STRESS AND URBAN TREES

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Introduction

Despite the probable harm that unfavourable environments do to the natural forest ecosystem, there is much evidence that some forest trees are uniquely resistant to environmental stress. Bristlecone Pines (*Pinus aristata*), are the world's oldest living things, having survived for thousand of years, in an extremely hostile environment. The survival of these trees has required integration and coordination of physiological processes occuring in widely separated roots and shoots. As Kozlowski (1979) has observed, it is remarkable that trees can live for more than 3,000 years and maintain the necessary transport of food, water, hormonal growth regulators and minerals over distances of several hundred feet. The survival of old and large trees is even more remarkable when it is considered that the stem tissue, through which carbohydrates move between the crown and the roots, is a layer of inner bark that is little more than a fraction of a millimeter thick. It is obvious that from a physiological standpoint, trees have evolved in such a way as to survive the periodic environmental extremes encountered in nature.

The environmental changes that alter tree growth do not do so directly but rather indirectly through their influence on rates and balances between photosynthesis, respiration, assimilation, hormone synthesis, absorption of water and minerals, translocation of growth requirements and more subtle changes in physiochemical conditions within the tree. It is not a purpose of this paper to examine the physiological disfunctions and growth responses of trees subjected to normal or abnormal stress. Rather, this paper examines the types of abiotic stress to which trees are exposed in an urban setting and provides some tabular information on tree species sensitivity to stress. Nevertheless, a brief discussion on the nature of stress opens the section entitled Discussion.

The importance of stress in the urban setting is not that it necessarily takes its toll in the rapid and obvious death of trees but rather that the manifestations of stress, such as growth inhibition, twig and branch dieback, loss of vigor, abnormal coloration, excessive deadwood and change of growth habit, stem cracks or loss of bark, as well as diminished longevity means that many urban trees fall far short of reaching their full potential yield of benefits to the urban population.

Trees growing in the urban setting may be broken into a number of classes. For example, street trees in narrow tree lawns

along the edge of streets, trees in centre medians, trees in both large and small urban gardens; trees in parks as single trees, clumps of trees or larger areas of closed canopy; trees in derelict land, trees in residential land that cannot be built upon such as ravines, steep banks and floodplains; trees in recreation sites such as golf courses; and finally trees in greenbelt or institutional lands retained for screening, erosion protection, future development and similar activities.

Each of these circumstances is one where the potential for abiotic stress, that is, stress of a non-pathological nature is potentially greater than the growing conditions of native forests. The more alien the conditions, the greater probability that stress thresholds will be exceeded for many tree species and for individual trees. Subsequently, these trees will require increased costs of maintenance or replacement than would have been required if either care in protection of an existing resource or more thoughtful choice of species had been taken long before stress symptoms or decline became evident.

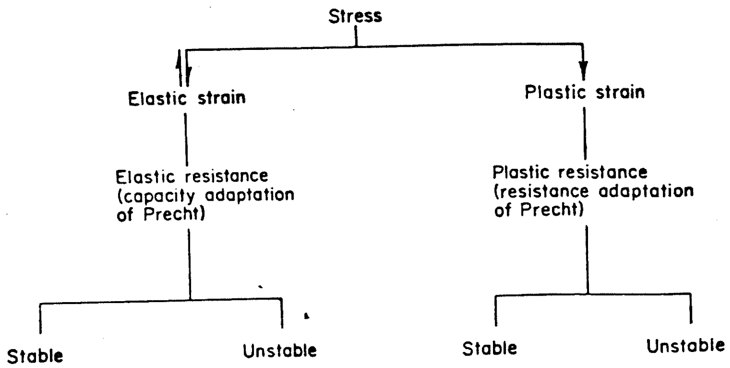
PATHOLOGICAL STRESS FACTORS OF PLANTS

Cause injury		*Cause disease*	
Abiotic	*Biotic*	*Abiotic*	*Biotic*
Moisture extremes Temperature extremes Wind Snow Ice Lightning Salt Radiation Pesticides	Birds Mammals	Air pollutants Mineral deficiencies and excesses	Nematodes Viruses Bacteria Fungi Plants (higher)

A principal purpose then of this paper is to examine the various stresses to which urban trees are subjected and in so doing to determine, wherever possible, those species that can withstand particular urban stress conditions and those species of trees that are particularly susceptible with the intention that this information can be used for more informed tree choice in urban planting.

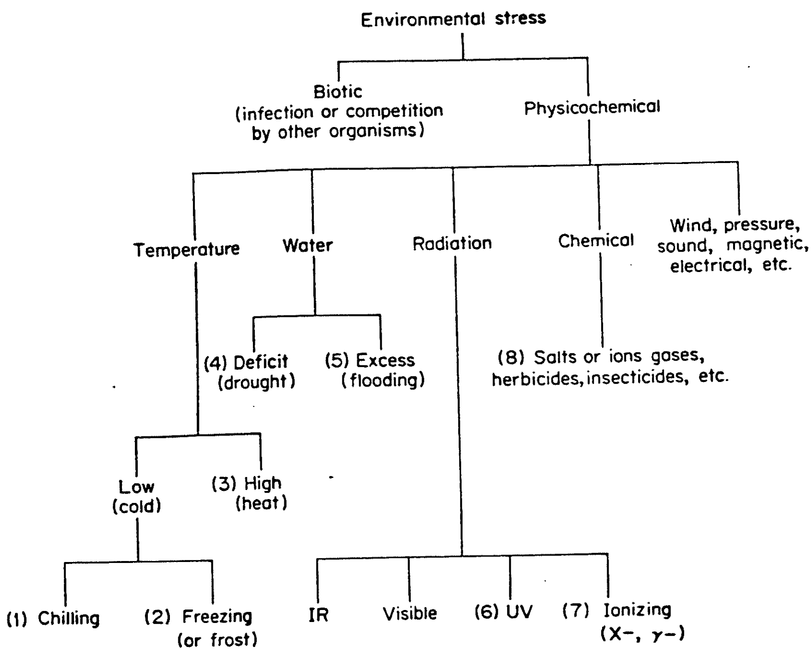
Discussion

The nature of stress injury and resistance in trees is discussed primarily by two authors; Levitt (1972) and Kozlowski (1979). From the work of these two researchers it has been determined that environmental stresses adversely affect trees in different ways. They mainly induce a direct plastic strain, recognized by rapid appearance of injury. An example would be the killing of physiologically active plants by sudden exposure to freezing temperatures. Environmental stress may also produce a non-injurious, reversible, elastic strain, which, if maintained for a long enough time may induce an irreversible and injurious plastic strain (Kozlowski 1979). Additionally, an environmental strain may cause injury by inducing a secondary stress. For example, high temperature may induce plant water deficits, which in turn cause injury. Such secondary stress injury may not develop for a considerable time. Hence, long exposure to the primary stress may be necessary. Conceivably, a secondary stress may induce a tertiary stress that may also cause injury or growth loss.



Adaptation to Stress.

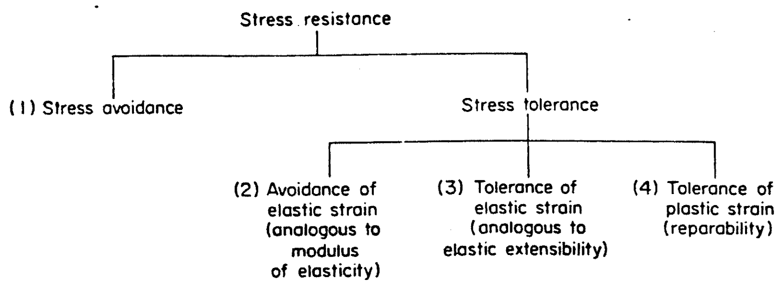
Levitt (1972) classifies environmental stresses as either biotic or physiochemical: the former encompasses infection or competition by other organisms; the latter includes effects of radiation, water, temperature, chemical substances, wind, pressure, sound and similar effects.



Kinds of environmental stresses to which an organism may be subjected.

Fortunately, trees, like other organisms, appear to be able to adapt to certain stresses. When stressed, they gradually change to decrease or prevent strain. It can be assumed that adaptations that have arisen by evolution over a long time are stable, at least in the mature plant. On the other hand, the adaptation threshold or ability may be poorly developed in the immature tree. Kozlowski observes that insomuch as growth is an integrated response to physiological changes, regulated by a complex of many fluctuating and interacting factors, including environment, responses may vary remarkedly in different parts of a tree and they may vary with the age of trees. Thus the effects of an environmental stress on trees must often depend on the phenological stage and physiological status of the tree at the time of the occurrence of the stress.

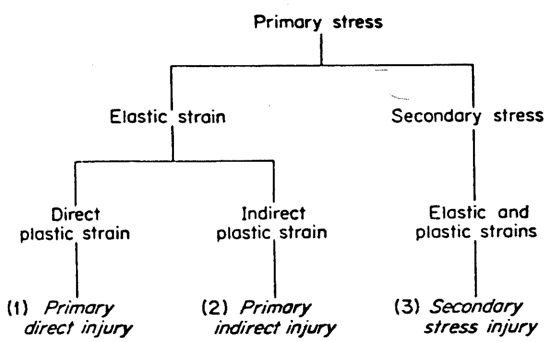
Levitt (1972) suggests, that a number of environmental stresses can give rise to various degrees of resistance adaptation in plants. Stress resistance may reflect stress avoidance, stress tolerance or both. Whereas a stress avoiding plant can somehow exclude the stress, a stress tolerant plant can prevent, decrease or repair the strain induced by stress.



Levitt notes that the term resistance to environmental stress has, until now, been used only for plastic resistance. The concept of an elastic resistance has not been clearly recognized. Levitt draws the distinction between elastic and plastic strains giving the definition for the former as a reversible physical or chemical change in the plant; and for the latter an irreversible physical or chemical change. Levitt goes on to note that another important consideration in plastic strain or change produced by stress is the consideration of time in the context of length of exposure. Not only may the degree of stress carry the plant from an elastic strain to a plastic strain but it may also be a function of duration of the stress.

Both Levitt and Kozlowski note that it is important to understand how stresses produce their injurious effects and how some trees have succeeded in surviving stresses that injure others. Levitt notes that an important first step in this assessment is understanding how a stress acts on a plant and how the type of injury which occurs may differ from plant to plant. The stress may induce a direct stress injury that can be readily recognized by the speed of its appearance. An example would be the rapid freezing strain produced by sudden low temperature stress. On the other hand, the stress may produce an elastic strain which is reversible and, therefore, not injurious of itself.

If maintained for a long enough time the reversibility of the strain may give rise to an indirect irreversible strain, which results in injury or death of the plant. This indirect stress injury may be recognized by the long exposure of days or months to the stress before the injury is produced. Levitt provides an example of indirect stress injury, the case of chilling stress, which exposes the plant to low temperature, too high to induce freezing. The strains may be mainly elastic, involving the slow-down of all of the physical and chemical processes in the plant which may not be injurious themselves, but which may disrupt the plant's metabolism, leading to a deficiency of a metabolic intermediate or production of toxic substances. A third case suggested by Levitt is that often referred to as secondary stress injury. Here, high temperature, for example, may not be injurious of itself but may produce a water deficit which can, in turn, injure the plant as lack of turgidity eventually results in severe wilting, cell collapse and death of tissue.



Kinds of stress injury.

While Levitt discusses, in some detail, stress avoidance, that is, the ability of certain trees to exclude a particular stress either partially or completely, it is stress tolerance the ability of a tree to come to thermodynamic equilibrium with a stress without suffering apparent injury through being able to prevent, decrease, or repair the strain, induced by stress that is perhaps more important in the context of this paper as is the point made by Kozlowski that the effect of an environmental stress may not be evident for a very long time.

TWOFOLD NATURE OF STRESS RESISTANCE

Stress	Condition of resistant plant cells exposed to the stress and surviving due to: Avoidance	Tolerance
(1) Low (chilling) temperatures	Warm	Cold
(2) Low (freezing) temperatures	Unfrozen	Frozen
(3) High temperatures	Cool	Hot
(4) Drought	High water potential	Low water potential
(5) Radiation	Low absorption	High absorption
(6) Salt (high conc.)	Low salt conc.	High salt conc.
(7) Flooding (O_2 def.)	High O_2 content	Low O_2 content

Since few of the papers examined in this review have used or described in detail any experimental protocol for determining their classifications of stress resistance or susceptibility, the work of Levitt and Kozlowski is of importance in considering the reliability of any of the tables provided by the authors examined for each type of stress discussed here. Notwithstanding this proviso, however, and the theoretical work conducted by Levitt and Kozlowski amongst others, there is certainly some merit in drawing on the field experience of the authors reviewed.

If, as this paper suggested earlier, the important need is for careful choice of species in the urban setting, a more important, yet little understood area is that of assessing the environment or some of the external forces that will affect a tree prior to its installation. Two pragmatic solutions to this dilemma are apparent. The first might be for the urban tree manager to equip himself with the knowledge and equipment that allows very accurate diagnosis of stress induced symptoms such as twig and branch dieback, short growth increments, decay, and such stress manifestations as small leaves, early fall colouration, heavy seed production, and unthriftiness. In this way it may be possible to determine a direct correlation between particular species, their environment and induced stresses that particular species cannot tolerate. While single instances will be of little assistance in preparing informative tools, a thorough examination of a large resource may yield patterns of stress and stress reaction that would implicate particular species as being unsuitable for urban conditions.

A second approach is that espoused by Tattar who suggests, as shown in the accompanying model, that the most appropriate approach to ensuring tree growth in the urban setting is by reproducing, as far as possible, the environmental conditions that trees have been exposed to during evolution in their natural setting.

STRESS MODELS FOR TREES IN THE URBAN ENVIRONMENT

Alpha Model

Low urban stress

"natural" forest ecosystem
natural site selection of trees for soil, temperature and moisture regimes present
people-pressure is rare or nonexistant

Omega Model

High urban stress

urban environment
planted trees, often exotic species, no follow-up care
temperature and moisture extremes
nutrient imbalance
people-pressure is common

Positive Interference by People

Beta Model

Minimal urban stress

"Forest-like" urban environment
Moisture and nutrient balance provided--watering, fertilizer
Temperature extremes moderated--mulching, group plantings, wide "green belts"
People-pressure minimized--barriers to traffic, sufficient root space, construction not allowed near trees, no salt, educational programs for youth
Trees selected for tolerance to urban stress
Proper planting including follow-up care for new trees

[1] Adapted from a paper presented at the 9th International Congress of Plant Protection, August, 1979, Washington, D.C.

While sound perhaps in theory, this approach is manifest impractical in two counts. The first is that some environmental stresses, such as light strike-back from buildings and weather conditions cannot be mitigated against

while others such as drought, though possible to overcome by watering, are largely impractical for most municipalities where the constraints on labour, equipment and funding preclude all but the most minimal maintenance programs. Tatter (1980) does, however, suggest in his Beta model that trees can be selected for tolerance to urban conditions. The remaining section of this paper examines this possibility in the context of abiotic stress and, wherever the information has been available, reviews species reaction to the stress type discussed.

A number of the authors read in the course of a literature review for this paper found to review stress and stress mechanisms in only a very general sense; while other authors, although discussing a particular stress in greater depth, did not provide any extensive accompanying tables. Moreover, some authors described the effects of a particular stress on only a few species and often by common name alone. No attempt has been made to add credibility to these reviews by tabular summaries of the information provided. Only those tables that were reasonably comprehensive are included in this paper. A common thread throughout all of the work examined in this brief review is that of limited applicability when information is viewed in the context of specific instances or when comparisons are attempted between one study and another. A case in point is that of salt resistance, where tables are provided by a number of authors but often no information is given as to whether the tolerance or susceptibility to salt is from root uptake or windblown salts, nor in some cases is information provided as to the type of salt involved. In addition, the whole concept of "injury" is poorly elucidated and described by almost all authors, with tables and text providing little indication as to whether the tables refer to a spectrum of damage from slight to severe and whether or not a number of plants were viewed in order to reduce the variability of result inherent in using semi-mature or mature tree stock of unknown origin for experimental purposes.

It must be concluded that in almost all cases the tabular information provided by most authors is of use only for general guidance and most tree species assessments are of but a relative nature. Finally, some authors do not indicate the source of some or all of their information. This has, I suspect, led to a duplication of some lists and the propagation of any misinformation from one source to another.

SOIL AERATION AND COMPACTION

Despite the probability that soil compaction plays an important role in the declining health of many urban trees, particularly in high foot traffic areas such as parks, golf courses and in the grass/tree or blacktop/tree interface of many landscaped areas, particularly in recent development sites, very little appears in the literature concerning this problem. Kramer and Yelenosky writing in 1963 reported on their research "Soil Aeration and Growth of Shade Trees" found that, as a result of questionnaires sent out "Yellow Poplar was least tolerant of compaction followed by White Oak, Sugar Maple, Honey Locust and at the other end of the scale American Elm the most tolerant".

In subsequent flooding experiments on these species only elm could tolerate two months of inundation and recover. Soil air measurements in a field experiment found that in compacted soils (not specified) where tree death was apparent, there was only 4% oxygen and over 20% carbon dioxide. There was substantially less oxygen in of the soil here than in an adjacent forested area (the comparative figure is not described).

Patterson (1977) provides a useful analysis of the effects of soil compaction on urban vegetation. He notes that soils are very complex, naturally formed entities which vary widely with the natural landscape. The principal mineral fractions to be considered are sand, silt and clay. The sand fraction (2.0 m - 0.05 m) is virtually inert but does provide vital structural capabilities for the soil mantle and assists in reducing compaction. Silt (0.05 m - 0.002 m) also provides structural support as well as some contribution to fertility. The clay fraction (0.002 m and smaller) provides much of the nutrient and thus fertility capability of the soil and supplies much of the matrix of soil structure and till.

Patterson suggests that these three fractions combined provide 45% of an "ideal" soil. The remaining 55% would be composed of 5% oranic matter, 25% air spaces (N_2 forming 79.2%, O_2 20.6% and CO_2 0.2%) and 25% water or moisture capability. These latter areas, or pore spaces, are ideally composed of equal amounts of air and water space, but fluctuate widely depending on rainfall, humidity, temperature, area use and degree of compaction.

Patterson has suggested (1966) that in areas of intense use the soil parameter which seems to best indicate soil condition is bulk density. Pearson suggests that bulk density is an expression of the mass per unit volume and can be an indicator of a wide variety of soil properties. Pore space then, ideally 50%, is the portion of the soil matrix that is directly and adversely affected by heavy use (Cordell and James 1971). Pore space distribution, i.e., the distribution of macro and micro pores does not remain constant, but is altered by compaction, cultivation, aggregation, fertilization, etc. (Waddington

1968). With compaction, for example, the solid phase of the soil increases per unit volume. In other words, the pores that suffer most from compaction are the large macro pores and there is a resulting increase in the smaller micro pores. Compaction creates poor soil moisture relationships with less available moisture for plants, irregular soil temperature relationships, a less desirable soil atmosphere, resistance to root penetration, increased runoff and erosion and other inter-related problems for tree growth. Reports vary when considering the percent pore space required for adequate plant growth. Percent pore space also seems to vary for different plant species. For example, Van Der Valk (1971) has suggested that when the percent total pore space is less than 44% growth can be impaired. Vigor of most plants seems to suffer under compacted soil conditions where the pore space volume drops below 30 percent. As there is a balance between soil atmosphere and soil water, saturation can cause soil pores to be filled with water, leaving little pore space for soil gases. As water is lost to evaporation, percolation, transpiration and other causes, the volume of the soil atmosphere increases. During very dry periods the gaseous phase predominates and little water is available for plant use. Sekiguch (1973) noted that for street trees moisture depletion can occur rapidly and can vary widely from location to location. According to a number of authors (Hady 1974, Dusberg and Baker 1970, and Youngberg 1970) oxygen in the soil profile is the key to regulating plant growth. It is generally concluded by these authors that an oxygen content of less than 10 percent by volume substantially decreases tree root growth. Pirone (1972) has listed some species affected by poor soil aeration. Most severely injured were Sugar Maple, Beech, Dogwood, Oak, Tulip Tree, Pines and Spruce. Less severely injured were Birch, Hickory and Hemlock; while least injured were Elm, Popular, Willow, Plane, Pin Oak and Locust.

Flooding

Gill (1970), in a review of flooding tolerance of woody species, found that type and degree of injury varied with species, soil type, and flooding regime. Symptoms included decreased growth rate of roots and shoots, decreased transpiration rates, leaf chlorisis, epinasty, leaf abscission, death of roots, absence of fruiting, increased susceptibility to predator and pathogen attack and, after prolonged exposure for some species, eventual death. The most critical factor was found to be a direct effect of exclusion of oxygen from the root system, with an increase in CO_2 accumulation and the production of certain metabolites such as sulfides which initially cause cessation of root growth and eventually death of tissues. Bernatzky (1978) suggests that oxygen supply is not the only factor enabling trees to survive. In most flood tolerant plants alcohol is the usual product of anaerobiosis. When flooded, these plants steadily increase their rate of ethanol production. Moreover, in flood tolerant trees there are a large number of substances that can accumulate during the period anoxio without any toxic effect on the plant's cells. Bernatzky also suggests that flood tolerance may be linked to the production of certain metabolites in the roots and by the translocation of anaerobic respiration products from the roots to the aerial sections of the tree. A higher root/shoot ratio is also suggested as leading to greater flood tolerance. Tattar (1978) notes that tree roots are injured when the oxygen concentration drops below 10 percent and root growth stops entirely at concentrations below 3 percent. When water stands over the roots, the soil becomes saturated for long periods during the growing season, gaseous exchange cannot take place between roots and air, and soil conditions become anaerobic. The roots suffocate under these conditions and most trees will soon begin to decline or die. The effects on a tree of any given period of inundation or soil saturation seems to vary with the species, time of year, and duration of suffocation stress. In general, it seems the effects of water excess will be greatest during the growing season, will be directly related to the duration of the stress and will occur most quickly on upland species not tolerant to natural flooding. Bell and

Johnson (1974) confirm this finding from flood-caused mortality around Illinois reservoirs. Increased flooding duration resulted in increased mortality amongst upland species, while floodplain species were completely tolerant. Many of the latter completed their annual growth cycle in spite of flood conditions throughout the growing season. In a short note in the Journal of Arboriculture, Baker (1978) found, in a three year flooding test of seedlings under natural conditions, that Green Ash and Sycamore showed 95 percent survival while Water Tupelo gave 64 percent survival and surprisingly, Cottonwood was consistently poor, averaging 21 percent survival. Sweet Gum was very variable and exhibited 0-80 percent survival, possibly depending on seed province. Kozlowski and Davies (1975) noted that the symptoms of flooding were leaf yellowing and mottling, shedding and death of leaves, inhibition of shoot and root growth, death of twigs, branches and roots, and eventually death of individual trees. These authors also noted that extent of injury depended largely on species, soil type, drainage conditions and duration of flooding.

White, in an interesting study reported in 1973, observed the aftermath of the torrential rains of Hurricane Agnes in 1972 which struck New York State, where damage not only included rapid flash flooding along stream and river banks which subsided within 24 or 72 hours, but also lakeshore areas which were inundated from 10 to 15 days. A list of species is provided in the short article of shade and ornamental trees as well as evergreens that died as a result of the flooding. The author notes that no plant was listed unless a number of specimens of the same type had been observed. Also included was a short list of evergreen, shade tree and shrub "survivors". These plants had tolerated the unusual conditions and had no leaf drop or apparent ill effects when checked even some three months after flooding had taken place.

Drought

Tattar (1978) notes that trees are subject to two kinds of water deficiency stress:

(i) Short term drought during one growing season, and

(ii) Long term drought that accumulates moisture stress over more than one growing season.

Tattar suggests that the latter is the most important to trees because, in contrast to annual crop plants, trees are sensitive to year-round moisture conditions. As Smith (1970) observes, adequate supply of water is of critical importance for tree development. In addition to being the primary component of green tissues, frequently 90 to 95 percent of the fresh weight, water renders mechanical strength via cell turgor to unlignified tissues, acts in metabolic reactions both as a raw material and as a conditioner of various reactants, and assumes a fundamental role in the distribution of disolved materials in the transpiration stream.

Many site factors increase the susceptibility of shade and ornamental trees to moisture stress. Restricted root space is probably one of the most important contributing factors to moisture deficiency stress. In many cases, trees growing in confined locations such as street trees, are sandwiched between roads, sidewalks and residential driveways. These trees are often not able to extend their roots into sufficient soil area for them to meet the demands for moisture from the tree crown. Such trees can usually survive under normal moisture conditions by growing at a slow rate but are usually the first to be affected by drought conditions. Trees in shallow soil may also be prone to moisture stress, while trees whose roots are shallow because of high water tables would be susceptible to drought when the water table falls. An important contributing factor to moisture stress is, of course, subnormal rain and snowfall as was experienced in Britain in 1976 (Agripress 1978). In this instance the severe drought in the summer of 1976, followed by a dry winter, caused considerable Beech dieback with Birch almost totally defoliated in some locations as well as Larch and Western Hemlock being badly hit amongst the conifers. In almost all locations; Oak with its generally deeper root system were found to be little affected.

Water deficits in plant growth has been extensively reviewed by Kozlowski (1968). Extremely complex hypotheses as to the mechanisms of drought injury have been developed by this author and others. However, it seems that it is most commonly a complex of dehydration and overheating. Dehydration and overheating alter normal metabolism and protoplasmic structure. Severe overheating causes hydrolosis of proteins into constituent peptides and amino acids. Toxic amounts of ammonia may be released during this process. In addition to hydrolysis, other reactions to moisture stress are thought to be important. Dehydration increases the protoplasmic viscosity and interferes with the process of phosphorylation. This would critically reduce a tree's ability to accumulate and transform energy. As drought increases, there is also mechanical injury to protoplasm when cells rapidly loose water and cell walls and membranes collapse. Zahner writing in Kozlowski (1968) notes that water deficits affect not only foliar components of the tree but that root development, reproductive growth, growth in girth and extension growth are all diminished by drought stress. Bernatzky (1978) notes that reduction of root growth gives diminished absorption of nutrients and water and increased danger of death through drought and windfall. Beernatzky also notes that trees having tap root systems and intermediate root systems (as shown in the accompanying table) are probably less prone to moisture stress. Caution is urged on the user of this table, however, in that root characteristics may be modified by repeated transplanting, by particular site and soil conditions, and by obstructing layers in the soil profile.

Kozlowski and Davies writing in 1975 suggested that resistance to water movement through a tree causes internal water deficits due to transporation during the day. At night the stomata close so that absorption and transpiration can overcome the deficit. However, the effects of drought conditions on a tree first produce closing of the stomata through loss of turgidity of the guard cells. Wilting then takes place, first as an incipient reaction with no observable leaf droop, followed by temporary wilting where the leaves droop but recover at night, and then permanent wilting, which requires rewetting of the soil for recovery. If prolonged, permanent collapse of cell tissue occurs. In addition to wilting, which Smith suggests is very evident in such trees as Black Cherry and Dogwood, leaf discolouration and distortion occurs, particularly on broad-leaf trees where marginal scorch tends to progress inward toward the mid-leaf region. Frequently leaves will curl upward. Another clear symptom of drought stress, well seen on maples adjacent to the campus, is premature autumn colouration. Smith (1970) notes that Black Cherry, Yellow Popular, and Hickory commonly turn yellow before wilting or curling, while coniferous species reacting to early summer drought will have shorter needles with yellow tips later turning brown and progressing down the needle. Hamilton (1978) reporting the effect of California's drought on landscape horticulture found that stunting, leaf burn, necrosis and early leaf fall were all evident on such species as Populus nigra, Magnolia grandiflora, Aesculus hippocastanum, Fraxinus velutina, Platanus acerifolia, and Eucalyptus globulus as well as foliage, twig and limb dieback in Arbutus menziesii, Sequoiadendron giganteum and Sequoia sempervirens. Junipers were found to be the most drought hardy along with the true cedars, while at the other end of the spectrum Magnolia and Betula alba were found to be the most drought sensitive. Other symptoms recorded by some authors (Hinckley 1975, Smith 1970, Hibben 1978, and Etherington 1979) include stem cankers and drought cracks, the latter particularly on coniferous species, progressive dieback in the upper portion of crowns, invasion of bark by canker fungi, and actual stem shrinkage.

Before leaving this section it is perhaps worth noting that winter drying can also be associated with drought conditions. Broad-leaved and needled evergreens are subject to loss of water in the winter. Since the soil around the roots is normally frozen, water lost through transpiration at this time cannot be replaced. The severest winter water loss usually occurs in late winter on warm and windy days. The symptoms of this winter burn are often not fully evident until spring and the affected foliage, appearing yellow to brown, presents a sharp contrast with the newly emerging green foliage.

High Temperature

Trees in the northern hemisphere exhibit the most successful growth at some average, optimum range of temperatures. Tree species also have a maxima and a minima temperature range for growth which, if exceeded, will result in abnormal physiological responses. High temperatures are probably more readily attained in the natural environment than is commonly realized. Smith (1970), for example, notes that during the summer the south side of a pine tree may reach 55° C (130° F) and that soil surfaces exposed directly to the sun may exhibit temperatures in the range 55° to 75° C (168° F) in some arid and desert conditions.

The exact mechanisms of heat injury do not appear to be well understood. Overheating appears to alter the colloidal-chemical properties of protoplasm and induce metabolic changes which may contribute to abnormal physiology. High temperatures seem to cause denaturation of proteins. Protein decompostion may in turn lead to the release of ammonia in toxic amounts. It is interesting to note that in some heat resistant plants high temperatures have been shown to induce the accumulation of organic acids. These acids react with ammonia produced from protein decomposition to form various salts and amides which in turn mitigate the ammonia's toxic influence. Whatever the mechanism, trees, as members of the plant community, are poikilothermic organisms, with their own temperatures tending to approach the temperature of the surroundings. It is only when ambient temperatures exceed 35° C that cessation of photosynthesis occurs and incipient damage to physiological processes will occur.

A number of symptoms are important in recognizing temperature stress. Perhaps the most commonly recognized is that of sunscald, also referred to as sun scorch, where thin barked trees such as Alder, Dogwood and Beech have become suddenly exposed to direct intense sunlight. This situation is commonly experienced in the Lower Mainland of British Columbia whenever forested areas are excessively thinned to create housing lots or recreational areas. Two events may occur as a result of this type of stress, summer sunscald and winter sunscald. Summer sunscald is heat injury to the exposed bark during the summer and often results in bark killing with subsequent canker formation. Wood beneath the dead bark is sometimes invaded by decay fungi and trees may break in this area after being affected for a few years. Where summer sunscald injury has been combined with accompanying drying of sites, tree losses can be substantial, particularly on sites with a predominance of Alder. Winter sunscald is injury from rapid changes in bark temperature during cold and sunny winter days. Such injury, especially on species with dark bark, appears to occur when the sunny side becomes much warmer than the surrounding air temperature. The rapid temperature changes in the later part of the day can result in bark injury that usually occurs on the southwest side of individual trees.

Other symptoms of high temperature stress include leaf burning, characterized by the development of reddened or browned patches on broad-leafed species and necrosis of the distal portions of coniferous needles on conifer species. Another symptom of high temperature stress is evident in forest nurseries. Seedling damage is very common during the first or second year in the seed beds. Small seedlings seem to typically collapse, while larger individuals become girdled but remain standing. The latter gradually decline as the flow of food materials from the leaves is restricted by small lesions. Lath shading of conifer seedlings has now become a wide spread practice in many nurseries. My own experience at the Forestry Commission Nursery at Bankfoot Scotland has been of the loss of 100,000 Sitka Spruce seedlings as a result of 3 days exposure to temperatures in the high 90° F (33° C).

Harris (1972) has reported on the problem of high temperature limb breakage. This phenomena as yet has no explanation. Limbs fall from trees on hot still summer afternoons. Elm, Oak, Pine, Plane, True Cedar, and Douglas Fir appear to be implicated. The factors involved seem to be high temperature, moisture stress and wood strength. The problem is evident in the Lower Mainland particularly in the Municipality of West Vancouver where Douglas Fir high temperature limb breakage has been of concern for safety reasons in Lighthouse Park.

Low Temperature

The use of the term stress in the context of low temperatures may be somewhat misleading since cold temperature effects are normally viewed in the context of direct injury. Native trees which have adapted to northern climate are not usually injured by low temperatures. Exotic trees from more southern latitudes have not adapted to temperature peculiarities of particular locations and are usually the most prone to cold temperature injury. Woody plants have adapted to winter conditions by an established pattern of growth and dormancy that follows the yearly weather cycle very closely. They can tolerate extreme cold during the winter but little during the growing season. As fall approaches trees begin to become more progressively cold hardy, reaching a peak of hardiness in mid-winter. A decrease in hardiness begins in early spring and the trees may reach a low point of cold tolerance during the spring flush. Tattar (1978) notes that this is the most vulnerable time for cold injury. A spring frost can do considerable damage to many trees and may even kill them. Injuries are most commonly seen on flowering trees such as Crabapples, Magnolias and Lilacs whose flowers are often killed by light frosts. Obviously, the later into the spring season the frost occurs, the greater the chances that even native trees will be injured. Most authors (Schoeneweiss 1978, Smith 1970, Levitt 1972, Levitt In Li 1978) agree that the damage to living cells is not from cold per se but from the formation of ice. Ice forms outside the plant cells. Intercellular freezing is the most rapid and damaging of the two (Smith 1970). Intracellular freezing is slower and more subtle in its effect (Levitt 1972). In this instance, ice formed on the external surface of the cell wall grows continuously, withdrawing water from the cell interior as the temperature declines. Cells frozen in this manner undergo a remarkable dehydration and may be injured in two ways: physical collapse and protein denaturation.

Native woody plants in relatively cold regions are capable of surviving extremely low temperatures without injury if they have had the opportunity to harden off. Soon after twig growth ceases, considerable changes take place in the cells of twigs, especially in deciduous trees (Smith 1970). There is a decrease of both water content and activity in the cambium cells and an increase in both starch granules and osmotic concentrations as the starch is converted to sugars. This increase in viscosity of vacuolar material is particularly noticeable in the parenchyma cells of bark and phloem. The actual mechanism which permits these hardened cells to resist freezing damage is unclear according to the authors sited above, but may involve increases in osmotic concentrations, the production of polyhydric alcohols, which may lower the freezing point in individual vacuoles, sugars acting to bind much of the free water and inhibiting ice formation, increased membrane flexibility, which avoids physical disruption, and increased solubility of proteins, also binding free water and inhibiting ice formation.

Snow and Ice Damage

Treshow (1970) in his text Environment and Plant Response devotes a whole chapter to climatic extremes such as lightning, hail, ice and snow. Though not always thought of in the context of stress, ice and snow damage associated with climatic extremes, Treshow suggests, is relatively common and sometimes causes devastating losses due to tree injury. Tattar (1978) suggests that damage is prevalent where there are weak forks that cause winter branch and trunk failure. Tattar also suggests that weak forks arise from branches growing at such an acute angle that normal wood formation is inhibited and structural weakness occurs. Some tree species such as Silver Maple are prone to weak forks, which can be eliminated either early when the tree is small or later by securing cables between susceptible limbs. Treshow (1970) notes that snow damage is very prevalent in the spring, particularly to Douglas Fir under 3 ft. high. Cedars are also suggested as being susceptible to breakage, particularly by heavy, wet snows. Davidson (1975) suggests that damage may not show up for a year or more, with flattening of branches breaking the bark, thus damaging the circulatory system with roots slowly dying and eventually causing death of the plant. Smith (1970) observes that snow damage is manifest in much the same way as wind injury. Stems and branches may be broken, lean may be produced or trees may be pushed over.

Morphological differences seem to determine the amount of snow injury. Butler (1974) found that physical breakage and injury were species, size and shape dependent, but also often reflected past maintenance practices. Van Cleve found that Picea mariana was more likely to be damaged by snow break than P. glauca while Smith (1970) reports that Noble Fir saplings suffer fewer snow injuries than does Douglas Fir, but more than Western Hemlock, Western White Pine and Silver Fir.

Ice in various forms may pose a significant threat to tree welfare in certain areas. Glazed frost, freezing rain and hail are all potentially capable of causing tree damage. Treshow (1970) reports on hail damage, and in one particular instance, the most conspicuous feature of injury seven years after the hail storm was dead tops and one-sided crowns of larger trees with the bare sides all facing the northwest direction, from which the hail had struck. On Aspen, abrasions on the smooth white bark had given rise to conspicuous black, rough calluses. Top dieback was noticed on White Spruce and Jack Pine, the latter having some bark completely stripped and little healing. Treshow suggests that hail wounds also bear a superficial resemblance to frost injury. On woody plants these wounds may be distinguished by the straight line normal wood with numerous vessels which soon appear again while in the case of frost, broad zones of parenchymatous tissue may be found due to the great extension of adjacent split edges.

Heavy accumulations of ice constrict twigs and branches from trees and reduce growth for many years. Breakage is most common, of course, when ice storms are accompanied by strong winds. Broken tops cause permanent crooks or forks in the bole. These injuries also make trees more vulnerable to attack by insects and fungi. Cayford (1961) found that Jack Pine was the most severely affected, followed by Cedar and Black Spruce. Semonin (1978) notes that glaze storms are frequently accompanied by heavy snowfall which, when accompanied by high winds, can be responsible for extensive damage. Smith (1970) suggests there is considerable variation in species resistance to ice injury. Eastern White Pine and Scot's Pine appear to suffer far greater damage than Northern White Cedar and Austrian Pine, while Norway Spruce and Eastern Red Cedar sustain practically no injury. Treshow (1970) concludes that because of the greater flexibility in manner of growth, conifers, as a whole, are more resistant to glaze injury than hardwoods.

Lightning

Urban trees in exposed locations such as open fields or hill tops, or trees in parks that rise above the forest canopy are sometimes struck by lightning. Injury can be variable and ranges from complete explosion, as was the case with the large cedar on northwest Marine Drive in Vancouver, or burning of the entire tree, to minimal damage to trunk and roots. Tattar (1978) suggests that even when only minor injury is evident on the trunk, considerable damage may have occurred to roots. This author also suggests that frequently trees may be subject to repeated strikes due to their exposed location. Treshow (1970) suggests that differences in susceptibility have been attributed to height, habitat, growth habit, chemical composition of individual trees and the unequal conductivity and water content of the wood. The fatty content of plant cells has been reported to influence conductivity and subsequently tolerance to injury. Beech wood is reported to contain large amounts of oil, while Oak wood is almost free from it and high in water content. This high degree of hydration may predispose Oak to lightning damage. The poor conduction and lightning resistance of such trees as Birch, Walnut and Linden are attributed to their high oil content. Oil content, and conductance, vary with the season so that damage may be greatest from spring and summer storms when trees are high in sugars, rather than oils. Treshow also suggests that the effects of lightning are not always immediate and sometimes only expressed after a year or two. Whereas breakage may be immediately conspicuous, trees may be less obviously stressed and not die for two or more years after a strike.

Smith (1970) suggests that Oak, Elm, Poplar and Pine are among the most commonly struck, while Beech is rarely struck. Treshow reports that Oak, Elm, Poplar, Tulip Tree, Ash and Pine are among the most prone to damage while Spruces are rarely hit. Pirone (1978) reports that Elm, Maple, Oak, Pine, Poplar, Spruce and Tulip Tree are the most popularly hit, while Beech, Birch and Horsechestnut are rarely struck. Boyce (1961) takes issue with trying to list susceptible and resistant trees. This author suggests that all trees, given the right conditions and locations, can be struck by lightning.

Light

In the last few years greater interest has been expressed about the impact of security lighting on landscape trees. Cathey (1975) reports that night-time lighting promotes continuous growth when the natural environment is signalling dormancy. This may cause trees to continue growing and at first frost to suffer considerable winter kill. Cathey examined 40 species of plants and found that _Betula, Catalpa, Platanus_ and _Tilia_ continued to grow vegetatively in response to all types of light source while Andresen (1974) in a survey of 19 American cities found no detrimental effects caused by high pressure sodium street lights. Cathey, in another study, reported in the American Society of Horticultural Science (1975) that high intensity discharge illuminaires, were probably less likely to affect plants than incandescent filament lamps. Roberts (1977) suggests that light quality (wave length) is not important in nature but must be considered when artificial illumination is used. However, the question of photoperiod and impact of lighting is difficult to quantify since different trees respond differently, even within species. Pirone (1978) warns against the use of Christmas lights in trees since these can damage cambium through the use of worn equipment or scorch leaves from poorly placed bulbs. Feature lighting in trees can also cause physical damage to urban trees. An example here are thin barked trees, such as the Beech on Granville Street in Vancouver, where high intensity feature lights close to the bark have caused cambial dieback and trunk wounds as a result of the heat generated by each light.

Finally, in the context of light, it is worth remarking that with the exception of Wilson (1973) little reference is made by authors to the probable stress induced by placing shade demanding species in open, exposed locations and light demanding species in, for example, areas of constant shadow. In the latter case phototropic reaction can become quite evident, with trees growing away from adjacent buildings. One of the most remarkable examples of this is in Washington D. C. where street planted Ginkgo have a pronounced lean away from buildings, particularly in locations with a northerly aspect.

Herbicides

Despite continuing removal of some herbicides and the restriction of others, both in terms of quantity and efficacy, available to the general public, considerable amounts of herbicides continue to be used in the urban setting by homeowners, municipalities and utility companies. Unfortunately, these substances are sometimes carelessly applied and may be distributed to areas where they can cause significant damage. Even when applied on windless days, thermal updrafts created by rising warm air can carry spray material aloft, while root translocation can occur from misapplication or lack of buffer zones. While woody plants are rate responsive to herbicides and death can occur if sufficient material enters the plant system, more frequent symptoms of herbicide damage involve rapid necrosis of exposed parts, defoliation, twig dieback, contortion of leaves, small leaves, and in some cases, particularly in susceptible plants, severe dieback or death. Hibbs (1978) also includes in symptoms cupped, chlorotic leaves, lack of apical dominance, enlarged bud size, parallel leaf venation, stem lesions, abnormal stem colouration, and nastic growth. This author points out that very careful examination is needed to ensure that herbicide damage symptoms are not confused with other conditions. Neely (1974) conducted an extensive study on 17 commercial products containing 11 herbicides commonly used to control weeds in lawns. Of the materials tests only Dicamba consistently produced symptoms, with White and Blue Spruce readily killed; Tulip Tree, Honey Locust, Oak and Linden exhibiting twig dieback; Walnut, Ash, Maple and Red Bud showing leaf distortion; and most conifers (as would be expected) unaffected. Smith (in a similar study) found that Simazine and Dichlobenil were the most harmful pre-emergent herbicides while Dicamba and 2, 4-D were the most harmful post-emergent herbicides causing damage to shade trees. While there is extensive literature on the effectiveness of herbicides, all too often the undesirable effects of drift and misapplication of stem foliar herbicides and soil sterilants, respectively, are poorly documented. There is no doubt the problem is relatively widespread. Almost one third of the woody plant material submitted to the Provincial Pathologist for disease diagnosis are found to be exhibiting symptoms of herbicide damage rather than active pathogens.

Domestic Gas

The widespread transportation and distribution of both natural and manufactured gas in underground systems is known to result in plant damage. Natural gas, which is generally thought to be less toxic, contains primarily methane and ethane. Both of these gases are phytotoxic (Smith 1970). Small impurities in the gas, however, may also contribute to the toxic effect. Certainly manufactured gas contains traces of hydrogen cyanide and carbon monoxide. Davis (1977) suggests that tree damage is caused by a combination of methane toxicity and a concomitant lack of oxygen. Garner (1973) found that leaking gas caused the soil to become anaerobic. Under anaerobic conditions microbial action can transform sulfates into hydrogen sulfides which in turn are toxic to trees. Smith (1970) observes that the most common symptom of gas damage is extremely sudden yellowing of tissue followed by wilting and dieback.

Leone et al (1977) and Flower (1977) review the difficulty in establishing tree cover on or adjacent to landfill areas where the production of methane on landfill sites can severely affect some tree species. Paul (1977) has found that *Carpinus*, *Sorbus*, *Prunus*, *Acer* and *Betula* are sensitive species; while *Populus*, *Salix* and *Platanus* are generally resistant species.

Nutrient Deficiencies

There is perhaps no environmental factor more important to the health of trees than the soil conditions in which they grow (Tattar 1978). Soil was once thought to be an inert entity, a medium containing only water and nutrients available for plant growth. Chemical stress induced by soil conditions can be due to unfavourable pH and/or imbalance in nutrients. Certainly pH plays some part in tree suitability for certain sites. At one end of the spectrum Spruces prefer a pH around 5, while Beech prefers calcareous soils with a pH around 8.5. More important perhaps is that normal growth and health of trees is clearly dependent on an adequate supply of the element, given in the attached table. Of these 16 elements, 9 are required in substantial amounts, and are often termed macronutrients, and 7 are required in small amounts as micronutrients; carbon and oxygen are derived from atmospheric carbon dioxide and hydrogen from soil water. The remaining 13 elements are generally supplied to the plant through the uptake of soil solution. As Smith (1970) observes, if one or more of these nutrients is absent or present in suboptimal amounts, physiological processes will be altered and abnormal metabolisms will result.

Tattar (1978) suggests that amongst urban trees, the most common nutrient imbalances reported are iron deficiency chlorosis, copper toxicity, boron toxicity and manganese deficiency. Iron deficiency, of course, is most prominent in alkaline soils. Species affected are given in the attached table. Although foliar feeding can overcome the problem, if undertaken on a consistant basis, long range control of iron deficiency in trees should involve permanent changes in soil pH. A problem which has only been recently recognized is that of copper treated burlap used in balled and burlapped stock sold through urban garden centres. Repeated applications of copper fungicides may also cause a soil build-up of copper that can eventually be toxic to plants (Tattar 1978). Boron is an essential micro element that may cause injury to plants when soil concentrations are too high (Smith 1980). Pine and Yew seem particularly susceptible to this problem. Manganese deficiency, like iron deficiency, is common in high pH soils. The problem is most pronounced on Maples, where trees may eventually decline and die if not treated. Typical symptoms for both coniferous and deciduous trees are given in the attached tables.

Salt

Of the large number of chemicals used in the urban landscape perhaps the most common group of chemicals that are toxic to trees are various deicing compounds. Sodium chloride (NaCl) and calcium chloride ($CaCl_2$) are the two chemicals most commonly used to melt ice and snow on sidewalks, driveways and highways. In fact, these chemicals are sometimes applied together. Sodium chloride, however, seems to be used most commonly, either alone or in combination with abrasives such as sand or cinders. Calcium chloride is used most commonly in extreme cold, below 20° F (-7° C) because it releases heat when it contacts water and melts snow and ice at much lower temperatures than can sodium chloride. It is, however, more expensive and more difficult to handle than sodium chloride.

As Smith (1975) noted, deicing salt lifted by traffic as salt-spray and then blown by winds or driven by turbulence onto roadside plants, where it coats the foliage of evergreens and the stems and branches of all woody plants, is perhaps more damaging than salt accumulation in the soil.

Tattar (1978) suggests that the exact effects of deicing salts in the soil on roots are complex, but that salts are known to make water and essential nutrients difficult to absorb by tree roots. The water is tightly held by the salt ions and more energy is required for the roots to absorb water. When sufficient water cannot be absorbed by the roots to meet the needs of the plant, water deficit occurs. The plant may respond to physiological drought by absorbing salts in an attempt to balance the soil concentration internally. This response is thought to be an important mechanism for salt tolerance by some plants but since this adjustment in metabolism usually requires considerable expenditure of energy, some trees use so much energy adjusting to soil salinity they stop growing, decline and eventually die. This is in contrast with salt tolerant plants which appear to be able to adjust to increased soil salinity with little or no decrease in growth. It has been noted by Lumis (1975) and Smith (1978) that nutrient balance in the plants in trees can also be affected by salt in the soil. The high concentration of sodium in salt contaminated soil makes potassium less available to the roots. While potassium and sodium have similar chemical properties, only potassium is useful to the plant. However, high concentrations of sodium in the soil can result in preferential absorption of sodium instead of potassium.

In the case of salt spray injury, it is presumed that it is due primarily to excessive accumulation of toxic ions, especially Cl from salts deposited on aerial organs. Chloride tends to migrate in the plant to leaf tips, where damage soon becomes evident as tip or marginal necrosis. Lumis (1975) has observed that the commonest symptom of aerial salt spray in conifers is moderate to extreme needle browning, starting at the tip, with browning and twig dieback mainly on the side facing the prevailing wind. No injury occurs on branches under continuous snow cover, where salt spray does not penetrate far into the plants or where plants are close together. Sheltered plants are not injured. It is suggested that injury first becomes apparent in February and early March and becomes more extensive through late spring and early summer. In deciduous trees, terminal leaf buds on the side facing exposure are normally slow to open or do not open, with new growth arising from basal section of branches facing the prevailing wind. This can give trees a tufted look. Lumis (1973) has also observed premature leaf abscission, twig dieback and inhibition of flowering as a result of salt exposure. Dirr (1976 and 1978) has conducted extensive research in the selection of trees for tolerance to salt injury, as outlined in the attached tables. Beckerson (1980) has drawn together a number of authors to provide a guide to plant sensitivity to environmental stress, including salt damage. Similar tables have also been prepared by Gaut (1907), Roth (1976), Rich (1971) and Daniels (1974). To some extent, the tables and data collected by a number of authors is contradictory. One area, however, that has long been of contention, has now been concluded as being caused by salt stress. This problem is one of Sugar Maple decline along roadsides in the eastern United States. Rich (1979) observed that these maples exhibited smaller light green leaves, scorched leaf edges, thin canopies, early fall colouration and leaf fall, twig and branch dieback and diminished growth ring increments. A correlation was found between these symptoms, leaf analysis and the road use of deicing salts. Rubens (1978) has now shown that Sugar Maple decline can be arrested by applying powered gypsum to the soil as a protective but not curative treatment, even though the continuing use of deicing salt on adjacent roads continues.

Air Pollution

In the course of reviewing the literature for this paper it quickly became evident that the most extensive body of information, at least in the context of available tables, was that for air pollution stress and damage on trees. In general, air pollution damaged to trees can be divided into three broad groups of pollutant types; particulate matter, non-photochemically produced gas pollutants and photochemically produced gaseous pollutants. Tattar (1978) also suggests that air pollutants may be classified according to their source, into two broad groups; point source emissions and diffuse oxidants. Point source emissions are defined as coming from stationary sources such as smoke stacks, while diffuse oxidants are defined as atmospheric contaminants from chemical reactions with oxygen that are powered by sunlight, as in the case of photochemical pollutants.

Mudd (1975), Carlson (1979), Smith (1970), Dochinger (1975), Wilson (1970), Treshow (1970), amongst many authors, have examined the specific effects of air pollutants on plant tissues. These effects appear to vary with the pollutant, host plant, time of year, and meteorological factors such as temperature, relative humidity, wind and solar radiation. In addition, symptoms known to be produced on plants by air pollutants seem also to be produced by stress from moisture, temperature and nutrient deficiencies. This, coupled with geographic factors such as mountains, valleys, lakes and proximity to source, appear to make accurate diagnosis of air pollution damage extremely difficult if it is not coupled in some way with air pollution monitoring. Moreover, even such monitoring appears to be potentially unreliable since some air pollutants, such as fluoride and chlorides, that are toxic in extremely low concentrations, require extremely sensitive analysis to accurately implicate these gases.

Mudd and Kozlowski (1975) in their extensive review Responses of Plants to Air Pollution, note that in addition to killing plants, atmospheric pollutants adversely affect plants in many ways. Pollution injuries are most commonly classed as acute, chronic or hidden. In acute injury collapsed marginal or intercostal leaf areas are noted, which at first have a water soaked appearance. Later these dry and bleach to an ivory colour in most species and in some may become brown or brownish red. These lesions are caused by absorption of enough gas to kill the tissues. Chronic injury involves leaf yellowing which may progress through stages of bleaching until most of the chlorophyll and carotenoids are destroyed and interveinal portions of the leaf are nearly white. Chronic injury is caused by absorption of gas that is somewhat insufficient to cause acute injury but may be caused by absorption of sublethal amounts over a long period of time. Carlson (1979) has found that histological changes occur in pollution injured leaves including plasmolysis, granulation or disorganization of cell content, cell collapse or disintegration and pigmentation of affected tissues. Mudd and Kozlowski refer to a "hidden" effect as being a stress reaction to air pollution damage causing a reduction of photosynthesis below the level expected for the amount of leaf destruction visually apparent. Further complicating the analysis of the mechanisms of air pollution damage is the fact that more than one pollutant is often responsible for injury and that air pollutants generally appear to be relatively non-specific agents which have many sites of action.

Particulate matter such as soot, dusts, and particles containing heavy metals appear to make up the bulk of this problem. Lepp (1976) has found that increased heavy metal contamination of the environment can be related to industrialization and increased consumption of leaded gasoline. Leaves were found to retain heavy metals and when these leaves fell the metals were released into the soil. Lepp found that the presence of calcium and phosphorus in the soil may decrease the uptake of heavy metals by tree roots. When heavy metals are translocated, they may be permanently incorporated into the walls of root cells, although a lower proportion is eventually transported to aerial parts. Lepp suggests that trees can act as long term sinks, particularly in acid soils where heavy metals are taken up more readily. Heavy metals are retained in longer lived tissues such as bark and wood. The biological activity of heavy metals such as lead is as yet poorly understood in terms of physiological disturbance in tree species.

The effect of cement dust on trees has been reviewed by Rhoads (1976). Severe foliar chlorosis, leaf scorch, branch dieback and eventual death can result from prolonged exposure to particulate depositions. It was also found that acid loving species, particularly Quercus and Pinus declined due to unavailability of certain essential nutrients.

Of the non-photochemically produced gaseous pollutants, probably the most extensively studied are oxides of sulphur. (National Environmental Research Centre 1973). Sulphur dioxide (SO_2) appears to be by far the most important sulphur pollutant. The bulk of severe SO_2 damage to urban trees appears to occur around electrical generating stations. Sulphur dioxide enters the leaves through open stomata, is absorbed on the moist reactive surfaces of the spongy mesophyll and reacted into sulfite. Sulfite is very toxic to the cells and will quickly kill them when the external sulphur concentration is 0.50 parts per million or greater. However, stress may occur at as low as 0.03 parts per million for susceptible species under favourable conditions (Davies 1969). On broad leaf species symptoms include irregular marginal interveinal necrotic blotches bleached white to straw. In the case of conifers needle tips are chronically necrotic, often with a banded appearance Linzon (1971).

Fluorides

Of the halogen compounds, the most important pollutant is hydrogen fluoride, although hydrogen chloride (HCl) and chlorine (Cl_2) are also produced at some chemical or plastic manufacturing plants. The mechanism of fluoride effects on trees is discussed by Smith (1970). It appears that fluoride is absorbed from the air, translocated in tissues and accumulated in leaf tips and margins. The toxicant remains in a soluble form and seems to retain the chemical properties of free inorganic fluoride. The excessive concentration results in disruption of enzyme systems and eventual death of cells. Apparently the actual mechanism of injury is not yet fully understood. Lanphear (1971) reports that injury from fluoride appears as tip necrosis in conifers and tip and marginal necrosis in broad-leaf trees. Injury in conifers usually begins with yellowing of the needle tissue, which progressively turns to tan and then to red-brown. Injury in broad-leaf trees usually begins with fading of leaf tissue, followed by red-brown necrosis which is usually sharply defined from the healthy tissue. Emerging leaf tissues appear more susceptible to acute injury and consequently more sever injury appears in the spring. Pine appears to be a particularly susceptible species.

Taylor, writing in Mudd and Kozlowski (1975), reports that during combustion of fuels, some of the nitrogen in the air is oxidized to NO and a comparatively small amount of NO_2. The rate of NO formation increases in proportion to the temperature of combustion. During daylight, atmospheric NO may also be quantitatively converted to NO_2 by photochemical reaction involving the absorption of sunlight and interaction with hydrocarbons and oxygen. Adverse direct effects of nitrogen oxides on plant life are generally limited to areas in close proximity to urban industrial developments where the emissions are concentrated. It appears that a wide range of responses related to stage of growth and conditions of light, temperature, humidity and/or water stress and fertilization at time of exposure affect the direct the degree of nitrogen oxide damage.

Thompson also notes that the mechanisms by which nitrogen dioxide cause injury to plants have received little attention in biochemical and histological studies. It is well known that NO_2 reacts with water to form a mixture of nitrous and nitric acids. The author suggests that this probably occurs as the gas reaches the wet surface of the spongy parenchyma in the leaves of trees, and when the acid exceeds a given threshold the tissues are injured. Smith (1970) reports that acute NO_2 injury is often manifest as necrotic lesions similar to SO_2 on broad-leaf plants, but no authors provide any definitive symptoms for conifers.

Damage caused by ethylene, ammonia, carbon monoxide, mercury vapour and aldehydes is briefly mentioned by some authors reviewing non-photochemically produced gaseous pollutants. However, the information is spotty and no tables were discovered for any of these pollutants.

Smith (1970) suggests that until recently, non-photochemically produced pollutants were thought to be responsible for most air pollution damage to plants. Approximately 20 years ago, however, a new type of pollution was recognized, especially in the Los Angeles region of California. These pollutants required alteration after release from their source by reaction with sunlight, other atmospheric materials, or both, to become phytotoxic. Heath, writing in Mudd and Kozlowski (1975), notes that the production of ozone in polluted urban atmospheres has been the subject of much controversy and study. This author notes that the precise biochemical mechanisms of photochemical oxidant damage to trees has not yet been satisfactorily characterized. A number of authors (Genys 1978, Brennan 1976, Karnosky 1978, 1979, Clark 1980, Davis 1974 and Hay 1977) have reviewed the impact of ozone on tree growth and much of the work of these authors is included in the tables attached to this paper. The symptoms of ozone damage appear on sensitive plant species as necrosis, chlorosis and flecking of the upper leaf surface. These visible symptoms are thought to result by way of the following sequence of events; ozone interaction with some component of the cells and leaf tissue, collapse of the cell, localized accumulation of extracellular water, bleaching of the chlorophyll and breakdown of the leaf structure. The flecking may later become red-brown pigmented stipple or bleach straw to white fleck. Conifers may show tip burn or yellow to brown banding of needles (Lanphear 1971). Pine, in particular White Pine, Green and White Ash and European Larch all appear to be sensitive and suitable as indicator tree species (Lanphear 1971).

Finally, an air pollution complex that has been implicated in tree damage is that of peroxyacetyl nitrate (PAN) of the hydrocarbons released from internal combustion engines are several olefins and aromatics (Smith 1970). The compounds are oxidized in the presence of nitrogen oxides and light shortly after their release. The resulting decomposition products, rich in aldehydes, are further reacted with ozone in the atmosphere to produce PAN. As with a number of other air pollutants, the exact mechanisms by which PAN affect trees is not known. Symptoms appear on broad-leaf species as collapse of the tissue on the underside of leaves, giving a glazed, silvered or bronzed appearance. Conifers generally display rather unspecific needle blight symptoms with some chlorosis or bleaching (Lanphear 1971). Although little work as been published on the influence of PAN on trees Hindawi (1970), Treshow (1970), U.S. Forest Service (1973) and Kozlowski (1980) have prepared tables on the effects of peroxyacetyl nitrate on some urban trees.

A number of stresses to which some urban trees are probably exposed are ill-defined in the literature. An example is the effect of Hedera helix in its arborescent stage. In West Vancouver along Marine Drive alone, some 20 trees have been recently removed from various locations because they died from the smothering effects of the vines. Despite the many references examined for this paper, only one British writer specifically addressed the urban problem (Mitchell 1975), although there is a considerable body of reference work on Dwarf Mistletoe in forestry.

Another example is the spillage of hydrocarbon fuels through deliberate dumping. For example, waste oil disposal on the periphery of some park sites is a problem in Burnaby. Another example is the loss of oils from damaged equipment. Line rupture in clearing equipment on new urban housing sites can dump as much as 100 gallons of hydraulic oil on the edge of tree retention sites. Tattar (1970) refers to the problem of dog urine which is a strong alkaline solution. The problem is said to be three fold; soil effects, dieback of lower branches and loss of foliage directly exposed. Conifers such as the various cypress types seem most commonly affected.

Finally, there are stress effects that go unreported in the urban tree literature, although they must play a part in affecting tree growth, particularly in narrow streets with tall buildings. An obvious stress will be that caused by the Venturi effect, when wind passes through narrow spaces in a street location and is speeded up, causing turbulent air to buffet street trees. While the stressing effect of wind has been examined by some authors (Martojoewono 1960, Moore 1977, van Eimern et al 1964), as has the effect of tying trees to tree supports (Harris 1978), no review was found on the tolerance of various species to constant wind rocking.

Conclusions

An extensive array of tables that provide comparative assessments of tree reaction can be found for the most prominent stress factors known to effect urban trees. It is not clear that these tables can be considered any more than a general guide for the urban plantsman faced with choosing tree species for particular locations. Genetic variation of different tree provenances and of individuals within trees, the vagaries of specific site conditions under which any particular stressing agent may occur, as well as timing and duration of the stress, may all affect the probability of reproducing the conditions used to assess and categorize the stress thresholds of any genus or species found in the tables.

Little appears in the discussion of stress about the probable synergism that occurs when more than one stress factor impinges upon a tree or trees. The complexity of such research is recognized but for the potential user, the need is for tables that establish the "hardiness" of a species under a broad range of simultaneous and arduous conditions. Moreover, little appears to be known at present of the predisposing condition that stress may provide for disease or insect infestation of urban trees. A number of poorly explained diebacks and declines have now been identified and stress appears to be implicated in these complex diseases.

Some tables found are both extensive and informative. The authors have attempted to provide clear indications of the origin and parameters under which the data used to categorize a tree has been collected. On the other hand, however, many tables are restricted to a few species, often poorly identified. It remains for an extensive overview to be prepared on the stress reaction that can be anticipated from those trees commonly in urban settings. Most tables presently available are presented as an amalgam of experience and writings of other workers. Few tables are prepared as a result of direct research. While reoccurrence of a particular species in a number of tables may corroborate the individual findings, it is not always obvious that the origins of information are independent. While this casts some doubt on the usefulness of such tables, in fact it may cause some to be misled or some species to be unnecessarily maligned for use in some locations, the general conclusion should be that tabular references of the type gathered for this paper are useful for general guidance in tree choice. The more credible the study researcher, or the more explicit the study criteria and value system, the more useful the table.

Perhaps another inference that can be drawn from the tables so far assembled is the need for researchers in urban tree stress to provide the data in comparable form and for experimental protocols and assessments to be explicitly stated for each tree comparison and tree stress state examined.

Although an attempt has been made throughout this paper to briefly describe the symptoms associated with a particular stress on particular species, it cannot be implied that adequate diagnostic information is available to the average practitioner. While the arborist has available excellent colour references for air pollution damage on plants (Jacbson and Hill 1970, Anon. Grounds Maintenance 1971) and the symptoms of nutrient stress are fairly well documented, the general area of diagnostic tools for stress recognition, either pictorial or descriptive, is relatively poor. This a deficiency of particular importance in education where younger arboriculturalists and foresters are initially denied the enquiring yet knowledgeable eye that should come with years of field experience. There is, moreover, a far too ready tendency to overlook the broad view of particular sites and to concentrate too much on the tree itself without a holistic appreciation for a site as it was, as it is now, and how it will be in the future.

Diagnosis of stress in all but the most mundane of circumstances is still largely an art form. The advent of the Shigometer, using electrical resistance to determine decay and vigor, is hopefully only a beginning step in a more sophisticated array of tools and references available to monitor tree and environmental conditions in the urban setting.

In western and eastern civilizations alike, the tree has played an important role in mitigating the sterility, scale and enormity of the city. Urban environments have become increasingly hostile to plants and man. As space becomes more valuable, taller buildings are built, green space gives way to concrete and blacktop and population exceeds the carrying capacity of a livable reality. As we forfeit the livability of our own environment, so too we encroach precipitously the place for trees, one of the last few natural elements in an almost completely alien, engineered city world.

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STRESS AND URBAN TREES

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Course: Forestry 500

Date: December 16, 1980

STRESS AND URBAN TREES

Introduction

Despite the probable harm that unfavourable environments do to the natural forest ecosystem, there is much evidence that some forest trees are uniquely resistant to environmental stress. Bristlecone Pines (*Pinus aristata*), are the world's oldest living things, having survived for thousand of years, in an extremely hostile environment. The survival of these trees has required integration and coordination of physiological processes occuring in widely separated roots and shoots. As Kozlowski (1979) has observed, it is remarkable that trees can live for more than 3,000 years and maintain the necessary transport of food, water, hormonal growth regulators and minerals over distances of several hundred feet. The survival of old and large trees is even more remarkable when it is considered that the stem tissue, through which carbohydrates move between the crown and the roots, is a layer of inner bark that is little more than a fraction of a millimeter thick. It is obvious that from a physiological standpoint, trees have evolved in such a way as to survive the periodic environmental extremes encountered in nature.

The environmental changes that alter tree growth do not do so directly but rather indirectly through their influence on rates and balances between photosynthesis, respiration, assimilation, hormone synthesis, absorption of water and minerals, translocation of growth requirements and more subtle changes in physiochemical conditions within the tree. It is not a purpose of this paper to examine the physiological disfunctions and growth responses of trees subjected to normal or abnormal stress. Rather, this paper examines the types of abiotic stress to which trees are exposed in an urban setting and provides some tabular information on tree species sensitivity to stress. Nevertheless, a brief discussion on the nature of stress opens the section entitled Discussion.

The importance of stress in the urban setting is not that it necessarily takes its toll in the rapid and obvious death of trees but rather that the manifestations of stress, such as growth inhibition, twig and branch dieback, loss of vigor, abnormal coloration, excessive deadwood and change of growth habit, stem cracks or loss of bark, as well as diminished longevity means that many urban trees fall far short of reaching their full potential yield of benefits to the urban population.

Trees growing in the urban setting may be broken into a number of classes. For example, street trees in narrow tree lawns

along the edge of streets, trees in centre medians, trees in both large and small urban gardens; trees in parks as single trees, clumps of trees or larger areas of closed canopy; trees in derelict land, trees in residential land that cannot be built upon such as ravines, steep banks and floodplains; trees in recreation sites such as golf courses; and finally trees in greenbelt or institutional lands retained for screening, erosion protection, future development and similar activities.

Each of these circumstances is one where the potential for abiotic stress, that is, stress of a non-pathological nature is potentially greater than the growing conditions of native forests. The more alien the conditions, the greater probability that stress thresholds will be exceeded for many tree species and for individual trees. Subsequently, these trees will require increased costs of maintenance or replacement than would have been required if either care in protection of an existing resource or more thoughtful choice of species had been taken long before stress symptoms or decline became evident.

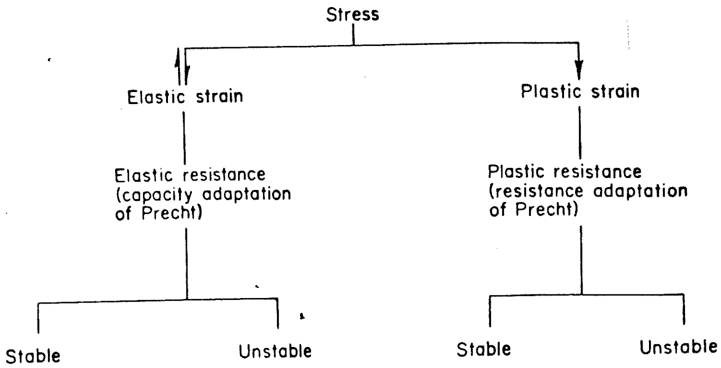
PATHOLOGICAL STRESS FACTORS OF PLANTS

Cause injury		*Cause disease*	
Abiotic	*Biotic*	*Abiotic*	*Biotic*
Moisture extremes	Birds	Air pollutants	Nematodes
Temperature extremes	Mammals	Mineral deficiencies and excesses	Viruses
Wind			Bacteria
Snow			Fungi
Ice			Plants (higher)
Lightning			
Salt			
Radiation			
Pesticides			

A principal purpose then of this paper is to examine the various stresses to which urban trees are subjected and in so doing to determine, wherever possible, those species that can withstand particular urban stress conditions and those species of trees that are particularly susceptible with the intention that this information can be used for more informed tree choice in urban planting.

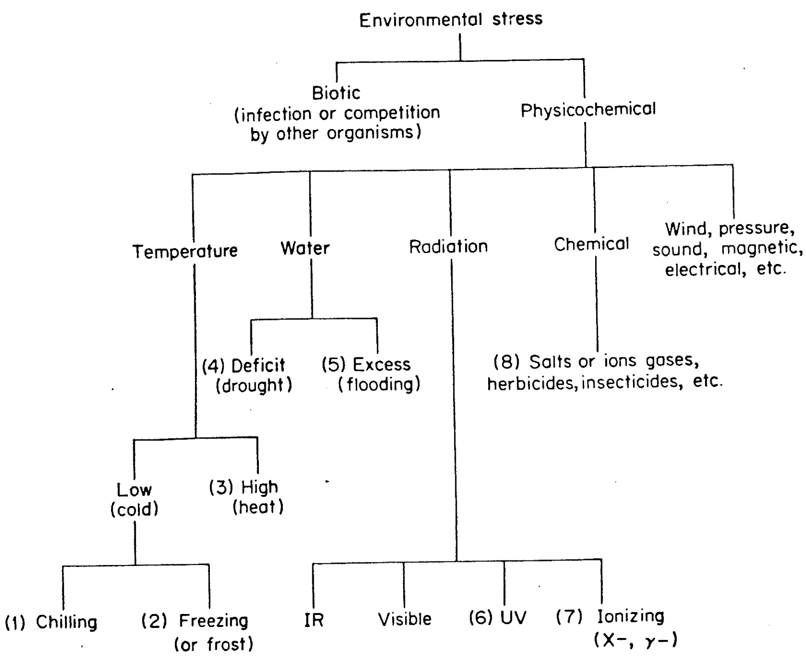
Discussion

The nature of stress injury and resistance in trees is discussed primarily by two authors; Levitt (1972) and Kozlowski (1979). From the work of these two researchers it has been determined that environmental stresses adversely affect trees in different ways. They mainly induce a direct plastic strain, recognized by rapid appearance of injury. An example would be the killing of physiologically active plants by sudden exposure to freezing temperatures. Environmental stress may also produce a non-injurious, reversible, elastic strain, which, if maintained for a long enough time may induce an irreversible and injurious plastic strain (Kozlowski 1979). Additionally, an environmental strain may cause injury by inducing a secondary stress. For example, high temperature may induce plant water deficits, which in turn cause injury. Such secondary stress injury may not develop for a considerable time. Hence, long exposure to the primary stress may be necessary. Conceivably, a secondary stress may induce a tertiary stress that may also cause injury or growth loss.



Adaptation to Stress.

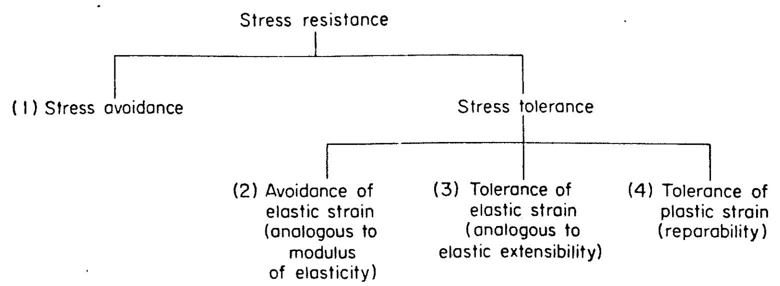
Levitt (1972) classifies environmental stresses as either biotic or physiochemical: the former encompasses infection or competition by other organisms; the latter includes effects of radiation, water, temperature, chemical substances, wind, pressure, sound and similar effects.



Kinds of environmental stresses to which an organism may be subjected.

Fortunately, trees, like other organisms, appear to be able to adapt to certain stresses. When stressed, they gradually change to decrease or prevent strain. It can be assumed that adaptations that have arisen by evolution over a long time are stable, at least in the mature plant. On the other hand, the adaptation threshold or ability may be poorly developed in the immature tree. Kozlowski observes that insomuch as growth is an integrated response to physiological changes, regulated by a complex of many fluctuating and interacting factors, including environment, responses may vary remarkedly in different parts of a tree and they may vary with the age of trees. Thus the effects of an environmental stress on trees must often depend on the phenological stage and physiological status of the tree at the time of the occurrence of the stress.

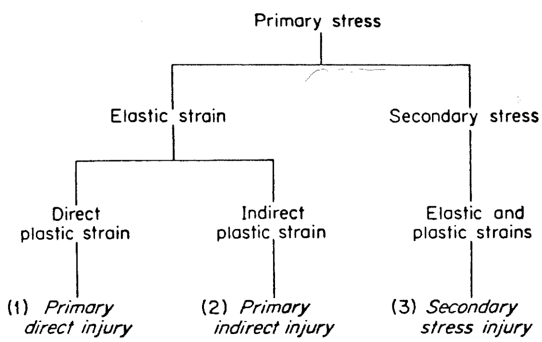
Levitt (1972) suggests, that a number of environmental stresses can give rise to various degrees of resistance adaptation in plants. Stress resistance may reflect stress avoidance, stress tolerance or both. Whereas a stress avoiding plant can somehow exclude the stress, a stress tolerant plant can prevent, decrease or repair the strain induced by stress.



Levitt notes that the term resistance to environmental stress has, until now, been used only for plastic resistance. The concept of an elastic resistance has not been clearly recognized. Levitt draws the distinction between elastic and plastic strains giving the definition for the former as a reversible physical or chemical change in the plant; and for the latter an irreversible physical or chemical change. Levitt goes on to note that another important consideration in plastic strain or change produced by stress is the consideration of time in the context of length of exposure. Not only may the degree of stress carry the plant from an elastic strain to a plastic strain but it may also be a function of duration of the stress.

Both Levitt and Kozlowski note that it is important to understand how stresses produce their injurious effects and how some trees have succeeded in surviving stresses that injure others. Levitt notes that an important first step in this assessment is understanding how a stress acts on a plant and how the type of injury which occurs may differ from plant to plant. The stress may induce a direct stress injury that can be readily recognized by the speed of its appearance. An example would be the rapid freezing strain produced by sudden low temperature stress. On the other hand, the stress may produce an elastic strain which is reversible and, therefore, not injurious of itself.

If maintained for a long enough time the reversibility of the strain may give rise to an indirect irreversible strain, which results in injury or death of the plant. This indirect stress injury may be recognized by the long exposure of days or months to the stress before the injury is produced. Levitt provides an example of indirect stress injury, the case of chilling stress, which exposes the plant to low temperature, too high to induce freezing. The strains may be mainly elastic, involving the slow-down of all of the physical and chemical processes in the plant which may not be injurious themselves, but which may disrupt the plant's metabolism, leading to a deficiency of a metabolic intermediate or production of toxic substances. A third case suggested by Levitt is that often referred to as secondary stress injury. Here, high temperature, for example, may not be injurious of itself but may produce a water deficit which can, in turn, injure the plant as lack of turgidity eventually results in severe wilting, cell collapse and death of tissue.



Kinds of stress injury.

While Levitt discusses, in some detail, stress avoidance, that is, the ability of certain trees to exclude a particular stress either partially or completely, it is stress tolerance the ability of a tree to come to thermodynamic equilibrium with a stress without suffering apparent injury through being able to prevent, decrease, or repair the strain, induced by stress that is perhaps more important in the context of this paper as is the point made by Kozlowski that the effect of an environmental stress may not be evident for a very long time.

TWOFOLD NATURE OF STRESS RESISTANCE

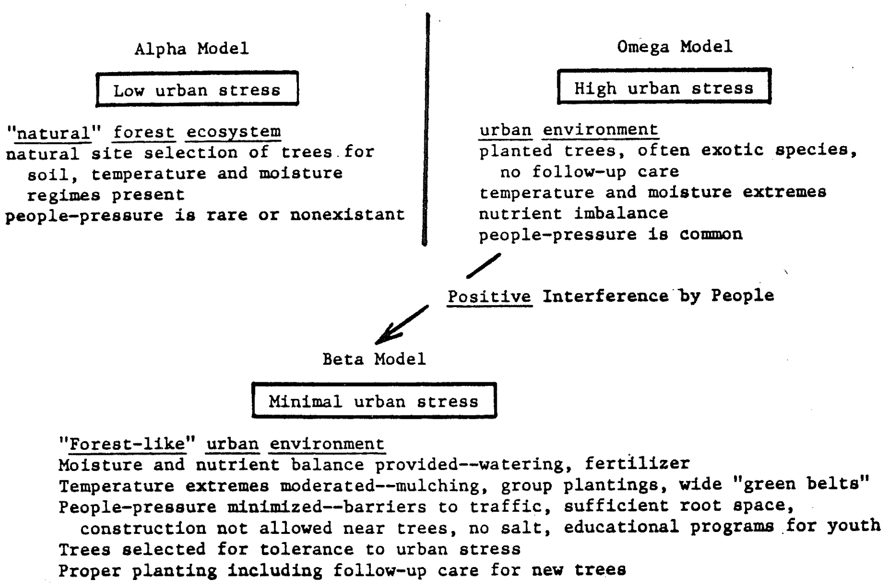
Stress	Condition of resistant plant cells exposed to the stress and surviving due to	
	Avoidance	Tolerance
(1) Low (chilling) temperatures	Warm	Cold
(2) Low (freezing) temperatures	Unfrozen	Frozen
(3) High temperatures	Cool	Hot
(4) Drought	High water potential	Low water potential
(5) Radiation	Low absorption	High absorption
(6) Salt (high conc.)	Low salt conc.	High salt conc.
(7) Flooding (O_2 def.)	High O_2 content	Low O_2 content

Since few of the papers examined in this review have used or described in detail any experimental protocol for determining their classifications of stress resistance or susceptibility, the work of Levitt and Kozlowski is of importance in considering the reliability of any of the tables provided by the authors examined for each type of stress discussed here. Notwithstanding this proviso, however, and the theoretical work conducted by Levitt and Kozlowski amongst others, there is certainly some merit in drawing on the field experience of the authors reviewed.

If, as this paper suggested earlier, the important need is for careful choice of species in the urban setting, a more important, yet little understood area is that of assessing the environment or some of the external forces that will affect a tree prior to its installation. Two pragmatic solutions to this dilemma are apparent. The first might be for the urban tree manager to equip himself with the knowledge and equipment that allows very accurate diagnosis of stress induced symptoms such as twig and branch dieback, short growth increments, decay, and such stress manifestations as small leaves, early fall colouration, heavy seed production, and unthriftiness. In this way it may be possible to determine a direct correlation between particular species, their environment and induced stresses that particular species cannot tolerate. While single instances will be of little assistance in preparing informative tools, a thorough examination of a large resource may yield patterns of stress and stress reaction that would implicate particular species as being unsuitable for urban conditions.

A second approach is that espoused by Tattar who suggests, as shown in the accompanying model, that the most appropriate approach to ensuring tree growth in the urban setting is by reproducing, as far as possible, the environmental conditions that trees have been exposed to during evolution in their natural setting.

STRESS MODELS FOR TREES IN THE URBAN ENVIRONMENT



[1] Adapted from a paper presented at the 9th International Congress of Plant Protection, August, 1979, Washington, D.C.

While sound perhaps in theory, this approach is manifest impractical in two counts. The first is that some environmental stresses, such as light strike-back from buildings and weather conditions cannot be mitigated against

while others such as drought, though possible to overcome by watering, are largely impractical for most municipalities where the constraints on labour, equipment and funding preclude all but the most minimal maintenance programs. Tatter (1980) does, however, suggest in his Beta model that trees can be selected for tolerance to urban conditions. The remaining section of this paper examines this possibility in the context of abiotic stress and, wherever the information has been available, reviews species reaction to the stress type discussed.

A number of the authors read in the course of a literature review for this paper found to review stress and stress mechanisms in only a very general sense; while other authors, although discussing a particular stress in greater depth, did not provide any extensive accompanying tables. Moreover, some authors described the effects of a particular stress on only a few species and often by common name alone. No attempt has been made to add credibility to these reviews by tabular summaries of the information provided. Only those tables that were reasonably comprehensive are included in this paper. A common thread throughout all of the work examined in this brief review is that of limited applicability when information is viewed in the context of specific instances or when comparisons are attempted between one study and another. A case in point is that of salt resistance, where tables are provided by a number of authors but often no information is given as to whether the tolerance or susceptibility to salt is from root uptake or windblown salts, nor in some cases is information provided as to the type of salt involved. In addition, the whole concept of "injury" is poorly elucidated and described by almost all authors, with tables and text providing little indication as to whether the tables refer to a spectrum of damage from slight to severe and whether or not a number of plants were viewed in order to reduce the variability of result inherent in using semi-mature or mature tree stock of unknown origin for experimental purposes.

It must be concluded that in almost all cases the tabular information provided by most authors is of use only for general guidance and most tree species assessments are of but a relative nature. Finally, some authors do not indicate the source of some or all of their information. This has, I suspect, led to a duplication of some lists and the propagation of any misinformation from one source to another.

SOIL AERATION AND COMPACTION

Despite the probability that soil compaction plays an important role in the declining health of many urban trees, particularly in high foot traffic areas such as parks, golf courses and in the grass/tree or blacktop/tree interface of many landscaped areas, particularly in recent development sites, very little appears in the literature concerning this problem. Kramer and Yelenosky writing in 1963 reported on their research "Soil Aeration and Growth of Shade Trees" found that, as a result of questionnaires sent out "Yellow Poplar was least tolerant of compaction followed by White Oak, Sugar Maple, Honey Locust and at the other end of the scale American Elm the most tolerant".

In subsequent flooding experiments on these species only elm could tolerate two months of inundation and recover. Soil air measurements in a field experiment found that in compacted soils (not specified) where tree death was apparent, there was only 4% oxygen and over 20% carbon dioxide. There was substantially less oxygen in of the soil here than in an adjacent forested area (the comparative figure is not described).

Patterson (1977) provides a useful analysis of the effects of soil compaction on urban vegetation. He notes that soils are very complex, naturally formed entities which vary widely with the natural landscape. The principal mineral fractions to be considered are sand, silt and clay. The sand fraction (2.0 m - 0.05 m) is virtually inert but does provide vital structural capabilities for the soil mantle and assists in reducing compaction. Silt (0.05 m - 0.002 m) also provides structural support as well as some contribution to fertility. The clay fraction (0.002 m and smaller) provides much of the nutrient and thus fertility capability of the soil and supplies much of the matrix of soil structure and till.

Patterson suggests that these three fractions combined provide 45% of an "ideal" soil. The remaining 55% would be composed of 5% oranic matter, 25% air spaces (N_2 forming 79.2%, 0_2 20.6% and CO_2 0.2%) and 25% water or moisture capability. These latter areas, or pore spaces, are ideally composed of equal amounts of air and water space, but fluctuate widely depending on rainfall, humidity, temperature, area use and degree of compaction.

Patterson has suggested (1966) that in areas of intense use the soil parameter which seems to best indicate soil condition is bulk density. Pearson suggests that bulk density is an expression of the mass per unit volume and can be an indicator of a wide variety of soil properties. Pore space then, ideally 50%, is the portion of the soil matrix that is directly and adversely affected by heavy use (Cordell and James 1971). Pore space distribution, i.e., the distribution of macro and micro pores does not remain constant, but is altered by compaction, cultivation, aggregation, fertilization, etc. (Waddington

1968). With compaction, for example, the solid phase of the soil increases per unit volume. In other words, the pores that suffer most from compaction are the large macro pores and there is a resulting increase in the smaller micro pores. Compaction creates poor soil moisture relationships with less available moisture for plants, irregular soil temperature relationships, a less desirable soil atmosphere, resistance to root penetration, increased runoff and erosion and other inter-related problems for tree growth. Reports vary when considering the percent pore space required for adequate plant growth. Percent pore space also seems to vary for different plant species. For example, Van Der Valk (1971) has suggested that when the percent total pore space is less than 44% growth can be impaired. Vigor of most plants seems to suffer under compacted soil conditions where the pore space volume drops below 30 percent. As there is a balance between soil atmosphere and soil water, saturation can cause soil pores to be filled with water, leaving little pore space for soil gases. As water is lost to evaporation, percolation, transpiration and other causes, the volume of the soil atmosphere increases. During very dry periods the gaseous phase predominates and little water is available for plant use. Sekiguch (1973) noted that for street trees moisture depletion can occur rapidly and can vary widely from location to location. According to a number of authors (Hady 1974, Dusberg and Baker 1970, and Youngberg 1970) oxygen in the soil profile is the key to regulating plant growth. It is generally concluded by these authors that an oxygen content of less than 10 percent by volume substantially decreases tree root growth. Pirone (1972) has listed some species affected by poor soil aeration. Most severely injured were Sugar Maple, Beech, Dogwood, Oak, Tulip Tree, Pines and Spruce. Less severely injured were Birch, Hickory and Hemlock; while least injured were Elm, Popular, Willow, Plane, Pin Oak and Locust.

Flooding

Gill (1970), in a review of flooding tolerance of woody species, found that type and degree of injury varied with species, soil type, and flooding regime. Symptoms included decreased growth rate of roots and shoots, decreased transpiration rates, leaf chlorisis, epinasty, leaf abscission, death of roots, absence of fruiting, increased susceptibility to predator and pathogen attack and, after prolonged exposure for some species, eventual death. The most critical factor was found to be a direct effect of exclusion of oxygen from the root system, with an increase in CO_2 accumulation and the production of certain metabolites such as sulfides which initially cause cessation of root growth and eventually death of tissues. Bernatzky (1978) suggests that oxygen supply is not the only factor enabling trees to survive. In most flood tolerant plants alcohol is the usual product of anaerobiosis. When flooded, these plants steadily increase their rate of ethanol production. Moreover, in flood tolerant trees there are a large number of substances that can accumulate during the period anoxio without any toxic effect on the plant's cells. Bernatzky also suggests that flood tolerance may be linked to the production of certain metabolites in the roots and by the translocation of anaerobic respiration products from the roots to the aerial sections of the tree. A higher root/shoot ratio is also suggested as leading to greater flood tolerance. Tattar (1978) notes that tree roots are injured when the oxygen concentration drops below 10 percent and root growth stops entirely at concentrations below 3 percent. When water stands over the roots, the soil becomes saturated for long periods during the growing season, gaseous exchange cannot take place between roots and air, and soil conditions become anaerobic. The roots suffocate under these conditions and most trees will soon begin to decline or die. The effects on a tree of any given period of inundation or soil saturation seems to vary with the species, time of year, and duration of suffocation stress. In general, it seems the effects of water excess will be greatest during the growing season, will be directly related to the duration of the stress and will occur most quickly on upland species not tolerant to natural flooding. Bell and

Johnson (1974) confirm this finding from flood-caused mortality around Illinois reservoirs. Increased flooding duration resulted in increased mortality amongst upland species, while floodplain species were completely tolerant. Many of the latter completed their annual growth cycle in spite of flood conditions throughout the growing season. In a short note in the Journal of Arboriculture, Baker (1978) found, in a three year flooding test of seedlings under natural conditions, that Green Ash and Sycamore showed 95 percent survival while Water Tupelo gave 64 percent survival and surprisingly, Cottonwood was consistently poor, averaging 21 percent survival. Sweet Gum was very variable and exhibited 0-80 percent survival, possibly depending on seed provinence. Kozlowski and Davies (1975) noted that the symptoms of flooding were leaf yellowing and mottling, shedding and death of leaves, inhibition of shoot and root growth, death of twigs, branches and roots, and eventually death of individual trees. These authors also noted that extent of injury depended largely on species, soil type, drainage conditions and duration of flooding.

White, in an interesting study reported in 1973, observed the aftermath of the torrential rains of Hurricane Agnes in 1972 which struck New York State, where damage not only included rapid flash flooding along stream and river banks which subsided within 24 or 72 hours, but also lakeshore areas which were inundated from 10 to 15 days. A list of species is provided in the short article of shade and ornamental trees as well as evergreens that died as a result of the flooding. The author notes that no plant was listed unless a number of specimens of the same type had been observed. Also included was a short list of evergreen, shade tree and shrub "survivors". These plants had tolerated the unusual conditions and had no leaf drop or apparent ill effects when checked even some three months after flooding had taken place.

Drought

Tattar (1978) notes that trees are subject to two kinds of water deficiency stress:

(i) Short term drought during one growing season, and

(ii) Long term drought that accumulates moisture stress over more than one growing season.

Tattar suggests that the latter is the most important to trees because, in contrast to annual crop plants, trees are sensitive to year-round moisture conditions. As Smith (1970) observes, adequate supply of water is of critical importance for tree development. In addition to being the primary component of green tissues, frequently 90 to 95 percent of the fresh weight, water renders mechanical strength via cell turgor to unlignified tissues, acts in metabolic reactions both as a raw material and as a conditioner of various reactants, and assumes a fundamental role in the distribution of disolved materials in the transpiration stream.

Many site factors increase the susceptibility of shade and ornamental trees to moisture stress. Restricted root space is probably one of the most important contributing factors to moisture deficiency stress. In many cases, trees growing in confined locations such as street trees, are sandwiched between roads, sidewalks and residential driveways. These trees are often not able to extend their roots into sufficient soil area for them to meet the demands for moisture from the tree crown. Such trees can usually survive under normal moisture conditions by growing at a slow rate but are usually the first to be affected by drought conditions. Trees in shallow soil may also be prone to moisture stress, while trees whose roots are shallow because of high water tables would be susceptible to drought when the water table falls. An important contributing factor to moisture stress is, of course, subnormal rain and snowfall as was experienced in Britain in 1976 (Agripress 1978). In this instance the severe drought in the summer of 1976, followed by a dry winter, caused considerable Beech dieback with Birch almost totally defoliated in some locations as well as Larch and Western Hemlock being badly hit amongst the conifers. In almost all locations, Oak with its generally deeper root system were found to be little affected.

Water deficits in plant growth has been extensively reviewed by Kozlowski (1968). Extremely complex hypotheses as to the mechanisms of drought injury have been developed by this author and others. However, it seems that it is most commonly a complex of dehydration and overheating. Dehydration and overheating alter normal metabolism and protoplasmic structure. Severe overheating causes hydrolosis of proteins into constituent peptides and amino acids. Toxic amounts of ammonia may be released during this process. In addition to hydrolysis, other reactions to moisture stress are thought to be important. Dehydration increases the protoplasmic viscosity and interferes with the process of phosphorylation. This would critically reduce a tree's ability to accumulate and transform energy. As drought increases, there is also mechanical injury to protoplasm when cells rapidly loose water and cell walls and membranes collapse. Zahner writing in Kozlowski (1968) notes that water deficits affect not only foliar components of the tree but that root development, reproductive growth, growth in girth and extension growth are all diminished by drought stress. Bernatzky (1978) notes that reduction of root growth gives diminished absorption of nutrients and water and increased danger of death through drought and windfall. Beernatzky also notes that trees having tap root systems and intermediate root systems (as shown in the accompanying table) are probably less prone to moisture stress. Caution is urged on the user of this table, however, in that root characteristics may be modified by repeated transplanting, by particular site and soil conditions, and by obstructing layers in the soil profile.

Kozlowski and Davies writing in 1975 suggested that resistance to water movement through a tree causes internal water deficits due to transporation during the day. At night the stomata close so that absorption and transpiration can overcome the deficit. However, the effects of drought conditions on a tree first produce closing of the stomata through loss of turgidity of the guard cells. Wilting then takes place, first as an incipient reaction with no observable leaf droop, followed by temporary wilting where the leaves droop but recover at night, and then permanent wilting, which requires rewetting of the soil for recovery. If prolonged, permanent collapse of cell tissue occurs. In addition to wilting, which Smith suggests is very evident in such trees as Black Cherry and Dogwood, leaf discolouration and distortion occurs, particularly on broad-leaf trees where marginal scorch tends to progress inward toward the mid-leaf region. Frequently leaves will curl upward. Another clear symptom of drought stress, well seen on maples adjacent to the campus, is premature autumn colouration. Smith (1970) notes that Black Cherry, Yellow Popular, and Hickory commonly turn yellow before wilting or curling, while coniferous species reacting to early summer drought will have shorter needles with yellow tips later turning brown and progressing down the needle. Hamilton (1978) reporting the effect of California's drought on landscape horticulture found that stunting, leaf burn, necrosis and early leaf fall were all evident on such species as *Populus nigra*, *Magnolia grandiflora*, *Aesculus hippocastanum*, *Fraxinus velutina*, *Platanus acerifolia*, and *Eucalyptus globulus* as well as foliage, twig and limb dieback in *Arbutus menziesii*, *Sequoiadendron giganteum* and *Sequoia sempervirens*. Junipers were found to be the most drought hardy along with the true cedars, while at the other end of the spectrum *Magnolia* and *Betula alba* were found to be the most drought sensitive. Other symptoms recorded by some authors (Hinckley 1975, Smith 1970, Hibben 1978, and Etherington 1979) include stem cankers and drought cracks, the latter particularly on coniferous species, progressive dieback in the upper portion of crowns, invasion of bark by canker fungi, and actual stem shrinkage.

Before leaving this section it is perhaps worth noting that winter drying can also be associated with drought conditions. Broad-leaved and needled evergreens are subject to loss of water in the winter. Since the soil around the roots is normally frozen, water lost through transpiration at this time cannot be replaced. The severest winter water loss usually occurs in late winter on warm and windy days. The symptoms of this winter burn are often not fully evident until spring and the affected foliage, appearing yellow to brown, presents a sharp contrast with the newly emerging green foliage.

High Temperature

Trees in the northern hemisphere exhibit the most successful growth at some average, optimum range of temperatures. Tree species also have a maxima and a minima temperature range for growth which, if exceeded, will result in abnormal physiological responses. High temperatures are probably more readily attained in the natural environment than is commonly realized. Smith (1970), for example, notes that during the summer the south side of a pine tree may reach 55° C (130° F) and that soil surfaces exposed directly to the sun may exhibit temperatures in the range 55° to 75° C (168° F) in some arid and desert conditions.

The exact mechanisms of heat injury do not appear to be well understood. Overheating appears to alter the colloidal-chemical properties of protoplasm and induce metabolic changes which may contribute to abnormal physiology. High temperatures seem to cause denaturation of proteins. Protein decompostion may in turn lead to the release of ammonia in toxic amounts. It is interesting to note that in some heat resistant plants high temperatures have been shown to induce the accumulation of organic acids. These acids react with ammonia produced from protein decomposition to form various salts and amides which in turn mitigate the ammonia's toxic influence. Whatever the mechanism, trees, as members of the plant community, are poikilothermic organisms, with their own temperatures tending to approach the temperature of the surroundings. It is only when ambient temperatures exceed 35° C that cessation of photosynthesis occurs and incipient damage to physiological processes will occur.

A number of symptoms are important in recognizing temperature stress. Perhaps the most commonly recognized is that of sunscald, also referred to as sun scorch, where thin barked trees such as Alder, Dogwood and Beech have become suddenly exposed to direct intense sunlight. This situation is commonly experienced in the Lower Mainland of British Columbia whenever forested areas are excessively thinned to create housing lots or recreational areas. Two events may occur as a result of this type of stress, summer sunscald and winter sunscald. Summer sunscald is heat injury to the exposed bark during the summer and often results in bark killing with subsequent canker formation. Wood beneath the dead bark is sometimes invaded by decay fungi and trees may break in this area after being affected for a few years. Where summer sunscald injury has been combined with accompanying drying of sites, tree losses can be substantial, particularly on sites with a predominance of Alder. Winter sunscald is injury from rapid changes in bark temperature during cold and sunny winter days. Such injury, especially on species with dark bark, appears to occur when the sunny side becomes much warmer than the surrounding air temperature. The rapid temperature changes in the later part of the day can result in bark injury that usually occurs on the southwest side of individual trees.

Other symptoms of high temperature stress include leaf burning, characterized by the development of reddened or browned patches on broad-leafed species and necrosis of the distal portions of coniferous needles on conifer species. Another symptom of high temperature stress is evident in forest nurseries. Seedling damage is very common during the first or second year in the seed beds. Small seedlings seem to typically collapse, while larger individuals become girdled but remain standing. The latter gradually decline as the flow of food materials from the leaves is restricted by small lesions. Lath shading of conifer seedlings has now become a wide spread practice in many nurseries. My own experience at the Forestry Commission Nursery at Bankfoot Scotland has been of the loss of 100,000 Sitka Spruce seedlings as a result of 3 days exposure to temperatures in the high 90° F (33° C).

Harris (1972) has reported on the problem of high temperature limb breakage. This phenomena as yet has no explanation. Limbs fall from trees on hot still summer afternoons. Elm, Oak, Pine, Plane, True Cedar, and Douglas Fir appear to be implicated. The factors involved seem to be high temperature, moisture stress and wood strength. The problem is evident in the Lower Mainland particularly in the Municipality of West Vancouver where Douglas Fir high temperature limb breakage has been of concern for safety reasons in Lighthouse Park.

Low Temperature

The use of the term stress in the context of low temperatures may be somewhat misleading since cold temperature effects are normally viewed in the context of direct injury. Native trees which have adapted to northern climate are not usually injured by low temperatures. Exotic trees from more southern latitudes have not adapted to temperature peculiarities of particular locations and are usually the most prone to cold temperature injury. Woody plants have adapted to winter conditions by an established pattern of growth and dormancy that follows the yearly weather cycle very closely. They can tolerate extreme cold during the winter but little during the growing season. As fall approaches trees begin to become more progressively cold hardy, reaching a peak of hardiness in mid-winter. A decrease in hardiness begins in early spring and the trees may reach a low point of cold tolerance during the spring flush. Tattar (1978) notes that this is the most vulnerable time for cold injury. A spring frost can do considerable damage to many trees and may even kill them. Injuries are most commonly seen on flowering trees such as Crabapples, Magnolias and Lilacs whose flowers are often killed by light frosts. Obviously, the later into the spring season the frost occurs, the greater the chances that even native trees will be injured. Most authors (Schoeneweiss 1978, Smith 1970, Levitt 1972, Levitt _In_ Li 1978) agree that the damage to living cells is not from cold per se but from the formation of ice. Ice forms outside the plant cells. Intercellular freezing is the most rapid and damaging of the two (Smith 1970). Intracellular freezing is slower and more subtle in its effect (Levitt 1972). In this instance, ice formed on the external surface of the cell wall grows continuously, withdrawing water from the cell interior as the temperature declines. Cells frozen in this manner undergo a remarkable dehydration and may be injured in two ways: physical collapse and protein denaturation.

Native woody plants in relatively cold regions are capable of surviving extremely low temperatures without injury if they have had the opportunity to harden off. Soon after twig growth ceases, considerable changes take place in the cells of twigs, especially in deciduous trees (Smith 1970). There is a decrease of both water content and activity in the cambium cells and an increase in both starch granules and osmotic concentrations as the starch is converted to sugars. This increase in viscosity of vacuolar material is particularly noticeable in the parenchyma cells of bark and phloem. The actual mechanism which permits these hardened cells to resist freezing damage is unclear according to the authors sited above, but may involve increases in osmotic concentrations, the production of polyhydric alcohols, which may lower the freezing point in individual vacuoles, sugars acting to bind much of the free water and inhibiting ice formation, increased membrane flexibility, which avoids physical disruption, and increased solubility of proteins, also binding free water and inhibiting ice formation.

Snow and Ice Damage

Treshow (1970) in his text Environment and Plant Response devotes a whole chapter to climatic extremes such as lightning, hail, ice and snow. Though not always thought of in the context of stress, ice and snow damage associated with climatic extremes, Treshow suggests, is relatively common and sometimes causes devastating losses due to tree injury. Tattar (1978) suggests that damage is prevalent where there are weak forks that cause winter branch and trunk failure. Tattar also suggests that weak forks arise from branches growing at such an acute angle that normal wood formation is inhibited and structural weakness occurs. Some tree species such as Silver Maple are prone to weak forks, which can be eliminated either early when the tree is small or later by securing cables between susceptible limbs. Treshow (1970) notes that snow damage is very prevalent in the spring, particularly to Douglas Fir under 3 ft. high. Cedars are also suggested as being susceptible to breakage, particularly by heavy, wet snows. Davidson (1975) suggests that damage may not show up for a year or more, with flattening of branches breaking the bark, thus damaging the circulatory system with roots slowly dying and eventually causing death of the plant. Smith (1970) observes that snow damage is manifest in much the same way as wind injury. Stems and branches may be broken, lean may be produced or trees may be pushed over.

Morphological differences seem to determine the amount of snow injury. Butler (1974) found that physical breakage and injury were species, size and shape dependent, but also often reflected past maintenance practices. Van Cleve found that *Picea mariana* was more likely to be damaged by snow break than *P. glauca* while Smith (1970) reports that Noble Fir saplings suffer fewer snow injuries than does Douglas Fir, but more than Western Hemlock, Western White Pine and Silver Fir.

Ice in various forms may pose a significant threat to tree welfare in certain areas. Glazed frost, freezing rain and hail are all potentially capable of causing tree damage. Treshow (1970) reports on hail damage, and in one particular instance, the most conspicuous feature of injury seven years after the hail storm was dead tops and one-sided crowns of larger trees with the bare sides all facing the northwest direction, from which the hail had struck. On Aspen, abrasions on the smooth white bark had given rise to conspicuous black, rough calluses. Top dieback was noticed on White Spruce and Jack Pine, the latter having some bark completely stripped and little healing. Treshow suggests that hail wounds also bear a superficial resemblance to frost injury. On woody plants these wounds may be distinguished by the straight line normal wood with numerous vessels which soon appear again while in the case of frost, broad zones of parenchymatous tissue may be found due to the great extension of adjacent split edges.

Heavy accumulations of ice constrict twigs and branches from trees and reduce growth for many years. Breakage is most common, of course, when ice storms are accompanied by strong winds. Broken tops cause permanent crooks or forks in the bole. These injuries also make trees more vulnerable to attack by insects and fungi. Cayford (1961) found that Jack Pine was the most severely affected, followed by Cedar and Black Spruce. Semonin (1978) notes that glaze storms are frequently accompanied by heavy snowfall which, when accompanied by high winds, can be responsible for extensive damage. Smith (1970) suggests there is considerable variation in species resistance to ice injury. Eastern White Pine and Scot's Pine appear to suffer far greater damage than Northern White Cedar and Austrian Pine, while Norway Spruce and Eastern Red Cedar sustain practically no injury. Treshow (1970) concludes that because of the greater flexibility in manner of growth, conifers, as a whole, are more resistant to glaze injury than hardwoods.

Lightning

Urban trees in exposed locations such as open fields or hill tops, or trees in parks that rise above the forest canopy are sometimes struck by lightning. Injury can be variable and ranges from complete explosion, as was the case with the large cedar on northwest Marine Drive in Vancouver, or burning of the entire tree, to minimal damage to trunk and roots. Tattar (1978) suggests that even when only minor injury is evident on the trunk, considerable damage may have occurred to roots. This author also suggests that frequently trees may be subject to repeated strikes due to their exposed location. Treshow (1970) suggests that differences in susceptibility have been attributed to height, habitat, growth habit, chemical composition of individual trees and the unequal conductivity and water content of the wood. The fatty content of plant cells has been reported to influence conductivity and subsequently tolerance to injury. Beech wood is reported to contain large amounts of oil, while Oak wood is almost free from it and high in water content. This high degree of hydration may predispose Oak to lightning damage. The poor conduction and lightning resistance of such trees as Birch, Walnut and Linden are attributed to their high oil content. Oil content, and conductance, vary with the season so that damage may be greatest from spring and summer storms when trees are high in sugars, rather than oils. Treshow also suggests that the effects of lightning are not always immediate and sometimes only expressed after a year or two. Whereas breakage may be immediately conspicuous, trees may be less obviously stressed and not die for two or more years after a strike.

Smith (1970) suggests that Oak, Elm, Poplar and Pine are among the most commonly struck, while Beech is rarely struck. Treshow reports that Oak, Elm, Poplar, Tulip Tree, Ash and Pine are among the most prone to damage while Spruces are rarely hit. Pirone (1978) reports that Elm, Maple, Oak, Pine, Poplar, Spruce and Tulip Tree are the most popularly hit, while Beech, Birch and Horsechestnut are rarely struck. Boyce (1961) takes issue with trying to list susceptible and resistant trees. This author suggests that all trees, given the right conditions and locations, can be struck by lightning.

Light

In the last few years greater interest has been expressed about the impact of security lighting on landscape trees. Cathey (1975) reports that night-time lighting promotes continuous growth when the natural environment is signalling dormancy. This may cause trees to continue growing and at first frost to suffer considerable winter kill. Cathey examined 40 species of plants and found that _Betula_, _Catalpa_, _Platanus_ and _Tilia_ continued to grow vegetatively in response to all types of light source while Andresen (1974) in a survey of 19 American cities found no detrimental effects caused by high pressure sodium street lights. Cathey, in another study, reported in the American Society of Horticultural Science (1975) that high intensity discharge illuminaires, were probably less likely to affect plants than incandescent filament lamps. Roberts (1977) suggests that light quality (wave length) is not important in nature but must be considered when artificial illumination is used. However, the question of photoperiod and impact of lighting is difficult to quantify since different trees respond differently, even within species. Pirone (1978) warns against the use of Christmas lights in trees since these can damage cambium through the use of worn equipment or scorch leaves from poorly placed bulbs. Feature lighting in trees can also cause physical damage to urban trees. An example here are thin barked trees, such as the Beech on Granville Street in Vancouver, where high intensity feature lights close to the bark have caused cambial dieback and trunk wounds as a result of the heat generated by each light.

Finally, in the context of light, it is worth remarking that with the exception of Wilson (1973) little reference is made by authors to the probable stress induced by placing shade demanding species in open, exposed locations and light demanding species in, for example, areas of constant shadow. In the latter case phototropic reaction can become quite evident, with trees growing away from adjacent buildings. One of the most remarkable examples of this is in Washington D. C. where street planted Ginkgo have a pronounced lean away from buildings, particularly in locations with a northerly aspect.

Herbicides

Despite continuing removal of some herbicides and the restriction of others, both in terms of quantity and efficacy, available to the general public, considerable amounts of herbicides continue to be used in the urban setting by homeowners, municipalities and utility companies. Unfortunately, these substances are sometimes carelessly applied and may be distributed to areas where they can cause significant damage. Even when applied on windless days, thermal updrafts created by rising warm air can carry spray material aloft, while root translocation can occur from misapplication or lack of buffer zones. While woody plants are rate responsive to herbicides and death can occur if sufficient material enters the plant system, more frequent symptoms of herbicide damage involve rapid necrosis of exposed parts, defoliation, twig dieback, contortion of leaves, small leaves, and in some cases, particularly in susceptible plants, severe dieback or death. Hibbs (1978) also includes in symptoms cupped, chlorotic leaves, lack of apical dominance, enlarged bud size, parallel leaf venation, stem lesions, abnormal stem colouration, and nastic growth. This author points out that very careful examination is needed to ensure that herbicide damage symptoms are not confused with other conditions. Neely (1974) conducted an extensive study on 17 commercial products containing 11 herbicides commonly used to control weeds in lawns. Of the materials tests only Dicamba consistently produced symptoms, with White and Blue Spruce readily killed; Tulip Tree, Honey Locust, Oak and Linden exhibiting twig dieback; Walnut, Ash, Maple and Red Bud showing leaf distortion; and most conifers (as would be expected) unaffected. Smith (in a similar study) found that Simazine and Dichlobenil were the most harmful pre-emergent herbicides while Dicamba and 2, 4-D were the most harmful post-emergent herbicides causing damage to shade trees. While there is extensive literature on the effectiveness of herbicides, all too often the undesirable effects of drift and misapplication of stem foliar herbicides and soil sterilants, respectively, are poorly documented. There is no doubt the problem is relatively widespread. Almost one third of the woody plant material submitted to the Provincial Pathologist for disease diagnosis are found to be exhibiting symptoms of herbicide damage rather than active pathogens.

Domestic Gas

The widespread transportation and distribution of both natural and manufactured gas in underground systems is known to result in plant damage. Natural gas, which is generally thought to be less toxic, contains primarily methane and ethane. Both of these gases are phytotoxic (Smith 1970). Small impurities in the gas, however, may also contribute to the toxic effect. Certainly manufactured gas contains traces of hydrogen cyanide and carbon monoxide. Davis (1977) suggests that tree damage is caused by a combination of methane toxicity and a concomitant lack of oxygen. Garner (1973) found that leaking gas caused the soil to become anaerobic. Under anaerobic conditions microbial action can transform sulfates into hydrogen sulfides which in turn are toxic to trees. Smith (1970) observes that the most common symptom of gas damage is extremely sudden yellowing of tissue followed by wilting and dieback.

Leone *et al* (1977) and Flower (1977) review the difficulty in establishing tree cover on or adjacent to landfill areas where the production of methane on landfill sites can severely affect some tree species. Paul (1977) has found that *Carpinus*, *Sorbus*, *Prunus*, *Acer* and *Betula* are sensitive species; while *Populus*, *Salix* and *Platanus* are generally resistant species.

Nutrient Deficiencies

There is perhaps no environmental factor more important to the health of trees than the soil conditions in which they grow (Tattar 1978). Soil was once thought to be an inert entity, a medium containing only water and nutrients available for plant growth. Chemical stress induced by soil conditions can be due to unfavourable pH and/or imbalance in nutrients. Certainly pH plays some part in tree suitability for certain sites. At one end of the spectrum Spruces prefer a pH around 5, while Beech prefers calcareous soils with a pH around 8.5. More important perhaps is that normal growth and health of trees is clearly dependent on an adequate supply of the element, given in the attached table. Of these 16 elements, 9 are required in substantial amounts, and are often termed macronutrients, and 7 are required in small amounts as micronutrients; carbon and oxygen are derived from atmospheric carbon dioxide and hydrogen from soil water. The remaining 13 elements are generally supplied to the plant through the uptake of soil solution. As Smith (1970) observes, if one or more of these nutrients is absent or present in suboptimal amounts, physiological processes will be altered and abnormal metabolisms will result.

Tattar (1978) suggests that amongst urban trees, the most common nutrient imbalances reported are iron deficiency chlorosis, copper toxicity, boron toxicity and manganese deficiency. Iron deficiency, of course, is most prominent in alkaline soils. Species affected are given in the attached table. Although foliar feeding can overcome the problem, if undertaken on a consistant basis, long range control of iron deficiency in trees should involve permanent changes in soil pH. A problem which has only been recently recognized is that of copper treated burlap used in balled and burlapped stock sold through urban garden centres. Repeated applications of copper fungicides may also cause a soil build-up of copper that can eventually be toxic to plants (Tattar 1978). Boron is an essential micro element that may cause injury to plants when soil concentrations are too high (Smith 1980). Pine and Yew seem particularly susceptible to this problem. Manganese deficiency, like iron deficiency, is common in high pH soils. The problem is most pronounced on Maples, where trees may eventually decline and die if not treated. Typical symptoms for both coniferous and deciduous trees are given in the attached tables.

Salt

Of the large number of chemicals used in the urban landscape perhaps the most common group of chemicals that are toxic to trees are various deicing compounds. Sodium chloride ($NaCl$) and calcium chloride ($CaCl_2$) are the two chemicals most commonly used to melt ice and snow on sidewalks, driveways and highways. In fact, these chemicals are sometimes applied together. Sodium chloride, however, seems to be used most commonly, either alone or in combination with abrasives such as sand or cinders. Calcium chloride is used most commonly in extreme cold, below 20° F (-7° C) because it releases heat when it contacts water and melts snow and ice at much lower temperatures than can sodium chloride. It is, however, more expensive and more difficult to handle than sodium chloride.

As Smith (1975) noted, deicing salt lifted by traffic as salt-spray and then blown by winds or driven by turbulence onto roadside plants, where it coats the foliage of evergreens and the stems and branches of all woody plants, is perhaps more damaging than salt accumulation in the soil.

Tattar (1978) suggests that the exact effects of deicing salts in the soil on roots are complex, but that salts are known to make water and essential nutrients difficult to absorb by tree roots. The water is tightly held by the salt ions and more energy is required for the roots to absorb water. When sufficient water cannot be absorbed by the roots to meet the needs of the plant, water deficit occurs. The plant may respond to physiological drought by absorbing salts in an attempt to balance the soil concentration internally. This response is thought to be an important mechanism for salt tolerance by some plants but since this adjustment in metabolism usually requires considerable expenditure of energy, some trees use so much energy adjusting to soil salinity they stop growing, decline and eventually die. This is in contrast with salt tolerant plants which appear to be able to adjust to increased soil salinity with little or no decrease in growth. It has been noted by Lumis (1975) and Smith (1978) that nutrient balance in the plants in trees can also be affected by salt in the soil. The high concentration of sodium in salt contaminated soil makes potassium less available to the roots. While potassium and sodium have similar chemical properties, only potassium is useful to the plant. However, high concentrations of sodium in the soil can result in preferential absorption of sodium instead of potassium.

In the case of salt spray injury, it is presumed that it is due primarily to excessive accumulation of toxic ions, especially Cl from salts deposited on aerial organs. Chloride tends to migrate in the plant to leaf tips, where damage soon becomes evident as tip or marginal necrosis. Lumis (1975) has observed that the commonest symptom of aerial salt spray in conifers is moderate to extreme needle browning, starting at the tip, with browning and twig dieback mainly on the side facing the prevailing wind. No injury occurs on branches under continuous snow cover, where salt spray does not penetrate far into the plants or where plants are close together. Sheltered plants are not injured. It is suggested that injury first becomes apparent in February and early March and becomes more extensive through late spring and early summer. In deciduous trees, terminal leaf buds on the side facing exposure are normally slow to open or do not open, with new growth arising from basal section of branches facing the prevailing wind. This can give trees a tufted look. Lumis (1973) has also observed premature leaf abscission, twig dieback and inhibition of flowering as a result of salt exposure. Dirr (1976 and 1978) has conducted extensive research in the selection of trees for tolerance to salt injury, as outlined in the attached tables. Beckerson (1980) has drawn together a number of authors to provide a guide to plant sensitivity to environmental stress, including salt damage. Similar tables have also been prepared by Gaut (1907), Roth (1976), Rich (1971) and Daniels (1974). To some extent, the tables and data collected by a number of authors is contradictory. One area, however, that has long been of contention, has now been concluded as being caused by salt stress. This problem is one of Sugar Maple decline along roadsides in the eastern United States. Rich (1979) observed that these maples exhibited smaller light green leaves, scorched leaf edges, thin canopies, early fall colouration and leaf fall, twig and branch dieback and diminished growth ring increments. A correlation was found between these symptoms, leaf analysis and the road use of deicing salts. Rubens (1978) has now shown that Sugar Maple decline can be arrested by applying powered gypsum to the soil as a protective but not curative treatment, even though the continuing use of deicing salt on adjacent roads continues.

Air Pollution

In the course of reviewing the literature for this paper it quickly became evident that the most extensive body of information, at least in the context of available tables, was that for air pollution stress and damage on trees. In general, air pollution damaged to trees can be divided into three broad groups of pollutant types; particulate matter, non-photochemically produced gas pollutants and photochemically produced gaseous pollutants. Tattar (1978) also suggests that air pollutants may be classified according to their source, into two broad groups; point source emissions and diffuse oxidants. Point source emissions are defined as coming from stationary sources such as smoke stacks, while diffuse oxidants are defined as atmospheric contaminants from chemical reactions with oxygen that are powered by sunlight, as in the case of photochemical pollutants.

Mudd (1975), Carlson (1979), Smith (1970), Dochinger (1975), Wilson (1970), Treshow (1970), amongst many authors, have examined the specific effects of air pollutants on plant tissues. These effects appear to vary with the pollutant, host plant, time of year, and meteorological factors such as temperature, relative humidity, wind and solar radiation. In addition, symptoms known to be produced on plants by air pollutants seem also to be produced by stress from moisture, temperature and nutrient deficiencies. This, coupled with geographic factors such as mountains, valleys, lakes and proximity to source, appear to make accurate diagnosis of air pollution damage extremely difficult if it is not coupled in some way with air pollution monitoring. Moreover, even such monitoring appears to be potentially unreliable since some air pollutants, such as fluoride and chlorides, that are toxic in extremely low concentrations, require extremely sensitive analysis to accurately implicate these gases.

Mudd and Kozlowski (1975) in their extensive review Responses of Plants to Air Pollution, note that in addition to killing plants, atmospheric pollutants adversely affect plants in many ways. Pollution injuries are most commonly classed as acute, chronic or hidden. In acute injury collapsed marginal or intercostal leaf areas are noted, which at first have a water soaked appearance. Later these dry and bleach to an ivory colour in most species and in some may become brown or brownish red. These lesions are caused by absorption of enough gas to kill the tissues. Chronic injury involves leaf yellowing which may progress through stages of bleaching until most of the chlorophyll and carotenoids are destroyed and interveinal portions of the leaf are nearly white. Chronic injury is caused by absorption of gas that is somewhat insufficient to cause acute injury but may be caused by absorption of sublethal amounts over a long period of time. Carlson (1979) has found that histological changes occur in pollution injured leaves including plasmolysis, granulation or disorganization of cell content, cell collapse or disintegration and pigmentation of affected tissues. Mudd and Kozlowski refer to a "hidden" effect as being a stress reaction to air pollution damage causing a reduction of photosynthesis below the level expected for the amount of leaf destruction visually apparent. Further complicating the analysis of the mechanisms of air pollution damage is the fact that more than one pollutant is often responsible for injury and that air pollutants generally appear to be relatively non-specific agents which have many sites of action.

Particulate matter such as soot, dusts, and particles containing heavy metals appear to make up the bulk of this problem. Lepp (1976) has found that increased heavy metal contamination of the environment can be related to industrialization and increased consumption of leaded gasoline. Leaves were found to retain heavy metals and when these leaves fell the metals were released into the soil. Lepp found that the presence of calcium and phosphorus in the soil may decrease the uptake of heavy metals by tree roots. When heavy metals are translocated, they may be permanently incorporated into the walls of root cells, although a lower proportion is eventually transported to aerial parts. Lepp suggests that trees can act as long term sinks, particularly in acid soils where heavy metals are taken up more readily. Heavy metals are retained in longer lived tissues such as bark and wood. The biological activity of heavy metals such as lead is as yet poorly understood in terms of physiological disturbance in tree species.

The effect of cement dust on trees has been reviewed by Rhoads (1976). Severe foliar chlorosis, leaf scorch, branch dieback and eventual death can result from prolonged exposure to particulate depositions. It was also found that acid loving species, particularly *Quercus* and *Pinus* declined due to unavailability of certain essential nutrients.

Of the non-photochemically produced gaseous pollutants, probably the most extensively studied are oxides of sulphur. (National Environmental Research Centre 1973). Sulphur dioxide (SO_2) appears to be by far the most important sulphur pollutant. The bulk of severe SO_2 damage to urban trees appears to occur around electrical generating stations. Sulphur dioxide enters the leaves through open stomata, is absorbed on the moist reactive surfaces of the spongy mesophyll and reacted into sulfite. Sulfite is very toxic to the cells and will quickly kill them when the external sulphur concentration is 0.50 parts per million or greater. However, stress may occur at as low as 0.03 parts per million for susceptible species under favourable conditions (Davies 1969). On broad leaf species symptoms include irregular marginal interveinal necrotic blotches bleached white to straw. In the case of conifers needle tips are chronically necrotic, often with a banded appearance Linzon (1971).

Fluorides

Of the halogen compounds, the most important pollutant is hydrogen fluoride, although hydrogen chloride (HCl) and chlorine (Cl_2) are also produced at some chemical or plastic manufacturing plants. The mechanism of fluoride effects on trees is discussed by Smith (1970). It appears that fluoride is absorbed from the air, translocated in tissues and accumulated in leaf tips and margins. The toxicant remains in a soluble form and seems to retain the chemical properties of free inorganic fluoride. The excessive concentration results in disruption of enzyme systems and eventual death of cells. Apparently the actual mechanism of injury is not yet fully understood. Lanphear (1971) reports that injury from fluoride appears as tip necrosis in conifers and tip and marginal necrosis in broad-leaf trees. Injury in conifers usually begins with yellowing of the needle tissue, which progressively turns to tan and then to red-brown. Injury in broad-leaf trees usually begins with fading of leaf tissue, followed by red-brown necrosis which is usually sharply defined from the healthy tissue. Emerging leaf tissues appear more susceptible to acute injury and consequently more sever injury appears in the spring. Pine appears to be a particularly susceptible species.

Taylor, writing in Mudd and Kozlowski (1975), reports that during combustion of fuels, some of the nitrogen in the air is oxidized to NO and a comparatively small amount of NO_2. The rate of NO formation increases in proportion to the temperature of combustion. During daylight, atmospheric NO may also be quantitatively converted to NO_2 by photochemical reaction involving the absorption of sunlight and interaction with hydrocarbons and oxygen. Adverse direct effects of nitrogen oxides on plant life are generally limited to areas in close proximity to urban industrial developments where the emissions are concentrated. It appears that a wide range of responses related to stage of growth and conditions of light, temperature, humidity and/or water stress and fertilization at time of exposure affect the direct the degree of nitrogen oxide damage.

Thompson also notes that the mechanisms by which nitrogen dioxide cause injury to plants have received little attention in biochemical and histological studies. It is well known that NO_2 reacts with water to form a mixture of nitrous and nitric acids. The author suggests that this probably occurs as the gas reaches the wet surface of the spongy parenchyma in the leaves of trees, and when the acid exceeds a given threshold the tissues are injured. Smith (1970) reports that acute NO_2 injury is often manifest as necrotic lesions similar to SO_2 on broad-leaf plants, but no authors provide any definitive symptoms for conifers.

Damage caused by ethylene, ammonia, carbon monoxide, mercury vapour and aldehydes is briefly mentioned by some authors reviewing non-photochemically produced gaseous pollutants. However, the information is spotty and no tables were discovered for any of these pollutants.

Smith (1970) suggests that until recently, non-photochemically produced pollutants were thought to be responsible for most air pollution damage to plants. Approximately 20 years ago, however, a new type of pollution was recognized, especially in the Los Angeles region of California. These pollutants required alteration after release from their source by reaction with sunlight, other atmospheric materials, or both, to become phytotoxic. Heath, writing in Mudd and Kozlowski (1975), notes that the production of ozone in polluted urban atmospheres has been the subject of much controversy and study. This author notes that the precise biochemical mechanisms of photochemical oxidant damage to trees has not yet been satisfactorily characterized. A number of authors (Genys 1978, Brennan 1976, Karnosky 1978, 1979, Clark 1980, Davis 1974 and Hay 1977) have reviewed the impact of ozone on tree growth and much of the work of these authors is included in the tables attached to this paper. The symptoms of ozone damage appear on sensitive plant species as necrosis, chlorosis and flecking of the upper leaf surface. These visible symptoms are thought to result by way of the following sequence of events; ozone interaction with some component of the cells and leaf tissue, collapse of the cell, localized accumulation of extracellular water, bleaching of the chlorophyll and breakdown of the leaf structure. The flecking may later become red-brown pigmented stipple or bleach straw to white fleck. Conifers may show tip burn or yellow to brown banding of needles (Lanphear 1971). Pine, in particular White Pine, Green and White Ash and European Larch all appear to be sensitive and suitable as indicator tree species (Lanphear 1971).

Finally, an air pollution complex that has been implicated in tree damage is that of peroxyacetyl nitrate (PAN) of the hydrocarbons released from internal combustion engines are several olefins and aromatics (Smith 1970). The compounds are oxidized in the presence of nitrogen oxides and light shortly after their release. The resulting decomposition products, rich in aldehydes, are further reacted with ozone in the atmosphere to produce PAN. As with a number of other air pollutants, the exact mechanisms by which PAN affect trees is not known. Symptoms appear on broad-leaf species as collapse of the tissue on the underside of leaves, giving a glazed, silvered or bronzed appearance. Conifers generally display rather unspecific needle blight symptoms with some chlorosis or bleaching (Lanphear 1971). Although little work as been published on the influence of PAN on trees Hindawi (1970), Treshow (1970), U.S. Forest Service (1973) and Kozlowski (1980) have prepared tables on the effects of peroxyacetyl nitrate on some urban trees.

A number of stresses to which some urban trees are probably exposed are ill-defined in the literature. An example is the effect of Hedera helix in its arborescent stage. In West Vancouver along Marine Drive alone, some 20 trees have been recently removed from various locations because they died from the smothering effects of the vines. Despite the many references examined for this paper, only one British writer specifically addressed the urban problem (Mitchell 1975), although there is a considerable body of reference work on Dwarf Mistletoe in forestry.

Another example is the spillage of hydrocarbon fuels through deliberate dumping. For example, waste oil disposal on the periphery of some park sites is a problem in Burnaby. Another example is the loss of oils from damaged equipment. Line rupture in clearing equipment on new urban housing sites can dump as much as 100 gallons of hydraulic oil on the edge of tree retention sites. Tattar (1970) refers to the problem of dog urine which is a strong alkaline solution. The problem is said to be three fold; soil effects, dieback of lower branches and loss of foliage directly exposed. Conifers such as the various cypress types seem most commonly affected.

Finally, there are stress effects that go unreported in the urban tree literature, although they must play a part in affecting tree growth, particularly in narrow streets with tall buildings. An obvious stress will be that caused by the Venturi effect, when wind passes through narrow spaces in a street location and is speeded up, causing turbulent air to buffet street trees. While the stressing effect of wind has been examined by some authors (Martojoewono 1960, Moore 1977, van Eimern et al 1964), as has the effect of tying trees to tree supports (Harris 1978), no review was found on the tolerance of various species to constant wind rocking.

Conclusions

An extensive array of tables that provide comparative assessments of tree reaction can be found for the most prominent stress factors known to effect urban trees. It is not clear that these tables can be considered any more than a general guide for the urban plantsman faced with choosing tree species for particular locations. Genetic variation of different tree provenances and of individuals within trees, the vagaries of specific site conditions under which any particular stressing agent may occur, as well as timing and duration of the stress, may all affect the probability of reproducing the conditions used to assess and categorize the stress thresholds of any genus or species found in the tables.

Little appears in the discussion of stress about the probable synergism that occurs when more than one stress factor impinges upon a tree or trees. The complexity of such research is recognized but for the potential user, the need is for tables that establish the "hardiness" of a species under a broad range of simultaneous and arduous conditions. Moreover, little appears to be known at present of the predisposing condition that stress may provide for disease or insect infestation of urban trees. A number of poorly explained diebacks and declines have now been identified and stress appears to be implicated in these complex diseases.

Some tables found are both extensive and informative. The authors have attempted to provide clear indications of the origin and parameters under which the data used to categorize a tree has been collected. On the other hand, however, many tables are restricted to a few species, often poorly identified. It remains for an extensive overview to be prepared on the stress reaction that can be anticipated from those trees commonly in urban settings. Most tables presently available are presented as an amalgam of experience and writings of other workers. Few tables are prepared as a result of direct research. While reoccurrence of a particular species in a number of tables may corroborate the individual findings, it is not always obvious that the origins of information are independent. While this casts some doubt on the usefulness of such tables, in fact it may cause some to be misled or some species to be unnecessarily maligned for use in some locations, the general conclusion should be that tabular references of the type gathered for this paper are useful for general guidance in tree choice. The more credible the study researcher, or the more explicit the study criteria and value system, the more useful the table.

Perhaps another inference that can be drawn from the tables so far assembled is the need for researchers in urban tree stress to provide the data in comparable form and for experimental protocols and assessments to be explicitly stated for each tree comparison and tree stress state examined.

Although an attempt has been made throughout this paper to briefly describe the symptoms associated with a particular stress on particular species, it cannot be implied that adequate diagnostic information is available to the average practitioner. While the arborist has available excellent colour references for air pollution damage on plants (Jacbson and Hill 1970, Anon. Grounds Maintenance 1971) and the symptoms of nutrient stress are fairly well documented, the general area of diagnostic tools for stress recognition, either pictorial or descriptive, is relatively poor. This a deficiency of particular importance in education where younger arboriculturalists and foresters are initially denied the enquiring yet knowledgeable eye that should come with years of field experience. There is, moreover, a far too ready tendency to overlook the broad view of particular sites and to concentrate too much on the tree itself without a holistic appreciation for a site as it was, as it is now, and how it will be in the future.

Diagnosis of stress in all but the most mundane of circumstances is still largely an art form. The advent of the Shigometer, using electrical resistance to determine decay and vigor, is hopefully only a beginning step in a more sophisticated array of tools and references available to monitor tree and environmental conditions in the urban setting.

In western and eastern civilizations alike, the tree has played an important role in mitigating the sterility, scale and enormity of the city. Urban environments have become increasingly hostile to plants and man. As space becomes more valuable, taller buildings are built, green space gives way to concrete and blacktop and population exceeds the carrying capacity of a livable reality. As we forfeit the livability of our own environment, so too we encroach precipitously the place for trees, one of the last few natural elements in an almost completely alien, engineered city world.

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Key for Tables

S = Sensitive
M = Moderately sensitive
I = Insensitive
— = No info. available

DECIDUOUS TREES

Species	Hardiness Zone[10,21](*)	SO_2	O_3	Salt	References
Acer ginnala (Amur maple)	2	—	—	M/S	14,18
Acer negundo (Manitoba maple)	2	M/S	M/I	M/S	7,8,14,15,16, 17,24
Acer platanoides (Norway maple)	5*	I	I	I	7,8,14,16,17, 18,22,23
Acer pseudoplatanus (Sycamore maple)	5	—	—	S	13
Acer rubrum (Red maple)	3b*	M/I	I	M/S	7,8,12,14,16, 18,22
Acer saccharinum (Silver maple)	2b*	I	—	M/I	7,8,14,15, 16,18
Acer saccharum (Sugar maple)	4*	I	I	M/I	7,8,12,15,16, 17,18,22
Aesculus hippocastanum (Common horsechestnut)	5b*	—	—	I	14,16,18
Ailanthus altissima (Tree of Heaven)	6*	—	S	I	5,7,8,12,14, 16,18
Amelanchier laevis (Allegany serviceberry)	3b*	—	—	S	14,18
Betula davurica (Dahurian birch)	4/5	—	—	S	13
Betula papyrifera (Paper birch)	2*	S	I	M	7,8,14,16, 18,22
Betula pendula (European birch)	2	S	I	M	7,8,14,22
Carpinus betulus (European hornbeam)	4	—	—	S	13,14
Carya ovata (Shagbark hickory)	4	—	—	M/I	14,16,18
Catalpa speciosa (Northern catalpa)	5b*	M	—	M	14,15,16,18
Cercis canadensis (Eastern redbud)	6*	—	M/S	S	7,8,14,25
Elaeagnus angustifolia (Russian olive)	2b*	—	—	I	13,14,16,18
Fagus grandifolia (American beech)	4*	—	—	M/S	14,16,17,18
Fagus sylvatica (European beech)	4	—	I	S	7,8,13,14
Fraxinus americana (White ash)	3b*	S	S	M/I	7,8,12,14,15, 16,18,22
Fraxinus pennsylvanica (Green ash)	3	S	S	M	7,8,14,22
Fraxinus pennsylvanica lanceolata (Cutleaf green ash)	2b*	—	S	M	7,12,18
Ginkgo biloba (Maidenhair tree)	4*	I	—	M	8,12,14
Gleditsia triacanthos (Honey locust)	4	—	S	—	8,12,22
Gleditsia triacanthos inermis (Thornless honey locust)	4	—	—	I	16,18
Juglans nigra (Black walnut)	3b*	—	I	M/I	8,12,14,16 18
Juglans regia (English walnut)	4	—	S	M/I	7,8,14,16,17
Kalmia latifolia (Mountain-laurel kalmia)	5b*	—	I	—	5
Liquidambar styraciflua (American sweetgum)	5	—	M/S	—	12,22
Liriodendron tulipifera (Tulip tree)	5b*	—	S	S	7,12,14
Nyssa sylvatica (Sour-Gum)	5b*	—	I	—	6,7,12
Platanus acerifolia (London plane tree)	6*	I	—	S	8,14,15
Platanus occidentalis (American sycamore)	5b*	—	S	S	7,8,12,14
Populus alba (White poplar)	3	—	—	M/I	13,14
Populus balsamifera (Balsam poplar)	1	I	—	—	7,8
Populus x canadensis (Carolina poplar)	5	I	—	—	8,15
Populus deltoides (Cottonwood)	2	—	—	I	14,16,18
Populus grandidentata (Large-toothed aspen)	3	S	—	M/I	7,8,14,15
Populus nigra (Lombardy poplar)	4	S	—	M/I	7,8,14,16,18
Populus tremuloides (Trembling aspen)	2*	S	—	M/I	7,8,12,15,16, 18,24
Prunus avium var. Bing (Bing cherry)	3	—	S	—	8
Prunus virginiana (Choke cherry)	2	M	—	M/I	14,15,16,18
Quercus alba (White oak)	4*	M	S	M/S	7,8,12,14,22
Quercus imbricaria (Shingle oak)	4b*	—	I	—	7,8
Quercus macrocarpa (Bur oak)	2	—	I	M/S	7,8,14,16
Quercus palustris (Pin oak)	4*	I	M/S	S	7,8,12,14,22, 23
Quercus robur (English oak)	5*	—	I	I	7,8,13
Quercus rubra (Red oak)	3*	I	I	I	7,12,15,16, 18,22
Quercus velutina (Black oak)	5	—	M	—	7,8
Robinia pseudoacacia (Black locust)	3	—	I	I	7,8,12,14,16, 18
Salix alba "tristis" (Weeping golden willow)	4*	—	—	M/S	14,16,17,18

*These numbers correspond to reference list which appears in alphabetical order at the end of the article.

Salix nigra (Black willow)	3	S	—	M/I	7,8,14,15,16, 18
Sorbus aucuparia (European mountain ash)	3*	M	S	I	7,8,18,25
Tilia americana (Basswood)	2b*	M/S	I	M	7,8,12,14,15, 18,22
Tilia cordata (Littleleaf linden)	3	I	I	—	5,7,8,15
Ulmus americana (White elm)	2	M	—	M/I	7,8,14,15,16, 18
Ulmus procera (English elm)	6	—	—	I	13
Ulmus parvifolia (Chinese elm)	5	S	M	—	5,7,8,15,23

CONIFEROUS TREES

Species	Hardiness Zone[10,21](*)	SO_2	O_3	Salt	References
Abies balsamea (Balsam fir)	3	M	I	M	7,8,9,14,15
Abies concolor (White fir)	4*	I	I	I	7,8,9,14,24
Juniperus chinensis (Spreading juniper)	4	—	—	I	1
Juniperus communis (Common juniper)	2	I	—	—	8
Juniperus scopulorum (Rocky mountain juniper)	3b*	I	—	—	7,8
Juniperus virginiana (Eastern red cedar)	2	—	—	M/I	14,18
Larix decidua (European larch)	3b*	—	S	I	7,8,9,14
Picea abies (Norway spruce)	2b*	—	I	M/S	7,9,14,16,18
Picea engelmannii (Engelmann spruce)	5	M	—	—	7,8,15
Picea glauca (White spruce)	1b*	M/I	I	S	7,8,9,15, 16,18
Picea glauca var. denstata (Blackhills spruce)	2	—	I	—	8
Picea pungens (Blue spruce)	2*	I	I	I	7,8,9,16,18
Pinus banksiana (Jack pine)	2	S	S	I	2a,7,8,9,14, 15,16,18
Pinus bungeana (Lacebark pine)	4	I	I	—	10
Pinus flexilis (Limber pine)	2	I	—	—	7
Pinus mugo (Mugho pine)	1*	—	—	I	14,16,18
Pinus nigra (Austrian pine)	5*	M	S	I	7,8,9,14,15, 16,17,18
Pinus parviflora (Japanese white pine)	5	I	I	—	10
Pinus ponderosa (Ponderosa pine)	3b*	M	S	—	7,8,19
Pinus resinosa (Red pine)	2	S/M	I	S	2a,7,8,9,14, 15,16,18
Pinus strobus (Eastern white pine)	3*	S	M/S	S	2a,2b,3,4,7, 8,9,14,15,16, 17,18,22
Pinus sylvestris (Scot's pine)	3*	S	M/S	M/S	9,10,14,16, 18,22
Pseudotsuga menziesii (Douglas fir)	4*	M/S	I	M/S	7,8,9,14,15, 22
Taxus cuspidata (Japanese yew)	4	—	I	M/S	14,25
Taxus x media "densiformis" (Dense yew)	5*	—	I	—	8
Taxus x media "hicksii" (Hicksii yew)	5*	—	I	—	23
Taxus x media "hatfieldii" (Hatfields pyramidal yew)	4	—	I	—	8
Thuja occidentalis (White cedar)	3*	I	I	M/S	1,7,8,12,14, 15,16,17,18
Thuja orientalis (Oriental cedar)	5/6	—	I	—	9
Thuja plicata (Western red cedar)	5	I	—	—	7,8,15
Tsuga canadensis (Canadian hemlock)	4*	I	I	S	7,8,11,12,14, 16,18

Important trees of northeastern U S that are sensitive or resistant to air pollutants.[1]

Species	Arborists' Rating[2]	Reports[3] Which Indicate Resistance (R) or Sensitivity (S) to			
		Ozone	Sulfur Dioxide	Nitrogen Oxide	Fluoride
Acer platanoides	1.7	R1, 2, 7, 8	S9	S1, 7	
A. rubrum	1.9	R1, S4	R1, S7		
A. saccharum	2.3	R1, 2, 7, 8, S4	R1, 7		
Betula spp.		R1, 2, S8	S1, 2, 3, 7, 8		S7, 8
Fraxinus americana	1.5	S1, 7, 8			
F. pennsylvanica	1.5	S1, 2, 4, 7, 8	R1		S3, 7
F. velutina					R1, 3, 7
Ginkgo biloba	1.0		R1, 7	S1, 7	
Gleditsia triacanthos	1.4	S1, 2, 3, 7, 8			R8
Liquidamber styraciflua	1.6	S1, 2, 7			
Picea pungens		R1, 2, 8	S9	S1, 7	S1, 3, 7, 8
Pinus strobus	2.3	S1, 2, 3, 7, 8	S1, 2, 3, 7, 8, 9, 10	S1, 7	S1, 3, 6, 7, 8, 10
P. sylvestris	1.7	S1, 2, 7	S5, 7, 9, 10		S1, 3, 6, 7, 8, 10
Prunus serotina			S7		
Pseudotsuga menziesii		R1, 2, 8	S2, 8, 9, 10		S1, 3, 6, 7, 8
Quercus alba		S1, 2, 7, 8			
Q. palustris	1.4	S1, 2, 7			
Q. rubra	1.5	R1, 2, 7, 8	R1, 7, 8		
Tilia americana	1.4	R2, S7	S2		R1, 8
T. cordata	1.6	R2, 7, 8, S1	S5, 9, 10	S1, 7	R1, 7, S3, 6, 10

[1] Importance of native and introduced species based on commerical timber, landscape, or Christmas tree values.
[2] Unpublished data of Gerhold from survey of municipal arborists. Scale of 1 to 3 based on survival or growth (1) not affected, (2) moderately affected, (3) severely affected by air pollutants.
[3] Reports which indicate that species are resistant or moderately to very sensitive are: (1) Anon. 1973, (2) Davis 1973, (3) Jacobson and Hill 1970, (4) Jensen 1973, (5) Ranft and Dässler 1970, (6) Rohmeder and von Schonborn 1965, (7) Scott 1973, (8) Sucoff and Bailey 1971, (9) van Haut and Stratmann 1970, (10) Wentzel 1968.

Sensitivity of woody plants to noxious gases at concentrations of 0.5–2 ppm (SO_2) and 0.3–0.5 ppm (HF); the gradation of the responses is based on externally visible damage. (After Ranft and Dässler, 1970, and Dässler *et al.*, 1972)

Sensitivity	to SO_2	to HF
Very sensitive	*Pinus sylvestris* *Larix decidua* *Picea abies* *Salix purpurea*	*Juglans regia* *Vitis vinifera* *Berberis vulgaris* *Pinus sylvestris* *Picea abies* *Larix decidua*
Sensitive	*Salix fragilis* *Salix pentandra* *Berberis vulgaris* *Rubus idaeus* *Tilia cordata* *Vitis vinifera* *Pinus nigra*	*Tilia cordata* *Rubus idaeus* *Carpinus betulus* *Pinus nigra*
Very resistant	*Juniperus sabina* *Thuja orientalis* *Buxus sempervirens* *Ligustrum vulgare* *Quercus petraea* *Platanus acerifolia*	*Chamaecyparis pisifera* *Acer campestre* *Acer platanoides* *Evonymus europaea* *Quercus robur* *Sambucus racemosa*

Additional data on sensitivity to noxious gases in various woody plants and herbaceous species are found in Garber (1967), Krüssmann (1970), and Treshow (1970).

Tolerance of Some Woody Plants to Sulfur Dioxide[a]

Tolerant	Intermediate	Sensitive
Arborvitae	Alder, mountain	Alder, thinleaf
Cedar, Western red	Basswood	Aspen
Fir, white	Boxelder	Ash, green
Ginko	Cottonwood	Birch
Hawthorn, black	Dogwood, red osier	Elm, Chinese
Juniper	Douglas fir	Larch, western
Linden, Littleleaf	Elm, American	Maple, Manitoba
Maple, Norway	Fir, balsam	Maple, Rocky Mountain
Maple, silver	Fir, grand	Mulberry, Texas
Maple, sugar	Hawthorn, red	Pine, eastern white
Oak, pin	Hemlock, western	Pine, jack
Oak, red	Honeysuckle, tartarian	Pine, red
Pine, limber	Lilac	Poplar, Lombardy
Pine, pinyon	Maple, red	Serviceberry
Poplar, Carolina	Mountain-ash, European	Willow, black
Spruce, blue	Mountain-laurel	
Yew, pacific	Oak, white	
	Pine, Austrian	
	Pine, ponderosa	
	Pine, western white	
	Poplar, balsam	
	Spruce, Engleman	
	Spruce, white	

[a] From Davis and Wilhour (1976).

RELATIVE SUSCEPTIBILITY OF TREES TO SULFUR DIOXIDE

Sensitive	Intermediate	Tolerant
Betula alleghaniensis	*Abies balsamea*	*Abies amabilis*
Betula papyrifera	*Abies grandis*	*Abies concolor*
Betula populifolia	*Acer negundo*	*Acer platanoides*
Fraxinus pennsylvanica	*Acer rubrum*	*Acer saccharinum*
Larix occidentalis	*Picea engelmannii*	*Acer saccharum*
Pinus banksiana	*Picea glauca*	*Juniperus occidentalis*
Pinus resinosa	*Pinus contorta*	*Picea pungens*
Pinus strobus	*Pinus monticola*	*Pinus edulis*
Populus grandidentata	*Pinus nigra*	*Pinus flexilis*
Populus tremuloides	*Pinus ponderosa*	*Quercus gambelii*
Salix nigra	*Populus balsamifera*	*Quercus palustris*
	Populus deltoides	*Quercus rubra*
	Populus trichocarpa	*Thuja occidentalis*
	Pseudotsuga menziesii	*Thuja plicata*
	Quercus alba	*Tilia cordata*
	Tilia americana	
	Tsuga heterophylla	
	Ulmus americana	

SOURCE: Reprinted, by permission, from Davies and Gerhold 1976, table 2.

CONCENTRATIONS OF SULFUR DIOXIDE CAUSING INJURY TO SENSITIVE VEGETATION[a]

Species	Concentration[b] μg/m³	(ppm)	Exposure time, hr	Effect[c]	Conditions	Reference
White pine (*Pinus strobus* L.)	131	(0.05)	1	Needle injury rating of *3*	Branch exposure chamber in greenhouse	127
	131	(0.05)	2	Needle injury rating of *5*		
	131	(0.05)	3	Needle injury rating of *8*		
	262	(0.10)	1	Needle injury rating of *5*		
	262	(0.10)	2.5	Needle injury rating of *8*		
Alfalfa (*Medicago sativa* L.)	1310	(0.5)	4	5% leaf injury	Greenhouse exposure chambers	70
	1310	(0.5)	4	19% leaf injury		
Broccoli (*Brassica oleracea* var. *botrytis* L.)	655	(0.25)	4	6% leaf injury	Same	70
	1310	(0.5)	4	4% leaf injury		
	1310	(0.5)	4	None		
Apple (*Malus* sp. "Manks Codlin")	1258	(0.48)	6	Leaf injury rating of *6*	Branch exposure chambers in natural stands	128
Pear *Prunus* sp, "Legipont"	1258	(0.48)	6	Leaf injury rating of *4*	Same	128
"Conference"	1336	(0.51)	6	Leaf injury rating of *5*		
Mountain ash (*Sorbus aucuparia* L.)	1415	(0.54)	3	Leaf injury rating of *3*	Same	128
	2175	(0.83)	3	Leaf injury rating of 7		

[a] The vegetation was observed or exposed when growing under environmental conditions that made it most sensitive to SO_2.

[b] Average concentrations over the reported time periods. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.

[c] The effects are reported differently in each reference. Their definition is briefly described:

1. Reference 127: The needle injury rating is based on a *1* to *8* scale with *1* as no injury and *8* as 2 to 3 cm of tip necrosis.
2. Reference 70: The values reflect the average percentage foliar injury on the three most severely injured leaves.
3. Reference 128: The leaf injury rating is based on a *0* to *10* scale with *0* as no injury and *10* as the entire leaf surface injured.

SULFUR DIOXIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamae)		●	
White fir (Abies concolor)		●	
Silver fir (Abies pectinata)		●	
Lawson cypress (Cupressus lawsonianu)	●		
Juniper (Juniperus sp.)	●		
Larch (Larix sp.)			●
Engelman spruce (Picea engelmannii)			●
White spruce (Picea glauca)	●		
Jack pine (Pinus banksiana)			●
Lodgepole pine (Pinus contorta latifolia)		●	
Western white pine (Pinus monticola)			●
Dwarf mugo pine (Pinus mugo mughus)	●		
Austrian pine (Pinus nigra)	●		
Ponderosa pine (Pinus ponderosa)			●
Eastern white pine (Pinus strobus)			●
Douglas fir (Pseudotsuga menziesii)		●	
White cedar (Thuja accidentalis)	●		
Western red cedar (Thuja plicata)	●		
Mountain hemlock (Tsuga mertensiana)			●

SULFUR DIOXIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Hedge maple (Acer campestre)	●		
Red maple (Acer rubra)	●		
Sugar maple (Acer saccharum)	●		
Mountain maple (Acer spicatum)	●		
Birch (Betula sp.)			●
European hornbeam (Carpinus betulus)	●		
Catalpa (Catalpa sp.)			●
White dogwood (Cornus florida)	●		
European beech (Fagus sylvatica)	●		
Green ash (Fraxinus pennsylvanica)	●		
Maidenhair tree (Gingko biloba)	●		
English holly (Ilex aquifolium)	●		
English walnut (Juglans regia)			●
Tulip tree (Litriodendron tulipfera)	●		
Apple (Malus sp.)			●
Texas mulberry (Morus microphylla)			●
Black gum (Nyssa sylvatica)	●		
Sourwood (Oxydendron arboreum)	●		
American planetree (Platanus occidentalis)	●		
Oriental planetree (Platanus orientalis)	●		
Balsam poplar (Populus balsamifera)		●	
Eastern cottonwood (Populus deltoides)	●		
Bigtooth aspen (Populus grandidentata)		●	
Lombardy poplar (Populus nigra 'Italica')			●
Quaking aspen (Populus tremuloides)			●
Pear (Pyrus communis)			●
English oak (Quercus robur)	●		
Red oak (Quercus rubra)	●		
Black locust (Robinia pseudocacia)	●		
Willow (Salix sp.)			●
European mountain ash (Sorbus aucuparia)			●
American elm (Ulmus americana)			●

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	

[a]From David and Gerhold (1976).

Relative sensitivity of native and cultivated plants to sulfur dioxide. (A low number indicates high sensitivity.)*

Sensitive		*Intermediate*		*Resistant*	
Alfalfa	1.0	Yellow pine†	1.6	Gladiolus	1.1—4.0
Barley	1.0	Dandelion	1.6	Sweet cherry	2.6
Endive	1.0	Sugarbeet	1.6	Purslane	2.6
Cotton	1.0	Aster	1.6	Rose	2.8—4.3
Gaura	1.0	Tomato	1.3—1.7	Sumac	2.8
Cheatgrass	1.0	Lambs' quarter	1.8	Shepherds' purse	3.0
Mallow	1.1	Apple	1.8	Maple	3.3
Ragweed	1.1	Catalpa	1.9	Box elder	3.3
Rhubarb	1.1	Sweet clover	1.9	Virginia creeper	3.8
Radish	1.2	Cabbage	2.0	Onion	3.8
Lettuce	1.2	Marigold	2.1	Lilac	4.0
Zinnia	1.2	Pea	2.1	Corn	4.0
Spinach	1.2	Linden	2.3	Cucumber	4.2
Bean	1.1—1.5	Douglas fir	2.3	Salt grass	4.6
Curly dock	1.2	Peach	2.3	Chrysanthemum	5.3—7.3
Table beet	1.3	Apricot	2.3	Citrus	6.5—6.9
Buckwheat	1.3	Cocklebur	2.3	Arborvitae	7.8
Plantain	1.3	Elm	2.4	Currant blossoms	12.0
Sunflower	1.3—1.4	Iris	2.4	Live oak	14.0
Clover	1.4	Poplar	2.5	Apple Blossoms	25.0
Rye	1.4	Yellow pine	2.4—4.7	Apple buds	87.0
Carrot	1.5				
Wheat	1.5				
Larch	1.5				

* Adapted from Thomas et al., 1950.
† Year-old seedlings in May, 1.6; in August, 2.4–4.7.

Relative sensitivity of selected forest species to SO_2 (22, 26, 27, 37).

SENSITIVE	TOLERANT
Ash	Blackgum
Aspen	Boxelder
Birch	Dogwood
Blackberry	Juniper
Carelessweed	Maple
Catalpa	Oak, live
Dewberry	Sourwood
Elm, American	Spruce
Larch	Sycamore
Oak, blackjack**	Tuliptree*
Pine, eastern white	
Pine, jack	
Pine, loblolly** (seedlings to 6 ft.)	
Pine, Virginia** (seedlings to 6 ft.)	
Poplar	
Ragweed	

*Sensitive Spring and Early Summer
**Unpublished Tennessee Valley Authority Data

Resistance of trees to sulphur dioxide

			Author
Very sensitive		Fir, Spruce Douglas fir	Wentzel, 1969
	Salix purporea	*Pinus sylvestris* *Larix decidua* *Picea abies*	Ranft and Daessler, 1970
Sensitive			
	Linden, Ash, Beech, Hornbeam Cherry, Plum	Pine, Larch White pine	Wentzel, 1969
	Berberis vulgaris *Salix fragilis* *Salix pentandra* *Tilia cordata*	*Pinus nigra*	Ranft and Daessler, 1970
Relatively insensitive			
	Oak, Alder, Poplar Maple, Elder Pear, Peach	Austrian pine *Arbor vitae* Yew	Wentzel, 1969
	Buxus sempervirens *Ligustrum vulgare* *Platanus acerifolia* *Quercus petraea*	*Juniperus sabina*	Ranft and Daessler, 1970

OZONE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamea)	●		
White fir (Abies concolor)		●	
Western juniper (Juniperus occidentalis)	●		
European larch (Laris decidua)			●
Japanese larch (Larix leptolepis)			●
Incense cedar (Libocedrus decurrens)		●	
Norway spruce (Picea abies)	●		
White spruce (Picea glauca)	●		
Black Hills spruce (Picea glauca densata)	●		
Colorado spruce (Picea pungens)	●		
Knobcane pine (Pinus attenuata)		●	
Jack pine (Pinus banksiana)			●
Coulter pine (Pinus coulteri)		●	
Jeffrey pine (Pinus jeffreyi)			●
Sugar pine (Pinus lambertiana)	●		
Singleleaf pinyon pine (Pinus monophylla)	●		
Austrian pine (Pinus nigra)			●
Ponderosa pine (Pinus ponderosa)			●
Monterey pine (Pinus radiata)			●
Red pine (Pinus resinosa)	●		
Pitch pine (Pinus rigida)			●
Digger pine (Pinus sabiniana)	●		
Eastern write pine (Pinus strobus)			●
Scotch pine (Pinus sylvestris)			●
Torrey pine (Pinus torreyana)	●		
Virginia pine (Pinus virginiana)			●
Big cone Douglas fir (Pseudotsuga macrocarpa)		●	
Douglas fir (Pseudotsuga menziesii)	●		
Giant sequoia (Sequoia gigantea)	●		
Redwood (Sequoia sempervirens)	●		
Arborvitae (Thuja sp.)	●		
Eastern hemlock (Tsuga canadensis)			●

OZONE

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (Acer negundo)			●
Norway maple (Acer platoides)	●		
Red maple (Acer rubra)	●		
Silver maple (Acer saccharinum)			●
Sugar maple (Acer saccharum)	●		
Alder (Alnus sp.)			●
European white birch (Betula pendula)	●		
Catalpa (Catalpa sp.)			●
Judas tree (Cercis chinensis)			●
White dogwood (Cornus florida)	●		
White ash (Fraxinus americana)			●
Green ash (Fraxinus pennsylvanica)			●
Honeylocust (Gleditsia triacanthos)			●
Black walnut (Juglans nigra)	●		
Sweetgum (Liquidambar styraciflua)			●
Tulip tree (Liriodendron tulipfera)			●
Siberian crab (Malus baccata)			●
Maple leaf mulberry (Morus alba acerfolia)			●
American planetree (Platanus occidentalis)			●
California sycamore (Platanus racemosa)			●
Quaking aspen (Populus tremuloides)			●
White oak (Quercus alba)			●
Scarlet oak (Quercus coccinea)			●
Gambel oak (Quercus gambelii)			●
Shingle oak (Quercus imbricaria)	●		
Pin oak (Quercus palustris)			●
English oak (Quercus robur)	●		
Red oak (Quercus rubra)	●		
Black locust (Robinia pseudoacacia)			●
Weeping willow (Salix babylonica)			●
European mountain ash (Sorbus aucuparia)	●		
Little leaf linden (Tilia cordata)			●

Susceptibility of Trees to Ozone

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

Source: Reprinted, by permission, from Davies and Gerhold 1976, table 3.

RELATIVE SUSCEPTIBILITY OF SELECTED TREE SEEDLINGS TO OZONE INJURY[a]

Injured	*Uninjured*
Fraxinus americana	*Abies balsamea*
Larix leptolepis	*A. concolor*
Liriodendron tulipifera	*Acer saccharum*
Pinus banksiana	*Betula pendula*
P. nigra	*Picea abies*
P. rigida	*P. glauca*
P. strobus	*P. glauca* var. *densata*
P. virginiana	*P. pungens*
Quercus alba	*Pinus resinosa*
Tsuga canadensis	*Pseudotsuga menziesii*
	Thuja occidentalis
	Tilia cordata

[a]From Davis and Wood (1968). Reproduced by permission of The American Phytopathological Society.

Relative sensitivity of selected forest species to ozone (10, 37, 43).

SENSITIVE	TOLERANT
Ash	Birch, European white
Honey locust	Black walnut
Larch, European	Dogwood, gray
Oak, white	Fir, balsam
Pine, Virginia	Fir, white
Pine, eastern white	Maple
Pine, jack	Oak, red
Poplar	Spruce
Sweetgum	
Sycamore	
Tuliptree	

Resistance of trees to ozone (Wood and Coppolino, 1972)

Sensitive	
	Green ash
	White ash
	Mountain ash
	Sweet gum
	Pin oak
	Scarlet oak
	White oak
	Hybrid poplar
	Sycamore
	Redbud
Relatively insensitive	
	European white birch
	Grey dogwood
	Flowering dogwood
	Little leaf linden
	Norway maple
	Sugar maple
	English oak
	Shingle oak
	Tulip poplar

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 ×		Pesudotsuga menziesii
trichocarpa	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).

Tolerance of Some Woody Plants to Ozone[a]

Tolerant	Intermediate	Sensitive
Arborvitae	Boxelder	Ash, green
Birch, European white	Cedar, incense	Ash, white
Dogwood, white	Cherry, Lambert	Aspen, quaking
Fir, balsam	Elm, Chinese	Azalea
Fir, Douglas	Gum, sweet	Cotoneaster
Fir, White	Larch, Japanese	Honey locust
Gum, black	Lilac	Larch, European
Holly	Oak, black	Mountain-ash, European
Linden, American	Oak, pin	Oak, Gambel
Linden, little-leaf	Oak, scarlet	Oak, white
Maple, Norway	Pine, eastern white	Pine, Austrian
Maple, sugar	Pine, lodgepole	Pine, Jack
Oak, English	Pine, pitch	Pine, Jeffrey
Oak, red	Pine, Scotch	Pine, loblolly
Pine, red	Pine, shortleaf	Pine, Monterey
Spruce, blue	Pine, slash	Pine, ponderosa
Spruce, Norway	Pine, sugar	Pine, Virginia
Spruce, White	Redbud, eastern	Poplar, tulip
Walnut, black		Sycamore, American
Yew		Tree of Heaven
		Walnut English

Sensitivity of woody plants to ozone

*Sensitive**	*Intermediate*	*Resistant*
Fragrant sumac	Chinese apricot	Siberian elm
English walnut	Pyracantha	European beech
Thornless honey locust	Thompson seedless grape	European white birch
Chinese lilac	Blue-leaf honeysuckle	Bartlett pear
Bing cherry	Silverberry	Virginia creeper
Lodense privet		Norway maple
Concord grape		Viburnum
Quaking aspen		American linden
Gambel oak		Bur oak
Snowberry		
Hopa crab		
Green ash		
Bridal wreath		

* Sensitive category injured below 30 pphm for four hours; intermediate injured at 40 pphm for four hours; resistant damaged at 53–56 pphm for four hours.

HYDROGEN FLUORIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Juniper (Juniperus sp.)	●		
Western larch (Larix occidentalis)			●
White spruce (Picea glauca)	●		
Colorado spruce (Picea pungens)			●
Lodgepole pine (Pinus contorta (latifolia)			●
Dwarf mugo pine (Pinus mugo mughus)			●
Ponderosa pine (Pinus ponderosa)			●
Eastern white pine (Pinus strobus)			●
Scotch pine (Pinus sylvestris)			●
Loblolly pine (Pinus taeda)			●
Douglas fir (Pseudotsuga menziesii)			●
Japanese yew (Taxus cuspidata)		●	
Arborvitae (Thuja sp.)		●	

HYDROGEN FLUORIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Hedge maple (Acer campestre)		●	
Boxelder (Acer negundo)			●
Silver maple (Acer saccharinum)		●	
Tree of heaven (Ailanthus altissima)	●		
European black alder (Alnus glutinosa)	●		
European white birch (Betula pendula)		●	
Cutlead European birch (Betula pendula 'Gracilis')	●		
European hornbeam (Carpinus betulus)		●	
Spanish chestnut (Castanea sativa)		●	
Cornelian cherry (Cornus mas)	●		
European filbert (Corylus avellana)		●	
Russian olive (Elaeagnus angustifolia)	●		
European beech (Fagus sylvatica)		●	
European ash (Fraxinus excelsior)		●	
Green ash (Fraxinus pennsylvanica)		●	
Modesto ash (Fraxinus velutina 'Modesto')	●		
English holly (Ilex aquifolium)		●	
Black walnut (Juglans nigra)		●	
English walnut (Juglans regia)		●	
Red mulberry (Morus rubra)		●	
Paulownia (Paulownia sp.)			●
Planetree (Platanus sp.)	●		
Oriental planetree (Platanus orientalis)		●	
Lombardy poplar (Populus nigra 'Italica')		●	
Quaking aspen (Populus tremuloides)		●	
Eugene poplar (Populus canadensis eugenei)		●	
Flowering apricot (Prunus americana)			●
Flowering plum (Prunus cerasifera)	●		
Bradshaw plum (Prunus domestica 'Bradshaw')			●
Oriental cherry (Prunus serrulata)	●		
English oak (Quercus robur)		●	
Smooth sumac (Rhus glabra)		●	
Black locust (Robinia pseudoacacia)		●	
Willow (Salix sp.)	●		
European elder (Sambucus nigra)	●		
European red elder (Sambucus racemosa)	●		
European mountain ash (Sorbus aucuparia)	●		
American mountain ash (Sorbus domestica)	●		
American linden (Tilia americana)	●		
Little leaf linden (Tilia cordata)	●		
European linden (Tilia europaea)		●	
American elm (Ulmus americana)	●		

Tolerance of Some Woody Plants to Hydrogen Fluoride[a]

Tolerant	Intermediate	Sensitive
Alder, European black	Arbovitae	Apricot, flowering
Ash, American mountain	Ash, European	Boxelder
Ash, European mountain	Ash, green	Fir, Douglas
Ash, Modesto	Beech, European	Larch, western
Birch, European cut-leaf	Birch, European white	Paulownia
Cherry, Cornelian	Chestnut, Spanish	Pine, eastern white
Cherry, Oriental	Filbert, European	Pine, loblolly
Elder, European	Holly, English	Pine, Mugho
Elm, American	Linden, European	Pine, ponderosa
Juniper	Locust, black	Pine, Scots
Linden, American	Maple, hedge	Spruce, blue
Linden, little-leaf	Maple, silver	
Planetree	Mulberry, red	
Plum, flowering	Oak, English	
Russian olive	Planetree, Oriental	
Spruce, white	Poplar, Eugene	
Tree of Heaven	Poplar, Lombardy	
Willow	Walnut, black	
	Walnut, English	

Relative sensitivity of selected forest species to fluoride (22).

SENSITIVE	INTERMEDIATE	TOLERANT
Boxelder	Ash, green	Birch, white
Pine, eastern white	Cherry, choke	Dogwood
Pine, Scots	Maple, Norway	Elm, American
Redbud*	Maple, silver	Juniper
	Mulberry, red	Poplar, balsam
	Oak	Sweetgum
	Poplar, Carolina	Sycamore
	Rhododendron	Tree-of-Heaven
	Serviceberry	Willow
	Sumac	
	Walnut, black	

*Unpublished Tennessee Valley Authority Data

TABLE 16.4. *Relative sensitivity of plants to fluoride.*

Sensitive	*Intermediate*	*Resistant*
Gladiolus (some varieties)*	Walnut (English)	Linden (American)
Apricot (Chinese and Royal)	Apricot (Moorpark, Tilton)	Pyracantha
Oregon grape	Citrus (Lemon, tangerine)†	Ailanthus†
Peach (fruit)	Walnut (Black)	Elm (American)†
Corn†	Poplar (Lombardy, Carolina)†	Tomato
Plum (Bradshaw)	Grape (Concord)	Asparagus
Prune (Italian)	Aspen (Quaking)	Wheat
Grape (European var.)	Barley (young plants)	Birch†
Pine (Ponderosa)	Grapefruit†	Current
Larch (Western)	Cherry (Bing, Royal Ann)†	Mt. Ash (European)
Pine (Eastern white, Lodgepole, Scotch, Mugho)	Sumac	Elderberry
Fir (Douglas)	Orange†	Cherry (Flowering)
Spruce (Blue)	Lilac	Sunflower
Blueberry	Peach (leaves)	Pigweed
Tulip (some varieties)	Chokecherry	Squash
Box elder	Maple (Rocky Mt., hedge, silver)	Virginia creeper
	Serviceberry	Burdock
	Spruce (white)	Strawberry
	Arborvitae	Pear
	Chickweed	Bridal wreath
	Raspberry	Ash (Modesto)
	Rose	Willow (Laurel leaf)
	Yew	Juniper
	Apple (Delicious)	
	Aster	
	Ash (green)†	
	Mulberry†	
	Geranium	
	Paeonia	
	Linden (European)	
	Sorghum†	
	Lambs quarter	
	Goldenrod	
	Rhododendron	
	Yellow clover	

* Plants are listed in approximate order of increasing tolerance
† Predominant symptom chlorosis rather than necrosis

Resistance of trees to fluorine

			Author
Very sensitive			
	Beech, Hornbeam Linden, Peach	Larch, Spruce Fir, Douglas Fir	Wentzel, 1969
	Berberis vulgaris *Juglans regia* *Vitis vinifera*	*Larix decidua* *Picea abies* *Pinus sylvestris*	Daessler et al., 1972
Sensitive			
	Maple, Birch Ash, Elder Apple, Pear	Pine White pine	Wentzel, 1969
	Carpinus betulus *Rubus ideaus* *Tilia cordata*	*Pinus nigra*	Daessler et al., 1972
Relatively insensitive			
	Willow, Alder Oak, Red oak Locust	Australian pine Yew, *Arbor vitae* Juniper	Wentzel, 1969
Very insensitive			
	Acer campestre *Acer platanoides* *Euonymus europaeus* *Quercus robur* *Sambucus racemosa*	*Chamaecyparis pisifera*	Daessler et al., 1972

Resistance of trees to nitrogen dioxide (van Hauten and Stratmann, 1967)

Very sensitive		
	White birch	*Larix europaea*
	Apple, wild tree	*Larix leptolepis*
	Pear, wild tree	
Sensitive		
	Acer platanoides	*Abies homolepis*
	Acer palmatum	*Abies pectinata*
	Tilia grandifolia	*Chamaecyparis lawsoniana*
	Tilia parvifolia	*Picea alba*
		Picea homolepis
Relatively insensitive		
	Carpinus betulus	*Pinus austriaca*
	Fagus sylvatica	*Pinus montana mughus*
	Fagus sylvatica atropurpurea	*Taxus baccata*
	Ginkgo biloba	
	Robinia pseudacacia	
	Sambucus nigra	
	Quercus robur	
	Ulmus montana	

Resistance of trees to nitrogen trioxide (Ewert in Keller, 1973b)

Very sensitive		
	Alnus glutinosa	*Pinus strobus*
	Alnus incana	
	Carpinus betulus	
	Tilia cordata	
	Tilia tomentosa	
Sensitive		
	Acer pseudoplatanus	*Larix* species
	Betula pendula	*Picea abies*
	Fagus sylvatica	*Pinus sylvestris*
	Fraxinus excelsior	*Thuja occidentalis*
Relatively insensitive		
	Acer campestre	*Chamaecyparis* species
	Acer negundo	
	Quercus borealis	
	Quercus robur	
	Robinia pseudacacia	

Empirical Resistance to NO_2 as Measured by Leaf Sensitivity

Resistance Group I: Sensitive

Field and Horticultural Crops
- Spring vetch (*Vicia sativum*)
- Garden peas (*Pisum sativa*)
- Lucerne (*Medicago sativa*)
- Crimson or Italian clover (*Trifolium incarnatum*)
- Red clover (*Trifolium pratense*)
- Carrots (*Daucus carota*)
- Common lettuce (*Lactuca sativa*)
- Common tobacco plant (*Nicotiana tabacum*)
- White mustard (*Sinapis alba*)
- Lupine (*Lupinus augustrifolius*)
- Common oats (*Avena sativa*)
- Parsley (*Petroselinum hortense*)
- Leek (*Allium porrum*)
- Viper's grass (*Scorzonera hispanica*)
- Barley (*Hordeum distichon*)
- Rhubarb (*Rheum rhubarbarum*)

Ornamental Plants
- Great snapdragon (*Antirrhinum majus*)
- Tuberous-rooted begonia (*Begonia multiflora*)
- Rose (*Rosa* sp.)
- Sweet pea (*Lathyrus odoratus*)
- China aster (*Callistephus chinensis*)

Coniferous Trees
- Larch (*Larix europea*)
- Japanese larch (*Larix leptolepis*)

Deciduous Trees
- Weeping birch (*Betula pendula*)
- Showy apple (*Malus* sp.)
- Wild pear tree (*Pyrus* sp.)

Resistance Group II: Medium Sensitive

Deciduous Trees
- Norway maple (*Acer platanoides*)
- Fan maple (*Acer palmatum*)
- Winter lime (*Tilia parvifolia*)
- Summer lime (*Tilia grandiflora*)

Coniferous Trees
- Blue spruce (*Picea pungens glauca*)
- White spruce (*Picea alba*)
- Lawson's cypress (*Chamaecyparis lawsoniana*)
- Nikko or Japanese fir (*Abies homolepis*)
- Common silver fir (*Abies pectinata*)

Resistance Group II: Medium Sensitive (*Continued*)
Ornamental Plants
Fuchsia (*Fuchsia hybrida*)
Petunia (*Petunia multiflora*)
Rhododendron (*Rhododendron catawbiense*)
Dahlia (*Dahlia variabilis*)
Field and Horticultural Crops
Rye (*Secale cereale*)
Celery (*Apium graveolens* var. *rapaceum*)
Maize (*Zea mays*)
Common wheat (*Triticum sativum*)
Tomato (*Solanum lycopersicum*)
Potato (*Solanum tuberosum*)
Pine strawberry (*Fragaria chiloensis* var. *grandiflora*)
Resistance Group III: Relatively Insensitive
Deciduous Trees
Black locust (*Robinia pseudoacacia*)
Hornbeam (*Carpinus betulus*)
Common beech (*Fagus sylvatica*)
Common elder (*Sambucus nigra*)
Gingko tree (*Ginkgo biloba*)
Mountain elm (*Ulmus montana*)
Purple-leaved beech (*Fagus sylvatica atropurpurea*)
Common oak (*Quercus pendunculata*)
Coniferous Trees
Common yew tree (*Taxus baccata*)
Black pine (*Pinus austriaca*)
Knee pine or dwarf mountain pine (*Pinus montana mughus*)
Field and Horticultural Crops
Kohlrabi (*Brassica oleracea* var. *gongylodes*)
Onion (*Allium cepa*)
White cabbage (*Brassica oleracea* var. *capitata alba*)
Kale (*Brassica oleracea acephala*)
Red cabbage (*Brassica oleracea* var. *capitata rubra*)
Ornamental Plants
Oxeye daisy (*Chrysanthemum leucanthemum*)
Lily of the Valley (*Convallaria majalis*)
Common gladiolus (*Gladiolus communis*)
Plantain lily or Funkia (*Hosta* sp.)

OXIDES OF NITROGEN

SOFTWOODS	Tolerant	Intermediate	Sensitive
European larch (Larix decidua)		●	
White spruce (Picea glauca)			●
Colorado spruce (Picea pungens)			●
Dwarf mugo pine (Pinus mugo mughus)			●
Austrian pine (Pinus nigra)			●
Eastern white pine (Pinus strobus)			●

OXIDES OF NITROGEN

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese maple (Acer palmatum)			●
Norway maple (Acer platanoides)			●
European hornbeam (Carpinus betulus)			●
European beech (Fagus sylvatica)			●
Maidenhair tree (Gingko biloba)			●
Apple (Malus sp.)			●
Pear (Pyrus communis)			●
Black locust (Robinia pseudoacacia)			●
European elder (Sambucus nigra)			●
Little leaf linden (Tilia cordata)			●
Large leaf linden (Tilia grandiflora)			●

CHLORINE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Jack pine (Pinus banksiana)		●	
Short leaf pine (Pinus echinata)		●	
Eastern white pine (Pinus strobus)			●
Loblolly pine (Pinus taeda)		●	
Yew (Taxus sp.)	●		
Hemlock (Tsuga sp.)	●		

CHLORINE

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (Acer negundo)			●
Sugar maple (Acer saccharum)			●
Horse chestnut (Aesculus hippocastanum)			●
Tree of heaven (Ailanthus altissima)			●
Russian olive (Eleagnus angustifolia)	●		
Chinese holly (Ilex chinesis)	●		
Sweetgum (Liquidambar styraciflua)			●
Apple (Malus sp.)			●
Black gum (Nyssa sylvatica)		●	
Black cherry (Prunus serotina)		●	
Pin oak (Quercus palustris)			●
Red oak (Quercus rubra)	●		
Sassafras (Sassafras albidum)			●

HYDROGEN CHLORIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamea)	●		
Larch (Larix sp.)			●
Norway spruce (Picea abies)	●		
Austrian pine (Pinus nigra)	●		
Eastern white pine (Pinus strobus)	●		
Arborvitae (Thuja sp.)	●		

HYDROGEN CHLORIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Maple (Acer sp.)	●		
Birch (Betula sp.)	●		
Cherry (Prunus sp.)			●
Black cherry (Prunus serotina)	●		
Pear (Pyrus communis)	●		
Oak (Quarcus sp.)	●		
Red oak (Quercus rubra)	●		

PEROXYACETYL NITRATE (PAN)

SOFTWOODS	Tolerant	Intermediate	Sensitive
European larch (Larix decidua)	●		
Japanese larch (Larix leptolepis)	●		
White spruce (Picea glauca)	●		
Colorado spruce (Picea pungens)	●		
Jack pine (Pinus banksiana)	●		
Austrian pine (Pinus nigra)	●		
Pitch pine (Pinus rigida)	●		
Eastern white pine (Pinus strobus)	●		
Douglas fir (Pseudotsuga menziesii)	●		
Eastern hemlock (Tsuga canadensis)	●		

PEROXYACETYL NITRATE (PAN)

HARDWOODS	Tolerant	Intermediate	Sensitive
Sugar maple (Acer saccharum)	●		
Tulip tree (Liriodendron tulipfera)			●
Little leaf linden (Tilia cordata)			●

MERCURY VAPOR

SOFTWOODS	Tolerant	Intermediate	Sensitive
Eastern white pine (Pinus strobus)			●

MERCURY VAPOR

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese maple (Acer palmatum)		●	
Persimmon (Diospyros virginiana)		●	
Chinese holly (Ilex chinesis)	●		
Mimosa (Mimosa sp.)			●
Oak (Quercus sp.)		●	
Willow (Salix sp.)			●

ETHYLENE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Arborvitae (Thuja sp.)			●

ETHYLENE

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese holly (Ilex crenata)			●

Tree species intolerant to flooding with suggested replacements from taxonomically related groups which are known to withstand flooding (Crawford, 1974) and suggestions from other authors

Kind	Intolerant	Tolerant
Beech	*Fagus sylvatica*	*Nothofagus dombeyii* *N. antarctica* *N. pumilo*
Elm	*Ulmus glabra* *U. procera* *U. carpinifolia*	*Ulmus americana* *U. alata* *Celtis occidentalis*
Ash	*Fraxinus excelsior*	*Fraxinus pennsylvanica* *F. chinensis*
Sycamore and maples	*Acer pseudoplatanus* *A. campestre* *A. platanoides*	*Acer saccharinum* *Platanus* x hybrida *P. occidentalis*
Holly	*Ilex aquifolium*	*Ilex decidua*
Oak	*Quercus robur*	*Quercis petraea* *Q. palustris* *Q. phellos* *Q. shumardii*
Eucalypts and myrtles		*Myrceugenella apiculata* *Myrceugenia exsucca*
Locusts		*Gleditsia triacanthos*
Pine	*Pinus*	*Pinus contorta* *P. thunbergii* *P. taeda* *P. palustris*
Larch	*Larix decidua*	*Larix laricina* *Taxodium distichum* *T. ascendens*
Cedar	*Cedrus libanotica* *C. deodora* *C. atlantica*	*Libocedrus chilensis* *Fitzroya cupressoides*
Author		
Polster (in Lyr et al., 1967)	*Celtis occidentalis* *C. laevigata* *Liquidambar styraciflua* *Ulmus americana*	*Populus* *Salix* *Alnus* *Fraxinus profunda* *Nyssa aquatica* *Prunus padus*

Author	Intolerant	Tolerant
Kruessmann, 1974	*Acer saccharum*	*Acer rubrum*
	Betula papyrifera	*Malus* 'Dolgo'
	B. populifolia	*Morus alba*
	Cercis canadensis	*Fraxinus americana*
	Cladastris lutea	*Juglans nigra*
	Cornus florida	*Salix alba*
	Crataegus lavallei	*S. discolor*
	Magnolia soulangiana	*Tilia cordata*
	Malus species	
	Prunus persica	
	P. serotina	
	P. subhirtella	
	Quercus rubra	
	Robinia pseudacacia	
	Sorbus aucuparia	
	Picea abies	
	P. pungens	
	P. pungens 'Glauca'	
	Taxus cuspidata 'Expansa'	
	T. media 'Hicksii'	
	Thuja occidentalis	
	Tsuga canadensis	

Tolerance of Various Tree Species to Wet Sites and Occasional Flooding

Tolerant	Intolerant
Ash	Chestnut oak
Black gum	Eastern white pine
Cottonwood	Hemlock
Elm	Paper birch
Overcup oak	Red cedar
Pin oak	Red oak
Poplars	Red pine
Red maple	White spruce
River birch	Sugar maple
Silver maple	
Sweetgum	
Sycamore	
White cedar	
Willows	

Locality	Resistant to flooding	Notes
Po flood-plain, Italy.		
Danube bottomlands, Upper Austria.	*Populus* spp., *Salix* spp. *Alnus incana.* *Tilia* sp., *Fraxinus* sp. *Acer* sp.	 Lost leaves but recovered well. 10% mortality. 50% mortality. Intolerant—*Sambucus nigra.*
Volga flood-plain, U.S.S.R.	*Fraxinus pennsylvanica, Acer negundo, Salix* spp. *Populus nigra, P. deltoides, P. balsamifera, Salix* sp. *Quercus robur, Fraxinus pennsylvanica, Gleditsia triacanthos,* etc. *Populus alba.* *Fraxinus excelsior, Ulmus pumila, Cornus* sp., etc.	30–45 days' continuous flooding on heavy soils. 30–45 days' continuous flooding on light soils. Up to 30 days' continuous flooding on heavy soils. Up to 30 days on light soils. Up to 15 days (on heavy soils) in years of very high water level.
Outside dykes of islet on River Weser, near Bremen, Germany.	*Populus* × *euramericana.*	Flooded up to 80 times a year, including 5–15 times in summer; d.b.h. at 10 years old, 30–35 cm.
River banks in Angola	*Populus deltoides.*	Timing of rains unsuitable for riparian Poplar growing, but this is the most promising species.
Volga-Don basin, droughty regions of flood-plain, U.S.S.R.	 *Salix alba, Alnus glutinosa.* *S. alba, F. pennsylvanica.* *S. alba, Populus nigra, F. pennsylvanica.* *P. balsamifera, P. alba, P. deltoides,* shrub Willows, *F. pennsylvanica.* *P. balsamifera, P. alba, P. deltoides* and *P. alba* var. *pyramidalis, Betula verrucosa, Quercus robur, Ulmus pumila.*	*N.B.*—Exact choice of species listed depends on soil type; e.g. clay-loam, sand/silt deposits, beach sands, saline, etc. Spring/summer flooding for >60 days by stagnant water. Spring/summer flooding for <60 days by stagnant water. Spring/summer flooding for >60 days by flowing water. Spring/summer flooding for 30–60 days by flowing water. Spring/summer flooding for 10–30 days by flowing water.
Danube flood-plain, Rumania.	*Populus* × *euramericana* cvs. 'Robusta R.16', 'Robusta Oltenita', and 'Celei', *Salix alba* (clones R.204, R.202, R.103, R.206).	Growing season 200 days, soil fertile, extremes of temperature, long periods of flooding in first part of growing season, drought in second.
Danube 'dam-bank zone', i.e. the zone between the river bed and the flood-protection dams, Rumania	*Salix alba, Populus* × *euramericana* cvs. 'Robusta' ('R.16' and 'R.20'), 'Serotina' ('R.3' and 'R.4'), and 'Celei', *P. alba, P. nigra.*	Flooding was in the growing season; height of Danube can vary by 5–9 metres. Planting was on a commercial basis.
Danube flood-plain, Rumania.	*Populus* × *euramericana.*	
Flood-plain embankments, Rumania.	*Salix alba, S. triandra, S. cinerea, Populus nigra, P. alba, P.* × *euramericana* (cvs. 'Robusta' and 'Marilandica'), *Fraxinus pennsylvanica, Taxodium distichum.*	

Recommended for bank protection	Notes	Author
Populus spp.		Montanari, 1954.
Populus spp., *Salix* spp.		Traunmüller, 1954.
		Rubanov, 1959.
Populus × *euramericana.*	Reduced wave and ice damage to dykes, the trees themselves not damaging dykes.	Grabhorn, 1960.
Populus deltoides.	Soil characteristics not good for riparian Poplar growing, but this is the most promising species.	Silva, 1965.
No erosion problem in stagnant conditions. A selection of those tree species listed in the preceding column as resistant to flooding by flowing water, depending on soil type and duration of flooding. Various shrubs, e.g. shrub Willows, *Rhus cotinus, Cornus sanguinea, Ribes aureum, R. nigrum, Acer tataricum, Amorpha fruticosa.*		Treščevskij, 1966.
As in column 2.	Ice movements at end of winter a hazard, as well as force of flowing water.	Clonaru *et al.*, 1966.
Salix alba; all *Populus* spp.	Winter ice drift a hazard, as well as water erosion.	Radu *et al.*, 1968.
Populus × *euramericana.*		Ionescu, 1968.
Salix alba, S. cinerea, S. triandra.	Young and middle-aged Willow stands recommended for protection of dam-bank zone, planted as close as possible to bank	Lupe *et al.*, 1968.

Locality	Resistant to flooding	Notes
Tennessee Valley reservoirs, U.S.A.	*Taxodium distichum, Nyssa aquatica, Chamaecyparis thyoides.* *Quercus nigra, Q. phellos, Fraxinus pennsylvanica, Liquidambar styraciflua, Platanus occidentalis*	Recommended for upper drawdown zone, covered intermittently in growing season by 1–3 feet of water. For reservoir surcharge zones, 1–15 feet above normal high-water level; flooded occasionally in dormant season. 11,000 acres planted on a commercial basis.
Volga hydro-electric reservoirs, U.S.S.R.		
Hydro-electric reservoirs, U.S.S.R.	*Salix* spp.	>2 months' submergence can be tolerated.
Wildfowl water-impoundment plantings, U.S.A.	*Populus deltoides, Liquidambar styraciflua, Fraxinus pennsylvanica.*	Impoundments of up to 90 cm. depth from February to July increased radial growth by 52%, by increasing soil moisture content over whole growing season.
Derdap hydro-electric reservoir, on the Danube, nr. Belgrade, Jugoslavia.		
Rybinsk reservoir, U.S.S.R.	*Alnus glutinosa.*	Recommended for replacing the Pine forests, which were dying owing to underflooding when the reservoir was filled.
Reservoirs in U.S.S.R.		
Rybinsk reservoir, U.S.S.R.	*Salix* sp., *Betula* sp.	Discusses measures for promoting natural regeneration of these species (and *Pinus sylvestris*) on the banks, shores, shoals and beaches.
Kuibyshev reservoir, U.S.S.R.	*Salix viminalis, S. rossica, S. dasyclados, S. triandra,* and other *Salix* spp. *Alnus glutinosa.*	Recommended for planting the upper drawdown zone; lowest trees inundated for all of growing season except August.

Recommended for bank protection	Notes	Author
		Silker, 1948.
Salix acutifolia, *Populus simonii*, *P. balsamifera*.		Vetkasov, 1958.
Salix triandra, *S. purpurea*, *S. alba*, *S. acutifolia*, *S. caprea*, *S. daphnoides*.	Species used were all indigenous and occurred locally.	Kulikov, 1966.
		Broadfoot, 1967. (Also 1958.)
Populus spp. and *Salix* spp.	Minimum belt widths for bank protection, 120 metres.	Šimunović, 1969.
Salix cinerea. *S. triandra*.	For peaty banks. For sandy banks.	Turkov, 1969.
Taxodium distichum.		Bjallovič, 1968.
		Kudinov and Igtisamov, 1968.
		Mamaev, 1958.

Locality	Resistant to flooding	Notes
Danube flood-plain, Hungary.	*Populus* × *euramericana* cvs. 'Robusta' and 'I-214'.	Greater tolerance found with increasing age of saplings. Summer flooding lasted 64–140 days. Site preparation important for survival.
Brăila marshes, Rumania.	*Populus* × *canadensis* (*P.* × *euramericana*).	Increased tolerance found with increasing stand age.
Flood-plain embankments, Rumania.	*Salix alba.*	Can withstand up to 120 days' submersion by flowing water, provided it has $\nless$30 cm. of aerated soil for the rest of the year.
	Populus nigra, P. × *euramericana.*	Can withstand up to 50 days' submersion, but need $\nless$60 cm. of aerated soil for the rest of the year.
River banks in Central Europe.		
Flooded plantations in Holland.	*Populus* × *euramericana* cvs. 'Serotina', 'Robusta', 'Heidemij', 'Marilandica' and 'Regenerata', *Salix* spp.	Flooding lasted until mid-August—depth 150 cm. Older stands were most tolerant.
Flooded plantations in the Hansag region, Hungary.	*Populus* × *euramericana* cvs. 'Robusta', 'I-214', 'Marilandica' and 'Serotina', *Salix* spp.	Mound-planting and drainage were very beneficial. *Alnus* sp. stands were intolerant.
European stream and river banks.	*Alnus glutinosa, Salix purpurea, S. alba, S. fragilis, S. triandra, S.* × *rubens, S. viminalis, S. cinerea, S. elaeagnos, Populus nigra.*	
Yangtze River flood-plain, China.	*Salix matsudana, S. babylonica, Fraxinus chinensis, Tamarix chinensis, Pterocarya stenoptera, Pyrus calleryana, Amorpha fruticosa, Campsis chinensis, Juniperus chinensis, Pinus thunbergii.*	Exceptional floods lasting in some cases 140 days; floodwater 0·8 to 6·6 m. deep.

Salt Tolerance of Some Common Trees and Shrubs

Tolerant	Sensitive
Shrubs	
Adam's needle	Arctic blue willow
Autumn elaeagnus	Boxwood
Bayberry	Japanese barberry
Beach plum	Multiflora rose
Buffaloberry	Van houtle spirea
California privet	Viburnums
Matrimony vine	Winged spindle tree
Pfitzer juniper	
Rugosa rose	
Tartarian honeysuckle	
Evergreen trees	
Austrian pine	Balsam fir
Colorado blue spruce	Canadian hemlock
Japanese black pine	Douglas fir
Pitch pine	Eastern white pine
Red cedar	Red pine
White spruce	
Yews	
Deciduous trees	
Big tooth aspen	American elm
Black cherry	American linden
Black locust	Boxwood
Box elder	Ironwood
Burr oak	Little-leaf linden
English oak	Red maple
Golden willow	Shagbark hickory
Green ash	Silver maple
Honey locust	Speckled alder
Quaking aspen	Sugar maple
Red oak	
Russian olive	
Siberian crabapple	
Siberian elm	
Weeping willow	
White oak	
White poplar	

. Species list of roadside trees and shrubs rated for their resistance to air-borne highway salt spray

DECIDUOUS TREES	INJURY RATING*
Horse-chestnut *Aesculus hippocastanum* L.	1
Tree of Heaven *Ailanthus altissima* (Mill.) Swing	1
Norway maple *Acer platanoides* L.	1
Cottonwood *Populus deltoides* Bartr.	1
Black locust *Robinia pseudoacacia* L.	1
Honey locust *Gleditsia triacanthos* L.	1-2
Red oak *Quercus rubra* L.	1-2
Sugar maple *Acer saccharum* Marsh	1-2
English walnut *Juglans regia* L.	1-2
Black walnut *Juglans nigra* L.	1-2
Shagbark hickory *Carya ovata* (Mill.) K. Koch	1-2
Choke cherry *Prunus virginiana* L.	1-2
White ash *Fraxinus americana* L.	2
White elm *Ulmus americana* L.	2
Black willow *Salix nigra* Marsh	2
Mountain ash *Sorbus* spp.	2
Poplar *Populus* spp.	2
Silver maple *Acer saccharinum* L.	2
Chinese elm *Ulmus pumila* L.	2
Red maple *Acer rubrum* L.	2-3
Lombardy poplar *Populus nigra italica* Muenchh.	2-3
Basswood *Tilia americana* L.	2-3
White birch *Betula papyrifera* Marsh	2-3
Gray birch *Betula populifolia* Marsh	2-3
Catalpa *Catalpa speciosa* Warder.	2-3
Pear *Pyrus* spp.	2-3
Quince *Cydonia oblonga* Mill.	2-3
Trembling aspen *Populus tremuloides* Michx.	3
Largetooth aspen *Populus grandidentata* Michx.	3
Crabapple *Malus* spp.	3
Golden willow *Salix alba tristis* Gaud.	3
Bur oak *Quercus macrocarpa* Michx.	3-4
Apple *Malus* spp.	3-4
Hawthorn *Crataegus* spp.	4
Manitoba maple *Acer negundo* L.	4-5
Allegheny serviceberry *Amelanchier laevis* Wieg.	4-5
White mulberry *Morus alba* L.	4-5
Beech *Fagus grandifolia* Ehrh.	5

DECIDUOUS SHRUBS	INJURY RATING*
Siberian pea-tree *Caragana arborescens* Lam.	1
Staghorn sumac *Rhus typhina* L.	1-2
Japanese lilac *Syringa amurensis japonica* (Maxim.) Fr. & Sav.	1-2
Common lilac *Syringa vulgaris* L.	1-2
Honeysuckle *Lonicera* spp.	1-2
European cranberry-bush *Viburnum opulus* L.	1-3
Russian olive *Elaeagnus angustifolia* L.	1-3
Mock orange *Philadelphus* spp.	1-3
Japanese barberry *Berberis thunbergii atropurpurea* Chenault.	2
Burning bush *Euonymus alata* [Thunb.) Sieb.	2
Forsythia *Forsythia x intermedia* Zab.	2-3
Privet *Ligustrum* spp.	2-3
Alder buckthron *Rhamnus frangula* L.	2-3
Speckled alder *Alnus rugosa* (Du Roi) Spreng.	3
Flowering quince *Chaenomeles lagenaria* (Loisel.) Koidz.	3-4
Bumalda spirea *Spirea x bumalda* Burv.	3-4
Beauty bush *Kolkwitzia amabilis* Graebn.	3-4
Gray dogwood *Cornus racemosa* Lam.	3-4
Red osier dogwood *Cornus stolonifera* Michx.	4-5

CONIFERS	INJURY RATING
Blue spruce *Picea pungens* Englem.	1
Jack pine *Pinus divaricata* (Ait.) Dumont	1-2
Mugo pine *Pinus mago* Turra.	1-2
Austrian pine *Pinus nigra* Arnold	2
Tamarack *Larix laricina* (Du Roi) K. Koch	2
Juniper *Juniperus* spp.	2-3
Norway spruce *Picea abies* (L.) Karst.	3
White cedar *Thuja occidentalis* L.	3-4
Yew *Taxus* spp.	4
Red pine *Pinus resinosa* Ait.	4-5
Scots pine *Pinus sylvestris* L.	4-5
White spruce *Picea glauca* (Moench) Voss	4-5
Hemlock *Tsuga canadensis* L.	4-5
White pine *Pinus strobus* L.	5

* A rating of 1 indicates no twig dieback or needle browning of conifers and no dieback, tufting, or inhibition of flowering of deciduous trees and shrubs. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting, and lack of flowering of deciduous trees and shrubs. Under severe conditions plants rated 5 will eventually die. Ratings of 2, 3 and 4 encompass slight, moderate and extensive gradations of the above injury symptoms.

Relative salt tolerance of trees.

[By authors: **(1)** Buschbom (2), **(2)** Carpenter (3), **(3)** Dirr (5,6,7), **(4)** Hanes, et al (12), **(5)** Lumis, et al (20,21), **(6)** Monk and Wiebe (22,23), **(7)** Pellett (25), **(8)** Shortle and Rich (28), and **(9)** Wyman (32,33).]

	Salt-tolerance rating		
Species	Good	Moderate	Poor
Abies balsamea	—	1	7
Acer campestre	1	6	—
Acer ginnala	—	—	1
Acer negundo	—	1,7	5
Acer platanoides	1,3,5,9	7	—
Acer pseudoplatanus	9	—	2
Acer rubrum	—	5	2,7,8
Acer saccharinum	1	5	7
Acer saccharum	5	—	2,7,8
Acer tataricum	—	—	1
Aesculus hippocastanum	1,5,9	—	—
Ailanthus altissima	5,9	—	—
Alnus glutinosa	—	—	1,2
Alnus incana	—	—	7
Alnus rugosa	—	1,5	2,8
Amelanchier canadensis	9	—	—
Amelanchier laevis	—	—	5
Amelanchier species	—	—	1
Betula allegheniensis	8	—	—
Betula lenta	8	—	—
Betula papyrifera	8	5,7	—
Betula pendula	—	1,7	—
Betula populifolia	8	5	—
Betula species	—	2	—
Caragana arborescens	1,5	—	—
Carpinus betulus	—	—	1,2
Carpinus caroliniana	—	—	7,8
Carya ovata	5	—	8
Carya species	—	—	7
Catalpa speciosa	—	5	—
Celtis occidentalis	—	—	1
Cercis canadensis	—	—	3
Chamaecyparis pisifera	—	—	1
Corylus species	—	—	1,2
Crataegus crusgalli	9	—	1
Crataegus species	—	—	1,5
Elaeagnus angustifolia	1,3,5,6,7,9	—	—
Euonymus (tree species)	—	—	1
Fagus grandifolia	—	2	1,5,7
Fagus sylvatica	—	—	1,2,7
Fraxinus americana	8	5,7	—
Fraxinus excelsior	1	—	—
Fraxinus pennsylvanica	6	2,7	—
Gleditsia triacanthos inermis	2,3,5,7	—	1
Hippophae rhamnoides	1,9	—	—
Juglans nigra	5	—	2,7
Juglans regia	5	—	2,7
Juniperus virginiana	8,9	2,7	—
Ilex opaca	9	—	—
Larix decidua	1	—	—
Larix laricina	5	—	—
Larix leptolepis	1	—	—
Larix species	—	—	2,7
Liriodendron tulipifera	—	—	4
Magnolia grandiflora	9	—	—
Malus baccata	—	2,7	—
Malus species & cultivars	—	3,5	6
Metasequoia glyptostroboides	—	—	1
Morus alba	2,6,7,9	—	5
Nyssa sylvatica	9	—	—
Picea abies	—	5,7	1
Picea asperata	9	—	—
Picea glauca	—	2	5
Picea pungens	5	—	—
Picea pungens glauca	5,9	2	—
Pinus banksiana	5	—	—
Pinus cembra	1	—	—
Pinus mugo	5	—	—
Pinus nigra	5,9	—	—
Pinus ponderosa	—	2	—
Pinus resinosa	—	—	5,7,8
Pinus rigida	9	—	—
Pinus strobus	—	—	5,7,8
Pinus sylvestris	9	7	1,3
Pinus thunbergii	9	—	—
Platanus x hybrida	—	—	1
Populus alba	1,2,3,7,9	—	—
Popular alba 'Pyramidalis'	3	—	—
Populus angustifolia	2	—	—
Populus deltoides	5	2	—
Populus grandidentata	8	5	—
Populus nigra 'Italica'	—	5	2,7
Populus tremuloides	8	1,2,5	—
Populus species	—	5	—
Prunus armeniaca	2,6	—	—
Prunus avium	—	1	—
Prunus padus	1	—	—
Prunus serotina	8,9	—	1
Prunus virginiana	5	—	—
Pseudotsuga menziesii	—	1,2	7
Pyrus species	—	5	—
Quercus alba	2,3,6,7,8,9	—	1
Quercus bicolor	—	—	1
Quercus macrocarpa	7	1	5
Quercus marilandica	9	—	—
Quercus muhlenbergii	—	—	1
Quercus palustris	—	—	1
Quercus robur	2,6	—	1
Quercus rubra	2,5,7,8	—	—
Rhamnus cathartica	3,5,9	—	—
Rhamnus davurica	1	—	—
Rhamnus frangula	3	5	—
Rhus typhina	3,5,9	—	—
Robinia pseudoacacia	1,3,5,6,7,8,9	—	—
Robinia pseudoacacia 'Umbraculifera'	3	—	—
Salix alba	—	2	1
Salix alba 'Tristis'	7	3	—
Salix matsudana 'Tortuosa'	3	—	—
Salix nigra	—	5	—
Salix species	1,7	—	—
Sorbus species	—	1,5	—
Syringa amurensis japonica	5	—	—
Tamarix pentandra	1,2,6,7,9	—	—
Taxus cuspidata	—	7	5
Thuja occidentalis	—	2	5
Tilia americana	—	5	7,8
Tilia cordata	—	—	2,7
Tilia euchlora	—	—	1
Tilia platyphyllos	1	—	—
Tsuga canadensis	—	—	5,7,8
Ulmus americana	—	5,7	8
Ulmus glabra	1,2	—	—
Ulmus pumila	7	5	—
Viburnum species	—	—	2

Salt resistance of trees

Ruge, 1972a (after Walter et al., 1974)	Buschbom, 1972	Emschermann, 1973	Chrometzka et al., 1973	Daniels, 1974	Chrometzka, 1974b
Relatively tolerant					Decreasing salt compatibility
Platanus acerifolia	*Acer campestre*	*Acer platanoides*	*Elaeagnus angustifolia*	*Acer negundo*	*Acer campestre*
Quercus robur	*Elaeagnus commutata*	*Fraxinus excelsior*	*Hippophae rhamnoides*	*Elaeagnus angustifolia*	*Alnus glutionosa*
Quercus rubra	*Fraxinus ornus*	*Lonicera xylosteum*	*Viburnum lantana*	*Fraxinus pennsylvanica*	*Alnus incana*
Sorbus	*Halimodendron*	*Ribes alpinum*		*Malus baccata*	*Crataegus monogyna*
Crataegus	*Lycium halimifolium*	*Rosa rugosa*		*Populus alba*	*Crataegus oxyacantha*
Sophora	*Populus canescens*	*Symphoricarpus albus*		*Morus* species	*Robinia pseudacacia*
Robinia pseudacacia	*Ribes aureum*	*Ulmus glabra*		*Quercus alba*	*Populus nigra*
Fraxinus excelsior	*Salix alba*			*Quercus borealis*	*Quercus robur*
Tilia tomentosa	*Tamarix* species			*Quercus robur*	*Quercus sessiliflora*
	Ulmus glabra			*Robinia pseudacacia*	*Quercus rubra*
Less tolerant				Sensitive to salt	
	Hippophae rhamnoides	*Acer campestre*	*Acer campestre*	*Abies balsamea* *	*Acer platanoides*
	Alnus incana	*Alnus glutinosa*	*Acer ginnala*	*Acer saccharum*	*Salix caprea*
	Lonicera xylosteum	*Salix caprea*	*Acer pseudoplatanus*	*Berberis thunbergii*	*Salix viridis*
	Populus tremula	*Ulmus carpinifolia*	*Alnus glutinosa*	*Buxus sempervirens*	*Betula pendula*
	Prunus avium		*Alnus incana*	*Carpinus betulus*	*Carpinus betulus*
	Prunus padus		*Alnus viridis*	*Euonymus alatus*	*Sorbus aucuparia*
			Betula pendula	*Fagus grandiflora*	*Prunus padus*
Very sensitive to salt			*Carpinus betulus*	*Fagus sylvatica*	*Prunus serotina*
			Crataegus monogyna	*Juniperus virginiana*	*Tilia cordata*
Aesculus hippocastanum	*Carpinus betulus*	*Carpinus betulus*	*Crataegus oxyacantha*	*Larix* species	*Corylus avellana*
Acer species	*Betula pubescens*	*Cornus sanguinea*		*Malus* species	*Sambucus nigra*
Tilia species	*Cornus mas*	*Corylus avellana*	*Corylus avellana*	*Picea glauca*	Conifers
	Cotoneaster integerrima	*Crataegus monogyna*	*Ligustrum vulgare*	*Picea pungens*	
	Corylus avellana	*Fagus sylvatica*	*Quercus rubra*	*Populus nigra italica*	
	Fagus silvatica	*Prunus serotina*	*Quercus* multi-species	*Populus tremuloides*	
	Picea abies	*Rosa canina*	*Salix caprea*	*Pseudotsuga menziesii*	
	Pyracantha coccinea	*Sambucus racemosa*	*Salix viridis*	*Tilia cordata*	
	Prunus spinosa		*Sorbus aucuparia*	*Tsuga canadensis*	
	Taxus baccata		*Symphoricarpus orbiculata*		
			Symphoricarpus chenaultii	* *Acer pseudoplatanus*	
			Prunus padus		
			Prunus serotina		
			Prunus spinosa		
			Tilia cordata		
			All conifers		

Sensitivity of roadside trees and shrubs to aerial drift of deicing salt.

Common name (species)	Sensitivity rating[z]
Deciduous trees	
Norway maple (*Acer platatanoids* L.)	1
Horse-chestnut (*Aesculus hippocastanum* L.)	1
Tree of heaven [*Ailanthus altissima* (Mill.) Swing]	1
Cottonwood (*Populus deltoides* Bart.)	1
Black locust (*Robinia pseudoacacia* L.)	1
Sugar maple (*Acer saccharum* March)	1-2
Shagbark hickory [*Carya ovata* (Mill.) K. Koch	1-2
Honey locust (*Gleditsia triacanthos* L.)	1-2
Black walnut (*Juglans nigra* L.)	1-2
English walnut (*Juglans regia* L.)	1-2
Choke cherry (*Prunus virginiana* L.)	1-2
Red oak (*Quercus rubra* L.)	1-2
Silver maple (*Acer saccharinum* L.)	2
White ash (*Fraxinus americana* L.)	2
Poplar (*Populus* spp.)	2
Black willow (*Salix nigra* Marsh)	2
Mountain ash (*Sorbus* spp.)	2
White elm (*Ulmus americana* L.)	2
Chinese Elm (*Ulmus pumila* L.)	2
Red maple (*Acer rubrum* L.)	2-3
White birch (*Betula papyrifera* Marsh)	2-3
Grey birch (*Betula populifolia* March)	2-3
Catalpa (*Caltalpa speciosa* Warder.)	2-3
Quince (*Cydonia oblonga* Mill.)	2-3
Lombardy poplar (*Populus nigra italica* Muenchh)	2-3
Pear (*Pyrus* spp.)	2-3
Basswood (*Tilia americana* L.)	2-3
Crabapple (*Malus* spp.)	3
Largetooth aspen (*Populus gradidentata* Michx.)	3
Trembling aspen (*Populus tremuloides* Michx.)	3
Weeping golden willow (*Salix alba* 'Tristis' Gaud.)	3
Apple (*Malus* spp.)	3-4
Bur oak (*Quercus macrocarpa* Michx.)	3-4
Hawthorn (*Crataegus* spp.)	4
Manitoba maple (*Acer negundo* L.)	4-5
Allegheny serviceberry (*Amelanchier laevis* Wieg.)	4-5
White mulberry (*Morus alba* L.)	4-5
Beech (*Fagus gradifolia* Ehrh.)	5

Common name (species)	Sensitivity rating[z]
Deciduous shrubs	
Siberian pea-tree (*Caragana arborescens* Lam.)	1
European buckthorn (*Rhamnus cathartica* L.)	1
Honeysuckle (*Lonicera* spp.)	1-2
Staghorn sumac (*Rhus typhina* L.)	1-2
Japanese lilac [*Syringa amurensis japonica* (Maxim.) Fr. & Sav.]	1-2
Common lilac (*Syringa vulgaris* L.)	1-2
Russian olive (*Elaeagnus angustifolia* L.)	1-3
Mockorange (*Philadelphus* spp.)	1-3
European cranberry-bush (*Viburnum opulus* L.)	1-3
Japanese barberry (*Berberis thunbergii* 'Atropupurea' Chenalt)	2
Burningbush [*Euonymus alata* (Thunb.) Sieb.	2
Forsythia (*Forysthia xintermedia* Zab.)	2-3
Privet (*Ligustrum* spp.)	2-3
Alder buckthorn (*Rhamnus frangula* L.)	2-3
Speckled alder [*Alnus rugosa* (Du Roi) Spreng.]	3
Flowering quince (*Chaenomeles speciosa* Nakai)	3-4
Gray dogwood (*Cornus racemosa* Lam.)	3-4
Beauty-bush (*Kolkwitzia amabilis* Graebn.)	3-4
Bumalda spirea (*Spirea* x *bumalda* Burv.)	3-4
Red Osier dogwood (*Cornus stolonifera* Michx.)	4-5
Conifers	
Blue spruce (*Picea pungens* 'Glauca' Reg.)	1
Jack pine [*Pinus divaricata* (Ait.) Dumont]	1-2
Mugo pine (*Pinus mugo* Turra.)	1-2
Tamarack [*Larix laricina* (Du Roi) K. Koch]	2
Austrian pine (*Pinus nigra* Arnold)	2
Juniper (*Juniperus* spp.)	2-3
Norway spruce [*Picea abies* (L.) Karst.]	3
White cedar (*Thuja occidentalis* L.)	3-4
Yew (*Taxus* spp.)	4
White spruce [*Picea glauca* (Moench) Voss]	4-5
Red pine (*Pinus resinosa* Ait.)	4-5
Scots pine (*Pinus sylvestris* L.)	4-5
Hemlock (*Tsuga canadensis* L.)	4-5
White pine (*Pinus strobus* L.)	5

[z]Ratings of 1 indicate no twig dieback or needle browning of conifers and no dieback, tufting of inhibition of flowering of deciduous plants. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting and lack of flowering of deciduous species. Under sever conditions plants rated 5 will eventually die. Ratings of 2, 3 and 4 encompass slight , moderate and extensive gradations of the above symptoms.

Species that are sentivite to salt.

Abies balsamea, Balsam fir
Acer pseudoplatanus, Sycamore maple
Acer saccharum, Sugar maple
Berberis thunbergi, Japanese barberry
Buxus sempervirens, Boxwood
Carpinus betulus, European hornbeam
Euonymus alatus, Winged euonymus
Fagus grandiflora, American beech
Fagus sylvatica, European beech
Juniperus virginiana, Eastern redcedar
Larix sp., Larch
Malus sp., Apple
Picea glauca, White spruce
Picea pungens, Blue Colorado spruce
Populus nigra italica, Lombardy poplar
Populus tremuloides, Quaking aspen
Pseudotsuga menziesii, Douglas fir
Tilia cordata, Littleleaf linden
Tsuga canadensis, Hemlock

Species that are tolerant to salt.

Acer negundo, Box-elder
Eleagnus angustifolia, Russianolive
Fraxinus pennsylvanica, Green ash
Gleditsia triacanthos, Common Honeylocust
Malus baccata, Siberian crabapple
Morus sp., Mulberry
Populus alba, Silver poplar
Quercus alba, White oak
Quercus borealis, Red oak
Quercus robur, English oak
Robinia pseudoacacia, Black locust

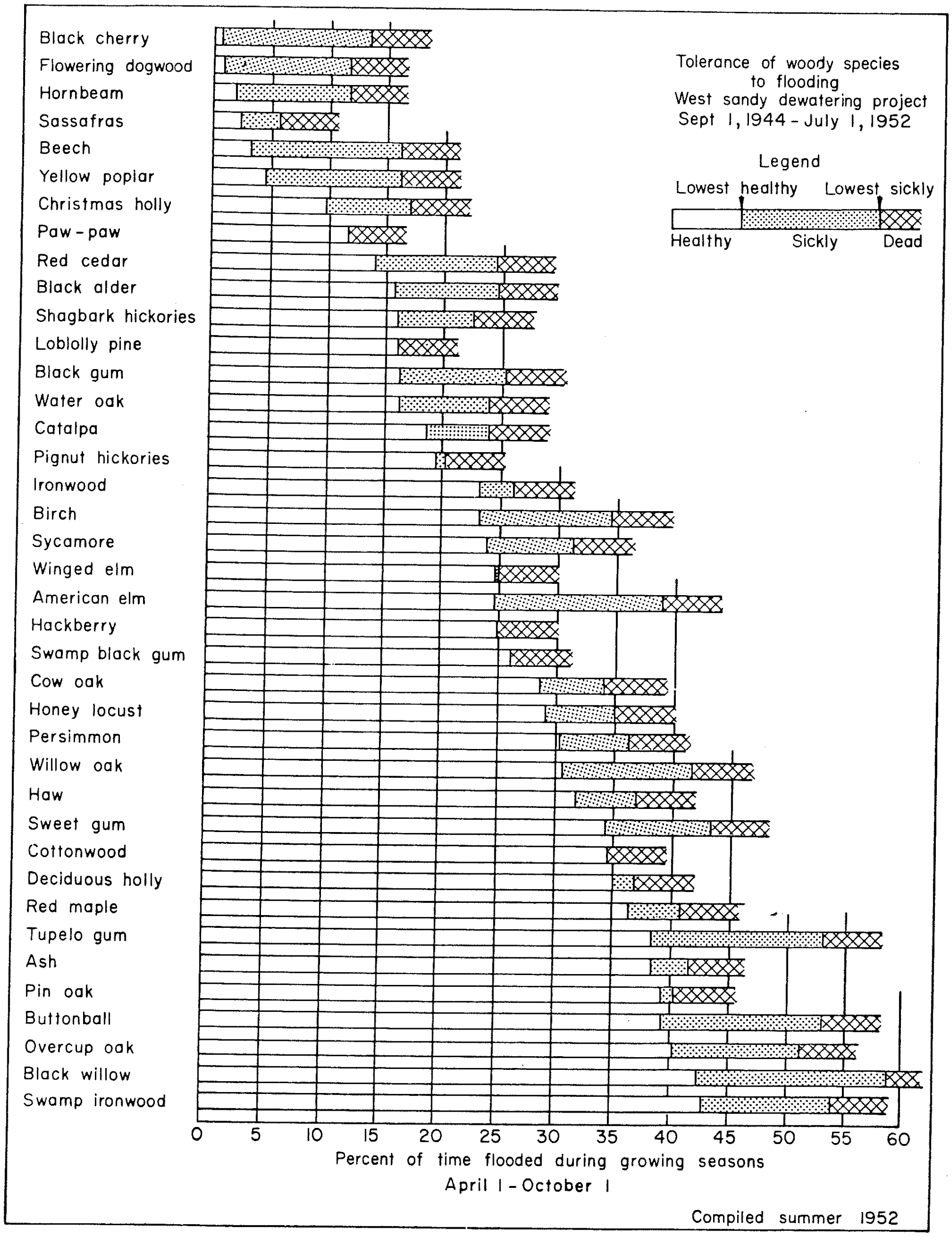

Fig. 2. Tolerance of Kentucky woody species to flooding during the growing season. [From Hall and Smith (1955). Reproduced by permission of Society of American Foresters.]

Shade and Ornamental Trees

Acer saccharum—Sugar Maple
Acer platanoides—Norway Maple
Betula papyrifera—White Birth
Betula populifia—Gray Birch
Cercis canadensis—Redbud
Cladrastic lutea—Yellowwood
Cornus florida—White Flowering Dogwood
Cornus florida rubra—Red Flowering Dogwood
Cornus florida 'Cloud 9'—'Cherokee Chief'
Crataegus phaenopyrum-Washington Hawthorn
Crataegus lavallei—Lavalle Hawthorn
Magnolia soulangiana—Saucer Magnolia
Malus sp. 'Lodi,' 'McIntosh,' 'Radiant,' 'Hope,' Bechtel
Prunus persica—Flowering Peach
Prunus serotina—Black Cherry
Prunus subhirtella pendula—Weeping Cherry
Quercus borealis—Red Oak
Robinia pseudoacacia—Black Locust
Sorbus aucuparia—European Mountain Ash

Evergreens

Picea excelsa—Norway Spruce
Picea pungens—Colorado Spruce
Picea pungens glauca—Colorado Blue Spruce
Taxus cuspidata—Upright Yew
Taxus cuspidata expansa—Spreading Yew
Taxus media "Hicksii"—Hick's Yew
Thuja occidentalis—American Arborvitae
Tsuga canadensis—Canadian Hemlock
Celastrus orbiculatus—Oriental Bittersweet
Euonymus fortunei 'Coloratus'—Purpleleaf Wintercreeper
Euonymus fortunei 'Vegetus'—Bigleaf Wintercreeper
Forsythia sp. — All varieties
Ligustrum amurense—Amur Privet
Ligustrum vulgare—Polish or English Privet
Lonicera morrowi—Morrow Honeysuckle
Lonicera tatarica—Tatarian Honeysuckle
Philadelphus coronarius—Sweet Mock-orange
Physocarpus opulifolius —Nine-bark

Observation on the same sites showed a remarkable list of plants that apparently will tolerate such unusual conditions. All had no leaf drop and appeared perfectly normal, even on a second check in late October before killing frosts. All had tolerated the same amounts of water as the first group and for the same amount of time. My "survivor" list follows:

Evergreen "Survivors"

Juniperus virginiana—Red Cedar
Juniperus chinensis pfitzeriana—Pfitzer Juniper

Shade Tree "Survivors"

Acer rubrum—Red Maple
Cornus mas—Cornelian Cherry
Fraxinus americana—White Ash
Gleditsia inermis—Thornless Honeylocust
Juglans nigra—Black Walnut
Malus 'Dolgo'—Dolgo Crabapple
Morus alba—Mulberry
Platanus occidentalis—American Sycamore
Populus deltoides—Cottonwood
Salix alba—White Willow
Salix discolor—Pussy Willow
Tilia cordata—European Littleleaf Linden

Shrub "Survivors"

Berberis thunbergi—Japanese Barberry
Cornus paniculata—Gray-stem Dogwood
Ligustrum obtusifolium Regelianum—Regel Privet
Viburnum dentatum—Arrowwood
Viburnum lentago—Sweet Viburnum
Viburnum trilobum—American Cranberrybush

Recommended for bank protection	Notes	Author
		Simon, 1966.
	Some damage by bending, breaking and uprooting.	Popescu and Necşulescu, 1967.
		~~Sabău, 1967.~~
Salix acutifolia.	Recommended for exposed banks, because of its exceptional root development.	Raschke, 1957.
		Kolster, 1966.
		Máté and Balsay, 1966.
As in column 2.		Seibert, 1969.
		Anon., 1955.

Various types of low temperature injuries

Conditions Leading to Damage	Symptoms	Susceptible Plants
FALL FROST Cool summer followed by warm, early autumn; summer or early fall fertilization and abundant summer watering. Tissues not "hardened" and mature.	Killing back of twigs, branches or entire plants.	Practically all.
SPRING FROST Sudden drop in temperature after new growth is well advanced. Plants growing in low-lying "frost pockets" are damaged most severely.	Wilting, blackening or browning and death of tender twigs, leaves and flowers.	Practically all.
EXCESS WINTER COLD Abnormally low temperatures especially where soil is poorly drained and/or shallow. Worst following low-snowfall winters or where soil is bare of mulch and smaller plants. Damage most severe when plants fed with large amounts of high-N fertilizer and growing vigorously later in the fall.	Above-ground parts wilt and die back during late spring or summer. Roots and inner bark are killed and often discolored. Evergreens may lose their leaves; deciduous trees and shrubs often fail to leaf out properly. Plants may take on a brownish cast.	Shallow-rooted trees, e.g., ash, elm, maple, pine, that are not well adapted.
FROST CRACKS When cold winter nights follow warm sunny days. Trees growing in poorly drained soils are most susceptible.	Long vertical cracks in wood on south or southwest sides of trunk. Cracks often reopen in following winters. Wood-decay fungi may enter such wounds.	Isolated, vigorous deciduous trees: certain maples, elms, beeches, apple and crabapple, flowering cherries, plums, lindens, poplars, horsechestnut, oaks, golden-rain trees, ashes, tuliptree, walnut, willows, London plane, and introduced trees.
FROST CANKERS (WINTER SUNSCALD) Hot winter sun heats up localized areas on trunk, large branches or crotches. Trees suddenly exposed to a marked increase in sunlight are most liable to injury.	Exposed bark and underlying wood on south or southwestern sides is killed in well-defined cankers; often invaded later by secondary fungi, bacteria and insects. Splitting and peeling of bark is common.	Common on certain maples, London plane, elms, beeches, apple, poplars (aspens), boxwood, and other smooth-barked trees and shrubs.
WINTER DRYING Excessive rapid changes in temperature, especially when accompanied by drying winds and bright sun. Exposed plants growing in a warm, sunny spot in frozen soil are most susceptible.	Scorching and bronzing of leaf margins of broad-leaved evergreens. Leaves of all evergreens may wilt, turn yellow to brown, and die. Buds are killed; twigs die back. Deciduous trees and shrubs are slow to leaf out; leaves may be small and off-color; twig dieback is common.	All narrow- and broad-leaved evergreens, plus wide range of deciduous trees and shrubs.
ICE AND SNOW Heavy loads cause cracking and splitting of twigs and branches.	Browning of foliage and dieback of wood to site of injury.	Yews, junipers, boxwood and other multiple-stem evergreens. Brittle trees: Silver and red maples, American and Chinese elms, sycamore, tree-of-Heaven, tuliptree, honey-locust, birches, poplars, boxelder and willows.

Table 37. Frost resistance (temperature at the first appearance of injury), initial freezing (temperature at the beginning of ice formation) and protoplasmic frost tolerance in evergreen leaves and needles in winter. The frost tolerance corresponds to the difference between the temperature at first appearance of injury and the initial freezing temperature. (From Larcher, 1973)

Plant	Frost injury	Initial freezing	Frost tolerance
Eucalyptus globulus	− 3°C	− 3°C	*none*
Citrus limon	− 5	− 5	*none*
Ceratonia siliqua	− 5	− 5	*none*
Nerium oleander	− 7	− 7	*none*
Olea europaea	−10	−10	*none*
Pinus pinea	−11	− 7	*4°C*
Quercus ilex	−13	− 8	*5*
Cupressus sempervirens	−14	− 5	*9*
Taxus baccata	−20	− 6	*14*
Abies alba	−30	− 7	*23*
Picea abies	−38	− 7	*31*
Pinus cembra	−42	− 7	*35*

SUSCEPTIBILITY OF GENERA AND SPECIES OF HARDWOODS TO FOLIAGE DAMAGE BY LATE FROSTS[a]

Highly susceptible	*Moderately susceptible*	*Less susceptible*	*Least susceptible*
American chestnut	Magnolia	Basswood	Birch
Ash	Oak	Maple	Cherry
Beech			Elm
Black locust			Hawthorn
Sassafras			Willow
Sycamore			
Walnut			
Yellow poplar			

[a]From Tryon and True (1964). Reproduced by permission of West Virginia Agricultural Experiment Station.

SUMMARY OF FROST TYPES AND DAMAGE TO FORESTS[a]

Characteristic	Advective frost	Radiation frost
Cause	Horizontal movement of cold air mass into a warmer area	Cooling of ground and adjacent air through loss of heat from longwave terrestrial radiation.
Condition of atmosphere	Windy, overcast, often with precipitation, including snow	Clear with still air, cloudless sky
Area involved	Large, may be hundreds of mi² and may be confined to mountain tops	Small, often only valley bottoms and lower slopes
Severity	Usually causes heavy damage if buds have broken	Variable. Damage may be very light to heavy
Elevation and damage	Damage may become heavier with increase in elevation	Damage usually greater on lower slopes and valleys
Uniformity	Degree of damage uniform within same elevation belt	Degree of damage spotty from area to area, and even within same locality
Frequency	Less common	More common
Time of occurrence	Early in spring, late in fall	First in fall, last in spring, and throughout frost danger period

[a]From Tryon and True (1964). Reproduced by permission of West Virginia Agricultural Experiment Station.

VARIATIONS IN FREEZING RESISTANCE OF NORTH AMERICAN TREE SPECIES AND MINIMUM TEMPERATURES AT NORTHERN LIMITS OF NATURAL RANGES OR ARTIFICIAL PLANTINGS

Relative Hardiness Classification	Representative Species	Average Minimum Temperatures at Northern Limits of Growth (°C)		Observed Freezing Resistance
		Natural Range	Artificial Plantings	(°C)
Tender evergreen species	*Quercus virginiana*	−3.9 to −6.7	−9 to −12	−7 to −8
Hardy evergreen species	*Magnolia grandiflora*	−9 to −12	−18 to −20	−15 to −20
Hardy deciduous species	*Liquidambar styraciflua*	−18 to −20	−26 to −29	−25 to −30
Very hardy deciduous species	*Ulmus americana*	−37 to −46	−40 to −43	−40 to −50
Extremely hardy deciduous species	*Betula papyrifera*	below −46	below −46	below −80
	Populus deltoides	−32 to −34	−37 to −45	below −80
	Salix nigra	−32 to −34	−37 to −45	below −80

SOURCE: Reprinted, by permission, from Sakai and Weiser 1973, table 11. © 1973 by the Ecological Society of America.

TREES RATED ACCORDING TO DEGREE OF SNOW DAMAGE OBSERVED AT LAVA LAKE[a]

Tree species	*Snow damage ratings, spring, 1964*	*Trees studied (%)*
Western white pine	None	18.2
	Very light	54.5
	Light	18.2
	Moderate	9.1
	Severe	—
Western hemlock	None	33.3
	Very light	33.3
	Light	25.0
	Moderate	8.4
	Severe	—
Pacific silver fir	None	—
	Very light	57.1
	Light	35.7
	Moderate	7.2
	Severe	—
Douglas fir	None	—
	Very light	8.3
	Light	41.7
	Moderate	25.0
	Severe	25.0
Noble fir	None	—
	Very light	45.5
	Light	54.5
	Moderate	—
	Severe	—

[a]From Williams (1966). Reproduced by permission of U.S. Forest Service.

Average branch losses from 9 different species of deciduous trees from a heavy snow load.

Species	**Number of trees**	**Tree Size (dbh in inches)**	**Diameter of broken branches in inches** 0-3	3-6	6-9	9-12	12	**Ave. Percent canopy loss/tree**
Green Ash	22	6-36	2.0	0.1	—	1.1	—	3.6
Honeylocust	211	0-18	4.1	0.1	—	—	—	4.2
Cottonwood	52	6-48	7.2	2.4	0.4	0.2	—	10.2
Silver maple	14	6-48	7.2	2.5	1.0	—	—	10.7
Hackberry	144	0-12	14.0	—	—	—	—	14.0
Russian olive	86	0-24	11.6	5.8	—	—	—	17.4
Weeping willow	5	18-36	6.6	8.4	3.0	—	—	18.0
American elm	23	6-36	6.5	8.1	2.4	—	2.2	19.2
Siberian elm	15	6-36	9.7	21.1	0.7	—	—	31.5

SUSCEPTIBILITY OF TREES TO BREAKING BY ICE ACCUMULATION[a]

Species	Number examined	Percent injured little	Percent injured moderately	Percent badly broken
Salix babylonica	2	0	0	100
Betula alba	3	0	0	100
Betula lutea	5	0	0	100
Ulmus americana	111	6	10	84
Populus deltoides and hybrid poplars	34	9	41	50
Betula pendula	10	10	30	60
Acer saccharinum	117	11	21	68
Platanus occidentalis	6	17	33	50
Castanea dentata	11	27	46	27
Populus nigra var. *italica*	29	34.5	31	34.5
Pinus strobus	11	36	9	55
Prunus americana	29	38	17	45
Acer saccharum	102	41	26	33
Prunus sp. (Cherry)	26	42	16	42
Robinia pseudoacacia	11	55	9	36
Juniperus virginiana	88	55	19	26
Liriodendron tulipifera	7	57	43	0
Pyrus malus	37	73	16	11
Carya ovata	4	75	0	25
Tsuga canadensis	4	75	0	25
Acer negundo	8	75	25	0
Diospyros virginiana	21	76	24	0
Picea abies	39	77	18	5
Acer platanoides	9	77	23	0
Thuja occidentalis	29	79	14	7
Quercus alba	10	80	0	20
Salix discolor	7	86	14	0
Pinus sylvestris	7	86	14	0
Prunus sp. (Plum)	18	89	11	0
Catalpa speciosa	36	94	6	0
Pyrus communis	30	97	3	0
Juglans nigra	48	98	2	0
Pseudotsuga taxifolia	2	100	0	0
Pinus nigra	3	100	0	0
Magnolia tripetala	3	100	0	0
Gleditsia triacanthos	5	100	0	0
Ailanthus glandulosa	42	100	0	0

[a] From Croxton (1939). Reproduced by permission of the Ecological Society of America.

Table 1. **WOODY PLANTS TOLERANT TO HERBICIDES**

An [X] in the column indicates the herbicide can be safety used for that plant listed.

	ALANAP	BETASAN	CASORON	CHLORO IPC	DACTHAL	ENIDE	EPTAM	KERB	ORNAMENTAL WEEDER	PRINCEP	RONSTAR	SURFLAN	TREFLAN
Evergreens													
Narrowleaf													
Arborvitae	X		X	X	X	X			X	X	X	X	X
Chamaecyparis						X	X						
Eastern Red Cedar	X		X			X				X			X
Fir				X	X		X	X					
Fir, Balsam				X						X			X
Fir, Douglas								X		X			X
Fir, Fraser										X			
Hemlock				X		X	X		X	X			X
Juniper	X	X	X	X	X	X	X	X	X	X	X	X	X
Pine	X			X	X		X	X	X		X		
Pine, Austrian										X			X
Pine, Japanese Black													X
Pine, Mugo										X			
Pine, Red										X			X
Pine, Scotch										X			X
Pine, White										X			X
Spruce	X			X	X		X				X		
Spruce, Blue										X			X
Spruce, Norway										X			X
Spruce, White										X			X
Yew	X		X	X	X	X	X	X	X	X	X		X
Broadleaf													
Boxwood		X	X		X		X					X	X
Cherry Laurel						X							X
Euonymus				X		X			X		X		X
Firethorn		X	X			X						X	X
Holly	X	X	X		X	X	X	X	X		X		
Holly, Japanese							X						X
Japanese Pieris					X		X		X				X
Leucothoe			X				X						
Mahonia				X		X				X		X	
Mountain Laurel			X	X	X	X							X
Rhododendron	X		X	X	X	X	X	X	X				X
Deciduous Trees													
Ash			X		X	X					X		
Ash, White						X			X				X
Bald Cypress						X							X
Beech						X							
Birch			X	X	X	X					X		
Birch, European													X
Chinese Chestnut					X	X							X
Corktree, Amur			X										
Crabapple			X		X	X					X		X
Dogwood			X		X	X	X		X	X	X		X
Dogwood, Kousa													X
Elm			X		X								
Elm, American										X			
Elm, Siberian										X			

	ALANAP	BETASAN	CASORON	CHLORO IPC	DACTHAL	ENIDE	EPTAM	KERB	ORNAMENTAL WEEDER	PRINCEP	RONSTAR	SURFLAN	TREFLAN
Goldenraintree			X										
Hackberry			X										
Hawthorn					X								
Honeylocust										X			X
Linden			X				X						
London Planetree													X
Magnolia			X	X	X		X		X				
Maple	X		X	X	X	X	X						
Maple, Norway													X
Maple, Red									X				X
Maple, Silver													X
Maple, Sugar						X							X
Mountain Ash			X										
Oak			X		X	X	X						
Oak, Pin													X
Oak, Red									X	X			X
Oak, Scarlet													X
Poplar	X		X	X	X	X							
Redbud					X	X							X
Russian Olive			X		X	X				X	X		
Sassafras									X				
Sweetgum					X	X							X
Sycamore					X	X							X
Tuliptree					X	X							X
Tupelo													X
Walnut			X		X	X							X
Willow			X		X	X							X
Deciduous shrubs													
Abelia		X			X								
Azalea	X	X			X	X			X				X
Azalea, Mollis			X										
Barberry			X	X	X	X	X			X	X	X	X
Beautybush			X			X							
Cinquefoil					X								X
Cotoneaster			X		X	X			X	X	X	X	X
Currant						X							
Deutzia			X		X								X
Euonymus, Winged			X		X	X	X					X	X
Flowering Almond			X										
Flowering Quince			X										
Forsythia			X	X	X	X		X			X	X	X
Hibiscus						X							

2-4-D

SOFTWOODS	Tolerant	Intermediate	Sensitive
Colorado spruce (Picea pungens)		●	
Yew (Taxus sp.)		●	
Hemlock (Tsuga sp.)		●	

2-4-D

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (Acer negundo)			●
Norway maple (Acer platanoides)			●
Tree of heaven (Ailanthus altissima)			●
Birch (Betula sp.)			●
Hickory (Carya sp.)			●
American yellowwood (Cladrastis lutea)			●
Dogwood (Cornus sp.)			●
Ash (Fraxinus sp.)	●		
Sweetgum (Liquidambar styraciflua)		●	
Apple (Malus sp.)			●
Mulberry (Morus sp.)		●	
London planetree (Platanus acerifolia)			●
Pin oak (Quercus palustris)		●	
Red oak (Quercus rubra)		●	
Black oak (Quercus velutina)			●
Linden (Tilia sp.)			●

RELATIVE DROUGHT RESISTANCE OF SELECTED SPECIES[a]

Resistant	Intermediate	Sensitive
Ulmus parvifolia	*Pinus resinosa*	*Acer* spp.
Fraxinus pennsylvanica	*Pinus strobus*	*Abies grandis*
Pinus ponderosa		
Juniperus virginiana		

[a]From Parker (1956). Reproduced by permission of the New York Botanical Garden.

THE PHYSIOLOGICAL STATES OF WILTING[a,b]

Type of wilting	*Frequency*	*Degree of turgor loss*	*Visible effects*	*Duration*
Incipient	Probably daily around mid-day, especially in summer	Slight and short-lived	None	Short. Recovery takes place when the transpiration rate falls slightly
Transient	Often, mainly on hot, dry, or windy days	More marked	Obvious drooping of leaves and perhaps of herbaceous stems	Short. Recovery takes place when transpiration is reduced, as at night
Permanent	Occasionally, chiefly during prolonged dry periods	Very severe	Marked drooping of leaves and often of herbaceous stems	Persists until soil moisture is replenished. So little water is available that deficits cannot be restored merely by reducing transpiration
Irreversible	Only in very prolonged dry periods	Complete, and permanent	Very severe drooping of softer parts, followed by withering	Permanent. Tissues have become so dessicated that virtually no water is absorbed even if supplied. Death follows

[a]From Knight (1965). Reproduced by permission of Dover Publications, Inc.
[b]Permanent and irreversible wilting might be considered "pathological" wilting.

Attempt to classify some trees according to their photoperiodical characteristics (after Nitsch and others in Lyr et al., 1967)

Species		Country of origin	Type
Acer pseudoplatanus	Sycamore maple	Europe	D ?
Acer rubrum	Red maple	North America	A
Acer saccharum	Sugar maple	North America	B ?
Aesculus hippocastanum	Horse chestnut	Europe	D
Alnus incana	Grey alder	Europe	A
Betula pubescens	Hairy birch	Europe	A
Betula lutea	Yellow birch	North America	A
Betula papyrifera	Paperbark birch	North America	A
Buxus sempervirens	Common box	South Europe	D
Catalpa speciosa	Indian bean	North America	A
Cornus florida	Flowering dogwood	North America	A
Eucalyptus bicostata			
E. niphophila and others	Australian Gum	Australia	C
Fagus grandifolia	American beech	North America	A ?
Fagus sylvatica	European beech	Europe	A+B
Ficus religiosa	Holy tree of Buddha	India	A
Fraxinus americana	White ash	North America	D
Juniperus horizontalis	Creeping juniper	North America	C
Larix decidua	European larch	Europe	A
Liriodendron tulipifera	Tulip tree	North America	A
Morus alba	White mulberry	China	A ?
Paulownia tomentosa	Royal paulownia	China	D
Phellodendron amurense		Asia	A ?
Picea abies	Norway spruce	Europe	B
Pinus sylvestris	Scotch pine	Europe	B
Pinus banksiana and many others	Pines		B
Platanus occidentalis	Plane tree	North America	A
Populus alba	White poplar	Europe	A
Populus nigra	Black poplar	Europe	A
Populus tremula and many others	Poplars		A
Prunus avium	Wild cherry	Asia	D
Pseudotsuga taxifolia	Douglas fir	North America	B
Quercus borealis maxima (Ashe)	Northern red oak	North America	B
Quercus stellata		North America	B
Quercus suber	Cork oak	South Europe	B
Rhododendron catawbiense		North America	B
Rhus typhina	Staghorn sumach	North America	A
Robinia pseudacacia	Locust	North America	A
Syringa vulgaris	Lilac	SE Europe	D
Thuja occidentalis	*Arbor vitae*	North America	C
Thuja plicata		North America	C
Tsuga canadensis	Hemlock	North America	A
Ulmus americana	White elm	North America	A
Viburnum opulus	Guelder rose	Europe	A
Viburnum prunifolium		North America	D
Various tropical woods and *Citrus* species			C

SYMPTOMS OF NUTRIENT ELEMENT DEFICIENCY[a]

Element	*Conifer seedlings*	*Hardwood seedlings*
Nitrogen	Foliage uniformly pale green, yellowish, or yellow; older foliage dying in some species. Stems somewhat reddish in young seedlings. Tree leaves often short	Leaves small, uniformly faded, green or yellowish. Shoots short and spindly. In later stages, hardwood leaves may become red or purple
Phosphorus	Leaves sometimes pale, turning brown at tops. Sometimes purpling, becoming necrotic. Youngest foliage may remain green	Leaves small, bluish-green, veins purplish. Basal leaves may abcise. Shoots thin, short, upright
Potassium	Leaves short, chlorotic, often brown tipped. Yellow tipping in some species In some species, older leaves dying, younger are green	Leaves scorched or chlorotic, on tips and margins. Leaves sometimes dark bluish-green, upward curling, with speckling. Dieback. Also reddening in some species
Magnesium	Leaves yellowing and later browning at tips. Sometimes purpling. Older foliage sometimes yellower than younger. Growth not seriously affected	Basal older leaves marginal interveinal chlorosis and necrosis, early deciduousness. Growth near normal except where deficiency very severe. Sometimes reddening
Calcium	Young needles yellow; all needles brown or yellow on tips; no buds developed. Leaves stunted near terminal bud in some cases	Young leaves distorted, tips hooked downward, and margins curled. Margins may show some chlorosis; some spotting and brown scorching. Leafdrop; dieback. Older leaves relatively dark green
Iron	Young needles bright yellow; no top buds developed	Young leaves straw colored. Top of trees may be straw colored, with leaves marginal tip burned. Growth not seriously affected in moderate deficiency
Zinc	Inwardly folding apical needles, yellow mottling. Later bronzing and short, stiff, dark-green needles	Whitish green chlorosis with somewhat greener main veins. Rosetting, shoots long and narrow. In nut trees, nuts have kernels not ripening normally
Boron	In pines: reduced growth and necrosis in tops and growing points of roots. Young needles dead near apical bud	Young leaves often small, twisted, and somewhat corky main veins. Rosetting, dieback and sapoozing. Mottled chlorosis in some
Manganese	Paleness, retarded growth, dying. Buds turning brown; needles becoming pale green or yellow at tips (*Pinus radiata*)	New leaves may be lighter green in interveinal areas, giving herringbone appearance. Spotting and necrosis may appear. Leafdrop; dieback
Copper	In pine: foliage bluish-green and tips of secondary needles dead; needles curved downward	Leaves of plum and apple whitish and soft. In peach, long and narrow leaves may be mottled green and white; irregular margins. Dieback
Molybdenum	Foliage becomes bluish in pine. No symptoms at first	In younger leaves: light-green chlorosis, but main and small veins green. Old leaves: marginal burning

[a]From Parker (1965). Reproduced by permission of the Institute for the Advancement of Science and Culture.

ELEMENTS ESSENTIAL FOR THE GROWTH AND DEVELOPMENT OF HIGHER PLANTS

Macronutrients	*Micronutrients*
Carbon	Iron
Oxygen	Boron
Hydrogen	Copper
Nitrogen	Zinc
Phosphorus	Molybdenum
Potassium	Manganese
Sulfur	Chlorine
Magnesium	
Calcium	

Some Woody Plants Susceptible to Iron Deficiency Chlorosis

Trees	Trees	Shrubs
American elm	Oak, black	Azalea
American holly	Oak, mossy cup	Forsythia
Bald cypress	Oak, pin	Hydrangea
Birch, canoe	Oak, red	Magnolia
Birch, yellow	Oak, swamp white	Rhododendron
Cherry, black	Oak, white	Rose
Cherry, mazzard	Oak, willow	
Cottonwood	Pine, jack	
Eucalyptus	Pine, ponderosa	
Flowering dogwood	Pine, white	
Horse chestnut	Sweetgum	
London plane	Walnut	
Maple, Norway		
Maple, red		
Maple, silver		
Maple, sugar		

Sensitivity of Woody Plants to Artificial Light[a]

High	Intermediate	Low
Acer ginnala (Amur maple)	*Acer rubrum* (red maple)	*Capinus japonica* (Hornbeam)
Acer platanoides (Norway maple)	*Acer palmatum* (Japanese maple)	*Fagus sylvatica* (European beech)
Betula papyrifera (Paper birch)	*Cercis canadensis* (Redbud)	*Ginkgo-bilola* (Ginkgo)
Betula pendula (European white birch)	*Cornus controversa* (Giant dogwood)	*Ilex opaca* (American holly)
Betula populifolia (White birch)	*Cornus sanquinea* (Bloodtwig dogwood)	*Liquidamber styraciflua* (Sweetgum)
Catalpa bignonioides (Catalpa)	*Gleditsia triacanthos* (Honeylocust)	*Magnolia grandiflora* (Bull bay)
Cornus alba (Tatarian dogwood)	*Halesia carolina* (Silver-bell)	*Malus boccata* (Siberian crabapple)
Cornus florida (Dogwood)	*Koelreuteria paniculata* (Goldenrain-tree)	*Malus sargenti* (Sargent's crabapple)
Cornus stolonifera (Red-osier dogwood)	*Ostrya viginicana* (Ironwood)	*Pinus nigra* (Austrian pine)
Platanus acerifolia (Sycamore)	*Phellodendron amurense* (Cork-tree)	*Pyrus calleryana* (Bradford pear)
Ulmus america (American elm)	*Sophora japonica* (Japanese pagoda-tree)	*Quercus palustris* (Pin oak)
Ulmus pumila (Siberian elm)	*Tilia cordata* (Littleleaf linden)	*Quercus phellos* (Willow oak)
Zelkova serrata (Zelkova)		*Quercus robur* (English oak)
		Quercus shumardi (Shumard oak)
		Tilia x europaea (European linden)

[a] From Cathey and Campbell (1975).

Sensitivity of 40 plants to security lighting:

High

Acer ginnala, Amur maple
Acer platanoides, Norway maple
Betula papyrifera, Paper birch
Betula pendula, European white birch
Betula populifolia, White birch
Catalpa bignonioides, Catalpa
Cornus alba, Tatarian dogwood
Cornus florida, Dogwood
Cornus stolonifera, Red-osier dogwood
Platanus acerifolia, Sycamore
Ulmus americana, American elm
Ulmus pumila, Siberian elm
Zelkova serrata, Zelkova

Intermediate

Acer rubrum, Red maple
Acer palmatum, Japanese maple
Cercis canadensis, Redbud
Cornus controversa, Giant dogwood
Cornus sanquinea, Bloodtwig dogwood
Gleditsia triacanthos, Honeylocust
Halesia carolina, Silver-bell
Koelreuteria paniculata, Goldenrain-tree
Ostrya virginicana, Ironwood
Phellodendron amurense, Cork-tree
Sophora japonica, Japanese pagoda-tree
Tilia cordata, Littleleaf linden

Low

Carpinus japonica, Hornbeam
Fagus sylvatica, European beech
Ginkgo bilola, Ginkgo
Ilex opaca, American holly
Liquidamber styraciflua, Sweetgum
Magnolia grandiflora, Bull bay
Malus boccata, Siberian crabapple
Malus sargenti, Sargent's crabapple
Pinus nigra, Austrian pine
Pyrus calleryana, Bradford pear
Quercus palustris, Pin oak
Quercus phellos, Willow oak
Quercus robur, English oak
Quercus shumardi, Shumard oak
Tilia x europaea, European linden

Plants have been listed alphabetically and are not grouped in descending order of sensitivity. A high, intermediate, or low rating identifies the relative responsiveness of the plants to security lighting. Plants with low sensitivity would be preferred in areas with security lighting.

Species Potentially Resistant to Landfill Gases

Green ash[abc]	Cottonwood[d]
Sour gum[ab]	American sycamore[d]
Sweet gale[ab]	Juniper[d]
White ash[ad]	Pussy willow[d]
Red cedar[ad]	Silver maple
White willow[ad]	Thornless honeysuckle
Red maple[d]	

[a]Transports O_2 to roots
[b]Oxidizes rhizosphere
[c]Initiates 2 deg. roots
[d]Tolerates flooding

Shade tolerance of some trees (after Baker, Lyr and other authors)

Very shade tolerant	
Abies balsamea	*Acer saccharum*
Taxus baccata	*Carpinus betulus*
Thuja plicata	*Cornus florida*
Tsuga canadensis	*Cornus mas*
	Corylus avellana
	Fagus sylvatica
	Fagus grandiflora
Shade-tolerant	
Abies concolor	*Acer pennsylvanicum*
Picea glauca	*Acer rubrum*
Picea rubens	*Alnus glutinosa*
Picea sitchensis	*Fraxinus excelsior*
Pinus nigra	*Fraxinus ornus*
Pseudotsuga taxifolia	*Tilia americana*
	Tilia parvifolia
Intermediate	
Picea abies	*Betula alleghеniensis*
Pinus cembra	*Fraxinus americana*
Pinus lambertiana	*Quercus alba*
Pinus monticola	*Quercus borealis maxima*
Pinus strobus	
Sequoia sempervirens	
Shade-intolerant	
Pinus ponderosa	*Betula papyrifera*
Pinus resinosa	*Liriodendron tulipifera*
Pinus taeda	
Very shade-intolerant	
Larix decidua	*Betula pendula*
Larix laricina	*Betula populifolia*
Pinus banksiana	*Populus tremuloides*
Pinus palustris	*Robinia pseudacacia*
Pinus silvestris	

Root system of some trees (after several authors)

Generally having a tap root system

Abies alba
Carya illinoensis
Carya ovata
Fraxinus excelsior
Juglans nigra
Juniperus communis
Juniperus virginiana
Larix decidua
Larix kaempferi
Liriodendron tulipifera
Maclura pomifera
Pinus palustris
Pinus ponderosa
Pinus sylvestris
Pyrus communis
Quercus alba
Quercus macrocarpa
Quercus petraea
Quercus robur
Sorbus domestica
Sorbus torminalis
Sophora japonica
Ulmus glabra
Ulmus laevis
Ulmus minor

Generally having a lateral root system (large, shallow and flat spreading below the surface roots)

Acer campestre
Acer saccharinum
Acer saccharum
Alnus incana
Betula papyrifera
Betula pendula
Betula pubescens
Catalpa species
Elaeagnus angustifolia
Fagus grandifolia
Fagus sylvatica
Larix laricina
Liquidambar styraciflua
Malus silvestris
Nyssa sylvatica
Picea abies
Picea omorica
Pinus banksiana
Pinus strobus
Populus
Salix

Having an intermediate root system (wide spreading and deep lateral roots)

Acer negundo
Acer platanoides
Acer pseudoplatanus
Aesculus hippocastanum
Caragana arborescens
Carpinus betulus
Fraxinus pennsylvanica
Ginkgo biloba
Gleditsia triacanthos
Pinus nigra
Platanus hybrida
Platanus occidentalis
Prunus avium
Pseudotsuga menziesii
Quercus borealis
Quercus pseudoturneri
Robinia pseudacacia
Taxus baccata
Tilia americana
Tilia cordata
Tilia euchlora
Tilia tomentosa
Tilia platyphyllos

Species Adaptable to Flooded or Poorly Aerated Soils (Hook 1972)

White willow	White birch
Brittle willow	Scotch pine
Creeping willow	Norway spruce
Sycamore	Sweet gum
Swamp tupelo	Yellow poplar
Sour gum	Sweet gum
Green ash	

Pirone (l972) classified susceptibility of species to poor aeration as follows:

Most Severely Injured
Sugar maple (*Acer saccharum*)
Beech (*Fagus*)
Dogwood (*Cornus*)
Oak (*Quercus*)
Tulip tree (*Liriodendron*)
Pines (*Pinus*)
Spruces (*Picea*)

Less Severely Injured
Birch (*Betula*)
Hickory (*Carya*)
Hemlock (*Tsuga*)

Least Injured
Elm (*Ulmus*)
Poplar (*Populus*)

along the edge of streets, trees in centre medians, trees in both large and small urban gardens; trees in parks as single trees, clumps of trees or larger areas of closed canopy; trees in derelict land, trees in residential land that cannot be built upon such as ravines, steep banks and floodplains; trees in recreation sites such as golf courses; and finally trees in greenbelt or institutional lands retained for screening, erosion protection, future development and similar activities.

Each of these circumstances is one where the potential for abiotic stress, that is, stress of a non-pathological nature is potentially greater than the growing conditions of native forests. The more alien the conditions, the greater probability that stress thresholds will be exceeded for many tree species and for individual trees. Subsequently, these trees will require increased costs of maintenance or replacement than would have been required if either care in protection of an existing resource or more thoughtful choice of species had been taken long before stress symptoms or decline became evident.

Levitt (1972) classifies environmental stresses as either biotic or physiochemical: the former encompasses infection or competition by other organisms; the latter includes effects of radiation, water, temperature, chemical substances, wind, pressure, sound and similar effects.

Fortunately, trees, like other organisms, appear to be able to adapt to certain stresses. When stressed, they gradually change to decrease or prevent strain. It can be assumed that adaptations that have arisen by evolution over a long time are stable, at least in the mature plant. On the other hand, the adaptation threshold or ability may be poorly developed in the immature tree. Kozlowski observes that insomuch as growth is an integrated response to physiological changes, regulated by a complex of many fluctuating and interacting factors, including environment, responses may vary remarkedly in different parts of a tree and they may vary with the age of trees. Thus the effects of an environmental stress on trees must often depend on the phenological stage and physiological status of the tree at the time of the occurrence of the stress.

Levitt (1972) suggests, that a number of environmental stresses can give rise to various degrees of resistance adaptation in plants. Stress resistance may reflect stress avoidance, stress tolerance or both. Whereas a stress avoiding plant can somehow exclude the stress, a stress tolerant plant can prevent, decrease or repair the strain induced by stress.

Levitt notes that the term resistance to environmental stress has, until now, been used only for plastic resistance. The concept of an elastic resistance has not been clearly recognized. Levitt draws the distinction between elastic and plastic strains giving the definition for the former as a reversible physical or chemical change in the plant; and for the latter an irreversible physical or chemical change. Levitt goes on to note that another important consideration in plastic strain or change produced by stress is the consideration of time in the context of length of exposure. Not only may the degree of stress carry the plant from an elastic strain to a plastic strain but it may also be a function of duration of the stress.

Both Levitt and Kozlowski note that it is important to understand how stresses produce their injurious effects and how some trees have succeeded in surviving stresses that injure others. Levitt notes that an important first step in this assessment is understanding how a stress acts on a plant and how the type of injury which occurs may differ from plant to plant. The stress may induce a direct stress injury that can be readily recognized by the speed of its appearance. An example would be the rapid freezing strain produced by sudden low temperature stress. On the other hand, the stress may produce an elastic strain which is reversible and, therefore, not injurious of itself. If maintained for a long enough time the reversibility of the strain may give rise to an indirect irreversible strain, which results in injury or death of the plant. This indirect stress injury may be recognized by the long exposure of days or months to the stress before the injury is produced. Levitt provides an example of indirect stress injury, the case of chilling stress, which exposes the plant to low temperature, too high to induce freezing. The strains may be mainly elastic, involving the slow-down of all of the physical and chemical processes in the plant which may not be injurious themselves, but which may disrupt the plant's metabolism, leading to a deficiency of a metabolic intermediate or production of toxic substances. A third case suggested by Levitt is that often referred to as secondary stress injury. Here, high temperature, for example, may not be injurious of itself but may produce a water deficit which can, in turn, injure the plant as lack of turgidity eventually results in severe wilting, cell collapse and death of tissue.

While Levitt discusses, in some detail, stress avoidance, that is, the ability of certain trees to exclude a particular stress either partially or completely, it is stress tolerance the ability of a tree to come to thermodynamic equilibrium with a stress without suffering apparent injury through being able to prevent, decrease, or repair the strain, induced by stress that is perhaps more important in the context of this paper as is the point made by Kozlowski that the effect of an environmental stress may not be evident for a very long time.

Since few of the papers examined in this review have used or described in detail any experimental protocol for determining their classifications of stress resistance or susceptibility, the work of Levitt and Kozlowski is of importance in considering the reliability of any of the tables provided by the authors examined for each type of stress discussed here. Notwithstanding this proviso, however, and the theoretical work conducted by Levitt and Kozlowski amongst others, there is certainly some merit in drawing on the field experience of the authors reviewed.

A second approach is that espoused by Tattar who suggests, as shown in the accompanying model, that the most appropriate approach to ensuring tree growth in the urban setting is by reproducing, as far as possible, the environmental conditions that trees have been exposed to during evolution in their natural setting.

While sound perhaps in theory, this approach is manifest impractical in two counts. The first is that some environmental stresses, such as light strike-back from buildings and weather conditions cannot be mitigated against

Key for Tables

S	=	Sensitive
M	=	Moderately sensitive
I	=	Insensitive
–	=	No info. available

DECIDUOUS TREES

Species	Hardiness Zone[10,21](*)	SO_2	O_3	Salt	References
Acer ginnala (Amur maple)	2	–	–	M/S	14.18
Acer negundo (Manitoba maple)	2	M/S	M/I	M/S	7.8.14.15.16.17.24
Acer platanoides (Norway maple)	5*	I	I	I	7.8.14.16.17.18.22.23
Acer pseudoplatanus (Sycamore maple)	5	–	–	S	13
Acer rubrum (Red maple)	3b*	M/I	I	M/S	7.8.12.14.16.18.22
Acer saccharinum (Silver maple)	2b*	I	–	M/I	7.8.14.15.16.18
Acer saccharum (Sugar maple)	4*	I	I	M/I	7.8.12.15.16.17.18.22
Aesculus hippocastanum (Common horsechestnut)	5b*	–	–	I	14.16.18
Ailanthus altissima (Tree of Heaven)	6*	–	S	I	5.7.8.12.14.16.18
Amelanchier laevis (Allegany serviceberry)	3b*	–	–	S	14.18
Betula davurica (Dahurian birch)	4/5	–	–	S	13
Betula papyrifera (Paper birch)	2*	S	I	M	7.8.14.16.18.22
Betula pendula (European birch)	2	S	I	M	7.8.14.22
Carpinus betulus (European hornbeam)	4	–	–	S	13.14
Carya ovata (Shagbark hickory)	4	–	–	M/I	14.16.18
Catalpa speciosa (Northern catalpa)	5b*	M	–	M	14.15.16.18
Cercis canadensis (Eastern redbud)	6*	–	M/S	S	7.8.14.25
Elaeagnus angustifolia (Russian olive)	2b*	–	–	I	13.14.16.18
Fagus grandifolia (American beech)	4*	–	–	M/S	14.16.17.18
Fagus sylvatica (European beech)	4	–	I	S	7.8.13.14
Fraxinus americana (White ash)	3b*	S	S	M/I	7.8.12.14.15.16.18.22
Fraxinus pennsylvanica (Green ash)	3	S	S	M	7.8.14.22
Fraxinus pennsylvanica lanceolata (Cutleaf green ash)	2b*	–	S	M	7.12.18
Ginkgo biloba (Maidenhair tree)	4*	I	–	M	8.12.14
Gleditsia triacanthos (Honey locust)	4	–	S	–	8.12.22
Gleditsia triacanthos inermis (Thornless honey locust)	4	–	–	I	16.18
Juglans nigra (Black walnut)	3b*	–	I	M/I	8.12.14.16.18
Juglans regia (English walnut)	4	–	S	M/I	7.8.14.16.17
Kalmia latifolia (Mountain laurel kalmia)	5b*	–	I	–	5
Liquidambar styraciflua (American sweetgum)	5	–	M/S	–	12.22
Liriodendron tulipifera (Tulip tree)	5b*	–	S	S	7.12.14
Nyssa sylvatica (Sour-Gum)	5b*	–	I	–	6.7.12
Platanus acerifolia (London plane tree)	6*	I	–	S	8.14.15
Platanus occidentalis (American sycamore)	5b*	–	S	S	7.8.12.14
Populus alba (White poplar)	3	–	–	M/I	13.14
Populus balsamifera (Balsam poplar)	1	I	–	–	7.8
Populus x canadensis (Carolina poplar)	5	I	–	–	8.15
Populus deltoides (Cottonwood)	2	–	–	I	14.16.18
Populus grandidentata (Large-toothed aspen)	3	S	–	M/I	7.8.14.15
Populus nigra (Lombardy poplar)	4	S	–	M/I	7.8.14.16.18
Populus tremuloides (Trembling aspen)	2*	S	–	M/I	7.8.12.15.16.18.24
Prunus avium var. Bing (Bing cherry)	3	–	S	–	8
Prunus virginiana (Choke cherry)	2	M	–	M/I	14.15.16.18
Quercus alba (White oak)	4*	M	S	M/S	7.8.12.14.22
Quercus imbricaria (Shingle oak)	4b*	–	I	–	7.8
Quercus macrocarpa (Bur oak)	2	–	I	M/S	7.8.14.16
Quercus palustris (Pin oak)	4*	I	M/S	S	7.8.12.14.22.23
Quercus robur (English oak)	5*	–	I	I	7.8.13
Quercus rubra (Red oak)	3*	I	I	I	7.12.15.16.18.22
Quercus velutina (Black oak)	5	–	M	–	7.8
Robinia pseudoacacia (Black locust)	3	–	I	I	7.8.12.14.16.18
Salix alba "tristis" (Weeping golden willow)	4*	–	–	M/S	14.16.17.18

*These numbers correspond to reference list which appears in alphabetical order at the end of the article.

Salix nigra (Black willow)	3	S		M/I	7.8.14.15.16.18
Sorbus aucuparia (European mountain ash)	3*	M	S	I	7.8.18.25
Tilia americana (Basswood)	2b*	M/S	I	M	7.8.12.14.15.18.22
Tilia cordata (Littleleaf linden)	3	I	I		5.7.8.15
Ulmus americana (White elm)	2	M		M/I	7.8.14.15.16.18
Ulmus procera (English elm)	6	–		I	13
Ulmus parvifolia (Chinese elm)	5	S	M		5.7.8.15.23

CONIFEROUS TREES

Species	Hardiness Zone[10,21](*)	SO_2	O_3	Salt	References
Abies balsamea (Balsam fir)	3	M	I	M	7.8.9.14.15
Abies concolor (White fir)	4*	I	I	I	7.8.9.14.24
Juniperus chinensis (Spreading juniper)	4			I	1
Juniperus communis (Common juniper)	2	I			8
Juniperus scopulorum (Rocky mountain juniper)	3b*	I			7.8
Juniperus virginiana (Eastern red cedar)	2	–	–	M/I	14.18
Larix decidua (European larch)	3b*	–	S	I	7.8.9.14
Picea abies (Norway spruce)	2b*	–	I	M/S	7.9.14.16.18
Picea engelmannii (Engelmann spruce)	5	M	–	–	7.8.15
Picea glauca (White spruce)	1b*	M/I	I	S	7.8.9.15.16.18
Picea glauca var. denstata (Blackhills spruce)	2	–	I	–	8
Picea pungens (Blue spruce)	2*	I	I	I	7.8.9.16.18
Pinus banksiana (Jack pine)	2	S	S	I	2a.7.8.9.14.15.16.18
Pinus bungeana (Lacebark pine)	4	I	I	–	10
Pinus flexilis (Limber pine)	2	I	–	–	7
Pinus mugo (Mugho pine)	1*	–	–	I	14.16.18
Pinus nigra (Austrian pine)	5*	M	S	I	7.8.9.14.15.16.17.18
Pinus parviflora (Japanese white pine)	5	I	I	–	10
Pinus ponderosa (Ponderosa pine)	3b*	M	S	–	7.8.19
Pinus resinosa (Red pine)	2	S/M	I	S	2a.7.8.9.14.15.16.18
Pinus strobus (Eastern white pine)	3*	S	M/S	S	2a.2b.3.4.7.8.9.14.15.16.17.18.22
Pinus sylvestris (Scot's pine)	3*	S	M/S	M/S	9.10.14.16.18.22
Pseudotsuga menziesii (Douglas fir)	4*	M/S	I	M/S	7.8.9.14.15.22
Taxus cuspidata (Japanese yew)	4	–	I	M/S	14.25
Taxus x media "densiformis" (Dense yew)	5*	–	I	–	8
Taxus x media "hicksii" (Hicksii yew)	5*	–	I	–	23
Taxus x media "hatfieldii" (Hatfields pyramidal yew)	4	–	I	–	8
Thuja occidentalis (White cedar)	3*	I	I	M/S	1.7.8.12.14.15.16.17.18
Thuja orientalis (Oriental cedar)	5/6	–	I	–	9
Thuja plicata (Western red cedar)	5	I	–	–	7.8.15
Tsuga canadensis (Canadian hemlock)	4*	I	I	S	7.8.11.12.14.16.18

Important trees of northeastern U S that are sensitive or resistant to air pollutants.[1]

Species	Arborists' Rating[2]	Reports[3] Which Indicate Resistance (R) or Sensitivity (S) to			
		Ozone	Sulfur Dioxide	Nitrogen Oxide	Fluoride
Acer platanoides	1.7	R1, 2, 7, 8	S9	S1, 7	
A. rubrum	1.9	R1, S4	R1, S7		
A. saccharum	2.3	R1, 2, 7, 8, S4	R1, 7		
Betula spp.		R1, 2, S8	S1, 2, 3, 7, 8		S7, 8
Fraxinus americana	1.5	S1, 7, 8			
F. pennsylvanica	1.5	S1, 2, 4, 7, 8	R1		S3, 7
F. velutina					R1, 3, 7
Ginkgo biloba	1.0		R1, 7	S1, 7	
Gleditsia triacanthos	1.4	S1, 2, 3, 7, 8			R8
Liquidamber styraciflua	1.6	S1, 2, 7			
Picea pungens		R1, 2, 8	S9	S1, 7	S1, 3, 7, 8
Pinus strobus	2.3	S1, 2, 3, 7, 8	S1, 2, 3, 7, 8, 9, 10	S1, 7	S1, 3, 6, 7, 8, 10
P. sylvestris	1.7	S1, 2, 7	S5, 7, 9, 10		S1, 3, 6, 7, 8, 10
Prunus serotina			S7		
Pseudotsuga menziesii		R1, 2, 8	S2, 8, 9, 10		S1, 3, 6, 7, 8
Quercus alba		S1, 2, 7, 8			
Q. palustris	1.4	S1, 2, 7			
Q. rubra	1.5	R1, 2, 7, 8	R1, 7, 8		
Tilia americana	1.4	R2, S7	S2		R1, 8
T. cordata	1.6	R2, 7, 8, S1	S5, 9, 10	S1, 7	R1, 7, S3, 6, 10

[1] Importance of native and introduced species based on commerical timber, landscape, or Christmas tree values.

[2] Unpublished data of Gerhold from survey of municipal arborists. Scale of 1 to 3 based on survival or growth (1) not affected, (2) moderately affected, (3) severely affected by air pollutants.

[3] Reports which indicate that species are resistant or moderately to very sensitive are: (1) Anon. 1973, (2) Davis 1973, (3) Jacobson and Hill 1970, (4) Jensen 1973, (5) Ranft and Dässler 1970, (6) Rohmeder and von Schonborn 1965, (7) Scott 1973, (8) Sucoff and Bailey 1971, (9) van Haut and Stratmann 1970, (10) Wentzel 1968.

Sensitivity of woody plants to noxious gases at concentrations of 0.5–2 ppm (SO_2) and 0.3–0.5 ppm (HF); the gradation of the responses is based on externally visible damage. (After Ranft and Dässler, 1970, and Dässler *et al.*, 1972)

Sensitivity	to SO_2	to HF
Very sensitive	*Pinus sylvestris*	*Juglans regia*
	Larix decidua	*Vitis vinifera*
	Picea abies	*Berberis vulgaris*
	Salix purpurea	*Pinus sylvestris*
		Picea abies
		Larix decidua
Sensitive	*Salix fragilis*	*Tilia cordata*
	Salix pentandra	*Rubus idaeus*
	Berberis vulgaris	*Carpinus betulus*
	Rubus idaeus	*Pinus nigra*
	Tilia cordata	
	Vitis vinifera	
	Pinus nigra	
Very resistant	*Juniperus sabina*	*Chamaecyparis pisifera*
	Thuja orientalis	*Acer campestre*
	Buxus sempervirens	*Acer platanoides*
	Ligustrum vulgare	*Evonymus europaea*
	Quercus petraea	*Quercus robur*
	Platanus acerifolia	*Sambucus racemosa*

Additional data on sensitivity to noxious gases in various woody plants and herbaceous species are found in Garber (1967), Krüssmann (1970), and Treshow (1970).

Tolerance of Some Woody Plants to Sulfur Dioxide[a]

Tolerant	Intermediate	Sensitive
Arborvitae	Alder, mountain	Alder, thinleaf
Cedar, Western red	Basswood	Aspen
Fir, white	Boxelder	Ash, green
Ginko	Cottonwood	Birch
Hawthorn, black	Dogwood, red osier	Elm, Chinese
Juniper	Douglas fir	Larch, western
Linden, Littleleaf	Elm, American	Maple, Manitoba
Maple, Norway	Fir, balsam	Maple, Rocky Mountain
Maple, silver	Fir, grand	Mulberry, Texas
Maple, sugar	Hawthorn, red	Pine, eastern white
Oak, pin	Hemlock, western	Pine, jack
Oak, red	Honeysuckle, tartarian	Pine, red
Pine, limber	Lilac	Poplar, Lombardy
Pine, pinyon	Maple, red	Serviceberry
Poplar, Carolina	Mountain-ash, European	Willow, black
Spruce, blue	Mountain-laurel	
Yew, pacific	Oak, white	
	Pine, Austrian	
	Pine, ponderosa	
	Pine, western white	
	Poplar, balsam	
	Spruce, Engleman	
	Spruce, white	

[a] From Davis and Wilhour (1976).

Relative Susceptibility of Trees to Sulfur Dioxide

Sensitive	Intermediate	Tolerant
Betula alleghaniensis	*Abies balsamea*	*Abies amabilis*
Betula papyrifera	*Abies grandis*	*Abies concolor*
Betula populifolia	*Acer negundo*	*Acer platanoides*
Fraxinus pennsylvanica	*Acer rubrum*	*Acer saccharinum*
Larix occidentalis	*Picea engelmannii*	*Acer saccharum*
Pinus banksiana	*Picea glauca*	*Juniperus occidentalis*
Pinus resinosa	*Pinus contorta*	*Picea pungens*
Pinus strobus	*Pinus monticola*	*Pinus edulis*
Populus grandidentata	*Pinus nigra*	*Pinus flexilis*
Populus tremuloides	*Pinus ponderosa*	*Quercus gambelii*
Salix nigra	*Populus balsamifera*	*Quercus palustris*
	Populus deltoides	*Quercus rubra*
	Populus trichocarpa	*Thuja occidentalis*
	Pseudotsuga menziesii	*Thuja plicata*
	Quercus alba	*Tilia cordata*
	Tilia americana	
	Tsuga heterophylla	
	Ulmus americana	

SOURCE: Reprinted, by permission, from Davies and Gerhold 1976, table 2.

CONCENTRATIONS OF SULFUR DIOXIDE CAUSING INJURY TO SENSITIVE VEGETATION[a]

Species	Concentration[b] μg/m³	(ppm)	Exposure time, hr	Effect[c]	Conditions	Reference
White pine (*Pinus strobus* L.)	131	(0.05)	1	Needle injury rating of *3*	Branch exposure chamber in greenhouse	127
	131	(0.05)	2	Needle injury rating of *5*		
	131	(0.05)	3	Needle injury rating of *8*		
	262	(0.10)	1	Needle injury rating of *5*		
	262	(0.10)	2.5	Needle injury rating of *8*		
Alfalfa (*Medicago sativa* L.)	1310	(0.5)	4	5% leaf injury	Greenhouse exposure chambers	70
	1310	(0.5)	4	19% leaf injury		
Broccoli (*Brassica oleracea* var. *botrytis* L.)	655	(0.25)	4	6% leaf injury	Same	70
	1310	(0.5)	4	4% leaf injury		
	1310	(0.5)	4	None		
Apple (*Malus* sp. "Manks Codlin")	1258	(0.48)	6	Leaf injury rating of *6*	Branch exposure chambers in natural stands	128
Pear *Prunus* sp, "Legipont"	1258	(0.48)	6	Leaf injury rating of *4*	Same	128
"Conference"	1336	(0.51)	6	Leaf injury rating of *5*		
Mountain ash (*Sorbus aucuparia* L.)	1415	(0.54)	3	Leaf injury rating of *3*	Same	128
	2175	(0.83)	3	Leaf injury rating of 7		

[a] The vegetation was observed or exposed when growing under environmental conditions that made it most sensitive to SO_2.

[b] Average concentrations over the reported time periods. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.

[c] The effects are reported differently in each reference. Their definition is briefly described:

1. Reference 127: The needle injury rating is based on a *1* to *8* scale with *1* as no injury and *8* as 2 to 3 cm of tip necrosis.
2. Reference 70: The values reflect the average percentage foliar injury on the three most severely injured leaves.
3. Reference 128: The leaf injury rating is based on a *0* to *10* scale with *0* as no injury and *10* as the entire leaf surface injured.

SULFUR DIOXIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamae)		●	
White fir (Abies concolor)		●	
Silver fir (Abies pectinata)		●	
Lawson cypress (Cupressus lawsonianu)	●		
Juniper (Juniperus sp.)	●		
Larch (Larix sp.)			●
Engelman spruce (Picea engelmannii)			●
White spruce (Picea glauca)	●		
Jack pine (Pinus banksiana)			●
Lodgepole pine (Pinus contorta latifolia)		●	
Western white pine (Pinus monticola)			●
Dwarf mugo pine (Pinus mugo mughus)	●		
Austrian pine (Pinus nigra)	●		
Ponderosa pine (Pinus ponderosa)			●
Eastern white pine (Pinus strobus)			●
Douglas fir (Pseudotsuga menziesii)		●	
White cedar (Thuja accidentalis)	●		
Western red cedar (Thuja plicata)	●		
Mountain hemlock (Tsuga mertensiana)			●

SULFUR DIOXIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Hedge maple (Acer campestre)	●		
Red maple (Acer rubra)	●		
Sugar maple (Acer saccharum)	●		
Mountain maple (Acer spicatum)	●		
Birch (Betula sp.)			●
European hornbeam (Carpinus betulus)	●		
Catalpa (Catalpa sp.)			●
White dogwood (Cornus florida)	●		
European beech (Fagus sylvatica)	●		
Green ash (Fraxinus pennsylvanica)	●		
Maidenhair tree (Gingko biloba)	●		
English holly (Ilex aquifolium)	●		
English walnut (Juglans regia)			●
Tulip tree (Litriodendron tulipfera)	●		
Apple (Malus sp.)			●
Texas mulberry (Morus microphylla)			●
Black gum (Nyssa sylvatica)	●		
Sourwood (Oxydendron arboreum)	●		
American planetree (Platanus occidentalis)	●		
Oriental planetree (Platanus orientalis)	●		
Balsam poplar (Populus balsamifera)		●	
Eastern cottonwood (Populus deltoides)	●		
Bigtooth aspen (Populus grandidentata)		●	
Lombardy poplar (Populus nigra 'Italica')			●
Quaking aspen (Populus tremuloides)			●
Pear (Pyrus communis)			●
English oak (Quercus robur)	●		
Red oak (Quercus rubra)	●		
Black locust (Robinia pseudocacia)	●		
Willow (Salix sp.)			●
European mountain ash (Sorbus aucuparia)			●
American elm (Ulmus americana)			●

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	
Salix 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	

[a] From Davis and Gerhold (1976).

Relative sensitivity of native and cultivated plants to sulfur dioxide (A low number indicates high sensitivity.)*

Sensitive		*Intermediate*		*Resistant*	
Alfalfa	1.0	Yellow pine†	1.6	Gladiolus	1.1—4.0
Barley	1.0	Dandelion	1.6	Sweet cherry	2.6
Endive	1.0	Sugarbeet	1.6	Purslane	2.6
Cotton	1.0	Aster	1.6	Rose	2.8—4.3
[illegible]	1.0	Tomato	1.3—1.7	Sumac	2.8
Orchardgrass	1.0	Lambs' quarter	1.8	Shepherds' purse	3.0
Mallow	1.1	Apple	1.8	Maple	3.3
Ragweed	1.1	Catalpa	1.9	Box elder	3.3
Rhubarb	1.1	Sweet clover	1.9	Virginia creeper	3.8
Radish	1.2	Cabbage	2.0	Onion	3.8
Lettuce	1.2	Marigold	2.1	Lilac	4.0
Zinnia	1.2	Pea	2.1	Corn	4.0
Spinach	1.2	Linden	2.3	Cucumber	4.2
Bean	1.1—1.5	Douglas fir	2.3	Salt grass	4.6
Curly dock	1.2	Peach	2.3	Chrysanthemum	5.3—7.3
Table beet	1.3	Apricot	2.3	Citrus	6.5—6.9
Buckwheat	1.3	Cocklebur	2.3	Arborvitae	7.8
Plantain	1.3	Elm	2.4	Currant blossoms	12.0
Sunflower	1.3—1.4	Iris	2.4	Live oak	14.0
[illegible]	1.4	Poplar	2.5	Apple Blossoms	25.0
[illegible]	1.4	Yellow pine	2.4—4.7	Apple buds	87.0
[illegible]	1.5				
[illegible]	1.5				
[illegible]	1.5				

* Adapted from Thomas et al., 1950.
† [illegible] old seedlings in May, 1.6; in August, 2.4–4.7.

Relative sensitivity of selected forest species to SO_2 (22, 26, 27, 37).

SENSITIVE	TOLERANT
Ash	Blackgum
Aspen	Boxelder
Birch	Dogwood
Blackberry	Juniper
Carelessweed	Maple
Catalpa	Oak, live
Dewberry	Sourwood
Elm, American	Spruce
Larch	Sycamore
Oak, blackjack**	Tuliptree*
Pine, eastern white	
Pine, jack	
Pine, loblolly** (seedlings to 6 ft.)	
Pine, Virginia** (seedlings to 6 ft.)	
Poplar	
Ragweed	

*Sensitive Spring and Early Summer
**Unpublished Tennessee Valley Authority Data

Resistance of trees to sulphur dioxide

			Author
Very sensitive		Fir, Spruce Douglas fir	Wentzel, 1969
	Salix purporea	*Pinus sylvestris* *Larix decidua* *Picea abies*	Ranft and Daessler, 1970
Sensitive			
	Linden, Ash, Beech, Hornbeam Cherry, Plum	Pine, Larch White pine	Wentzel, 1969
	Berberis vulgaris *Salix fragilis* *Salix pentandra* *Tilia cordata*	*Pinus nigra*	Ranft and Daessler, 1970
Relatively insensitive			
	Oak, Alder, Poplar Maple, Elder Pear, Peach	Austrian pine *Arbor vitae* Yew	Wentzel, 1969
	Buxus sempervirens *Ligustrum vulgare* *Platanus acerifolia* *Quercus petraea*	*Juniperus sabina*	Ranft and Daessler, 1970

OZONE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamea)	●		
White fir (Abies concolor)		●	
Western juniper (Juniperus occidentalis)	●		
European larch (Laris decidua)			●
Japanese larch (Larix leptolepis)			●
Incense cedar (Libocedrus decurrens)		●	
Norway spruce (Picea abies)	●		
White spruce (Picea glauca)	●		
Black Hills spruce (Picea glauca densata)	●		
Colorado spruce (Picea pungens)	●		
Knobcane pine (Pinus attenuata)		●	
Jack pine (Pinus banksiana)			●
Coulter pine (Pinus coulteri)		●	
Jeffrey pine (Pinus jeffreyi)			●
Sugar pine (Pinus lambertiana)	●		
Singleleaf pinyon pine (Pinus monophylla)	●		
Austrian pine (Pinus nigra)			●
Ponderosa pine (Pinus ponderosa)			●
Monterey pine (Pinus radiata)			●
Red pine (Pinus resinosa)	●		
Pitch pine (Pinus rigida)			●
Digger pine (Pinus sabiniana)	●		
Eastern write pine (Pinus strobus)			●
Scotch pine (Pinus sylvestris)			●
Torrey pine (Pinus torreyana)	●		
Virginia pine (Pinus virginiana)			●
Big cone Douglas fir (Pseudotsuga macrocarpa)		●	
Douglas fir (Pseudotsuga menziesii)	●		
Giant sequoia (Sequoia gigantea)	●		
Redwood (Sequoia sempervirens)	●		
Arborvitae (Thuja sp.)	●		
Eastern hemlock (Tsuga canadensis)			●

OZONE

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (Acer negundo)			●
Norway maple (Acer platoides)	●		
Red maple (Acer rubra)	●		
Silver maple (Acer saccharinum)			●
Sugar maple (Acer saccharum)	●		
Alder (Alnus sp.)			●
European white birch (Betula pendula)	●		
Catalpa (Catalpa sp.)			●
Judas tree (Cercis chinensis)			●
White dogwood (Cornus florida)	●		
White ash (Fraxinus americana)			●
Green ash (Fraxinus pennsylvanica)			●
Honeylocust (Gleditsia triacanthos)			●
Black walnut (Juglans nigra)	●		
Sweetgum (Liquidambar styraciflua)			●
Tulip tree (Liriodendron tulipfera)			●
Siberian crab (Malus baccata)			●
Maple leaf mulberry (Morus alba acerfolia)			●
American planetree (Platanus occidentalis)			●
California sycamore (Platanus racemosa)			●
Quaking aspen (Populus tremuloides)			●
White oak (Quercus alba)			●
Scarlet oak (Quercus coccinea)			●
Gambel oak (Quercus gambelii)			●
Shingle oak (Quercus imbricaria)	●		
Pin oak (Quercus palustris)			●
English oak (Quercus robur)	●		
Red oak (Quercus rubra)	●		
Black locust (Robinia pseudoacacia)			●
Weeping willow (Salix babylonica)			●
European mountain ash (Sorbus aucuparia)	●		
Little leaf linden (Tilia cordata)			●

SUSCEPTIBILITY OF TREES TO OZONE

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

SOURCE: Reprinted, by permission, from Davies and Gerhold 1976, table 3.

RELATIVE SUSCEPTIBILITY OF SELECTED TREE SEEDLINGS TO OZONE INJURY[a]

Injured	*Uninjured*
Fraxinus americana	*Abies balsamea*
Larix leptolepis	*A. concolor*
Liriodendron tulipifera	*Acer saccharum*
Pinus banksiana	*Betula pendula*
P. nigra	*Picea abies*
P. rigida	*P. glauca*
P. strobus	*P. glauca* var. *densata*
P. virginiana	*P. pungens*
Quercus alba	*Pinus resinosa*
Tsuga canadensis	*Pseudotsuga menziesii*
	Thuja occidentalis
	Tilia cordata

[a]From Davis and Wood (1968). Reproduced by permission of The American Phytopathological Society.

Relative sensitivity of selected forest species to ozone (10, 37, 43).

SENSITIVE	TOLERANT
Ash	Birch, European white
Honey locust	Black walnut
Larch, European	Dogwood, gray
Oak, white	Fir, balsam
Pine, Virginia	Fir, white
Pine, eastern white	Maple
Pine, jack	Oak, red
Poplar	Spruce
Sweetgum	
Sycamore	
Tuliptree	

Resistance of trees to ozone (Wood and Coppolino, 1972)

Sensitive	
	Green ash
	White ash
	Mountain ash
	Sweet gum
	Pin oak
	Scarlet oak
	White oak
	Hybrid poplar
	Sycamore
	Redbud
Relatively insensitive	
	European white birch
	Grey dogwood
	Flowering dogwood
	Little leaf linden
	Norway maple
	Sugar maple
	English oak
	Shingle oak
	Tulip poplar

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).

Tolerance of Some Woody Plants to Ozone[a]

Tolerant	Intermediate	Sensitive
Arborvitae	Boxelder	Ash, green
Birch, European white	Cedar, incense	Ash, white
Dogwood, white	Cherry, Lambert	Aspen, quaking
Fir, balsam	Elm, Chinese	Azalea
Fir, Douglas	Gum, sweet	Cotoneaster
Fir, White	Larch, Japanese	Honey locust
Gum, black	Lilac	Larch, European
Holly	Oak, black	Mountain-ash, European
Linden, American	Oak, pin	Oak, Gambel
Linden, little-leaf	Oak, scarlet	Oak, white
Maple, Norway	Pine, eastern white	Pine, Austrian
Maple, sugar	Pine, lodgepole	Pine, Jack
Oak, English	Pine, pitch	Pine, Jeffrey
Oak, red	Pine, Scotch	Pine, loblolly
Pine, red	Pine, shortleaf	Pine, Monterey
Spruce, blue	Pine, slash	Pine, ponderosa
Spruce, Norway	Pine, sugar	Pine, Virginia
Spruce, White	Redbud, eastern	Poplar, tulip
Walnut, black		Sycamore, American
Yew		Tree of Heaven
		Walnut English

Sensitivity of woody plants to ozone

*Sensitive**	*Intermediate*	*Resistant*
Fragrant sumac	Chinese apricot	Siberian elm
English walnut	Pyracantha	European beech
Thornless honey locust	Thompson seedless grape	European white birch
Chinese lilac	Blue-leaf honeysuckle	Bartlett pear
Bing cherry	Silverberry	Virginia creeper
Lodense privet		Norway maple
Concord grape		Viburnum
Quaking aspen		American linden
Gambel oak		Bur oak
Snowberry		
Hopa crab		
Green ash		
Bridal wreath		

* Sensitive category injured below 30 pphm for four hours; intermediate injured at 40 pphm for four hours; resistant damaged at 53–56 pphm for four hours.

HYDROGEN FLUORIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Juniper (Juniperus sp.)	●		
Western larch (Larix occidentalis)			●
White spruce (Picea glauca)	●		
Colorado spruce (Picea pungens)			●
Lodgepole pine (Pinus contorta (latifolia)			●
Dwarf mugo pine (Pinus mugo mughus)			●
Ponderosa pine (Pinus ponderosa)			●
Eastern white pine (Pinus strobus)			●
Scotch pine (Pinus sylvestris)			●
Loblolly pine (Pinus taeda)			●
Douglas fir (Pseudotsuga menziesii)			●
Japanese yew (Taxus cuspidata)		●	
Arborvitae (Thuja sp.)		●	

HYDROGEN FLUORIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Hedge maple (Acer campestre)		●	
Boxelder (Acer negundo)			●
Silver maple (Acer saccharinum)		●	
Tree of heaven (Ailanthus altissima)	●		
European black alder (Alnus glutinosa)	●		
European white birch (Betula pendula)		●	
Cutleaf European birch (Betula pendula 'Gracilis')	●		
European hornbeam (Carpinus betulus)		●	
Spanish chestnut (Castanea sativa)		●	
Cornelian cherry (Cornus mas)	●		
European filbert (Corylus avellana)		●	
Russian olive (Elaeagnus angustifolia)	●		
European beech (Fagus sylvatica)		●	
European ash (Fraxinus excelsior)		●	
Green ash (Fraxinus pennsylvanica)		●	
Modesto ash (Fraxinus velutina 'Modesto')	●		
English holly (Ilex aquifolium)		●	
Black walnut (Juglans nigra)		●	
English walnut (Juglans regia)		●	
Red mulberry (Morus rubra)		●	
Paulownia (Paulownia sp.)			●
Planetree (Platanus sp.)	●		
Oriental planetree (Platanus orientalis)		●	
Lombardy poplar (Populus nigra 'Italica')		●	
Quaking aspen (Populus tremuloides)		●	
Eugene poplar (Populus canadensis eugenei)		●	
Flowering apricot (Prunus americana)			●
Flowering plum (Prunus cerasifera)	●		
Bradshaw plum (Prunus domestica 'Bradshaw')			●
Oriental cherry (Prunus serrulata)	●		
English oak (Quercus robur)		●	
Smooth sumac (Rhus glabra)		●	
Black locust (Robinia pseudoacacia)		●	
Willow (Salix sp.)	●		
European elder (Sambucus nigra)	●		
European red elder (Sambucus racemosa)	●		
European mountain ash (Sorbus aucuparia)	●		
American mountain ash (Sorbus domestica)	●		
American linden (Tilia americana)	●		
Little leaf linden (Tilia cordata)	●		
European linden (Tilia europaea)		●	
American elm (Ulmus americana)	●		

Tolerance of Some Woody Plants to Hydrogen Fluoride[a]

Tolerant	Intermediate	Sensitive
Alder, European black	Arbovitae	Apricot, flowering
Ash, American mountain	Ash, European	Boxelder
Ash, European mountain	Ash, green	Fir, Douglas
Ash, Modesto	Beech, European	Larch, western
Birch, European cut-leaf	Birch, European white	Paulownia
Cherry, Cornelian	Chestnut, Spanish	Pine, eastern white
Cherry, Oriental	Filbert, European	Pine, loblolly
Elder, European	Holly, English	Pine, Mugho
Elm, American	Linden, European	Pine, ponderosa
Juniper	Locust, black	Pine, Scots
Linden, American	Maple, hedge	Spruce, blue
Linden, little-leaf	Maple, silver	
Planetree	Mulberry, red	
Plum, flowering	Oak, English	
Russian olive	Planetree, Oriental	
Spruce, white	Poplar, Eugene	
Tree of Heaven	Poplar, Lombardy	
Willow	Walnut, black	
	Walnut, English	

Relative sensitivity of selected forest species to fluoride (22).

SENSITIVE	INTERMEDIATE	TOLERANT
Boxelder	Ash, green	Birch, white
Pine, eastern white	Cherry, choke	Dogwood
Pine, Scots	Maple, Norway	Elm, American
Redbud*	Maple, silver	Juniper
	Mulberry, red	Poplar, balsam
	Oak	Sweetgum
	Poplar, Carolina	Sycamore
	Rhododendron	Tree-of-Heaven
	Serviceberry	Willow
	Sumac	
	Walnut, black	

*Unpublished Tennessee Valley Authority Data

Tolerance of Some Woody Plants to Ozone[a]

Tolerant	Intermediate	Sensitive
Arborvitae	Boxelder	Ash, green
Birch, European white	Cedar, incense	Ash, white
Dogwood, white	Cherry, Lambert	Aspen, quaking
Fir, balsam	Elm, Chinese	Azalea
Fir, Douglas	Gum, sweet	Cotoneaster
Fir, White	Larch, Japanese	Honey locust
Gum, black	Lilac	Larch, European
Holly	Oak, black	Mountain-ash, European
Linden, American	Oak, pin	Oak, Gambel
Linden, little-leaf	Oak, scarlet	Oak, white
Maple, Norway	Pine, eastern white	Pine, Austrian
Maple, sugar	Pine, lodgepole	Pine, Jack
Oak, English	Pine, pitch	Pine, Jeffrey
Oak, red	Pine, Scotch	Pine, loblolly
Pine, red	Pine, shortleaf	Pine, Monterey
Spruce, blue	Pine, slash	Pine, ponderosa
Spruce, Norway	Pine, sugar	Pine, Virginia
Spruce, White	Redbud, eastern	Poplar, tulip
Walnut, black		Sycamore, American
Yew		Tree of Heaven
		Walnut English

Sensitivity of woody plants to ozone

*Sensitive**	*Intermediate*	*Resistant*
Fragrant sumac	Chinese apricot	Siberian elm
English walnut	Pyracantha	European beech
Thornless honey locust	Thompson seedless grape	European white birch
Chinese lilac	Blue-leaf honeysuckle	Bartlett pear
Bing cherry	Silverberry	Virginia creeper
Lodense privet		Norway maple
Concord grape		Viburnum
Quaking aspen		American linden
Gambel oak		Bur oak
Snowberry		
Hopa crab		
Green ash		
Bridal wreath		

* Sensitive category injured below 30 pphm for four hours; intermediate injured at 40 pphm for four hours; resistant damaged at 53–56 pphm for four hours.

TABLE 16.4. *Relative sensitivity of plants to fluoride.*

Sensitive	*Intermediate*	*Resistant*
Gladiolus (some varieties)*	Walnut (English)	Linden (American)
Apricot (Chinese and Royal)	Apricot (Moorpark, Tilton)	Pyracantha
Oregon grape	Citrus (Lemon, tangerine)†	Ailanthus†
Peach (fruit)	Walnut (Black)	Elm (American)†
Corn†	Poplar (Lombardy, Carolina)†	Tomato
Plum (Bradshaw)	Grape (Concord)	Asparagus
Prune (Italian)	Aspen (Quaking)	Wheat
Grape (European var.)	Barley (young plants)	Birch†
Pine (Ponderosa)	Grapefruit†	Current
Larch (Western)	Cherry (Bing, Royal Ann)†	Mt. Ash (European)
Pine (Eastern white, Lodgepole, Scotch, Mugho)	Sumac	Elderberry
Fir (Douglas)	Orange†	Cherry (Flowering)
Spruce (Blue)	Lilac	Sunflower
Blueberry	Peach (leaves)	Pigweed
Tulip (some varieties)	Chokecherry	Squash
Box elder	Maple (Rocky Mt., hedge, silver)	Virginia creeper
	Serviceberry	Burdock
	Spruce (white)	Strawberry
	Arborvitae	Pear
	Chickweed	Bridal wreath
	Raspberry	Ash (Modesto)
	Rose	Willow (Laurel leaf)
	Yew	Juniper
	Apple (Delicious)	
	Aster	
	Ash (green)†	
	Mulberry†	
	Geranium	
	Paeonia	
	Linden (European)	
	Sorghum†	
	Lambs quarter	
	Goldenrod	
	Rhododendron	
	Yellow clover	

* Plants are listed in approximate order of increasing tolerance
† Predominant symptom chlorosis rather than necrosis

Resistance of trees to fluorine

			Author
Very sensitive			
	Beech, Hornbeam Linden, Peach	Larch, Spruce Fir, Douglas Fir	Wentzel, 1969
	Berberis vulgaris *Juglans regia* *Vitis vinifera*	*Larix decidua* *Picea abies* *Pinus sylvestris*	Daessler et al., 1972
Sensitive			
	Maple, Birch Ash, Elder Apple, Pear	Pine White pine	Wentzel, 1969
	Carpinus betulus *Rubus ideaus* *Tilia cordata*	*Pinus nigra*	Daessler et al., 1972
Relatively insensitive			
	Willow, Alder Oak, Red oak Locust	Australian pine Yew, *Arbor vitae* Juniper	Wentzel, 1969
Very insensitive			
	Acer campestre *Acer platanoides* *Euonymus europaeus* *Quercus robur* *Sambucus racemosa*	*Chamaecyparis pisifera*	Daessler et al., 1972

Resistance of trees to nitrogen dioxide (van Hauten and Stratmann, 1967)

Category	Deciduous	Conifers
Very sensitive	White birch Apple, wild tree Pear, wild tree	*Larix europaea* *Larix leptolepis*
Sensitive	*Acer platanoides* *Acer palmatum* *Tilia grandifolia* *Tilia parvifolia*	*Abies homolepis* *Abies pectinata* *Chamaecyparis lawsoniana* *Picea alba* *Picea homolepis*
Relatively insensitive	*Carpinus betulus* *Fagus sylvatica* *Fagus sylvatica atropurpurea* *Ginkgo biloba* *Robinia pseudacacia* *Sambucus nigra* *Quercus robur* *Ulmus montana*	*Pinus austriaca* *Pinus montana mughus* *Taxus baccata*

Resistance of trees to nitrogen trioxide (Ewert in Keller, 1973b)

Category	Deciduous	Conifers
Very sensitive	*Alnus glutinosa* *Alnus incana* *Carpinus betulus* *Tilia cordata* *Tilia tomentosa*	*Pinus strobus*
Sensitive	*Acer pseudoplatanus* *Betula pendula* *Fagus sylvatica* *Fraxinus excelsior*	*Larix* species *Picea abies* *Pinus sylvestris* *Thuja occidentalis*
Relatively insensitive	*Acer campestre* *Acer negundo* *Quercus borealis* *Quercus robur* *Robinia pseudacacia*	*Chamaecyparis* species

Empirical Resistance to NO_2 as Measured by Leaf Sensitivity

Resistance Group I: Sensitive

Field and Horticultural Crops
- Spring vetch (*Vicia sativum*)
- Garden peas (*Pisum sativa*)
- Lucerne (*Medicago sativa*)
- Crimson or Italian clover (*Trifolium incarnatum*)
- Red clover (*Trifolium pratense*)
- Carrots (*Daucus carota*)
- Common lettuce (*Lactuca sativa*)
- Common tobacco plant (*Nicotiana tabacum*)
- White mustard (*Sinapis alba*)
- Lupine (*Lupinus augustrifolius*)
- Common oats (*Avena sativa*)
- Parsley (*Petroselinum hortense*)
- Leek (*Allium porrum*)
- Viper's grass (*Scorzonera hispanica*)
- Barley (*Hordeum distichon*)
- Rhubarb (*Rheum rhubarbarum*)

Ornamental Plants
- Great snapdragon (*Antirrhinum majus*)
- Tuberous-rooted begonia (*Begonia multiflora*)
- Rose (*Rosa* sp.)
- Sweet pea (*Lathyrus odoratus*)
- China aster (*Callistephus chinensis*)

Coniferous Trees
- Larch (*Larix europea*)
- Japanese larch (*Larix leptolepis*)

Deciduous Trees
- Weeping birch (*Betula pendula*)
- Showy apple (*Malus* sp.)
- Wild pear tree (*Pyrus* sp.)

Resistance Group II: Medium Sensitive

Deciduous Trees
- Norway maple (*Acer platanoides*)
- Fan maple (*Acer palmatum*)
- Winter lime (*Tilia parvifolia*)
- Summer lime (*Tilia grandiflora*)

Coniferous Trees
- Blue spruce (*Picea pungens glauca*)
- White spruce (*Picea alba*)
- Lawson's cypress (*Chamaecyparis lawsoniana*)
- Nikko or Japanese fir (*Abies homolepis*)
- Common silver fir (*Abies pectinata*)

Resistance Group II: Medium Sensitive (*Continued*)
Ornamental Plants
Fuchsia (*Fuchsia hybrida*)
Petunia (*Petunia multiflora*)
Rhododendron (*Rhododendron catawbiense*)
Dahlia (*Dahlia variabilis*)
Field and Horticultural Crops
Rye (*Secale cereale*)
Celery (*Apium graveolens* var. *rapaceum*)
Maize (*Zea mays*)
Common wheat (*Triticum sativum*)
Tomato (*Solanum lycopersicum*)
Potato (*Solanum tuberosum*)
Pine strawberry (*Fragaria chiloensis* var. *grandiflora*)
Resistance Group III: Relatively Insensitive
Deciduous Trees
Black locust (*Robinia pseudoacacia*)
Hornbeam (*Carpinus betulus*)
Common beech (*Fagus sylvatica*)
Common elder (*Sambucus nigra*)
Gingko tree (*Ginkgo biloba*)
Mountain elm (*Ulmus montana*)
Purple-leaved beech (*Fagus sylvatica atropurpurea*)
Common oak (*Quercus pendunculata*)
Coniferous Trees
Common yew tree (*Taxus baccata*)
Black pine (*Pinus austriaca*)
Knee pine or dwarf mountain pine (*Pinus montana mughus*)
Field and Horticultural Crops
Kohlrabi (*Brassica oleracea* var. *gongylodes*)
Onion (*Allium cepa*)
White cabbage (*Brassica oleracea* var. *capitata alba*)
Kale (*Brassica oleracea acephala*)
Red cabbage (*Brassica oleracea* var. *capitata rubra*)
Ornamental Plants
Oxeye daisy (*Chrysanthemum leucanthemum*)
Lily of the Valley (*Convallaria majalis*)
Common gladiolus (*Gladiolus communis*)
Plantain lily or Funkia (*Hosta* sp.)

OXIDES OF NITROGEN

SOFTWOODS	Tolerant	Intermediate	Sensitive
European larch (Larix decidua)		●	
White spruce (Picea glauca)			●
Colorado spruce (Picea pungens)			●
Dwarf mugo pine (Pinus mugo mughus)			●
Austrian pine (Pinus nigra)			●
Eastern white pine (Pinus strobus)			●

OXIDES OF NITROGEN

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese maple (Acer palmatum)			●
Norway maple (Acer platanoides)			●
European hornbeam (Carpinus betulus)			●
European beech (Fagus sylvatica)			●
Maidenhair tree (Gingko biloba)			●
Apple (Malus sp.)			●
Pear (Pyrus communis)			●
Black locust (Robinia pseudoacacia)			●
European elder (Sambucus nigra)			●
Little leaf linden (Tilia cordata)			●
Large leaf linden (Tilia grandiflora)			●

CHLORINE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Jack pine (Pinus banksiana)		●	
Short leaf pine (Pinus echinata)		●	
Eastern white pine (Pinus strobus)			●
Loblolly pine (Pinus taeda)		●	
Yew (Taxus sp.)	●		
Hemlock (Tsuga sp.)	●		

CHLORINE

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (Acer negundo)			●
Sugar maple (Acer saccharum)			●
Horse chestnut (Aesculus hippocastanum)			●
Tree of heaven (Ailanthus altissima)			●
Russian olive (Eleagnus angustifolia)	●		
Chinese holly (Ilex chinesis)	●		
Sweetgum (Liquidambar styraciflua)			●
Apple (Malus sp.)			●
Black gum (Nyssa sylvatica)		●	
Black cherry (Prunus serotina)		●	
Pin oak (Quercus palustris)			●
Red oak (Quercus rubra)	●		
Sassafras (Sassafras albidum)			●

HYDROGEN CHLORIDE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Balsam fir (Abies balsamea)	●		
Larch (Larix sp.)			●
Norway spruce (Picea abies)	●		
Austrian pine (Pinus nigra)	●		
Eastern white pine (Pinus strobus)	●		
Arborvitae (Thuja sp.)	●		

HYDROGEN CHLORIDE

HARDWOODS	Tolerant	Intermediate	Sensitive
Maple (Acer sp.)	●		
Birch (Betula sp.)	●		
Cherry (Prunus sp.)			●
Black cherry (Prunus serotina)	●		
Pear (Pyrus communis)	●		
Oak (Quarcus sp.)	●		
Red oak (Quercus rubra)	●		

PEROXYACETYL NITRATE (PAN)

SOFTWOODS	Tolerant	Intermediate	Sensitive
European larch (Larix decidua)	●		
Japanese larch (Larix leptolepis)	●		
White spruce (Picea glauca)	●		
Colorado spruce (Picea pungens)	●		
Jack pine (Pinus banksiana)	●		
Austrian pine (Pinus nigra)	●		
Pitch pine (Pinus rigida)	●		
Eastern white pine (Pinus strobus)	●		
Douglas fir (Pseudotsuga menziesii)	●		
Eastern hemlock (Tsuga canadensis)	●		

PEROXYACETYL NITRATE (PAN)

HARDWOODS	Tolerant	Intermediate	Sensitive
Sugar maple (Acer saccharum)	●		
Tulip tree (Liriodendron tulipfera)			●
Little leaf linden (Tilia cordata)			●

MERCURY VAPOR

SOFTWOODS	Tolerant	Intermediate	Sensitive
Eastern white pine (Pinus strobus)			●

MERCURY VAPOR

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese maple (Acer palmatum)		●	
Persimmon (Diospyros virginiana)		●	
Chinese holly (Ilex chinesis)	●		
Mimosa (Mimosa sp.)			●
Oak (Quercus sp.)		●	
Willow (Salix sp.)			●

ETHYLENE

SOFTWOODS	Tolerant	Intermediate	Sensitive
Arborvitae (Thuja sp.)			●

ETHYLENE

HARDWOODS	Tolerant	Intermediate	Sensitive
Japanese holly (Ilex crenata)			●

Relative salt tolerance of trees.

[By authors: **(1)** Buschbom (2), **(2)** Carpenter (3), **(3)** Dirr (5,6,7), **(4)** Hanes, et al (12), **(5)** Lumis, et al (20,21), **(6)** Monk and Wiebe (22,23), **(7)** Pellett (25), **(8)** Shortle and Rich (28), and **(9)** Wyman (32,33).]

	Salt-tolerance rating		
Species	Good	Moderate	Poor
Abies balsamea	—	1	7
Acer campestre	1	6	—
Acer ginnala	—	—	1
Acer negundo	—	1,7	5
Acer platanoides	1,3,5,9	7	—
Acer pseudoplatanus	9	—	2
Acer rubrum	—	5	2,7,8
Acer saccharinum	1	5	7
Acer saccharum	5	—	2,7,8
Acer tataricum	—	—	1
Aesculus hippocastanum	1,5,9	—	—
Ailanthus altissima	5,9	—	—
Alnus glutinosa	—	—	1,2
Alnus incana	—	—	7
Alnus rugosa	—	1,5	2,8
Amelanchier canadensis	9	—	—
Amelanchier laevis	—	—	5
Amelanchier species	—	—	1
Betula alleghenensis	8	—	—
Betula lenta	8	—	—
Betula papyrifera	8	5,7	—
Betula pendula	—	1,7	—
Betula populifolia	8	5	—
Betula species	—	2	—
Caragana arborescens	1,5	—	—
Carpinus betulus	—	—	1,2
Carpinus caroliniana	—	—	7,8
Carya ovata	5	—	8
Carya species	—	—	7
Catalpa speciosa	—	5	—
Celtis occidentalis	—	—	1
Cercis canadensis	—	—	3
Chamaecyparis pisifera	—	—	1
Corylus species	—	—	1,2
Crataegus crusgalli	9	—	1
Crataegus species	—	—	1,5
Elaeagnus angustifolia	1,3,5,6,7,9	—	—
Euonymus (tree species)	—	—	1
Fagus grandifolia	—	2	1,5,7
Fagus sylvatica	—	—	1,2,7
Fraxinus americana	8	5,7	—
Fraxinus excelsior	1	—	—
Fraxinus pennsylvanica	6	2,7	—
Gleditsia triacanthos inermis	2,3,5,7	—	1
Hippophae rhamnoides	1,9	—	—
Juglans nigra	5	—	2,7
Juglans regia	5	—	2,7
Juniperus virginiana	8,9	2,7	—
Ilex opaca	9	—	—
Larix decidua	1	—	—
Larix laricina	5	—	—
Larix leptolepis	1	—	—
Larix species	—	—	2,7
Liriodendron tulipifera	—	—	4
Magnolia grandiflora	9	—	—
Malus baccata	—	2,7	—
Malus species & cultivars	—	3,5	6
Metasequoia glyptostroboides	—	—	1
Morus alba	2,6,7,9	—	5
Nyssa sylvatica	9	—	—
Picea abies	—	5,7	1
Picea asperata	9	—	—
Picea glauca	—	2	5
Picea pungens	5	—	—
Picea pungens glauca	5,9	2	—
Pinus banksiana	5	—	—
Pinus cembra	1	—	—
Pinus mugo	5	—	—
Pinus nigra	5,9	—	—
Pinus ponderosa	—	2	—
Pinus resinosa	—	—	5,7,8
Pinus rigida	9	—	—
Pinus strobus	—	—	5,7,8
Pinus sylvestris	9	7	1,3
Pinus thunbergii	9	—	—
Platanus x hybrida	—	—	1
Populus alba	1,2,3,7,9	—	—
Popular alba 'Pyramidalis'	3	—	—
Populus angustifolia	2	—	—
Populus deltoides	5	2	—
Populus grandidentata	8	5	—
Populus nigra 'Italica'	—	5	2,7
Populus tremuloides	8	1,2,5	—
Populus species	—	5	—
Prunus armeniaca	2,6	—	—
Prunus avium	—	1	—
Prunus padus	1	—	—
Prunus serotina	8,9	—	1
Prunus virginiana	5	—	—
Pseudotsuga menziesii	—	1,2	7
Pyrus species	—	5	—
Quercus alba	2,3,6,7,8,9	—	1
Quercus bicolor	—	—	1
Quercus macrocarpa	7	1	5
Quercus marilandica	9	—	—
Quercus muhlenbergii	—	—	1
Quercus palustris	—	—	1
Quercus robur	2,6	—	1
Quercus rubra	2,5,7,8	—	—
Rhamnus cathartica	3,5,9	—	—
Rhamnus davurica	1	—	—
Rhamnus frangula	3	5	—
Rhus typhina	3,5,9	—	—
Robinia pseudoacacia	1,3,5,6,7,8,9	—	—
Robinia pseudoacacia 'Umbraculifera'	3	—	—
Salix alba	—	2	1
Salix alba 'Tristis'	7	3	—
Salix matsudana 'Tortuosa'	3	—	—
Salix nigra	—	5	—
Salix species	1,7	—	—
Sorbus species	—	1,5	—
Syringa amurensis japonica	5	—	—
Tamarix pentandra	1,2,6,7,9	—	—
Taxus cuspidata	—	7	5
Thuja occidentalis	—	2	5
Tilia americana	—	5	7,8
Tilia cordata	—	—	2,7
Tilia euchlora	—	—	1
Tilia platyphyllos	1	—	—
Tsuga canadensis	—	—	5,7,8
Ulmus americana	—	5,7	8
Ulmus glabra	1,2	—	—
Ulmus pumila	7	5	—
Viburnum species	—	—	2

Salt resistance of trees

Ruge, 1972a (after Walter et al., 1974)	Buschbom, 1972	Emschermann, 1973	Chrometzka et al., 1973	Daniels, 1974	Chrometzka, 1974b
Relatively tolerant					Decreasing salt compatibility
Platanus acerifolia	*Acer campestre*	*Acer platanoides*	*Elaeagnus angustifolia*	*Acer negundo*	*Acer campestre*
Quercus robur	*Elaeagnus commutata*	*Fraxinus excelsior*	*Hippophae rhamnoides*	*Elaeagnus angustifolia*	*Alnus glutionosa*
Quercus rubra	*Fraxinus ornus*	*Lonicera xylosteum*	*Viburnum lantana*	*Fraxinus pennsylvanica*	*Alnus incana*
Sorbus	*Halimodendron*	*Ribes alpinum*		*Malus baccata*	*Crataegus monogyna*
Crataegus	*Lycium halimifolium*	*Rosa rugosa*		*Populus alba*	*Crataegus oxyacantha*
Sophora	*Populus canescens*	*Symphoricarpus albus*		*Morus* species	*Robinia pseudacacia*
Robinia pseudacacia	*Ribes aureum*	*Ulmus glabra*		*Quercus alba*	*Populus nigra*
Fraxinus excelsior	*Salix alba*			*Quercus borealis*	*Quercus robur*
Tilia tomentosa	*Tamarix* species			*Quercus robur*	*Quercus sessiliflora*
	Ulmus glabra			*Robinia pseudacacia*	*Quercus rubra*
Less tolerant				Sensitive to salt	
	Hippophae rhamnoides	*Acer campestre*	*Acer campestre*	*Abies balsamea* *	*Acer platanoides*
	Alnus incana	*Alnus glutinosa*	*Acer ginnala*	*Acer saccharum*	*Salix caprea*
	Lonicera xylosteum	*Salix caprea*	*Acer pseudoplatanus*	*Berberis thunbergii*	*Salix viridis*
	Populus tremula	*Ulmus carpinifolia*	*Alnus glutinosa*	*Buxus sempervirens*	*Betula pendula*
	Prunus avium		*Alnus incana*	*Carpinus betulus*	*Carpinus betulus*
	Prunus padus		*Alnus viridis*	*Euonymus alatus*	*Sorbus aucuparia*
			Betula pendula	*Fagus grandiflora*	*Prunus padus*
Very sensitive to salt			*Carpinus betulus*	*Fagus sylvatica*	*Prunus serotina*
			Crataegus monogyna	*Juniperus virginiana*	*Tilia cordata*
Aesculus hippocastanum	*Carpinus betulus*	*Carpinus betulus*	*Crataegus oxyacantha*	*Larix* species	*Corylus avellana*
Acer species	*Betula pubescens*	*Cornus sanguinea*		*Malus* species	*Sambucus nigra*
Tilia species	*Cornus mas*	*Corylus avellana*	*Corylus avellana*	*Picea glauca*	Conifers
	Cotoneaster integerrima	*Crataegus monogyna*	*Ligustrum vulgare*	*Picea pungens*	
	Corylus avellana	*Fagus sylvatica*	*Quercus rubra*	*Populus nigra italica*	
	Fagus silvatica	*Prunus serotina*	*Quercus* multi-species	*Populus tremuloides*	
	Picea abies	*Rosa canina*	*Salix caprea*	*Pseudotsuga menziesii*	
	Pyracantha coccinea	*Sambucus racemosa*	*Salix viridis*	*Tilia cordata*	
	Prunus spinosa		*Sorbus aucuparia*	*Tsuga canadensis*	
	Taxus baccata		*Symphoricarpus orbiculata*		
			Symphoricarpus chenaultii	* *Acer pseudoplatanus*	
			Prunus padus		
			Prunus serotina		
			Prunus spinosa		
			Tilia cordata		
			All conifers		

Sensitivity of roadside trees and shrubs to aerial drift of deicing salt.

Common name (species)	Sensitivity rating[z]
Deciduous trees	
Norway maple (*Acer platatanoids* L.)	1
Horse-chestnut (*Aesculus hippocastanum* L.)	1
Tree of heaven [*Ailanthus altissima* (Mill.) Swing]	1
Cottonwood (*Populus deltoides* Bart.)	1
Black locust (*Robinia pseudoacacia* L.)	1
Sugar maple (*Acer saccharum* March)	1-2
Shagbark hickory [*Carya ovata* (Mill.) K. Koch	1-2
Honey locust (*Gleditsia triacanthos* L.)	1-2
Black walnut (*Juglans nigra* L.)	1-2
English walnut (*Juglans regia* L.)	1-2
Choke cherry (*Prunus virginiana* L.)	1-2
Red oak (*Quercus rubra* L.)	1-2
Silver maple (*Acer saccharinum* L.)	2
White ash (*Fraxinus americana* L.)	2
Poplar (*Populus* spp.)	2
Black willow (*Salix nigra* Marsh)	2
Mountain ash (*Sorbus* spp.)	2
White elm (*Ulmus americana* L.)	2
Chinese Elm (*Ulmus pumila* L.)	2
Red maple (*Acer rubrum* L.)	2-3
White birch (*Betula papyrifera* Marsh)	2-3
Grey birch (*Betula populifolia* March)	2-3
Catalpa (*Caltalpa speciosa* Warder.)	2-3
Quince (*Cydonia oblonga* Mill.)	2-3
Lombardy poplar (*Populus nigra italica* Muenchh)	2-3
Pear (*Pyrus* spp.)	2-3
Basswood (*Tilia americana* L.)	2-3
Crabapple (*Malus* spp.)	3
Largetooth aspen (*Populus gradidentata* Michx.)	3
Trembling aspen (*Populus tremuloides* Michx.)	3
Weeping golden willow (*Salix alba* 'Tristis' Gaud.)	3
Apple (*Malus* spp.)	3-4
Bur oak (*Quercus macrocarpa* Michx.)	3-4
Hawthorn (*Crataegus* spp.)	4
Manitoba maple (*Acer negundo* L.)	4-5
Allegheny serviceberry (*Amelanchier laevis* Wieg.)	4-5
White mulberry (*Morus alba* L.)	4-5
Beech (*Fagus gradifolia* Ehrh.)	5

Common name (species)	Sensitivity rating[z]
Deciduous shrubs	
Siberian pea-tree (*Caragana arborescens* Lam.)	1
European buckthorn (*Rhamnus cathartica* L.)	1
Honeysuckle (*Lonicera* spp.)	1-2
Staghorn sumac (*Rhus typhina* L.)	1-2
Japanese lilac [*Syringa amurensis japonica* (Maxim.) Fr. & Sav.]	1-2
Common lilac (*Syringa vulgaris* L.)	1-2
Russian olive (*Elaeagnus angustifolia* L.)	1-3
Mockorange (*Philadelphus* spp.)	1-3
European cranberry-bush (*Viburnum opulus* L.)	1-3
Japanese barberry (*Berberis thunbergii* 'Atropupurea' Chenalt)	2
Burningbush [*Euonymus alata* (Thunb.) Sieb.	2
Forsythia (*Forysthia xintermedia* Zab.)	2-3
Privet (*Ligustrum* spp.)	2-3
Alder buckthorn (*Rhamnus frangula* L.)	2-3
Speckled alder [*Alnus rugosa* (Du Roi) Spreng.]	3
Flowering quince (*Chaenomeles speciosa* Nakai)	3-4
Gray dogwood (*Cornus racemosa* Lam.)	3-4
Beauty-bush (*Kolkwitzia amabilis* Graebn.)	3-4
Bumalda spirea (*Spirea* x *bumalda* Burv.)	3-4
Red Osier dogwood (*Cornus stolonifera* Michx.)	4-5
Conifers	
Blue spruce (*Picea pungens* 'Glauca' Reg.)	1
Jack pine [*Pinus divaricata* (Ait.) Dumont]	1-2
Mugo pine (*Pinus mugo* Turra.)	1-2
Tamarack [*Larix laricina* (Du Roi) K. Koch]	2
Austrian pine (*Pinus nigra* Arnold)	2
Juniper (*Juniperus* spp.)	2-3
Norway spruce [*Picea abies* (L.) Karst.]	3
White cedar (*Thuja occidentalis* L.)	3-4
Yew (*Taxus* spp.)	4
White spruce [*Picea glauca* (Moench) Voss]	4-5
Red pine (*Pinus resinosa* Ait.)	4-5
Scots pine (*Pinus sylvestris* L.)	4-5
Hemlock (*Tsuga canadensis* L.)	4-5
White pine (*Pinus strobus* L.)	5

[z]Ratings of 1 indicate no twig dieback or needle browning of conifers and no dieback, tufting of inhibition of flowering of deciduous plants. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting and lack of flowering of deciduous species. Under sever conditions plants rated 5 will eventually die. Ratings of 2, 3 and 4 encompass slight, moderate and extensive gradations of the above symptoms.

Species that are sentivite to salt.

Abies balsamea. Balsam fir
Acer pseudoplatanus. Sycamore maple
Acer saccharum. Sugar maple
Berberis thunbergi. Japanese barberry
Buxus sempervirens. Boxwood
Carpinus betulus. European hornbeam
Euonymus alatus. Winged euonymus
Fagus grandiflora. American beech
Fagus sylvatica. European beech
Juniperus virginiana. Eastern redcedar
Larix sp.. Larch
Malus sp.. Apple
Picea glauca. White spruce
Picea pungens. Blue Colorado spruce
Populus nigra italica. Lombardy poplar
Populus tremuloides. Quaking aspen
Pseudotsuga menziesii. Douglas fir
Tilia cordata. Littleleaf linden
Tsuga canadensis. Hemlock

Species that are tolerant to salt.

Acer negundo. Box-elder
Eleagnus angustifolia. Russianolive
Fraxinus pennsylvanica. Green ash
Gleditsia triacanthos. Common Honeylocust
Malus baccata. Siberian crabapple
Morus sp.. Mulberry
Populus alba. Silver poplar
Quercus alba. White oak
Quercus borealis. Red oak
Quercus robur. English oak
Robinia pseudoacacia. Black locust

. Species list of roadside trees and shrubs rated for their resistance to air-borne highway salt spray

DECIDUOUS TREES	INJURY RATING*
Horse-chestnut *Aesculus hippocastanum* L.	1
Tree of Heaven *Ailanthus altissima* (Mill.) Swing	1
Norway maple *Acer platanoides* L.	1
Cottonwood *Populus deltoides* Bartr.	1
Black locust *Robinia pseudoacacia* L.	1
Honey locust *Gleditsia triacanthos* L.	1-2
Red oak *Quercus rubra* L.	1-2
Sugar maple *Acer saccharum* Marsh	1-2
English walnut *Juglans regia* L.	1-2
Black walnut *Juglans nigra* L.	1-2
Shagbark hickory *Carya ovata* (Mill.) K. Koch	1-2
Choke cherry *Prunus virginiana* L.	1-2
White ash *Fraxinus americana* L.	2
White elm *Ulmus americana* L.	2
Black willow *Salix nigra* Marsh	2
Mountain ash *Sorbus* spp.	2
Poplar *Populus* spp.	2
Silver maple *Acer saccharinum* L.	2
Chinese elm *Ulmus pumila* L.	2
Red maple *Acer rubrum* L.	2-3
Lombardy poplar *Populus nigra italica Muenchh.*	2-3
Basswood *Tilia americana* L.	2-3
White birch *Betula papyrifera* Marsh	2-3
Gray birch *Betula populifolia* Marsh	2-3
Catalpa *Catalpa speciosa* Warder.	2-3
Pear *Pyrus* spp.	2-3
Quince *Cydonia oblonga* Mill.	2-3
Trembling aspen *Populus tremuloides* Michx.	3
Largetooth aspen *Populus grandidentata* Michx.	3
Crabapple *Malus* spp.	3
Golden willow *Salix alba tristis* Gaud.	3
Bur oak *Quercus macrocarpa* Michx.	3-4
Apple *Malus* spp.	3-4
Hawthorn *Crataegus* spp.	4
Manitoba maple *Acer negundo* L.	4-5
Allegheny serviceberry *Amelanchier laevis* Wieg.	4-5
White mulberry *Morus alba* L.	4-5
Beech *Fagus grandifolia* Ehrh.	5

DECIDUOUS SHRUBS	INJURY RATING*
Siberian pea-tree *Caragana arborescens* Lam.	1
Staghorn sumac *Rhus typhina* L.	1-2
Japanese lilac *Syringa amurensis japonica* (Maxim.) Fr. & Sav.	1-2
Common lilac *Syringa vulgaris* L.	1-2
Honeysuckle *Lonicera* spp.	1-2
European cranberry-bush *Viburnum opulus* L.	1-3
Russian olive *Elaeagnus angustifolia* L.	1-3
Mock orange *Philadelphus* spp.	1-3
Japanese barberry *Berberis thunbergii atropurpurea* Chenault.	2
Burning bush *Euonymus alata* [Thunb.) Sieb.	2
Forsythia *Forsythia x intermedia* Zab.	2-3
Privet *Ligustrum* spp.	2-3
Alder buckthron *Rhamnus frangula* L.	2-3
Speckled alder *Alnus rugosa* (Du Roi) Spreng.	3
Flowering quince *Chaenomeles lagenaria* (Loisel.) Koidz.	3-4
Bumalda spirea *Spirea x bumalda* Burv.	3-4
Beauty bush *Kolkwitzia amabilis* Graebn.	3-4
Gray dogwood *Cornus racemosa* Lam.	3-4
Red osier dogwood *Cornus stolonifera* Michx.	4-5

CONIFERS	INJURY RATING
Blue spruce *Picea pungens* Englem.	1
Jack pine *Pinus divaricata* (Ait.) Dumont	1-2
Mugo pine *Pinus mago* Turra.	1-2
Austrian pine *Pinus nigra* Arnold	2
Tamarack *Larix laricina* (Du Roi) K. Koch	2
Juniper *Juniperus* spp.	2-3
Norway spruce *Picea abies* (L.) Karst.	3
White cedar *Thuja occidentalis* L.	3-4
Yew *Taxus* spp.	4
Red pine *Pinus resinosa* Ait.	4-5
Scots pine *Pinus sylvestris* L.	4-5
White spruce *Picea glauca* (Moench) Voss	4-5
Hemlock *Tsuga canadensis* L.	4-5
White pine *Pinus strobus* L.	5

* A rating of 1 indicates no twig dieback or needle browning of conifers and no dieback, tufting, or inhibition of flowering of deciduous trees and shrubs. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting, and lack of flowering of deciduous trees and shrubs. Under severe conditions plants rated 5 will eventually die. Ratings of 2, 3 and 4 encompass slight, moderate and extensive gradations of the above injury symptoms.

Salt Tolerance of Some Common Trees and Shrubs

Tolerant	Sensitive
Shrubs	
Adam's needle	Arctic blue willow
Autumn elaeagnus	Boxwood
Bayberry	Japanese barberry
Beach plum	Multiflora rose
Buffaloberry	Van houtle spirea
California privet	Viburnums
Matrimony vine	Winged spindle tree
Pfitzer juniper	
Rugosa rose	
Tartarian honeysuckle	
Evergreen trees	
Austrian pine	Balsam fir
Colorado blue spruce	Canadian hemlock
Japanese black pine	Douglas fir
Pitch pine	Eastern white pine
Red cedar	Red pine
White spruce	
Yews	
Deciduous trees	
Big tooth aspen	American elm
Black cherry	American linden
Black locust	Boxwood
Box elder	Ironwood
Burr oak	Little-leaf linden
English oak	Red maple
Golden willow	Shagbark hickory
Green ash	Silver maple
Honey locust	Speckled alder
Quaking aspen	Sugar maple
Red oak	
Russian olive	
Siberian crabapple	
Siberian elm	
Weeping willow	
White oak	
White poplar	

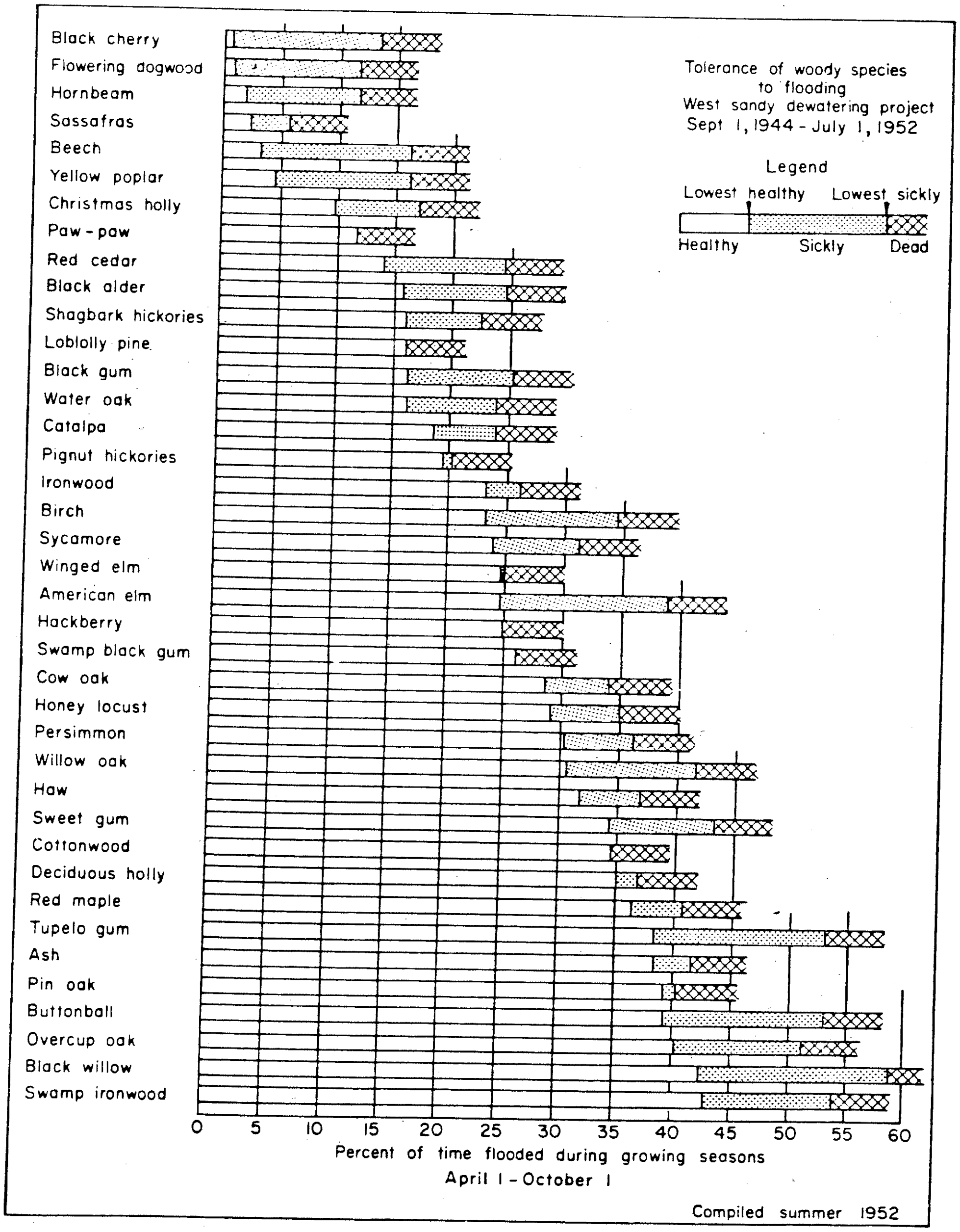

Fig. 2. Tolerance of Kentucky woody species to flooding during the growing season. [From Hall and Smith (1955). Reproduced by permission of Society of American Foresters.]

Tree species intolerant to flooding with suggested replacements from taxonomically related groups which are known to withstand flooding (Crawford, 1974) and suggestions from other authors

Kind	Intolerant	Tolerant
Beech	*Fagus sylvatica*	*Nothofagus dombeyii* *N. antarctica* *N. pumilo*
Elm	*Ulmus glabra* *U. procera* *U. carpinifolia*	*Ulmus americana* *U. alata* *Celtis occidentalis*
Ash	*Fraxinus excelsior*	*Fraxinus pennsylvanica* *F. chinensis*
Sycamore and maples	*Acer pseudoplatanus* *A. campestre* *A. platanoides*	*Acer saccharinum* *Platanus* x hybrida *P. occidentalis*
Holly	*Ilex aquifolium*	*Ilex decidua*
Oak	*Quercus robur*	*Quercis petraea* *Q. palustris* *Q. phellos* *Q. shumardii*
Eucalypts and myrtles		*Myrceugenella apiculata* *Myrceugenia exsucca*
Locusts		*Gleditsia triacanthos*
Pine	*Pinus*	*Pinus contorta* *P. thunbergii* *P. taeda* *P. palustris*
Larch	*Larix decidua*	*Larix laricina* *Taxodium distichum* *T. ascendens*
Cedar	*Cedrus libanotica* *C. deodora* *C. atlantica*	*Libocedrus chilensis* *Fitzroya cupressoides*
Author		
Polster (in Lyr et al., 1967)	*Celtis occidentalis* *C. laevigata* *Liquidambar styraciflua* *Ulmus americana*	*Populus* *Salix* *Alnus* *Fraxinus profunda* *Nyssa aquatica* *Prunus padus*

Author	Intolerant	Tolerant
Kruessmann, 1974	*Acer saccharum*	*Acer rubrum*
	Betula papyrifera	*Malus* 'Dolgo'
	B. populifolia	*Morus alba*
	Cercis canadensis	*Fraxinus americana*
	Cladastris lutea	*Juglans nigra*
	Cornus florida	*Salix alba*
	Crataegus lavallei	*S. discolor*
	Magnolia soulangiana	*Tilia cordata*
	Malus species	
	Prunus persica	
	P. serotina	
	P. subhirtella	
	Quercus rubra	
	Robinia pseudacacia	
	Sorbus aucuparia	
	Picea abies	
	P. pungens	
	P. pungens 'Glauca'	
	Taxus cuspidata 'Expansa'	
	T. media 'Hicksii'	
	Thuja occidentalis	
	Tsuga canadensis	

Tolerance of Various Tree Species to Wet Sites and Occasional Flooding

Tolerant	Intolerant
Ash	Chestnut oak
Black gum	Eastern white pine
Cottonwood	Hemlock
Elm	Paper birch
Overcup oak	Red cedar
Pin oak	Red oak
Poplars	Red pine
Red maple	White spruce
River birch	Sugar maple
Silver maple	
Sweetgum	
Sycamore	
White cedar	
Willows	

Shade and Ornamental Trees

Acer saccharum—Sugar Maple
Acer platanoides—Norway Maple
Betula papyrifera—White Birth
Betula populifia—Gray Birch
Cercis canadensis—Redbud
Cladrastic lutea—Yellowwood
Cornus florida—White Flowering Dogwood
Cornus florida rubra—Red Flowering Dogwood
Cornus florida 'Cloud 9'—'Cherokee Chief'
Crataegus phaenopyrum-Washington Hawthorn
Crataegus lavallei—Lavalle Hawthorn
Magnolia soulangiana—Saucer Magnolia
Malus sp. 'Lodi,' 'McIntosh,' 'Radiant,' 'Hope,' Bechtel
Prunus persica—Flowering Peach
Prunus serotina—Black Cherry
Prunus subhirtella pendula—Weeping Cherry
Quercus borealis—Red Oak
Robinia pseudoacacia—Black Locust
Sorbus aucuparia—European Mountain Ash

Evergreens

Picea excelsa—Norway Spruce
Picea pungens—Colorado Spruce
Picea pungens glauca—Colorado Blue Spruce
Taxus cuspidata—Upright Yew
Taxus cuspidata expansa—Spreading Yew
Taxus media "Hicksii"—Hick's Yew
Thuja occidentalis—American Arborvitae
Tsuga canadensis—Canadian Hemlock
Celastrus orbiculatus—Oriental Bittersweet
Euonymus fortunei 'Coloratus'—Purpleleaf Wintercreeper
Euonymus fortunei 'Vegetus'—Bigleaf Wintercreeper
Forsythia sp. — All varieties
Ligustrum amurense—Amur Privet
Ligustrum vulgare—Polish or English Privet
Lonicera morrowi—Morrow Honeysuckle
Lonicera tatarica—Tatarian Honeysuckle
Philadelphus coronarius—Sweet Mock-orange
Physocarpus opulifolius —Nine-bark

Observation on the same sites showed a remarkable list of plants that apparently will tolerate such unusual conditions. All had no leaf drop and appeared perfectly normal, even on a second check in late October before killing frosts. All had tolerated the same amounts of water as the first group and for the same amount of time. My "survivor" list follows:

Evergreen "Survivors"

Juniperus virginiana—Red Cedar
Juniperus chinensis pfitzeriana—Pfitzer Juniper

Shade Tree "Survivors"

Acer rubrum—Red Maple
Cornus mas—Cornelian Cherry
Fraxinus americana—White Ash
Gleditsia inermis—Thornless Honeylocust
Juglans nigra—Black Walnut
Malus 'Dolgo'—Dolgo Crabapple
Morus alba—Mulberry
Platanus occidentalis—American Sycamore
Populus deltoides—Cottonwood
Salix alba—White Willow
Salix discolor—Pussy Willow
Tilia cordata—European Littleleaf Linden

Shrub "Survivors"

Berberis thunbergi—Japanese Barberry
Cornus paniculata—Gray-stem Dogwood
Ligustrum obtusifolium Regelianum—Regel Privet
Viburnum dentatum—Arrowwood
Viburnum lentago—Sweet Viburnum
Viburnum trilobum—American Cranberrybush

Species Adaptable to Flooded or Poorly Aerated Soils (Hook 1972)

White willow	White birch
Brittle willow	Scotch pine
Creeping willow	Norway spruce
Sycamore	Sweet gum
Swamp tupelo	Yellow poplar
Sour gum	Sweet gum
Green ash	

Pirone (1972) classified susceptibility of species to poor aeration as follows:

Most Severely Injured
Sugar maple (*Acer saccharum*)
Beech (*Fagus*)
Dogwood (*Cornus*)
Oak (*Quercus*)
Tulip tree (*Liriodendron*)
Pines (*Pinus*)
Spruces (*Picea*)

Less Severely Injured
Birch (*Betula*)
Hickory (*Carya*)
Hemlock (*Tsuga*)

Least Injured
Elm (*Ulmus*)
Poplar (*Populus*)

Locality	Resistant to flooding	Notes
Po flood-plain, Italy.		
Danube bottomlands, Upper Austria.	*Populus* spp., *Salix* spp. *Alnus incana.* *Tilia* sp., *Fraxinus* sp. *Acer* sp.	Lost leaves but recovered well. 10% mortality. 50% mortality. Intolerant—*Sambucus nigra.*
Volga flood-plain, U.S.S.R.	*Fraxinus pennsylvanica, Acer negundo, Salix* spp. *Populus nigra, P. deltoides, P. balsamifera, Salix* sp. *Quercus robur, Fraxinus pennsylvanica, Gleditsia triacanthos,* etc. *Populus alba.* *Fraxinus excelsior, Ulmus pumila, Cornus* sp., etc.	30–45 days' continuous flooding on heavy soils. 30–45 days' continuous flooding on light soils. Up to 30 days' continuous flooding on heavy soils. Up to 30 days on light soils. Up to 15 days (on heavy soils) in years of very high water level.
Outside dykes of islet on River Weser, near Bremen, Germany.	*Populus* × *euramericana.*	Flooded up to 80 times a year, including 5–15 times in summer; d.b.h. at 10 years old, 30–35 cm.
River banks in Angola	*Populus deltoides.*	Timing of rains unsuitable for riparian Poplar growing, but this is the most promising species.
Volga-Don basin, droughty regions of flood-plain, U.S.S.R.	 *Salix alba, Alnus glutinosa.* *S. alba, F. pennsylvanica.* *S. alba, Populus nigra, F. pennsylvanica.* *P. balsamifera, P. alba, P. deltoides,* shrub Willows, *F. pennsylvanica.* *P. balsamifera, P. alba, P. deltoides* and *P. alba* var. *pyramidalis, Betula verrucosa, Quercus robur, Ulmus pumila.*	*N.B.*—Exact choice of species listed depends on soil type; e.g. clay-loam, sand/silt deposits, beach sands, saline, etc. Spring/summer flooding for >60 days by stagnant water. Spring/summer flooding for <60 days by stagnant water. Spring/summer flooding for >60 days by flowing water. Spring/summer flooding for 30–60 days by flowing water. Spring/summer flooding for 10–30 days by flowing water.
Danube flood-plain, Rumania.	*Populus* × *euramericana* cvs. 'Robusta R.16', 'Robusta Oltenita', and 'Celei', *Salix alba* (clones R.204, R.202, R.103, R.206).	Growing season 200 days, soil fertile, extremes of temperature, long periods of flooding in first part of growing season, drought in second.
Danube 'dam-bank zone', i.e. the zone between the river bed and the flood-protection dams, Rumania	*Salix alba, Populus* × *euramericana* cvs. 'Robusta' ('R.16' and 'R.20'), 'Serotina' ('R.3' and 'R.4'), and 'Celei', *P. alba, P. nigra.*	Flooding was in the growing season; height of Danube can vary by 5–9 metres. Planting was on a commercial basis.
Danube flood-plain, Rumania.	*Populus* × *euramericana.*	
Flood-plain embankments, Rumania.	*Salix alba, S. triandra, S. cinerea, Populus nigra, P. alba, P.* × *euramericana* (cvs. 'Robusta' and 'Marilandica'), *Fraxinus pennsylvanica, Taxodium distichum.*	

Recommended for bank protection	Notes	Author
Populus spp.		Montanari, 1954.
Populus spp., *Salix* spp.		Traunmüller, 1954.
		Rubanov, 1959.
Populus × *euramericana.*	Reduced wave and ice damage to dykes, the trees themselves not damaging dykes.	Grabhorn, 1960.
Populus deltoides.	Soil characteristics not good for riparian Poplar growing, but this is the most promising species.	Silva, 1965.
No erosion problem in stagnant conditions. A selection of those tree species listed in the preceding column as resistant to flooding by flowing water, depending on soil type and duration of flooding. Various shrubs, e.g. shrub Willows, *Rhus cotinus, Cornus sanguinea, Ribes aureum, R. nigrum, Acer tataricum, Amorpha fruticosa.*		Treščevskij, 1966.
As in column 2.	Ice movements at end of winter a hazard, as well as force of flowing water.	Clonaru *et al.*, 1966.
Salix alba; all *Populus* spp.	Winter ice drift a hazard, as well as water erosion.	Radu *et al.*, 1968.
Populus × *euramericana.*		Ionescu, 1968.
Salix alba, S. cinerea, S. triandra.	Young and middle-aged Willow stands recommended for protection of dam-bank zone, planted as close as possible to bank	Lupe *et al.*, 1968.

THE FLOODING TOLERANCE OF WOODY SPECIES

Locality	Resistant to flooding	Notes
Tennessee Valley reservoirs, U.S.A.	*Taxodium distichum, Nyssa aquatica, Chamaecyparis thyoides.*	Recommended for upper drawdown zone, covered intermittently in growing season by 1–3 feet of water.
	Quercus nigra, Q. phellos, Fraxinus pennsylvanica, Liquidambar styraciflua, Platanus occidentalis	For reservoir surcharge zones, 1–15 feet above normal high-water level; flooded occasionally in dormant season. 11,000 acres planted on a commercial basis.
Volga hydro-electric reservoirs, U.S.S.R.		
Hydro-electric reservoirs, U.S.S.R.	*Salix* spp.	>2 months' submergence can be tolerated.
Wildfowl water-impoundment plantings, U.S.A.	*Populus deltoides, Liquidambar styraciflua, Fraxinus pennsylvanica.*	Impoundments of up to 90 cm. depth from February to July increased radial growth by 52%, by increasing soil moisture content over whole growing season.
Derdap hydro-electric reservoir, on the Danube, nr. Belgrade, Jugoslavia.		
Rybinsk reservoir, U.S.S.R.	*Alnus glutinosa.*	Recommended for replacing the Pine forests, which were dying owing to underflooding when the reservoir was filled.
Reservoirs in U.S.S.R.		
Rybinsk reservoir, U.S.S.R.	*Salix* sp., *Betula* sp.	Discusses measures for promoting natural regeneration of these species (and *Pinus sylvestris*) on the banks, shores, shoals and beaches.
Kuibyshev reservoir, U.S.S.R.	*Salix viminalis, S. rossica, S. dasyclados, S. triandra,* and other *Salix* spp. *Alnus glutinosa.*	Recommended for planting the upper drawdown zone; lowest trees inundated for all of growing season except August.

Recommended for bank protection	Notes	Author
		Silker, 1948.
Salix acutifolia, Populus simonii, P. balsamifera.		Vetkasov, 1958.
Salix triandra, S. purpurea, S. alba, S. acutifolia, S. caprea, S. daphnoides.	Species used were all indigenous and occurred locally.	Kulikov, 1966.
		Broadfoot, 1967. (Also 1958.)
Populus spp. and *Salix* spp.	Minimum belt widths for bank protection, 120 metres.	Šimunović, 1969.
Salix cinerea. *S. triandra.*	For peaty banks. For sandy banks.	Turkov, 1969.
Taxodium distichum.		Bjallovič, 1968.
		Kudinov and Igtisamov, 1968.
		Mamaev, 1958.

Locality	Resistant to flooding	Notes
Danube flood-plain, Hungary.	*Populus* × *euramericana* cvs. 'Robusta' and 'I-214'.	Greater tolerance found with increasing age of saplings. Summer flooding lasted 64–140 days. Site preparation important for survival.
Brăila marshes, Rumania.	*Populus* × *canadensis* (*P.* × *euramericana*).	Increased tolerance found with increasing stand age.
Flood-plain embankments, Rumania.	*Salix alba*. *Populus nigra*, *P.* × *euramericana*.	Can withstand up to 120 days' submersion by flowing water, provided it has $\not<$30 cm. of aerated soil for the rest of the year. Can withstand up to 50 days' submersion, but need $\not<$60 cm. of aerated soil for the rest of the year.
River banks in Central Europe.		
Flooded plantations in Holland.	*Populus* × *euramericana* cvs. 'Serotina', 'Robusta', 'Heidemij', 'Marilandica' and 'Regenerata', *Salix* spp.	Flooding lasted until mid-August—depth 150 cm. Older stands were most tolerant.
Flooded plantations in the Hansag region, Hungary.	*Populus* × *euramericana* cvs. 'Robusta', 'I-214', 'Marilandica' and 'Serotina', *Salix* spp.	Mound-planting and drainage were very beneficial. *Alnus* sp.stands were intolerant.
European stream and river banks.	*Alnus glutinosa*, *Salix purpurea*, *S. alba*, *S. fragilis*, *S. triandra*, *S.* × *rubens*, *S. viminalis*, *S. cinerea*, *S. elaeagnos*, *Populus nigra*.	
Yangtze River flood-plain, China.	*Salix matsudana*, *S. babylonica*, *Fraxinus chinensis*, *Tamarix chinensis*, *Pterocarya stenoptera*, *Pyrus calleryana*, *Amorpha fruticosa*, *Campsis chinensis*, *Juniperus chinensis*, *Pinus thunbergii*.	Exceptional floods lasting in some cases 140 days; floodwater 0·8 to 6·6 m. deep.

Recommended for bank protection	Notes	Author
		Simon, 1966.
	Some damage by bending, breaking and uprooting.	Popescu and Necşulescu, 1967.
		Sabău, 1967.
Salix acutifolia.	Recommended for exposed banks, because of its exceptional root development.	Raschke, 1957.
		Kolster, 1966.
		Máté and Balsay, 1966.
As in column 2.		Seibert, 1969.
		Anon., 1955.

Various types of low temperature injuries

Conditions Leading to Damage	Symptoms	Susceptible Plants
FALL FROST Cool summer followed by warm, early autumn; summer or early fall fertilization and abundant summer watering. Tissues not "hardened" and mature.	Killing back of twigs, branches or entire plants.	Practically all.
SPRING FROST Sudden drop in temperature after new growth is well advanced. Plants growing in low-lying "frost pockets" are damaged most severely.	Wilting, blackening or browning and death of tender twigs, leaves and flowers.	Practically all.
EXCESS WINTER COLD Abnormally low temperatures especially where soil is poorly drained and/or shallow. Worst following low-snowfall winters or where soil is bare of mulch and smaller plants. Damage most severe when plants fed with large amounts of high-N fertilizer and growing vigorously later in the fall.	Above-ground parts wilt and die back during late spring or summer. Roots and inner bark are killed and often discolored. Evergreens may lose their leaves; deciduous trees and shrubs often fail to leaf out properly. Plants may take on a brownish cast.	Shallow-rooted trees, e.g., ash, elm, maple, pine, that are not well adapted.
FROST CRACKS When cold winter nights follow warm sunny days. Trees growing in poorly drained soils are most susceptible.	Long vertical cracks in wood on south or southwest sides of trunk. Cracks often reopen in following winters. Wood-decay fungi may enter such wounds.	Isolated, vigorous deciduous trees: certain maples, elms, beeches, apple and crabapple, flowering cherries, plums, lindens, poplars, horsechestnut, oaks, golden-rain trees, ashes, tuliptree, walnut, willows, London plane, and introduced trees.
FROST CANKERS (WINTER SUNSCALD) Hot winter sun heats up localized areas on trunk, large branches or crotches. Trees suddenly exposed to a marked increase in sunlight are most liable to injury.	Exposed bark and underlying wood on south or southwestern sides is killed in well-defined cankers; often invaded later by secondary fungi, bacteria and insects. Splitting and peeling of bark is common.	Common on certain maples, London plane, elms, beeches, apple, poplars (aspens), boxwood, and other smooth-barked trees and shrubs.
WINTER DRYING Excessive rapid changes in temperature, especially when accompanied by drying winds and bright sun. Exposed plants growing in a warm, sunny spot in frozen soil are most susceptible.	Scorching and bronzing of leaf margins of broad-leaved evergreens. Leaves of all evergreens may wilt, turn yellow to brown, and die. Buds are killed; twigs die back. Deciduous trees and shrubs are slow to leaf out; leaves may be small and off-color; twig dieback is common.	All narrow- and broad-leaved evergreens, plus wide range of deciduous trees and shrubs.
ICE AND SNOW Heavy loads cause cracking and splitting of twigs and branches.	Browning of foliage and dieback of wood to site of injury.	Yews, junipers, boxwood and other multiple-stem evergreens. Brittle trees: Silver and red maples, American and Chinese elms, sycamore, tree-of-Heaven, tuliptree, honey-locust, birches, poplars, boxelder and willows.

Table 37. Frost resistance (temperature at the first appearance of injury), initial freezing (temperature at the beginning of ice formation) and protoplasmic frost tolerance in evergreen leaves and needles in winter. The frost tolerance corresponds to the difference between the temperature at first appearance of injury and the initial freezing temperature. (From Larcher, 1973)

Plant	Frost injury	Initial freezing	Frost tolerance
Eucalyptus globulus	− 3°C	− 3°C	*none*
Citrus limon	− 5	− 5	*none*
Ceratonia siliqua	− 5	− 5	*none*
Nerium oleander	− 7	− 7	*none*
Olea europaea	−10	−10	*none*
Pinus pinea	−11	− 7	*4°C*
Quercus ilex	−13	− 8	*5*
Cupressus sempervirens	−14	− 5	*9*
Taxus baccata	−20	− 6	*14*
Abies alba	−30	− 7	*23*
Picea abies	−38	− 7	*31*
Pinus cembra	−42	− 7	*35*

SUSCEPTIBILITY OF GENERA AND SPECIES OF HARDWOODS TO FOLIAGE DAMAGE BY LATE FROSTS[a]

Highly susceptible	*Moderately susceptible*	*Less susceptible*	*Least susceptible*
American chestnut	Magnolia	Basswood	Birch
Ash	Oak	Maple	Cherry
Beech			Elm
Black locust			Hawthorn
Sassafras			Willow
Sycamore			
Walnut			
Yellow poplar			

[a]From Tryon and True (1964). Reproduced by permission of West Virginia Agricultural Experiment Station.

SUMMARY OF FROST TYPES AND DAMAGE TO FORESTS[a]

Characteristic	Advective frost	Radiation frost
Cause	Horizontal movement of cold air mass into a warmer area	Cooling of ground and adjacent air through loss of heat from longwave terrestrial radiation.
Condition of atmosphere	Windy, overcast, often with precipitation, including snow	Clear with still air, cloudless sky
Area involved	Large, may be hundreds of mi^2 and may be confined to mountain tops	Small, often only valley bottoms and lower slopes
Severity	Usually causes heavy damage if buds have broken	Variable. Damage may be very light to heavy
Elevation and damage	Damage may become heavier with increase in elevation	Damage usually greater on lower slopes and valleys
Uniformity	Degree of damage uniform within same elevation belt	Degree of damage spotty from area to area, and even within same locality
Frequency	Less common	More common
Time of occurrence	Early in spring, late in fall	First in fall, last in spring, and throughout frost danger period

[a]From Tryon and True (1964). Reproduced by permission of West Virginia Agricultural Experiment Station.

VARIATIONS IN FREEZING RESISTANCE OF NORTH AMERICAN TREE SPECIES AND MINIMUM TEMPERATURES AT NORTHERN LIMITS OF NATURAL RANGES OR ARTIFICIAL PLANTINGS

Relative Hardiness Classification	Representative Species	Average Minimum Temperatures at Northern Limits of Growth (°C) Natural Range	Artificial Plantings	Observed Freezing Resistance (°C)
Tender evergreen species	*Quercus virginiana*	−3.9 to −6.7	−9 to −12	−7 to −8
Hardy evergreen species	*Magnolia grandiflora*	−9 to −12	−18 to −20	−15 to −20
Hardy deciduous species	*Liquidambar styraciflua*	−18 to −20	−26 to −29	−25 to −30
Very hardy deciduous species	*Ulmus americana*	−37 to −46	−40 to −43	−40 to −50
Extremely hardy deciduous species	*Betula papyrifera*	below −46	below −46	below −80
	Populus deltoides	−32 to −34	−37 to −45	below −80
	Salix nigra	−32 to −34	−37 to −45	below −80

SOURCE: Reprinted, by permission, from Sakai and Weiser 1973, table 11. © 1973 by the Ecological Society of America.

TREES RATED ACCORDING TO DEGREE OF SNOW DAMAGE OBSERVED AT LAVA LAKE[a]

Tree species	Snow damage ratings, spring, 1964	Trees studied (%)
Western white pine	None	18.2
	Very light	54.5
	Light	18.2
	Moderate	9.1
	Severe	—
Western hemlock	None	33.3
	Very light	33.3
	Light	25.0
	Moderate	8.4
	Severe	—
Pacific silver fir	None	—
	Very light	57.1
	Light	35.7
	Moderate	7.2
	Severe	—
Douglas fir	None	—
	Very light	8.3
	Light	41.7
	Moderate	25.0
	Severe	25.0
Noble fir	None	—
	Very light	45.5
	Light	54.5
	Moderate	—
	Severe	—

[a]From Williams (1966). Reproduced by permission of U.S. Forest Service.

Average branch losses from 9 different species of deciduous trees from a heavy snow load.

Species	Number of trees	Tree Size (dbh in inches)	Diameter of broken branches in inches 0-3	3-6	6-9	9-12	12	Ave. Percent canopy loss/tree
Green Ash	22	6-36	2.0	0.1	—	1.1	—	3.6
Honeylocust	211	0-18	4.1	0.1	—	—	—	4.2
Cottonwood	52	6-48	7.2	2.4	0.4	0.2	—	10.2
Silver maple	14	6-48	7.2	2.5	1.0	—	—	10.7
Hackberry	144	0-12	14.0	—	—	—	—	14.0
Russian olive	86	0-24	11.6	5.8	—	—	—	17.4
Weeping willow	5	18-36	6.6	8.4	3.0	—	—	18.0
American elm	23	6-36	6.5	8.1	2.4	—	2.2	19.2
Siberian elm	15	6-36	9.7	21.1	0.7	—	—	31.5

SUSCEPTIBILITY OF TREES TO BREAKING BY ICE ACCUMULATION[a]

Species	Number examined	Percent injured little	Percent injured moderately	Percent badly broken
Salix babylonica	2	0	0	100
Betula alba	3	0	0	100
Betula lutea	5	0	0	100
Ulmus americana	111	6	10	84
Populus deltoides and hybrid poplars	34	9	41	50
Betula pendula	10	10	30	60
Acer saccharinum	117	11	21	68
Platanus occidentalis	6	17	33	50
Castanea dentata	11	27	46	27
Populus nigra var. *italica*	29	34.5	31	34.5
Pinus strobus	11	36	9	55
Prunus americana	29	38	17	45
Acer saccharum	102	41	26	33
Prunus sp. (Cherry)	26	42	16	42
Robinia pseudoacacia	11	55	9	36
Juniperus virginiana	88	55	19	26
Liriodendron tulipifera	7	57	43	0
Pyrus malus	37	73	16	11
Carya ovata	4	75	0	25
Tsuga canadensis	4	75	0	25
Acer negundo	8	75	25	0
Diospyros virginiana	21	76	24	0
Picea abies	39	77	18	5
Acer platanoides	9	77	23	0
Thuja occidentalis	29	79	14	7
Quercus alba	10	80	0	20
Salix discolor	7	86	14	0
Pinus sylvestris	7	86	14	0
Prunus sp. (Plum)	18	89	11	0
Catalpa speciosa	36	94	6	0
Pyrus communis	30	97	3	0
Juglans nigra	48	98	2	0
Pseudotsuga taxifolia	2	100	0	0
Pinus nigra	3	100	0	0
Magnolia tripetala	3	100	0	0
Gleditsia triacanthos	5	100	0	0
Ailanthus glandulosa	42	100	0	0

[a] From Croxton (1939). Reproduced by permission of the Ecological Society of America.

Table 1. WOODY PLANTS TOLERANT TO HERBICIDES

An [X] in the column indicates the herbicide can be safety used for that plant listed.

	ALANAP	BETASAN	CASORON	CHLORO IPC	DACTHAL	ENIDE	EPTAM	KERB	ORNAMENTAL WEEDER	PRINCEP	RONSTAR	SURFLAN	TREFLAN
Evergreens													
Narrowleaf													
Arborvitae	X		X	X	X	X			X	X	X	X	X
Chamaecyparis						X	X						
Eastern Red Cedar	X		X			X				X			X
Fir				X	X		X	X					
Fir, Balsam				X						X			X
Fir, Douglas								X		X			X
Fir, Fraser										X			
Hemlock				X		X	X		X	X			X
Juniper	X	X	X	X	X	X	X	X	X	X	X	X	X
Pine	X			X	X		X	X	X		X		
Pine, Austrian										X			X
Pine, Japanese Black													X
Pine, Mugo										X			
Pine, Red										X			X
Pine, Scotch										X			X
Pine, White										X			X
Spruce	X			X	X		X				X		
Spruce, Blue										X			X
Spruce, Norway										X			X
Spruce, White										X			X
Yew	X		X	X	X	X	X	X	X	X	X		X
Broadleaf													
Boxwood		X	X		X		X					X	X
Cherry Laurel						X							X
Euonymus				X		X			X		X		X
Firethorn		X	X			X						X	X
Holly	X	X	X		X	X	X	X	X		X		
Holly, Japanese							X						X
Japanese Pieris					X		X		X				X
Leucothoe			X				X						
Mahonia				X		X				X		X	
Mountain Laurel			X	X	X	X							X
Rhododendron	X		X	X	X	X	X	X	X				X
Deciduous Trees													
Ash			X		X	X					X		
Ash, White						X			X				X
Bald Cypress						X							X
Beech						X							
Birch			X	X	X	X					X		
Birch, European													X
Chinese Chestnut					X	X							X
Corktree, Amur			X										
Crabapple			X		X	X					X		X
Dogwood			X		X	X	X		X	X	X		X
Dogwood, Kousa													X
Elm			X		X								
Elm, American										X			
Elm, Siberian										X			

	ALANAP	BETASAN	CASORON	CHLORO IPC	DACTHAL	ENIDE	EPTAM	KERB	ORNAMENTAL WEEDER	PRINCEP	RONSTAR	SURFLAN	TREFLAN
Goldenraintree......			X										
Hackberry..........			X										
Hawthorn..........					X								
Honeylocust........										X			X
Linden.............			X				X						
London Planetree...													X
Magnolia...........			X	X	X		X		X				
Maple.............	X		X	X	X	X	X						
Maple, Norway......													X
Maple, Red.........									X				X
Maple, Silver........													X
Maple, Sugar.......						X							X
Mountain Ash.......			X										
Oak...............			X		X	X	X						
Oak, Pin...........													X
Oak, Red...........									X	X			X
Oak, Scarlet........													X
Poplar.............	X		X	X	X	X							
Redbud............					X	X							X
Russian Olive.......			X		X	X				X	X		
Sassafras..........									X				
Sweetgum.........					X	X							X
Sycamore..........					X	X							X
Tuliptree...........					X	X							X
Tupelo.............													X
Walnut.............			X		X	X							X
Willow.............			X		X	X							X
Deciduous shrubs													
Abelia.............		X			X								
Azalea.............	X	X			X	X			X				X
Azalea, Mollis.......			X										
Barberry...........			X	X	X	X	X			X	X	X	X
Beautybush........			X			X							
Cinquefoil..........					X								X
Cotoneaster........			X		X	X			X	X	X	X	X
Currant............						X							
Deutzia............			X		X								X
Euonymus, Winged..			X		X	X	X					X	X
Flowering Almond...			X										
Flowering Quince....			X										
Forsythia...........			X	X	X	X		X			X	X	X
Hibiscus...........						X							

2-4-D

SOFTWOODS	Tolerant	Intermediate	Sensitive
Colorado spruce (*Picea pungens*)		●	
Yew (*Taxus* sp.)		●	
Hemlock (*Tsuga* sp.)		●	

2-4-D

HARDWOODS	Tolerant	Intermediate	Sensitive
Boxelder (*Acer negundo*)			●
Norway maple (*Acer platanoides*)			●
Tree of heaven (*Ailanthus altissima*)			●
Birch (*Betula* sp.)			●
Hickory (*Carya* sp.)			●
American yellowwood (*Cladrastis lutea*)			●
Dogwood (*Cornus* sp.)			●
Ash (*Fraxinus* sp.)	●		
Sweetgum (*Liquidambar styraciflua*)		●	
Apple (*Malus* sp.)			●
Mulberry (*Morus* sp.)		●	
London planetree (*Platanus acerifolia*)			●
Pin oak (*Quercus palustris*)		●	
Red oak (*Quercus rubra*)		●	
Black oak (*Quercus velutina*)			●
Linden (*Tilia* sp.)			●

RELATIVE DROUGHT RESISTANCE OF SELECTED SPECIES[a]

Resistant	*Intermediate*	*Sensitive*
Ulmus parvifolia *Fraxinus pennsylvanica* *Pinus ponderosa* *Juniperus virginiana*	*Pinus resinosa* *Pinus strobus*	*Acer* spp. *Abies grandis*

[a]From Parker (1956). Reproduced by permission of the New York Botanical Garden.

THE PHYSIOLOGICAL STATES OF WILTING[a,b]

Type of wilting	*Frequency*	*Degree of turgor loss*	*Visible effects*	*Duration*
Incipient	Probably daily around mid-day, especially in summer	Slight and short-lived	None	Short. Recovery takes place when the transpiration rate falls slightly
Transient	Often, mainly on hot, dry, or windy days	More marked	Obvious drooping of leaves and perhaps of herbaceous stems	Short. Recovery takes place when transpiration is reduced, as at night
Permanent	Occasionally, chiefly during prolonged dry periods	Very severe	Marked drooping of leaves and often of herbaceous stems	Persists until soil moisture is replenished. So little water is available that deficits cannot be restored merely by reducing transpiration
Irreversible	Only in very prolonged dry periods	Complete, and permanent	Very severe drooping of softer parts, followed by withering	Permanent. Tissues have become so dessicated that virtually no water is absorbed even if supplied. Death follows

[a]From Knight (1965). Reproduced by permission of Dover Publications, Inc.
[b]Permanent and irreversible wilting might be considered "pathological" wilting.

Attempt to classify some trees according to their photoperiodical characteristics (after Nitsch and others in Lyr et al., 1967)

Species		Country of origin	Type
Acer pseudoplatanus	Sycamore maple	Europe	D ?
Acer rubrum	Red maple	North America	A
Acer saccharum	Sugar maple	North America	B ?
Aesculus hippocastanum	Horse chestnut	Europe	D
Alnus incana	Grey alder	Europe	A
Betula pubescens	Hairy birch	Europe	A
Betula lutea	Yellow birch	North America	A
Betula papyrifera	Paperbark birch	North America	A
Buxus sempervirens	Common box	South Europe	D
Catalpa speciosa	Indian bean	North America	A
Cornus florida	Flowering dogwood	North America	A
Eucalyptus bicostata			
E. niphophila and others	Australian Gum	Australia	C
Fagus grandifolia	American beech	North America	A ?
Fagus sylvatica	European beech	Europe	A+B
Ficus religiosa	Holy tree of Buddha	India	A
Fraxinus americana	White ash	North America	D
Juniperus horizontalis	Creeping juniper	North America	C
Larix decidua	European larch	Europe	A
Liriodendron tulipifera	Tulip tree	North America	A
Morus alba	White mulberry	China	A ?
Paulownia tomentosa	Royal paulownia	China	D
Phellodendron amurense		Asia	A ?
Picea abies	Norway spruce	Europe	B
Pinus sylvestris	Scotch pine	Europe	B
Pinus banksiana and many others	Pines		B
Platanus occidentalis	Plane tree	North America	A
Populus alba	White poplar	Europe	A
Populus nigra	Black poplar	Europe	A
Populus tremula and many others	Poplars		A
Prunus avium	Wild cherry	Asia	D
Pseudotsuga taxifolia	Douglas fir	North America	B
Quercus borealis maxima (Ashe)	Northern red oak	North America	B
Quercus stellata		North America	B
Quercus suber	Cork oak	South Europe	B
Rhododendron catawbiense		North America	B
Rhus typhina	Staghorn sumach	North America	A
Robinia pseudacacia	Locust	North America	A
Syringa vulgaris	Lilac	SE Europe	D
Thuja occidentalis	*Arbor vitae*	North America	C
Thuja plicata		North America	C
Tsuga canadensis	Hemlock	North America	A
Ulmus americana	White elm	North America	A
Viburnum opulus	Guelder rose	Europe	A
Viburnum prunifolium		North America	D
Various tropical woods and *Citrus* species			C

SYMPTOMS OF NUTRIENT ELEMENT DEFICIENCY[a]

Element	*Conifer seedlings*	*Hardwood seedlings*
Nitrogen	Foliage uniformly pale green, yellowish, or yellow; older foliage dying in some species. Stems somewhat reddish in young seedlings. Tree leaves often short	Leaves small, uniformly faded, green or yellowish. Shoots short and spindly. In later stages, hardwood leaves may become red or purple
Phosphorus	Leaves sometimes pale, turning brown at tops. Sometimes purpling, becoming necrotic. Youngest foliage may remain green	Leaves small, bluish-green, veins purplish. Basal leaves may abcise. Shoots thin, short, upright
Potassium	Leaves short, chlorotic, often brown tipped. Yellow tipping in some species In some species, older leaves dying, younger are green	Leaves scorched or chlorotic, on tips and margins. Leaves sometimes dark bluish-green, upward curling, with speckling. Dieback. Also reddening in some species
Magnesium	Leaves yellowing and later browning at tips. Sometimes purpling. Older foliage sometimes yellower than younger. Growth not seriously affected	Basal older leaves marginal interveinal chlorosis and necrosis, early deciduousness. Growth near normal except where deficiency very severe. Sometimes reddening
Calcium	Young needles yellow; all needles brown or yellow on tips; no buds developed. Leaves stunted near terminal bud in some cases	Young leaves distorted, tips hooked downward, and margins curled. Margins may show some chlorosis; some spotting and brown scorching. Leafdrop; dieback. Older leaves relatively dark green
Iron	Young needles bright yellow; no top buds developed	Young leaves straw colored. Top of trees may be straw colored, with leaves marginal tip burned. Growth not seriously affected in moderate deficiency
Zinc	Inwardly folding apical needles, yellow mottling. Later bronzing and short, stiff, dark-green needles	Whitish green chlorosis with somewhat greener main veins. Rosetting, shoots long and narrow. In nut trees, nuts have kernels not ripening normally
Boron	In pines: reduced growth and necrosis in tops and growing points of roots. Young needles dead near apical bud	Young leaves often small, twisted, and somewhat corky main veins. Rosetting, dieback and sapoozing. Mottled chlorosis in some
Manganese	Paleness, retarded growth, dying. Buds turning brown; needles becoming pale green or yellow at tips (*Pinus radiata*)	New leaves may be lighter green in interveinal areas, giving herringbone appearance. Spotting and necrosis may appear. Leafdrop; dieback
Copper	In pine: foliage bluish-green and tips of secondary needles dead; needles curved downward	Leaves of plum and apple whitish and soft. In peach, long and narrow leaves may be mottled green and white; irregular margins. Dieback
Molybdenum	Foliage becomes bluish in pine. No symptoms at first	In younger leaves: light-green chlorosis, but main and small veins green. Old leaves: marginal burning

[a]From Parker (1965). Reproduced by permission of the Institute for the Advancement of Science and Culture.

ELEMENTS ESSENTIAL FOR THE GROWTH AND DEVELOPMENT OF HIGHER PLANTS

Macronutrients	*Micronutrients*
Carbon	Iron
Oxygen	Boron
Hydrogen	Copper
Nitrogen	Zinc
Phosphorus	Molybdenum
Potassium	Manganese
Sulfur	Chlorine
Magnesium	
Calcium	

Some Woody Plants Susceptible to Iron Deficiency Chlorosis

Trees	Trees	Shrubs
American elm	Oak, black	Azalea
American holly	Oak, mossy cup	Forsythia
Bald cypress	Oak, pin	Hydrangea
Birch, canoe	Oak, red	Magnolia
Birch, yellow	Oak, swamp white	Rhododendron
Cherry, black	Oak, white	Rose
Cherry, mazzard	Oak, willow	
Cottonwood	Pine, jack	
Eucalyptus	Pine, ponderosa	
Flowering dogwood	Pine, white	
Horse chestnut	Sweetgum	
London plane	Walnut	
Maple, Norway		
Maple, red		
Maple, silver		
Maple, sugar		

Sensitivity of 40 plants to security lighting:

High

Acer ginnala, Amur maple
Acer platanoides, Norway maple
Betula papyrifera, Paper birch
Betula pendula, European white birch
Betula populifolia, White birch
Catalpa bignonioides, Catalpa
Cornus alba, Tatarian dogwood
Cornus florida, Dogwood
Cornus stolonifera, Red-osier dogwood
Platanus acerifolia, Sycamore
Ulmus americana, American elm
Ulmus pumila, Siberian elm
Zelkova serrata, Zelkova

Intermediate

Acer rubrum, Red maple
Acer palmatum, Japanese maple
Cercis canadensis, Redbud
Cornus controversa, Giant dogwood
Cornus sanquinea, Bloodtwig dogwood
Gleditsia triacanthos, Honeylocust
Halesia carolina, Silver-bell
Koelreuteria paniculata, Goldenrain-tree
Ostrya virginicana, Ironwood
Phellodendron amurense, Cork-tree
Sophora japonica, Japanese pagoda-tree
Tilia cordata, Littleleaf linden

Low

Carpinus japonica, Hornbeam
Fagus sylvatica, European beech
Ginkgo bilola, Ginkgo
Ilex opaca, American holly
Liquidamber styraciflua, Sweetgum
Magnolia grandiflora, Bull bay
Malus boccata, Siberian crabapple
Malus sargenti, Sargent's crabapple
Pinus nigra, Austrian pine
Pyrus calleryana, Bradford pear
Quercus palustris, Pin oak
Quercus phellos, Willow oak
Quercus robur, English oak
Quercus shumardi, Shumard oak
Tilia x europaea, European linden

Plants have been listed alphabetically and are not grouped in descending order of sensitivity. A high, intermediate, or low rating identifies the relative responsiveness of the plants to security lighting. Plants with low sensitivity would be preferred in areas with security lighting.

Sensitivity of Woody Plants to Artificial Light[a]

High	Intermediate	Low
Acer ginnala (Amur maple)	*Acer rubrum* (red maple)	*Capinus japonica* (Hornbeam)
Acer platanoides (Norway maple)	*Acer palmatum* (Japanese maple)	*Fagus sylvatica* (European beech)
Betula papyrifera (Paper birch)	*Cercis canadensis* (Redbud)	*Ginkgo-bilola* (Ginkgo)
Betula pendula (European white birch)	*Cornus controversa* (Giant dogwood)	*Ilex opaca* (American holly)
Betula populifolia (White birch)	*Cornus sanquinea* (Bloodtwig dogwood)	*Liquidamber styraciflua* (Sweetgum)
Catalpa bignonioides (Catalpa)	*Gleditsia triacanthos* (Honeylocust)	*Magnolia grandiflora* (Bull bay)
Cornus alba (Tatarian dogwood)	*Halesia carolina* (Silver-bell)	*Malus boccata* (Siberian crabapple)
Cornus florida (Dogwood)	*Koelreuteria paniculata* (Goldenrain-tree)	*Malus sargenti* (Sargent's crabapple)
Cornus stolonifera (Red-osier dogwood)	*Ostrya viginicana* (Ironwood)	*Pinus nigra* (Austrian pine)
Platanus acerifolia (Sycamore)	*Phellodendron amurense* (Cork-tree)	*Pyrus calleryana* (Bradford pear)
Ulmus america (American elm)	*Sophora japonica* (Japanese pagoda-tree)	*Quercus palustris* (Pin oak)
Ulmus pumila (Siberian elm)	*Tilia cordata* (Littleleaf linden)	*Quercus phellos* (Willow oak)
Zelkova serrata (Zelkova)		*Quercus robur* (English oak)
		Quercus shumardi (Shumard oak)
		Tilia x europaea (European linden)

[a] From Cathey and Campbell (1975).

Species Potentially Resistant to Landfill Gases

Green ash[abc]	Cottonwood[d]
Sour gum[ab]	American sycamore[d]
Sweet gale[ab]	Juniper[d]
White ash[ad]	Pussy willow[d]
Red cedar[ad]	Silver maple
White willow[ad]	Thornless honeysuckle
Red maple[d]	

[a]Transports O_2 to roots

[b]Oxidizes rhizosphere

[c]Initiates 2 deg. roots

[d]Tolerates flooding

Shade tolerance of some trees (after Baker, Lyr and other authors)

Very shade tolerant	
Abies balsamea	*Acer saccharum*
Taxus baccata	*Carpinus betulus*
Thuja plicata	*Cornus florida*
Tsuga canadensis	*Cornus mas*
	Corylus avellana
	Fagus sylvatica
	Fagus grandiflora
Shade-tolerant	
Abies concolor	*Acer pennsylvanicum*
Picea glauca	*Acer rubrum*
Picea rubens	*Alnus glutinosa*
Picea sitchensis	*Fraxinus excelsior*
Pinus nigra	*Fraxinus ornus*
Pseudotsuga taxifolia	*Tilia americana*
	Tilia parvifolia
Intermediate	
Picea abies	*Betula allegheniensis*
Pinus cembra	*Fraxinus americana*
Pinus lambertiana	*Quercus alba*
Pinus monticola	*Quercus borealis maxima*
Pinus strobus	
Sequoia sempervirens	
Shade-intolerant	
Pinus ponderosa	*Betula papyrifera*
Pinus resinosa	*Liriodendron tulipifera*
Pinus taeda	
Very shade-intolerant	
Larix decidua	*Betula pendula*
Larix laricina	*Betula populifolia*
Pinus banksiana	*Populus tremuloides*
Pinus palustris	*Robinia pseudacacia*
Pinus silvestris	

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Plants have been listed alphabetically and are not grouped in descending order of sensitivity. A high, intermediate, or low rating identifies the relative responsiveness of the plants to security lighting. Plants with low sensitivity would be preferred in areas with security lighting.

Root system of some trees (after several authors)

Generally having a tap root system

Abies alba
Carya illinoensis
Carya ovata
Fraxinus excelsior
Juglans nigra
Juniperus communis
Juniperus virginiana
Larix decidua
Larix kaempferi
Liriodendron tulipifera
Maclura pomifera
Pinus palustris
Pinus ponderosa
Pinus sylvestris
Pyrus communis
Quercus alba
Quercus macrocarpa
Quercus petraea
Quercus robur
Sorbus domestica
Sorbus torminalis
Sophora japonica
Ulmus glabra
Ulmus laevis
Ulmus minor

Generally having a lateral root system (large, shallow and flat spreading below the surface roots)

Acer campestre
Acer saccharinum
Acer saccharum
Alnus incana
Betula papyrifera
Betula pendula
Betula pubescens
Catalpa species
Elaeagnus angustifolia
Fagus grandifolia
Fagus sylvatica
Larix laricina
Liquidambar styraciflua
Malus silvestris
Nyssa sylvatica
Picea abies
Picea omorica
Pinus banksiana
Pinus strobus
Populus
Salix

Having an intermediate root system (wide spreading and deep lateral roots)

Acer negundo
Acer platanoides
Acer pseudoplatanus
Aesculus hippocastanum
Caragana arborescens
Carpinus betulus
Fraxinus pennsylvanica
Ginkgo biloba
Gleditsia triacanthos
Pinus nigra
Platanus hybrida
Platanus occidentalis
Prunus avium
Pseudotsuga menziesii
Quercus borealis
Quercus pseudoturneri
Robinia pseudacacia
Taxus baccata
Tilia americana
Tilia cordata
Tilia euchlora
Tilia tomentosa
Tilia platyphyllos

Species in Landfill Screening Experiment

- American basswood
- American sycamore
- Bayberry
- Black gum
- Black pine
- Euonymus
- Ginkgo
- Green ash
- Honey locust
- Hybrid poplar
- Japanese yew
- Mixed poplar
- Norway spruce
- Pin oak
- Red maple
- Rhododendron
- Sweet gum
- Weeping willow
- White pine

Trees growing well under city conditions

Common name	Latin name	Fall color	Flowers	Size
American hackberry	*Celtis occidentalis*	Not showy	Not showy	Large
Callery pear	*Pyrus calleryana*	Orange-yellow	White	Medium
Crabapple	*Malus* species	Not showy	White-red	Small-medium
European ash	*Fraxinus excelsior*	Not showy	Not showy	Medium
European hornbeam	*Carpinus betulus*	Not showy	Not showy	Small
Golden-rain-tree	*Koelreuteria paniculata*	Not showy	Yellow	Small
Green ash	*Fraxinus pennsylvanica*	Yellow	Not showy	Large
Hedge maple	*Acer campestre*	Not showy	Not showy	Medium
Japanese pagoda	*Sophora japonica*	Not showy	White	Medium
Japanese zelkova	*Zelkova serrata*	Not showy	Not showy	Medium
Lavalle hawthorn	*Crataegus* x *lavallei*	Not showy	White	Small
Littleleaf linden	*Tilia cordata*	Not showy	Not showy	Medium
London plane-tree	*Platanus acerifolia*	Not showy	Not showy	Large
Norway maple	*Acer platanoides*	Yellow	Yellow-green	Medium
'Ohio Pioneer' hawthorn	*Crataegus punctata* 'Ohio Pioneer'	Not showy	White	Small
Plum-leaved hawthorn	*Crataegus prunifolia*	Orange	White	Small
Blireiana plum	*Prunus blireiana*	Wine	Pink	Small
Red oak	*Quercus rubra*	Not showy—red	Not showy	Large
River birch	*Betula nigra*	Not showy	Not showy	Medium
Sargent cherry	*Prunus sargentii*	Orange	White	Medium
Serviceberry (apple)	*Amelanchier* x *grandiflora*	Orange	White	Small
Silverbell (mountain)	*Halesia monticola*	Not showy	White	Small
Silver linden	*Tilia tomentosa*	Yellow	Not showy	Medium
Silver maple	*Acer saccharinum*	Not showy	Not showy	Large
Sugar hackberry	*Celtis laevigata*	Not showy	Not showy	Large
Thornless honeylocust	*Gleditsia triacanthos 'Inermis'*	Not showy	Not showy	Large
Washington hawthorn	*Crataegus phaenopyrum*	Orange	White	Small
White ash	*Fraxinus americana*	Yellow-red	Not showy	Large
'Winter King' hawthorn	*Crataegus viridis* 'Winter King'	Not showy	White	Small

□