HOW WIND AFFECTS TREES

by WILLIAM R. CHANEY, Professor of Tree Physiology
Department of Forestry and Natural Resources
Purdue University, West Lafayette, IN 47907

Who has seen the wind?
Neither you nor I:
But when the trees bow down their heads,
The wind is passing by.

—Christina Rossetti

Wind in trees does more than rustle leaves. The gentle breezes, prevailing winds, and cyclonic occurrences that arise from daily and seasonal changes in solar heating all affect the growth, form, and very survival of trees. Arborists need to be aware of the impact of wind on trees because it affects the quality of nursery stock and subsequent growth of trees planted in the landscape. Wind is an important factor that should be considered when selecting the right tree for a planting site.

WHAT IS WIND?

The Greeks and Romans were mystified by wind and were justly terrified of its destructive power. Aeolus, King of the Winds, was one of the few gods in their pantheon who was considered to actually live on the earth. Since his responsibilities were so vast, he had four assistants, the north, south, east, and west Winds. Today we understand what causes the wind, but some of its effects on trees are less well known.

Wind is air in motion. Air moves from a region of high pressure to one of low pressure, the difference due to unequal heating of the atmosphere. The same principle accounts for air escaping from a balloon that is blown-up and then released. The stretched wall of the balloon accounts for the pressure difference inside and outside the balloon. For wind, it is the heat from the sun that causes air masses to have different pressures. Equatorial regions of the earth receive more direct sunlight and are warmer than regions to the north or south. The warm air rises creating a low-pressure void that is filled by high-pressure cool air flowing from the poles toward the equator. At the equator the air is warmed, rises, and returns toward the poles. This pattern is modified by two factors. One is the greater speed of the earth's rotation at the equator than at the poles because of the longer circumference at the equator. The other factor is the difference in temperature of oceans and

Continued on page 3

land masses. In the northern hemisphere the wind blowing from the north toward the equator is deflected by the rotation of the earth to become northeasterly and is known as the northeast trade wind. In contrast, the prevailing wind in the southern hemisphere is from the southeast.

Continents in temperate zones tend to become very hot in summer and the low pressures, caused by the rising warm air, produce winds that blow inland from surrounding seas. The cold of winter reverses the pressure, and winds tend to blow out to sea. Daily changes in wind direction occur in the same manner as seasonal ones, causing more local effects. In summer, the land is warmer than the sea during the day and colder at night, causing a breeze to blow landward during the day and seaward at night. These land and sea breezes can affect trees as far as 30 miles from the shore. Similar changes in seasonal and daily air-flow patterns occur between mountain tops and valleys.

EFFECTS OF WIND ON TREES

Destructive Winds. The strongest wind ever reliably recorded on the surface of the earth was 231 mph on Mount Washington in New Hampshire. Considerably stronger winds, however, are thought to occur near the center of tornadoes. The destructive force of wind can indeed be awesome. Hurricanes and tornadoes can easily leave whole forests and urban areas littered with uprooted trees and broken branches. Nearly two million cubic yards of trees and broken branches, about 10% of the total tree residues removed from urban areas each year, result from damage caused by strong winds, hurricanes, and tornadoes. The costs to local governments, utility companies, and private landowners for cleanup and disposal are staggering.

Catastrophic events caused by wind actually have an ecological role in natural landscapes by opening gaps in forests that provide for a diversity of herbs, trees, and animals. When considered collectively, the amount of land area disturbed is surprisingly large. For example, presettlement survey records in Wisconsin reveal a widespread pattern of catastrophic windthrow covering 11,900 acres annually in the northeastern part of the state. Twenty-one percent of mortality in a mature American beech-southern magnolia forest in southeast Texas was attributed to wind. During a 15-year period of observations in New Jersey forests, twice as many trees were killed by wind than by all other causes. In temperate rain forests dominated by western hemlock along the northwest coast of North America, windthrow is the most frequent form of natural disturbance and an important force in the selection of trees and plants that occur there. Other reports of large-scale disturbance of forests by winds in many regions of the world suggest that severe winds are an alternative mechanism for forest turnover in humid climates where fires are rare.

Strong winds cause trees to sway, pulling and stretching their roots. The movement disrupts root-soil contact, decreasing water absorption and increasing the severity of water stress in trees. The leaf biomass of 12 different western conifers was found to be reduced by as much as 36% by occasional wind storms. Although major canopy damage of this magnitude appears to occur only at 9 to 16 year intervals, such damage obviously affects growth and adds an additional measure of uncertainty to forest productivity estimates. In hardwoods, it is common for 1 to 3 percent of the leaf surface area to be ripped, damaged, or literally torn away by wind every year. The durability of leaves buffeted about by the wind and exposed to other factors of the environment is amazing, but it is not surprising that almost no leaves survive an entire growing season completely undamaged.

Trees growing in dense forest stands become very prone to windthrow when surrounding trees are removed, exposing the remaining ones to the full force of the wind. A crucial factor in determining a tree's resistance to breakage or uprooting is the air drag or sail effect of the canopy. Deciduous hardwoods seem to suffer windthrow more commonly during the growing season when they have leaves to catch the wind. However, many trees such as sycamore (*Platanus occidentalis*), yellow poplar (*Liriodendron tulipifera*), sweetgum (*Liquidambar styraciflua*), and black locust (*Robinia pseudoacacia*) have

Continued on page 5

Tree toppled by wind, luckily missing the house and utility lines.

Flattened petiole of cottonwood allows the leaves to reconfigure in strong wind, reducing damage.

leaves that curl or cluster together in strong wind, reducing the exposed surface area and wind drag on the canopy.

Another adaptation to strong wind is a flattened petiole, such as that of aspen, that causes the leaves to quake in even the slightest breeze. In strong wind, the flat petiole permits the leaves to twist easily and re-configure, accounting for the resistance of aspen and other poplars to wind damage. Many conifers are more susceptible than broad-leaved trees to damage by wind because they have foliage throughout the year. However, the steeple-shaped crown of spruces and firs adapted to mountainous areas, reduces the air drag by the canopy and improves the chance for these trees to survive the frequent strong winds.

Steeple-shaped canopy of subalpine fir reduces wind drag.

Prop roots extending from trunk of tropical tree help stabilize the tree.

Open grown, strongly tapered trees common in urban areas are most stable. However, poor construction practices that allow excessive compaction, trenching, removal, or filling of soil around the base of trees can damage root systems, making trees more susceptible to windthrow. Restricted root development of trees growing on shallow or waterlogged soil also increases the likelihood of windthrow. If heavy rains precede high winds and soften the soil, uprooting is more likely than if the soil is dry. In dry soil, stems often break-off before the roots fail. Overmaturity and root- or butt-rot diseases also increase the chance for wind to break the stem near ground level.

Role in Soil Formation. Soil upheaval as trees are blown-over with their larger roots intact, "arborturbation", creates mounds and pits that influence soil formation, plant succession, and mycorrhizal development in natural forests. On relatively well-drained sites in New Zealand, for example, normal development of a yellow-brown soil profile was altered towards organic soil in the pits and leached soil on the mounds. Mounds were colonized more rapidly than pits by ground-cover plants. Wet soils in pits promoted tree diseases and inhibited mycorrhizal development. Pits and mounds usually become unrecognizable on the land surface within about 100 years after disturbance, but their earlier existence contributed to the soil pattern found in these forests.

MODERATE WINDS

Although not as dramatic as the effects of gale force winds, gentle breezes and prevailing winds also influence trees in subtle as well as quite obvious ways. The rate of heat loss from leaf and twig surfaces, gas exchange through stomates, and even the growth in girth of tree trunks can be influenced by

Continued on page 6

Buttresses supporting tree in shallow tropical soil.

Wind sculptured divi divi tree that epitomizes the wind swipt coast of Aruba.

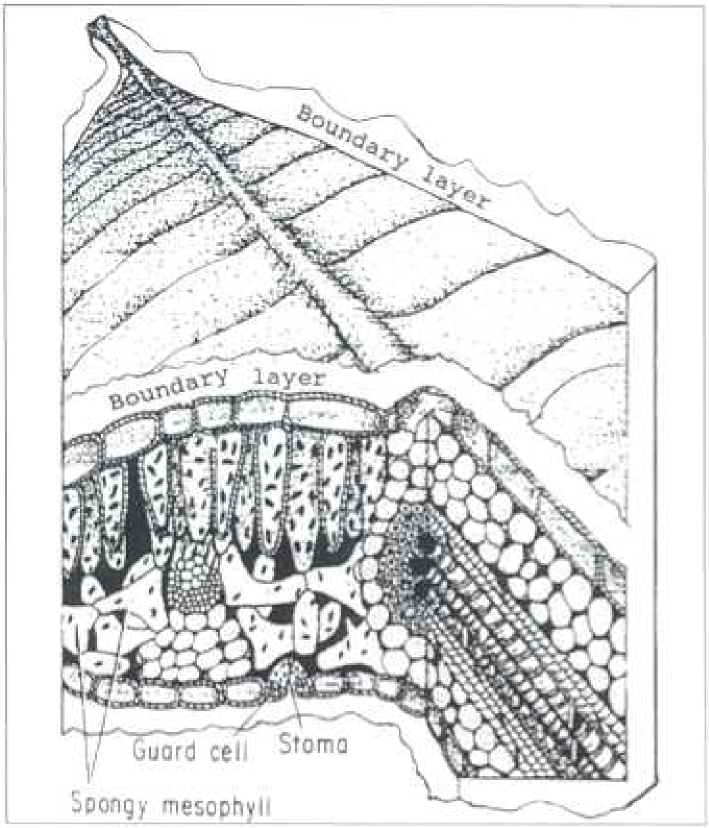

Figure 1. Cross section of a leaf showing boundary layer.

HOW WIND AFFECTS TREES *Continued*

mild winds. Moderate winds have distinct effects in sculpting the very shape of trees.

Boundary Layer. There is a layer of still air surrounding leaves, or any surface for that matter, called the boundary layer (Figure 1). This layer is important in the heat economy and gas exchange of leaves. The thicker the boundary layer the greater the resistance to both transfer of heat, and movement of carbon dioxide and water vapor into and out of leaves. The thickness of the boundary layer depends upon the size and shape of a leaf, the presence or absence of hairs (trichomes) on its surface, and above all, on the speed of air movement around the leaf. Large, broad leaves have a thicker boundary layer than narrow leaves or those with deeply indented lobes on the leaf margin. Surface appendages like trichomes increase the thickness of the boundary layer. In still air, the boundary layer can be several millimeters thick, while a moderate wind will sweep it away entirely.

Heat Exchange. In very still air during warm weather a tree is enclosed in a superheated envelope of boundary layer air next to its surface that resists the loss of heat by conduction. Wind reduces or removes the boundary layer, increasing the rate of cooling just as a breeze has a cooling effect on us. In cold weather, conductive heat loss is even greater.

The direction of heat conduction is usually away from the surface of tree parts, but if the plant surface is cooler than the air, the direction of heat transfer is reversed. Once a leaf or twig is at air temperature, wind will tend to maintain this equilibrium by both removing and adding heat. Consequently, wind will not increase cold injury in trees if they can tolerate the air temperature. In fact, wind can be a benefit and will keep exposed tree parts at air temperature when they might have been further supercooled by radiation loss under clear-sky conditions. However, in areas where the ground freezes in winter, wind can be injurious by increasing moisture loss and causing winter burn by excessively drying tissues, particularly in conifer needles.

Leaf Gas Exchange. Effects of wind on transpiration are complex. Mild wind reduces the thickness of the boundary layer and removes the moisture-laden air from around stomatal openings, replacing it with dryer air and increasing the rate of transpiration. Wind influence is greatest when humidity is low and soil moisture adequate. When relative humidity is near saturation, wind has less effect on transpiration because air moved to leaves from the surrounding area already has a higher moisture content and does little to alter the diffusion gradient from a leaf to the air around stomatal openings. In dry soil, stomatal closure induced by water stress becomes the dominant resistance to water loss by transpiration and removal of the boundary layer by wind has practically no influence.

Violent shaking of leaves in some species causes stomates to close, reducing transpiration. Stomates also may close in persistent winds due to dehydration of their guard cells. Under intense sunlight, when leaves are warmer than the air, even mild breezes, which should increase transpiration, may actually decrease it by cooling leaves and reducing the vapor pressure gradient that drives moisture loss. Plants exposed to protracted periods of wind may show permanently increased rates of transpiration. This is almost certainly due to mechanical damage of the leaf surface and the stomates.

Under calm daylight conditions, the level of CO_2 in a tree canopy drops below that in the surrounding atmosphere as the gas moves into leaves and is used in photosynthesis. A slight breeze will mix the air and replace some of the CO_2, but if the CO_2 level in the leaf canopy is to be maintained, wind speed will need to be about 12 mph. Winds of this speed may increase photosynthesis by 10 to 20 percent if other factors are not limiting. Unfortunately, respiration also may increase by 20 to 40 percent in moderate winds. This increase is due to effects on stomatal gas exchange or in response to leaves being ripped or otherwise damaged.

Species vary in their response to wind. Most rhododendrons (*Rhododendron sp.*), for example, are sensitive to moderate wind and react by closing their stomates, reducing loss of water by transpiration to less than that lost in still air. In contrast, trees such as larch (*Larix sp.*) or alder (*Alnus sp.*) under the same wind conditions maintain open stomates and continue to photosynthesize and transpire. Stomatal closure may completely inhibit photosynthesis without eliminating water loss because the leaf cuticle of most trees is more permeable to water than to CO_2. Table 1 lists a few commonly planted trees and shrubs that do not tolerate prolonged exposure to wind.

Continued on page 7

Table 1.

Some Woody Plants That Do Not Tolerate Wind

Acer circinatum - Vine maple
Acer davidii - David maple
Acer grosseri - Snake-skin maple
Acer japonicum - Fullmoon maple
Acer palmatum - Japanese maple
Asimina triloba - Pawpaw
Calocedrus decurrens - California incense-cedar
Camellia sp. - Camellias
Chamaecyparis lawsoniana - Port-Orford-Cedar
Cornus florida - Flowering dogwood
Cornus kousa - Chinese dogwood
Cotoneaster frigidus - Himalayan cotoneaster
Cotoneaster lacteus - Milky cotoneaster
Cryptomeria japonica - Japanese-cedar
Franklinia alatamaha - Franklin-tree
Ilex sp. - most evergreen Holly
Laburnum sp. - Goldenchain tree
Magnolia acuminata - Cucumbertree
Magnolia fraseri - Fraser magnolia
Magnolia hypoleuca - Japanese magnolia
Magnolia macrophylla - Bigleaf magnolia
Magnolia sieboldii - Oyama magnolia
Magnolia tripetala - Umbrella magnolia
Oxydendrum arboreum - Sourwood
Pinus wallichiana - Himalayan pine
Podocarpus macrophyllus - Yew podocarp
Rhododendron sp. - most Rhododendrons
Sequoia sempervirens - Coast redwood
Sequoiadendron giganteum - Giant sequoia
Stewartia sp. - Stewartias
Taxus sp. - Yews
Thuja sp. - Arborvitae
Torreya sp. - Nutmegs
Tsuga sp. - Hemlocks
Viburnum acerifolium - Mapleleaf viburnum
Viburnum alnifolium - Hobblebush
Viburnum davidii - David viburnum
Viburnum japanicum - Japanese viburnum
Viburnum odoratissimum - Sweet viburnum
Vibunrum plicatum - Japanese snowball
Vibrunum rhytidophyllum - Leatherleaf viburnum
Viburnum sieboldii - Siebold viburnum
Viburnum suspensum - Sandankwa vibrunum
Viburnum tinus - Laurestinus viburnum
Viburnum utile - Honan viburnum

Source: Harrison L. Flint, Landscape Plants for Eastern North America, John Wiley & Sons, 1997.

Shoot and Trunk Growth. A tree stem must be free to move or flex for proper development. The diameter of the lower trunk is greater in free-swaying trees than in those prevented from moving. Free-swaying trees also are shorter than those held rigidly or protected. The effect of movement on tree form is quite apparent in the rounding-over of the silhouette of a dense woodlot canopy. The trees along the edges are shorter due principally to the greater swaying of trees on the perimeter than of those protected from winds within the stand. The wind action results in a redistribution of growth such that the trees are shorter with more tapered trunks on the edge of the woods. Similarly, isolated trees in landscape situations are normally shorter and more tapered than their forest grown counterparts. The regulatory control of growth distribution in a tree is complex and not completely understood. However, it appears that the stress of movement in a tree stem induces production of the hormone ethylene known to have important roles in growth control.

Cross-sections of tree stems exposed to wind from one direction often are elliptical because more cambial activity occurs on the leeward side. In fact, secondary growth may cease completely on the windward side of the trunk and increase on the leeward side. An extreme illustration is a section of trunk taken from a Monterey cypress that grew on Cypress Point, just north of Carmel Bay in California. It was 74 inches in the diameter that grew parallel to the prevailing wind, but was only 9 inches in the opposite diameter. Only 50 growth rings were formed on the windward side of the section, but the leeward side had 304 rings.

Root systems also tend to form more structural root mass on the leeward side when exposed to persistent prevailing winds from one direction. This adaptive growth in response to wind movement improves the rigidity of the soil-root plate and counteracts the increasing vulnerability to windthrow as a tree grows in height. Observations in a white spruce stand that was thinned revealed an immediate increase in thickening of structural roots of the trees remaining. However, there was a four-year delay before an increase in stem diameter occurred.

To avoid abnormal development, staking newly planted trees should not be done unless absolutely essential. On windy sites with heavy soils, it may be necessary to stabilize the tree with stakes and guys for a few months to prevent young roots from being damaged as they grow into the surrounding soil. Once sufficient root growth has anchored a newly planted tree in the soil, the guys should be removed. Trees that are guyed for extended periods are unstable and often topple in the wind after the support is removed. Conventional nursery practices of staking and severely pruning lateral branches of container-grown trees tend to produce spindly trees that often are unstable when planted in the landscape. Better quality trees can be grown by eliminating staking in the nursery, leaving lateral branches on the stem, and spacing containers so the tree tops are free to move in the wind.

Continued on page 8

Reaction Wood. Trees tilted by the wind, even if only slightly moved from a vertical orientation, produce modified cells along the bole called reaction wood. Reaction wood of broad-leaved trees, which occurs on the upper side of tilted tree trunks, is called tension wood. The reaction wood that forms in conifers, called compression wood, occurs on the lower side of inclined trees. Reaction wood creates stresses and strains in the trunk that tend to bend the tree back to its upright position over a period of years. Lumber cut from trees with reaction wood has several commercially undesirable characteristics such as a tendency for increased shrinkage, warping, and weakness.


Single-staked trees in a nursery, a practice with questionable benefit.

When a tree is tilted from its upright position, growth regulators are redistributed and account for the altered development of cells in the wood. Several hormones are probably involved, and auxin plays a primary role. When a tree is tilted, auxin moves to the lower side of the stem, resulting in a concentration gradient from the upper to the lower side. Compression wood formation in conifers is stimulated by high auxin levels, whereas in hardwoods the low auxin level on the upper side of the stem induces tension wood to form. There is evidence that the hormone ethylene also has an important regulatory role in reaction wood formation, since it is produced in response to the stress in a tree's stem due to its leaning. Auxin and ethylene are known to interact in the regulation of numerous growth processes.

Buttress Formation. Even more dramatic effects of wind on tree form occur in the tropics. Here, the trunks of trees commonly develop enlarged bases or fluted buttresses. These structures effectively support large trees on shallow soils where anchorage by the roots is poor. Buttresses provide the maximum support for the least amount of wood, similar to a metal I-beam. They also increase the leverage required for overturning a tree by moving the "hinge point" of the root system further from the base of the tree, creating a broad platform that minimizes toppling in the wind. Other tropical trees have stilt or prop roots that emerge several feet up the trunk and grow down to the forest floor, providing additional support against the wind.


Krummholz resulting from strong winds and severe weather at high elevation in the Rocky Mountains.

Sculpting Influence. When branches are continually bent in one direction by prevailing winds, they become "wind trained" and hold their position permanently. Some branches grow completely around the trunk from the windward to the leeward side. More likely however, new growth is so desiccated on the side of a tree facing a prevailing wind that it is killed before it can develop. These lopsided trees with branches extending from only one side are called "flag trees" because they resemble a flag fully extended from its pole by the wind.

Wind that carries sand or particles of ice and snow is a particularly strong abrasive force that often erodes away the buds on the windward side of trees. On the leeward side, the new shoots are protected by the tree and growth continues there, resulting over a period of time in asymmetric trees of amazing and contorted shapes. Such disfigured trees, called krummholz (meaning crooked tree), are commonly found in exposed places at high altitudes in the mountains where otherwise upright trees are gnarled and twisted in a life-long struggle against crippling conditions. In the Rocky Mountains, altitudinal differences in wind velocity are relatively small during the summer, but in the winter the force of the wind at the upper timberline increases sharply. Here, Englemann spruce (*Picea englemannii*) are both dwarfed and misshapen. Their lower branches form a low mat that is protected from desiccation by snow cover that accumulates early in the autumn.

A fascinating example of wind effects on trees occurs in "wave forests" at high altitudes in several mountain ranges throughout the world. Here clumps of spruce and fir, referred to as tree islands, are widely scattered in a landscape dominated by alpine tundra. However, they behave less like islands and more like sailboats running before the wind. Exposed stems and needles on their windward sides die in winter because of physiological drought or physical damage, whereas shoots and needles on their leeward sides survive in the protection of upwind branches and wind-drifted snow. Prostrate branches protected by snow and buried by litter develop adventitious roots and produce new shoots that slowly extend

Continued on page 10

the leeward side of the tree island. This new growth is counterbalanced by the death of trees exposed to the withering wind on the opposite side. As a tree island migrates across the landscape, at a barely perceptible rate of 1 to 2 inches annually, it leaves a trail of dead stems and branches behind. These disintegrate with time, but are visible as scattered wood fragments for as much as 50 feet windward of living segments of a tree island. Some species do not reproduce by stem layering, and thus tree islands of these species remain anchored in their original position on the landscape.

Asymmetric growth, matted vegetation, and sheared tree tops seen along the sea coasts are likewise produced by wind to some extent, but in this case an added factor plays a part. The wind picks up ocean spray as it blows over the breaking waves, carrying the salty mist inland for distances up to several miles. Trees near the coast are sprayed lightly almost daily, and few coastal trees are completely tolerant to the drying effects of salt spray.

Role in Reproduction. Wind plays a direct role in transporting pollen, fruits, and seeds. Nearly all conifers rely on wind pollination, as do some hardwood trees including cottonwoods (*Populus sp.*), oaks (*Quercus sp.*), ashes (*Fraxinus sp.*), elms (*Ulmus sp.*), hickories (*Carya sp.*), and sycamores (*Platanus sp.*). Pollen grains of these trees are light or, as in conifers, have bladder-like wings that increase their buoyancy. The quantities of pollen produced by wind pollinated trees is enormous. Each male cone of black pine produces about 1.5 million pollen grains and a male cone of common juniper can produce 400,000 grains. Although fewer pollen grains are produced by flowers of hardwood trees, the numbers are still staggering.

Wind dissemination of fruits and seeds is aided by structural modifications. For example, hairs attached to seeds of willow, cottonwood, and sycamore allow them to float considerable distances. Wings are obvious on seeds and fruits of many conifers, maple, yellow poplar, basswood, sweetgum, and birch. Many winged fruits do not travel far because of their size, but the gliding or spinning imparted by their appendages is sufficient to assure transport beyond the shading and competitive effects of the parent tree.

Copious quantities of pine pollen depend on wind to carry it to receptive female cones.

The amount of pollen in the air and the distance tree seeds can be blown are obviously of great ecological importance for perpetuation of the species in natural stands. In urban areas where most trees are planted in selected locations, wind-blown pollen and seeds are not necessary for regeneration, but instead become somewhat of a nuisance. In some areas sidewalks, porches, floors, tables, and even pets may be dusted with pollen. People with hay fever suffer from even small quantities of pollen in the air. Seeds are blown into gutters, yards, and flower beds where they frequently germinate, producing weed trees.

Transport of Fungal Spores, Insects, and Pollutants. Fungal diseases are spread among landscape trees by wind-carried spores. The diseases often reduce the aesthetic value of trees or result in a weakened condition that predispose them to damage by strong winds. It is estimated that a large fruiting body of *Fomes applanatus*, a heart rot fungi, may produce 5 trillion spores, discharged at a rate of about 30 billion a day for 6 months. A single cedar apple rust gall was reported to produce nearly 7.5 trillion basidiospores.

A few insects that threaten trees are spread by the wind. Gypsy moth larvae, for example, hang on silk threads from the canopy of an infested tree and are blown by the wind to another tree. As a consequence, this destructive insect is advancing its range at a rate of about 13 mile each year in the eastern and central U.S.

Air pollutants too are carried by the wind and frequently are transported great distances from their source. For example, most of the air pollutants impacting trees in Scandinavian countries are transported by the prevailing winds from the industrialized regions of England and central Europe. Local wind stirring in tree canopies accelerates absorption of transported gaseous pollutants by decreasing the thickness of the leaf boundary layer and thus reducing the resistance to diffusion of the toxins into leaves.

APPLICATION TO ARBORISTS

It is clear that moderate winds influence many aspects of tree growth, even at times altering a tree's shape and form. Strong winds damage trees in urban areas and are an important ecological factor in native forests. Wind is one of the most important environmental factors influencing the work of arborists because it affects trees from pollination through all phases of growth and is often a cause of damage and death. There are a few practices arborists can employ to reduce the chance of wind damage to trees. Of course, planting trees with brittle wood such as silver maple or Chinese elm should be avoided. Planting sites should be selected so that there is room for trees to develop adequate root systems. Trees known to be intolerant of persistent wind should not be planted in exposed, windy sites. Regularly pruned trees will withstand strong winds better than those with dense canopies and dead, weakened branches. ■