98-200S Guide to Ozone Injury.rev.qxd 10/25/99 1:21 PM Page 1

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-446
September 1999

A Guide to Ozone Injury in Vascular Plants of the Pacific Northwest

Sarah Brace, David L. Peterson,
and Darci Bowers

Authors

SARAH BRACE was a graduate research assistant, DAVID L. PETERSON is a research biologist and professor, and DARCI BOWERS was a research technologist, U.S. Geological Survey-Biological Resources Division, Forest and Rangeland Ecosystem Science Center, University of Washington Field Station, Box 352100, Seattle, WA 98195. Publication of this report was supported by the USDA Forest Service, Pacific Northwest Research Station (under cooperative agreement no. PNW 96-8002-1CA), Pacific Northwest Region, and Forest Health Monitoring Program, and by the National Park Service through Mount Rainier National Park (under cooperative agreement no. 1443-CA9000-95-019, subagreement 7).

A Guide to Ozone Injury in Vascular Plants of the Pacific Northwest

Sarah Brace, David L. Peterson, and Darci Bowers

U.S. Department of Agriculture Forest Service
Pacific Northwest Research Station
Portland, Oregon
General Technial Report PNW-GTR-446
September 1999

In cooperation with:
U.S. Department of Agriculture, Forest Service,
Pacific Northwest Region
U.S. Department of the Interior, National Park Service,
Mount Rainer National Park

Abstract

Brace, Sarah; Peterson, David L.; Bowers, Darci. 1999. A guide to ozone injury in vascular plants of the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-446. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 63 p.

Controlled-exposure studies have shown that several plant species native to the Pacific Northwest are potentially sensitive to elevated ambient concentrations of tropospheric ozone. This guide reports visual and descriptive documentation of ozone injury symptoms for common tree, shrub, and herbaceous species in the region. Symptoms observed in leaves of these species include chlorotic mottle, pigmented stipple, necrosis, and premature senescence, with considerable variation among and within species. Resource managers and scientists can use the photo documentation in this guide to identify potential injury to plants in the field, and to distinguish ozone injury from other pathological conditions.

Keywords: Air pollution, forest health, forest pathology, ozone, vegetation injury.

Summary

The potential effects of air pollution on forest ecosytems is a growing concern as human population and pollutant sources in the Pacific Northwest continue to increase. Tropospheric ozone, a photo-oxidant produced from nitrogen oxides and volatile organic compounds in the presence of sunlight, is toxic to sensitive plant species at relatively low concentrations. Because ambient ozone exposure is often higher in downwind wildland areas than in the urban areas from which the ozone precursors emanate, there is potential for physiological damage to vegetation in National Forests and other public lands.

To determine if ozone is causing damage to plant species under field conditions, the characteristics of injury symptoms must be documented. These symptoms typically differ widely and require diagnosis of injury by species. In this study, we subjected common vascular plant species of Pacific Northwest forest ecosystems to controlled fumigations with ozone at levels above typical ambient conditions. We identified the appearance of visible injury symptoms for each species by comparing plants exposed to ozone with control plants receiving no ozone. Most plant species exhibited sufficient sensitivity to ozone to develop injury symptoms under the ozone fumigations that were used.

Photographs of ozone injury symptoms, descriptions of those symptoms, and photographs of control plants were compiled by species. This photographic documentation can be used by trained field personnel to identify potential ozone injury to forest vegetation and to distinguish it from other types of pathological disorders. This ozone injury guide contains only a small subset of native vascular plants in the Pacific Northwest; other species may have different sensitivities and symptoms than the species that were tested. A cautious "pathological" approach to confirming ozone injury should be used by referring to this guide in conjunction with other available biotic and abiotic information about the health of local forest vegetation.

Introduction

Ozone can have deleterious effects on the physiological function and productivity of a wide range of plant species, including agricultural crops, conifers, hardwoods, shrubs, herbaceous perennials, and lichens. Elevated ambient ozone concentrations in the troposphere (the portion of the atmosphere extending about 11 kilometers upward from Earth's surface) can affect plants in a variety of ways depending on the duration of exposure, maximum concentration, and presence of compounding stresses, such as drought, competition, nutrient deficiency, and pathogens (Smith 1990, Treshow and Anderson 1991). Injury can result in reduced photosynthesis, lower growth rates, accelerated senescence of older foliage, and loss of vigor (Muir and Armentano 1988, Weber and others 1993). In addition, there can be visible foliage symptoms associated with ozone injury, including chlorotic mottle, tip or margin burn, stipple, and necrosis (Temple et al. 1992, Treshow and Anderson 1991). Exposure studies on ozone sensitivity have focused primarily on species native to the Northeastern (Reich and Amundson 1985, Woodbury and Laurence 1994), Southeastern (McLaughlin and others 1982), and Southwestern (Miller and others 1983, Peterson and others 1995, Westman and Temple 1989) United States. Ozone sensitivity has been tested for only a few vascular species native to the Pacific Northwest (Brace and others 1996).

Ozone levels in the Puget Sound basin have exceeded the National Ambient Air Quality Standard (NAAQS) on several occasions during the past 20 years; exceedances may be more frequent under the new NAAQS (issued in 1997). As human populations of the Seattle and Tacoma (Washington), Portland (Oregon), and Vancouver (British Columbia) metropolitan areas continue to grow, there is growing concern about the effects of ozone on natural resources (Peterson and others 1992), particularly in downwind rural and wildland areas west of the Cascade Range (Brace and Peterson 1998; Cooper and Peterson, in press). There may be some effects already, but we have little information on the characteristics of visible ozone injury in vegetation on which to base impact assessments. Better visual and descriptive information on ozone injury is needed, so that species potentially at risk can be identified and monitored. Species sensitive to ozone are useful as bioindicators only with a clear description of injury symptoms and at least some measure of air pollutant exposure.

Table 1--Vascular plant species studied for ozone sensitivity

Scientific name	Common name	Ozone exposure[a]	Reference
Abies lasiocarpa (Hook.) Nutt.	Subalpine fir	Episodic 120	Brace and others 1996
Acer circinatum Pursh	Vine maple	Episodic 120	Brace and others 1996
Acer macrophyllum Pursh	Bigleaf maple	Episodic 120	Brace and others 1996
Alnus rubra Bong.	Red alder	Peak 214	Brace and others 1996
Alnus sinuata (Regel) Rydb.	Sitka alder	Episodic 120	Brace and others 1996
Amelanchier alnifolia (Nutt.) Nutt.	Western serviceberry	Peak 126	Brace and others 1996
Berberis nervosa Pursh	Oregongrape	Peak 126	Brace and others 1996
Cassiope mertensiana (Bong.) G. Don.	Mertens' mountain heather	Episodic 120	Brace and others 1996
Erigeron peregrinus (Pursh) Greene	Wandering daisy	Peak 126	Brace and others 1996
Gaultheria shallon Pursh	Salal	Peak 126	Brace and others 1996
Holodiscus discolor (Pursh) Maxim.	Ocean-spray	Peak 126	Brace and others 1996
Lonicera involucrata (Rich.) Banks	Black twin-berry	Peak 126	Brace and others 1996
Lupinus latifolius Aqardh	Broadleaf lupine	Peak 214	Brace and others 1996
Phyllodoce empetriformis (Sw.) D. Don.	Pink mountain-heather	Peak 126	Brace and others 1996
Physocarpus capitatus (Pursh) Kuntze	Pacific ninebark	Peak 126	Brace and others 1996
Physocarpus malvaceus (Greene) Kuntze	Mallow ninebark	Daily max. > 100	Mavity and others 1995
Pinus contorta var. *latifolia* Engelm.	Lodgepole pine	Base by 1.8	Hogsett and others 1989
Pinus ponderosa Dougl. ex Laws. var. *ponderosa*	Ponderosa pine	Field exposure	Peterson and others 1991
Polystichum munitum (Kaulf.) Presl	Sword-fern	Episodic 120	Brace and others 1996
Populus tremuloides Michx.	Quaking aspen	Base by 2.0	Hogsett and others 1989
Populus trichocarpa Torr. & Gray	Black cottonwood	Peak 214	Brace and others 1996
Potentilla flabellifolia Hook.	Fan-leafed cinquefoil	Peak 126	Brace and others 1996
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir	Base by 1.8	Hogsett and others 1989
Ribes bracteosum Dougl.	Stink currant	Peak 126	Brace and others 1996
Rubus parviflorus Nutt.	Thimbleberry	Peak 126	Brace and others 1996
Rubus spectabilis Pursh	Salmonberry	Peak 126	Brace and others 1996
Salix scouleriana Barratt ex. Hook.	Scouler willow	Peak 214	Brace and others 1996
Sambucus racemosa L.	Red elderberry	Daily max. > 100	Mavity and others 1995
Tsuga heterophylla (Raf.) Sarg.	Western hemlock	Base by 1.8	Hogsett and others 1989
Tsuga mertensiana (Bong.) Carr.	Mountain hemlock	Episodic 120	Brace and others 1996
Vaccinium membranaceum Dougl.	Thin-leaved huckleberry	Peak 126	Brace and others 1996
Vaccinium parvifolium Smith	Red bilberry	Peak 126	Brace and others 1996

[a]See text for description of ozone exposures.

Visible symptoms in foliage resulting from ozone exposure can be considered as indicators of either acute or chronic injury (Miller 1989; Skelly and others, n.d.). Acute injury, caused by cell mortality which develops within a few hours to days following exposure, can appear visually as stipple (many small red, purple, or other pigmented spots), fleck (many small yellow spots), bleaching (loss of green color), or bifacial necrosis (areas of dead cells on both sides of a leaf). Acute injury is normally induced by relatively high ozone concentrations. Chronic injury develops more slowly (days to weeks) and is characterized by chlorosis (areas of the leaf with a bright yellow color), stipple, necrosis, and premature senescence (leaf drop). Chronic injury is normally induced by long-term, low ozone concentrations. Any combination of symptoms can occur in response to ozone exposure, depending on environmental conditions and physiological condition of the plant. Symptoms of ozone injury can be confused with, and perhaps exacerbated by, other sources of stress (e.g., insects, fungi) and nutritional disorders (Skelly and others, n.d.).

This publication documents visible foliar injury of common Pacific Northwest tree, shrub, and herbaceous species fumigated with ozone under controlled, experimental conditions. Visual documentation and associated descriptive information in this guide can be used by resource managers and scientists to identify potential ozone injury to vegetation in the field.

Methods

Plant Material

Thirty-two plant species native to Pacific Northwest forest ecosystems were subjected to ozone fumigation (table 1). All species are common and widespread in the Pacific Northwest, although most are restricted in elevational range, and most of the species examined here are more common on the west side of the Cascade Range. Seeds, cuttings, and transplants from many species were collected by the USDA Forest Service (Pacific Northwest Region, Portland, Oregon). Other plant material sources were Mount Rainier National Park (Ashford, Washington), Oyster Bay Nursery (Olympia, Washington), J. & J. Landscaping Company (Bothell, Washington), and Julius Rosso Nursery (Seattle, Washington).[1]

---

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Information reported here is from three different sources (Hogsett and others 1989 [including unpublished photographic information], Mavity and others 1995, Brace and others 1996), but the general procedures of plant propagation and fumigation were similar. Plants of species grown from seed were germinated in 10-centimeter pots in standard potting soil in a greenhouse. Some plants were later transplanted into larger pots to minimize root crowding and associated soil moisture stress. Living plants collected in the field (typically shrubs and large herbaceous species) were transplanted into 4- or 8-liter pots in standard potting soil. Cuttings from *Alnus rubra*, *Populus trichocarpa,* and *Salix scouleriana* were collected in the field and planted in 4-liter pots with the same soil mixture. Transplants and cuttings remained outdoors during the winter prior to fumigation to allow plants to adapt somewhat to the container environment. Of the commercial nursery plants, most were 1-year-old seedlings grown in 4-liter pots; *Abies lasiocarpa* and *Tsuga mertensiana* were 6- to 8-year-old saplings grown in 2- to 4-liter pots.

Most plants were transported to the U.S. Environmental Protection Agency (EPA) research laboratory in Corvallis, Oregon. Two species (table 1) were grown and fumigated at the USDA Forest Service Center for Forest Environmental Studies (CFES) in Macon, Georgia. At both locations, plants remained in a greenhouse or outdoors for 2 to 3 weeks before the start of exposure studies to acclimate to local conditions. Plants were watered periodically with a nutrient solution (Downs and Hellmers 1975) to provide adequate soil moisture and nutrients, and they were sprayed as necessary for insect pests. There was no requirement for minimum plant size or number of leaves, although all plants were required to have a healthy appearance in terms of leaf coloration.

Ozone Fumigation Treatments

Open-top field chambers and enclosed greenhouse chambers were used for ozone fumigation treatments (all plant species except two) at the EPA facility. Open-top chambers (3 meters in diameter by 2.4 meters in height), ozone delivery, data processing, and quality control are described in Hogsett and others (1985). Enclosed greenhouse chambers (Heck and others 1968) are considerably smaller (106 centimeters wide by 76 centimeters deep by 96 centimeters high) than open-top chambers. Ozone delivery, data processing, and quality control procedures are similar to those described for the open-top chambers. Control plants were placed in chambers with charcoal-filtered air. Fumigations were conducted for 5 to

8 weeks during the summer, with four to eight plants per species, and an equal number of treatment and control plants (Brace and others 1996).

Three different exposures were used in most treatments at the EPA lab. The Peak 214 episodic exposure is an ozone profile that combines typical diurnal ozone patterns (morning low concentrations and afternoon high concentrations) with periodic peaks representing ozone episodes. The profile is designed as a 28-day period with seven peak events of 214 parts per billion by volume (ppbv); the 28-day cycle is repeated to provide longer exposure periods. The Episodic 120 exposure is similar to the Peak 214 in diurnal pattern and peak and has seven events greater than 120 ppbv with one peak in the 28-day cycle greater than 200 ppbv. An increase in the number of intermediate peaks in the Episodic 120 results in a cumulative ozone dose over the 28 days that is similar to that of the Peak 214. The Peak 214 and Episodic 120 exposures were used in open-top chambers. The Peak 126 exposure is a daily peak profile in which ozone concentrations continuously cycle between a mid-day maximum concentration (126 ppbv) and midnight minimum (20 ppbv). This exposure was used in enclosed greenhouse chambers only. The base-by-1.8 and base-by-2.0 exposures are episodic ozone profiles based on data originally derived from sites in the upper Midwest with various multipliers for the peaks (Hogsett and others 1989). The 30-day base profile has seven peaks greater than 60 ppbv; the base-by-2.0 profile also has seven peaks, but they are twice as high. The rest of the days less than 60 ppbv are the same in all profiles.

Continuously stirred tank reactors (Mavity and others 1995) were used for fumigation treatments (three species: *Artemisia tridentata*, *Physocarpus malvaceus*, *Sambucus racemosa*) at the CFES facility. Maximum expression of ozone injury symptoms was obtained with an ozone exposure profile that had daily maximum concentrations greater than 100 ppbv on half of the days. The duration of exposures for all species was 31 days.

Photographic Documentation of Ozone Injury

Plants were photographed before the start of ozone-exposure treatments; the photographs generally included the entire plant and close-ups of the leaf. Once exposures began, plants were monitored daily for development of foliar symptoms by comparing plants exposed to ozone vs.

those exposed to charcoal-filtered air and noting any differences (EPA lab), and by observing plants exposed to high vs. low levels of ozone (CFES lab). Specific characteristics recorded for leaves included degree and distribution of abnormal coloration (especially chlorosis), mottling, curling, and senescence. At the onset of foliar symptoms, plants were photographed and symptoms were documented. Photographs were taken again at the end of the treatment period. In some cases (Hogsett and others 1989, Mavity and others 1995), characteristics such as plant growth and biomass also were noted, but only visible injury was identified for most plant species (Brace and others 1996). Only foliar injury is reported here as an aid to visual identification in the field.

Summary of Observed Ozone Injury

Most species exhibited some degree of foliar injury during the 8-week exposures, although the nature of the injury and the date that injury was first visible differed among species. A wide variety of symptoms were noted, including chlorotic mottle, pigmented stipple, and necrosis. Visual characteristics of injury were consistent within species, although the degree of injury and onset of injury differed somewhat, possibly owing to genetic variation among plants and different physiological vigor related to transplanting and other potential stresses. Injury usually appeared on older foliage first followed by injury on younger foliage; foliar damage was uniform on leaves rather than localized. In a few cases, senescence and leaf abscission were accelerated, sometimes in the absence of apparent visual symptoms.

Abies lasiocarpa, *Berberis nervosa*, *Cassiope mertensiana*, *Erigeron peregrinus*, *Phyllodoce empetriformis*, *Polystichum munitum*, and *Tsuga mertensiana* exhibited no visible difference between treatment and control plants, so photographs are not included in the photo guide. The Mount Rainier variety of *Gaultheria shallon* had some foliar injury, but the nursery variety of this species did not, suggesting that there are differences in ozone sensitivity related to genetic differences in plant sources.

Acer circinatum, *Erigeron peregrinus*, *Phyllodoce empetriformis*, and *Potentilla flabellifolia* exhibited accelerated senescence of older foliage. In addition, ozone-treated *Potentilla flabellifolia* flowered several weeks before the control plants. The effect of ozone-induced altered phenology on subalpine and alpine vegetation may be significant, given the short annual period during which these species must grow, flower, and set seed. Accelerated phenology and premature flowering could result in lower carbon assimilation, poorer seed quality, and loss of vigor.

Using the Guide to Diagnose Injury

The photos and descriptions on the following pages can be used as an aid to identifying ozone injury. With the exception of *Pinus ponderosa*, photos depicting symptoms of ozone injury are from plants treated with controlled exposures of ozone. Although the symptoms in the photos are the ones most likely to be observed in the field, we have not yet confirmed these symptoms under field conditions in the Pacific Northwest. The photographic evidence is considered diagnostic for the species shown here, but because this is only a small sample of Northwestern vascular flora, various combinations of symptoms might be expected in other species. However, the photos display a sufficient range of symptoms that can be used as a guide to potential ozone injury in most plant species. Diagnosis of injury requires attention to sources of variation within each species and to the environmental context of individual plants observed. Investigators are encouraged to make multiple observations of potential injury symptoms within and between years, record measurements and observations of individual plants and site characteristics, and take photographs.

The greatest concern in diagnosis of ozone injury is distinguishing ozone symptoms from a wide range of potential symptoms caused by other agents. Physical abrasion of the leaf surface, feeding by insects, fungal pathogens, nutritional deficiencies, and foliar desiccation can all produce visible symptoms similar to those of ozone injury in some plant species. Photographs and descriptions of these symptoms can be found in various publications on plant pathology (e.g., Pettinger 1982, Scharpf 1993). A few guides on air pollutant injury (e.g., Nash et al. 1996, 1997; Flagler 1998; Skelly and others, n.d.) also are available. It is strongly recommended that a plant pathologist, preferably someone with training in air pollution symptomatology, be consulted if ozone injury is suspected. If a pathologist cannot observe the symptoms onsite in the field, then foliar specimens can be clipped, stored in an airtight bag, refrigerated at 4^{o} C, and mailed as soon as possible to another location where a pathologist is available. Photographs of the foliage should be taken as well.

Although ozone injury can be observed opportunistically, it is usually best identified through a systematic survey. This is particularly true where ozone causes only subtle injury, affects a small portion of a plant population, or produces injury only in certain microenvironments. The survey can use permanent vegetation plots revisited periodically over time or can simply involve observations at different geographic locations (e.g., high vs. low elevations) and in different microhabitats (e.g., upland vs. riparian). Maximium expression of injury is generally expected in mid to late summer following a significant period of ambient ozone exposure, although acute injury can be expressed at any time. Leaf necrosis, mortality, and senescence must be distinguished from normal phenological patterns, particularly in the late summer and during periods of low soil moisture.

There is wide variation in ozone sensitivity among plant species. Injury observed in one species does not imply injury in other species in the same area. There also is considerable variation within genera; e.g., *Pinus ponderosa* is sensitive to ozone but many other *Pinus* species are resistant. Genetic variation also produces a range of sensitivities within species such that, for a given species, individual plants with and without symptoms can be found in the same area. Because of this variation within species, it may be necessary to conduct extensive surveys to detect ozone injury.

The most convincing evidence of ozone injury is consistent observations of symptoms in the field over multiple years in areas where ambient ozone concentration data are available, followed by reproduction of the observed symptoms under controlled conditions. In this approach, the investigator observes and photographs ozone symptoms in the field and records (1) relevant biotic (e.g., presence of insects and fungal pathogens) and abiotic (e.g., physical injury to leaves) characteristics of affected plants; (2) variation in the appearance of symptoms at different spatial scales (within affected plants, between plants in the same area, and among plant populations); (3) microenvironmental conditions, such as soil moisture, soil fertility, and light; and (4) macroenvironmental conditions, such as spatial and temporal patterns of ozone concentrations (where data are available) and weather during the preceding few months. Seeds or cuttings should be collected from the affected plants and propagated in a greenhouse remote from the field location. After propagated plants have matured somewhat, they are included in a controlled fumigation experiment: one set of plants is subjected to controlled ozone exposures and another set to ozone-free air, as described elsewhere in this paper. If the plants exposed to ozone produce symptoms identical to those observed in the field, and if the control plants have no symptoms, this can be considered firm validation of ozone injury in the field. Although this level of verification may not be feasible in all cases, it is the definitive approach to confirmation of ozone injury in plants. Casual observations of potential ozone injury in the field have limited value without additional verification.

Acknowledgments

Preparation of this publication was a cooperative multiagency effort over a period of three years. We thank Bob Bachman and Sally Campbell (USDA Forest Service, Pacific Northwest Region) for financial support for our studies of ozone effects and for encouragement. Barbara Samora (Mount Rainier National Park) provided financial support for publication costs and additional support for our air quality research. Chris Andersen and Bill Hogsett (U.S. Environmental Protection Agency) graciously allowed us to use the controlled-exposure facility in Corvallis, Oregon, and contributed photos from some of their previous studies. Blaine Baker, Craig Hendricks, and Milt Plocher provided technical assistance and expert photography. Erika Mavity contributed photos from her previous studies. Technical reviews of the manuscript were provided by Bob Bachman, Sally Campbell, and Gretchen Smith.

References

Brace, S.; Peterson, D.L. 1998. Tropospheric ozone distribution in the Mount Rainier region of the Cascade mountains, U.S.A. Atmospheric Environment. 32: 3629-3627.

Brace, S.; Peterson, D.L.; Horner, D. [and others]. 1996. Ozone injury in common plant species of the Cascade mountains, U.S.A.: results of controlled exposures. In: Proceedings of the 1996 annual meeting of the Pacific Northwest International Section of the Air and Waste Management Association; 1996 December 11-13; Seattle. Seattle: Pacific Northwest International Section, Air and Waste Management Association: Paper SS-II-1.

Cooper, S.M.; Peterson, D.L. [In press]. Spatial distribution of tropospheric ozone in western Washington, USA. Environmental Pollution.

Downs, R.J.; Hellmers, H. 1975. Environment and the experimental control of plant growth. New York: Academic Press.

Heck, W.W.; Dunning, J.A.; Johnson, H. 1968. Design of a simple plant exposure chamber. Publ. APTD-68-6. Washington, DC: National Center for Air Pollution Control.

Hogsett, W.; Plocher, M.; Wildman, V. [and others]. 1985. Growth responses of two varieties of slash pine to chronic ozone exposures. Canadian Journal of Botany. 63: 2369-2376.

Hogsett, W.E.; Tingey, D.T.; Hendricks, C.; Rossi, D. 1989. Sensitivity of western conifers to SO_2 and seasonal interaction of acid fog and ozone. In: Olson, R.K.; Lefohn, A.S., eds. Effects of air pollution on western forests. APCA Trans. Ser. Pittsburgh, PA: Air Pollution Control Association: 469-491.

Mavity, E.; Stratton, D.; Berrang, P. 1995. Effects of ozone on several species of plants which are native to the Western United States. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Chattahoochee-Oconee National Forests, 508 Oak Street NW, Gainesville, GA 30501.

McLaughlin, S.B.; McConthy, R.K.; Duvick, D.; Mann, L.K. 1982. Effects of chronic air pollution on photosynthesis, carbon allocation, and growth of white pine trees. Forest Science. 28: 60-70.

Miller P.R. 1989. Biomarkers for defining air pollution effects in western coniferous forests. Washington, DC: National Academy Press.

Miller, P.R.; Longbotham, G.J.; Longbotham, C.R. 1983. Sensitivity of selected western conifers to ozone. Plant Disease. 67: 1113-1115.

Muir, P.S.; Armentano T.V. 1988. Evaluating oxidant injury to foliage of *Pinus ponderosa*: a comparison of methods. Canadian Journal of Forest Research. 18: 498-505.

Nash, B.; Saunders, M.; Miller, B. [and others]. 1996. AQUIMS: a computerized system for interpreting and integrating information on air pollution effects on natural resources. In: Proceedings, Eco-Informa '96: Global networks for environmental information; 1996 November 4-7; Lake Buena Vista, FL. Ann Arbor, MI: Environmental Research Institute of Michigan: 575-580. Vol. 11.

Nash, B.L.; Tonnessen, K.A.; Heuer, K.K. [and others]. 1997. Using the AQUIMS air quality decision support system to identify natural resources at risk from air pollution. In: Annual convention and exposition of the American Society of Photogrammetry and Remote Sensing/American Congress on Surveying and Mapping: Resource technology; 1997 April 7-10; Seattle. Bethesda, MD: American Society of Photogrammetry and Remote Sensing; American Congress on Surveying and Mapping: 362-369. Vol. 4.

Peterson, D.L.; Arbaugh, M.J.; Robinson, L.J. 1991. Regional growth changes in ozone-stressed ponderosa pine (*Pinus ponderosa*) in the Sierra Nevada, California, USA. The Holocene. 1: 50-61.

Peterson, D.L.; Silsbee, D.G.; Poth, M. [and others]. 1995. Growth response of bigcone Douglas-fir (*Pseudotsuga macrocarpa*) to long-term ozone exposure in southern California. Journal of the Air and Waste Management Association. 45: 36-45.

Peterson, J.; Schmoldt, D.; Peterson, D. [and others]. 1992. Guidelines for evaluating air pollution impacts on class I wilderness areas in the Pacific Northwest. Gen. Tech. Rep. PNW-299. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Pettinger, L.F. 1982. A field guide to important forest insects and diseases of Oregon and Washington. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Forest Pest Management.

Reich, P.B.; Amundson, R.G. 1985. Ambient levels of ozone reduce net photosynthesis in tree and crop species. Science. 230: 566-570.

Scharpf, R.F. 1993. Diseases of Pacific coast conifers. Agric. Handb. 521. Washington, DC: U.S. Department of Agriculture, Forest Service.

Skelly, J.M.; David, D.D.; Merrill, W. [and others]. [N.d.]. Diagnosing injury to Eastern forest trees. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region, Forest Pest Management.

Smith, W.H. 1990. Air pollution and forests. New York: Springer-Verlag.

Temple, P.J.; Reichers, G.H.; Miller, P.R. 1992. Foliar injury responses of ponderosa pine seedlings to ozone, wet and dry acidic deposition, and drought. Environmental and Experimental Botany. 32: 101-113.

Treshow, M.; Anderson, F.K. 1991. Plant stress from air pollution. New York: John Wiley and Sons.

Weber, J.A.; Clark, C.S.; Hogsett W.E. 1993. Analysis of the relationships among O_3 uptake, conductance, and photosynthesis in needles of *Pinus ponderosa*. Tree Physiology. 13: 157-172.

Westman, W.E.; Temple P.J. 1989. Acid mist and ozone effects on the leaf chemistry of two western conifer species. Environmental Pollution. 57: 9-26.

Woodbury, P.B.; Laurence, J.A. 1994. Chronic ozone exposure alters the growth of leaves, stems, and roots of hybrid *Populus*. Environmental Pollution. 85: 103-108.

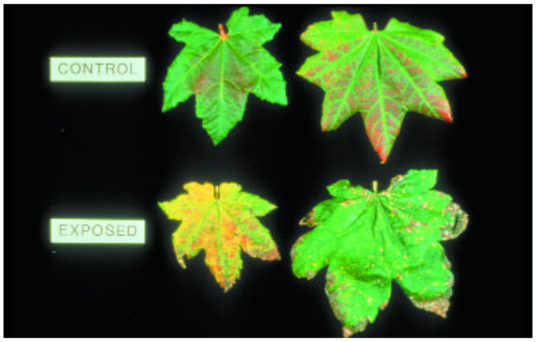
PHOTO GUIDE

Acer circinatum (Vine maple)

Description and habitat
Shrub or multibranched deciduous tree up to 7 meters tall. Grows in moist sites in low to middle elevation forests on the western slopes of the Cascades, in gaps or patches where filtered sunlight reaches the understory. Also grows in areas disturbed by avalanches, clearcuts, and river channel movement.

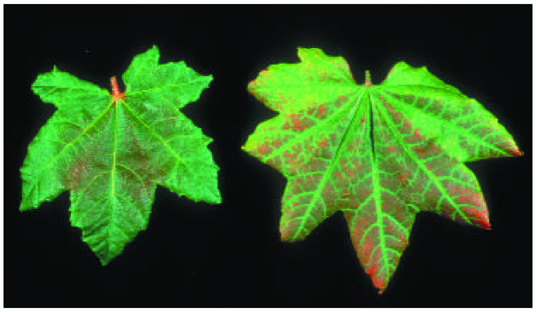
Leaves
Opposite leaves, 5 to 12 centimeters wide with seven to nine lobes and toothed margins. Hairy on lower surface and along veins of upper surface. Leaves turn brilliant gold or red in autumn.

Ozone injury symptoms
Leaves droop and curl slightly; early senescence.



No injury (above) and injury (below) closeup.


Whole-plant view of injury (L) and no injury (R).


Uninjured leaf closeup.

Acer macrophyllum (Bigleaf maple)

Description and habitat

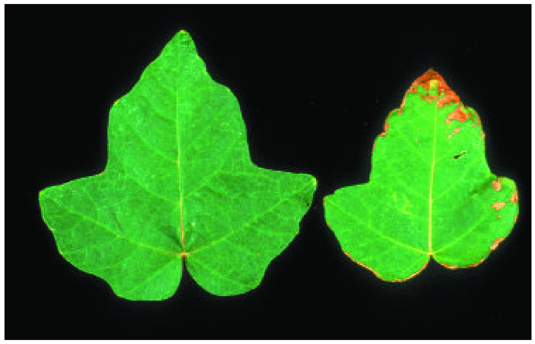
Large deciduous tree with multiple long stems often densely coated in mosses, lichens, and ferns. Grows in moist sites in low elevation forests on river terraces and other level sites and in areas disturbed by fire or logging.

Leaves

Large five-lobed opposite leaves with deep clefts 15 to 30 centimeters wide. Dark green above and paler green underside. Turns to pale yellow in autumn.

Ozone injury symptoms

Leaves hang pendulously (rather than horizontally) and edges curl under giving leaf a wilted appearance. Slight marginal necrosis following prolonged exposure on some plants, indicating variability in sensitivity.



With injury.

Whole-plant view of injury (L) and no injury (R).

No injury.

Alnus rubra (Red alder)

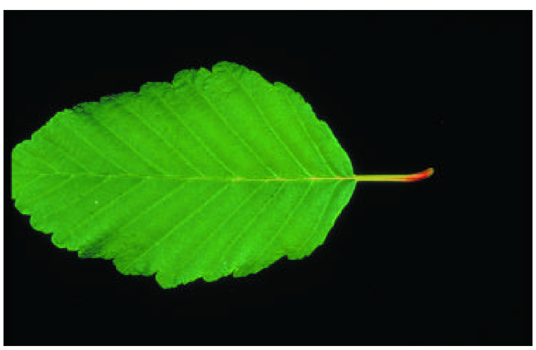
Description and habitat
Deciduous tree or large shrub reaching 25 meters in height. Grows at low elevations in moist sites, including lowland forests, riparian areas, and recently disturbed sites. Often grows in clumps or pure stands.

Leaves
Alternate, broadly elliptical leaves, 5 to 15 centimeters long, with wavy, bluntly toothed, rolled margin and sharply pointed tip. Upper surface is uniformly dark green and smooth; underside is pale green-gray and hairy.

Ozone injury symptoms
Dark pigmented stipple first appears on interveinal tissue of upper leaf surface, appearing on older foliage first and gradually covering the entire leaf. Stipple is uniform and increases in density following prolonged exposure. Necrotic spotting and chlorotic mottle also may develop.

With injury.

With injury.



No injury.

Alnus sinuata (Sitka alder)

Description and habitat

Shrub or small tree with multiple branches, 1 to 5 meters tall, found in moist sites such as steamsides, wet meadows, and avalanche tracks. Grows from mid to subalpine elevations on western slopes of the Cascades, often in clumps.

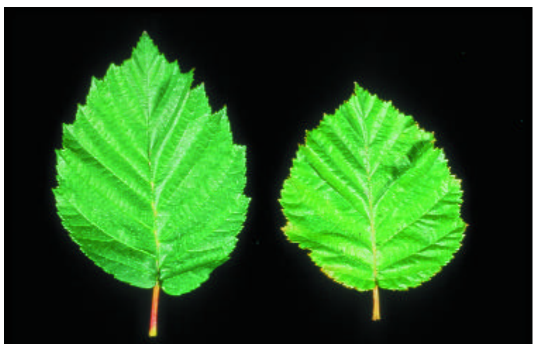
Leaves

Alternate, thin, shiny leaves, oval with sinuate, double-toothed margin and pointed tip, 4 to 10 centimeters long. Leaves are slightly sticky on underside.

Ozone injury symptoms

Dark purple stipple appears on older leaves first, followed by necrotic spotting that continues to spread with prolonged exposure eventually covering entire leaf.

With injury.



No injury.

Amelanchier alnifolia (Western serviceberry)

Description and habitat

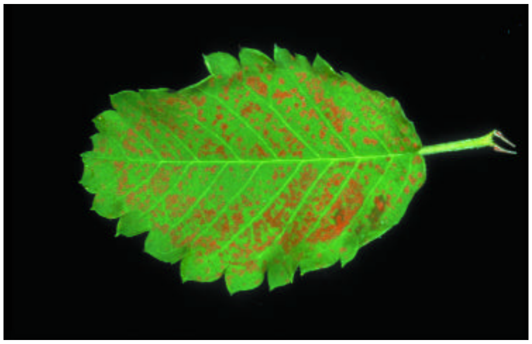
Deciduous shrub, 1 to 5 meters tall, spreads by rhizomes and often occurs in clumps or thickets. Found in well-drained soils on rocky outcrops and slopes, forest edges, and meadows at low to middle elevations.

Leaves

Alternate, oval leaves, 4 to 10 centimeters long, with toothed margins on top half.

Ozone injury symptoms

Red and purple stipple appear initially, followed by chlorotic mottle and blotchy necrotic spots in interveinal tissue.



With injury.

No injury.

Gaultheria shallon (Salal)

Description and habitat

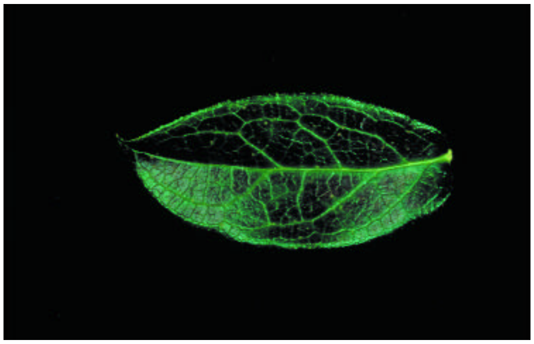
Spreading low shrub, layered, ranging in height from 0.2 to 3 meters. Short, branched stems are angular and hairy. Grows in understory in wet to dry coniferous forests, at low to middle elevations, and along coastal rocky bluffs and shorelines.

Leaves

Evergreen, alternate, leathery and generally egg-shaped leaves, shiny, and finely toothed, 5 to 10 centimeters long.

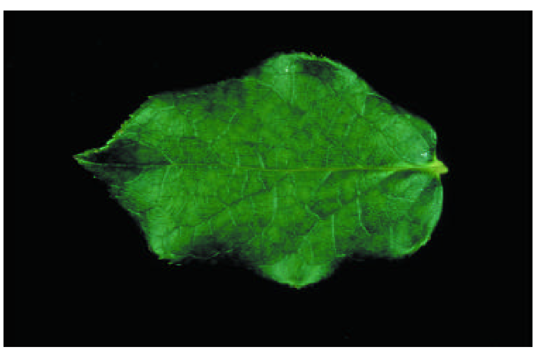
Ozone injury symptoms

Dark stipple spreading to dark, purple-brown spots on younger foliage, gradually spreading to older leaves.



With injury.

With injury.



No injury.

Holodiscus discolor (Ocean-spray)

Description and habitat

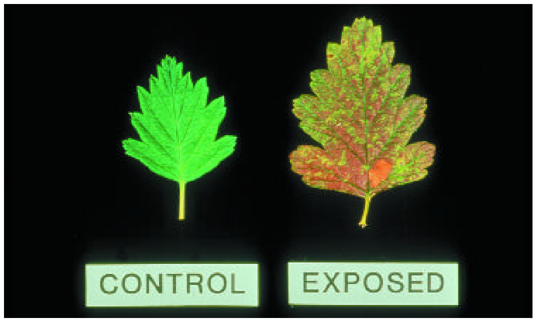
Upright shrub with multiple stems, up to 4 meters. Grows in open forests and clearings in dry to moist sites at low to middle elevations on western slopes of the Cascades. Cream-colored flowers, brown and dry on the stems, remain over winter, providing easy identification when leaves are absent.

Leaves

Alternate, deciduous egg-shaped leaves, 3 to 6 centimeters long, with hairs on upper and lower surface, pale green. Margins are lobed or toothed. Leaves have reddish hue in autumn.

Ozone injury symptoms

Leaves develop bronze color ranging from spotty and grainy to solid, with injury first appearing at the base of the stem and spreading outward. Injury appeared on older foliage first and symptoms seemed to stabilize with prolonged exposure.



No injury (L) and injured (R).

With injury.

No injury.

Lonicera involucrata (Black twin-berry)

Description and habitat

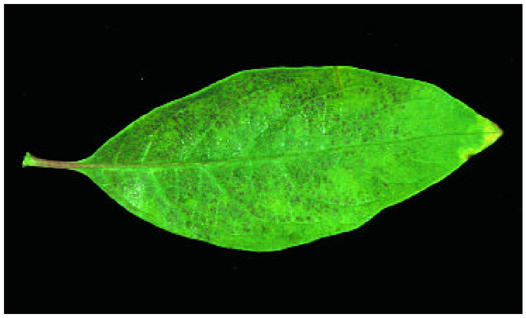
Straggly to upright shrub, 0.5 to 3 meters tall. New twigs are square. Grows in moist forests, clearings, riparian areas, and wet sites at low to subalpine elevations.

Leaves

Deciduous, opposite, elliptical to lanceolate leaves, 6 to 8 centimeters long. Leaves are short stalked, pointed, and lightly pubescent on underside.

Ozone injury symptoms

Chlorosis and black stipple on older foliage.



With injury.

No injury.

Lupinus latifolius (Broadleaf lupine)

Description and habitat

Multiple-stemmed perennial herb with slender, hairy branches arising from a branched rhizome. Grows to 60 centimeters tall. Found at low to subalpine elevations in open meadows and disturbed sites on western slopes of the Cascades.

Leaves

Palmately compound leaves up to 5 centimeters in length, with six to eight pointed leaflets on a long stalk. Leaves give plant a light and airy appearance.

Ozone injury symptoms

Black stipple on leaf margin and tips, moving inward to cover entire leaf. Bronze appearance on margins, overall yellowing of leaf.

With injury.

With injury.

No injury.

Physocarpus capitatus (Pacific ninebark)

General description

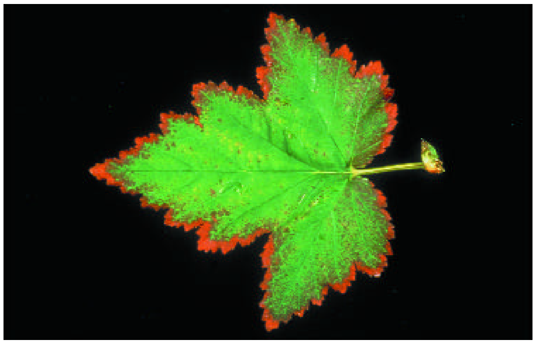
Spreading to upright deciduous shrub with reaching, angled branches up to 4 meters tall. Branches have bark that takes on a shredded appearance over time.

Leaves

Alternate three- to five-lobed leaves, 3 to 6 centimeters long, toothed, shiny and dark above with deep veins, lighter and hairy below.

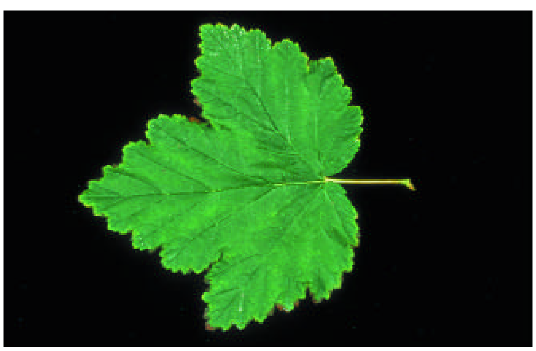
Ozone injury symptoms

Black stipple over entire leaf; older foliage showing injury first.



With injury.

With injury.



No injury.

Physocarpus malvaceus (Mallow ninebark)

Description and habitat

Spreading to erect deciduous shrub 0.5 to 2.5 meters tall, with reddish to yellowish-brown flaky bark. Grows in the understory of relatively open coniferous understory at low to middle elevations on the east side of the Cascades.

Leaves

Palmately veined leaves, three lobed, 2.5 to 8 centimeters long.

Ozone injury symptoms

Red stipple and premature senescence of leaves.

With injury.

With injury.

Whole-plant view of injury (L) and no injury (R).

Pinus contorta var. *latifolia* (Lodgepole pine)

Description and habitat
Narrow tree up to 25 meters tall (but shorter on harsh sites such as near treeline), with thin, scaly bark, long needles, and cones often oblique and pointing outward. Usually found at high elevations on well-drained soils, often in pure stands.

Leaves
Two needles per fascicle, 3 to 7 centimeters long, stout, slightly flattened and often twisted, yellow-green to dark green.

Ozone injury symptom
Chlorotic mottle.

With injury.

No injury.

Pinus ponderosa var. *ponderosa* (Ponderosa pine)

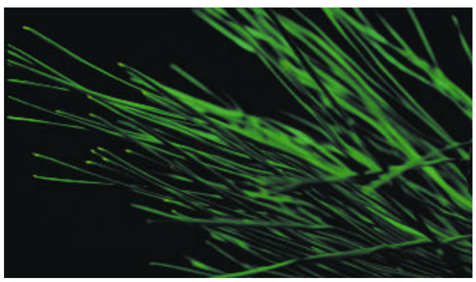
Description and habitat
Up to 40 meters tall with high, open crown. Common on low to middle elevation sites on the east side of the Cascades and locally common at a few sites in the Puget Sound region. Often grows with grasses and smaller understory shrubs in open, parklike spacing.

Leaves
Three needles per fascicle, 10 to 25 centimeters long, pale green, and typically remain on the tree for 3 to 4 years.

Ozone injury symptoms
Chlorotic mottle, especially on older needles; accelerated senescence.

With injury.

With injury.



No injury.

No injury.

Populus tremuloides (Quaking aspen)

Description and habitat
Deciduous tree, 12 to 20 meters tall, with smooth, whitish bark (turning gray on older trees), a narrow, rounded crown of thin foliage, and leaves with a characteristic trembling appearance in wind. Found mostly in riparian areas, avalanche tracks, and other disturbed sites on the east side of the Cascades, often in pure stands.

Leaves
Nearly round leaves, abruptly short-pointed, rounded at base, finely saw-toothed, and thin, 4 to 7.5 centimeters long.

Ozone injury symptoms
Chlorotic fleck and necrotic mottle.

With injury.

With injury.

No injury.

Populus trichocarpa (Black cottonwood)

Description and habitat

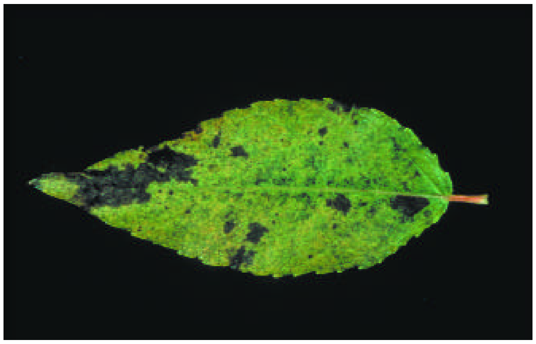
Deciduous, large tree up to 50 meters tall. Grows in riparian strips, flood plains, and other moist to wet areas from low to middle elevation. Found in pure stands or mixed with *Alnus rubra* and *Acer macrophyllum*.

Leaves

Deciduous, alternate, heart-shaped leaves with pointed tips and finely toothed margins. Leaves are thick and shiny above, pale below, 3 to 5 centimeters in diameter, 8 to 12 centimeters long.

Ozone injury symptoms

Chlorosis of older leaves first, then dark pigmented stipple; accelerated senescence.



With injury.

With injury.

No injury.

Potentilla flabellifolia (Fan-leafed cinquefoil)

Description and habitat

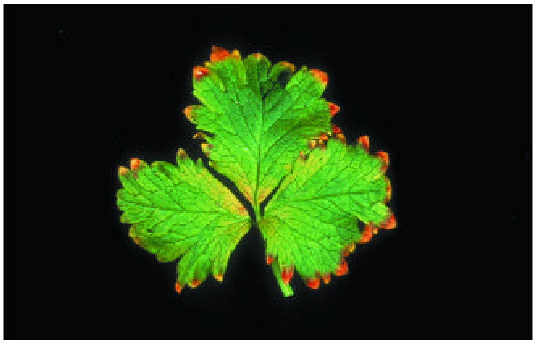
Densely spreading, low plant up to 30 centimeters tall, with branched, woody stems. Grows in moist alpine and subalpine meadows and rocky sites.

Leaves

Leaves are clustered at base and along stem. Compound leaves with three fan-shaped lobes, deeply toothed and hairless, 2 to 3 centimeters long.

Ozone injury symptoms

Leaf curl and chlorosis, with marginal necrosis. Accelerated flowering and early leaf senescence.



With injury.

No injury.

Pseudotsuga menziesii (Douglas-fir)

Description and habitat

Large, to 70 meters tall, crown of young trees pyramidal with a stiffly erect leader, branches spreading to drooping. Found at low to middle elevations, including moist, west-side montane locations and dry east-side locations, often dominating sites with well-drained soils, mixed with other conifer species such as *Tsuga heterophylla* (west side) and *Pinus ponderosa* (east side).

Leaves

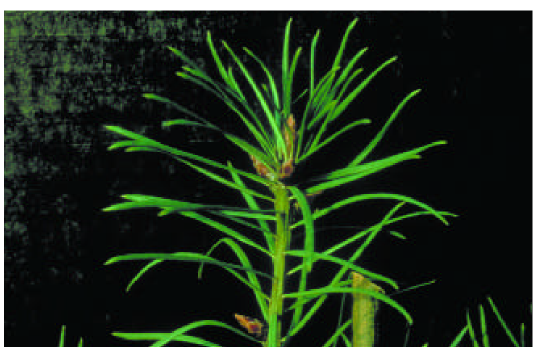
Needles flat, yellowish-green, 2 to 3 centimeters long, with pointed tips.

Ozone injury symptom

Chlorotic mottle.

With injury.

With injury.



No injury.

Ribes bracteosum (Stink currant)

Description and habitat

Upright deciduous shrub, up to 7 meters in height. Grows in moist, exposed areas from low to subalpine elevations.

Leaves

Alternate deciduous maple-shaped leaves, 5 to 20 centimeters wide, with five to seven deep lobes and toothed margins. Yellow glands on stems and leaves have a distinctive acrid odor when crushed.

Ozone injury symptoms

Leaves have yellow blotchy appearance and dark brown or black stipple.

With injury.

No injury.

Rubus parviflorus (Thimbleberry)

Description and habitat

Upright deciduous shrub, up to 3 meters tall, often growing in thick clumps from branching rhizomes. New growth is hairy and glandular. Grows in open clearings or disturbed sites, or open forests (often with *Alnus*) from low to subalpine elevations.

Leaves

Deciduous, alternate, maple-shaped leaves with three to seven lobes, on long stalks covered with fine hairs. Up to 25 centimeters wide.

Ozone injury symptoms

Inner leaf necrosis, chlorosis and bronzing, followed by leaf droop and accelerated senescence.

With injury.

No injury.

Rubus spectabilis (Salmonberry)

Description and habitat

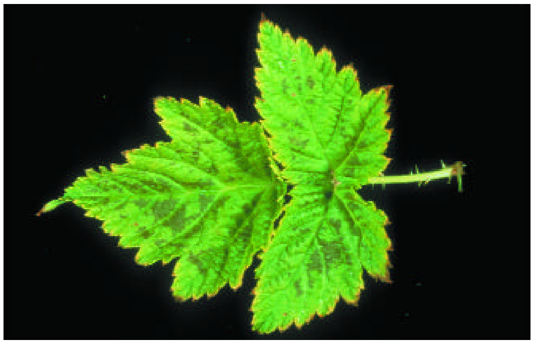
Upright deciduous shrub, up to 4 meters in height, often growing in thick clumps from branching rhizomes. Branches and twigs have scattered thorns. Grows on moist sites in forest clearings and disturbed areas, from low to subalpine elevations.

Leaves

Alternate stems each with three leaflets, which are sharply toothed and deeply veined.

Ozone injury symptoms

Purple-brown pigmentation in interveinal portion of older leaves, as well as chlorosis.



With injury.

With injury.

No injury.

Salix scouleriana (Scouler willow)

Description and habitat

Deciduous shrub or small tree with multiple stems up to 12 meters tall. Branches have brown to yellow-brown color and twigs are coated in dense soft hairs. Grows at low to middle elevations in clearings, streamsides, forest edges and mixed conifer-deciduous forests.

Leaves

Alternate, elongated tear-shaped leaves, 3 to 8 centimeters long. Leaves are narrow at the base and widest just above the middle, with rounded tip. Young leaves velvety and light colored, older leaves almost hairless and darker on upper surface.

Ozone injury symptoms

Chlorosis and black stipple over entire leaf, older leaves showing more developed symptoms, followed by premature senescence.

With injury.

With injury.

No injury.

Sambucus racemosa (Red elderberry)

Description and habitat
Deciduous shrub or small tree up to 6 meters tall. Grows along river banks, forest clearings, and other moist sites from low to middle elevations.

Leaves
Opposite leaves, 5 to 15 centimeters long, consisting of five to seven lance-shaped leaflets.

Ozone injury symptom
Slight chlorotic mottle.

With injury.

With injury.

With injury.

No injury.

Tsuga heterophylla (Western hemlock)

Description and habitat

To 60 meters tall with a narrow crown and drooping leader, downward-extended branches and feathery foliage. Ranges from relatively dry to relatively moist sites, often germinating on decaying wood, shade tolerant and often found in the understory, common from low to middle elevations.

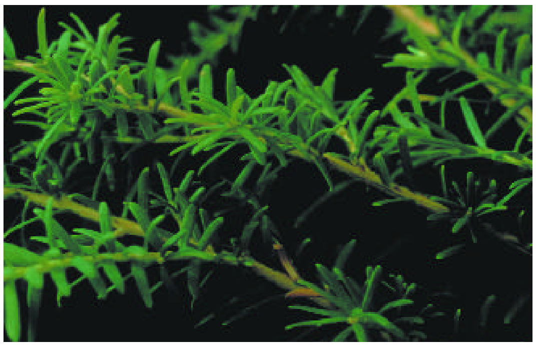
Leaves

Needles short, flat, blunt, widely and irregularly spaced, of unequal length (from 0.5 to 2 centimeters), whitish with two lines of stomata below.

Ozone injury symptom

Chlorotic mottle.

With injury.



With injury.

No injury.

Vaccinium membranaceum (Thin-leaved huckleberry)

Description and habitat

Upright or spreading, densely branched deciduous shrub up to 1.5 meters tall. Young branches with distinctive yellowish color. Grows in understory of dry to moist coniferous forests and in clearings from mid to subalpine elevations.

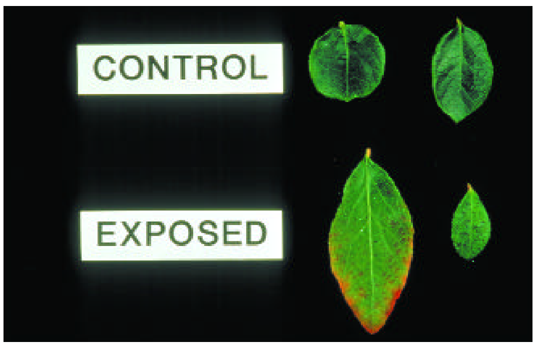
Leaves

Thin, lance-shaped leaves, with pointed tip and finely toothed margins. Leaves are 2 to 4 centimeters long with pale undersurface, turning red to purple in autumn.

Ozone injury symptom

Black stipple appearing on older foliage first.

With injury.



Injured (bottom) and not injured (top).

No injury.

Vaccinium parvifolium (Red bilberry)

Description and habitat

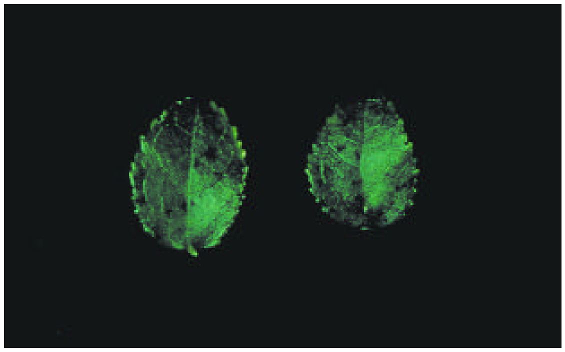
Upright deciduous shrub, up to 4 meters tall, with angled branches and delicate foliage giving plant a light, airy appearance. Grows in moist, low-elevation coniferous forests or forest edges, often on dead logs or in soils containing decaying wood.

Leaves

Thin, oval leaves, up to 3 centimeters long; margins smooth except on some young leaves.

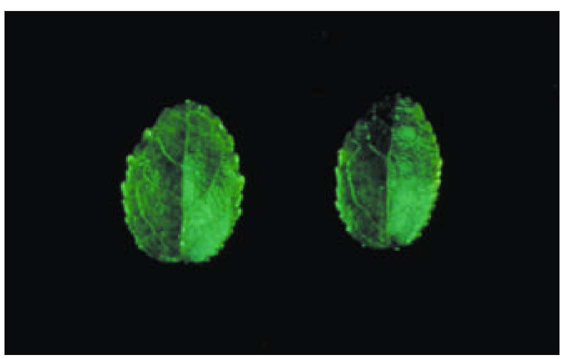
Ozone injury symptoms

Blotchy chlorosis and dark stipple, uniformly spread over leaf surface.



With injury.

With injury.



No injury.

Brace, Sarah; Peterson, David L.; Bowers, Darci. 1999. A guide to ozone injury in vascular plants of the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-446. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 63 p.

Controlled-exposure studies have shown that several plant species native to the Pacific Northwest are potentially sensitive to elevated ambient concentrations of tropospheric ozone. This guide reports visual and descriptive documentation of ozone injury symptoms for common tree, shrub, and herbaceous species in the region. Symptoms observed in leaves of these species include chlorotic mottle, pigmented stipple, necrosis, and premature senescence, with considerable variation among and within species. Resource managers and scientists can use the photo documentation in this guide to identify potential injury to plants in the field, and to distinquish ozone injury from other pathological conditions.

Keywords: Air pollution, forest health, forest pathology, ozone, vegetation injury.

Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, OR 97208-3890

do NOT detach label