 foot wide belt would be required to reduce noise from a heavily travelled highway, to acceptable levels in a residential area on the other side of the noise barrier. Bernatzky (1968) discussed the design of urban tree plantings for maximum effectiveness in filtering out gaseous and particulate pollutants, improving microclimate, and reducing noise. Plans have been formulated for using German forests for air cleansing, noise abatement, and related functions (Knabe 1973).

Research needs related to the purpose of this report have been identified by several authors, for various geographic regions or subject matter areas. Air pollutants are recognized as an important part of the problem of growing trees for the 45 million people in Megalopolis (Doolittle 1969). Information is needed in relation to choosing species for planting and breeding pollution resistant varieties. Heck *et al.* (1973) and Hansbrough (1967) discussed relationships between forest or ornamental trees and air quality, pointing out numerous gaps in our knowledge. Knabe (1966, 1967) provided European insight into air pollution research needs of the United States. He regarded *Pinus strobus* a promising species for resistance breeding, because it shows great variation in resistance and can be propagated vegetatively. A more recent literature review (Knabe 1972) is particularly useful, even though it emphasizes mainly Germany's research needs. These are classified according to their value in meeting practical applications, or their potential for leading to new methods for the solution of problems. Subjects covered include regional distribution of damage, diagnosis, evaluating losses, methods for reducing damage, defining boundaries of emission areas, setting air quality criteria and risks, biological indicators, physiological mechanisms, and secondary effects. Kisser (1966) has discussed air pollution research needs from the view point of biological knowledge, as this relates to injuries and land management problems.

SECTION II

CONCLUSIONS

Eastern white pine has been damaged substantially by phytotoxic gases in many places. Air pollution is likely to pose a hazard to this species and others for a long time. Sulfur dioxide, ozone, and nitrogen oxides are regarded as the most important pollutants that damage this species. Direct effects of ozone and sulfur dioxides have been studied extensively in fumigation experiments and in nature, and there is some effects information on effects of nitrogen oxides and gas mixtures. Less is known about chronic effects and very little about indirect influences on ecosystems, though scientists have expressed concern about these problems.

Nitrogen oxides can injure foliage and reduce height and diameter growth of white pines, which vary greatly in sensitivity. Nitrogen oxides, alone or mixed with sulfur dioxide, inflict damage resembling the chlorotic dwarf disease caused by ozone and sulfur dioxide.

Ozone injuries to pine needles have been described in great detail, and the dosages and environmental conditions which are conducive to injuries are understood quite well. There have been a few studies on physiological effects and relationships with fungi. While white pine is generally quite sensitive to ozone and also sulfur dioxide, some clones are much more vulnerable than others.

Sulfur dioxide from industrial emissions has caused severe and extensive damage to white pines. Knowledge about threshold concentrations of sulfur dioxide and environmental influences on injuries comes mainly from outdoor studies and some fumigation experiments. Fertilizer applications have reduced injuries in several instances.

The mixtures of gases to which trees may be exposed in nature make it difficult to diagnose injuries, and almost impossible to prove the cause with complete certainty. Clear, ample evidence does exist that the rather common chlorotic dwarf disease of white pine is caused by ozone and sulfur dioxide, and these gases are responsible for the variously named symptoms associated with it. Semi-mature needle blight, a similar physiogenic disease, is different in certain respects.

Breeding varieties with improved resistance to air pollutants can be justified as a component of a pollution control strategy, not as an alternative to controlling emissions. Improvement objectives include resistance to major pollutants at concentrations below those injurious to humans, environmental adaptation, resistance to other pathogens, and other qualities related to uses of trees for timber or amenity purposes. Specific goals need to be clearly defined. Evidence of wide genetic

variation found in at least 15 tree species, including eastern white pine, indicates ample opportunities for selection. Populations from regions with harsher climates seem to have higher levels of resistance. These might have pre-adapted tolerance to air pollutants because of their ability to withstand adverse natural conditions such as droughts and frosts. Selection methods that have been used successfully include phenotypic selection in damaged forests, fumigation of young trees in chambers of various types, and pre-selection using rapid tests of cut branches or leaves. Environmental variables and data frequency distributions have received attention in designing selection procedures and making genetic estimates. Clonal repeatability analyses and heritability estimates indicate moderate to strong genetic control over resistance to air pollutants in white pine and Scotch pine. Breeding projects to improve resistance to air pollutants have been started for Norway spruce, Scotch pine, European and Japanese larches, poplars, red maple, and white pine. Various methods have been employed, and initial progress has been encouraging. Some very important research problems have been identified which will require long-term support for reducing air pollution damage to timber and landscape trees species.

SECTION III

RECOMMENDATIONS

Emphasis in research should shift now from extending knowledge about pathological effects of air pollutants toward protecting eastern white pine and other tree species against excessive damage. Reasonable goals should be defined, a strategy developed, a set of plans implemented, and supporting research continued.

Goals for protecting trees against air pollutants surely will represent a compromise. Increased costs of emission abatement or of breeding resistant cultivars should be balanced against additional protection attained. Both tangible and intangible values of reducing visible injuries and restoring better growth rates should be considered.

The development of a strategy and the plans to implement it will require additional information. Surveys of damage to forests and landscape trees will be needed to subdivide geographic regions according to risk classes. Existing eastern white pines or planted bioindicator clones can serve as standards for comparisons. Localities characterized by the most favorable benefit/cost ratios should receive attention first, and others proportionately.

A carefully integrated, dynamic research program should be developed to support protection efforts. Frequent reviews of technical aspects and comparisons of costs to benefits are advisable. Research areas which deserve high priority include short- and long-term impacts of air pollutants on forest ecosystems and landscape trees; pathological effects of gas mixtures; genetic variation in sensitivity of natural populations; and breeding of resistant cultivars.

SECTION IV

AIR POLLUTANT EFFECTS ON EASTERN WHITE PINE

Air pollutants conceivably might have some favorable effects on eastern white pine, but most of the pertinent literature is concerned with direct injuries to individual trees and forests. The immediate impact and the ultimate significance of such injuries for individuals and for ecosystems is not obvious in many cases. A classification of the kinds of effects proposed by Smith (1974) offers a useful frame of reference. Class I effects occur at low dosages, during which vegetation is uninjured and may act as an important sink for contaminants. Class II effects at intermediate dosages may adversely affect sensitive individuals or species by nutrient stress, reduced photosynthesis or reproduction, predisposition to insects or microbes, or direct disease induction. Class III effects at high dosages may induce acute morbidity or mortality. Deleterious consequences may include reduced forest productivity, shifts in species composition, and disease or insect outbreaks. In some instances, nutrient cycling, water yield and quality, microclimate, soil erosion tendencies, and overall stability in an ecosystem can be affected adversely.

Conifers are among the plants most sensitive to air pollutants, because of the long life of their assimilation organs and the low capability for regeneration. Halbwachs (1971) has summarized chronic and acute injuries to conifers caused by several pollutants to foliage and entire plants. Microscopic effects on needle tissues and physiological reactions also are described. Typical symptoms have been defined but these often resemble symptoms resulting from other stresses. This has caused continuing difficulties in investigations, and is one of the reasons why fumigation chambers have been used widely for qualitative and quantitative control of exposure.

The terminology applied to diseases of eastern white pine caused by air pollutants has caused some confusion (see Costonis and Sinclair 1969 a, b, Houston 1974). "Needle blight" is a general term which has been used for a group of symptoms; these may include dwarfing, chlorotic or necrotic tissues, and banding. It originated before air pollutants had been proven to be causal agents. "Chlorotic dwarf" also refers to a syndrome of leaf symptoms, leading to stunting of whole plants, probably caused by mixtures of ozone and sulfur dioxide (Dochinger _et al_. 1970, Dochinger and Heck 1969, Dochinger and Seliskar 1970), and possibly also by oxides of nitrogen and sulfur dioxide (Skelly _et al_. 1972). The phenological stage when portions of needles are most sensitive is a principal basis for distinguishing between "emergence tipburn" (Berry and Ripperton 1963), "post emergence chronic tipburn" (Berry and Hepting 1964), and "semimature tissue needle blight" (Linzon 1967). The names of other white pine needle disorders (Costonis and Sinclair 1969 a) are not common in recent literature: "yellow dwarf", "red needle blight",

"short needle". Many articles do not refer to a disorder by name, but rather describe symptoms caused by specified pollutants.

The protocol in this report is to discuss effects that are attributable to the pollutants nitrogen oxides, ozone, sulfur dioxide, and mixtures of gases. Relationships to the principal named diseases are discussed in conformance to terminology in the literature.

NITROGEN OXIDES

Published information on nitrogen oxide effects on eastern white pine is not very extensive. Several pines were examined for injuries in Virginia near a source of moderately high concentrations of NO and NO_2 (Skelly *et al.* 1970). Ambient levels were monitored at seven stations, and the highest one hour concentration was over 0.58 ppm at a distance of 0.5 mile from the source. Levels of SO_2 at the same station were 0.67 ppm for a two hour collection period at the same period. At one mile or more from the source, native *Pinus strobus* had developed significant chlorotic mottle on older needles and some tipburn. Some highly sensitive trees had severe chlorosis and reduced height growth. *Pinus strobus* seedlings, planted 200 yards from the source three years prior to the study, were severely stunted, showed no appreciable growth after planting, and had tipburn. *Pinus taeda*, *P. echinata* and *P. virginiana* apparently were less susceptible. They also had chlorotic mottle and in some instances severe chlorosis and tipburn, but no significant growth losses. Striking tree to tree variation in sensitivity existed in *Pinus strobus* (Skelly *et al.* 1972). It was concluded that oxides of nitrogen at moderate concentrations, acting alone or with low sulfur dioxide concentrations, may cause acute or chronic damage to conifers. The damage to white pines appears similar to chlorotic dwarf disease caused by ozone and sulfur dioxide.

Fluctuating operations of a munitions factory made it possible to study effects of NO and NO_2 on diameter growth of *Pinus strobus* and *Liriodendron tulipifera* (Stone and Skelly 1973, 1974). Production levels of nitric acid and nitrated products were high during three periods, and near zero during intervals between. Diameter growth was measured on increment cores from natural stands within 0.2 mile of the source. In both species growth was depressed 50 percent, but recovered sharply during 1946-1949 when emissions were reduced. Significant negative relationships were found between tree growth and munition production levels ($r = .50$ and $.52$), and positive correlations were found with rainfall ($r = .37$ and $.43$).

OZONE

The oxidants ozone, peroxyacetyl-nitrate, and nitrogen dioxide have comparable but not identical effects on plants (Taylor 1968). *Pinus strobus* is included among the most sensitive plants.

Ozone was identified as a likely cause of emergence tipburn of Pinus strobus quite recently (Berry 1961). Isolations of fungi from roots did not reveal any causal pathogen. Injured trees recovered when they were transplanted to areas where the severity of disease was lower. Grafted scions retained their original condition regardless of rootstock type. This evidence indicated that an atmospheric agent was responsible. Ozone fumigation with 10 pphm for two hours caused typical symptoms on ramets from one susceptible tree, and no symptoms on ramets from a resistant tree. Ozone concentrations approaching 5 pphm can cause emergence tipburn symptoms of white pine blight (Berry and Ripperton 1963). Very similar results were obtained when symptoms and concentrations were monitored in field experiments and greenhouse fumigation chambers. Potted, sensitive ramets were protected from injury in carbon filtered chambers. Typical foliar symptoms are common on white pines in urban locations, too (Hibben 1969).

The symptomatology of ozone injury to eastern white pine has been described in detail (Costonis and Sinclair 1969, Sinclair and Costonis 1967). The blighted condition is a syndrome of acute and chronic ozone injuries. The reactions of individuals vary greatly. A small proportion of trees in a population exhibit mild symptoms each year and severe injuries occasionally. A very small percentage is severely injured every year. These are stunted and have conspicuously burned or chlorotic foliage that is retained only one year instead of the normal 27 months. The most tolerant trees have dark green foliage retained until September or October of its third season. Needles of sensitive trees are susceptible to ozone injury from emergence until they have completed elongation and hardened off. Acute injuries may occur on elongating needles after experimental exposures to as little as 3 pphm for 48 hours or 7 pphm for 4 hours. The period of greatest susceptibility is in June and July. The most sensitive tissue is in a zone a few millimeters wide located 10 to 20 mm from the needle sheath. If trees are injured several times, the most recent injury occurs nearest the needle base. The first external symptom is inconspicuous silver flecking visible only under magnification. Flecks radiate from stomata in the sensitive zone, and are caused by the collapse of mesophyll cells adjacent to stomata. Usually all needles in a fascicle and most fascicles on a branch develop new symptoms in the same portions of needles at the same time. After severe injuries yellowish to pinkish spots develop which may become necrotic, and enlarge to form shrunken dead bands, causing death of the needle tip which is called "tipburn". The degree of injury to sensitive trees depends on ozone concentration and environmental conditions. In the presence of free moisture, "water spot" lesions may develop on any face of a needle, instead of being restricted to stomatal surfaces; these are less dependent on the stage of tissue maturity. Injuries are more likely to occur at higher temperatures during and after fumigation and in the presence of sunlight. Exposure to 40 to 60 pphm ozone caused symptoms different from those found in the field or after fumigation with low concentrations, and caused injuries to both susceptible and resistant trees (Costonis and Sinclair 1969 b).

The threshold of ozone dosage at which visible injuries to Pinus strobus occur has differed greatly in various experiments. The lowest dosages are 3 to 10 pphm for 1 to 48 hours (Berry 1961, Berry and Ripperton 1963, Costonis and Sinclair 1969 a, b). Moderate dosages are 10 to 25 pphm for 4 to 8 hours (Berry 1971, Davis and Wood 1968, Davis and Wood 1972, Wood and Davis 1969). A much higher threshold of 50 to 100 pphm for 4 hours has been reported by Botkin et at. (1971, 1972). Houston (1974) found that among 47 trees selected for sensitivity to tipburn, none were injured when ramets were fumigated with 5 pphm for 6 hours; 20% were injured at 10 pphm; 60% at 30 pphm, and 20% at 60 pphm.

Genetic or environmental differences can explain the variation observed in threshold dosages, and furthermore these are subject to seasonal variation. This is supported by observations in several reports already cited. In addition, a study of Pinus virginiana (Davis 1970) may apply also to other pines. Ozone sensitivity was influenced by environmental conditions before, during, and after fumigation. High temperature before and after exposure increased sensitivity, but lowered it during fumigation. High humidity during fumigation greatly increased sensitivity, but had little effect before or afterwards. Age of seedlings does not appear to be an important source of variation, as three, five, and seven week old pines did not differ in sensitivity, and they behaved much like two to five year old trees (Berry 1971).

Ozone can also influence physiological processes below threshold exposures, without any visible symptoms developing other than reductions in growth. Photosynthesis was depressed and respiration was stimulated in young seedlings of Pinus strobus and three southern pines exposed to 5 to 15 pphm O_3 for 5 to 18 weeks (Barnes 1972a). In contrast, Botkin et al. (1971) had to use dosages of 50 to 100 pphm for 3 to 7 hours to demonstrate supression of photosynthesis. Total soluble carbohydrates, reducing sugars, and ascorbic acid were elevated after prolonged exposures to 5 pphm (Barnes 1972b). In seedlings exposed to 15 pphm, soluble sugars were higher than in controls, but ascorbic acid was not. Carbohydrate and ascorbic acid levels may be useful in estimating needle maturity and sensitivity to ozone (Barnes and Berry 1969). Effects of ozone on CO_2 fixation patterns were studied using Pinus strobus seedlings and detached shoots (Wilkinson and Barnes 1973). Dosages as low at 10 pphm for 10 minutes caused significant differences. Results indicate the impairment of enzymes involved in the transfer of carbon into sucrose. An increase of ^{14}C in alanine was the most consistent effect, and may be one of the earliest detectable manifestations of ozone effects at the biochemical level.

Relationships of Pinus strobus with fungi may be influenced by ozone (Costonis and Sinclair 1967, 1972). Lophodermium pinastri and Aureobasidium pullulans were isolated most frequently from injured needles,

the latter only from dead tissues. L. pinastri was isolated more frequently from trees susceptible to ozone than from resistant ones, whether or not they had been fumigated.

The relative sensitivity of Pinus strobus to ozone has been compared to other species by several investigators. Davis and Wood (1972) found that several conifers and hardwoods were more sensitive, others more resistant. Such comparisons are subject to the kinds of variation discussed in relation to thresholds. Whether the criterion is leaf injury or impact on the growth and health of whole plants can also make quite a difference. No matter how available data are interpreted, however, Pinus strobus is rather sensitive to ozone.

SULFUR DIOXIDE

Industrial emissions of sulfur dioxide have caused extensive damage to white pines. Concentrated fumes near metal smelters have eradicated the species within five miles, caused mortality and severe injuries at distances of at least 20 miles, and other effects have been traced to 30 miles (Gordon and Gorham 1963, Gorham and Gordon 1960). In a 720 square mile area where the most severe injuries occurred near Sudbury, Canada, direct damage to trees in a 10 year period was estimated at $117,000 (Linzon 1971, 1973), though only 7.6 percent of the trees in productive forests were white pines.

Sulfur dioxide concentrations and injuries to vegetation around Sudbury have been reported for the period 1964-1968 (Dreisinger and McGovern 1970). Half-hour concentrations reached 286 pphm, compared to 364 pphm during the previous 10 year period. At ten stations the presence of sulfur dioxide was recorded 13% of the time. Concentrations were above 25 pphm 1.26% of the time, and above 50 pphm 0.38% of the time. Dosages considered to be injurious to vegetation were 95 pphm for one hour, 55 pphm for two hours, 35 pphm for four hours, or 25 pphm for eight hours. Because environmental conditions modify plant responses, injuries have failed to occur in some instances at concentrations two to four times greater. In other cases, injuries have occurred at levels 25 percent less than these concentrations, and always during June or July when hot, humid weather prevailed. Over 2000 square miles were subjected to one or more potentially injurious fumigations during the five year period, and 1,271 square miles to five or more. Trembling aspen, jack pine, white birch, and white pine were the most sensitive trees when ranked according to foliage injuries. White pine suffered most from repeated heavy fumigations, however, while the aspen and birch recovered more readily. The most resistant species were red oak, sugar maple, white spruce, and cedar.

Severe injuries have also been attributed to emissions of sulfur dioxide from petroleum refineries (Linzon 1965) and coal burning power generating stations (Drummond and Wood 1967, Gordon 1972). In addition direct injuries to foliage, effects on seeds may also inhibit natural reproduction, at least in Scotch pine (Mrkva 1969). Pines exposed to higher concentrations of sulfur dioxide produced smaller cones, less seed, and lighter seed than those farther from the source of emission.

Chemical analyses of plant tissues have given us some insight into injuries caused by sulfur dioxide. Bortitz (1968) demonstrated that sulfur dioxide is taken up by conifers not only during the growing season, but also in the winter; it can be translocated on warm winter days and is capable of damaging plants. Sulfur contents of foliage can confirm exposure to SO_2, and thus is useful in diagnosing injuries (Stefan 1971). Branches of Pinus strobus and four other pines were fumigated with SO_2 to study uptake and contents under various conditions (Godzik 1972). Accumulations were greatest in the tips of needles, and they may explain necrosis of those parts. There were large differences among species in contents. When expressed on a dry weight basis, Pinus strobus contained more than any other species, and seven times as much as Pinus nigra. It contained half as much per needle as Pinus nigra, less than Pinus rigida, the same as Pinus sylvestris, and more than Pinus montana. The different sensitivities of species could not be explained mainly by differences in uptake rates.

Fumigation experiments of other types also have produced valuable information. Keller and Muller (1958) found that photosynthesis and net assimilation were depressed, while respiration and transpiration increased upon exposure of three conifer species to SO_2. Three to seven week old seedlings of Pinus strobus and two other pines were injured less by sulfur dioxide than by ozone at the same concentration (Berry 1971), while the opposite was true when older grafted plants were fumigated (Costonis 1970, Houston 1974). The latter, however had been selected for sensitivity to air pollutants, while the younger seedlings had not; so older trees are not necessarily more sensitive. The selected clones were injured at concentrations as low as 5 pphm. Observations in a 10 year old white pine plantation showed that 6 pphm SO_2 for four hours could cause acute injuries to some trees (Costonis 1971). Susceptible trees were most sensitive during a six to eight week period when new needles were elongating.

The sensitivity of Pinus strobus to sulfur dioxide has been compared to other species in several fumigation experiments. Both Wentzel (1968) and Enderlein and Vogl (1966) regard it as similar to Pinus sylvestris, and more sensitive than Pinus nigra. This ranking makes it possible to compare Pinus strobus to 200 other woody species fumigated and observed in polluted regions by Ranft and Dässler (1970), and places it among the most sensitive. Wentzel's discussion of complexities encountered in

trying to compare susceptibilities of species to air pollutants are especially useful in relating chamber fumigations to outdoor exposures. Important variables may include pollutant type and dosage, plant age and developmental stage, crown habit, height of the crown above ground, foliage sensitivity, regenerative capacity, and environmental conditions.

Fertilizer applications have reduced sulfur dioxide injuries to white pines in several studies. In an experiment with six fertilizers and a control treatment, nitrogen increased the resistance of two to four year old white pines, Scotch pines, and spruces (Enderlein and Kastner 1967); deficiencies of phosphorus, potassium, magnesium, calcium, and especially nitrogen increased injuries to fumigated one year old pines. Needle tip necrosis was reduced by application of a 28-19-17 fertilizer to some sensitive clones exposed to sulfur dioxide in a greenhouse, and also in a plantation where the ambient air contained sulfur dioxide (Cotrufo and Berry 1970). Unfertilized ramets were injured more severely. However, other symptoms such as banding and mottling were not alleviated by the fertilizer treatments. In a subsequent factorial fertilizer experiment using potted ramets of one clone (Cotrufo 1974), nitrogen increased needle tip necrosis while phosphorus reduced needle injury.

MIXTURES OF OZONE, SULFUR DIOXIDE, NITROGEN OXIDES

After unintentional exposures of white pines to air pollutants, it is often difficult to ascertain whether single or multiple gases or other pathological agents were the cause of injuries. Various kinds of problems are involved in obtaining indisputable proof, despite all the research that has been conducted. For example, in a recent episode (Ellertson et al. 1972) ten percent of the white pines in an industrial region were killed and many others severely injured, while others intermingled with them remained healthy. The causal agent was determined to be airborne and abiotic, but could not be identified. Sulfur dioxide was suspected to be a contributory agent. The damage claims of Christmas tree growers in western Maryland and West Virginia provide another illustration (Anderson 1970, Freeman 1969). It was claimed that foliage injuries and abnormal growth first appeared in 1967 after a new coal-burning electric generator began operations. Several experts who examined the trees affirmed that the symptoms were typical of air pollutant injuries. The courtroom testimony of other highly qualified specialists was contradictory, and suggested other causes such as mites or fly ash. The issue was not fully resolved, as there was an out-of-court settlement in favor of the plaintiffs. The outcomes of similar cases which followed are still pending.

In the diagnosis of post emergence chronic tipburn prior to 1960, sulfur dioxide was suspected of being the principal toxicant, possibly acting together with fluorides and ozone (Berry and Hepting 1964). The

disease had been noted only near industrial areas which have substantial emissions. Symptoms can develop up to 20 miles from tall stacks, so some trees must be highly sensitive. There was no difference in sulfur content of diseased versus healthy trees, and fluorine contents were not high enough to cause toxicity. Yet an atmospheric physiogenic factor was determined to be the cause. No insects or fungi associated with diseased trees were primary causal agents. Neither fertilizing nor pruning had any effect on the occurrence of tipburn, though in some cases vigor was improved by fertilizing. Diseased trees recovered after being transplanted outside the affected area. Grafting of diseased and healthy scions on both types of rootstocks, in all combinations, caused no change in symptoms, and disease was not transmitted to the rootstocks. Ramets moved to an unpolluted environment recovered. Later experiments with grafted pines demonstrated differential sensitivity of clones to sulfur dioxide, fluorides, and oxidants (Berry 1973). Tipburn and mottling are primary symptoms of post emergence chronic tipburn. Extensive foliage injuries are believed to result in severe root mortality, which in turn causes reduced needle and shoot growth and chlorosis. The symptoms are similar to other white pine diseases. Some ways of distinguishing among three types of tipburn and two fungal diseases have been described by Hepting and Berry (1961).

Semi-mature needle blight is another disease which may result from exposure to gas mixtures, though its exact cause is still unknown (Linzon and Costonis 1971). It is a physiogenic disease in which symptoms are expressed by a distal reddening only in needle regions where suberization of endodermal cells is proceeding. Symptoms resemble those of ozone injury somewhat, but white pines susceptible to semi-mature needle blight are more tolerant to fumigation with ozone than resistant trees (Linzon 1966, 1967). Also the incidence of the disease does not appear to be correlated with high ozone levels. Typical symptoms caused by ozone or sulfur dioxide alone differ from those of semi-mature needle blight in several ways (Linzon 1966). Intergrafting experiments have shown that semi-mature needle blight is different from chlorotic dwarf disease (Linzon and Costonis 1971).

Both ozone and sulfur dioxide are responsible for the chlorotic dwarf condition of eastern white pine. The disease is common throughout eastern and midwestern United States (Dochinger and Seliskar 1963, 1965). Chlorotic dwarf trees are sparsely foliated, and branches are tufted due to premature shedding of all but the current year's needles (Dochinger 1968 a, b). New foliage is light green upon emergence, though it soon becomes mottled with chlorotic spots, and often yellowed by early summer. Current needles are thin, curled, twisted, and may exhibit tipburn after drought in summer or winter. All plant parts are abnormally small. Emergence tipburn, another needle blight, appears on some but not all chlorotic dwarf trees, and also on some "healthy" pines (Dochinger and Seliskar 1965). This indicates that each disease is independent of the other.

Several kinds of studies have clarified the cause of chlorotic dwarf (Dochinger and Seliskar 1970). The recovery of diseased pines enclosed in charcoal-filtered chambers demonstrated that gaseous disperoids are responsible (Dochinger et al. 1965). No mottling appeared, premature needle losses were arrested, and lengths of needles and shoots far exceeded previous ones. Trees in chambers with coarse filters or no filters continued to exhibit chlorotic dwarf symptoms. Experiments with grafts showed that the disease is under strong genetic control, because healthy and diseased scions retained their original condition on opposite rootstocks (Dochinger and Seliskar 1963). Oxides of nitrogen alone or with sulfur dioxide cause similar damage (Skelly et al. 1972). The etiology of other physiogenic needle blights of white pine may be explained similarly by gaseous synergisms, even when levels of single gases are insufficient to injure trees.

Fumigation experiments have shown that ozone and sulfur dioxide, acting alone or together, cause the early symptoms of needle mottling and defoliation in the chlorotic dwarf syndrome (Dochinger and Heck 1969). In experiments reported by Dochinger and Seliskar (1970) and Dochinger et al. (1970), levels of ozone and sulfur dioxide were too low to produce all of the chlorotic dwarf symptoms. Mixtures caused more typical symptoms, and more damage than the sum resulting from separate gases at the same concentrations. Somewhat different results were obtained by Costonis (1973), who found the greatest injury resulted after separate exposures to each gas followed by a combined treatment. Also, two hour exposure of sensitive clones to 5 pphm ozone plus 5 pphm sulfur dioxide caused less injury than 5 pphm sulfur dioxide alone, but more than ozone alone. Houston (1974) reported that sensitive clones exposed six hours to 2.5 pphm sulfur dioxide mixed with 5 pphm ozone sustained as much injury as at 5 or 15 pphm sulfur dioxide alone; no symptoms developed at 2.5 pphm sulfur dioxide or 5 pphm ozone.

Susceptible seedlings fumigated up to one month by Jaeger and Banfield (1970) were more sensitive to 5 pphm ozone than 5 pphm sulfur dioxide. All plants exposed to mixed gases for 10 or more days developed profuse spotting on new and year old needles, plus some necrosis. Lesions usually developed first on semi-mature tissue, then mature tissue, and rarely on immature tissue. High humidity was much more conducive to damage than fair weather. In another experiment by Banfield (1972), gas mixtures caused blight at lower dosages than those of single gases which induced symptoms. No injuries resulted from 10 pphm ozone for four days followed by 5 pphm sulfur dioxide for four days, though all plants exposed to a mixture at these levels developed symptoms.

Comparisons of these several experiments show they are in reasonably good agreement. Inconsistencies probably could be explained by genetic differences in plant materials, environmental conditions, and phenological stages at which various dosages were applied.

Dochinger (1970) stated, "Chlorotic dwarf exemplifies the chronic impact that air pollution can have on our conifers. Even though we may expect some progress in the abatement of air pollution, we must realize that there will be an increase of damage to sensitive trees in and around areas of urban and industrial expansion." Monitoring of pollutants and injuries to white pines has provided confirming evidence. In an Ohio plantation during the 1967 and 1968 growing seasons, 25 percent of the days had at least 5 pphm sulfur dioxide for 2 hours; 60 percent of the days had 5.5 pphm ozone for at least one hour; and 16 percent of the days had 5 pphm of each gas in mixture (Dochinger et al. 1970). In another white pine plantation (Costonis 1971), 6 pphm sulfur dioxide for 4 hours caused serious injuries to some trees on several occasions. During the study ozone did not exceed 4 pphm, and concentrations were not correlated with injury levels. Trees were most sensitive during a 6 to 8 week period when new needles were elongating. New symptoms of ozone-induced needle blight in a New York plantation were detected 5 times in 1966 and 12 times in 1967 (Costonis and Sinclair 1969 b). The highest recorded four hour mean ozone concentration preceding new symptom development was 4.4 to 5.2 pphm in 1966 and 5.0 to 8.5 pphm in 1967.

Two kinds of control methods for chlorotic dwarf disease have been found to be effective; genetic and environmental. Genetic variation in susceptibility may be utilized by discarding more sensitive seedlings during normal nursery grading practices (Dochinger 1968 b) or by selecting and breeding resistant varieties (Dochinger and Seliskar 1970). Needle mottling was the best of eleven characteristics by which chlorotic dwarf susceptibility could be detected among seedlings. Following selection, non-mottled seedlings were symptomatic only 5 percent of the time and mottled seedlings were dwarfed 100 percent of the time. Application of a high nitrogen fertilizer to white pines up to 6 feet in height, at rates of one to four cups per tree, reduced air pollution damage (Will and Skelly 1974). Most but not all trees responded favorably, for some trees which had been severely affected by air pollutants died after being fertilized. Although other environmental factors besides nutrition influence responses to air pollutants, such as humidity and temperature, they cannot be readily manipulated to reduce damage.

SECTION V

BREEDING TREES FOR IMPROVED RESISTANCE TO AIR POLLUTANTS

Recognition of genetic differences between healthy white pines next to blighted ones has led to attempts to utilize such genetic variation. The breeding of pollution resistant varieties has been proposed, and some white pines have already been selected. When any new plant breeding program is being contemplated, it is worthwhile to consider all information related to planning such a long undertaking. In the present case, pertinent information from other tree species will be useful, particularly pines and other conifers.

A question that should be raised at the outset is whether any efforts at all should be devoted to the breeding of pollution resistant plants. Would it not be better if all available resources were invested in the complete elimination of noxious emissions at their sources? This is indeed a laudable goal, but not one that is likely to be realized soon, if ever, for reasons discussed previously. Resistance breeding can be justified, therefore, not as an alternative to controlling emissions, but as a component of a comprehensive pollution control strategy that can be recommended in certain circumstances. If in some localities sensitive species are likely to be damaged occasionally by phytotoxic gases, then the most economical way of reducing damage may be by planting more resistant varieties. The longevity and perennial habit of trees make them especially vulnerable to rare, unpredictable pollution episodes. For this reason they are also especially deserving of built-in genetic protection.

Clearly defined objectives are essential for an effective breeding program. Five kinds of goals were mentioned by Knabe (1967): (1) improved resistance to major pollutants at concentrations somewhat below those injurious to humans, (2) environmental adaptation to the region where the improved variety will be grown, (3) resistance to other important pathogens, (4) rapid growth and good wood quality of forest species, (5) high filtering capacity and long life of trees planted in urban regions. Plant breeders may need to compromise between selecting trees that tolerate pollution best and those that absorb pollutants at higher rates (Anon. 1974). Wentzel (1963, 1967) pointed out that there is a practical limit to the degree to which resistance to pollutants may be improved. He stated that even the most resistant species will succumb to pollutants at some point. In the case of Norway spruce (which is similar to eastern white pine in its sensitivity and variability), Wentzel proposed that the utility of resistant varieties may be expressed as a 20 year extension of the period during which trees remain healthy in a region having chronic air pollution. It will be important to resolve how the goal of pollution resistance should be set--in terms of

acute exposures vs. chronic effects, and in terms of single gases vs. mixtures. Information on other pathogens, environmental adaptation, growth, and wood quality of white pine has been related to breeding goals in Bingham et al. (1972) and Wright (1970).

GENETIC VARIATION IN RESISTANCE

The existence of sufficient genetic variation in resistance is another prerequisite for success in improvment programs. Large differences have been noted between species, and also between varieties of the same species, in their ability to thrive in polluted regions (Apel 1965, Janson 1925, Krussman 1963). The difficulties in making such comparisons have been discussed by Wentzel (1964, 1968). The presence of considerable genetic variation in white pine is implied by observations of adjacent healthy and injured trees that are commonplace in the literature. It has been confirmed by several studies already cited, in which grafts from healthy and injured trees retain their characteristics after subsequent fumigations in nature or in fumigation chambers. These reports indicate genetic variation within populations. Variation among populations of a species and among species is also of interest. Information on these types of resistence has been summarized by Karnosky (1974) and Ryder (1973).

References to intra-specific variation are compiled in Table 1. Included are eight conifers and seven deciduous species or hybrid groups, within which significant genetic variation has been found in reactions to one or more of four air pollutants. The studies were conducted in North America and Europe.

There are some indications that populations from colder, dryer, or more continental regions are less sensitive. For example, Scotch pines from the Pyrenees Mountains were injured more by sulfur dioxide than others from Finland (Vogl 1969). Washington and Oregon provenances of lodgepole pine were more susceptible to sulfur dioxide than those from Idaho and Wyoming (Lang et al. 1971, Tzschacksch et al. 1969). In Norway spruce, the most resistant populations came from northern regions and high elevations (Tzschacksch and Weiss 1972). A ponderosa pine population from Arizona was injured less than one from California (Karpen 1970). In contrast, red maples from Alabama were injured less than populations from Pennsylvania or Minnesota (Townsend and Dochinger 1974).

Kulagin (1973) classified tolerance to gases on an ecological basis, in attempting to predict the relative susceptibilities of plant species. He reasoned that air pollutants are novel environmental factors, and plants have had insufficient time for the evolution of protective mechanisms against them. But plants do have means of protection against

TABLE 1. EVIDENCE OF GENETIC VARIATION IN REACTION OF TREES TO AIR POLLUTANTS AMONG AND WITHIN POPULATIONS

Species	Differences Among	Pollutant	References
Acacia farnesia	populations	CO	McMillan & Cope 1969
Acer rubrum	populations	O_3	Townsend & Dochinger 1974
Acer saccharum	seedlings	O_3	Hibben 1969
Larix decidua, *leptolepis*	families	SO_2	Schönbach *et al*. 1964
	families	SO_2	Enderlein *et al*. 1966, 1967
Picea abies	clones	SO_2, HF	Rohmeder *et al*. 1962
	populations	SO_2	Tzschacksch & Weiss 1972
	families	SO_2	Enderlein *et al* 1966, 1967
Pinus contorta	populations	SO_2	Enderlein & Vogl 1966
	populations	SO_2	Lang *et al*. 1971
	populations	SO_2	Tzschacksch *et al*. 1969
Pinus ponderosa	populations	O_x, HF	Hepting 1964
	populations	SO_2, O_3 ?	Karpen 1970

TABLE 1. Continued.

Species	Differences Among	Pollutant	References
Pinus strobus	clones	O_3, SO_2	Houston 1974
	clones	HF, O_3, SO_2	Berry 1973
Pinus sylvestris	clones	HF, SO_2	Rohmeder *et al*. 1962
	populations	SO_2	Vogl 1969
	clones, families	SO_2	Vogl 1970
Platanus	families	O_3, SO_2	Santamour 1969
Populus hybrids	clones	SO_2	Dochinger *et al*. 1972
	clones	SO_2	Lampadius *et al*. 1970
	clones	O_3	Wood & Coppolino 1972
Populus tremuloides	clones	O_3, SO_2	Karnosky 1974
Pseudotsuga menziesii	populations	SO_2	Enderlein & Vogl 1966
Ulmus americana	families	O_3, SO_2	Santamour 1969
	clones	O_3, SO_2	Karnosky 1974

adverse natural conditions such as drought, frosts, leaf-damaging pests, and possibly volcanic gases. These might preadapt plants so that they are tolerant or resistant to effects of air pollutants. Examples of such mechanisms may include thick epidermis or waxes which limit gas exchange of leaves, compact internal tissues, closing of stomata during drought, and plant habits which reduce contact between leaves and gases. Relationships have been found between ozone sensitivity and leaf morphology and anatomy of four California pines (Evans and Miller 1972). Low sensitivity was correlated with fewer stomata and more constricted cavities, suggesting that resistance is related to limited gas exchange. The resistance of some spruces to sulfur dioxide may be due to their ability to produce greater amounts of wax and thus lower diffusion of gases through stomata (Hartel and Papesch 1955). Near an industrial plant that emitted sulfur dioxide, the amounts of wax on healthier trees increased when gas concentrations were higher, and reached levels never observed under natural conditions. Trees that showed acute damage had normal or slightly elevated amounts of wax. Variations in sulfur content of needles may reflect differences among individuals in gas uptake rates (Themlitz 1960). Biochemical characterisitics have also been investigated as indicators of relative resistance, such as oxidizability of cell contents (Antipov and Chekalisnkaya 1966) and essential oils (Cvrkal 1959).

Various possible types of resistance to sulfur dioxide were classified by Vogl et al. (1965), and physiological implications for breeding were discussed. Some of these cause reduced uptake of sulfur dioxide, and others reduce injury of leaves or entire plants despite exposure of cells to high pollutant levels. Certain ones can be useful to breeders, while others may complicate selection if they are not taken into account.

SELECTION METHODS

There are several ways of comparing relative sensitivities of trees in order to select the most resistant ones for propagation or breeding. Indirect selection for physiological, anatomical, or morphological traits correlated with resistance could be practiced. However, it is likely to be less effective than direct selection for resistance unless all correlated traits are completely understood, and also more easily measured (Gerhold 1972).

The safest procedure is to select the healthiest of trees that have been exposed repeatedly to air pollutants in nature, based on performance of whole plants similar in age and environmental conditions. This approach has been used successfully with Norway spruce and Scotch pine (Rohmeder et al. 1962, Rohmeder and von Schönborn 1965, 1967, 1968); and eastern white pine (Houston 1974, Houston and Stairs 1973). Repeated observations of crown damage to spruce trees over a period of years

indicated that most individuals remained in the same resistance category, though some shifts in both directions were noted (Lampadius et al. 1970, Wentzel 1967). Some trees that at first seemed resistant later died. In older forests dominant trees generally were more sensitive than co-dominant trees. In younger stands suppressed trees were killed by pollutants before more successful competitors. The resistance of trees that have been selected in this manner needs to be ascertained by subsequent fumigation tests using progeny or vegetative propagules.

Another method is to fumigate many trees when they are small, and then retest the more resistant ones when they are older. This makes it possible to achieve higher selection intensities under better controlled conditions. Young white pines have been selected sequentially for resistance to sulfur dioxide from a power station, fluorides from a fertilizer plant, and oxidants from vehicular traffic (Berry 1973). Of 1428 survivors from 2400 seedlings, 4.5 percent were resistant to all three types of pollutants. By using fumigation chambers, many more exposures per year are possible and environmental conditions may be carefully controlled.

Conventional chambers have been used for many of the studies in Table 1. In others, specially designed outdoor chambers were employed that simulate real conditions more closely. Gerhold et al. (1972) developed a tubing fumigation system which is especially suited for estimating genetic parameters needed for a breeding program.

Rapid tests in which detached plant parts are fumigated may be useful for making initial selections or for experimental purposes. A method for fumigating excised twigs was developed for Larix (Bortitz and Vogl 1965) and later adapted to Pinus (Vogl and Bortitz 1968). A similar technique employs excised pine needle fascicles (Schütt et al. 1970).

More precise results can be achieved if effects of dosage, growth stage, environmental conditions, and other non-genetic variables can be defined, as has been done with Virginia pine exposed to ozone (Davis and Wood 1973 a, b). In the absence of such information, or because of it, several investigators have recommended that plants be fumigated on several dates during the growing season (Demeritt et al. 1971, Tzschacksch et al. 1969, and others). Better estimates of resistance levels can be derived from repeated exposures, because these take into account interactions of genotypes with varying environments, and reduce random variability.

Data from fumigation experiments commonly are characterized by binomial rather than normal frequency distributions (Demeritt et al. 1971, Tzschacksch 1972). These may be caused by deviations from optimum fumigant dosages, different resistance levels or types, climatic variables, or nutrition levels. The distributions may have important implications for experimental design, data analysis, and plant selection.

INHERITANCE OF RESISTANCE

Estimates of the degree of genetic control over variation in resistance are rare. Genetic information is needed for designing efficient selection procedures and for predicting the amount of improvement that can be achieved through alternative breeding methods.

The upper limit of genetic control for tolerance to sulfur dioxide and ozone was estimated by clonal repeatability analysis of white pines exposed in greenhouse fumigation chambers (Houston and Stairs 1973). Selected tolerant and sensitive clones were exposed 6 hours to 2.5 pphm sulfur dioxide and 5 pphm ozone. Repeatability estimates of 0.5 for needle elongation and 0.8 for needle injuries indicated strong genetic control. The results suggest that resistant individuals could be identified in the field with little error. Nothing has been reported about genetic transmission of resistance to offspring in white pine.

A similar study by Karnosky (1975) gave evidence of strong genetic control of response to sulfur dioxide and ozone by trembling aspen. Clonal repeatability estimates were 0.5 for sulfur dioxide plus ozone, and 0.6 for each of the gases applied singly.

Grafted Scotch pine clones and their progenies have been compared in sensitivity to sulfur dioxide (Vogl 1970). Significant differences were found among clones and among families. Clones had been selected previously by rapid tests. There were large differences among some families obtained by mating two males to each of six females. The family means suggested the possibility of specific combining ability, though general and specific components were not reported. High correlation between clone values and offspring values was implied, but not supported by the data.

Demeritt and Gerhold (Unpublished ms.) derived heritability estimates from 30 open pollinated Scotch pine families representing a single population. Seedlings in a nursery were fumigated separately with ozone and sulfur dioxide on several dates. The variance components estimated from needle injury data indicated moderate to strong genetic control. Experiments with other populations indicated weak to moderate genetic control. In a related study (Demeritt et al. 1971), ozone injuries were weakly and positively correlated with sulfur dioxide injuries, and neither was correlated with height of seedlings. Thus it should be possible to select effectively for both types of resistance, with no adverse effects of growth rate. Discontinuities in the distributions of injury scores suggested that few genes or different mechanisms may govern resistance.

BREEDING AND PROPAGATING METHODS

Many combinations of methods may be employed in designing a complete process for selecting, breeding, and mass producing resistant varieties (Knabe 1967). Several tree improvement programs have been started in which resistance to air pollutants is a main objective. They are in early stages of development, so it would be premature to compare the effectiveness of alternative methods. However, there are indications that worthwhile progress is being made.

The development of Norway spruce and Scotch pine varieties with improved resistance to industrial fumes started about 1956 in West Germany (Rohmeder *et al*. 1962, Rohmeder and von Schönborn 1965, 1967, 1968, Wentzel 1967). Phenotypically resistant trees were selected in severely damaged forests and propagated by grafting. Subsequent fumigation tests with SO_2 and HF showed that selection had been very effective for Norway spruce, and to a lesser degree also for Scotch pine. When injury levels of selected clones were tested, they were found to be far below those of normal grafts or seedlings used for comparison. They were also injured less than several deciduous species that are generally considered less sensitive, though the practical implications of this have been disputed by Wentzel (1967). Trees that were selected for resistance to SO_2 generally were also resistant to HF, and *vice versa*. The Norway spruce clones are being propagated by rooted cuttings. Seed orchards have been established by grafting for the production of seed-propagated varieties that can be planted in industrial regions.

A combination of selection methods that would be suitable for improving sulfur dioxide resistance in larch possibly also Scotch pine has been proposed by Polster *et al*. (1965). The leaves are regarded as the most important plant part for expressing resistance. Rapid tests are to be used for initial selections of parent trees. Selected trees are mated, and their progenies fumigated in outdoor chambers. The best families are then planted in industrial regions for further selection according to resistance and growth rate. The best parents may be grafted into seed orchards. Seeds for the growing of resistant varieties could be harvested ten years after selection started.

Seedlings of *Larix decidua* and *L. decidua* x *leptolepis* were evaluated for resistance to sulfur dioxide in fumigation experiments and field plantings (Enderlein *et al*. 1966, 1967, Schönbach *et al*. 1964). The most resistant families in fumigations were hybrids. These were also injured the least and grew tallest in forest conditions. The results are encouraging, in that juvenile selection and seed propagation seem to be feasible, though further confirmation at more advanced ages is needed.

Nine poplar clones were compared in field trials and fumigation chambers at four dosages of sulfur dioxide (Lampadius et al. 1970). The most resistant one and the least resistant two had consistent performances, but others varied widely. It was concluded that young plants in fumigation experiments are imperfect predictors of resistance expressed in forests. Interaction of genotypes with environments is one of the reasons. Another is reliance on leaf injuries, which do not adequately measure recovery and growth of whole plants after injury. Nevertheless, it is acknowledged that fumigation experiments have utility for initial selection.

Dässler (1967) conducted a similar study with five poplar clones and eleven conifer species, comparing potted plants in fumigation chambers to exposures under forest conditions. The results compared favorably, indicating that short, acute exposures are useful for experimental purposes.

The reliability of rapid tests of sulfur dioxide resistance was evaluated using four of 16 Scotch pine clones (Vogl and Bortitz 1968). The two most resistant and the two least resistant, selected according to rapid tests, were compared under various conditions. The ranks remained the same after exposure to 0.6 ppm for several days, to 200 ppm, and at various seasons with different weather conditions.

All of the tree improvement projects mentioned so far are European ones. The main efforts in the United States have been directed toward white pine (Berry 1973, Houston and Stairs 1973), Scotch pine (Gerhold and Palpant 1968), loblolly pine (in 17th Annual Report, Cooperative Tree Improvement and Hardwood Research Programs. School of Forest Resources, North Carolina State University 1973, pages 50, 51), and red maple (Anon. 1974). The work on white pine consisted mainly of selection, vegetative propagation, and testing, as described previously. Little has been published on the other species, except for Scotch pine.

The breeding objectives, selection methods, and information needed for the design of a Scotch pine breeding system were described by Gerhold and Palpant (1968). The goals of the program were to maximize resistance to sulfur dioxide and ozone, to maintain the environmental adaptability of varieties commonly used in northeastern United States, and to exploit remaining variability in ornamental qualities on an opportunistic basis. Several hundred artificial matings were made among trees from diverse geographic origins, extending from Scotland to Siberia, and Spain to Sweden (Karrfalt et al. 1976). Seedlings from the initial matings have been selected after fumigation tests conducted under nursery conditions (Demeritt et al. 1971, Gerhold et al. 1972). Further progress is uncertain because of a lapse in financial support.

Research needs related to pollution-resistant trees for northeastern United States were analyzed recently (Gerhold, H. D. 1976). Long-term research is needed on six questions:

1. Which of the commercially available species and cultivars can be recommended for planting in polluted localities?

2. In which species should genetic improvement projects be started?

3. What methods are most effective in selecting for pollution resistance? Subsidiary questions involve selection criteria, frequency and season of exposures, environmental and age effects, fumigation dosages and gas mixtures, and types of fumigation chambers.

4. What is the best way of searching for resistant genotypes?

5. Which breeding methods and mating designs are most effective for creating improved varieties?

6. Which propagation methods are most appropriate for mass producing new varieties?

These questions are inter-related. Priorities for research can be set most logically by considering the relative sensitivities of species, their values in plantings, and the probable success of breeding projects in operational and commercial contexts. Several experts who have reviewed related literature have recommended research on improving the genetic resistance of trees to air pollutants (Doolittle 1969, Heck et al. 1973, Kisser 1966, Knabe 1972, Sinclair 1969). These kinds of research are not likely to be carried out unless substantial, long-term support is provided by Federal agencies responsible for reducing pollution damage to timber and landscape species.

SECTION VI

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16. ABSTRACT

Effects of the main phytotoxic gases that injure eastern white pine (Pinus strobus L.) and the possibilities of breeding resistant trees are discussed in a comprehensive literature review. The main purpose of the report is to summarize knowledge which may be used in providing protection to a valuable species. Implicitly related topics are reviewed briefly, including sorption and emission of gases by plants, air quality standards, bioindicators for monitoring air quality, and silvicultural measures for protecting trees against injuries.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
1. Eastern White Pine (Pinus Strobus L.) 2. Pollution (SO_2, O_3, and NO_2) 3. Resistance 4. Breeding	1. Breeding for resistance 2. Air pollution effects	

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