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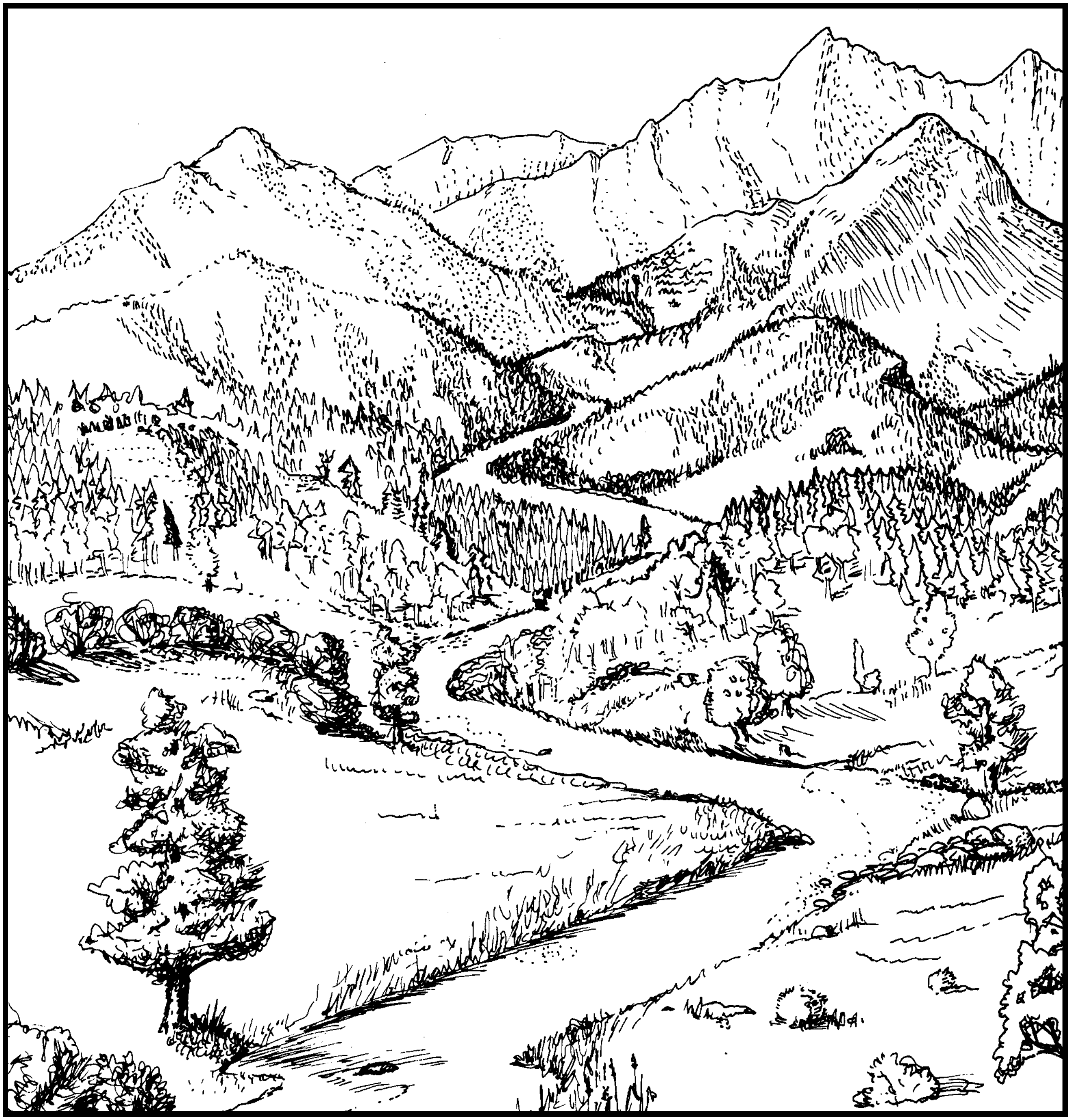
# Guidelines for Evaluating Air Pollution Impacts on Class I Wilderness Areas in the Pacific Northwest

Janice Peterson, Daniel Schmoldt, David Peterson,
Joseph Eilers, Richard Fisher, and Robert Bachman



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# Guidelines for Evaluating Air Pollution Impacts on Class I Wilderness Areas in the Pacific Northwest

## From a workshop held in May 1990, Orcas Island, Washington

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Joseph Eilers, Richard Fisher, and Robert Bachman

**U.S. Department of Agriculture**
**Forest Service**
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## Abstract

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Forest Service air resource managers in the Pacific Northwest are responsible for protecting class I wilderness areas from air pollution. To do this, they need scientifically defensible information to determine critical concentrations of air pollution having the potential to impact class I wilderness values. This report documents the results of a workshop where current information on air pollution effects on aquatic and terrestrial resources and visibility was gathered from participating scientists and managers. Critical air pollution concentrations were determined for sulfur dioxide, nitrogen dioxide, and ozone. Critical values for sulfur and nitrogen deposition to forest ecosystems are listed.



Keywords: Alr pollution, visibility, air resource management, lichens, class I wilderness, Pacific Northwest.

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# Introduction

Class I wilderness areas [1] managed by the USDA Forest Service contain sensitive ecosystems and outstanding scenery that have the potential to be degraded by existing or future air pollutant emissions. The Clean Air Act as amended in 1977 (Public Law 95-95) gives Federal land managers, including the Forest Service, ". . . an affirmative responsibility to protect the air quality related values (including visibility) . . . within a class I area." The 1990 amendments to the Clean Air Act (Public Law 101-549) reaffirm the importance of this responsibility. Forest Service land managers need information to help them prevent air pollution from causing unacceptable changes to air quality-related values (AQRVs) (table 1) within lands they are mandated to protect.

Information required by Forest Service managers to protect AQRVs in class I areas includes:

- Components, or sensitive receptors (table 1), of the AQRVs that exist within the class I areas and are the most vulnerable to degradation from air pollution.
- Acceptable limits of air pollution-caused changes (limits of acceptable change) for these sensitive receptors.
- The amount necessary and condition under which various pollutants could be expected to cause more than the acceptable change in sensitive receptors.
- The current level of air pollution impact within the wilderness.
- Legal mechanisms that empower Forest Service managers in air resource management decisionmaking.

This report summarizes the results of a workshop designed to provide Forest Service air resource managers in Washington and Oregon with the information described in the first three categories shown above. Legal mechanisms for Forest Service managers to participate in air resource management decisionmaking are already established and are described in a following section, "Legal Mechanisms."

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[1] Class I wildernesses are those greater than 2024 hectares that were in existence as of August 7, 1977, and any later expansions made to these wildernesses. All other National Forest System lands are class II.

**Table 1—Examples of air quality-related values, sensitive receptors, and potential air pollution-caused changes**

| Air-quality related values | Sensitive receptors | Potential air pollution-caused changes |
|---|---|---|
| Flora and fauna | Grand fir, lichens, and zooplankton | Growth, mortality, reproduction, visible injury, succession, productivity |
| Soil | Alpine soils | Cation exchange capacity, base saturation, pH, structure, metals concentration |
| Water | Vernal pools | Total alkalinity, metals concentration, anion and cation concentration, pH, dissolved oxygen |
| Visibility | High-use vista | Contrast, visual range, coloration |
| Biological diversity | Diatoms | Loss or depletion of a species |
| Cultural-archaeological | Cave drawings | Decomposition rate |
| Odor | Wilderness user | Anthropogenic odors |

## Workshop Organization

The 4-day workshop was held on Orcas Island, Washington, in May 1990. Participants included about 30 scientists knowledgeable in the effects of air pollution on ecosystems, 30 Forest Service managers with air resource management responsibilities, and a few supporting resource people. The participants were organized into five working groups to review and discuss AQRVs, sensitive receptors, pollutant loadings, and resource impacts. Each working group specialized in one of the following areas: aquatic habitats (biota), aquatic habitats (chemistry), terrestrial habitats (lower plants [lichens and bryophytes]), terrestrial habitats (higher plants), or visibility. Participants were divided into workgroups as follows: [2]

**Aquatic habitats-biota** — Dave Brakke (group leader), Ann Acheson (recorder), Jim Bull, Lynn Burditt, Nancy Diaz, Dennis Haddow, Monty Heath, John Hook, Phil Kaufman, Deborah Potter, and Bob Wissmar.

**Aquatic habitats-chemistry** — Jim Clayton (group leader), Val Descamps (recorder), Roger Blair, Joe Eilers, Dale Horn, George Ice, Randy Shepard, Kirk Wolff, Richard Woodward.

**Terrestrial habitats-lower plants** — Jim Agee (group leader), Shirley Clark (recorder), Bob Brackett, Sue Ferguson, Rob Harrison, Bill Lowery, Fred Rhoades, Bruce Ryan

**Terrestrial habitats-higher plants** — Dave Tingey (group leader), Susan Caplan (recorder), Tony Basabe, Clif Benoit, Phyllis Green, Jan Henderson, Deborah Mangis, Lou Pitelka, and Walt Schloer.

**Visibility** — Mark Pitchford (group leader), Margaret Petersen (recorder), Jim Bates, Margi Böhm, Jim DeHerrera, Dave Dietrich, Rich Fisher, Dick Grace, Ron Henry, Tim Larson, Ron Pugh, Terry Skorheim, and Bernie Weingardt.

[2] Affiliations of participants are given in appendix F.

**Other staff** — Bob Bachman, Jim Brain, Dave Bray, John Drabek, Doug Fox, Rich Kang, Mike Kania, Dave Peterson, Janice Peterson, Dan Schmoldt, and Walt Weaver.

Forest Service managers were responsible for (1) identifying and describing AQRVs existing in each class I wilderness and (2) for defining the limits of acceptable change for the AQRVs identified as sensitive receptors. The scientists' roles were to (1) identify sensitive receptors among the AQRVs listed for the class I wilderness areas, (2) describe their relative susceptibility to air pollutants, and (3) determine the quantity of various pollutants expected to cause limits of acceptable change to be exceeded. Information was gathered on the sensitivity of AQRVs to the effects of sulfur and nitrogen deposition, ozone exposure, and particulate (as they apply to visibility impairment). A detailed description of the workshop design and the formal knowledge elicitation techniques used to gather information can be found in Schmoldt and Peterson (1991).

## Legal Mechanisms

### Wilderness Act

The Wilderness Act (Public Law 88-157) gives the Forest Service the responsibility to manage designated wildernesses to preserve and protect their wilderness character. The Wilderness Act defines wilderness as ". . . an area where the earth and its community of life are untrammeled by man. . ." and ". . . an area of undeveloped Federal land retaining its primeval character and influence. . . " It is to be "protected and managed so as to preserve its natural conditions. . . ." Untrammeled means not subject to human controls or manipulations that hamper the free play of natural forces. The regulations for managing wilderness and primitive areas state that". . . National Forest Wilderness resources shall be managed to promote, perpetuate, and where necessary, restore the wilderness character of the land. . . ." The National Forest Management Act (Public Law 94-588) gives the Forest Service the authority to determine the management goals and objectives for wilderness.

The Wilderness Act and regulations developed to implement it do not directly address air quality or air pollution impacts to wilderness. They do provide, however, direction to the Forest Service for determining what should be protected in wilderness (the earth and its community of life) and to what degree (preserve its natural conditions). As a result, the Pacific Northwest Region of the Forest Service (Region 6) established the following management principles related to air quality and wilderness:

- All components of the wilderness resource are equally important.
- A wilderness component is important even if the users of the wilderness are unaware of its existence.
- All trophic levels are equally important; for example, micro-organisms are equally important as elk or grizzly bears.
- Even the most sensitive components are to be protected, not just those of "average" or "normal" sensitivity.
- Each wilderness component is important for itself, as well as for how it interacts with other components of the ecosystem.
- Wilderness components are to be protected from human-caused change, not just damage.

Although it may not be possible to manage every wilderness in a natural or near-natural state, each wilderness should be managed for as pristine a condition as the specific biophysical, legal, and political situations will allow.

## The Clean Air Act and the PSD Program

The Clean Air Act Amendments of 1977 include a program for preventing significant deterioration of air quality, referred to as the “PSD program.” The basic objective of the PSD program is to prevent substantial degradation of air quality in areas in compliance with national ambient air quality standards (NAAQS). Primary NAAQS were established by the Environmental Protection Agency (EPA) at levels designed to protect human health. Secondary NAAQS also were established at levels to protect human welfare, though economic and political considerations may have influenced these standards. Welfare standards are not considered sufficient to protect sensitive ecosystem components, thereby making it vital that the Federal air resource manager become involved in the PSD process.

Before certain new or modified air pollution sources are created, a PSD permit must be sought from the appropriate air regulatory agency. In Region 6, the Oregon Department of Environmental Quality and the Washington Department of Ecology have been delegated the authority to manage the PSD permitting program. Exceptions to this rule occur when the proposed facility is to be on an Indian reservation or when the permit is for an energy facility under the jurisdiction of the State of Washington Energy Facility Site Evaluation Council; in these cases, EPA Region 10 is responsible for PSD permits.

To receive a permit to operate, the applicant must demonstrate that the proposed polluting facility will (1) not violate national or state ambient air quality standards; (2) use the pollution control technology required by the state or EPA to limit emissions; (3) not violate either class I or class II PSD increments for sulfur dioxide, nitrogen dioxide, or particulate; and (4) neither cause nor contribute to adverse impacts to AQRVs in any class I area.

The PSD increments are allowable pollutant concentrations that can be added to baseline concentrations over either a 24-hour or an annual period. The values developed by the EPA as PSD increments were not selected by any existing information on concentration limits needed to protect specific resource values. It therefore is possible that a class I wilderness could be impacted without exceeding the increments; for example, the particulate increment does not prevent visibility impairment.

The role of the Forest Service manager is to determine if there is a potential for a new source of air pollution to exceed a limit of acceptable change in a sensitive receptor or AQRV. This determination does not depend on whether the PSD increments have been exceeded or not. The PSD increments do not necessarily provide adequate protection; for example, there is no PSD increment for ozone although the national ozone standard of 120 parts per billion exceeds the level of known adverse impacts to vegetation. An important consideration is determining whether the baseline or ambient pollutant levels are near levels known to cause an effect or impact; if so, the limit of acceptable change may not be sufficient to protect the resource.

If a proposed facility will not violate any class I increments but the Forest Service can demonstrate to the satisfaction of the air regulatory agency that there will bean adverse impact to a class I wilderness, the regulatory agency shall not issue the PSD permit unless provisions are included to mitigate this adverse impact. The Forest Service air resource manager is responsible for determining whether or not the proposed facility will cause a change in a sensitive receptor beyond the limit of acceptable change. The states must consider the concerns of the Federal land manager, but are not bound by them. A state’s discretion is limited to whether or not the Federal land manager has

satisfactorily demonstrated that the source will have an adverse impact on an AQRV. It therefore is incumbent on the Federal land manager to submit a scientifically sound demonstration that the proposed facility will cause a change beyond the limit of acceptable change.

Three questions must be answered in response to every PSD permit application:

1. What are the identified sensitive receptors within each class I wilderness that could be impacted by the new source?

2. What are the limits of acceptable change for the identified sensitive receptors?

3. Will the proposed facility result in pollutant concentrations or atmospheric deposition that will cause the identified limit of acceptable change to be exceeded?

The answers to the first two questions should be based on the management goals and objectives for wilderness areas. The third is a technical question whose answer must be based on modeled analyses of emissions, meteorology, topography, atmospheric chemistry, and pollutant deposition.

If a proposed facility will cause a violation of class I increments, the PSD permit still can be issued if the applicant demonstrates to the satisfaction of the air regulatory agency that the facility will not create an adverse impact to a class I area. When the increments are exceeded, the burden of proof is on the applicant to demonstrate that a particular new polluting source will not impact wilderness AQRVs. When increments are not exceeded, the burden of proof is with the Federal land manager.

Close coordination between the Forest Service and the air regulatory agency is required in the PSD permitting process. The air regulatory agency makes the final determination to grantor deny a PSD permit in nearly all cases. The Forest Service never has the authority to grantor deny a PSD permit; however, the Forest Service is the party authorized to define limits of acceptable change for sensitive receptors in class I wilderness areas—that is, to define what constitutes an adverse impact to an AQRV.

The Forest Service must be able to provide timely, credible, and effective recommendations to state air regulatory agencies to protect wilderness from potential air pollution impacts. States often have short time frames for reviewing permit applications, which requires the Forest Service to develop and submit permit recommendations quickly. Lengthy analyses, based on individual cases as they occur, consequently cannot be performed within the time constraints of the permitting process. The intent of the workshop and this resulting document was to streamline the procedures that a Federal land manager might follow to make an informed and valid recommendation.

For a Forest Service recommendation to be effective it must be (1) scientifically sound, (2) legally acceptable, and (3) philosophically justified. The Forest Service could make, for example, a timely permit recommendation that was scientifically accurate; however, if a state did not understand the legal mandates and philosophy behind what the Forest Service was trying to protect, the state could reject the Forest Service recommendation. It is important that the Forest Service coordinate with public interest groups and inform the general public about air pollution and wilderness protection concerns.

## Conclusions

Forest Service air resource managers have legal mechanisms available to them to help protect class I wilderness from air pollution impacts. The Clean Air Act is an available tool for meeting the management goals and objectives developed under the Wilderness Act and the National Forest Management Act. To effectively participate in the PSD process, Forest Service managers must (1) make management decisions on which components of the wilderness resource should be protected from air pollution impacts and to what degree; (2) provide high-quality information on the existing condition of air quality-related values, atmospheric deposition, and air chemistry in wilderness; and (3) understand the complexities of state PSD permitting processes and be skillful in using the process. By working with state air regulatory agencies and developing and implementing effective wilderness air resource monitoring programs, Forest Service managers can help maintain the wilderness resource for present and future generations.

# Overview of the Pacific Northwest Region

The Pacific Northwest is diverse in environment and vegetation. Oregon and Washington encompass wet coastal and dry interior mountain ranges, extensive coastline, interior valleys and basins, and high desert plateau. Moisture, temperature, and geologic features differ greatly. Natural vegetation types range from dense coastal forests of towering conifers through woodland and savanna to shrub steppe. Landforms range from level river valleys and lava plains to precipitous mountain slopes. Elevations start at sea level and extend to over 4200 meters. Volcanism has dominated the shaping of much of the landscape, although sedimentary and metamorphic geologic materials also are common. Soils in mountainous areas often are poorly developed, especially in areas subject to recent glaciation.

The climate of Oregon and Washington is highly variable due to the complex interaction between maritime and continental air masses and the mountain ranges, particularly the Cascade Range that divides the States into eastern and western parts. Western Oregon and Washington have maritime climates characterized by mild temperatures with prolonged cloudy periods and muted temperature extremes. Winters tend to be wet and mild and summers cool and relatively dry. This area receives heavy precipitation, primarily as rain, with 75 to 85 percent of it occurring from October through March. Snow is proportionally more important at higher elevations.

Eastern Oregon and Washington combine features of both maritime and continental climates. Temperatures fluctuate more widely than west of the Cascade Range: winters are colder, summers are hotter, and frost-free seasons are shorter. Precipitation is considerably less than to the west because of the rain shadow effect of the Cascade Range.

The forests of western Washington and northwestern Oregon are the prime example of mesic temperate forests in the world (Franklin and Dyrness 1973). Many of the dominant species, including Douglas-fir, western hemlock, and Sitka spruce, are endemic to this coastal forest region.[1] These and other species find their center of distribution and attain their maximum development here.

Interior southwestern Oregon is warmer and drier, and California species such as sugar pine, incense-cedar, and tanoak give this forest region its character. The eastern Washington and Oregon forests are primarily Rocky Mountain forest types where

[1] Scientific nomenclature for all species is given in appendix E.

ponderosa pine dominates at lower elevations and subalpine fir at higher elevations. In the interior forests of the eastern slopes of the Cascade Range and in extreme northeastern Washington, Pacific coastal elements mix with the Rocky Mountain elements. Steppe and shrub-steppe, characterized by bunchgrasses (for example, *Festuca idahoensis, Poa sandbergii, Agropyron spicaturn)* and sagebrushes *(Artemisia* spp.), occupy basins in the rain shadow east of the Cascade Range.

Sixteen class I wilderness areas managed by the Forest Service are located in Washington and Oregon for a total land area of just under 1.2 million hectares (table 2). Twelve of the 16 distinct areas are located in the Cascade Range, 3 in northeast Oregon, and 1 in the Oregon coast lowlands (fig. 1). In general, these areas are characterized by rugged, high-elevation terrain, snow-covered mountain peaks, flower-filled alpine and subalpine meadows, panoramic vistas, crystal-clear lakes and streams, and abundant fish and wildlife. Many of the areas support populations of threatened and endangered plants and animals. In some cases, the only known population of a species is within the boundary of one of these wilderness areas. For example, one of the reasons for designation of the Kalmiopsis Wilderness was for protection of *Kalmiopsis leachiana,* a small heath shrub with limited distribution.

**Table 2—Class I wilderness areas in Washington and Oregon managed by the Forest Service**

| Class I Wilderness | Hectares |
|---|---|
| Alpine Lakes | 123 580 |
| Diamond Peak | 21 177 |
| Eagle Cap | 145 506 |
| Gearhart Mountain | 9 236 |
| Glacier Peak | 233 253 |
| Goat Rocks | 42 749 |
| Hells Canyon | 85 270 |
| Kalmiopsis | 68 353 |
| Mountain Lakes | 9 337 |
| Mount Adams | 18 929 |
| Mount Hood | 18 826 |
| Mount Jefferson | 43 285 |
| Mount Washington | 21 170 |
| Paysaten | 214 427 |
| Strawberry Mountain | 27 640 |
| Three Sisters | 115 338 |
| Total | 1 198 180 |

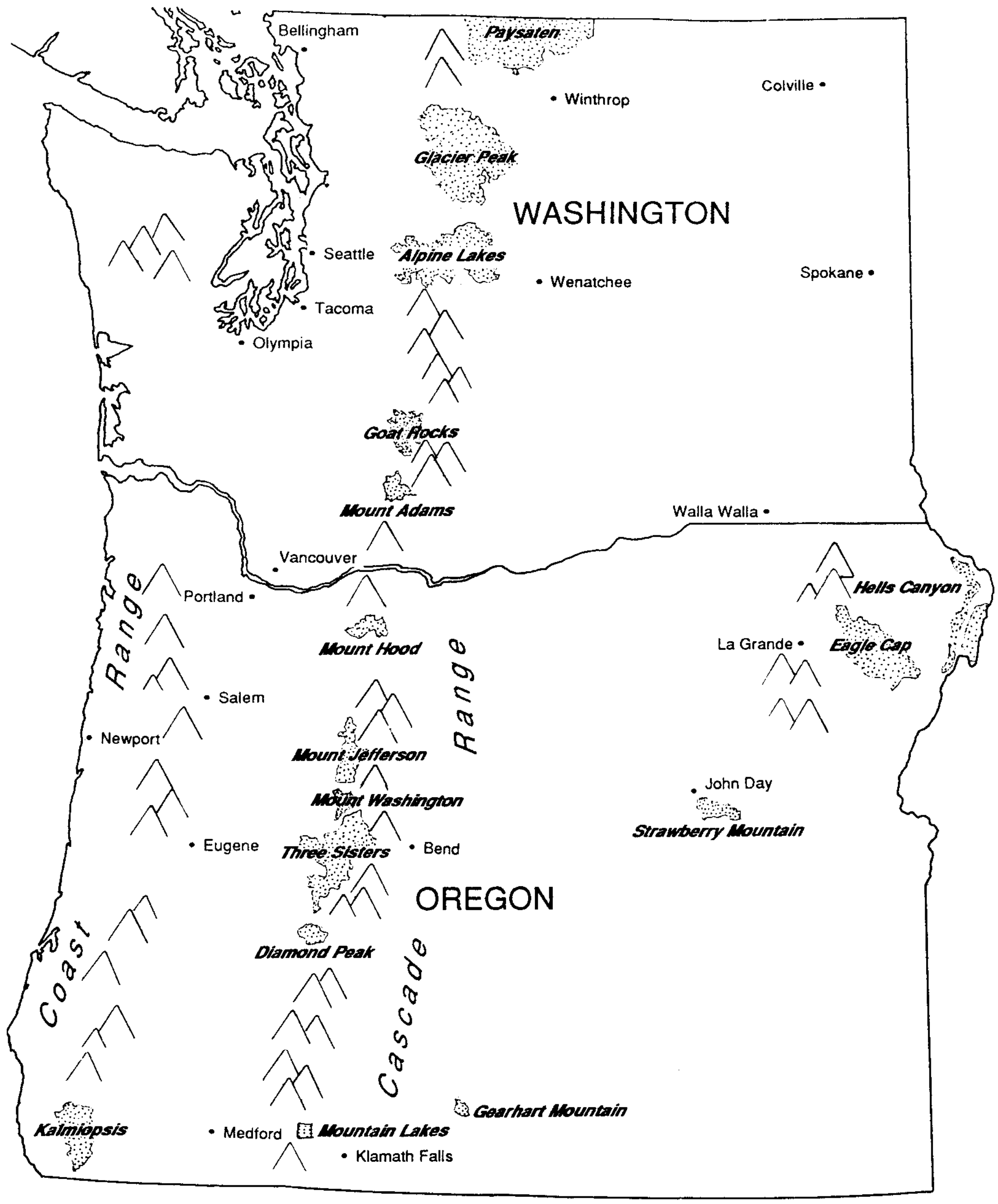


Figure 1 —Location of Oregon and Washington class I wilderness areas.

# Workshop Results—Terrestrial Resources [1]

The effects of air pollutants on terrestrial resources have been studied for the past 50 years. The sensitivity of plant species to abnormally high exposures of ozone, nitrogen, sulfur, and other pollutants has been the focus of many of these studies. Ozone causes plant injury at some locations in California and the Eastern United States, but phytotoxic concentrations of pollutants are generally rare in class I areas of the Pacific Northwest (for example, Böhm 1989), and relatively little is known about the effects of pollutants on ecosystems in this region.

During the 1980s, there was a major research effort in North America and Europe to evaluate forest health and vigor. The motivation for this research effort was increased awareness of the concept of “forest decline” and how stress in forest ecosystems might be affected by atmospheric deposition, including acidic precipitation and ozone (Smith 1984). Much of this work focused on the physiological and growth status of forest stands, and it established dose-response relations under experimental conditions for economically important tree species. There has been less emphasis on the effect of pollutants on organisms such as lichens and mosses. Relatively few taxa of higher plants were evaluated in these studies, and the difficulty of identifying physiological stress in the field has made it difficult to quantify the relation between pollutants and specific organisms or processes.

The members of the terrestrial subgroup addressed two different classes of terrestrial sensitive receptors: trees and herbaceous plants, and lichens and bryophytes. These taxa were evaluated separately for pollutant effects and screening guidelines. Generic guidelines were developed that apply to plant species in all class I areas in the Northwest, because there is insufficient information to justify guidelines for specific wilderness areas.

## Ecosystems and Species

Ten ecosystem types were identified that can be used to help identify specific AQRVs in Pacific Northwest class I wilderness. These types are intended to encompass the range of terrestrial systems (for example, Franklin and Dyrness 1973) that might be found at any location from rocky outcrops to intermittent wetlands. These ecosystem types are shown in the following tabulation:

[1] Compiled by David Peterson.

| Ecosystem | Abbreviation |
|---|---|
| Douglas-fir/western hemlock | DF |
| Pacific silver fir | SF |
| West-side subalpine | WS |
| East-side subalpine | ES |
| West-side alpine | WA |
| East-side alpine | EA |
| East-side Douglas-fir | ED |
| East-side ponderosa pine | EP |
| Sagebrush shrubland | SH |
| Mixed evergreen | ME |

These ecosystems are found in Pacific Northwest class I wilderness areas as shown in table 3.

Sixteen conifer species are commonly found in these ecosystems (Franklin and Dyrness 1973). Their relative abundance and successional status in the different ecosystems are shown in table 4.

## Trees and Herbaceous Plants

### Ozone

Some areas of the United States experience phytotoxic levels of ozone, and studies have tended to focus on dominant species in those areas (for example, Miller and others 1989). Few data are available for dominant tree species of the Pacific Northwest, especially for mature trees, and almost no data for herbaceous species. As a result, screening guidelines were established to be general enough to apply to all species for potential stress from air pollutants.

Exposure of plants to elevated levels of ozone can produce several quantifiable effects, including visible injury, reduced photosynthetic capacity, increased respiration, premature leaf senescence, and reduced growth (Peterson and others 1987, 1991; Pronos and Vogler 1981; Reich and Amundson 1985). The severity of effects depends on pollutant concentration, duration of exposure, and other environmental factors. Sensitivity to ozone differs within and among species because of differences in uptake (Reich 1987) and genetic factors (Karnosky and Steiner 1981).

The immediate effect of elevated ozone levels in wilderness areas may be one or more of the following: foliar injury, decreased leaf longevity, reduced carbon gain of foliage, and reduced plant growth. Other effects could include alteration of carbon allocation, greater susceptibility to environmental stress (such as low soil moisture, insects, and fungi), changes in plant community composition, and loss of sensitive genotypes from a population (Fox and others 1989, Treshow 1984).

Although a change in a physiological process (for example, photosynthesis) is probably the earliest detectable evidence of pollutant stress, visible signs of damage (for example, chlorosis or leaf senescence) are easier and more practical to detect in class I areas. Much of the existing data on ozone stress in conifers has been compiled for ponderosa pine and Jeffrey pine because of their high sensitivity to elevated ozone concentrations. Injury levels have been established for these species for chlorotic injury and needle longevity, based on studies conducted in the Sierra Nevada and San Bernardino Mountains of California (Duriscoe and Stolte 1989, Miller and others 1989, Pronos and others 1978). These and other data collected by these researchers are the best information

**Table—Ecosystem types that can be expected in specific Pacific Northwest class I wilderness areas**

| | Ecosystem [a] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wilderness | DF | SF | WS | ES | WA | EA | ED | EP | SH | ME |
| Alpine Lakes | X | X | X | X | X | X | | | | |
| Diamond Peak | | | X | X | X | X | | | | |
| Eagle Cap | | | | X | | X | X | | | |
| Gearhart | | | | X | | | X | X | | |
| Glacier Peak | X | X | X | X | X | X | X | X | | |
| Goat Rocks | | | | | X | X | | | | |
| Hells Canyon | | | | X | | X | X | X | X | |
| Kalmiopsis | | | X | | | | | | | X |
| Mount Adams | | | | X | | X | | | | |
| Mount Hood | | | X | | X | | | | | |
| Mount Jefferson | X | X | X | X | X | X | X | X | | |
| Mount Washington | X | X | X | | X | X | | | | |
| Mountain Lakes | | | X | X | X | X | | | | |
| Pasayten | | X | | X | | X | X | X | | |
| Strawberry Mt. | | | | | | X | X | X | X | |
| Three Sisters | X | X | X | X | X | X | X | X | | |

[a] Ecosystems:
DF Douglas-fir/western hemlock;
SF Pacific silver fir;
WS west-side subalpine;
ES east-side subalpine;
WA west-side alpine;
EA east-side alpine;
ED east-side Douglas-fir
EP east-side ponderosa pine;
SH sagebrush shrubland; and
ME mixed evergreen.

available on field-level analysis of pollutant stress. Additional experimental data on the effects of ozone on seedlings are mailable for some conifers found in the Pacific Northwest (Hogsett and others 1989). These data sources were used to develop condition classes for all conifers considered as sensitive receptors, even though data were not available for all species.

Four condition classes were established with respect to ozone effects: no injury, slight injury, moderate injury, and severe injury. These condition classes are based on a per-tree evaluation. A given stand can have trees in multiple condition classes, so overall stand condition can be stated as percentages of each condition class. Acceptable distribution of condition classes can be set, or alternatively the condition of a stand can be defined conservatively as being synonymous with the tree with the most severe condition class. Condition classes and ozone concentrations associated with those classes [2] (Miller and others 1983) are as follows:

[2] Miller, Paul R. 1989. Unpublished date on ozone effects on conifers. On file with: USDA Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507.

| Condition class | Needle age class with chlorotic mottle | Needle retention (percent of normal) | Ozone concentration (7-hr growing season mean) |
|---|---|---|---|
| *Amount of injury* | *Years* | *Percent* | *Parts per billion* |
| None | None | >80 | <60 |
| Slight | 5 | 71-80 | 61-70 |
| Moderate | 3-4 | 41-70 | 71-90 |
| Severe | 1-2 | <40 | >90 |

These condition classes are based on visible injury characteristics observable in the field (Muir and Armentano 1988). The relation of these condition classes to tree growth is unknown, although it has been shown for Jeffrey pine that photosynthesis is reduced by 50 percent when 30 percent of needles show chlorotic mottle (Patterson and Rundel 1989). Only detailed long-term monitoring of many mature trees will establish the relation between growth and ozone exposure (Peterson and Arbaugh 1988; Peterson and others 1987, 1991).

Areas of the Cascade Range east of Puget Sound and Portland are subject to episodes of high ozone concentration during periods of atmospheric stability. The affect of these occasional episodes on conifers is poorly quantified but may produce substantial stress and affect the condition class of trees (Hogsett and others 1989). We offer no guidelines here for these ozone episodes, because there are no data to base any on. The potential effects of these episodes on plants should be considered, however, when the impacts of ozone exposure on wilderness are being evaluated. The probability of effects will likely be greater downwind from large metropolitan areas.

Hardwood tree species have different leaf injury symptoms than conifers, and few data are available on the effects of ozone on hardwoods (Jensen and Masters 1975). The condition classes for hardwoods are similar to those for conifers, although an additional class has been added:

| Condition class | Leaf area with chlorotic mottle | Ozone concentration (7-hr growing season mean) |
|---|---|---|
| *Amount of injury* | *Percent* | *Parts per billion* |
| None | 0 | <70 |
| Very slight | 1-20 | <70 |
| Slight | 21-40 | 71-90 |
| Moderate | 41-60 | 91-120 |
| Severe | 61-100 | >120 |

There are so few data on the effects of ozone on herbaceous plant species in the Pacific Northwest that it is difficult to define condition classes. The condition classes for hardwood species therefore should be used until additional data are available.

**Table 4—Conifer types and their successional status in the 10 Pacific Northwest ecosystem types**

| Conifer species | Ecosystem [a] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DF | SF | WS | ES | WA | EA | ED | EP | SH | ME |
| Douglas-fir | S | S | | s | | | C | | | S,C |
| Western hemlock | C | c | | | | | | | | |
| Western redcedar | c | c | | | | | | | | |
| Pacific silver fir | | C | c | | | | | | | |
| Alaska yellow-cedar | | c | c | | | | | | | |
| Mountain hemlock | | | C | c | c | | | | | |
| Subalpine fir | | | s,c | C | | c | | | | |
| Western white pine | s | s | | | | | | | | |
| Lodgepole pine | | | | S | | | S | | | |
| Alpine larch | | | | c | | c | | | | |
| Whitebark pine | | | | s | | s | | | | |
| Grand fir | | | | | | | C | | | |
| Noble fir | | s | s | | | | | | | |
| White fir | | | | | | | C | | | c |
| Ponderosa pine | | | | | | | S | C | | s |
| Western juniper | | | | | | | | | c | |
| Port-Orford-cedar | | | | | | | | | | c |
| Red fir | | | | | | | | | | c |
| Incense-cedar | | | | | | | | | | c |
| Western larch | | | | | | | s | | | |
| Sugar pine | | | | | | | s | | | s |

S = major early seral species;
C = major late seral species;
s = minor early seral species; and
c = minor late seral species.

[a] Ecosystems:
DF Douglas-fir/western hemlock;
SF Pacific silver fir;
WS west-side subalpine;
ES east-aide subalpine;
WA west-eide alpine;
EA east-side alpine;
ED east-side Douglas-fir
EP east-side ponderosa pine;
SH sagebrush shrubland; and
ME mixed evergreen.

## Sulfur

Few data are available on the effects of sulfur compounds on mature trees or other native plants, and there is a wide range of sensitivities to ambient sulfur compounds (Davis and Wilhour 1976, Westman and others 1985). Limited data on tree seedlings [3] (Hogsett and others 1989) indicate that sulfur dioxide ($SO_2$) concentrations below 20 parts per billion (24-hour mean) do not produce visible injury symptoms. Slight injury is found to ponderosa pine and lodgepole pine above 40 parts per billion and moderate injury above 65 parts per billion. Slight injury is found for Douglas-fir above 65 parts per billion. It is difficult to set condition classes for Pacific Northwest plant species based on so few data. Only general guidelines therefore are suggested that are based on these data, evidence from recent studies, and expert opinion of workshop participants. To maximize protection of all plant species, maximum $SO_2$ concentrations should not exceed 40 to 50 parts per billion, and annual average $SO_2$ should not exceed 8 to 12 parts per billion.

Despite the lack of good quantitative information, the relative sensitivity of Pacific Northwest tree species to $SO_2$ can be ranked (Davis and Wilhour 1976). This list can be referred to if a greater level of resolution is needed. Sensitivity to $SO_2$ is as follows, listed from most to least sensitive:

| Conifers | Broadleaf trees |
|---|---|
| Grand fir | Thinleaf alder |
| Subalpine fir | Western paper birch |
| Western redcedar | Sitka mountain-ash |
| Western hemlock | Water birch |
| Douglas-fir | Douglas maple |
| Western white pine | Bitter cherry |
| Ponderosa pine | Common chokecherry |
| Lodgepole pine | Blueberry elder |
| Western larch | Willow (several species) |
| Engelmann spruce | Columbia hawthorn |
| Western juniper | Black cottonwood |
| Pacific yew | Black hawthorn |
| | Quaking aspen |

Total sulfur loadings generally are low in the Pacific Northwest, although there are some areas adjacent to smelters and power plants where total sulfur deposition is locally high. The effects of sulfur deposition, especially sulfates, often are mediated through soil processes such as cation exchange. Deposition must be high to have potentially toxic effects. Fox and others (1989) determined that 20 kilograms of sulfur per hectare per year is the maximum long-term deposition that can be tolerated without impacts in most terrestrial ecosystems; this is based on several assumptions about soil cation exchange capacity and mineral weathering rates. Effects are very unlikely below 5 kilograms per hectare per year. Without additional data, these general guidelines can be used for the Pacific Northwest as a first approximation. Soil properties differ widely in the region, however, and it is important to consider soil effects with respect to specific wildernesses.

[3] Miller, Paul R. 1989. Unpublished date on $SO_2$ effects on conifers. On file with: USDA Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside CA 92507.

**Nitrogen**

Few data are available on the effects of nitrogen dioxide ($NO_2$) on plant species in the Pacific Northwest. Scattered data from scientific studies (for example US-EPA 1982) and expert opinion of workshop participants were used to establish some general guidelines for injury and exposure:

| Condition class | $NO_2$ concentration (24-hour annual mean) |
|---|---|
| *Amount of injury* | *Parts per billion* |
| None | <15 |
| Potential | 15-50 |
| Severe | >50 |

These values are defined for all plant species in the Pacific Northwest and should be used only as general guidelines. individual plant species have a wide range of sensitivities.

Nitrogen is a critical nutrient for many plant metabolic processes. Long-term deposition of elevated levels of nitrogen compounds may affect soil microbiological processes, resistance to insects and pathogens, winter injury in conifers, and foliar leaching. Perhaps more important are the potential effects of long-term nitrogen deposition on ecosystem structure and diversity. Nitrogen is a potential fertilizer that can be assimilated preferentially by some plant species (Miller and others 1976); for example, plant species in a nitrogen-poor system, such as a bog, may be replaced by species with higher nitrogen requirements. Based on limited data on ecosystem effects (for example, Fox and others 1989, Smith 1990, US-EPA 1982), generic condition classes can beset for different vegetation types as follows:

| Vegetation type | Potential injury from total nitrogen deposition | | |
|---|---|---|---|
| | No injury | Potential injury | Severe injury |
| | | $Kg \bullet ha^{-1} \bullet yr^{-1}$ | |
| Coniferous forest | <3 | 3-15 | >15 |
| Hardwood forest | <5 | 5-20 | >20 |
| Shrubs | <3 | 3-5 | >5 |
| Herbaceous plants | <3 | 3-10 | >10 |

It should again be recognized that these are general guidelines that do not account for variation in plant resistance. It is also known that acidic fog, which contains sulfur and nitrogen compounds, has the potential to alter the growth of seedlings of some Pacific Northwest tree species (Hogsett and others 1989). These effects generally do not occur under experimental conditions unless pH is below 3.5. This level of acidity has been measured at Stampede Pass in the Mount Baker-Snoqualmie National Forest. Unfortunately, too few data on cloud chemistry or plant effects are available to set guidelines for acidity at this time.

## Lichens and Bryophytes [4]

Lichens and bryophytes are known to be sensitive receptors for air pollution, as determined by several studies (Ferry and others 1973, Galun and Rohnen 1988, Nash and Wirth 1988). There is, however, little information on the sensitivity of lichens and bryophytes in the Pacific Northwest to air pollution. [5] The taxonomy and distribution of lichens in this region also are poorly known.

Lichens and bryophytes play an important role in subalpine and alpine areas by acting as food sources and cover. They also contribute other, less obvious, wilderness values. They are responsible for initial soil development and stabilization in disturbed areas or areas without soil. Epiphytic species, which grow on trees and shrubs, increase surfaces that intercept fog and other aerosols. Some (particularly lichens) emit organic molecules that add to many characteristic "wilderness odors." Their colors and textures contribute to the overall aesthetic values of wilderness.

Lichens are regarded as sensitive to air pollution for several reasons. Water and gas exchange proceeds uninhibited over the entire surface of a lichen, which has neither stomata nor cuticles to exclude gases. Lichens grow slowly and can live for centuries and thereby are exposed to pollution for along time. In addition, lichens tend to concentrate heavy metals and other elements and are not capable of shedding parts of the thallus injured by toxic gases. Lichens reflect the average, cumulative effects of air pollution over time, not just the acute effect of a given concentration.

Lichens often are the most sensitive component of the vegetation within a given ecosystem and can have predictive value in assessing future effects on vascular plants. Reduced vigor of lichens may have direct impacts on an ecosystem because of their importance for nitrogen-fixation, soil stabilization, rock weathering, and food for animals. Bryophytes have a similar crucial role in ecosystem structure and function, although their presence may be subtle to the casual observer.

Lichens and bryophytes have a wide range of sensitivity to various air pollutants, although dose-response relations are poorly quantified. There is some information on sensitivity to $SO_2$, but few data exist on sensitivity to nitrogen oxides ($NO_x$) or hydrogen fluoride (HF) (Nash and Wirth 1988). It is more logical to express the effect of air pollutants on lichens and bryophytes as concentrations, because little is known about cumulative effects of air pollutants. Three sensitivity classes of lichens and bryophytes to air pollution can be defined: sensitive, intermediate, and tolerant. These classes are based primarily on limited experimental data. These classes can be associated with prolonged exposure as follows:

| | Lichen sensitivity class | | |
|---|---|---|---|
| **Pollutant** | **Sensitive** | **Intermediate** | **Tolerant** |
| | | *Parts per billion* | |
| Ozone | <20 | 15-70 | >65 |
| $SO_2$ | 5-15 | 10-35 | >30 |

[4] For further information on lichens and bryophytes, please refer to appendix B.

[5] The National Park Service and Forest Service conducted a joint workshop in April 1991 that will result in a manual of standard methodology for lichen air pollution studies.

Lichens and bryophytes considered sensitive can be expected to show an impact from pollutant levels at or below those listed in the first column. Species considered tolerant can be expected to show no impact until pollutant levels exceed those shown in the last column. No sensitivity classes are indicated for $NO_x$ or HF, because there are too few data to base guidelines on. Overlapping ranges for pollutant exposure are indicated to express the uncertainty in defining sensitivity.

These guidelines are broadly applicable to both lichens and bryophytes. Additional information on species sensitivity is needed for these guidelines to be useful. One of the products of the workshop was an extensive list of lichen and bryophyte flora in the Pacific Northwest, including the known or expected presence of species in each wilderness, as well as the condition class of each species with respect to ozone and $SO_2$ (see appendix B).

## Interactions

The potential for interactions among pollutants should be considered in evaluations of their effects on natural resources. Three general types of interactions are (1) pollutant-pollutant, (2) pollutant-natural stress, (3) and pollutant-genotype. An interaction occurs when the presence of one stress modifies the response to a second stress such that the effect is not additive. The interaction can be antagonistic (less than additive) or synergistic (greater than additive). This can occur as the interactive effects of two gases, such as ozone and $SO_2$, on photosynthesis and growth. It also can occur as the interaction of a pollutant and natural factors, such as ozone stress, drought, and bark beetles (this particular interaction has been documented for conifers in southern California). It probably is beyond the scope of the PSD process to identify pollutant-genotype interactions, but it is important to recognize that there is differential sensitivity within and among populations. There are few data on stress interactions for pollutants and plant species in the Pacific Northwest. Limited data on lichens suggest that there likely are synergistic interactions for ozone and $SO_2$ (DeWit 1976), and ozone and $NO_x$ (Sigal and Nash 1983) for some species. Other potential interactions were estimated by workshop participants. Situations where interactions are likely are indicated in table 5.

**Table 5—Potential pollutant and natural stress interactions**

| | | Deposition | | | | |
|---|---|---|---|---|---|---|
| Pollutant | $SO_2$ | Total N | Total S | Drought | Cold | Insects or pathogens |
| Ozone | X[a] | X | | –[b] | +[c] | X |
| $SO_2$ | | X | | | | X |
| Cloud acidity | | | | | + | |
| Total N | | | | X | X | X |
| Total S | | | | | | |

[a] X = an interaction is likely, but it is not clear if it will be antagonistic or synergistic.
[b] – = antagonistic interaction is likely.
[c] + = synergistic interaction is likely.

# Workshop Results—Aquatic Resources [1]

Aquatic ecosystems, and the biota they contain, represent important air quality-related values in most class I wilderness areas of the Pacific Northwest. Most designated class I wilderness areas in this region are located in the Cascade Range and receive precipitation ranging from 80 centimeters in the southern portion to 300 centimeters in the north on the western slopes; precipitation on the eastern slopes decreases markedly (Jackson 1985). This abundant precipitation provides for extensive lakes, streams, and wetlands, many low in dissolved minerals and presumably sensitive to changes in chemical composition. Most lakes in this region are in subalpine settings, although a high percentage of lakes in the northern Washington Cascades are part of true alpine systems.

The only comprehensive quantitative assessment of aquatic resources in the Oregon and Washington Cascades is from the western lake survey (Landers and others 1987) in which an estimated 1,371 lakes larger than 1 hectare in surface area were represented by a sample of 159 lakes. At least 100 additional lakes are larger than 1 hectare in the non-Cascade areas of Region 6, including an estimated 73 lakes in the Blue Mountains with a median alkalinity of 123 microequivalents (µeq) per liter (Landers and others 1987) and lakes in the Oregon Dunes National Recreation Area within the Siuslaw National Forest. Although rivers, streams, and temporary ponds constitute an important portion of the aquatic resources in the region, only a few have been chemically characterized in a systematic fashion. Most of this section on aquatic resources therefore focuses on lakes.

There is a strong basis for concern that the long-term integrity of lakes in the Cascades could be affected if atmospheric deposition contains pollutants. As a population, lakes in the Pacific Northwest are among the most dilute (that is, contain few dissolved minerals) sampled in the United States, second only to those in the Sierra Nevada (Landers and others 1987). Individual lakes in this region are the most dilute aquatic systems reported anywhere (Eilers and others 1990) and are similar to commercially distilled water. Some of these lakes differ relatively little from the chemistry of current atmospheric deposition; thus it is easy to make the inference that the quality of these resources is closely linked to the chemistry of the deposition. If we compare the precipitation-weighted average annual chemistry at National Trends Network [2] (NTN) sites adjacent to the Cascades

[1] Compiled by Joseph Eilers.

[2] Monitoring sites sponsored by the National Atmospheric Deposition Program (NADP).

with selected lakes east of these sites, we find that the major difference between dilute lakes and precipitation is that the lakes are slightly enriched in calcium ($Ca^{2+}$) and bicarbonate ($HCO_3^-$) (fig. 2).

Concentrations of chloride ($Cl^-$) are lower in the lakes than in the precipitation because the NADP/NTN sites are at low elevation and receive more marine aerosols than high-elevation lakes do. The initial concern for potential impacts to these aquatic resources has focused on potential acidification from anthropogenic emissions of sulfur (S) and nitrogen (N) (Baker and others 1990b, Brakke 1984, Brakke and Waddell 1985, Duncan 1985, Eilers and others 1988, Landers and others 1987, Logan and others 1982, Loranger and Brakke 1988, Loranger and others 1986, Nelson 1991, Nelson and Baumgartner 1986, Nelson and Delwiche 1983, Welch and others 1986).

Sulfate ($SO_4^{2-}$), nitrate ($NO_3^-$), and ammonium ($NH_4^+$) all have the potential to acidify surface waters (Stumm and Morgan 1981). Increased $SO_4^{2-}$ typically is associated with chronic acidification of surface waters (Baker and others 1990b), although $NO_3^-$ (Henriksen and others 1988) and $NH_4^+$ (Schuurekes and others 1988) are important in some cases. Episodic acidification, however, typically is associated with rapid release of accumulated $NO_3^-$ in runoff from melting snow (Eshleman 1988, Schnoor and Nikolaidis 1989, Wigington and others 1990). Episodic acidification may be of particular concern because of the relative importance of nitrogen deposition and the extreme episodic nature of inputs from large snowmelt events and the rapid hydrologic response of watersheds in the West. The acidification of soils and surface waters can contribute to increased mobilization and availability of aluminum (Al), which can be highly toxic to aquatic life, especially if the Al is in the inorganic monomeric form ($Al_i$) (Baker and others 1990a). The toxic effects of surface water acidification are attributed to the combined increase in hydrogen ion ($H^+$) and Al in the presence of low Ca concentrations (Baker and others 1990a).

Organic acids also may play an important role in affecting the acid-base status of surface waters and their sensitivity to acidification. Only waters low in concentrations of both base cations and organic acids are highly susceptible to acidification though (Sullivan 1990). Waters high in base cations (and therefore alkalinity) receive substantial neutralization potential from their watersheds, and therefore typically have the capacity to completely neutralize acidic deposition inputs largely through increased weathering of base cations (Henriksen 1984, Brakke and others 1990). Waters high in organic acids have a similar strong buffering capability that resists further acidification (Kramer and Davies 1988). Nearly all surface waters in this region have low dissolved organic carbon; consequently, the issue of sensitivity in these systems is determined primarily by their base cation concentrations.

Other potential consequences of pollutants in the atmospheric deposition include eutrophication [3] of nitrogen-limited lakes and damage associated with trace contaminants such as metals (for example, mercury [Hg], cadmium [Cd]) and organic compounds (for example, polynuclear aromatic hydrocarbons [PAH] and pesticides). Cases of nitrogen

[3] Eutrophication is the process of increasing lake productivity usually associated with increasing nutrient loads to the lake. Increasing nutrient loads stimulate growth of algae and other aquatic plants, which usually results in decreased lake transparency and a large dissolved oxygen demand during aerobic decomposition.

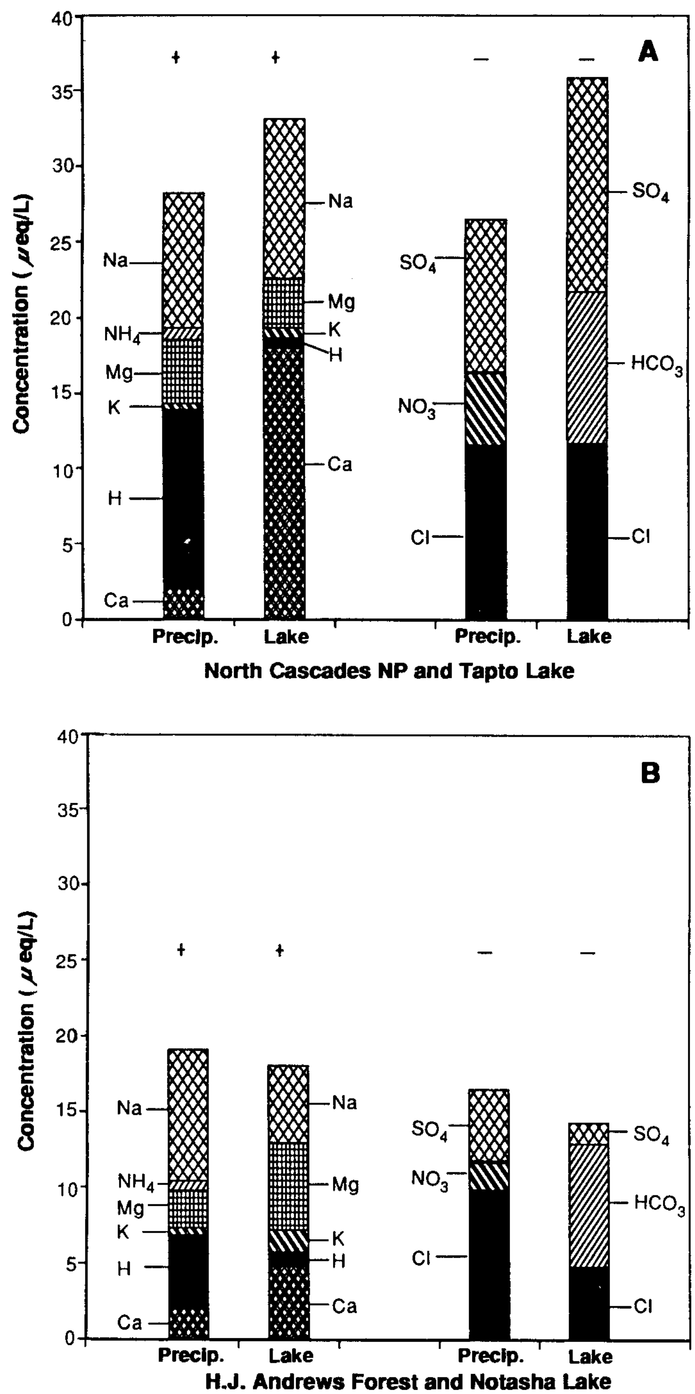


Figure 2—Major ion chemistry of precipitation at two NADP/NTN (1987) sites and adjacent dilute lakes sampled in the western lakes survey (Landers and other 1987) near the NADP sites. Both the precipitation and lake chemistry are from 1985. **A:** NADP/NTN site is at North Cascades National Park, WA (elevation 120 meters); lake sample is Tapto Lake, 4B1 -051 (elevation 1744 meters). **B:** NADP/NTN site is H.J. Andrews Experimental Forest, OR (elevation 436 meters); lake sample is Lake Notasha, 4B1 -060 (elevation 1836 meters).

limitation in oligotrophic [4] western lakes are becoming more widely documented (Axler and others 1981, Goldman 1981, Larson 1988, Morris and Lewis 1988), thereby indicating that increases in nitrogen deposition could be a concern in both episodic acidification and increases in lake productivity. Trace contaminants currently are not addressed in the PSD process and will not be discussed at length here.

Although concern for damage from deposition of atmospheric pollutants is primarily associated with the possible loss of sensitive biota, most studies of atmospheric impacts on aquatic ecosystems have focused on measuring changes in surface water chemistry. Most criteria for screening sensitive waters therefore are based on water chemistry. This reflects the relative ease and precision of collecting and measuring water chemistry compared to quantitative sampling of aquatic organisms. It also reflects a poor state of knowledge of aquatic communities; we are unaware of any comprehensive and systematic studies of aquatic biota in the Cascades. [5] Estimates of potential biological effects resulting from acidification of aquatic resources in the Pacific Northwest therefore must be made by using estimates of changes in water chemistry and changes observed for different aquatic communities from the Eastern United States and Northern Europe. We have attempted to note some groups of sensitive aquatic organisms, but identification of individual sensitive species for this region must wait until basic information on species distributions and their sensitivity to chemical stressors is developed.

## Current Chemical Status of Lakes in the Cascade Range

Potential changes in aquatic resources in this region from a deterioration of air quality can be better understood by first reviewing the current chemistry of these systems. The median alkalinity of lakes in the Cascade Range is near 100 µeq per liter, ranging from a median of 92 µeq per liter in Oregon to a median of 113 µeq per liter in Washington (Landers and others 1987). Of greater interest for the PSD process is the number of lakes in this region with alkalinity values in the range of 10 to 20 µeq per liter. The distribution of lake alkalinity in the Cascade Range from the Canadian border to California is shown in figure 3. The plot also indicates a wide range in lake alkalinity throughout the Cascade Range. The regression equation was developed from lakes sampled during fall when the lakes were well mixed; samples collected during other seasons may yield different predictive equations. Furthermore, local variations in geology and hydrologic flow paths can greatly modify lake alkalinity expected on the basis of generalized geology. This suggests that assessment of lake alkalinity in relatively small areas such as wilderness may require more detailed information than what is available from surveys such as Landers and others (1987). The lakes in the Cascade Range fortunately are primarily bicarbonate systems (Landers and others 1987), and one can estimate surface

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[4] Oligotrophic refers to the process of decreasing lake productivity that usually is associated with decreasing nutrient loads to the lake; it also is associated with toxic affects from increasing acidity and aluminum during acidification. Symptoms include increasing lake transparency, decreased color, and decreasing chlorophyll content.

[5] The National park service currently is funding several studies involving sampling of aquatic biota in the Pacific Northwest. In addition to a long-term study of Crater Lake (Larson 1988), extensive sampling of lakes is being conducted in North Cascades National Park (about 25 lakes), Mount Rainier National Park (about 25 lakes), and Olympic National Park (about 12 lakes). Results from these sampling programs are being compiled at the Cooperative Park Studies Unit, Corvallis, OR. Personal communication, Gary Larson, Oregon State University, Corvallis, OR 97331.

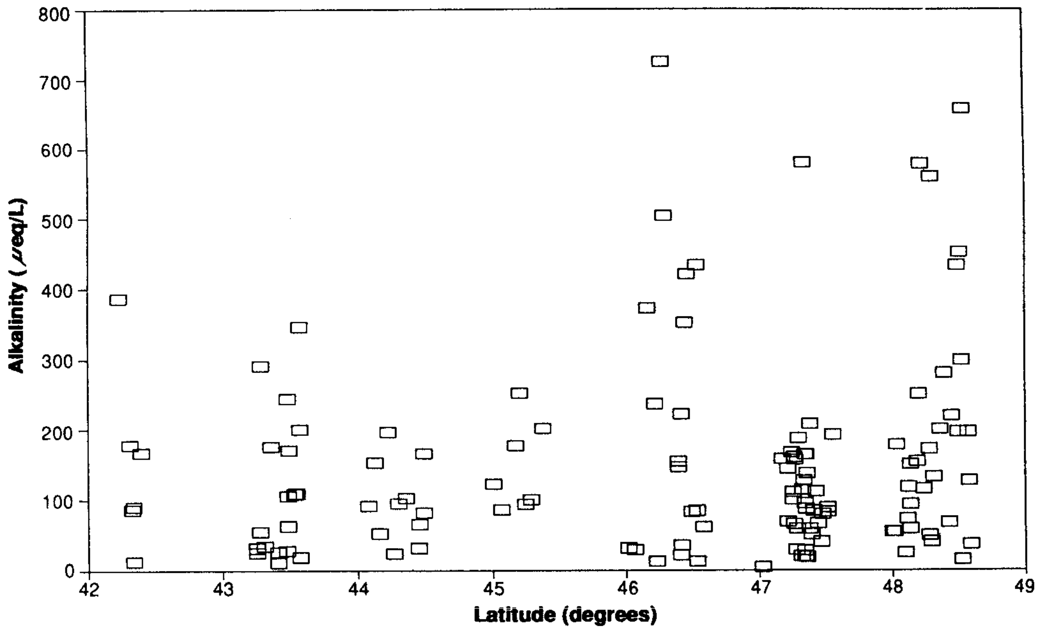


Figure 3—Alkalinity for western lakes survey lakes (Landers and others 1987) in the Cascade Range by latitude. Two lakes, high in alkalinity, are omitted from the plot.

water alkalinity simply from a measurement of conductivity. [6] A regression of alkalinity versus conductivity for lakes in the Cascade Range, omitting two high-alkalinity lakes, yields the following (fig. 4):

$$\text{alkalinity } (\mu\text{eq L}^{-1}) = -17.7 + 9.2\ [\text{conductivity, } \mu\text{S cm}^{-1}]\ .$$

$$n = 128,\ r^2 = 0.94,\ SE = 3.7$$

The high percentage of variance in alkalinity explained by conductivity shows that this inexpensive measurement can be used to conduct rapid assessments of surface water alkalinity throughout the Cascade Range. This regression equation will have poor predictive capability for lakes receiving substantial marine aerosols or those with watershed sources of sulfate; but for most lakes, conductivity can be used in a screening process to accurately estimate alkalinity. With the additional measurements of $SO_4^{2-}$ and pH, the process can be further refined to screen for acidic waters from either watershed or atmospheric sources of sulfur.

A summary of major ion chemistry for dilute lakes in the Cascade Range (table 6) illustrates that low-alkalinity lakes are found throughout the Cascade Range. Weathering of base cations is extremely low in many of these watersheds, and background $SO_4^{2-}$ values also are extremely low; sea-salt-corrected values for $SO_4^{2-}$ typically are near

[6] A few lakes in the west have substantial sources of Sulfate (Lenders and others 1987) attributed to the watershed sources of sulfur (Loranger and Brakke 1988, Stauffer 1990). When the sulfate concentrations are sufficiently great, the lakes can be acidic. For example, West Twin Lake in the Umpqua National Forest has en alkalinity of –5 µeq per liter and a sulfate ($S0_4^{2-}$) concentration of 307 µeq per liter (Eilers and Bernert 1990).

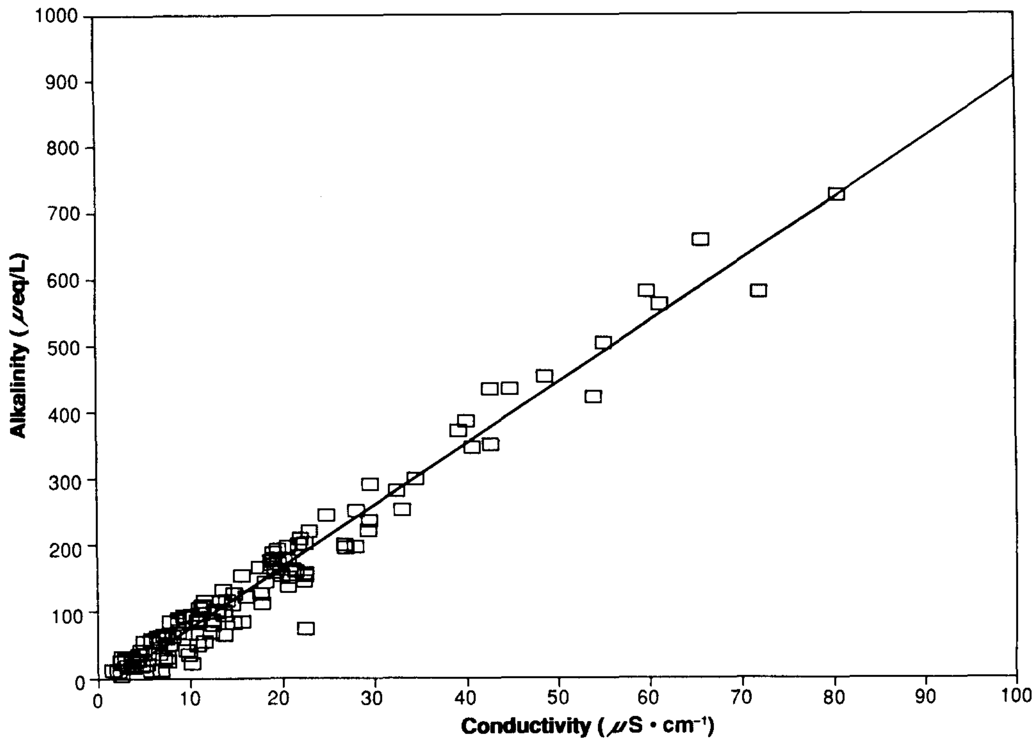


Figure 4—Alkalinity versus conductivity for lakes in the western lakes survey (Landers and others 1987) in the Cascade Range. The line represents the least-squares beat fit from the regression shown in the text.

zero. This is in general agreement with estimates of background sulfate concentrations for areas not receiving acidic deposition (Brakke and others 1969). It is generally accepted that surface waters with chemical characteristics as shown in table 6 are indicative of extremely sensitive systems, but as yet the lakes do not exhibit any signs of acidification from atmospheric deposition (Baker and others 1990b, Nelson 1991). The western lake survey (Landers and others 1987) provides a quantitative assessment of lakes in the region; however, the sampling intensity is generally insufficient to adequately characterize the lake populations in individual wilderness areas. Lake samples were taken on a single day, and all sampling was done in fall. A list of wilderness areas in the region and the number of western lake survey sample lakes show that the sample size was sufficient to develop an acceptable characterization of the lakes only in Alpine Lakes Wilderness (table 7).

## Sensitive Aquatic Indicators

As mentioned previously, the primary concern for maintaining high water quality in wilderness areas is preventing the loss of indigenous (and intentionally stocked) aquatic organisms; but other nonbiotic concerns, such as water clarity, also are important to the wilderness experience. The problems with the use of aquatic organisms as indicators of air pollution stress are twofold: first, little is known about the species of aquatic organisms present in these wilderness areas; and second, little is known about the potential response of these species to changes in water quality. Most studies of species response to acidification have been conducted on species typically found outside the Pacific Northwest.

Although the workshop participants were in favor of using organisms in a monitoring strategy, the absence of good biological data precludes their effective use now. The participants therefore favored use of chemical criteria as indicators of atmospheric

**Table 6—Minimum values for major ion chemistry from groups of lakes in the Oregon and Washington Cascade Range [a]**

| Measurements | Geographic area | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Oregon Cascade Range | | Umpqua National Forest | S. Wash. Cascade Range | Mount Rainier National Park | Wenatchee Mountains | Central Wash. Cascade Range | Mid. Wash. Cascade Range | N. Wash. Cascade Range | |
| Study | [b] | [c] | [d] | [b] | [e] | [b] | [f] | [b] | [g] | [b] |
| Sample size (number) | 42 | 63 | 9 | 20 | 16 | 32 | 31 | 24 | 33 | 12 |
| Population size | 443 | -- | -- | 218 | -- | 329 | -- | 248 | -- | 133 |
| pH (S.U.) | 5.98 | 5.83 | 5.00 [h] | 5.95 | 5.60 | 6.41 | 5.62 | 5.84 | 5.41 | 6.66 |
| Alkalinity (µeq $L^{-1}$) | 11 | 1 | -5 [h] | 4 | 17 | 18 | 4 | 25 | 3 | 15 |
| Conductivity (µS $cm^{-1}$) | 1.6 | 2.6 | 2.9 | 2.6 | 3.6 | 3.0 | 3.9 | 4.7 | 2.8 | 3.9 |
| Dissolved organic carbon (mg $L^{-1}$) | 0.7 | <0.1 | -- | 0.06 | -- | 0.1 | -- | 0.14 | -- | 0.09 |
| $Ca^{2+}$ (µeq $L^{-1}$) | 4 | 4 | 2 | 7 | 10 [i] | 17 | 12 | 34 | 10 | 18 |
| $Mg^{2+}$ (µeq $L^{-1}$) | 3 | 2 | <1 | 4 | 1 [i] | 3 | -- | 3 | 2 | 3 |
| $Na^{+}$ (µeq $L^{-1}$) | 5 | 5 | 7 | 11 | 10 [i] | 7 | -- | 6 | 5 | 11 |
| $K^{+}$ (µeq $L^{-1}$) | 2 | 1 | 2 | 1 | 1 [i] | 1 | -- | 1 | 1 | 1 |
| $SO_4^{2-}$ (µeq $L^{-1}$) | 0.6 | 0.6 | <1 | 4.4 | 0 [i] | 1.3 | -- | 0.6 | 9 | 4.7 |
| $Cl^{-}$ (µeq $L^{-1}$) | 1 | 8 | 2 | 6 | -- | 2 | -- | 1 | 14 | 2 |

[a] Minor ions such as $NH_4^+$, $NO_3^-$, and F, typically measured at their detection limits, are not shown.
[b] Eilers and others 1987, Landers and others 1987.
[c] Nelson and Delwiche 1983.
[d] Eilers and Bernert 1990.
[e] Nelson and Baumgartner 1986.
[f] Logan and others 1982.
[g] Brakke 1984.
[h] Mineral acid lake with a sulfate concentration of 307 µeq $L^{-1}$.
[i] Sea-salt corrected.

degradation; the assumption was that subsequent research will provide support for use of specific values linking the changes in water chemistry with undesirable biological impacts. Suggested water quality parameters that can be used to indicate air quality-related impacts in wilderness areas are shown in table 8. Most of these parameters, except Secchi disk transparency and dissolved oxygen concentrations, can be applied to both lakes and streams. The two named parameters were included to reflect potential changes in lake trophic status caused by either increased deposition of nutrients or effects on the watershed that might impact nutrient export to aquatic systems.

Aquatic organisms also were recognized as potentially valuable indicators of air pollution impacts to wilderness areas. Although no species were identified, selected taxonomic groups were thought to include sensitive species (table 9). The selection of these groups of organisms was based largely on use of these taxa in studies on biological impacts of acidic deposition in North America and Europe (Baker and others 1990a).

**Table 7—Lakes sampled in wilderness areas (excluding National Parks) in the western lake survey [a]**

| State and wilderness [b] | class | Lakes sampled | Lake population [c] | Minimum ANC |
|---|---|---|---|---|
| | | | | *µeq L⁻¹* |
| Washington: | | | | |
| Pasayten | I | 7 | 82 | 127 |
| Mount Baker | II | 1 | NC | 452 |
| Noisy Diobsud | II | 1 | NC | 281 |
| Lake Chelan-Sawtooth | II | 2 | NC | 150 |
| Boulder River | II | 1 | NC | 25 |
| Glacier Peak | I | 8 | 82 | 55 |
| Henry M. Jackson | II | 2 | NC | 79 |
| Alpine Lakes | I | 24 | 241 | 18 |
| Buckhorn | II | 1 | NC | 458 |
| William O. Douglas | II | 5 | NC | 21 |
| Clearwater | II | 1 | NC | 4 |
| Goat Rocks | I | 1 | NC | 504 |
| Indian Heaven | II | 1 | NC | 31 |
| Oregon: | | | | |
| Eagle Cap | I | 8 | 50 | 87 |
| Columbia | II | 1 | NC | 202 |
| Mount Hood | I | 1 | NC | 252 |
| Mount Jefferson | I | 2 | NC | 23 |
| Mount Washington | I | 1 | NC | 52 |
| Three Sisters | I | 8 | 79 | 18 |
| Waldo Lake | II | 2 | NC | 27 |
| Diamond Peak | I | 1 | NC | 35 |
| Sky Lakes | II | 5 | NC | 12 |

[a] Source: Eilers and others 1987. Additional lake data for some of these areas may be obtained from other sources (for example, Brakke 1984, Johnson and others 1985, Logan and others 1982, Nelson and Delwiche 1983, and U.S. Geological Survey open-file reports [for example, Dethier and others 1979]).

[b] Class I wilderness areas for which no western lakes survey samples were collected are Mount Adams, Hells Canyon (no lakes present), Strawberry Mountain, Gearhart Mountain, Kalmiopsis, and Mountain Lakes.

[c] Population estimates (N) for the number of lakes greater than 1 hectare in surface area. Because of the extremely small sample sizes for most of these areas, there is great uncertainty in these estimates. The population estimate for areas with fewer than 7 lakes (NC) is not presented.

Several concerns were identified in the use of biota to monitor effects in Region 6. It was the perception of the participants that the faunistic diversity of wilderness lakes was low, and locating enough organisms for affective biological monitoring might therefore be a problem; for example, molluscs and other benthic invertebrates were used to measure biological damage in Norwegian lakes (Økland and Økland 1986), but the low concentrations of calcium ion ($Ca^{2+}$) in many Cascade lakes may restrict the distribution of these organisms to lower elevation lakes. Other problems were noted with use of amphibians end fish as sensitive indicators: amphibian populations can be greatly affected by prada-

**Table 8—Identification and description of sensitive indicators for surface water**

| Indicator or parameter | Description | Indicates |
|---|---|---|
| Acid neutralizing capacity (ANC) | Alkalinity ($C_B$-$C_A$) (µeq $L^{-1}$) | Decrease is a direct measure of acidification |
| Conductivity | Specific conductance (µS $cm^{-1}$) | Can be related to alkalinity; use as a screening tool |
| pH | Hydrogen ion (-log [$H^+$]) | Increase is a direct measure of acidification |
| $Al_i$ | Inorganic monomeric aluminum (µg $L^{-1}$) | Only present in measurable amounts in acidified waters |
| $SO_4^{2-}$ | Sulfate (µeq $L^{-1}$) | Acid anion most often associated with chronic acidification |
| $NO_3^-$ | Nitrate (µeq $L^{-1}$) | Acid anion most often associated with episodic acidification |
| $NH_4^+$ | Ammonium (µeq $L^{-1}$) | $NH_4^+$ seldom present in wilderness lakes; increase suggests elevated N deposition |
| Total P | Total dissolved phosphorus (µg $L^{-1}$) | Often a limiting nutrient; changes affect trophic status |
| DO | Dissolved oxygen (mg $L^{-1}$) | Reduction in winter or increased diurnal fluctuations may represent increased productivity of waters |
| Secchi disk transparency | Water clarity (m) | Decrease indicates decreased transparency, possibly from increase in phytoplankton or organic acids; increased transparency may indicate acidification |

tion from fish, and it is possible that some amphibian populations already have been reduced by fish populations introduced through stocking programs. It also is difficult to rely on fisheries information alone as an indicator of impacts from atmospheric deposition because many trout populations are not self-sustaining.

## Guidelines for Setting Limits of Acceptable Change

Once the sensitive indicators have been defined, it is necessary to determine what changes in them will warrant a management response. All measures of water quality and biota have uncertainty associated with them, which arises from sampling error, analytical error, and natural variability associated with hydrologic processes. Selection of the limits of acceptable change requires incorporation of some element of uncertainty. If the level of uncertainty is too great, the resource may be degraded yet still be within the limits of acceptable change. Thus, in developing some initial limits of acceptable change, the aquatic group followed the guidance of the Forest Service mandate, which is to err for protection of the resource (Public Law 88-157).

**Table 9—Suggested taxonomic groups of aquatic organisms that should be investigated as candidates for sensitive indicators of stress from atmospheric pollutants**

| Taxonomic group | Primary habitat | Notes |
|---|---|---|
| Macroinvertebrates: | | |
| Molluscs (snails, clams) | Lakes, streams | Check for loss of species; may be limited by availability of calcium |
| Ephemeroptera (mayflies) | Lakes, streams | Check for loss of species; larval (aquatic) forms are the sensitive life stage |
| Plecoptera (stoneflies) | Lakes, streams | Check for loss of species; larval (aquatic) forms are the sensitive life stage |
| Trichoptera (caddisflies) | Lakes, streams, ponds | Check for loss of species; larval (aquatic) forms are the sensitive life stage |
| Plankton: | | |
| Phytoplankton | Lakes | Check for changes in species composition, especially loss of diatoms and increase in blue-greens |
| Zooplankton | Lakes | Check for changes in species composition, including a change to larger species associated with a reduction in predators (fish) |
| Amphibians | Lakes, streams, ponds, wetlands | Possible confounding effects from fish stocking |
| Fish | Lakes, streams | Also can be sampled for accumulation of trace contaminants; check for loss of year classes |
| Bryophytes (mosses) | Wetlands, lakes, streams | Accumulators of some trace metals |
| Macrophytes (aquatic plants) | Wetlands, lakes | Leaf chlorosis on emergent species |

Three condition classes were defined for each water quality indicator to reflect classes of impacts associated with changes in the indicator values: (1) no significant deterioration, (2) significant deterioration, and (3) severe deterioration. The values assigned to each class are intended to reflect realistic changes based on mechanisms of acidifying (or eutrophying) processes, observations in areas already acidified (or eutrophied), and the reliability of data on aquatic resources in these wildernesses (table 10). These values are intended to represent changes beyond those imposed by natural processes such as dilution. It was the intention of the participants that these values be used only as an interim guide until subsequent monitoring and research results become available.

The rationale for selecting these values is briefly summarized.

**ANC:** Acid neutralizing capacity (ANC) or alkalinity is the most direct measure of sensitivity to acidification for surface waters not impacted by acid deposition. Once acidic deposition has occurred, base cations are mobilized from the watersheds, and presumably, some of the ANC is consumed. For this reason, the test for sensitivity of areas already impacted by acid deposition is often performed by using base cations instead of ANC. A decline in ANC of less than 20 percent was deemed to be not serious; for example, a lake with an ANC of 20 µeq per liter would be allowed to decrease to 16 µeq per liter before deterioration could reasonably be measured. Any deterioration below ANC of 0 µeq per liter was considered severe, because at this level virtually all the neutralizing capacity has been consumed. Declines in pH will occur rapidly once ANC approaches zero.

For streams, three ANC classes were established to reflect different levels of tolerance for loss of ANC. This approach was considered preferable for streams because of the greater temporal variability in stream chemistry. Fluctuating aquatic systems, such as streams, may experience large pulses of N and S inputs, and it may be critically important to consider episodic events in determining pollutant effects. These episodic events include snowmelt, summer thunderstorms, and autumn rains (that may introduce large concentrations of organic materials). Consequently, ANC and pH indicators in table 10 are assigned values at peak flow, which may occur during a snowmelt episodic event. The occurrence of other episodic events is less reliably predicted, and their duration is shorter, thereby making measurement difficult.

**pH:** Organisms respond to changes in $H^+$ ion, not ANC. Thus although it often is difficult to obtain reliable measures of pH in dilute waters, it is important that every effort be made to do so. Above pH 6.0, it is difficult to detect any negative biological response (see, for example, Baker and others 1990a, Eilers and others 1984, Schindler 1988). Ninety-nine percent of the lakes in the western lakes survey population had pH greater than 6.0 (Landers and others 1987). Below pH 6.0, definite changes occur in community composition for sensitive taxonomic groups. At pH values less than 5.3, ANC is typically near zero and detrimental biological impacts become quite apparent. The impacts become increasingly severe below pH 5.0 as $Al_i$ (inorganic monomeric aluminum) is mobilized into solution. Low and high baseline classes for streams were distinguished and the allowable change in pH adjusted accordingly.

**Total Al:** As noted above, the damaging effects of acidification are associated with concomitant increases in both $H^+$ and inorganic monomeric aluminum (Al). The aluminum (Al) criteria for wilderness lakes was based on total dissolved Al, rather than $Al_i$, because of the difficulty in accurately measuring $Al_i$ for wilderness lakes. Total Al is probably a reasonable surrogate for $Al_i$ in most western wilderness lakes because these

**Table 10—Condition class definitions identified for sensitive indicators of aquatic resources [ab]**

| Indicator | Initial condition | No significant deterioration | Significant deterioration | Severe deterioration |
|---|---|---|---|---|
| ANC ($\mu eq\ L^{-1}$): [c] | | | | |
| Lakes | | < 20% | > 20% | ≤ 0 $\mu eq\ L^{-1}$ |
| Streams | ANC < 25 | No change | Any change | Any change |
| | ANC 25-100 | < 25% | 15-25 $\mu eq\ L^{-1}$ | < 15 $\mu eq\ L^{-1}$ |
| | ANC > 100 | < 50% | 15-25 $\mu eq\ L^{-1}$ | < 15 $\mu eq\ L^{-1}$ |
| pH: [c] | | | | |
| Lakes | | > 6.0 | 5.3-6.0 | < 5.3 |
| Streams | pH ≤ 6.3 | > 6.3 | 6.0-6.3 | < 6.0 |
| | pH > 6.3 | Δ< 0.2 | Δ 0.2-0.5 | Δ> 0.5 |
| Total aluminum ($\mu g\ L^{-1}$) [d] | | < 30 | 30-50 | > 50 |
| Sulfate ($\mu eq\ L^{-1}$) [d] | | < 5 | 5-10 | > 10 |
| Nitrate ($\mu eq\ L^{-1}$) [d] | | < 1 | 1-3 | > 3 |
| Ammonium ($\mu eq\ L^{-1}$) [d] | | < 1 | 1-3 | > 3 |
| Total phosphorus ($\mu g\ L^{-1}$) [d] | | < 5 | 5-10 | > 10 |
| Secchi disk transparency (m) [c] | | < 20% | 20-30% | > 30% |
| Dissolved oxygen ($mg\ L^{-1}$) [ce] | | < 1 | 1-4 | > 4 |

[a] Units represent those shown in parentheses unless stated otherwise.

[b] Note that conductivity, shown in table 6, is not shown here. Conductivity was proposed primarily as an inexpensive screening tool. Changes in conductivity (without supporting ion chemistry) are difficult to interpret because conductivity can increase sea consequence of both acidification and hydrologic fluctuations.

[c] Values represent the amount of decrease for an indicator unless specified otherwise.

[d] Values represent the amount of increase for an indicator unless specified otherwise.

[e] Assumes lakes are normally saturated. A value of 5 mg per Iiter of dissolved oxygen should be considered an absolute minimum threshold value for fish survival (Davis 1975, Wasters 1964).

systems have very low concentrations of dissolved organic carbon and likely contain little organically complexed Al. Dissolved organic carbon complexes Al, thereby making it far less toxic. Methyl isobutyl ketone (MlBK) -extractable (total monomeric) aluminum was undetectable in most western lakes (detection limit about 30 micrograms [µg] per liter by using methods from the western lakes survey). It was assumed that if Al was detectable (that is, greater than 30 µg per liter), then it may indicate some deterioration. Values greater than 50 µg per liter are important because this is a threshold response value for some sensitive species, although it must be emphasized that toxicity to $H^+$ and Al is a continuum (Baker and others 1990a).

**$SO_4^{2-}$:** Sulfate ($SO_4^{2-}$) is the anion most often associated with chronic acidification of surface waters. Natural sources of sulfate for Pacific Northwest lakes include marine aerosols and mineral sulfur in the watershed (Eilers and Bernert 1990, Loranger and Brakke 1988, Stauffer 1990). If the lakes are more than 75 kilometers from the ocean and sulfide ores are not present, the sulfate concentrations for Cascade lakes are expected to be less than 5 µeq per liter (the median $SO_4^{2-}$ for the Oregon Cascades was below the detection limit, 1.5 µeq per liter). Sulfate concentrations between 5 and 10 µeq per liter were considered significant because 5 µeq per liter or more of ANC could have been consumed. This would be significant for a lake with an initial ANC of 20 µeq per liter. Severe deterioration was considered to be associated with any increase in $SO_4^{2-}$ greater than 10 µeq per liter.

**$NO_3^-$:** Nitrate ($NO_3^-$) is the anion typically associated with episodic acidification. Although there are numerous natural sources of nitrate ($NO_3^-$), most wilderness lakes in the Pacific Northwest have no measurable $NO_3^-$ during summer and autumn. Biological uptake of nitrogen in aquatic and terrestrial ecosystems is highly efficient from spring through fall thereby resulting in generally low concentrations of $NO_3^-$ in surface waters. The $NO_3^-$ criteria assigned to these condition classes are based mainly on data collected in summer and fall; values in spring may reach measurable concentrations in some lakes, although none was measured in a sample from Lake Notasha, Sky Lakes Wilderness, immediately after spring ice-out (Eilers and others 1990).

**$NH_4^+$:** Ammonium ($NH_4^+$) has been implicated as a major ion in lake acidification in only a few cases (Schuurekes and others 1988). Ammonium is commonly produced by bacterial action, but under natural conditions, waters high in dissolved oxygen seldom have significant concentrations of $NH_4^+$ because it is quickly assimilated or oxidized to $NO_3^-$. For this reason, the $NH_4^+$ values assigned to the condition classes are identical to those for $NO_3^-$.

**TP:** Total phosphorus (TP) often is undetectable in lakes in the Cascades (Landers and others 1987). Increases in TP are a concern because of the potential to increase the lake productivity and thereby reduce its clarity. The values suggested here are subject to considerable uncertainty.

**Secchi disk:** Transparency as measured by lowering a Secchi disk into a lake is an inexpensive measure of phytoplankton production. Transparency in some cases may increase in acidified lakes. If nutrient deposition ($NO_3^-$, $NH_4^+$, TP) into lakes increases, it is conceivable that the lakes will become less oligotrophic and therefore less transparent.

**DO:** Dissolved oxygen (DO) is expected to be at or near saturation values in most Cascade lakes during the open water period. Dissolved oxygen is consumed in the lakes under ice cover during winter. Fish and other aquatic life may be suffocated if the oxygen is partially depleted through respiration. If deposition of nutrients greatly increases the fertility of these mountain lakes, then it is possible that winter oxygen demand will cause biological impairment. There were no data available to support the choice of the DO values in table 10.

The aquatic group considered establishing condition classes for biologically sensitive indicators but was constrained by lack of data (basic surveys of species and dose-response relations for these species). There was the perception that the community composition of many wilderness surface waters probably was limited to a few species.

A conservative approach in such a case would be for the Federal land manager to manage these systems for no loss of species. Alternatives such as measuring community processes (for example, primary productivity) were rejected because of the resistance of aquatic systems to change in major functional processes (Schindler 1987) and because of the considerable data requirements for accurately assessing a change in these parameters.

Other issues related to the topic of establishing limits of acceptable change for aquatic resources in Region 6 are addressed below.

## Loadings and Effects (Dose and Response)

It is difficult to predict the effects of various pollutant loadings on sensitive indicators in aquatic systems in the Cascade Range, particularly because there are few detailed watershed studies. Computer models exist, however, that can help estimate water chemistry changes based on N and S inputs to a watershed (Thornton and others 1990). These models assume that water chemistry is modified by solutions passing through soils and, therefore, provide a basis for estimating changes in soil chemical properties that alter aquatic systems. The ability of the soil to predict future aquatic chemistry changes can be estimated by modifying soil properties over time, with input (precipitation) chemistry driving the changes in soil solution chemistry. A brief modeling exercise that focuses on soils as an integrating factor was conducted with empirical data from the Alpine Lakes Wilderness. [7] It is unclear how appropriate these models may be for dilute lakes in the Oregon Cascades, which are typically seepage lakes receiving little watershed runoff. Other approaches focusing on in-lake processes may be needed to forecast changes in these lakes (Baker and Brezonik 1986).

## Pollutant Interactions

Because of the acidifying impact of nitrogen and sulfur deposition on aquatic systems, the addition of either one to a system in which one of them is already present will generally result in an additive impact from an increase in acidity. In addition, some interaction effects among ozone, sulfur dioxide, and nitrogen deposition may occur (see "Terrestrial Resources" above) in riparian-wetland areas where terrestrial flora are sensitive indicators (for example, mosses and lichens). It is currently unclear whether interaction effects among these three pollutants will be synergistic or antagonistic. Federal land managers nevertheless should be aware of potential interactions and be prepared to monitor to detect their effects.

## Research and Monitoring needs for Aquatic Resources

Although survey data for lakes in the Pacific Northwest are available to qualitatively document the high sensitivity of these systems to acidic deposition, major uncertainties regarding the quantitative aspects of this sensitivity for lakes, streams, and wetlands hamper the Federal land managers' ability to assess impacts associated with the PSD process. The major research and monitoring needs to reduce these uncertainties include the following items.

**Lakes:** The major ion chemistry of lakes in the region was characterized in the western lake survey (Landers and others 1987) and other localized surveys. Data for individual wilderness areas are insufficient, however, to characterize these resources (see table 7). Research and monitoring needs for lakes include (1) characterizing lake chemistry in individual wilderness areas, (2) establishing long-term monitoring of one to several lakes

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[7] Harrison, Robert. 1990 Unpublished data on soils in the Alpine Lakes Wilderness. On file with: University of Washington, College of Forest Resources, AR-10,Seattle,WA 98195.

and watersheds in the wilderness areas to detect trends, and (3) understanding processes controlling lake chemistry.

**Streams:** Most of the research on streams in the region seemingly has been conducted at low-elevation sites. There is a need to investigate stream chemistry in the higher Cascades. No compilation of stream chemistry in the Cascades has been prepared to provide an overall assessment of the sensitivity of streams to acidification. There is a need for both baseline (for example, current export of nitrogen from undisturbed watersheds) and episodic stream chemistry data.

**Wetlands and ponds:** No data are available to evaluate the potential sensitivity of wetlands, riparian corridors, or vernal pools (spring ponds) to damage from acidic deposition. Vernal pools could be highly sensitive to acidification; these habitats are major breeding areas for many amphibians.

**Deposition:** Estimates of wet deposition in the region are based on NADP/NTN sites located over 1000 meters lower than the aquatic resources of interest. Deposition data from higher elevation sites dominated by snow inputs are needed. Snow cores or snow pits could be considered as an alternative to establishing additional NADP sites (Laird and others 1986). There also are inconsistencies in snow chemistry for the Cascade Range that relate to the nitrogen deposition load (Eilers 1991).

**Biota:** No species-specific biological data are available to make assessments of either the distribution of sensitive species in the Cascades or their dose-response to pollutant exposure. Detailed biological surveys of aquatic organisms in the Cascade Range need to be compiled and related to chemistry and habitat type.

**Snowmelt:** Most of the data on aquatic resources in the Cascades have been collected in summer and fall. A major emphasis needs to be placed on gathering hydrologic and chemical data for lakes, streams, and ponds during the snowmelt period. Dilution of base cations will greatly increase the sensitivity of those systems to acidic deposition.

Several related issues need to be addressed. The Federal land manager needs to anticipate data requirements for quantitatively evaluating lake and stream response to atmospheric deposition. In addition to the information described above, ancillary information on watershed characteristics for selected sensitive resources needs to be gathered. The two models used extensively in forecasting lake and stream response to acidification in the National Acid Precipitation Assessment Program (NAPAP) were MAGIC (model of acidification of groundwater in catchments) (Cosby and others 1985a, 1985b, 1985c) and ILWAS (integrated lake and watershed acidification study) (Gherini and others 1985). Model requirements in MAGIC include detailed information on soil properties (for example, depth, bulk density, cation exchange capacity, S-adsorption, base cations, and extent of soil cover), vegetative cover, exposed bedrock (extent and composition), deposition, and hydrologic flowpaths. More intensive data collection is required to fully calibrate the ILWAS watershed simulation model (Chen and others 1983, 1984). The aquatic group encouraged the Forest Service to conduct example model runs with MAGIC for select key wilderness areas and also to explore the applicability of expanded empirical models for use in screening procedures.

Problems associated with conducting research in wilderness make obtaining these data difficult; not only is it challenging to gather data in mountainous areas, but also the added

burden of complying with administrative restrictions hinders these efforts. Because one of the purposes of establishing wilderness areas was for their scientific use (Public Law 88-157 Sec.2(c)(4)), some of the participants endorsed a relaxation of current management guidelines that impede the collection of data in wilderness. The Wilderness Act specifically allows for relaxation of wilderness restrictions to investigate water resources and other facilities serving in the public interest (Sec.4(d)(4)) and data gathering (Sec.4(d)(2)). This suggests that data collection necessary to preserve the quality of resources in the wilderness areas is consistent with the intent and letter of the act. Another issue of some importance to the Federal land manager is that numerous sensitive aquatic resources in Region 6 are present throughout class II wilderness areas (see table 7), but the protection afforded the class II areas through the PSD process is significantly less than that for class I wilderness.

The find issue discussed by the workshop participants concerned the pollutants addressed in the protection of wilderness resources. Under the PSD process, only nitrogen and sulfur are recognized to have the potential for causing significant biological impacts. In addition to addressing possible acidification of these resources, the Federal land manager needs to be aware that the potential for other nonregulated emissions to cause biological effects may be of equal or greater concern in this region. Other airborne pollutants of concern include nutrients and trace contaminants (for example, mercury, cadmium, PAH, pesticides). We recommend that research programs developed to protect aquatic resources in wilderness areas include measuring the inputs of these non-PSD-regulated substances.

# Workshop Results—Visibility [1]

## Introduction

The Clean Air Act as Amended in 1977 (Public Law 95-95) declared, as a national goal, the "prevention of any future, and the remedying of any existing, impairment of visibility in mandatory class I Federal areas which impairment results from manmade air pollution." The 1990 Clean Air Act amendments reaffirmed this national goal. Impairment of visibility is defined in the Clean Air Act as "reduction in visual range and atmospheric discoloration." The act further states that visibility is an AQRV for class I wilderness.

The workshop included a work group that described a method to assess potential impacts of new sources of air pollution on visibility in class I wilderness areas. Visibility is a unique wilderness value compared to those addressed by the terrestrial and aquatic work groups in that the resource needing protection is the experience of the wilderness visitor rather than a natural ecosystem process.

Prior to deliberations, the visibility work group established some foundations:

- The work-group objective was to establish a procedure for screening visibility for class I wilderness given the national goal and in anticipation of PSD permit applications. [2]

- The AQRV, visibility, could be defined as "the clarity of view within the class I wilderness, from inside to outside the class I wilderness, and from outside to inside the class I wilderness." [3]

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[1] Compiled by Richard Fisher.

[2] The Forest Service is presently designing an agency-standard technique for screening visibility impacts. This process, when complete, may supersede the process described in this section that was designed by the visibility work group.

[3] Work group members ware informed that Forest Service policy existent at the time of the workshop was that only views within a class I wilderness are to be managed; views from inside to outside, and outside to inside the class I wilderness are not considered. The group unanimously decided to go on record with the position that certain selected views outside specific class I wilderness are important to the public and should be evaluated by the Federal land manager. In February 1991, a national Forest Service workshop took a similar stance though official policy has yet to reflect this change.

- Although good visibility is a resource that is equally important throughout a class I wilderness area, its sensitivity differs from place to place and from time to time. It is a site-specific value affected by meteorology, topography, the position of the viewer with respect to the sun, and other variables including visitor use.

- Views should be protected from any type of visibility degradation whether caused by coherent plumes, haze layers, or regional haze.

- Views can be prioritized for monitoring ease. Sensitive views should be selected and monitored to determine the effects of air pollution on visibility.

- Decisions about screening visibility impacts should be made using a preferred local decision process.

## A Process to Manage Visibility

Visibility is a site-dependent value for which screening values can be assigned only case by case. Each scene holds values of coloration, texture, and pattern as well as potential to see distant features that must be rated individually. No standard procedures have been established to accomplish this task. The work group efforts were aimed at creating a process to identify sensitive views as well as characterize, evaluate, and eventually manage those views. The following process was established:

1. Select sensitive views.

2. Describe the elements (features) of each view that give it value.

3. Describe the sensitivity of each view to air pollution.

4. Establish a visibility goal (desired future condition).

5. Inventory and summarize the current condition.

6. Evaluate the current condition against the desired future condition.

7. Monitor changes and trends.

8. Predict the effect of projected additional pollutants.

9. Evaluate the impact of projected additional loadings and make a recommendation to the regulator.

Upon completion of step 5, the manager will have a notebook containing a description of sensitive views and the features of the views that could be adversely impacted by pollution. [4] The reasoning behind selection of sensitive views will be summarized and information necessary to model visibility impacts will be provided. Ideally, the notebook also would contain a spectrum of about 20 photographs of the current conditions affecting sensitive views and a brief discussion of how the features are or would be affected by air pollution. The spectrum can be compiled either of actual, cloud-free images or computer-

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[4] Monitoring over a long period may be necessary before a reasonable assessment of current conditions is possible. In fact, the complexities of monitoring, particularly by photographic techniques, may make it impractical to accomplish this step at some sites.

generated images representing roughly 5-percent increments of contrast change. The notebook will contain a visibility impairment table prepared specifically for each view and referenced to the photographic spectrum of the view. This table will give an estimated conservative (larger than actual) contrast change for a range of increased pollution.

The notebook allows the Federal land manager to evaluate the current visibility condition specific to the class I wilderness area and potential impacts given an estimate of additional pollution loading from a PSD applicant.

It may take several years to complete notebooks of all views for all wilderness areas. In the meantime, priority analysis of representative views would provide adequate guidelines for evaluating PSD permits within similar wilderness areas. Sites should be chosen to represent similar categories such as northern Cascade Range, southern Cascade Range, or Olympic Peninsula. The completed notebooks must be updated annually to include additional monitoring data or incorporate scientific advances, such as newly derived aerosol-to-visibility relations.

**Step 1—Select Sensitive Views**

Sensitive views are indicators used to define impairment for class I wilderness areas. When selecting sensitive views, the land manager needs the following:

- Area objectives as stated in the Forest plans and implementation schedules.
- Visitor comments about their experiences within the wilderness; note expectations and desired conditions.
- Observations from Forest Service staff including records from fire lookouts, ranger stations, and other vistas. These data might include notes of layered hazes, plumes, regional haze, sources of pollutants, duration of impact, time of year, coloration, and frequency of occurrence.
- Frequency and duration of visitor exposure to a view. The higher the exposure time, the more important the visual quality.
- Unique physical features important to the class I wilderness (for example, fossil bed, limestone outlier, natural arch, high pinnacle, glacial feature).
- Visually dominant features acting as focal points in a view. Features that are so physically dominant that the eye is drawn to them automatically (for example, a set of arêtes, a waterfall, a mountain range or peak, a high-contrast feature).
- At least one view should be primarily within the class I wilderness.

If a scene is selected for measurement of scene contrast to estimate light extinction or standard visual range, the same image may not be appropriate for feature-contrast measurements. Features suitable for feature-contrast may need to be closer to the observer than features suitable for measurement of scene contrast. The visual quality index (in the Forest Service landscape architects [5] or land management planners handbooks [6]) may be helpful in evaluating views.

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[5] Forest Service 2382. Visual resource management. Forest Service Handbook, Title 2300, Chapter 2380.

[6] Forest Service 1909.12. Land and resource management planners handbook. Forest Service Handbook, Title 1900.

**Step 2—Describe Elements (Features) of Each View and Give It Value**

Various attributes of the elements (features) in each view determine its sensitivity to additional atmospheric pollutant loadings. The importance or dominance of the features may vary with time of day, the season, and the distance from the observer. Observations should reflect these variances. To judge their potential impairment, the views for each class I wilderness need to be described by the following properties:

- Distance, azimuth, and elevation angle. Greater viewing distances require cleaner air. List all the important or representative views for the class I wilderness including their viewer-to-target (sight path) distance, azimuth, and elevation angle.

- Coloration. If the color of a feature, such as rock formation or unusual vegetation, is an important element of a view, it is more sensitive than a view of undifferentiated forest or other monochromatic scenes. Describe colorful elements of the view. Note the time of day and seasonal variations of color.

- Contrast. Views with low feature contrast or light-colored materials having low contrast with the sky are more sensitive than atypical forest scene. Describe both feature contrast and contrast with the sky.

- Texture. Texture or fine detail in a scene is lost before the grand features are rendered invisible. If the interest of a view depends on texture or detail, describe it.

- Dominant forms. The shape, size, and orientation of objects in a scene can influence how the human eye perceives them. Note unusual shapes such as long straight lines or multiple ridge lines.

The purpose of collecting this descriptive information is to relate the sensitivity of different views to visibility degradation. Where possible, descriptive information should be presented quantitatively. It may be useful to employ existing systems, such as those developed by landscape architects to describe some elements.

**Step 3—Describe the Sensitivity of Each View to Air Pollution**

The sensitivity of each important physical feature of a view to air pollution will differ in relation to its attributes. Impairment in the quality of the view "can be manifested as obscuring of distant features and changes in color, texture, contrast, and form. If distance is a constant, the most sensitive attribute is texture, closely followed by color. The least sensitive attribute is form.

**Step 4—Establish a Visibility Goal (Desired Future Condition)**

Use the information collected in steps 1 through 3, above, to state a clear and specific goal or, in terms of the land management planning process, a desired future condition. This goal should be stated in terms of frequency and duration of the condition as well as times of the day and year. A set of photographs illustrating the scenic quality of the goal should be helpful. There may be more than one set of photos representing different periods and different views for the class I wilderness. Remember that the Clean Air Act states the ultimate goal for class I areas is "no humanly perceptible change in coloration or contrast."

**Step 5—Inventory and Summarize the Current Condition**

Monitoring for class I wilderness areas should include the full complement of visibility measurements proposed by the EPA, including optical, visual, aerosol, and meteorological. Some monitoring sites may be representative of two or more class I wilderness areas depending on topography and meteorology. Monitoring may continue indefinitely but duration and frequency will be site dependent. Historical visibility conditions could be developed theoretically by estimating the natural pollutant loadings due to fire and other natural emission sources.

**Selection of a monitoring site** — Forest Service wilderness management policy does not normally allow structures, such as those needed to hold monitoring equipment, within wilderness boundaries, thereby making monitoring totally within the wilderness unlikely. To the extent possible, monitoring should be of, or representative of, sensitive views selected for the area (see step 1). In addition, consider the following:

- Location of the class I wilderness relative to known and proposed sources of air pollution.

- Using existing National Park Service, Interagency Monitoring of Protected Visual Environments (IMPROVE), Forest Service, state agency, or other monitoring sites; these may be sufficiently representative of the area in question.

- Monitoring logistics such as the ease of access in winter, power availability, security, and operator availability.

- Location of historical visibility-monitoring sites.

**Instrumentation** — Visual, optical, and aerosol measurements should be taken at each site:

- Scene monitoring is accomplished with photography. Three color photographs taken per day (9 a.m., noon, and 3 p.m.) is optimal. Two photographs per day at 9 a.m. and 3 p.m. or one per day at noon also is acceptable. It is desirable to not miss a day because of day-to-day changes in visibility; significant events could be overlooked. The photographs should be quantitatively and qualitatively evaluated as is currently done in the Forest Service visibility monitoring program.

- Optical measurements (1-hour averages or other appropriate monitoring periods) should be made with either a transmissometer or nephelometer. At remote locations where no line power exists, continuous measurements may not be possible. At these sites, the instrument can be cycled to sample a portion of each hour (for example, 10 minutes).

- Measurements of fine particles and aerosols should be made with a continuous, chemically analyzable sampler capable of measuring haze-causing as well as source-attributing constituents. Chemical mass balance analyses of particle data that follow EPA guidelines should be performed to discriminate between natural and anthropogenic pollution. (The chemical mass balance analysis is not always successful at making this distinction.)

- Meteorology at the monitoring site (1-hour averages) should include wind speed and direction, temperature, relative humidity, and precipitation. Barometric pressure data should also be collected when a nephelometer is used.

**Other considerations** — Comprehensive monitoring of current conditions includes other considerations:

- The Forest Service should have in place EPA-reviewed quality assurance and quality control procedures. Standard operating procedures and quality control procedures have been prepared for cameras, transmissometers, nephelometers, and fine particle and aerosol monitors, but they have not been approved by EPA.

- Nighttime visibility is recognized in some class I wilderness areas as a valuable experience to be protected. Recommendations for monitoring at night do not include photography. A photometer and lens may be used at the camera site for vertical measurements of the darkness of the sky. Further investigation of this issue is warranted. See appendix C for more information on night visibility.

- It is recommended that a selected spectrum of photographs, representing a range of existing conditions, be digitized. The data are least perishable in digital format.

- Anephelometer, capable of operating without line power and in a remote setting unattended for days at a time, is currently under development. Nephelometers have the logistic advantage of being single-point continuous-sampling instruments. A drawback is that nephelometers measure only light scattering, not light extinction. Precipitation events causing visibility reduction are not monitored because the instrument monitors air drawn into a sample chamber.

- Procedures for monitoring visibility should be consistent with EPA guidelines and be adopted by the Forest Service. These procedures should be incorporated into the Forest plans and wilderness implementation schedules in sufficient detail so that no question arises over monitoring and analyzing collected data.

**Creating a spectrum of scenes and descriptors** — The following series of calculations should be performed for sensitive views and lines-of-sight obtained from the detailed, view-specific information developed in this and previous steps. These calculations should be performed before a PSD permit application is reviewed.

1. Select the spectrum of slides. Twenty clear-sky photographs per view for each monitoring time during defined periods of interest (for example, seasons) will be selected to represent the range of observed visibility conditions from pristine to dirty. These photographs may be compiled in one of two ways. They maybe selected from real, on-site slides taken with a 35-mm camera, or they can be generated artificially by a computer degrading a digitized, pristine-day photograph.

2. Compute scene contrast. The contrast of selected terrain and horizon features should be measured on each slide. The spectrum can then be organized by scene contrast. The extinction coefficient or standard visual range of each slide can be estimated from the scene contrast measurement.

3. Estimate particle concentration. The PSD increments refer to particle pollution as all suspended particulate matter less than 10 microns in diameter (PM10). Unfortunately, PM10 concentration is a poor indicator of visual air quality. Correlations between PM10 concentration and visibility can be inherently weak because larger particles may dominate PM10 mass measurements but not seriously degrade visibility. Smaller particles (less than 2.5 microns in diameter [PM2.5]), on the other hand, usually do not constitute much of the mass but dominate the optical effects. Actual or estimated PM2.5 concentrations should be used in the following calculations for the scenic spectrum. Later, when the effect from additional atmospheric loading is estimated, PM2.5 data should be used if available. Otherwise, PM10 data can be used because the additional mass will simply add conservatism.

4. Compute feature contrast. Feature contrast is the difference in radiance values between texture or coloration of a feature somewhere below the horizon. Preferably, at least one such feature will be in the near field of view and within the class I wilderness. One or more feature contrast(s) should be computed for each spectrum slide by using the relation in appendix D.

5. Estimate light extinction.

   A. If long-term extinction data measured with a transmissometer exists, the frequency of occurrence of the extinction represented in each spectrum slide could be presented.

   B. Apply appropriate extinction efficiencies to measured aerosol constituent concentrations. If only PM2.5 mass is available and no direct research results relating PM2.5 to aerosol constituents exist, multiply this concentration by an extinction efficiency of 3 square meters per gram. If baseline aerosol composition is likely to include an unusually large amount of coarse particles in a situation where wind-blown dust is present, apply the extinction efficiency of 0.7 square meter per gram to correct for the coarse particle effect. Add this to an assumed extinction due to Rayleigh scattering of $1 \times 10^{-5}$ per meter for an average class I wilderness altitude of 1550 meters.

   C. If long-term photographic records are available where extinction was estimated from contrast measurements (by using the Koschmeider relation), the frequency of occurrence of the extinction represented on each spectrum slide could be presented.

   D. If long-term nephelometer data are available, the total extinction can be estimated by adding the measured scattering component of extinction to an estimate of the absorption component of extinction from particle absorption measurements of aerosol constituent concentrations. From the distribution of estimated extinction based on scattering measurements, the frequency of occurrence of the extinction represented on each spectrum slide can be presented.

6. Prepare a visibility impairment table. The data in the table are computed relations among aerosol constituent concentration increases, extinction decreases, and both scene contrast and feature contrast(s). This table can and should be prepared before a new source is reviewed for visibility impact. The equations used to compute the values in the visibility impairment table are given in appendix D.

**Step 6—Evtduate the Current Condition Against the Desired Future Condition**

If the current condition meets the goal, continue with steps 7 and 8; if not, contact the State air programs office and EPA to discuss possible mitigative measures.

**Step 7—Monitor Trends and Changes**

Continue monitoring established in step 5 to meet or obtain goal.

**Step 8—Predict the Effect of Projected Additional Loadings**

Use appropriate air quality dispersion models to compute cumulative ambient aerosol concentrations resulting from a proposed new source. Ensure that information about frequency, duration, and times of year and day are available. Use these data to find the predicted scene spectrum and visibility impairment table value.

## Step 9—Evaluate the Impact of Projected Additional Loadings and Make a Recommendation to the Regulator

When confronted with a PSD permit, Forest Service staff will consult the notebook prepared in step 5 by using one or more of the following pieces of predicted data:

- The frequency distribution and duration in hours with details about the time of year for the following:

  A. Twenty-four-hour average PM2.5 or specific aerosol concentrations, or

  B. Extinction computed from particle concentrations. If the properties of the particle constituent chemicals are not known, apply the generic urban industrial fine aerosol extinction efficiency of 5 square meters per gram. The total resultant extinction will be the predicted value plus the current extinction value.

- The contrast of a feature or whether the feature can be seen in the future case. The visibility impairment table can be used to estimate whether the threshold contrast has been reached. The contrast change is subtracted from the existing contrast. The manager then refers to the table to estimate the contrast threshold for the particular feature of interest.

The manager will be able to see the current condition on the photographs, as well as the general condition that might exist, by using a conservative estimate of the effects on class I wilderness visibility. Understanding the limitation of photographs, the manager also will be able to review the estimated numerical condition after the source is operating. The manager will then use professional judgment and knowledge of the area to determine if the change in visibility is adverse.

Using this screening process, the manager can arrive at one of the following decisions:

- The effect is unacceptable and additional measures are necessary to evaluate and mitigate the class I visibility impacts. The measures might be more refined air quality or visibility modeling, lower emissions, or different source-operating conditions. If further analysis still yields unacceptable impacts, the manager should recommend denial of the permit.

- There is no adverse effect and therefore, the permit should not be denied based on visibility impacts on the class I wilderness.

# Monitoring, Data Collection, and Criteria for Decisions on PSD Applications

In most cases, there are few data on which to base current guidelines for screening PSD applications. More data are needed to improve the quantitative rigor of these guidelines. Constraints on time and money always will limit scientific efforts in this area, so it is important to prioritize data needs for estimating pollution impacts and evaluating PSD applications.

It is extremely difficult and costly to determine the effects of air pollutants on entire AQRVs or ecosystems. It therefore is appropriate to focus on specific components, such as sensitive receptors, that have the greatest potential sensitivity to air pollution; for example, a permit applicant whose pollution source may contribute to elevated levels of nitrogen oxides or ozone should survey the existing and future condition of ponderosa pine, which is known to be sensitive to these gases. An applicant producing sulfur dioxide should survey soils in the relevant class I area to determine their sensitivity to change.

The recent effort by scientists and policy makers to understand effects of acidic deposition on ecosystems has produced several models of plant and ecosystem response (for example, Gay 1989). In the future, these or other models maybe appropriate for predicting ecosystem-specific effects of new sources. One of the goals of protecting wilderness should be to apply appropriate models to identify the sensitivity of various features of AQRVs to air pollutants. This could greatly expedite decisions about potential effects if large amounts of data from a specific wilderness are not available.

In general, there is little air quality monitoring information for the Pacific Northwest. The existing monitoring network is located mostly in and near metropolitan areas, with few measurements in mountain locations near class I areas. Improving this network in wildland areas would have a large immediate impact on our knowledge of atmospheric deposition in class I areas in the Pacific Northwest. The few data that exist on cloud chemistry suggest that cloudwater at high elevations in the Cascade Range may be highly acidic in some cases, although the level of exposure and the potential for biological impacts are unknown. A research and monitoring effort in this area would be an important contribution. The placement of additional monitors should be optimized to provide data applicable over relatively broad geographic areas. Protocols should be established for data collection and analysis to ensure high-quality results.

It is necessary to know natural rates of change in the absence of pollutant stress to

detect changes that might be associated with increased levels of air pollution. It also is important to recognize that for long-lived organisms, such as trees, community organization may reflect stochastic events related to disturbances, rather than a common tolerance of environmental conditions. In any case, a better understanding of basic ecological relations is needed at the population, community, and ecosystem levels. Research on these basic relations will contribute to the management objective of wilderness protection.

An effort much greater than what currently is underway is needed to characterize aquatic systems in wildernesses in the Pacific Northwest. Mountain lakes and streams differ in their responses to air pollutants because of differences in geologic substrate, buffer capacity, surface area, depth, and other factors. Pollutant impacts therefore can be quite specific. At the least, it is desirable to classify lakes and streams by their acid-neutralizing capacity or other factors so that aquatic systems can be grouped by potential effects. Models of the physical and chemical dynamics of hydrologic systems also can be used to develop estimates of biological effects.

Although some data already exist for terrestrial and aquatic effects from air pollutants, the view-specific nature of visibility management means that little or no information has been gathered to help make permit recommendations based on visibility impairment. The process described above is intended to outline how data collection can begin, with the result that visitor experience and air pollution frequency, intensity, and duration can be related. The current generation of visibility monitoring equipment is both obtrusive and limited by power and maintenance needs, which prevent its installation where it can be most effective. Future equipment improvements should allow for placement of equipment close to managed sensitive views. Visibility management is closely tied to human eyesight and to personal, cultural, and social expectations. Managers therefore need to integrate their data-collection efforts with interpretive methods developed in the social, psychological, and landscape sciences.

Several subjects must be addressed as part of the decisionmaking process for PSD permit applications. At the least, class I areas should have a complete inventory of sensitive receptors within each AQRV. These inventories can be updated as new information becomes available; for example, scientific data may indicate that a sensitive receptor should be added that was not previously thought to be sensitive to a pollutant. In addition, sensitive receptors should be monitored for a minimum of 3 consecutive years to evaluate natural temporal changes in the condition of natural resources. Scientific literature and unpublished data relevant to pollutant effects in each AQRV should be compiled and updated as necessary; site and species-level information should be obtained whenever possible. Monitoring requirements, data needs, and decision criteria for PSD applications should be summarized and made available, so potential applicants and regulatory agencies will be aware of Forest Service concerns for wilderness protection.

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# Appendix A: Atmospheric Deposition and Ozone in Pacific Northwest Class I Wilderness [1]

The air quality climate of an area is influenced by regional and local emissions of air pollutants, and regional and local meteorology. The physical and chemical state of the atmosphere determines the dispersion, transport, chemical transformation, and ultimately deposition of air pollutants. In many cases, meteorology is more important than atmospheric chemistry in controlling the place where, and the form in which, pollutants are deposited (for example, Cape and Unsworth 1987).

Estimates of pollutant loadings to an area usually require a detailed analysis of (1) emissions; (2) transport, dispersion, and chemical transformation of the pollutants in the atmosphere; “and (3) deposition processes and the relative roles played by each process in the total deposition of pollutants. Such an analysis can be based on statistical techniques of extrapolation, on atmospheric modeling, or on monitoring—each with varying degrees of uncertainty.

There are few air quality monitoring sites in the Pacific Northwest, and few of these are in mountainous or remote areas characteristic of class I wilderness. There are large differences in climate and deposition processes (for example, snow vs. rain, cloud frequency) among monitoring sites and wilderness areas primarily due to differences in elevation. Air quality data from one site or a large region therefore are not necessarily representative of specific sites in wilderness. Statistical extrapolation of available monitoring data to specific wilderness areas is compromised by lack of information on pollutant concentrations at high elevations and little information on the different mechanisms influencing deposition at high rather than low elevations. Application of atmospheric models is constrained by lack of detailed meteorological data and models validated for meteorological and topographic conditions of the Pacific Northwest.

Despite these constraints, it is necessary to have some estimate of current deposition levels in class I areas to evaluate the current and future condition of natural resources. We estimated pollution loadings in class I areas of the Pacific Northwest with the use of a geographic information system (ARC/INFO). The analysis integrated two types of

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[1] Prepared by Margi Böhm and Felix A. Basabe. Böhm was an atmospheric scientist with NSI Technology Services Corporation, U.S. Environmental Protection Agency, Environmental Research Laboratory, Western Conifers Research Cooperative, Corvallis, OR, at the time of the workshop. Basabe is a research associate at Huxley College, Western Washington University, Bellingham, WA.

knowledge: (1) monitoring data, and (2) information from local experience and the literature. Three data matrices were used: (1) locations and emission estimates of point and area sources of sulfur and nitrate; (2) air quality data for ambient ozone, fine sulfur particle concentrations, and ionic chemistry of rain, snow, and cloudwater; and (3) meteorological data on precipitation amounts at high elevation, estimates of mixing height, and air pollution Potential. Three information matrices were used: (1) changes in precipitation chemistry with elevation based on data in the literature, (2) changes in ozone concentrations with elevation based on data in the literature and standard ozone formation-scavenging theory, and (3) estimates of pollutant transport and diffusion within the mixed layer based on data in the literature and standard meteorological theory. Details on data sources can be found in Böhm and Vandetta (1990).

## Regional Air Pollution Problems

Until the past decade or so, threats from air pollution in Pacific Northwest class I areas were primarily from point sources such as smelters and power plants. The rapid expansion of metropolitan areas, particularly around the Puget Sound, is causing increasing levels of phytotoxic gases from nonpoint sources with potential deposition and visibility impacts in class I areas. Ambient ozone and cloudwater acidity deserve particular attention because of their potential for damage to tree species in the Pacific Northwest.

### Ozone

Episodes of high ozone concentration at low elevations west of the Cascade Range occur sporadically downwind from three urban areas: Vancouver, British Columbia the Puget Sound region in Washington; and Portland, Oregon. In western Washington, elevated ozone levels, or episodes, generally last for 1 to 5 days during high-pressure weather systems accompanied by high temperatures and low-level temperature inversions. Surface winds are from the north with a westerly sea breeze component. This meteorology and the complex terrain of the Cascade Range result in elevated ozone concentrations south and east of the major developed areas. Extreme ozone concentrations generally are confined to elevations below 1200 meters. The exception to this occurs when a temperature inversion is dissipated by a marine frontal intrusion that pushes trapped pollutants over the Cascade Range. This type of event is less common than pollution episodes at lower elevations, but the potential for high ozone levels (greater than 120 parts per billion) exists in western Washington wildernesses when it happens.

Low-level inversions also are common during winter on the east side of the Cascade Range. The depth of the inversion is persistent to 900 meters, frequently rises to 2100 meters, and spills through the Cascade passes into low elevations in the pass corridors on the west side. These conditions create the potential for widespread ozone exposure, although prevailing cloud cover and the reduced daylight period in winter probably reduce photochemical activity.

### Cloudwater Chemistry

The limited data available for cloud chemistry in the Pacific Northwest indicate that concentrations of hydrogen ($H^+$) and other ions in cloudwater are surprisingly high in some parts of the Cascade Range (Basabe and others 1989, Muir and Böhm 1989). Individual pH measurements as low as 3.1 have been measured and indicate that there may be potential for some physiological effects on sensitive plant species (Hogsett and others 1989).

It is dificult to extrapolate single-location cloud chemistry measurements to regional cloudwater deposition, because of complex terrain and variation in local meteorology. Wind is the most important factor in cloudwater deposition in areas downwind from pollution sources. Estimates of deposition in wilderness areas can be made more confidently if the monitoring location and wilderness are close to one another and in the same wind trajectory. There are four wilderness areas in the Pacific Northwest that fit these criteria well: Alpine Lakes, Glacier Peak, Goat Rocks, and Mount Adams. Cloudwater deposition can be estimated with some confidence in these areas but is more difficult to estimate in other areas.

## Summary

Several different chemical parameters can be used to express air quality data, including both total deposition and concentration data. The relevance of these different types of data differs depending on the resource affected. Table 11 summarizes a few air quality statistics for class I wilderness developed by using techniques discussed above. The reliability of these estimates differs greatly among wilderness areas, depending on the proximity of each area to a source of monitoring data and similarity in the atmospheric conditions of the two sites. The estimates are considered conservative because they do not include cloud water deposition or summer precipitation, and snow deposition often is underestimated. Greater detail on how these estimates were calculated, data sources, and reliability of estimates are found in Böhm and Vandetta (1990) and Böhm.[2]

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[2] Böhm, Margi. 1990. Unpublished data on atmospheric deposition in Oregon and Washington. On file with USDA Forest Service, Forestry Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105.

**Table 11—Estimate of current pollutant concentrations and deposition in wilderness areas**

| Wilderness | Ozone [a] | | Annual deposition range [b] | | Ion concentrations [c] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Rain + snow | | | Cloudwater | | |
| | Mean | Max. | Sulfur (S) | Nitrogen (N) | S | N | pH | S | N | pH |
| | *Parts per billion* | | *- - - - Kg/ha - - - -* | | *- - - - - - - Milligrams per liter - - - - - -* | | | | | |
| Alpine Lakes | 25-30 | >120 | 2.0-3.6 | 1.8-2.6 | 0.5 | 0.3 | 5.3 | 6.8 | 5.2 | 3.9 |
| Diamond Peak [d] | 25-30 | 60-80 | .7-2.0 | .5-1.1 | .3 | .2 | 5.6 | | | |
| Eagle Cap [d] | 30-35 | 40-60 | .3- .8 | .4- .8 | .2 | .2 | 5.5 | | | |
| Gearhart [d] | 25-30 | 60-80 | .3- .5 | .3- .5 | .2 | .3 | 5.8 | | | |
| Glacier Peak | 25-30 | 60-80 | 2.1-4.0 | 1.8-2.9 | .4 | .3 | 5.2 | 1.8 | 1.6 | 4.4 |
| Goat Rocks | 25-30 | 80-100 | 4.0-5.9 | 3.8-4.5 | .5 | .2 | 5.3 | 4.8 | 6.1 | 3.8 |
| Hells Canyon [d] | 30-35 | 40-60 | .3- .7 | .3- .6 | .2 | .2 | 5.5 | | | |
| Kalmiopsis [d] | 20-25 | 60-80 | 1.8-3.3 | .4- .9 | .4 | .1 | 5.6 | | | |
| Mount Adams | 25-30 | 80-100 | 4.0-5.4 | 4.1-4.5 | .5 | .2 | 5.3 | 4.8 | 6.1 | 3.8 |
| Mount Hood [d] | 30-35 | >120 | 1.5-4.3 | 1.1-2.7 | .4 | .3 | 5.4 | | | |
| Mount Jefferson [d] | 25-30 | 60-80 | 1.2-2.0 | .5- .9 | .3 | .1 | 5.5 | | | |
| Mount Washington [d] | 25-30 | 60-80 | 1.3-2.5 | .5-1.3 | .3 | .1 | 5.5 | | | |
| Mountain Lakes [d] | 25-30 | 60-80 | .8-1.3 | .5- .9 | .3 | .2 | 5.6 | | | |
| Pasayten | 25-30 | 60-80 | 2.0-3.6 | 1.8-2.6 | .4 | .3 | 5.5 | | | |
| Strawberry Mountain [d] | 30-35 | 40-60 | .3- .7 | .3- .6 | .2 | .2 | 5.5 | | | |
| Three Sisters [d] | 25-30 | 60-80 | .7-2.8 | .3-1.8 | .3 | .1 | 5.5 | | | |

[a] Hourly mean and maximum for May through October.

[b] *Sulfur* deposition is $S0_4^{2-}$, based on the volume weighted average for the sum of rain+snow deposition and cloudwater deposition. Nitrogen deposition is based on the volume weighted average for $NO_3$- and $NH_4^+$ for the sum of rain+snow deposition and cloudwater deposition.

[c] Sulfur concentration is the median value for $S0_4^{2-}$ concentration. Nitrogen concentration is the median value for the sum of $NO_3^-$ and $NH_4^+$ concentration.

[d] Applicable data on cloudwater chemistry are not available. Deposition and ion concentration therefore are based on date for rain+snow only; these estimates are probably much lower than actual.

# Appendix B: Lichens, Bryophytes, and Air Quality in Pacific Northwest Wilderness Areas [1]

## Introduction

Lichens and bryophytes are known to be sensitive receptors of air pollution, as discussed by numerous authors during the past century; some major collections of articles are those of Ferry and others (1973) and Nash and Wirth (1988). Another recent review is that of Galun and Ronen (1988). The most comprehensive bibliography on lichens in relation to air quality is that of Jürging and Burkhardt (1979-80). Additional references can be found in the ongoing series, "Literature on Lichens and Air Pollution" in the journal, *The Lichenologist.* Continuing series of "Recent Literature" compilations for lichens, mosses, and hepatics in t he journal, *The Bryologist,* also are useful sources of references.

In spite of the extensive literature on the subject in general, few studies on lichens or bryophytes as pollution monitors have focused on the Pacific Northwest (Fox and Ludwick 1976, Gough and others 1987, Johnson 1979). The taxonomy and distribution of Northwestern cryptograms, especially lichens, also are rather poorly known. Recent popular guides to the Northwestern species of lichens or bryophytes are those of Schofield (1969) and Vitt and others (1988). A recent guide to the lichens of California by Hale and Cole (1989) is useful for identifying many of the taxa found in the Northwest.

This appendix is a preliminary attempt to compile and interpret information from the literature and our own experience. A closer and more thorough examination of the literature may modify some of the conclusions presented here. In any case, more field and laboratory research dealing specifically with species in the Northwest is needed. We especially encourage more widespread surveys to obtain better species lists across the Region 6 wildernesses.

Table 12 is a best available estimate of lichens and mosses that might be expected in each Pacific Northwest ecosystem as defined in table 3 in the text. This list needs to be verified in the field to add overlooked species or to remove species not occurring in a specific ecosystem or wilderness area.

Our approach to screening of PSD applications is to define AQRVs as ecosystem-level units across which many lichens and bryophytes can be identified. We developed several matrices that the manager of a particular wilderness can use to identify sensitive

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[1] Prepared by Bruce Ryan and Fred Rhoades. Ryan is a botanist, Department of Botany NHB 166, Smithsonian Institution, Washing ton, DC 20560. Rhoades is a professor of biology, Western Washington University, Bellingham, WA 98225.

## Table 12—Tentative list of lichens by Pacific Northwest ecosystem

| Lichen | Ecosystem [a] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DF | SF | WS | ES | WA | EA | ED | EP | SH | ME |
| *Acarospora chlorophana* | | | | ? | + | + | ? | + | + | |
| *Alectoria sarmentosa* | + | ++ | + | + | | | | | | + |
| *Arthonia radiata* | + | | | | | | | | | + |
| *Aspicilia caesiocinerea* s.l. | + | + | + | + | + | + | + | + | + | + |
| *Bryoria abbreviate* | | | | + | | | + | + | | |
| *B. capillaries* | + | + | + | + | | | | | | + |
| *B. fremontii* | + | + | + | + | | | | ++ | | + |
| *B. fuscescens* | + | + | + | + | | | | + | | + |
| *B. glabra* | + | + | + | + | | | | | | + |
| *B. implexa* | + | + | + | + | | | | | | |
| *B. oregana* | + | + | + | ? | | | ? | ? | | |
| *B. trichodes* spp. *americana* | + | + | + | + | | | | | | + |
| *Buellia punctata* | + | ? | ? | ? | | | | | | + |
| *Calicium viride* | + | ? | | | | | | + | | |
| *Candelaria concolor* | + | | | | | | | + | + | ? |
| *Candelariella vitellina* | + | + | + | + | + | + | + | + | + | + |
| *Cetraria cucullata* | | | | | + | + | | | | |
| *C. islandica* | | | | + | + | + | | | | |
| *C. nivalis* | | | | | + | + | | | | |
| *Chrysothrix candelaris* | + | | | | | | | | | + |
| *Cladina arbuscula* | | + | + | + | + | | | | | |
| *C. rangiferina* | + | + | + | + | + | + | | | | |
| *Cladonia bellidiflora* | + | + | + | + | + | + | | | | |
| *C. chlorophaea* s.l. | + | + | + | + | | | | | | |
| *C. coniocrea* s.l. | + | | | | | | | | | + |
| *C. fimbriata* | + | | | | | | + | + | | + |
| *C. furcata* | + | | | | | | | | | + |
| *C. gracilis* | | | + | + | + | + | | | | |
| *c. spp.* | + | + | + | + | + | + | | + | + | + |
| *Coeocaulon muricatum* | | | + | + | + | + | | | | |
| *Collems spp.* (N) | + | + | + | + | | | | | + | + |
| *Evernia prunastri* | + | | | | | | | | | + |
| *Graphis scripts* | + | | | | | | | | | + |
| *Hypocenomyces scalaris* | + | ? | | | | | | + | | + |
| *Hypogymnia imshaugii* | ++ | ++ | ++ | ++ | | | + | + | | + |
| *H. physodes* | ++ | + | ? | ? | | | | | | + |
| *H. tubulosa* | + | | | | | | | | | |
| *Lecanora muralis* | ? | | | | | | | + | ++ | |
| *Lecidea atrobrunnea* s.l. | + | + | + | + | + | + | + | ++ | ++ | + |
| *Lepraria incana* s.l. | + | + | + | | | | | + | | + |
| *Leptochidium albociliatum* (N) | | | ? | | ? | | | + | + | ? |
| *Leptogium californicum* (N) | + | + | + | ? | + | ? | | + | + | + |
| *Letharia vulpina* | | | | + | | | + | ++ | | + |
| *L. columbiana* | | | | + | | | + | ++ | | + |
| *Lobaria oregana* (N) | + | + | | | | | | | | |
| *L. pulmonaria* (N) | + | | | | | | | | | |
| *L. scrobiculata* (N) | + | | | | | | | | | |
| *Melanelia elegantula* | + | + | + | ? | + | + | ? | ++ | + | + |
| *M. exasperate* | + | | | | | | | | | ? |
| *M. exasperatula* | + | ? | | | | | | | | ? |
| *M. fuliginosa (= M. glabratula)* | + | ? | | | | | | | | |
| *M. subaurifera* | + | | | | | | | + | | ? |
| *M. subolivacea* | + | ? | | | | | | + | + | + |
| *Mycoblastus alpinus* | + | + | + | + | | | ? | ? | | |
| *M. sanguinarius* | + | + | + | + | | | ? | ? | | |
| *Parmelia saxatilis* | + | ? | | | | | | + | | + |
| *P. sulcata* | + | + | ? | ? | | | | + | | + |

**Table 12—(Continued)**

| Lichen | DF | SF | WS | ES | WA | EA | ED | EP | SH | ME |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ecosystem [a] | | | | | | | | | |
| *Parmeliopsis ambigua* | ++ | ++ | ++ | + | | | + | + | | ++ |
| *P. hyperopta* | + | + | + | + | | | + | + | | + |
| *Parmotrema chinense* | + | | | | | | | | | +? |
| *Peffigera aphthosa* | + | + | + | + | | | | | | |
| *P. didactyla* (N) *(= P. spuria)* | + | + | + | + | + | + | | + | | + |
| *P. rufescens* s.I. (N) | + | + | + | + | + | + | + | ++ | + | + |
| *P. canina* (N) | + | ? | | | | | | + | | |
| *P. collina* (N) | + | ? | | | | | | + | | |
| *Pertusaria amara* | + | | | | | | | | | + |
| *Phaeophyscia orbicularis* | | | ? | ? | | | | | | |
| *P. sciastra* | ? | ? | ? | + | + | ? | | + | | + |
| *Physcia adscendens* | + | | | | | | | | | + |
| *P. aipolia* | + | | | | | | | | | ? |
| *P. caesia* | + | + | + | + | + | + | | | ? | + |
| *P. dubia* | + | + | + | ? | + | | | | | |
| *P. tenella* | + | ? | | | | | | | ? | + |
| *Physconia detersa* (*P. grisea* auct.) | + | | | | | | | + | ? | + |
| *Platismatia glauca* | ++ | ++ | ++ | + | | | | | | + |
| *Pseudocyphellaria anthraspis* (N) | + | ? | | | | | | | | + |
| *Pseudephebe minuscula* | | | ? | ? | + | + | | ? | | |
| *P. pubescens* | | | ? | ? | + | + | | + | | |
| *Ramalina farinacea* | + | | | | | | | | | + |
| *R. menziesii* | | | | | | | | | | + |
| *Rhizocarpon geographicum* | | | + | + | + | + | | | | |
| *Rhizoplaca chrysoleuca* | | | + | + | + | + | + | + | + | |
| *R. melanophthalma* | | | + | + | + | + | + | ++ | ++ | |
| *Sticta limbata* (N) | + | | | | | | | | | ? |
| *Tuckermannopsis canadensis* | | | | + | | | + | + | | + |
| *T. chlorophylls* | + | | | | | | | + | | + |
| *T. merrillii* | | | | + | | | + | ++ | | + |
| *T. saepinicola* | | | ? | ? | | | | | | |
| *Umbilicaria cylindrical* | | | | | + | + | | | | |
| *U. polyphylla* | | | ? | ? | ? | ? | | | | |
| *U.* spp. | | | + | + | + | + | + | + | + | + |
| *Usnea filipendula* | + | | | | | | | | | + |
| *U. sub floridana* | + | | | | | | | | | + |
| *U.* spp. | + | | | | | | | | | + |
| *Xanthoparmelia cumberlandia* | + | + | | | | | | + | | + |
| *Xanthoria candelaria* | | | | | + | + | + | + | + | + |
| *X. fallax* | | | | | | | | + | + | ? |
| *X. polycarpa* | ? | | | | | | | | + | + |

++ = abundant;
+? = present;
? = may be present and
(N) = nitrogen-fixing lichen.

[a] Ecosystems:
DF Douglas-firAvestern hemlock;
SF Pacific silver fir;
WS west-side subalpine;
ES east-side subalpine;
WA west-side alpine;
EA east-side alpine;
ED east-side Douglas-fir;
EP east-side ponderosa pine;
SH sagebrush shrubland; and
ME mixed evergreen.

## Species Sensitivities to Air Pollution

Data on sensitivity of lichens to ozone come primarily from Sigal and Nash (1983), with some additional information from Eversman and Sigal (1987), McCune (1988), Nash and Sigal (1979, 1980), Rosentreter and Ahmadjian (1977), and Sigal and Johnston (1986).

The sensitivities of most of the lichen species to sulfur dioxide are ranked according to the system of Wetmore, as published in a series of papers (Wetmore 1981, 1985, 1987, 1988b, 1989), with sensitivity classes slightly modified as described below. Additional information on the sensitivity of particular lichen species to sulfur dioxide comes from several field studies in Europe or eastern North America.

There are only a few studies of the effects of pollutants on lichens in the Pacific Northwest: Denisen and others (1977), Denisen and Carpenter (1973), Hoffman (1974), Johnson (1979), Rhoades (1988), and Taylor and Bell (1983). Moser (1983) studied the effects of gases from Mount St. Helens on lichens. Studies dealing with the effects of acid rain on lichens or bryophytes include those of Gilbert (1986), Gunther (1988), Hutchinson and others (1986), Lechowicz (1987), Robitaille and others (1977), and Sigal and Johnston (1986). The only direct information available on the effects of nitrogen oxides on lichens is from Nash (1976); information on the effects of peroxyacetyl nitrate (PAN) on lichens is from Sigal and Taylor (1 979).

Data on the sensitivity of lichens and bryophytes to fluorides come from Böritz and Ranft (1972), Clerc and Roh(1979, 1980), Comeau and LeBlanc (1972), Gilbert (1985), Horntveldt (1976), LeBlanc and others (1971, 1972b), Nash (1971), Perkins and Millar (1987a, 1987b), and Perkins and others (1976, 1980). Most of the information on the concentrations and effects of heavy metals comes from Nieboer and Richardson (1981). Some other major studies or reviews on this topic include Brown and Beckett(1983), Nieboer and others (1978), Puckett (1 988), and Seaward (1980).

The article by Winner (1988), dealing exclusively with bryophytes, was used the most extensively in preparing the list of sensitive mosses and liverworts; additional references to specific studies can be found in that article. Some of the other articles dealing with pollutant effects on bryophytes are Ferguson and others (1978), Gilbert (1969), and LeBlanc and Rao(1975).

### Sensitivity Classes

Concentrations used for defining boundaries between the “sensitive” and “intermediate” classes may be misleading because they are not necessarily the minimum concentrations needed to produce significant damage. Field studies have shown that many species show significant or even severe damage at lower concentrations, as described below. Due to the variability in methodology and units in fumigation studies, no attempt is made here to determine minimum pollutant levels for damage from fumigation studies.

Table 13 is a list of sensitivity classes for lichens and bryophytes. These classes represent different species’ tolerance levels to pollutants.

### Ozone

No field data are available on the sensitivity of lichens to ozone concentrations less than 20 parts per billion. The concentrations given by Sigal and Nash (1983) in parts per million per hour cannot be related with certainty to mean annual parts per billion. Sigal and Nash (1983) used a system of four sensitivity classes (very sensitive, sensitive, moderately tolerant, and tolerant), which we have adapted to a three-class system in table 13.

**Table 13—Definition of sensitivity classes for lichens and bryophytes** [a]

| Pollutant | Sensitivity class | | |
|---|---|---|---|
| | Sensitive | Intermediate | Tolerant |
| | *Parts per billion* | | |
| Ozone | <20 | 15-70 | >65 |
| Sulfur dioxide | 5-15 | 10-35 | >30 |
| Nitrogen oxides | ? | ? | ? |
| Fluoride | ? | ? | ? |

? = studies inconclusive

[a] The overlapping ranges represent uncertainty in the values.

Sources: LeBlanc and others 1972a, Martin and Jacquard 1968, Perkins and Millar 1987b.

## Sulfur Dioxide

Various authors have used up to 10 sensitivity classes for rating sensitivity of lichens to sulfur dioxide. Information is given below on the sensitivity of selected lichen species to sulfur dioxide levels below the 40 µg (micrograms) per cubic meter [2] concentration used as the limit for sensitive species.

**Five micrograms per cubic meter** — *Lobaria pulmonaria* is absent from areas with concentrations higher than 5 µg per cubic meter according to Denisen and others (1977). (As noted below, however, Hawksworth and Rose [1970] found this species in areas with 13-26 µg per cubic meter,)

**Eight to ten micrograms per cubic meter** — Trass (1968) related the value of 8 µg per cubic meter to a paleotolerance index of 2, the boundary between the "normal zone" ($SO_2$ entirely absent) and the first "mixed zone," which seems to imply that at least some damage to lichens occurs at this level or above. Trass (1973) later used the value of 10 µg per cubic meter for the same boundary. Johnson (1979) found that zone Ill (out of five zones) corresponds to 8 µg per cubic meter mean annual $SO_2$. Although he presented no data on $SO_2$ levels for the outer two zones, presumably the species restricted to zones IV and V are sensitive to even lower levels. Species are as follows:

*Caloplaca holocarpa* — Johnson (1979)
*Cladonia bellidiflora* — Johnson (1979)
*Evernia prunastri* — Johnson (1979)
*Lecanora circumborealis* — Trass (1973)
*Menegazzia terebrata* — Trass (1973)
*Mycoblastus sanguinarius* — Johnson (1979), Trass (1973)
*Ochrolechia androgyna* — Trass (1973)
*Ramalina farinacea* — Johnson (1979)
*Usnea hirta* — Johnson (1979)

Thirteen to fifteen micrograms per cubic meter—Some species of lichens are damaged or killed by mean annual levels of $SO_2$ as low as 13 µg per cubic meter

[2] Sulfur dioxide concentration in micrograms per cubic meter can be converted to parts per billion by multiplying by 0.382.

(Wetmore 1985). LeBlanc and Rao (1973) used a similar value (15 µg per cubic meter) for the boundary between zones IV and V. The value of 13 µg per cubic meter also corresponds to the boundary between the zone of relatively pure air and the next zone in the studies by Gilbert (1970), Hawksworth and Rose (1970), and Taoda(1972). But several of these species have been classified by others as being sensitive to intermediate or, in the case of *Phaeophyscia orbicularis,* intermediate in sensitivity to $SO_2$. Several workers have found losses in reproductive capacity at levels as low as 13 µg per cubic meter; for example, LeBlanc and Rao (1973) found that *Parmelia sulcata* no longer produced abundant soredia at higher levels. Species areas follows:

*Carxfelaria concolor* — LeBlanc and others (1972a)
*Cladonia fimbriata* — LeBlanc and others (1972a)
*Lobaria scrobiculata* — Hawksworth and Rose (1970)
*Metzgeria furcata* (bryophyte) — Gilbert (1970)
*Phaeophyscia orbicu/aris* — LeBlanc and others (1972a)
*Sticta limbata* — Hawksworth and Rose (1970)
*Usnea filipendula* — Hawksworth and Rose (1970)
*Xanthoria fallax* — LeBlanc and others (1972a)
*Xanthoria polycarp* — LeBlanc and others (1972a)

Twenty-five to thirty micrograms per cubic meter—Hawksworth and Rose (1970) report that lichen communities were unaffected in areas with levels less than 30 µg per cubic meter. But these authors also listed quite a few species (some of which are given above) that were restricted to areas with less than 13 µg per cubic meter and others (one is listed below) that were restricted to areas with levels of 13 to 26 µg per cubic meter. LeBlanc and others (1972a) found that 26 µg per cubic meter corresponds to an index of atmospheric purity value of 40, the lower boundary of zone IV. Trass (1968) related a similar level (27.5 µg per cubic meter) to a paleotolerance index of 5 (on a scale of 0 to 10), the boundary between two mixed zones.

Van Haluwyn and LeRond (1986) used 30 µg per cubic meter as the boundary between the more polluted zones (A-E) and the less polluted ones (F-G). Trass (1973) found that a paleotolerance index of 5 corresponds to 30 µg per cubic meter. McCune (1988) found statistically significant decreases in total lichen cover, species richness, and index of atmospheric purity values over a gradient of 23 to 40 µg per cubic meter annual mean sulfur dioxide, which indicates that at least some damage to the lichen vegetation occurs at levels as low as about 30 µg per cubic meter. Species are as follows:

*Bryoria implexa* — Trass (1973)
*Bryoria trichodes* subsp. *americana* — LeBlanc and others (1972a)
*Graphis scripta* — Trass (1973)
*Hypogymnia tubulosa* — Trass (1973)
*Lobaria pulmonaria* — Hawksworth and Rose (1970), Trass (1973) (as noted above, Denisen and others [1977] reported this species to be sensitive to levels as low as 5 µg per cubic meter)
*Melanelia subawifera* — Trass ( 1973)
*Parmeliopsis ambigua* — Trass (1973)
*Physcia aipolia* — LeBlanc and others (1972a), Van Haluwyn and LeRond (1988) (other authors have classified this species as intermediate in sensitivity to $SO_2$)
*Platismatia glauca* — Trass (1973)
*Tuckermannopsis chlorophylla* — Trass (1973)
*Usnea subfloridana* — Trass (1973)

## Fluoride

Little information is available on the minimum levels of fluoride (F) in the atmosphere needed to produce damage. Horntveldt (1976) found that 20 parts per million of F in the bark caused significant damage to *Hypogymnia physodes.* Most other authors related their results to concentrations of F within the thallus of the lichens (Clerc and Roh 1980; LeBlanc and others 1972b; Nash 1971; Perkins and Millar 1987a, 1987b).

## Summary

Table 14 gives estimates of pollution sensitivity for each lichen species. The classes represent the pollutant levels for which species have shown visible damage, reduced growth, or mortality.

These estimates differ in their reliability because they are based on different kinds of studies (field distribution in regions of known air quality, transplants, fumigation, records of deterioration, and historical comparisons). The right column of table 14 includes a list of species that are likely candidates for elemental analyses because (1) data on elemental content is available for these species; (2) many are tolerant to air pollution; (3) many are large, foliose or fruticose, easily collected and cleaned, and are least likely to be affected by substrate chemistry; and (4) most are easily identified and, therefore, not easily confused with other species.

Other common or distinctive lichens in the Pacific Northwest for which there are no data on reaction to ozone, sulfur dioxide, or nitrogen oxides are arranged by AQRV ecosystem in table 15. Estimated sensitivities based on similar species for which there are data are presented in table 16 for these species. Species for which heavy metal and sulfur content data are available are marked.

The habitats for common Pacific Northwest mosses are presented in table 17. Sufficient data are not available to identify the ecosystems where these mosses occur, but generalized habitat data are available from Vitt and others (1988). The sensitivities of bryophytes to air pollution are presented in table 18. Tolerance to sulfur dioxide is sometimes inferred from nonspecific statements in the literature such as “pollution tolerant” or “these species are listed in order of increasing sensitivity to sulfur dioxide.”

## Interactions Among Pollutants

There is little information on interactions among various pollutants affecting lichens and mosses. Sigal and Johnston (1986) found no significant ozone-acid rain interaction effects on *Lobaria pulmonaria.* Hutchinson and others (1986) found that sprays of sulfuric acid alone (pH 3.0) had a significantly greater effect on the moss *Pleurozium schreberi* than nitric acid alone or pH 5.6 sprays of any ratio of sulfuric and nitric acids. Manrique and Balaquer [3] describe a synergistic effect of sulfur dioxide and nitrate on several lichens, including *Evernia prunastri* and *Rarnalina farinacea.* Punz (1979a, 1979b) discusses the synergistic effects of various combinations of lead, sodium chloride, and sulfur dioxide. Eversman and Sigal (1987) found that $S0_2$ ameliorates the effect of ozone on photosynthesis of two lichen species, but that ozone and the combination of ozone and sulfur dioxide both produce similar levels of ultrastructural damage, which are greater than that of sulfur dioxide by itself.

DeWit (1976) found that for *Hypogymnia physodes* and *Physcia tenella* simultaneous fumigation with sulfur dioxide and ozone produces levels of damage above that produced by similar concentrations of each pollutant separately. Mandel and others (1975; cited by Taylor and Bell [1983]) found synergistic effects of sulfur dioxide and hydrogen

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[3] Unpublished data. On file with: Bruce Ryan, Department of Botany NHB 166, Smithsonian Institution, Washington, DC 20560.

**Table 14—Sensitivity of lichen species to types of air pollution [a]**

| Lichen | Ozone | Sulfur dioxide | Nitrous oxides/PAN | Fluoride | Heavy metal |
|---|---|---|---|---|---|
| *Acarospora chlorophana* | | S | | | |
| *Alectoria sarmentosa* | S | | | | * |
| *Arthonia radiata* | | I | | | |
| *Aspicilia caesiocinerea* s.l. | | T | | | |
| *Bryoria abbreviate* | S | | | | |
| *B. capillaries* | | S | | S | |
| *B. fremontii* | S | | | | |
| *B. fuscescens* | | I | | | |
| *B. glabra* | S | I | | | |
| *B. implexa* | | S | | | |
| *B. oregana* | S | | | | |
| *B. trichodes* spp. *americana* | | S-I | | | |
| *B.* spp. | | | | | * |
| *Buellia punctata* | | I-T | | | |
| *Calicium viride* | S | I-T | | | |
| *Candelaria concolor* | | S-I | | S | |
| *Candelariella vitellina* | | I | | T | |
| *Cetraria cucullata* | | I? | | | |
| *C. islandica* | | I | | I | |
| *C. nivalis* | | I? | | | |
| *Chrysothrix candellaris* | | T | | | |
| *Cladina arbuscula* | T | I | | I | * |
| *C. rangiferina* | | S-I | | I | * |
| *Cladonia bellidiffora* | | I-S | | | |
| *C. chlorophaea* | | I | | I | |
| *C. coniocrea* s.l. | | I | | I | |
| *C. fimbriata* | | S-I | | S-I | |
| *C. furcata* | | T-I | | I | * |
| *C. gracilis* | | T-I | | I | |
| *C.* spp. | S | | | | * |
| *Coeocaulon muricatum* | | T-I | | | |
| *Collema* spp. | S-I | T? | | | |
| *Evernia prunastri* | S | I-T | | S | * |
| *Graphis scripts* | | I | | | |
| *Hypocenomyces scalaris* | | I | | | |
| *Hypogymnia imshaugii* | T-I | T-I? | ? | ? | * |
| *H. physodes* | | I-T | | S-I | * |
| *H. tubulosa* | | | | S? | |
| *Lecanora muralis* | | T | | | * |
| *Lecidea atrobrunnea* s.l. | | T | | | |
| *Lepraria incana* s.l. | | T | | T | |
| *Leptochidium albociliatum* | S-I | | | | |
| *Leptogium californicum* | S-I | | | | |
| *Letharia vulpina* | T-I | T | | | |
| *L. columbiana* | T-I | T | | | |
| *Lobaria oregana* | | S | | | |
| *L. pulmonaria* | T-I? | S | | | |
| *L. scrobiculata* | | S | | | |
| *Melanelia elegantula* | T | | | | |
| *M. exasperate* | | I | | | |
| *M. exasperatula* | | I | | | |

**Table 14—(continued)** [a]

| Lichen | Ozone | Sulfur dioxide | Nitrous oxides/PAN | Fluoride | Heavy metal |
|---|---|---|---|---|---|
| *M. fuliginosa (= M. glabratula)* | | I | | I | |
| *M. subaurifera* | S | | S | | |
| *M. subolivacea* | T-I | | | | |
| *Mycoblastus sanguinarius* | | I-S | | | |
| *Parmelia sexatilis* | T | I | | S | |
| *P. sulcata* | S-I | I-T | S-I | S-I | |
| *Parmeliopsis ambigua* | | I | | T | |
| *P. hyperopta* | | I | | | |
| *Parmotrema chinense* | | S-I | | | |
| *Peltigera aphthosa* | | I? | | | |
| *P. canina* | S | T | | S | * |
| *P. collina* | S | | | | |
| *P. didactyla (= P. spuria)* | S | | | | |
| *P. rufescens* s.l. | S-I | | | ? | * |
| *Phaeophyscia orbicularis* | S | I | | S | |
| *P. sciastra* | S | | | | |
| *Physcia adscendens* | | I | | S | |
| *P. aipolia* | | I | | S | |
| *P. caesia* | | I | | | |
| *P. dubia* | | T | | S-I | |
| *P. tenella* | T | I | | S | |
| *Physconia detersa* (*P. grisea* auct.) | T | I-S | | | |
| *Platismatia glauca* | S | I | | ? | * |
| *Pseudocyphellaria anthraspis* | S | | | | |
| *Pseudephebe minuscula* | I | | | | |
| *P. pubescens* | I | | | | |
| *Ramalina farinacea* | S | S-I | | S | * |
| *R. menziesii* | S | | | | |
| *Rhizocarpon geographicum* | | T | | T | |
| *Rhizoplaca chrysoleuca* | | S | S | | |
| *R. melanophthalma* | | S | | | |
| *Stereocaulon paschale* | S | | | | |
| *Sticta limbata* | | S | | | |
| *Tuckermannopsis canadensis* | S | | | | |
| *T. chlorophylls* | | S | | I | * |
| *T. merrillii* | S-I | | | | |
| *T. saepinicola* | | T-I | | | |
| *Umbilicaria cylindrical* | | T-I | | | |
| *U. polyphylla* | | T-I | | T-I | |
| *Usnea filipendula* | | S | | | |
| *U. sub floridana* | | S-I | | S | |
| *U.* spp. | S | | | | * |
| *Xanthoparmelia cumberlandia* | | S | | | |
| *Xanthoria candelaria* | S | I-T | | | |
| *X. fallax* | T | I-S | S | | |
| *X. polycarpa* | T | I-S | | | |

S = sensitive;
I = intermediate;
T = tolerant;
? = studies inconclusive; and
* = elemental analysis date available.

**Table 15—Supplemental list of lichen species for Pacific Northwest ecosystems** [a]

| Lichen | Ecosystem [b] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DF | SF | WS | ES | WA | EA | ED | EP | SH | ME |
| *Cetraria* spp. | | + | + | + | + | | | | | |
| *Cladina mitis* | | + | + | + | + | | | | | |
| *Hydrothyria venosa* | + | + | | | | | | | | ? |
| *Hypogymnia enteromorpha* | + | + | + | ? | | | | | | + |
| *Lobaria linita* | + | + | + | ? | + | | | | | ? |
| *Nephroma* spp. | + | + | | | | | | | | + |
| *Pannaria* spp. | + | + | + | + | + | | | | | + |
| *Parmelia hygrophila* | + | | | | | | | | | + |
| *Parmeliella* spp. | + | + | + | + | + | | | | | + |
| *Peltigera* spp. | + | + | + | + | | | | | | + |
| *Pseudocyphellaria* spp. | + | + | | | | | | | | + |
| *Solorina crocea* | | | + | | + | + | | | | |
| *Sphaerophorus globosus* var. *gracilis* | + | + | + | | | | | | | + |
| *Stereocaulon* spp. | + | + | + | + | + | + | | | | + |
| *Sticta* spp. | + | + | | | | | | | + | |
| *Thamnolia* spp. | | | | | + | + | | | | |
| *Tholurna dissimilis* | | | + | + | | | | | | |
| *Umbilicaria* spp. | | | + | + | + | + | + | + | + | ? |
| *Usnea longissima* | + | | | | | | | | | + |

\+ = present; and
? = may be present.

[a] There are no date on ozone, sulfur dioxide, or nitrogen oxides for these species.

[b] Ecosystems:
DF Douglas-fir/Western hemlock;
SF Pacific silver fir;
WS west-side subalpine;
ES east-side subalpine;
WA west-side alpine;
EA east-side alpine;
ED east-side Douglas-fin;
EP east-side ponderosa pine;
SH sagebrush shrubland; and
ME mixed evergreen.

cited by Taylor and Bell [1983]) found synergistic effects of sulfur dioxide and hydrogen fluoride on vegetation: such effects also may occur in lichens. Wetmore (1985) suggests that the results of Sigal and Nash (1983) may reflect synergism between ozone and PAN. More research is clearly needed to define possible synergisms or interactions of pollutants affecting lichens and mosses.

## Research and Monitoring Needs

There is an urgent need to improve the reliability of these estimates by correlating field observations to experimentally induced observations of species common to these areas. The National Park Service and Forest Service conducted a joint workshop in April 1991 that will result in preparation of a manual of standard methodology for lichen air pollution studies.

**Table 16—Estimated sensitivity of supplemental lichens described in table 15**

| Lichen | Ozone | Sulfur dioxide | Nitrous oxides/PAN | Heavy metal |
|---|---|---|---|---|
| *Cetraria* spp. | S | | | |
| *Cladina mitis* | T | S-I | | |
| *Hydrothyria venosa* (N) | S | S | S | |
| *Hypogymnia enteromorpha* | T-I | I-T | | * |
| *Lobaria Iinita* | S | S | S | |
| *Mycoblastus alpinus* | | I-S | | |
| *Nephroma* spp. | S | S | S | |
| *Pannaria* spp. (N) | S | S | S | |
| *Parmelia hygrophila* | S-I | I-T | ? | |
| *Parmeliella* spp. (N) | S | S | S | |
| *Peltigers* spp. (N) | S | T-I | S-I | * |
| *Pseudocyphellaria* spp. (N) | S | | S | |
| *Solorina crocea* (N) | S | | S | |
| *Sphaerophorus globosus* var. *gracilis* | (No basis for an estimate.) | | | * |
| *Stereocaulon* spp. (N) | S | S | S | |
| *Sticta* spp. (N) | S | | S | |
| *Thamnolia* spp. | (No basis for an estimate.) | | | |
| *Tholurna dissimilis* | (No basis for an estimate.) | | | |
| *Umbilicaria* spp. | I? | | | * |
| *Usnea Iongissima* | S | | | |

(N) = nitrogen-fixing lichens;
S = sensitive;
I = intermediate;
T = tolerant; and
* = elemental analysis data available.

Wetmore (1988a) suggests the following steps as a floristic method of assessing air quality with lichens (also true for bryophytes):

1. Inventory all species found in all vegetation types throughout a specified area, including collection of voucher specimens.

2. Collect bulk samples of several common, easily collected, air pollution-tolerant species for baseline elemental analyses. For such analyses, it should be determined which ecosystems of a wilderness are most likely to be affected first by changes in air quality; this will minimize the amount of bulk sampling.

3. Conduct field observation of the presence or absence of symptoms likely due to air pollution injury; for example, discoloration, dead thalli, frequency of fertile thalli, abnormal growth, and loss or absence of sporophyte generations for bryophytes.

4. Prepare a lichen flora for the area and compare with historical records or with flora occurring in another area of the same region that is known to have clean air.

5. Map the distribution of pollution-sensitive species in the area to determine distribution voids potentially caused by air pollution.

6. Compare the elemental analyses of thalli with reports from other studies and among localities to determine if sublethal accumulation of pollutants is occurring.

**Table 17—Habitats of common Pacific Northwest bryophytes**

| Bryophyte | Ecosystem [a] AL | SA | WC | DC | SA | PT |
|---|---|---|---|---|---|---|
| *Amblystegium juratzkanum* | | ? | + | | | + |
| *A. serpens* | | ? | + | | | + |
| *Atrichum undulatum* | | | + | + | | |
| *Aulocomnium palustre* | + | + | + | + | | + |
| *Blepharostoma trichophyllum* | | | + | | | |
| *Brachythecium rivulare* | | + | + | + | | |
| *B. salebrosum* | | + | | + | | |
| *B. starkei* | + | + | + | | | |
| *Bryum argenteum* | + | + | + | + | + | |
| *Ceratodon purpureus* | + | + | + | + | + | |
| *Desmatodom latifolius* | | | | ? | ? | |
| *Dicranoweisia cirrata* | | | + | | | |
| *Dicranella heteromalla* | | + | + | + | | |
| *Dicranum scoparium* | + | + | + | + | | |
| *Funaria hygrometrica* | | + | + | + | + | |
| *Grimmia pulvinata* | | | + | | | |
| *Hylocomium splendens* | | + | + | + | | |
| *Kindbergia praelonga* | | | + | | | |
| *Marchantia polymorpha* | + | + | + | + | | + |
| *Metzgeria furcata* | | | + | | | |
| *Orthotrichum lyellii* | | | + | | | |
| *O.* spp. | + | + | + | + | | |
| *Pleurozium schreberi* | | + | + | + | | |
| *Pohlia nutans* | + | + | + | + | + | + |
| *Polytrichum commune* | | + | + | + | | |
| *P. juniperinum* | + | + | + | + | + | |
| *Ptilium crista-castrensis* | | + | + | + | | |
| *Rhytidialdelphus squarrosus* | | + | + | | | + |
| *Sphagnum* spp. | + | + | + | + | | + |
| *S. fuscum* | | | + | + | | + |
| *S. magellanicum* | | + | | | | + |
| *S. rubellum* | | | + | | | + |
| *Tetraphis pellucida* | | + | + | + | | |
| *Tortula muralis* | | | + | | | |
| *T. ruralis* | + | + | + | + | + | |

+ = present; and
? = may be present.

[a] Ecosystems:
AL = alpine;
SA = subalpine;
WC . wet coniferous forest;
DC = dry coniferous forest;
SA = savanna; and
PT = peatland.

Source: Vitt and others 1968.

**Table 18—Common Pacific Northwest bryophytes and their sensitivity to air pollution** [a]

| Bryophyte | Sulfur dioxide | Fluoride | Heavy metals |
|---|---|---|---|
| *Amblystegium juratzkanum* | T | | |
| *A. serpens* | S | | |
| *Atrichum undulatum* | I | | |
| *Aulocomnium palustre* | I | | |
| *Blepharostoma trichophyllum* | S | | |
| *Brachythecium rivulare* | | | * |
| *B. salebrosum* | I? | | |
| *B. starkei* | I? | | |
| *Bryum argenteum* | T | | |
| *Ceratodon purpureus* | T | | |
| *Desmatodom latifolius* | I? | | |
| *Dicranoweisia cirrata* | I | | * |
| *Dicranella heteromalla* | T | T-I | |
| *Dicranum scoparium* | | S-I | * |
| *Funaria hygrometrica* | T | S? | |
| *Grimmia pulvinata* | I | | |
| *Hylocomium splendens* | S | I | * |
| *Kindbergia praelonga* | T | | * |
| *Marchantia polymorpha* | T | | |
| *Metzgeria furcata* | S | | |
| *Orthotrichum lyellii* | ? | | |
| *O.* spp. | T? | | |
| *Pleurozium schreberi* | S-I | | * |
| *Pohlia nutans* | T-I | I | |
| *Polytrichum commune* | S | S | * |
| *P. juniperinum* | I | I | |
| *Ptilium crista-castrensis* | S | | |
| *Rhytidiadelphus squarrosus* | I | | |
| *Sphagnum* spp. | S | S | * |
| *S. fuscum* | | | * |
| *S. magellanicum* | | | * |
| *S. rubellum* | | | * |
| *Tetraphis pellucida* | I | | |
| *Tortula muralis* | T | | |
| *T. ruralis* | T? | | |

S = sensitive;
I = intermediate;
T = tolerant;
? = studies inconclusive; and
* = elemental analysis data available.

[a] The occurrence of these species in specific ecosystems is not known.

Other actions that should be considered in monitoring the air pollution sensitivity of lichens and mosses include (1) transplant studies, (2) field fumigation studies of sensitive species, (3) long-term visual monitoring at fixed photo points, and (4) transects on trees and rocks.

The Forest Service should implement the inventory and analyses recommended above independent of the PSD review process. The estimates in this report are provided to expedite screening efforts for PSD permits but do not substitute for a more thorough screening procedure based on real data.

# Appendix C: Night Visibility

Night visibility includes vertical and panoramic views of the night sky. It can be adversely impacted by (1) source light extinction obscuring some or all stars and planets; (2) source light diffusion decreasing the light intensity of visible stars and planets; or (3) increased night sky brightness due to increased light sources in and around the viewing area, and increased diffusion of light through the air mass causing reduction both in light intensity and the number of stars and planets visible in the night sky.

To determine the existing night visibility condition:

1. Locate areas where night sky views area resource value. Some areas will be less sensitive as a result of high elevation, steep terrain, or inaccessibility.

2. Obtain still or video photographs of horizontal and vertical views of the night sky. Consult local astronomers for assessment of the photographs.

3. If possible, correlate photographs to particle sampling and oral interviews of viewers. Potential viewers who may help determine existing night visibility conditions include professional astronomers, amateur astronomers, campers and hikers, professional photographers, amateur photographers, and personnel at military installations.

4. Obtain optical characterization of light scattering and light absorption. Scattering can be estimated from photographs. This is done with particle sampling in areas where sensitivity and concern for existing conditions are high.

## Source Impact Determination

A decrease in star magnitude from 6 to 7 will be used as the indicator of source-light diffusion effects. Stars of magnitude 6 are barely visible to the naked eye on a dark night. Extinction of 50 percent of the visible stars in the Milky Way will be used as the indicator of loss of light on a dark night. The inability to capture magnitude 6 stars in photographs with enough clarity to identify the star with the naked eye will be used as the indicator of increased night sky brightness.

## Comparison Methods

Primary data collection to determine existing conditions will include, at a minimum, viewer observations and photographs. In areas where sensitivity and concern for existing conditions are high, correlation of systematic particle sampling, optical characterization, and paired horizontal-vertical photographs from established monitoring sites could be used to establish the existing condition and provide sufficient data for modeling of pristine dark-night sky conditions.

Viewer observation should include oral interviews with viewers or written observations by wilderness guards or park rangers and documentation on interview sheets, visibility logs, and 35-mm photographs. The visibility log should include date, time, location of viewer, and subjective observations of the visibility conditions of the night sky.

Extinction of visible stars in the Milky Way will be evaluated by the observers and recorded in the visibility log. At least 1 calendar year of observations is needed to establish current night visibility of the Milky Way due to the rotation of Earth and variation in weather conditions. Observers will need training to assure consistency in the observations.

Decrease in star magnitude from 6 to 7 will be evaluated by both observation of selected magnitude 6 stars and photographic record. Magnitude 6 stars will be a sensitive indicator because they are barely visible with the naked eye, and source light diffusion could cause them to be invisible in the night sky. Repeated observation of selected stars that can be recognized in the field will track visibility overtime. This information will be recorded on visibility log sheets. Photographs will track both visibility of the stars and increases in light diffusion in the night sky. Stars near or part of known constellations will be more desirable for field observers.

After current conditions are established, periodic monitoring should be continued and data stored for long-term comparison.

# Appendix D: Calculation of Feature Contrast

Feature contrast is the difference in radiance values between texture or coloration of a feature somewhere below the horizon.

Calculation of feature contrast,

$$C_f = C_r K \ \exp^{-z},$$

where

$C_r$ = inherent contrast of the feature against another feature adjacent to it (measured on a clear day);

K = $[(1/C_o^1 + 1) + (\exp^{-z}) (C_o^1/C_o^1 + 1)]^{-1}$,

where

$C_o^1$ = contrast between the feature and the horizon; and

Z = $(b_{ext} M^{-1} \times D \times X)$ ,

where

$b_{ext} M^{-1}$ = average light extinction efficiency per unit species mass (square meters per gram),

= D distance between the observer and the target (m), and

= X particle concentration (micrograms per cubic meter).

Typical light extinction efficiencies are:

$b_{ext} M^{-1}$ = 0.1 where wind-blown dust predominates—rural West;

3.0 where there is a mix of windblown and anthropogenic sources—suburban West and rural East;

6.0 where sulfates and nitrates predominate-urban areas of both East and West; and

13.0 where soot predominates—smokey valleys, prescribed fire areas, and highly industrial areas where coal or wood are burned.

The visibility impairment table values are computed by using the following relation:

$$C = C_o \exp^{-z},$$

where

$C_o$ = the inherent contrast at the horizon (dimensionless, available from measurements).

# Appendix E: Species List

| Common name | Scientific name |
|---|---|
| Western hemlock | *Tsuga heterophylla* (Raf.) Sarg. |
| Mountain hemlock | *Tsuga mertensiana* (Bong.) Carr. |
| Sugar pine | *Pinus larnberliana* Dougl. |
| Ponderosa pine | *Pinus ponderosa* Dougl. ex Laws. |
| Jeffrey pine | *Pinus jeffreyi* Grev. & Balf. |
| Western white pine | *Pinus monticola* Dougl. ex D. Don |
| Lodgepole pine | *Pinus contorya* Dougl. ex Loud. |
| Whitebark pine | *Pinus albicaulis* Engelm. |
| Subalpine fir. | *Abies lasiocarpa* (Hook.) Nutt. |
| Pacific silver fir | *Abies amabilis* Dougl. ex Forbes |
| Grand fir | *Abies grandis* (Dougl. ex D. Don) Lindl. |
| Noble fir | *Abies procera* Rehd. |
| White fir | *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr. |
| Red fir | *Abies magnifka* A. Murr. |
| Alaska yellow-cedar | *Chamaecyparis nootkatensis* (D. Don) Spach |
| Port-Orford-cedar | *Chamaecypark lawsoniana* (A. Murr.) Parl. |
| Alpine larch | *Larix lyallii* Parl. |
| Western larch | *Larix occidentalis* Nutt. |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| Western juniper | *Juniperus occidentalis* Hook. |
| Western redcedar | *Thuja plicata* Donn ex D. Don |
| Incense-cedar | *Libocedrus decurrens* Torr. |
| Sitka spruce | *Picea stichensis* (Bong.) Carr. |
| Engelmann spruce | *Picea engelmannii* Parry ex Engelm. |
| Tanoak | *Lithocarpus densiflorus* (Hook. & Am.) Rehd. |
| Pacific yew | *Taxus brevifolia* Nutt. |
| Thinleaf alder | *Alnus tenuifolia* Nutt. |
| Western paper birch | *Betula papyrifera* var. *commutata* (Regel) Fern. |
| Sitka mountain-ash | *Sorbus sitchensis* Roem. |
| Water birch | *Betula occidentalis* Hook. |
| Douglas maple | *Acer glabrurn* Torr. |
| Bitter cherry | *Prunus emarginata* Dougl. ex Eaton |
| Common chokecherry | *Prunus virginiana* L. |
| Blueberry elder | *Sambucus cerulea* Raf. |
| willow | *Salix* spp. |

| Common name | Scientific name |
| --- | --- |
| Columbia hawthorn | *Crataegus columbiana* Howell |
| Black cottonwood | *Populus trichocarpa* Torr. & Gray |
| Black hawthorn | *Crataegus douglasii* Lindl. |
| Quaking aspen | *Populus tremuloides* Michx. |

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**Peterson, Janice; Schmoldt, Daniel; Peterson, David; Eilers, Joseph; Fisher, Richard; Bachman, Robert. 1992.** Guidelines for evaluating air pollution impacts on class I wilderness areas in the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-299. Portland, OR: US. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 83 p.

Forest Service air resource managers in the Pacific Northwest are responsible for protecting class I wilderness areas from air pollution. To do this, they need scientifically defensible information to determine critical concentrations of air pollution having the potential to impact class I wilderness values. This report documents the results of a workshop where current information on air pollution effects on aquatic and terrestrial resources and visibility was gathered from participating scientists and managers. Critical air pollution concentrations were determined for sulfur dioxide, nitrogen dioxide, and ozone. Critical values for sulfur and nitrogen deposition to forest ecosystems are listed.

Keywords: Air pollution, visibility, air resource management, lichens, class I wilderness, Pacific Northwest.



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