V. INTERIM GUIDELINES FOR THE PROTECTION OF SENSITIVE RESOURCES RELATIVE TO AIR QUALITY CONCERNS

A. REGIONAL COMPARISONS AS BASIS FOR GUIDELINES

1. Critical Loads Estimates

Most work conducted to date on the assessment of critical loads of sulfur and nitrogen for terrestrial and aquatic systems has focused largely on examination of ecosystems that have already been damaged (see Appendix D for a discussion of European research concerning this topic). Key questions of the research efforts have involved mapping areas where critical loads have been exceeded, determining levels to which deposition must be reduced to restore ecosystem functioning, and projecting the time scale of recovery processes. For national parks in the Pacific Northwest, however, atmospheric deposition of both sulfur and nitrogen has remained relatively low, and it is unlikely that significant damage to park resources associated with deposition of N and S has occurred thus far. Critical loads assessments have not been conducted for sensitive receptors in the Pacific Northwest, and such future efforts should focus on the establishment of S and N deposition loads that will protect sensitive resources within the parks.

Care must be taken in applying critical loads assessments to relatively pristine ecosystems, using values developed in areas that have received substantial deposition. Such caution is particularly warranted for empirical and other steady state modeling approaches. For example, application of empirical methods that rely on evaluation of base cation fluxes (e.g., Henriksen et al. 1992) to surface waters in the Pacific Northwest implicitly assume that the proportional (to acidic anion) mobilization of base cations is constant over time. Such an assumption may not be valid, particularly in view of the complex and diverse nature of cation-exchanging materials in the soil. A more appropriate method for estimating critical loads for Pacific Northwestern surface waters would be a dynamic modeling approach, which incorporates all major watershed neutralization and exchange processes. The MAGIC model (Cosby et al. 1985a,b) has been applied to lake resources in wilderness areas of Idaho, Montana, and Wyoming for projecting the response of lakewaters throughout the region to differing levels of future acidic deposition (Eilers et al. 1991). MAGIC could be applied to selected aquatic resources within the national parks as a means of estimating the critical load of sulfur for aquatic and soil systems.

Data are lacking with which to assess critical loads of sulfur for forest soils in the Pacific Northwest by using empirical criteria of aluminum concentrations or Ca:Al ratios in soil solution. Available data on aluminum concentrations in lakewaters throughout the region show very low concentrations (Landers et al. 1987, Nelson 1991), far below lakewater levels that would be expected in an area where soil solution [Al] was present in toxic ranges. Easthouse et al. (1993) conducted a field investigation of aluminum chemistry in two dilute alpine headwater lakes in the Alpine Lakes Wilderness in the central Washington Cascades (between NOCA and MORA). The study sites, Hi Ho Lake and Quartz Lake are small (2.4 and 0.3 ha, respectively) remote lakes, > 1200 m in elevation. Hi Ho Lake has pH about 5.5 and SO_4^{2-} concentrations of about 15 µeq/L. Quartz Lake is naturally low in pH (~ 5.3) due to local geologic sources of sulfur, resulting in lakewater SO_4^{2-} concentrations of about 37 µeq/L. Calcium concentrations in the two lakes are low (~ 20 and 11 µeq/L, respectively). Total monomeric (Al_m) and inorganic monomeric (Al_i) aluminum concentrations were measured by Easthouse et al. (in press) on five occasions in the two lakes during summer and autumn. The highest concentration of total monomeric Al (Al_m) measured in either lake was less than 0.1 mg/L; inorganic monomeric Al (Al_i) concentrations were generally < 0.05 mg/L. Although high in comparison with typical concentrations of Al found in the Western Lake Survey (autumn sampling, Landers et al. 1987), such concentrations are still quite low in comparison to many regions adversely impacted by acidic deposition (Baker et al. 1990a).

Dynamic models of nitrogen processing within forested ecosystems have not been developed to the same level as watershed sulfur models. Two independent research efforts are currently being funded by EPA to develop watershed models of nitrogen processes to supplement the sulfur-based models (R. Church, pers. comm.). The best available tools at the present time for assessing critical loads of N to resources within the national parks are empirical. Based on empirical evaluations, coniferous forest ecosystems in Europe and the northeastern United States become N-saturated at N deposition levels greater than about 10 kg/ha/yr (Grennfelt and Hultberg 1986, R.F. Wright, pers. comm.). Using such a criterion, deposition of N within the five national parks considered in this study (N load 0.89 to 2.09 kg/ha/yr) is well below the range of what would be considered critical for N-leaching in European forests. Such an estimate ignores, however, the potential importance of episodic chemistry, and the radically different forest management histories in the Pacific Northwest and Europe. The less intensive management of forests in the Pacific Northwest makes the systems less N-deficient. Consequently, values for critical loads of N in the national parks of the Pacific Northwest may be significantly lower than the estimates of 10 kg/ha/yr for European forests.

Independent of potential toxic effects of nitrogen addition, the fertilizing effects of nitrogen can cause major changes in ecosystem structure and diversity by altering competitive interactions among plants. Based on limited data on ecosystem effects, generic condition classes can be set for different vegetation types (Table 49). These guidelines do not account for species-level variation in plant sensitivity. Lacking more definitive data, the condition classes can be used as general guidelines for evaluating the potential risk of pollution impacts on certain species of taxa,

Table 49. Condition classes for vegetation in the Pacific Northwest based upon sensitivity to N deposition. From Horner and Peterson (1993).

	Total N deposition (kg/ha/yr)		
Vegetation Type	No Injury	Potential Injury	Severe Injury
Coniferous forest	< 3	3-15	> 15
Hardwood forest	< 5	5-20	> 20
Shrubs	< 3	3-5	> 5
Herbaceous plants	< 3	3-10	> 10

under present air quality conditions. For example, for a selected condition class (injury level), the corresponding pollutant exposure (or deposition) can be evaluated. See Appendix D for an explanation of the use of condition classes.

Because of the scarcity of available data and model simulations for calculating critical loads of sulfur (and nitrogen) for the national parks in the Pacific Northwest, perhaps the most defensible approach presently would involve comparison between surface waters, soil, and forest resources in this region and generally similar resources elsewhere for which more extensive data are available. It is likely that critical loads of acidifying substances for national parks in the Pacific Northwest will be low. Based on assessments of current surface water chemistry, lakes in this region are likely among the most sensitive aquatic systems anywhere in the world (Eilers et al. 1990, 1991). Other regions that have been judged to be extremely sensitive, and for which considerable data are available include Scandinavia (especially southern Norway) and the Galloway region of Scotland. Appropriate data for interregional comparison include both model estimates of critical loads and also quantified dose-response functions.

The highest wet nonmarine sulfur deposition within the Nordic countries is found in southern Norway and on the west coast of Sweden. The highest total S deposition is found in southern and southwestern Sweden and Denmark, where total S deposition is as high as 30 kg S/ha/yr in some spruce forests (Lövblad and Erisman 1992). Total S deposition is lower for pine and deciduous forests, and decreases to the north; in northern sections of the Nordic region, total S deposition in spruce forests is generally below 6 kg S/ha/yr. Total nitrogen deposition is highest in southern Sweden and Denmark, reaching levels higher than 25 kg N/ha/yr (Lövblad et al. 1992). The high levels of deposition in Europe are about an order of magnitude higher than the levels currently observed in the Cascade Mountains.

In North America, the highest S loadings tend to be adjacent to smelters and power plants where S deposition is locally high. The effects of S, especially as sulfates, often are mediated through soil processes such as cation exchange. Deposition must be high to produce potentially toxic effects. Fox et al. (1989) determined that 20 kg S/ha/yr is the maximum long-term deposition that can be tolerated without impacts in most terrestrial ecosystems, with certain assumptions about soil cation exchange capacity and mineral weathering rates. Effects in terrestrial ecosystems are unlikely below 5 kg/ha/yr. Variability in soil effects must be considered in applying this information to other locations (Binkley 1992, Peterson et al. 1992b).

The Coordination Center for Effects (CCE) was established to assist the UN/ECE in the production of maps of critical loads and exceedences as a basis for developing potential abatement strategies for sulfur and nitrogen. The CCE European map of critical loads of acidity (Kämäri et al. 1992) is based on data from both surface waters and soils, supplied by 14 individual countries. Most of the calculations were based on the steady-state mass balance method of estimating critical loads (Hettelingh et al. 1991), which incorporates the contributions of both sulfur and nitrogen to the total acidity. The resulting map portrayed large areas of Scandinavia, Finland, and Scotland, based on the fifth percentile of each 150- by 150-km map grid, as having critical loads of acidity < 20 meq/m^2/yr (3.2 kg S/ha/yr if considering only sulfur).

The Stockholm Environment Institute (SEI) constructed a European map of relative sensitivity to acidic deposition (Kuylenstierna and Chadwick 1989, Chadwick and Kuylenstierna 1990, Kämäri et al. 1992). Critical loads were assigned subjectively, based on categories of rock type, soil type, precipitation, and land use. Five classes of relative sensitivity were devised, and each was assigned critical load values, based on extrapolations from detailed site studies. The resulting SEI map generally was similar to the CCE map, and, like the CCE map, placed large areas of Scandinavia, Finland, and Scotland in the critical load class < 20 meq/m^2/yr (Kämäri et al. 1992). According to both maps, about 20% of Europe falls in this lowest critical load category
(< 20 meq/m^2/yr) and an additional 20% falls in the critical load category of 20-50 meq/m^2/yr.

Kämäri et al. (1993) employed a steady-state mass balance approach to calculating critical loads, for both sulfur and nitrogen, for the protection of lakes in Finland. Results of their calculations showed a wide variation in sensitivity to acidifying pollutants. Within the northern European study area, represented as a 150 by 150 km grid, the estimated critical load of S or N varied in some cases from zero to more than 100 meq/m^2/yr for individual lakes. In the most sensitive portions of Finland, critical loads of both S and N were estimated to be below 20 meq/m^2/yr (about 3 kg/ha/yr for both S and N) in a large percentage of the lakes.

These empirical and steady state approaches thus suggest that sensitive portions of northern Europe have critical loads of acidity (including both sulfur and nitrogen contributors to acidity) less than 20 meq/m^2/yr. Although the uncertainties associated with such calculations are undoubtedly quite high, these approaches have been used extensively.

A somewhat more rigorous approach has been applied in Norway by scientists from the Norwegian Institute for Water Research (NIVA). They have calculated, using the MAGIC model, critical loads of sulfur for forest soils within 12-

by 12-km grid squares (Frogner et al. 1992). The model scenarios were based on soil survey data, forest productivity data, deposition, and surface water chemistry data from the Norwegian 1000 lake survey. Of the 2300-grid squares within Norway, about 450 have coniferous forests; MAGIC simulations have been conducted for nearly half of these. Critical loads were calculated by using the criterion that the Ca/Al molar ratio in soil solution should not fall below 1.0 in the uppermost 50 cm of soil over the next 50 years. The model simulations suggest that soils having low critical loads are found throughout southern Norway. Current deposition exceeds the calculated critical loads in more than one-fourth of the grid squares. The critical load calculations using MAGIC for soils, based on Ca/Al = 1.0 are higher by about a factor 2 than MAGIC calculations by using a surface water criterion of ANC = 20 μeq/L.

Process-based model simulations for the critical loads of nitrogen to forest soils in Norway are not available. A model that simulates nitrogen cycling and retention is under development in conjunction with the NITREX project in Europe (Dise and Wright 1991), but nitrogen cannot be evaluated to the same level of detail as sulfur at the present time. Wright et al. (pers. comm.), however, have attempted to place bounds on N critical loads for forest soils, using the same grid network as was used by Frogner et al. (1992) for sulfur. Based on empirical data on N inputs and outputs at forested sites in Europe, Wright et al. (pers. comm.) determined that nitrogen leaching in Europe is initiated at input levels of 10 to 25 kg N/ha/yr. Once N breakthrough occurs, N leaching ranges up to 100% in some cases and is consistently above 50% at loadings higher than 25 kg N/ha/yr. Wright et al. (pers. comm.) prepared two maps of calculated critical loads of N for forest soils in Norway using the MAGIC model which was based on a sulfur deposition scenario of 80% of 1986 deposition levels. For the worst case, they assumed no nitrate leaching (100% retention) at deposition levels of 0 to 10 kg N/ha/yr, and 100% leaching at higher deposition levels. For the best case, they assumed zero leaching up to 25 kg N/ha/yr deposition, and 50% leaching at higher deposition levels. Depending on the assumed N retention, the most sensitive grids in southern Norway exhibited critical loads for forest soils in the range of 8 to 11 kg N/ha/yr (worst case N retention) to 21-28 kg N/ha/yr (best case N retention). These critical loads for protection of forest soils are much higher than estimates for protection of surface waters.

2.Quantified Dose-Response Functions

The data that are available for the regions under investigation for this report also can be compared and contrasted with more intensive dose-response data generated in other regions that have been impacted by acidic deposition and studied in greater detail. Such comparisons are useful to place bounds on the magnitude of the acidification response. Quantitative dose-response functions for sulfur have been determined by using various approaches, in several regions in North America and Europe. Such studies have included, for example, measured changes in water chemistry during periods when sulfur deposition changed appreciably, regional paleolimnological investigations, whole-catchment manipulation studies, and intensive process modeling.

Measured changes in surface water chemistry in areas that have experienced short-term (< 20-yr) changes in chemical constituents in response to changes in mineral acid inputs are available from several sources. These include results from manipulation experiments and changes in acidic deposition. Proportional changes in ANC (expressed as $[HCO_3^- - H^+]$), $[C_B]$, and $[Al_i]$, relative to changes in $[SO_4^*]$[1] or $[SO_4^* + NO_3^-]$, have been quantified for lakes and streams in the Sudbury region of Ontario (Dillon et al. 1986, Hutchinson and Havas 1986, Keller et al. 1986, Gunn and Keller 1990), the Galloway lakes area of Scotland (Wright et al. 1986, Wright et al. in review), a stream site at Hubbard Brook, New Hampshire (Sullivan 1990), catchment manipulation experiments in the RAIN project in Norway (Wright et al. 1988, 1990), Little Rock Lake in Wisconsin (Brezonik et al. 1993), and Bear Brook in Maine (Norton et al. 1993). Most of the observed changes have been coincident with decreased acidic deposition, and it is unclear whether acidification and recovery are symmetrical. F-factors in the range of 0.5 to 0.9 are apparently typical for lakes having low $[C_B]$, although lower values (0.35 to 0.39) were observed for the highly sensitive catchments at Sogndal, Norway (Wright et al. 1988, 1990), which are characterized by thin soils and much exposed bedrock, as is common in many areas of southern Norway, and the western United States. Measured proportional change in ANC relative to $[SO_4^{2-} + NO_3^-]$ change has been variable, within the range of 0.1 to 0.5. The proportional changes in Al have been smaller, ranging up to 0.2.

Trees and vascular plants

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 of how stress in forest ecosystems might be affected by acidic deposition, including acidic precipitation and ozone (Smith 1984). Much of this work focused on documenting the physiological and growth status of forest stands, and on establishing dose-response functions under experimental conditions for economically important tree species. Lichens, mosses, and other vegetation received less emphasis. Difficulties inherent in studying plant physiological processes under field conditions created limitations to testing pollution effects in natural ecosystems (Peterson et al. 1992a). Consequently, dose-response

[1] Asterisk designates that the estimate is for non-marine concentrations. The concentration of SO_4^{2-} derived from marine aerosols was estimated from measured Cl^- concentration and an assumed ratio of SO_4^{2-} to Cl^- in seawater.

functions are poorly documented in most forests, and the correspondence between field and laboratory research findings is often poor.

Ozone

More information is available on plant sensitivity to ozone than to N and S. Much of the ozone research has been conducted in California and has focused on dominant tree species in that region (e.g., Miller et al. 1983, 1989; Peterson et al. 1987, 1991, 1992a,b). Few data exist on the response of mature trees to pollutant exposure, and almost no data for herbaceous species exist. Table 50 lists some potentially sensitive vegetation in California, Idaho, Oregon, and Washington (Hogsett et al. 1989).

Ozone is the only regionally dispersed pollutant known to injure foliage and lead to tree mortality at ambient levels (Miller 1989, Woodman and Cowley 1987, Böhm 1992). Data on ozone stress in conifers have been compiled primarily for ponderosa pine and Jeffrey pine, which are sensitive to elevated ozone concentrations. Injury levels have been established for these species with respect to chlorotic injury and needle longevity based on field studies of large trees conducted in the Sierra Nevada and San Bernardino Mountains of California (Pronos et al. 1978, Pronos and Vogler 1981, Duriscoe and Stolte 1989, Miller et al. 1989). These data are the best information available anywhere on field level analysis of pollutant stress. Limited experimental data for seedlings of conifer species found in the Pacific Northwest (Hogsett et al. 1989) indicate differences in sensitivity among species and among individuals of a population (Table 51). For example, ponderosa pine is more sensitive to ozone than is Douglas-fir. Sensitivity classes

Sensitive Receptor	**AL**	**BD**	**BL**	**CH**	**DE**	**DP**	**JS**	**MC**	**MF**	**OW**	**PJ**	**RE**	**RI**	**SA**	**SF**	**DF**	**PS**	**WS**	**ES**	**WA**	**EA**	**ED**	**EP**	**SH**	**ME**
Lichens	X	X	X	-	X	-	X	X	X	X	-	X	-	-	X	-	-	-	-	-	-	-	-	-	-
Herbaceous plants	X	X	X	-	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ponderosa pine	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	X
Jeffrey pine	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
White fir	-	-	-	-	-	-	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	X	-	-	X
Sugar pine	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X
Incense cedar	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Douglas-fir	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	X	X	-	X	-	-	X	-	-	X
W. white pine	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
Lodgepole pine	-	-	-	-	-	-	-	-	X	-	-	-	-	-	X	-	X	-	X	-	-	X	-	-	-
Whitebark pine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-
Pacific silver fir	-	-	-	-	-	-	-	-	X	-	-	-	-	-	X	-	X	-	-	-	-	-	-	-	-
Mountain hemlock	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X	X	X	-	-	-	-	-
Aspen	-	-	-	-	-	-	-	-	X	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Alders	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Cottonwoods	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Junipers	-	-	-	-	-	-	X	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Western juniper	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Pinyon pine	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sagebrush	-	-	-	-	-	-	-	-	-	-	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-
Sedges	X	-	-	-	-	-	-	-	X	-	-	-	X	-	X	-	-	-	-	-	-	-	-	-	-
Alaska yellow cedar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-
Subalpine fir	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-
Alpine larch	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-

Grand fir	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Noble fir	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-
Port Orford cedar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Red fir	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Western larch	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Sugar pine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X

[a] Ecosystem: AL alpine; BD bigcone Douglas-fir; BL buckwheat/lichen/grass; CH chaparral; DE desert; DP digger pine; JS juniper shrubland; MC mixed conifer; MF montane forest; OW oak woodland; PJ pinyon pine/juniper; RE redwood; RI riparian; SA sagebrush; SF subalpine forest; DF Douglas fir/western hemlock; PS 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; ME mixed evergreen. From Peterson et al. (1992a,b).

Table 51. Sensitivity of tree species to O_3, S, and N pollution.

	Sensitivity		
Sensitive Receptor	Ozone	Sulfur	Nitrogen
Ponderosa pine	H	H	H
Jeffrey pine	H	H	H
White fir	M	H	H
Calif. black oak	M		
Douglas-fir	M	H	H
W. white pine	L-M		
Lodgepole pine	M	H	H
Aspen	H		
Alders	M		

Sensitivity ratings are : high (H), moderate (M), and low (L). Blanks indicate there is insufficient information to rate sensitivity. From Peterson et al. 1992a,b.

(e.g., Table 51) have been developed to characterize general dose-response functions of species taking into account variability in results reported in the literature which reflect differences in scientific methodology and natural species variability.

Condition classes based on injury levels also have been developed (Miller et al. 1983) that relate injury characteristics of trees in the field to ozone concentrations, thus taking into account the natural variability in sensitivity observed within native populations in the natural habitat. Additional long-term monitoring will be required to develop an understanding of ozone effects on the growth of mature trees (Peterson et al. 1987, 1991).

Peterson (1992a) synthesized these data sources to develop general conditions classes for conifers in relation to ozone exposure based on visible injury classes observed in the field (Table 52). Condition classes can be used to estimate the "average" amount of plant injury expected to result at different levels of ozone exposure. For use in regulatory decision-making, these condition classes can be used cautiously to estimate general stress levels of coniferous forests in response to ambient ozone concentrations. However, the accuracy of such condition classes will be influenced by the particular species, environmental conditions, and ozone statistic used in a given situation. Based on observations of visible injury in the field, the condition classes developed primarily for pines in Table 52 can be applied cautiously to other conifers. Although the tables below were developed using the 7-h growing season mean of ozone concentrations, additional ozone statistics or combinations of statistics may prove to be more biologically relevant in the future. Other work in California has shown that brief episodes of high ozone concentrations during atmospheric stability may produce substantial, although poorly quantified stress (Hogsett et al. 1989). The potential impacts of these acute episodes should be considered when evaluating ozone impacts. The larger controversy over the use of different ozone statistics to assess vegetation response is covered in Appendix D.

Hardwood tree species have different leaf injury symptoms than conifers, and there are few data available on the effects of ozone on hardwoods in the Pacific Northwest (Jensen and Masters 1975). The condition classes for hardwoods are similar to those for conifers, with an added class (Table 53). The limited data base for hardwoods reduces the reliability of the classes for hardwoods. The higher ozone levels for each class reflect the lower sensitivity of hardwoods to ozone, compared to conifers, although species-by-species ratings are needed for good reliability.

There are few data anywhere on responses of herbaceous and grass species to ozone. In California, some information exists on sensitivity of native species to ozone, including sweet cicely

Table 52. General Condition classes for conifers in relation to ozone exposure (Miller et al. 1983).

Condition Class	Needle Age Class With Chlorotic Mottle (yrs)	Needle Retention as Percent of Normal (pct)	Ozone Concentration (7-hr Growing Season Mean) (ppb)
No Injury	None	> 80	< 60
Slight Injury	≥ 5	71-80	61-70
Moderate Injury	3-4	41-70	71-90
Severe Injury	1-2	< 40	> 90

From: Peterson et al. (1992a)

Table 53.Condition classes for hardwoods in relation to ozone exposure.

Condition Class	Percent of Leaf Area with Stippling (pct)	Ozone Concentration (7-hr Growing Season Mean) (ppb)
No Injury	0	< 45
Very Slight Injury	1-20	45-70
Slight Injury	21-40	71-90
Moderate Injury	41-60	91-120
Severe injury	60-100	> 120

From: Peterson et al. (1992a)

(*Osmorhiza brachypoda*) (high sensitivity), squawbush (*Rhus trilobata*) (high), and perennial ryegrass (*Lolium perenne*) (moderate). These data are insufficient to make generalizations about all herbaceous species and grasses. Horner and Peterson (1993) suggest that the condition classes for hardwood species can be applied cautiously to herbaceous species until additional data are available.

Sulfur Dioxide

There are few data on the effects of S compounds on mature trees and native plants, and there is a wide range of sensitivities to ambient S compounds (Davis and Wilhour 1976, Westman et al. 1985). Limited data indicate that SO_2 concentrations below 20 ppb (24-hour mean) do not produce visible injury symptoms (Hogsett et al. 1989). Conifers generally begin to exhibit symptoms of injury at 40-65 ppb (24-hour mean) of SO_2. With limited quantitative data, the sensitivity of some tree species to SO_2 have been ranked (Davis and Wilhour 1976). The relative sensitivity to SO_2 is as follows, in decreasing order for conifers: Grand fir (*Abies grandis*), Subalpine fir (*Abies lasiocarpa*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) Douglas-fir (*Pseudotsuga menziesii*), western white pine (*Pinus monticola*), ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus cortorta*), western birch (*Larix occidentalis*), Engelmann spruce (*Picea engelmannii*), western juniper (*Juniperus occidentalis*), and Pacific yew (*Taxus brevifolia*). For hardwoods the order is thinleaf alder (*Alnus tenuifolia*), western paper birch (*Betula papyrifera*), sitka mountain ash (*Sorbus sitchensis*), water birch (*Betula occidentalis*), Douglas maple (*Acer glabrum*), bitter cherry (*Prunus emarginata*), chokecherry (*Prunus virginiana*), Blueberry elder (*Sambucus cerulea*), Willow (*Salix* species), Columbia hawthorn (*Crataegus columbiana*), black cottonwood (*Populus trichocarpa*), black hawthorn (*Crataegus douglasii*), and quaking aspen (*Populus tremuloides*).

Considering the lack of data for native species, data from California have been used to set general guidelines for vegetation (Peterson et al. 1992a,b).

In order to maximize protection of all plant species, maximum SO_2 concentrations should not exceed 40-50 ppb (24-hour mean), and annual average SO_2 concentrations should not exceed 8-12 ppb.

Nitrogen Dioxide

Few data are available on the effects of NO_2 on plant species in the Pacific Northwest. Limited data from elsewhere in the United States and in Europe, however, have been used to establish some general guidelines for injury and exposure (EPA 1982, Peterson et al. 1992a,b). These values should be used only for general guidelines as individual plant species exhibit a wide range of sensitivities (Table 54).

Table 54. Plant condition classes in relation to NO_2 exposure.

Condition Class	NO_2 Concentration (24-hr Annual Mean) ppb
No Injury	< 15
Potential Injury	15-50
Severe Injury	> 50

From: Peterson et al. (1992a,b)

Interactions

The potential for interactions among pollutants should be considered when evaluating the effects of pollutants on natural resources (Peterson et. al. 1992b). The interaction can be antagonistic (less than additive, or canceling), or synergistic (greater than additive). Few data are available on interaction effects on plant species. Limited data on lichens indicate a likely synergy for ozone and SO_2 (DeWitt 1976), and ozone/NO_x (Sigal and Nash 1983). Although it is difficult to make generalizations, situations can be identified for which complex interactions are likely. Acidic fog which contains N and S compounds also may alter the growth of some tree species, but effects normally occur only if pH is below 3.5 (Hogsett et al. 1989). Far too few data are available to set guidelines at this time.

Lichens and bryophytes

Lichens and bryophytes are among the most sensitive of terrestrial organisms to pollution (Nash and Wirth 1988, Bates and Farmer 1992). Little is known about sensitivities of lichen and bryophyte species in the Pacific Northwest, however. Lichens exhibit a wide range of sensitivities to pollutants, although response is poorly quantified with respect to dose-response functions. More information is available on sensitivity to SO_2 and ozone than to nitrogen oxides or fluoride (Nash and Wirth 1988). Classes of lichen sensitivity to air pollution have been defined as sensitive, intermediate and tolerant, based on limited experimental data (Table 55). Sensitivity is usually expressed in relation to concentrations, because the cumulative effects of air pollutants are little known. Data on response to nitrogen oxides are currently inadequate to provide guidelines. According to Horner and Peterson (1993), the guidelines in Table 55 may be interpreted to be broadly applicable to both lichens and bryophytes.

These following classes were developed for *Hypogymnia enteromorpha*, from mixed-conifer forests in California. The classes with respect to ozone exposure have been quantified in more detail for H. enteromorpha, and to a lesser degree for other species (Table 56).

Table 55. Sensitivity classes for lichens in relation to prolonged exposure to pollutants. Determined for *Hypogymnia enteromorpha* (Sigal and Nash 1983).

Pollutant	Sensitivity Class (parts per billion)		
	Sensitive	Intermediate	Tolerant
Ozone (ppb)[a]	< 20	15-70	> 65
Sulfur dioxide (ppb)[b]	5-15	10-35	> 30

[a] Ozone concentration is the 7-hour mean for May-October
[b] Prolonged exposure

From: Peterson et al. 1992a

Table 56. Sensitivity classes for lichens with respect to ozone exposure are defined in terms of (1) morphological changes in *Hypogymnia enteromorpha*, and (2) relative presence of other species.

Sensitivity Data	Ozone Conc.[a] ppb	Description	
		Hypogymnia	Other Species
Very Sensitive	<20	Generally not bleached or convoluted Fertility > 75 pct.	Very sensitive species common
Sensitive	21-40	Majority not bleached, but large percentage bleached Most thalli slightly convoluted Fertility 65-85 pct.	A few very sensitive species absent Sensitive species common
Tolerant	41-70	Majority slightly bleached Unconvoluted to moderately convoluted Fertility 40-65 pct.	Some very sensitive species absent A few sensitive species present (*Usnea* sp.) Tolerant and sensitive species most common
Very Tolerant	> 70	Moderately to highly bleached Moderately to highly convoluted Fertility < 40 pct	A few very tolerant species common (*Parmelia subolivocea, P. multispora*) 50 pct of all species absent

[a] Ozone concentrations in the 7-hour mean for May-October. From: Peterson et al. 1992a.

Table 57a. Sensitivity classes in relation to ozone exposure for lichen species found in mixed-conifer forests.

Sensitivity Class	Lichen Species
Conifers	
Very Sensitive[a]	*Alectoria sarmentosa*
	Bryoria abbreviata
	Bryoria fremontil
	Bryoria oregana
	Calcium virile
	Cetraria canadensis
	Evernia prunastri
	Platismatia glauca
Sensitive[b]	*Centraria merrillii*
	Cladonia sp.
	Parmelia quercina
	Ramalina farinacea
	Usnea sp.
Tolerant	*Hypogymnia enteromorpha*
Very tolerant	*Letharia vulpina*
Oaks (Primarily California black oak)	
Very Sensitive[a]	*Evernia prunastri*
	Pseudocyphellaria anthraspis
Sensitive[b]	*Collema nigrescens*
	Parmelia sulcata
	Parmelia quercina
	Phaeophyscia ciliata
	Usnea sp.
Tolerant	*Parmelia (Melanelia) glabra*
	Parmelia (Melanelia) subolivacea
	Parmelia (Melanelia) multispora
	Parmelia (Melanelia) elegantula
Very Tolerant	*Physconia grisea*
	Xanthoria fallax

[a]Species in the very sensitive class have largely disappeared from the native habitat.
[b]Species in the sensitive class are found only in small amounts in the mountains adjacent to their former habitat.

From: Peterson et al. (1992b)

Ozone exposures at the highest level (>70 ppb) have caused the loss of up to 50% of lichen species in some areas of California (Sigal and Nash 1983). The more common lichen species and their sensitivity classes for ozone exposure are shown in Tables 57a,b,c (Peterson et al. 1992b). Visual criteria associated with condition classes for ozone also can be applied cautiously to effects of S and N exposure, in the absence of other criteria. There is considerable variation in species' sensitivities among studies. More experimental work is needed to differentiate the effects of small amounts of S pollution. There are insufficient data on the effects of N pollution to compile even a relative ranking of sensitivity.

Table 57b. Sensitivity classes in relation to ozone exposure for lichen species found in oaks woodland.

Sensitivity Class	Lichen species
Very Sensitive[a]	*Evernia prunastri*
	Peltigera collina
	Pseudocyphellaria anthraspis
	Ramalina farinacea
	Ramalina menziesii
Sensitive[b]	*Collema nigrescens*
	Leptogium californicum
	Parmelia quercina
	Parmelia sulcata
Tolerant	*Parmelia (Melanelia) glabra*
	Xanthoria polycarpa
Very Tolerant	*Physcia biziana*
	Physcia tenella
	Physconia grisea
	Xanthroia fallax

[a]Species in the very sensitive class have largely disappeared from their native habitat.
[b]Species in the sensitive class are found only in small amounts in the mountains adjacent to their former habitat.

From: Peterson et al. (1992b)

Table 57c. Sensitivity classes in relation to ozone exposure for lichen species found in mixed-conifer forests/oak woodland and subalpine forests.

Sensitivity Class	Lichen Species
Mixed Conifer Forest/ Oak Woodland: Conifers and Oaks	
Very Sensitive	*Alectoria sarmentosa*
	Bryoria sp.
	Evernia prunastri
	Peltigera canina
	Peltigera collina
	Pseydocyphellaria anthraspis
Sensitive	*Collema nigrescens*
	Parmelia sulcata
	Parmelia quercina
	Usnea sp.
Tolerant	*Melanelia glabra*
	Melanelia subolivacea
	Xanthoria polycarpa
Very Tolerant	*Letharia columbiana*
	Letharia vulpina
	Xanthoria fallax
Subalpine Forest: Conifers	
Very Sensitive	*Bryoria* sp.
	Pseudephebe minuscula
	Pseudephebe pubescens
Sensitive	*Cladonia* sp.
	Tuckermannopsis merrillii
	Usnea sp.
Tolerant (may not be found at higher elevations)	*Hypogymnia entermorpha*
Very Tolerant	*Letharia columbiana*
	Letharia vulpina

From: Peterson et al. (1992b)

3.National Parks in the Pacific Northwest

Quantification of sulfur and nitrogen dose-response functions is difficult for the national parks considered in this report. Limited data availability precludes rigorous quantitative assessment in most cases. In particular, data are scarce in the following categories:

- •stream and lake chemistry during snowmelt and precipitation events
- •seasonal surface water chemistry data, particularly for nitrogen and aluminum
- •model input parameters (especially soils characteristics) for watersheds
- •deposition (wet and dry) data at high-elevation sites

Consideration of the efficacy of adopting one or more acid deposition standards for the protection of surface water quality from potential adverse effects of sulfur and nitrogen deposition is a multifaceted problem. It requires that sulfur and nitrogen be treated both separately and in combination as potentially acidifying agents, and that estimates for each be generated for all individual, well-defined regions or subregions of interest. Appropriate criteria must be selected as being indicative of damaged water quality, for example ANC or pH. Once a criterion has been selected, a critical value must be estimated, below which the criterion should not be permitted to fall. The ANC criteria have been set at 0, 20, or 50 $\mu eq\ L^{-1}$ in various European applications, and pH criteria have been set at 5.3 and 6.0 in Canadian assessments. Selection of critical values for ANC or pH is confounded by the existence of lakes and streams that are acidic or very low in pH or ANC due entirely to natural factors, irrespective of acidic deposition. In particular, low contributions of base cations in solution, due to low weathering rates and minimal contact between drainage waters and mineral soils, and high concentrations of organic acids contribute to naturally low pH and ANC in surface waters.

Acid deposition standards might be selected on the basis of protecting aquatic systems from chronic acidification; conversely episodic acidification also might be considered and would be of obvious importance in regions where hydrology is dominated by spring snowmelt. Thus, selection of appropriate acid deposition standards involves consideration of a matrix of factors.

Based on analysis of available sulfur dose-response data for sensitive watersheds worldwide, it is clear that proportional changes in ANC and base cations in drainage waters in response to changes in sulfur inputs are highly variable. Documented F-factors ($\Delta C_B \div \Delta[SO_4^{2-}]$) generally are above 0.5, although lower values have been found.

Perhaps the best available estimate of an appropriate F-factor for highly sensitive watersheds, such as are found throughout mountainous regions of the western United States, would be based on the experimental values obtained at Sogndal, in western Norway ($F \approx 0.4$). This alpine watershed exhibits substantial areas of exposed bedrock, and contains shallow acidic soils. As such, it seems to be a reasonable surrogate for the most sensitive watersheds in the West.

Assuming $F \approx 0.4$, we calculated that relatively minor increases in lakewater SO_4^{2-} concentration would lead to chronic acidity (ANC < 0) in many lakes in the Cascade Range. An estimated 5% of the lakes in the Cascade region would become acidic with increased SO_4^{2-} concentration of only 30 μeq L^{-1}. An approximate four-fold increase in sulfur deposition in this region, to levels in the range of 2 to 8 kg S ha^{-1} yr^{-1} (6 to 24 kg/ha as SO_4^{2-}), would be required to achieve such chronic increases in lakewater SO_4^{2-} concentrations.

If the goal is to prevent *any* aquatic systems from becoming acidic (ANC ≤ 0), a more stringent standard may be required. There are many documented ultra-dilute Cascade Range that have ANC < 10 μeq/L. Although surface water chemistry has not been thoroughly characterized within the parks of the Pacific Northwest, it is clear that potentially highly-sensitive lakes and streams are found in North Cascades and Mount Rainier National Parks. The most complete water chemistry survey data available for North Cascades was conducted by Brakke (1984), who sampled 33 lakes in and around the park. The lowest measured ANC was for Lake Ann, located just outside the park boundaries. With ANC of 3.5 μeq/L, pH = 5.4, and conductivity of 2.8 μS/cm, this lake clearly represents the extreme of watershed sensitivity.

Larson et al. (1992) surveyed 27 subalpine and high mountain forest lakes in Mount Rainier National Park. Although complete chemistry was not measured for all lakes, Larson et al. (1992) reported lakes with alkalinity as low as 10 μeq/L and conductivity of 4 μS/cm. One of the Golden Lakes (4B1-069) sampled in the Western Lake Survey had an ANC of 12 μeq/L (Eilers et al. 1987).

In the absence of more extensive survey data for surface water in North Cascades and Mount Rainier National Parks, it is not possible to provide defensible estimates of the loadings of sulfur that might cause chronic acidification. However, assuming that the most sensitive systems range in ANC between 3 and 10 μeq/L, and assuming an F-factor of 0.4 (which is conservative with respect to protecting the resources), increases in lakewater SO_4^{2-} concentration of about 5 to 17 μeq/L would be sufficient to cause chronic acidity in these most sensitive waters. Increases in sulfur deposition in the range of only 1 to 5 kg S/ha/yr (3 to 15 kg/ha/yr as SO_4^{2-}) would be sufficient to cause such increases in SO_4^{2-} concentrations and thus likely lead to chronic acidity in some lakes and streams.

This estimate of increased SO_4^{2-} concentration required to acidify Cascade Range lakes within the lower percentiles of acid sensitivity are based on fall chemistry and chronic acidification processes. It is likely, however, that sensitive watersheds would experience episodic acidification (especially during snowmelt) at sulfur deposition levels lower than those that would cause chronic acidification. In most cases, episodic pH and ANC depressions during snowmelt are driven by natural processes (mainly base cation dilution) and nitrate enrichment. It seems likely that sulfur deposition will also contribute to episodic acidification of sensitive western surface waters at deposition levels below those that would cause chronic acidification. Episodes have been so little studied within the region, however, that it is not possible yet to provide quantitative estimates of episodic sulfur standards for the national parks of concern.

Analyses of existing water chemistry and deposition data for North Cascades and Mount Rainier National Parks lead to several important conclusions about future protection of potentially sensitive lakes and streams in these parks from acidification due to atmospheric deposition of sulfur. These conclusions have important implications regarding research needs and approaches for setting standards for sulfur deposition. Key conclusions include the following:

1. Total annual sulfur deposition is poorly known at the more sensitive sites, which tend to be located at higher elevations in remote regions of the parks. Extrapolation of low-elevation deposition monitoring data (e.g., NADP/NTN sites) to these high-elevation sites is problematic. Site-specific data of some measure of total deposition are needed. The problem of characterizing deposition at high-elevation areas remains an ongoing need for other federal land managers as well. Controversy remains regarding the best method of gathering deposition data in the Pacific Northwest including collection of snow cores, bulk deposition, and cloudwater chemistry. It may be that a combination of methods is required to fully assess annual deposition chemistry in the mountainous areas of the West.

2. Complete lake and streamwater chemistry are available for relatively few lakes and streams in the parks. Also, the data that are available generally are deficient in terms of full chemical characterization (i.e., key variables often not analyzed) or inadequate for these dilute waters (e.g., need Gran acid neutralizing capacity, not single-end-point alkalinity). Surface waters included in the surveys were not selected in such a fashion as to be statistically representative of waters within the parks. Thus, we can only guess at the relative sensitivity of lakes and streams in the parks to acidic deposition, based on available data for a few documented highly sensitive lakes.

3. The data available for assessment of surface water sensitivity to chronic acidification, although inadequate, suggest that extremely sensitive lakes (and likely also streams) are present in both of these parks. Modest increases in sulfur deposition (increases as low as 1 to 5 kg S/ha/yr) may be sufficient to chronically acidify (to ANC < 0) the most sensitive waters in the parks.

4. Acidic deposition may cause episodic acidification of surface waters at even lower levels of increased deposition. Characterization of episodic chemistry is almost nonexistent within the parks. Both sulfur and nitrogen may be important agents of episodic and seasonal acidification at current, or slightly increased, levels of deposition.

Using a variety of modeling approaches, critical loads for sulfur deposition have been estimated to be less than 20 meq/m^2/yr for many lakes in sensitive regions of Finland, Norway, and Scotland (e.g., Henriksen et al. 1990a,b; Kämäri et al. 1993; Jenkins et al., in press), based on an ANC criterion of zero. In the absence of additional data on surface water chemistry in Mount Rainier and North Cascades National Parks, it is not possible to provide rigorous estimates of critical loads for the protection of aquatic resources within the parks. We recommend an interim nonmarine sulfur deposition guideline of 20 meq/m^2/yr (about 3 kg S/ha/yr; 9 kg SO_4^*/ha/yr), based on the expected high degree of sensitivity of lakes and streams within these parks, analyses of the limited data available, and on more detailed calculations for highly sensitive regions elsewhere. This recommended load is based on a normalized site receiving 1 m annual precipitation.[2]

Note that this recommendation for maximum SO_4^{2-} loading to these two parks is predicated on the following:

- The recommended S loading will not necessarily protect all sensitive aquatic resources at all times. This recommended loading is adequate for protecting at least 95% of the resources from chronic acidification, but it may not be adequate for long-term protection of the most sensitive resources.

- The recommended S loading may not protect aquatic resources from episodic acidification from either S or N deposition. Episodic acidification will precede chronic acidification in many of the systems, particularly in view of the importance of snow to the hydrologic budgets of the alpine lakes.

- The recommended S loading does not address possible accumulation of N in low temperature lakes that remain ice covered for most of the year.

Many lakes in or near these two parks are probably at the stage where *any* increase in S deposition will result in loss of ANC. There is preliminary indication that one lake adjacent to MORA may have lost ANC as a result of atmospheric input of S. Summit Lake is located in the Clearwater Wilderness of the Mount Baker-Snoqualmie National Forest about 10 km north of the NW corner of the MORA boundary. The lake was sampled in 1985 (Eilers et al. 1987) and again in 1993 (Eilers and Bernert, unpublished data). Results from both samples show the lake to have SO_4^{2-} concentrations higher than expected marine contributions and an ANC near 0. The NADP/NTN data from the La Grande site 40 km southwest of the lake suggest that about

[2] This critical load is based on data from European sites which commonly have annual precipitation of about 1 m. Class I areas in the Pacific Northwest typically receive greater than 1 m annual precipitation and critical loads for S deposition should be adjusted upward to reflect the greater dilution of S from high precipitation.

4 μeq/L of the nonmarine base cations in Summit Lake can be attributed to wet deposition. Assuming that an additional 25% of the base cations in deposition are derived from dry deposition and that evapoconcentration is about 25%, precipitation accounts for about 75% of the nonmarine base cations in the lake. Thus, barring some unusual watershed processes (e.g., extremely low sedimentation rates, sequestering of base cations by bryophytes), nearly all of the non-marine SO_4^{2-} in Summit Lake can be attributed to sources other than weathering. The most likely explanation for this lake chemistry, given this limited information, is that Summit Lake has lost much of its ANC from atmospheric input of S.

Episodes of high ozone concentrations at low elevations east of the Cascade Range occur sporadically downwind of three urban areas: Vancouver, British Columbia; the Puget Sound region in Washington; and Portland, Oregon. National parks surrounding the Puget Sound, especially northeast and southeast of Seattle (MORA and NOCA), are more likely to be impacted by ozone than forests elsewhere in the Pacific Northwest. Some of the largest ozone values are near Pack Forest. Ozone levels along the western slopes of the Washington Cascades range from growing season means of 17 ppb in the north, to 31-35 ppb east of Seattle. Hourly concentrations can exceed 80 ppb, and values as high as 196 ppb have been recorded (Basabe et al. 1989b). At monitoring sites in the Cascade foothills, diurnal cycles in ozone average between 22-51 ppb during 70% of summer days (Böhm and Vandetta 1990). Forests located on the rim of valleys with large urban areas experience hourly ozone concentrations greater than 100 ppb. The frequency of occurrence of such high ozone levels seems to be related to the size of the city and the air pollution potential of the area. Few data on ozone concentrations in western forests are available, since most ozone monitoring sites are located close to urban complexes. Furthermore, ozone monitoring sites in the West are clustered, leaving large gaps, such as in Idaho. Consequently, recommendations for pollutant exposures to protect vegetation in the national parks must be extrapolated from data obtained elsewhere. Based on the existing information, we recommend one or more of the following ozone guidelines for vascular plants: < 70 ppb (7-h growing season mean, May-October), and 80-100 ppb (maximum hourly). To protect most vascular plants, maximum SO concentrations should not exceed 50-50 ppb (24-h mean), and annual average SO_2 concentrations should not exceed 8-12 ppb.

To protect most plant species from exposure to ozone, use of a more conservative cumulative statistics -- SUM06 or SUM08 -- for ozone has recently been considered. These indicators sum all hourly concentrations equal to and above 0.06-0.08 ppm (60-80 ppb). Due to the cumulative nature of ozone effects and the influence of higher concentrations on the effect, this level of measurement has proven to be relevant to minimizing effects on plants. Studies have compared air quality indicators for use as the NAAQS from the perspective of minimizing plant effects as well as maximizing the ability to detect declining air quality despite variable temporal patterns and site conditions. The previous NAAQS based on extreme values was found to be inadequate for protecting vegetation from ozone exposure (EPA 1993b). Based on the information evaluated in this report, we believe that the NAAQS ozone standard should include a cumulative statistic such as the SUM06 or SUM08 together with a measure of peak ozone concentrations, such as the maximum hourly mean. Strengths and limitations of the various statistics for quantifying ambient ozone are discussed in detail by Lefohn (1992), as reviewed in Appendix D.

Guidelines presented in this report should be applicable to similar ecosystems or areas with similar resources.

VI. LITERATURE CITED

Aber, J.D. and J.M. Melillo. 1991. Terrestrial ecosystems. Saunders College Publishing, Chicago. 429 pp.

Aber, J.D., K.J. Nadelhoffer, P. Steudler, and J.M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems: excess nitrogen from fossil fuel combustion may stress the biosphere. BioScience 39(6):378-386.

Agee, J.K. and J. Kertis. 1986. Vegetation cover types of the North Cascades. National Park Service, Cooperative Park Unit, College of Forest Resources, University of Washington, Seattle, WA.

Agee, J.K. and L. Smith. 1984. Subalpine tree establishment after fire in the Olympic Mountains, Washington. Ecology 65(3):810-819.

Anderson, R.L. 1989. Forest applications of biomarkers in southeastern forests. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 105-110.

Azevedo, H.D. and D.L. Morgan. 1974. Fog precipitation in coastal California forests. Ecology 55:1135-1141.

Baker, F.S. 1944. Mountain climates of the western United States. Ecol. Monogr. 14(2):224-254.

Baker, J.P., Bernard, D.P., Christensen, S.W., and Sale, M.J. 1990a. Biological Effects of Changes in Surface Water Acid-Base Chemistry. Report SOS/T 13. National Acid Precipitation Assessment Program, Washington, DC.

Baker, J.P., S.A. Gherini, S.W. Christensen, C.T. Driscoll, J. Gallagher, R.K. Munson, R.M. Newton, K.H. Reckhow, and C.L. Schofield. 1990b. Adirondack Lakes Survey: An Interpretive Analysis of Fish Communities and Water Chemistry, 1984-1987. Adirondack Lakes Survey Corporation, Ray Brook, NY.

Baldwin, J.H. and D. Kozak. 1986. Acid precipitation in the Pacific Northwest. Report to the Canadian Studies Faculty Research Grant Program. 81 pp.

Banks, T.W. 1991. Zooplankton community structure as influenced by fish in three subalpine lakes in Olympic National Park, Washington. MS Thesis, Western Washington University, Bellingham, WA.

Barnard, J.E. 1989. Large-scale monitoring. In: NRC Report, Biologic Markers of Air-Pollution Stress and Damage in Forests. National Research Council, Washington, DC. pp. 57-62.

Basabe, F.A. 1991. Study proposal: Cloudwater chemistry comparison between Stampede Pass and Alpine Lakes Wilderness. Huxley College. Western Washington University, Bellingham, Washington. 6 pp.

Basabe, F.A. 1993. 1993 Skagit Valley Ozone Report. Western Washington University, Bellingham, WA. 14 pp.

Basabe, F.A., R.L. Edmonds, W.L. Chang, and T.V. Larson. 1989a. Fog and cloudwater chemistry in Western Washington. In: Olson, R.K. and A.S. Lefohn (eds.). Symposium on the effects of air pollution on western forests. June 1989. Anaheim, CA. Air and Waste Management Association. pp. 33-49.

Basabe, F.A., R.L. Edmonds, and T.V. Larson. 1989b. Regional ozone in western Washington and southwest British Columbia. Paper presented at the 82nd Annual Meeting and Exhibition of the Air and Waste Management Association. 21 pp.

Bates, J.N. and A.M. Farmer, eds. 1992. Bryophytes and Lichens in a Changing Environment. Clarendon Press, Oxford, UK. 404 pp.

Battarbee, R.W., T.E.H. Allott, A.M. Kreiser, and S. Juggins. In press. Setting critical loads for UK surface waters: the diatom model.

Beier, C. and P. Gundersen. 1989. Atmospheric deposition to the edge of a spruce forest in Denmark. Environ. Pollut. 60:257-271.

Belnap, J., L. Sigal, W. Moir, and S. Eversman. 1993. Identification of sensitive species. In: Huckaby, L.S. (ed.). Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 67-88.

Bennett, P. 1985. Potential air injury to limber pine needles at Craters of the Moon National Monument. Unpublished report to Craters of the Moon National Monument. 4 pp.

Berg, V.S. 1989. Leaf cuticles as potential markers of air pollutant exposure in trees. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 333-339.

Berge, H. 1973. Plants as indicators of air pollution. Toxicology 1:79-89.

Binkley, D. 1992. Sensitivity of forest soils in the western U.S. to acidic deposition. In: Olson, R.K., D. Binkley, and M. Böhm (eds.). The Response of Western Forests to Air Pollution. Ecological Studies Vol. 97. Springer-Verlag, New York. pp. 153-182.

Binkley, D. and R.L. Graham. 1981. Biomass, production, and nutrient cycling of mosses in an old-growth Douglas-fir forest. Ecology 62:1387-1389.

Bjorklund, J. 1983. Bald eagle density and distribution on the Skagit River between Marblemount and Newhalem, winter 1982-83. North Cascades National Park, Ross Lake and Lake Chelan National Recreation Areas. Misc. Research Paper NCT-19. Sedro Woolley, WA.

Bjorklund, J. 1993. Endangered, threatened, and candidate wildlife of North Cascades National Park Service Complex, Washington. Report to the National Park Service, North Cascades National Park Complex. 6 pp.

Blakesley, J.A. and R.G. Wright. 1988. A review of scientific research at Craters of the Moon National Monument. Bull. No. 50. Forest, Wildlife and Range Experiment Station, Univ. of Idaho, Moscow.

Bledsoe, C.S., R.J. Zasoski, and J.K. Agee. 1985. Sulfur concentrations in native vegetation of Western Washington in relation to distance from point source pollution. Report to the National Park Service, Pacific Northwest Region, Seattle. 18 pp.

Bobbink, R., D. Boxman, E. Fremstad, G. Heil, A. Houdijk, and J. Roelofs. In press. Nitrogen eutrophication and critical load for nitrogen based upon changes in flora and fauna in semi-natural terrestrial ecosystems. Critical Loads for Nitrogen and Sulphur.

Böhm, M. 1992. Chapter 3., Air Quality and Deposition. In: Olson, R.K., D. Binkley, and M. Böhm (eds.). The Response of Western Forests to Air Pollution. Springer-Verlag, New York. pp. 63-152.

Böhm, M. and T. Vandetta. 1990. Atlas of air quality and deposition in or near forests of the western United States. EPA/600/3-90/081. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Bondietti, E.A., C.F. Baes, III, and S.B. McLaughling. 1989. The potential of trees to record aluminum mobilization and changes in alkaline earth availability. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 281-292.

Bormann, B.T., R.F. Tarrant, M.H. McClellan, and T. Savage. 1989. Chemistry of rainwater and cloudwater at remote sites in Alaska and Oregon. J. Environ. Qual. 18:149-152.

Boyle, T.P. and D.R. Beeson. 1991. Trophic status and assessment of non-point nutrient enrichment of Lake Crescent, Olympic National Park. Tech. Rept. NPS/PNRWR/NRTR-91/01. U.S. Dept. of the Interior, National Park Service, Pacific Northwest Region.

Brakke, D.F. 1984. Chemical surveys of North Cascade lakes. Report submitted to Washington State Department of Ecology. Western Washington University, Bellingham, WA.

Brakke, D.F. 1985. Chemical surveys of North Cascade lakes. Results of 1984 sampling. Report submitted to Washington State Department of Ecology. Western Washington University, Bellingham, WA.

Brandt, C.S. and W.W. Heck. 1968. Use of plants for pollutant identification and field monitoring. In: Stern, A.C. (ed.). Air Pollution. Vol. 1, 2nd ed. Academic Press, New York. pp. 428-443.

Bredemeier, M. 1989. Forest canopy transformation of atmospheric deposition. Water Air Soil Pollut. 40:121-138.

Brezonik, P.L., J.G. Eaton, T.M. Frost, P.J. Garrison, T.K. Kratz, C.E. Mach, J.H. McCormick, J.A. Perry, W.A. Rose, C.J. Sampson, B.C.L. Shelley, W.A. Swenson, and K.E. Webster. 1993. Experimental acidification of Little Rock Lake, Wisconsin: chemical and biological changes over the pH range 6.1 to 4.7. Can. J. Fish. Aquat. Sci. 50:1101-1121.

Brimblecone, P. 1978. Dew as a sink for SO_2. Tellus 30:151-157.

Brimblecone, P. and D.H. Stedman. 1982. Historical evidence for a dramatic increase in the nitrate component of acid rain. Nature 298:460-462.

Brubaker, L.B. and R.D. Ford. 1993. Growth variations in old-growth Douglas-fir forests of the Puget Sound area. National Council for Air and Stream Improvement, Tech. Bull. 648.

Buckingham, N.M. and E.L. Tisch. 1979. Vascular plants of the Olympic Peninsula, Washington. National Park Service, Coop. Park Service Report. B-79-2.

Bull, K.R. 1991. The critical loads/levels approach to gaseous pollutant emission control. Environ. Pollut. 69:105-123.

Bull, K.R. 1992. An introduction to critical loads. Environ. Pollut. 77:173-176.

Bunyak, J. 1993. Permit application guidance for new air pollution sources. Natural Resources Report 93-09. U.S. Dept. of Interior, National Park Service, Air Quality Division.

Buscher, P., N. Koedam, and D. Van Spreybroek. 1990. Cation-exchange properties and adaptation to soil acidity in bryophytes. New Phytol. 115:177-186.

Bytnerowicz, A. and N.E. Grulke. 1992. Physiological effects of air pollutants on western trees. In: Olson, R.K., D. Binkley, and M. Böhm (eds.). The Response of Western Forests to Air Pollution. Ecological Studies Series, Vol. 97. Springer-Verlag, New York. pp. 183-234.

Cape, J.N. 1988. Recent developments in the diagnosis and quantification of forest decline. In: Mathy, P. (ed.). Air Pollution and Ecosystems. D. Reidel, Dordrecht. pp. 262-305.

Cape, J.N. 1989. The use of biomarkers to monitor forest damage in Europe. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 63-71.

Cape, J.N. and M.H. Unsworth. 1987. Deposition, uptake, and residence of pollutants. In: Schulte-Hostede, S., N.M. Darrall, L.W. Blank, and A.R. Wellburn (eds.). Air Pollution and Plant Metabolism. Elsevier Appl. Science, NY. 381 pp.

Carter, D.L. 1970. Annotated list of birds of Craters of the Moon National Monument, Idaho. Unpublished report, Craters of the Moon National Monument Library. 13 pp.

Chadwick, J.M. and J.C.I. Kuylenstierna. 1990. The relative sensitivity of ecosystems in Europe to acidic deposition. Stockholm Environment Institute, Stockholm.

Chamberlain, A.C. 1967. Transport of Lycopodium spores and other small particles to rough surfaces. Proc. Royal Soc. 296:45-70.

Charlson, R.J. and H. Rodhe. 1982. Factors controlling the acidity of natural rainwater. Nature 295:683-685.

Chevone, B.I., D.E. Herzfeld, S.V. Kropa, and A.H. Chappelka. 1986. Direct effects of atmospheric sulfate deposition on vegetation. J. Air Pollut. Contr. Assoc. 36:813-815.

Church, M.R., K.W. Thorton, P.W. Shaffer, D.L. Stevens, B.P. Rochelle, R.G. Holdren, M.G. Johnson, J.J. Lee, R.S. Turner, D.L. Cassell, D.A. Lammers, W.G. Campbell, C.I. Liff, C.C. Brandt, L.H. Liegel, G.D. Bishop, D.C. Mortenson, and S.M. Pierson. 1989. Future Effects of Long-Term Sulfur Deposition on Surface Water Chemistry in the Northeast and Southern Blue Ridge Province (Results of the Direct/Delayed Response Project). U.S. Environmental Protection Agency Environmental Research Laboratory, Corvallis, OR.

Cionco, R.M. 1989. Forest winds coupled to surface layer windfields. In: Proceedings of the Sixth Joint Conference on Applications of Air Pollution Meteorology. Am. Meteor. Soc. and Air and Waste Mgmt. Assoc., 30, Jan 3, Anaheim, CA. pp. 196-199.

Comulada, A.B. 1981. A botanical reconnaissance of the Chillwack River Valley in North Cascades National Park, Washington. Master's Thesis, Western Washington University.

Cook, E. and J. Innes. 1989. Tree-ring analysis as an aid to evaluating the effects of air pollution on tree growth. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 63-71.

Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985a. Modelling the effects of acid deposition: assessment of a lumped-parameter model of soil water and streamwater chemistry. Water Resour. Res. 18:51-63.

Cosby, B.J., R.F. Wright, G.M. Hornberger, and J.N. Galloway. 1985b. Modelling the effects of acid deposition: estimation of long-term water quality responses in a small forested catchment. Water Resour. Res. 21:1591-1601.

Crandell, D.R. 1969a. Surficial geology of Mount Rainier National Park, Washington. U.S. Geol. Surv. Bull. 1288.

Crandell, D.R. 1969b. The geologic story of Mount Rainier, Washington. U.S. Geol. Surv. Bull. 1292.

Crandell, D.R. 1971. Postglacial lahars from Mount Rainier volcano, Washington. U.S. Geol. Surv. Prof. Pap. 677.

Daly, C. 1993. Precipitation in the United States. Oregon Climate Service, Corvallis, OR.

Davis, D.D. and R.G. Wilhour. 1976. Susceptibility of woody plants to sulfur dioxide and photochemical oxidants. EPA Report EPA-600/3-76-102. Environmental Research Laboratory, U.S. EPA, Corvallis, OR.

Day, T.A. 1984. Plant associations and soil factors in primary succession on cinder cones in Idaho. M.S. Thesis, University of Idaho, Moscow. 62 pp.

Day, T.A. and R.G. Wright. 1985. The vegetation types of Craters of the Moon National Monument. Forest, Wildlife and Ranger Experiment Station, University of Idaho, Moscow, ID.

Delmas, R.J. 1986. Past and present chemistry of north and south polar snow. In: Stonehouse, B. (ed.). Arctic Air Pollution. Cambridge University Press, Cambridge, UK. pp. 175-186.

Denison, R., B. Caldwell, B. Bormann, L. Eldred, C. Swanberg, and S. Anderson. 1977. The effects of acid rain on nitrogen fixation in western Washington coniferous forests. Water Air Soil Pollut. 8:21-34.

Denison, W.C. and S.M. Carpenter. 1973. A guide to air quality monitoring with lichens. Lichen Technology, Inc., Corvallis, OR.

Denmead, O.T. and E.F. Bradley. 1985. Flux-density relationships in a forest canopy. In: Hutchinson, B.A. and B.B. Hicks (eds.). The Forest Atmosphere Interaction. D. Reidel Publ. Co., Boston. pp. 421-442.

Depledge, M.H. 1994. The rational basis for the use of biomarkers and ecotoxicological tools. Chapter 12. In: Fossi, M.C. and C. Leonzio (eds.). Nondestructive Biomarkers in Vertebrates. Lewis Publ., London.

Dethier, D.P. 1979. Atmospheric contributions to stream water chemistry in the North Cascade Range, Washington. Water Resour. Res. 15(4):787-794.

de Vries, W. 1988. Critical deposition levels for nitrogen and sulphur on Dutch forest ecosystems. Water Air Soil Pollut. 42:221-239.

de Vries, W. 1990. Philosophy, structure and application methodology of a soil acidification model for the Netherlands. In: Kämäri, J. (ed.). Impact Models to Assess Regional Acidification. Kluwer Academic Publishers, Dordrecht. pp. 3-21.

de Vries, W. and J. Kros. 1991. Assessment of critical loads and the impact of deposition scenarios by steady state and dynamic soil acidification models. In: Heig, G.J. and T. Schneider (eds.). Acidification Research in the Netherlands. Elsevier, Amsterdam. pp. 569-624.

DeWitt, T. 1976. Epiphytic lichens and air pollution in the Netherlands. J. Cramer. Vaduz, The Netherlands.

Dillon, P.J., R.A. Reid, and R. Girard. 1986. Changes in the chemistry of lakes near Sudbury, Ontario, following reduction of SO_2 emission. Water Air Soil Pollut. 31:59-65.

Dise, N.B. and R.F. Wright (eds). 1991. The NITREX project (nitrogen saturation experiments). Norwegian Institute for Water Research, Oslo.

Douglas, G.W. 1971. A checklist of vascular plants, mosses, and lichens, birch, and mammals of the North Cascades of Washington. Report to the National Park Service.

Douglas, G.W. 1974. Lichens of the North Cascades Range, Washington. The Bryologist 77(4):582-592.

Douglas, G.W. and L.C. Bliss. 1977. Alpine and subalpine plant communities of the North Cascades Range, Washington, and British Columbia. Ecol. Monogr. 47(2):1242-1272.

Drever, J.I. and D.R. Hurcomb. 1986. Neutralization of atmospheric acidity by chemical weathering in an alpine drainage basin in the North Cascade Mountains. Geology 14:221-224.

Driscoll, C.T., M.D. Lehtinen, and T.J. Sullivan. 1994. Modeling the Acid-Base Chemistry of Organic Solutes in Adirondack, NY, Lakes. Water Resour. Res. 30:297-306.

Driscoll, C.T., R.M. Newton, C.P. Gubala, J.P. Baker, and S.W. Christensen. 1991. Adirondack Mountains. In: Charles, D.F. (ed.). Acidic Deposition and Aquatic Ecosystems. Regional Case Studies. Springer-Verlag, New York. pp. 133-202.

Duncan, L.C. 1992. Chemistry of rime and snow collected at a site in the central Washington Cascades. Environ. Sci. Tech. 26(1):61-66.

Duncan, L.C., M. Clise, S. Irby, and K. Krick. 1992. Measurement and assessment of the composition of bulk winter precipitation at sites in the Washington Cascades, Winter 1992. (Snoqualmie Pass, Stevens Pass). Precipitation Monitoring Report VIII. Final Report, Contract #C0091116. Central Washington University, Ellensburg, WA.

Duriscoe, D.M. and S.C.F. Stitt. 1993. Sampling methods and sample acquisition for elemental baseline study in North Cascades National Park Complex. Final Report.

Duriscoe, D.M. and K.W. Stolte. 1989. Photochemical oxidant injury to ponderosa pine (*Pinus ponderosa* Laws.) and Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in the National Parks of the Sierra California. In: Olson, R.K. and A.S. Lefohn (eds.). Transactions, symposium on the effects of air pollution on western forests. Air and Waste Management Association, Pittsburgh, PA. pp. 261-278.

Eary, L.E., E.A. Jenne, L.W. Vail, and D.C. Girvin. 1989. Numerical models for predicting watershed acidification. Arch. Environ. Contam. Toxicol. 18:29-53.

Easthouse, K.B., D.E. Spyridakis, and E.B. Welch. 1993. Aluminum chemistry in two pristine alpine lakes of the Central Cascades, Washington. Water Air Soil Pollut. 71:377-390.

ECE. 1990. Draft Manual for Mapping Critical Levels/Loads. Prepared by the Task Force on Mapping, Umweltbundesamt, Berlin.

Edmonds, R.L. and F.A. Basabe. 1989. Ozone concentrations above a Douglas-fir forest canopy in western Washington, U.S.A. Atmos. Environ. 23:625-629.

Edmonds, R.L. and T.B. Thomas. 1990. Litterfall and green needle decomposition in an old-growth temperate rainforest, Olympic Peninsula, Washington. Bull. Ecol. Soc. Amer. 7(2):61. Supplement.

Edmonds, R.L., J. Marra, R.D. Blew, and T.W. Cundy. 1992. Ecosystem and watershed studies in Olympic National Park. Annual Report to National Park Service, Pacific Northwest Region, under Coop. Agreement No. 9000-8-0007, Subagreement No. 7. Univ. of Washington, Seattle. 32 pp.

Edmonds, R.L., K. Maybury, and T.W. Cundy. 1991. Deposition and watershed studies in Olympic National Park. 1990 Annual Report to the National Park Service, Seattle, WA. Coop. Agreement No. CA-9000-8-0007, subagreement No. 7, Coll. For. Res., Univ. Washington, Seattle, WA. 73 pp.

Edmonds, R.L., T.B. Thomas, and K. Maybury. In Press. Tree population dynamics, growth, and mortality in old-growth forests in the western Olympic Mountains, Washington. Can. J. For. Res.

Eilers, J.M. 1991. Are lakes in the Cascade Mountains receiving high ammonium deposition? Northwest Sci. 65:238-247.

Eilers, J.M., D.F. Brakke, and D.H. Landers. 1988. Chemical and physical characteristics of lakes in the upper Midwest, United States. Environ. Sci. Technol. 22:164-172.

Eilers, J.M.. B.J. Cosby, and J.A. Bernert. 1991. Modeling lake response to acidic deposition in the northern Rocky Mountains. Report #91-02 to the USDA-Forest Service, Missoula, MT. E&S Environmental Chemistry, Inc., Corvallis, OR. 46 pp.

Eilers, J.M., P. Kanciruk, R.A. McCord, W.S. Overton, L. Hook, D.J. Blick, D.F. Brakke, P.E. Kellar, M.S. DeHaan, M.E. Silverstein, and D.H. Landers. 1987. Characteristics of lakes in the western United States. Volume II. Data compendium for selected physical and chemical variables. EPA-600/3-86/054b, U.S. Environmental Protection Agency, Washington, D.C. 492 pp.

Eilers, J.M., G.J. Lien, and R.G. Berg. 1984. Aquatic organisms in acidic environments: a literature review. Technical Bulletin No. 150. Dept. Natural Resources, Madison, Wisconsin. 18 pp.

Eilers, J.M., T.J. Sullivan, and K.C. Hurley. 1990. The most dilute lake in the world? Hydrobiologia 199:1-6.

Elwood, J.W., M.J. Sale, P.R. Kaufmann, and G.F. Cada. 1991. In: Charles, D.F. (ed.). Acidic Deposition and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag, New York. pp. 319-364.

Environmental Protection Agency. 1982. Air quality criteria for oxides of nitrogen. U.S. Environmental Protection Agency Completion Report: contract EPA-600/8-82-026. 815 pp.

Environmental Protection Agency. 1987. Handbook of Methods for Acid Deposition Studies. Laboratory Analysis for Surface Water Chemistry. EPA 600/4-87/026. Washington, DC.

Environmental Protection Agency. 1988. Review of the national ambient air quality standards for ozone assessment of scientific and technical information. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Environmental Protection Agency. 1993a. Developing a strategy to manage biodiversity. Corvallis Research Update 3(2):1-2.

Environmental Protection Agency. 1993b. Corvallis EPA scientists propose an alternative air quality indicator for secondary ozone NAAQS. Corvallis Research Update July:6-7.

Esserlieu, M.K. and R.J. Olson. 1986. Biological vulnerabilities of National Park Service Class I areas to atmospheric pollutants. ORNL/TM-9818. Oak Ridge National Laboratory, Oak Ridge, TN. 110 pp.

Farmer, A.M., J.W. Bates, and J.N.B. Bell. 1991. Comparisons of three woodland sites in NW Britain differing in richness of the epiphytic Lobarion pulmonariae community and levels of wet acidic deposition. Holarctic Ecol. 94:85-91.

Farmer, A.M., J.W. Bates, and J.N.B. Bell. 1992a. Ecophysiological effects of acid rain on bryophytes and lichens. In: Bates, J.W. and A.M. Farmer, (eds.), Bryophytes and Lichens in a Changing Environment. Clarendon Press, New York, USA. pp. 284-306.

Farmer, A.M., J.W. Bates, and J.N.B.Bell. 1992b. The transplantation of four species of Lobaria lichens to demonstrate a field acid rain effect. In: Schneider, T. (ed.). Acidification research: evaluation and policy applications Elsevier, Amsterdam.

Feder, W.A. 1978. Plants as bioassay systems for monitoring atmospheric pollutants. Environ. Health Perspect. 27:139-147.

Fenneman, N.M. 1946. Physical Divisions of the United States. 1 map (scale 1:7,000,000). U.S. Geological Survey, Washington, DC.

Ferguson, P. and J.A. Lee. 1983. Past and present sulphur pollution in the southern Pennines. Atmos. Environ. 17:1131-1137.

Ferry, B.W., S. Baddeley, and D.L. Hawksworth. 1973. Air Pollution and Lichens, Athlone Press, London.

Finlayson-Pitts, B.J. and J.N. Pitts. 1986. Atmospheric Chemistry: Fundamentals and Experimental Techniques. John Wiley & Sons, New York. 1098 pp.

Finnigan, J.J. 1985. Turbulent transport in flexible plant canopies. In: Hutchinson, B.A. and B.B. Hicks (eds.). The Forest Atmosphere Interaction. D. Reidel Publ. Co. Boston. pp. 443-480.

Forest Health Monitoring Program. 1993. Study of western plant ozone sensitivity. Interagency memo, dated January 20, 1993. 5 pp.

Forsius, M., J. Kämäri, and M. Posch. 1992. Critical loads for Finnish lakes: comparison of three steady-state models. Environ. Pollut. 77:185-193.

Fossi, M.C., C. Leonzio, and D.B. Peakall. 1994. Chapter 1. In: Fossi, M.C. and C. Leonzio (eds.). The use of non-destructive biomarkers in the hazard assessments of vertebrate populations. Nondestructive Biomarkers in Vertebrates. Lewis Publ., London.

Fowler, D. 1984. Transfer to terrestrial surfaces. Royal Soc. Phil. Trans., Series B, 305:281-297.

Fox, D.G., A.M. Bartuska, J.G. Byrne, E. Cowling, R. Fisher, G.E. Likens, S.E. Lindberg, R.A. Linthurst, J. Messer, and D. Nichols. 1989. A screening procedure to evaluate air pollution effects on Class I wilderness areas. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-GTR-168.

Franklin, J.F. and C.T. Dyrness. 1988. Natural Vegetation of Oregon and Washington. Oregon State Univ. Press, Corvallis, OR.

Frenzel, R.W. and E. Starkey. 1987. Concentrations of arsenic and lead in hair of mountain goats from Mount Rainier, Olympic, and North Cascades National Parks, Washington. CPSU/OSU87-3. Cooperative Park Studies Unit, Oregon State University, Corvallis, OR.

Frenzel, R.W., G.W. Witmer, and E. Starkey. 1987. Concentrations of metals and sulfur in Subalpine Fir needles and a lichen in Olympic and Mount Rainier National Parks, Washington. Cooperative Park Studies Unit, Oregon State University, Corvallis, OR.

Frenzel, R.W., G.W. Witmer, and E.E. Starkey. 1990. Heavy metal concentrations in a lichen of Mt. Rainier and Olympic National Parks, Washington, USA. Bull. Environ. Contam. Toxicol. 44:158-164.

Fritz-Sheridan, R. P. 1985. Impact of simulated acid rains on nitrogenase activity in *Peltigera apthhosa* and *P. polydactyla*. The Lichenologist 17:27-31.

Frogner, T., R.F. Wright, B.J. Cosby, J.M. Esser, A.O. Håöya, and G. Rudi. 1992. Map of critical loads for coniferous forest soils in Norway. Report 33, Ministry of Environment, Oslo. 30 pp.

Fry, B. 1989. Human perturbation of C, N, and S biogeochemical cycles: historical studies with stable isotopes. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 143-156.

Funk, W.H., E. Hindin, B.C. Moore, and C.R. Wasem. 1987. Water quality benchmarks in the North Cascades. Report 68. State of Washington Water Research Center, Pullman, WA.

Funk, W.H., B.C. Moore, D.L. Johnstone, J.P. Porter, S.T.J. Juul, C.K. Trout, and B.L. Becker. 1985. Baseline study of Reflection Lakes, Mount Rainier National Park. State of Washington Water Research Center, Washington State University and the University of Washington. Report 66. 58 pp.

Galloway, J.N., and G.E. Likens. 1976. Calibration of collection procedures for the determination of precipitation chemistry. Water Air Soil Pollut. 6:241-258.

Galun, M. and R. Rohnen. 1988. Interaction of lichens and pollutants. In: Galun, M. (ed.). CRC Handbook of Lichenology. CRC Press, Boca Raton, FL. pp. 55-72.

Garland, J.A. 1978. Dry and wet removal of sulfur from the atmosphere. Atmos. Environ. 12:349-362.

Garman, S.L., A.J. Hansen, D.L. Urban, and P.F. Lee. 1992. Alternative silvicultural practices and diversity of animal habitat in western Oregon: a computer simulation approach. In: Luker, P. (ed.). Proceedings of the 1992 Summer Simulation Conference. The Society for Computer Simulation. Reno, Nevada. pp. 777-781.

Gerhardt, K. and O. Kellner. 1986. Effects of nitrogen fertilizers on the field- and bottomlayer species in some Swedish coniferous forests. Meddelanden fran Vaxtbiologiska institutionen, Uppsala 1:1-47.

Gilbert, O.L. 1986. Field evidence for an acid rain effect on lichens. Environ. Pollut. (Series A) 40:227-231.

Gilbert, O.L. 1992. Lichen reinvasion with declining air pollution. In: Bates, J.W. and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Clarendon Press, Oxford. pp. 159-177.

Gladney, E.S., R.W. Ferenbaugh, K.W. Stolte, R.G. Bowker, M.G. Bell, J.D. Montoya, E.J. Nickell, and W. Welsh. 1993. Elemental concentrations in soils from North Cascades National Park, Washington. Draft Report.

Glesne, R., B. Freet, R.C. Kuntz II, J. Riedel, A. Braaten, R. Holmes, D.L. Peterson, G. Larson, J. Lattin, and W. Liss. 1993. Long-Term Ecological Monitoring Prototype Proposal for Lakes and Rivers. North Cascades National Park Service Complex.

Gmur, N.F., L.S. Evans, and E.A. Cunningham. 1983. Effects of ammonium sulfate aerosols on vegetation - II. Mode of entry and responses of vegetation. Atmos. Environ. 17(4):715-721.

Gough, L.P., L. L. Jackson, J. A. Sacklin. 1988. Determining baseline element composition of lichens. II Hypogymnia enteromorpha and Usnea spp. at Redwood National Park, California. Water Air Soil Pollut. 38:169-180.

Greeley, R. 1977. Basaltic plains volcanism. In: Greeley, R. and J.S. King (eds.). Volcanism of the eastern Snake River Plain, Idaho: a comparative planetary geology guidebook. National Aeronautics and Space Administration, Washington, DC. pp. 23-44.

Greene, S.E. and M. Klopsch. 1985. Soil and air temperatures for different habitats in Mount Rainier National Park. U.S. Forest Service, Pacific Northwest Research Station. Research Paper PNW-RP-342.

Grennfelt, P. and H. Hultberg. 1986. Effects of nitrogen deposition on the acidification of terrestrial and aquatic ecosystems. Water Air Soil Pollut. 30:945-963.

Grosjean, D. and M.W. M. Hisham. 1992. A passive sampler for atmospheric ozone. J. Air Waste Mgmt. Assoc. 42(2):169-173.

Gubala, C.P., C.T. Driscoll, R.M. Newton, and C.L. Schofield. 1991. The chemistry of a near-shore lake region during spring snowmelt. Environ. Sci. Tech. 25(12):2024-2030.

Gundersen, P. 1992. Mass balance approaches for establishing critical loads for nitrogen in terrestrial ecosystems. Background document for UN-ECE workshop Critical Loads for Nitrogen, Lökeberg, Sweden, 6-10 April, 1992.

Gunn, J.M. and W. Keller. 1990. Biological recovery of an acid lake after reductions in industrial emissions of sulphur. Nature 355:431-433.

Hale, M.E. 1983. The Biology of Lichens, 3rd Ed. Edward Arnold, London.

Hall, T.J. 1973. A limnological study of Shadow Lake, a subalpine lake at Mount Rainier National Park, Washington. Master's Thesis, Central Washington State College.

Hansen, A.J., D.L. Urban, S. Garman, B R. Noon, and W. McComb. 1990. Responses of wildlife habitats to forest management and climate change: a modeling approach. The Northwest Environmental Journal 6(2):623-630.

Hansen, A.J. et al. 1993. An approach for managing vertebrate diversity across multiple-use landscapes. Ecol. Appl. 3(3): 481-496.

Hanson, W.C. 1982. Cs concentrations in northern Alaskan eskimos. Hlth. Phys. 42:433-447.

Harr, R.D. 1982. Fog drip in the Bull Run Municipal Watershed, Oregon. Water Resour. Bull. 18:785-789.

Harris, A.G. 1990. Geology of the National Parks. Kendall/Hunt Publishing Co., Dubuque, IA.

Harris, D.V. and E.P. Kiven. 1985. The Geologic Story of the National Parks and Monuments. John Wiley & Sons. New York. 464 pp.

Hauhs, M., K. Rost-Siebert, G. Raben, T. Paces, and B. Vigerust. 1989. Summary of European Data. In: Malanchuk, J.L. and J. Nilsson (eds.). The Role of Nitrogen in the Acidification of Soils and Surface Waters. Miljørapport 1989: 10 (NORD 1989:92), Nordic Council of Ministers, Copenhagen. pp. 5-1-5-37.

Hawksworth, D.L. 1990. The long term effects of air pollutants on lichen communities in Europe and North America. In: Woodwell, G.M. (ed.), The Earth In Transition. Patterns and Processes of Biotic Impoverishment. Cambridge University Press, Cambridge, UK. pp. 45-64.

Heagle, A.S., D.E. Body, and G.E. Neely. 1974. Injury and yield response of soybean to chronic doses of ozone and sulfur dioxide in the field. Phytopathology 64:132-136.

Heagle, A.S., S. Spencer, and M.B. Letchworth. 1979. Yield response of winter wheat to chronic doses of ozone. Can. J. Bot. 57:1999-2005.

Heij, G.J. and T. Schneider. 1991. Summary. In: Heig. G.J. and T. Schneider (eds.). Acidification Research in the Netherlands. Elsevier, Amsterdam. pp. 3-24.

Henderson, J.A., D.H. Peter, R.D. Lesher, and D.C. Shaw. 1989. Forested plant associations of the Olympic National Forest. USDA-Forest Service, Pacific Northwest Region, R6 Ecology Program, R6-Technical Paper 001-88.

Henriksen, A. 1992. Nitrogen from Mountain to Fjord - a new Norwegian research project. International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems - Approach, Methodologies, Findings. Copenhagen, 18-20 May 1992.

Henriksen, A. and D.F. Brakke. 1988. Sulphate deposition to surface waters. Environ. Sci. Tech. 22:8-14.

Henriksen, A., J. Kämäri, M. Posch, G. Lövblad, M. Forsius, and A. Wilander. 1990b. Critical Loads to Surface Waters in Fennoscandia: Intra- and Inter-grid Variability of Critical Loads and their Exceedence. Miljørapport (Environmental report) 17. Nordic Council of Ministers, Copenhagen. 33 pages plus figures.

Henriksen, A., J. Kämäri, M. Posch, and A. Wilander. 1992. Critical loads of acidity: Nordic surface waters. Ambio 21(5):356-363.

Henriksen, A., L. Lien, and T.S. Traaen. 1990a. Critical loads for surface waters - chemical criteria for inputs of strong acids. Norwegian Institute for Water Research, Oslo, Acid Rain Research Report 22.

Hessen, D., O. Vadstein, and J. Magnusson. 1992. Nitrogen to marine areas, on the application of a critical load concept. Background Document for Workshop on Critical Loads of Nitrogen, held 6-10 April, 1992 in Lökeberg, Sweden.

Hettelingh, J.-P., R.J. Downing, and P.A.M. deSmet. 1991. Mapping critical loads for Europe. Technical Report No. 1. Coordination Center for Effects, Bilthoven, The Netherlands.

Hindawi, I.J. 1968. Injury by sulfur dioxides, hydrogen fluoride, and chlorine as observed and reflected in vegetation in the field. J. Air Pollut. Control. Assoc. 18:307-312.

Hobson, F.D. 1976. Classification system for the soils of Mount Rainier National Park. Report submitted for M.S., Washington State Univ., Pullman. 76 pp.

Hoffman, G.R. 1974. The influence of a paper mill on the ecological distribution of epiphytic cryptogams in the vicinity of Lewiston, Idaho, and Clarkston, Washington. Environ. Pollut. 7:283-301.

Hoffman, M.R., J.L. Collett, and B.C. Daube. 1989. Characterization of cloud chemistry and frequency of canopy exposure to clouds in the Sierra Nevada. Final Report submitted to the California Air Resources Board, Sacramento, CA.

Hogsett, W.E., D.T. Tingey, C. Hendricks, and D. Rossi. 1989. Sensitivity of Western conifers to SO_2 and seasonal interaction of acid fog and ozone. In: Olson, R.K. and A.S. Lefohn (eds.). Symposium on the effects of air pollution on western forests, June, 1989, Anaheim, CA. Air and Waste Mgmt. Assoc., Pittsburgh, PA. pp. 469-491.

Hogsett, W.E., D.T. Tingey, and S.R. Holman. 1985. A programmable exposure control system for determination of the effects of pollutant exposure regimes on plant growth. Atmos. Environ. 19:1135-1145.

Horner, D. and D.L. Peterson. 1993. Goat Rocks Wilderness Monitoring Plan. Report to Gifford Pinchot National Forest, USDA Forest Service. 118 pp.

Hutchinson, T.C. and M. Havas. 1986. Recovery of previously acidified lakes near Coniston, Canada following reductions in atmospheric sulphur and metal emissions. Water Air Soil Pollut. 28:319-333.

Idaho Department of Health and Welfare. 1991. 1990 Idaho Air Quality Annual Report. Division of Environmental Quality. 48 pp.

Jackson, L.L., J. Ford, and D. Schwartzman. 1993. Collection and chemical analysis of lichens for biomonitoring. In: Huckaby, L.S. (ed.). Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 96-115.

Jacob, D.J., F.H. Hair, J.M. Waldman, J.W. Munger, and M.R. Hoffman. 1984. A field investigation of physical and chemical mechanisms affecting pollutant concentrations in fog droplets. Tellus 36B:272-285.

Jacobsen, J.S. and A.C. Hill (eds.). 1970. Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas. Air Pollution Control Assoc., Pittsburgh, PA. 102 pp.

Jenkins, A., R.F. Wright, B.J. Cosby, R.C. Ferrier, and D.J. Waters. In Press. Changes in acidification of lochs in Galloway, southwestern Scotland: III. Critical loads for sulphur. J. Hydrol.

Jensen, K.J. and R.G. Masters. 1975. Growth of six woody species fumigated with ozone. Plant Dis. Rept. 59:760-762.

Johnson, A.H. 1979. Air pollution and the distribution of corticolous lichens in Seattle, Washington. Northwest Sci. 53(4):257-263.

Johnson, A.H. 1989. Decline of red spruce in the northern Appalachians: Determining if air pollution is an important factor. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 91-104.

Johnson, A.H., H. Van Miegerot, and W.T. Swank. 1989. Markers of air pollution in forests: Nutrient cycling. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 133-142.

Kahl, J.S., S.A. Norton, I.J. Fernandez, K.J. Nadelhoffer, C.T. Driscoll, and J.D. Aber. 1993. Experimental inducement of nitrogen saturation at the watershed scale. Environ. Sci. Tech. 27:565-568.

Kämäri, J., M. Amann, Y.-W Brodin, M.J. Chadwick, A. Henriksen, J.P. Hettelingh, J.C.I. Kuylenstierna, M. Posch, and H. Sverdrup. 1992. The use of critical loads for the assessment of future alternatives to acidification. Ambio 21(5):377-386.

Kämäri, J., M. Forsius, and M. Posch. 1993. Critical loads of sulfur and nitrogen for lakes II: Regional extent and variability in Finland. Water Air Soil Pollut. 66:77-96.

Keller, W., J.R. Pitblado, and N.I. Conroy. 1986. Water quality improvements in the Sudbury, Ontario, Canada area related to reduced smelter emissions. Water Air Soil Pollut. 31:765-774.

Kellner, O and M. Marshagen. 1991. Effects of irrigation and fertilization on the ground vegetation in a 130-year-old stand of Scots pine. Can. J. For. Res. 21:733-738.

Kerstiens, G. and K.J. Lendzian. 1989. Interactions between ozone and plant cuticles I. Ozone deposition and permeability. New Phytol. 112:13-19.

Kertis, J. and J.K. Agee. 1985. Reconnaissance surveys for endangered, threatened, rare, and endemic plant species in Mount Rainier National Park. National Park Service Cooperative Park Studies Unit, College of Forest Resources, University of Washington, Seattle.

Kilkelly Environmental Associates. 1989. Report on Pollutants Considered to Pose the Greatest Threat to Wildlife When Existing Water Quality Criteria Are Met. Workshop Summary Report: Water Quality Criteria to Protect Wildlife Resources. Report to U.S. Environmental Protection Agency, Office of Water Regulations and Standards, and U.S. Fish and Wildlife Service under EPA Contract No. 68-03-3439. Kilkelly Environmental Associates, Raleigh, NC.

Kuntz, M.A., D.E. Champion, E.C. Spiker, and R.H. Lefebvre. 1986a. Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho. Bull. Geol. Soc. Amer. 97:579-594.

Kuntz, M.A., E.C. Spiker, M. Rubin, D.E. Champion, and R.H. Lefebvre. 1986b. Radiocarbon studies of latest Pleistocene and Holocene lava flows of the Snake River Plain, Idaho. Quater. Res. 25:163-176.

Kuylenstierna, J.C.I. and J.M. Chadwick. 1989. The relative sensitivity of ecosystems in Europe to the indirect effects of acidic depositions. In: Kamari, J., D.F. Brakke, A. Jenkins, S.A. Norton, and R.F. Wright (eds.), Regional Acidification Models: Geographic Extent and Time Development. Springer-Verlag, Berlin. pp. 3-21.

Laird, L.B., H.E. Taylor, and V.C. Kennedy. 1986. Snow chemistry of the Cascade-Sierra Nevada Mountains. Environ. Sci. Tech. 20:275-290.

Landers, D.H., J.M. Eilers, D.F. Brakke, W.S. Overton, P.E. Kellar, M.E. Silverstein, R.D. Schonbrod, R.E. Crowe, R.A. Linthurst, J.M. Omernik, S.A. Teague, and E.P. Meier. 1987. Characteristics of Lakes in the Western United States. Volume I. Population descriptions and Physico-Chemical Relationships. EPA/600/3-86/054a. U.S. Environmental Protection Agency, Washington, D.C.

Larson, G.L. 1969. A limnological study of a high mountain lake in Mount Rainier National Park, Washington: USA. Master's Thesis, University of Washington.

Larson, G., C. Hawkins, B. Samora, and S. Gibbons. 1990. Water quality of glacial and nonglacial streams in Mount Rainier National Park. Cooperative Park Studies Unit, Oregon State Univ., Corvallis, OR.

Larson, G.L., C.D. McIntire, and R.W. Jacobs (eds.). 1993. Crater Lake Limnological Studies. Technical Report NPS/PNROSU/NRTR-93/03. National Park Service, Seattle, WA.

Larson, G.L., A. Wones, C.D. McIntire, and B. Samora. 1992. Limnology of subalpine and high mountain forest lakes, Mount Rainier National Park. Tech. Rept. NPS/PNR CPSU OSU/NRTR-92/01, Cooperative Park Studies Unit, Oregon State Univ., Corvallis, OR.

Lechowicz, M.J. 1982. The effect of simulated acid precipitation on photosynthesis in the caribou lichen, Cladina stellaris (Opiz.) Brodo. Water Air Soil Pollut. 34:71-77.

Lee, J.A., and C.J. Studholme. 1992. Responses of Sphagnum species to polluted environments. In: Bates, J.W. and A. M. Farmer, (eds.), Bryophytes and Lichens in a Changing Environment, Clarendon Press, New York, USA. pp. 314-332.

Lee, J.A., M.C. Press, S. Woodin, and P. Ferguson. 1987. Responses to acidic deposition in ombrotrophic mires in the UK. In: Hutchinson, T.C. and K.M. Meema (eds.). Effects of Atmospheric Pollutants on Forest, Wetlands, and Agricultural Ecosystems, NATO ASI Series G 16, Berlin. pp. 549-560 .

Lee, E.H., D.T. Tingey, and W.E. Hogsett. 1988. Evaluation of ozone exposure indices in exposure-response modeling. Environ. Pollut. 53:43-62.

Lefebvre, R.H. 1975. Mapping in the Craters of the Moon volcanic field, Idaho, with LANDSAT (ERTS) imagery. Proceedings, 10th International Symposium on Remote Sensing of the Environment. University of Michigan, Ann Arbor. 2:951-957.

Lefohn, A.S. 1992. Surface Level Ozone Exposures and their Effects on Vegetation. Lewis Publishers. 366 pp.

Lefohn, A.S. and S.V. Krupa. 1988. The relationship between hydrogen and sulfate ions in precipitation - a numerical analysis of rain and snowfall chemistry. Environ. Poll. 49(4):289-311.

Lefohn, A.S., J.A. Laurence, and R.J. Kohut. 1988. A comparison of indices that describe the relationship between exposure to ozone and reduction in the yield of agricultural crops. Atmos. Environ. 22:1229-1240.

Leonard,, W.P., H.A. Brown, L.L.C. Jones, K.R. McAllister, and R.M. Storm. 1993. Amphibians of Washington and Oregon. Seattle Audobon Society, Seattle, WA. 168 pp.

Leonzio, C. and M.C. Fossi. 1994. Nondestructive biomarker strategy: Perspectives and applications. Chapter 13. In: Fossi, M.C. and C. Leonzio (eds.). Nondestructive Biomarkers in Vertebrates. Lewis Publ., London.

Liss, W.J., E.K. Deimling, R. Hoffman, G.L. Larson, G. Lomnicky, C.D. McIntire, and R. Truitt. 1991. Annual Report 1990-1991. Ecological Effects of stocked fish on naturally fishless high mountain lakes: North Cascades National Park Service Complex. Draft.

Longton, R.E. 1984. The role of bryophytes in terrestrial ecosystems. J. of the Hattori Botanical Laboratory, 55:147-163.

Longton, R.E. 1992. In: Bates, J.W. and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Clarendon Press, New York. pp. 32-76.

Loranger, T.J. and D.F. Brakke. 1986. Chemical weathering characteristics of North Cascades watersheds. Institute for Watershed Studies, Western Washington University, Bellingham, WA.

Loranger, T.J. and D.F. Brakke. 1988. The extent of snowpack influence on water chemistry in a North Cascade lake. Water Resour. Res. 24(5):723-726.

Loranger, T.J., D.F. Brakke, M.B. Bonoff, and B.F. Gall. 1986. Temporal variability of lake waters in the North Cascades Mountains (Washington, U.S.A.). Water Air Soil Pollut. 31:123-129.

Lövblad, G. and J.W. Erisman. 1992. Deposition of nitrogen species on a small scale in Europe. Report of Working Group 5, Workshop on Critical Loads for Nitrogen.

Lövblad, G., M. Amann, B. Andersen, M. Hovmand, S. Joffre, and U. Pedersen. 1992. Deposition of sulfur and nitrogen in the Nordic Countries: Present and Future. Ambio 21(5):339-347.

MacKenzie, D. 1986. The rad-dosed reindeer. New Scientist 1539:37-40.

Malm, W.C., K.A. Gebhart, D. Huffman, J. Molenar, T. Cahill, and R. Eldred. 1993. Examining the relationship between atmospheric aerosols and light extinction at Mount Rainier and North Cascades National Parks. Submitted to Atmospheric Environment, March 1993.

Marx, D.H. and S.R. Shafer. 1989. Fungal and bacterial symbioses as potential biological markers of effects of atmospheric deposition on forest health. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 217-232.

Matthews, D. 1992. Cascade Olympic Natural History. Audobon Society of Portland. Raven Editions, Oregon.

McBean, G.A. 1968. An investigation of turbulence within the forest. J. Appl. Meteor. 7:410-416.

McBean, G.A. and S. Nikleva. 1986. Composition of snow in Pacific coastal mountains. Atmos. Environ. 20:1161-1164.

McCarthy, J.F. and L.R. Shugart. 1990. Biomarkers of Environmental Contamination. Lewis Publishers, Boca Raton, FL.

McNeil, R.C. 1982. Vegetation and fire history of a ponderosa pine-white fir forest in Crater Lake National Park. Master's Thesis, Oregon State University, Corvallis, OR.

Melack, J.M., and J.L. Stoddard. 1991. Sierra Nevada: Unacidified, very dilute waters and mildly acidic atmospheric deposition. In: Charles, D.F. (ed.) Acidic Deposition and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag, Inc., New York. pp. 503-530.

Miller, P.R. 1973. Oxidant-induced community change in a mixed conifer forest. In: Naegele, J.A. (ed.). Air Pollution Damage to Vegetation. Advances in Chemistry Series 122, Amer. Chem. Sci., Washington, DC. pp. 101-137.

Miller, P.R. 1989. Biomarkers for defining air pollution effects in western coniferous forests. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 111-118.

Miller, P.R., G.J. Longbotham, and C.R. Longbotham. 1983. Sensitivity of selected Western conifers to ozone. Plant Dis. 67:1113-1115.

Miller, P.R., J.R. McBride, S.L. Schilling, and A.P. Gomez. 1989. Trend of ozone damage to conifer forests between 1974 and 1988 in the San Bernardino Mountains of southern California. In: Olson, R.K. and A.S. Lefohns (eds.). Transactions, symposium on the effects of air pollution on western forests. Air and Waste Management Association, Pittsburgh, PA. pp. 309-323.

Miller, R.E., D.P. Lavender, and C.C. Grier. 1976. Nutrient cycling in the Douglas-fir type-silvicultural implications. Proc. of the Soc. of Am. For., 1975.

Moorhead, B. 1991. Mammals, amphibians, and reptiles of Olympic National Park. U.S. Department of the Interior, National Park Service.

Morgan, S.M., J.A. Lee, and T.W. Ashenden. 1992. Effects of nitrogen oxides on nitrate assimilation in bryophytes 120:89-97.

Moseley, R.K. et al. 1992. Idaho's rare vascular flora: a bibliography. USDA-Forest Service, Intermountain Res. Station, Technical Report GTR-INT-292.

Muir, P.S. and M. Böhm. 1989. Cloud chemistry and occurrence in the western United States: a synopsis of current information. In: Olson, R.K. and A.S. Lefohn (eds.). Effects of Air Pollution on Western Forests. Trans. Series No. 16, Air and Waste Mgmt. Assoc., Pittsburgh, PA. pp 73-101.

Murtaugh, J.G. 1961. Geology of Craters of the Moon National Monument, Idaho. M.S. Thesis, Univ. of Idaho, Moscow. 99 pp.

Musselman, R.C., A.J. Huerta, P.M. McCool, and R.J. Oshima. 1986. Response of beans to simulated ambient and uniform ozone distribution with equal peak concentrations. J. Am. Soc. Hort. Sci. 111:470-473.

Musselman, R.C., P.M. McCool, and T. Younglove. 1988. Selecting ozone exposure statistics for determining crop yield loss from air pollutants. Environ. Pollut. 53:63-78.

Musselman, R.C., R.J. Oshima, and R.E. Gallavan. 1983. Significance of pollutant concentration distribution in the response of "red kidney" beans to ozone. J. Am. Soc. Hort. Sci. 108:347-351.

NAPAP Aquatic Effects Working Group 1991. National Acid Precipitation Assessment Program 1990 Integrated Assessment Report. National Acid Precipitation Assessment Program, Washington, DC. 520 pp.

Nash, T.H. III. 1988. Correlating fumigation studies with field effects. In: Nash, T.H. and V. Wirth (eds.). Lichens, bryophytes, and air quality. Bibliotheca Lichenologica. J. Cramer, Berlin. pp. 201-216.

Nash, T.H. III and L.L. Sigal. 1979. Gross photosynthetic of lichen to short-term ozone fumigation. The Bryologist. 82:280-285.

Nash, T.H. and V. Wirth. 1988. Lichens, bryophytes, and air quality. Bibliotheca Lichenologica. J. Cramer, Berlin. 297 p.

Nash, T. H., C. M. Wetmore, W. Anderson, C. Bratt, W. C. Denison, S. Eversman, B. Maurray, and L. St. Clair. 1993. Floristics. In: Huckaby, L.S. (ed.). Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 6-15.

National Park Service. 1991. Natural resource plan for Mount Rainier National Park. National Park Service.

National Park Service. 1992. North Cascades - Official National Park Handbook #131. U.S. Department of the Interior, National Park Service.

National Research Council. 1989. Biologic Markers of Air Pollution Stress and Damage in Forests. Washington, DC. 363 pp.

National Research Council. 1992. Science and the National Parks. National Academy Press, Washington, DC. 122 pp.

NCASI. 1964. Laboratory and controlled experimental stream studies of the effects of kraft effluents on growth and production of fish. National Council for Air and Stream Improvement. Technical Bull. 173.

NCASI. 1974. Atmospheric emissions from the pulp and paper manufacturing industry. National Council for Air and Stream Improvement. Technical Bull. 69.

NCASI. 1982. Air quality protection aspects of forestry management. National Council for Air and Stream Improvement. Technical Bull. 390.

NCASI. 1984. Relationship between fine sediment and macroinvertebrate community characteristics - literature review and results of NCASI fine sediment studies. National Council for Air and Stream Improvement, Technical Bull. 418.

NCASI. 1986. Review of all available ambient ozone monitoring data for the years 1978-1983. National Council for Air and Stream Improvement. Technical Bull. 502.

NCASI. 1987. Tree ring and forest management: how can they document trends in forest health and productivity? National Council for Air and Stream Improvement. Technical Bull. 523.

NCASI. 1989. Early detection of air pollutant injury to coniferous forests using remote sensing. National Council for Air and Stream Improvement. Technical Bull. 571.

Nelson, P.O. 1991. Cascade Mountains. In: Charles, D.F. (ed.). Acid Deposition and Aquatic Ecosystems. Regional Case Studies. Springer-Verlag, New York. pp. 531-563.

Nelson, P.O. and R. Baumgartner. 1986. Major ions, acid-base and dissolved aluminum chemistry of selected lakes in Mount Rainier National Park. Final Report, CA-9000-3-0003, Subagreement No. 15. Oregon State University, Corvallis, OR.

Newell, A.D., C.F. Powers, and S.J. Christie. 1987. Analysis of data from long-term monitoring of lakes. EPA 600/4-87/014. U.S. Environmental Protection Agency, Corvallis, OR. 150 pp.

Nilsson, J. (ed.). 1986. Critical Loads for Sulphur and Nitrogen. Miljørapport 1986:11, Nordic Council of Ministers, Copenhagen.

Nilsson, J. and P. Grennfelt (eds.). 1988. Critical Loads for Sulphur and N, Report from a workshop held at Skokloster, Sweden, 19-24 March 1988, NORD miljørapport 1988:15, Nordic Council of Ministers, Copenhagen. pp. 225-268.

Nohrstedt, H.O., M. Wedin, and K. Gerhardt. 1988. Effekter av skogsgodsling pa kvavefixerande lavar. Instituet for Skogsforbattring 4:1-29.

Norby, R.J. 1989. Foliar nitrate reductase: a marker for assimilation of atmospheric nitrogen oxides. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 245-250.

Norton, S.A., J.S. Kahl, I.J. Fernandez, J.P. Schofield, L.E. Rustad, T.A. Haines, and J. Lee. 1993. The watershed manipulation project: two-year results at the Bear Brook Watershed in Maine (BBWM). In: Rasmussen, L., T. Brydges, and P. Mathy (eds.). Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems. ECSC-EEC-EAEC, Brussels. pp. 55-63.

Oechel, W.C. and K. Van Cleve. 1986. The role of bryophytes in nutrient cycling in the taiga. In: Van Cleve, K., F.S. Chapin, P.W. Flanagan, L.A. Viereck, and C.T. Dyrness (eds.), Forest Ecosystems in the Alaskan Taiga, Springer Verlag, New York. pp. 121-137.

Oke, T.R. 1987. Boundary Layer Climates. 2nd ed. Methusen & Co., London. 435 pp.

O'Leary, D. (ed.). 1988. Air quality in the national parks. Natural Resources Report 88-1. U.S. Dept. of Interior, National Park Service, Air Quality Division.

Olson, R.K. 1992. Physiography and forest types. In: Olson, R.K., D. Binkley, and M. Böhm (eds.). 1992. The Response of Western Forests to Air Pollution. Ecological Studies, Vol. 97, Springer-Verlag, New York. pp. 7-40.

Olson, R.K., D. Binkley, and M. Böhm (eds.). 1992. The Response of Western Forests to Air Pollution. Ecological Studies, Vol. 97, Springer-Verlag, New York. 532 p.

Oregon Department of Environmental Quality. 1993. 1992 Oregon Air Quality Annual Report. Air Quality Control Division. Portland, OR.

Pankratz, D. and J. Zwicker. 1987. Nitrate sampling in Shenandoah, Mt. Rainier, and Rocky Mountain National Parks. Report 87/688 to National Park Service, Air Quality Division, Lakewood, CO.

Patmont, C.R., G.J. Pelletier, E.B. Welch, D. Banton, and C.C. Ebbesmeyer. 1989. Lake Chelan Water Quality Assessment. Washington State Department of Ecology.

Patterson, M.T. and P.W. Rundell. 1989. Seasonal physiological responses of ozone stressed Jeffrey pine in Sequoia National Park, CA. In: Olson, R.K. and A.S. Lefohns (eds.). Transactions, symposium on the effects of air pollution on western forests. Air and Waste Management Association, Pittsburgh, PA. pp. 419-427.

Peakall, D.B. 1992. Animal Biomarkers as Pollution Indicators. Ecological Series 1. Chapman & Hall, London.

Pearson, L.C. 1990. Craters of the Moon lichen project. Report to the National Park Service.

Pearson, L.C. 1993. Active monitoring. In: Huckaby, L.S. (ed.) Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 89-95.

Pearson, L.C. and G.A. Rodgers. 1982. Air pollution damage to cell membranes in lichens, III. Field Experiments. Phyton. 22:329-337.

Peterson, B.J. and B. Fry. 1987. Stable isotopes in ecosystem studies. Ann. Rev. Ecol. Syst. 18:293-320.

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

Peterson, D.L., M.J. Arbaugh, V.A. Wakefield, and P.R. Miller. 1987. Evidence of growth reduction in ozone-stressed Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in Sequoia and Kings Canyon National Parks. J. Air Pollut. Contr. Assoc. 37:906-912.

Peterson, D.L., D.L. Schmoldt, J.M. Eilers, R.W. Fisher, and R.D. Doty. 1992b. Guidelines for evaluating air pollution impacts on class I wilderness areas in California. USDA Forest Service, Pacific Southwest Research Station, Gen. Tech. Rep. PSW-GTR-136. 34 pp.

Peterson, J., D. Schmoldt, D. Peterson, J. Eilers, R. Fisher, and R. Bachman. 1992a. Guidelines for evaluating air pollution impacts on class I wilderness areas in the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-299. USDA Forest Serv., Portland, OR. 83 pp.

Pitkin, P.H. 1975. Aspects of the ecology and distribution of some widespread corticolous bryophytes. Unpl. PhD Thesis., Oxford.

Placet, M., R.E. Gattye, F.C. Fehsenfeld, and G.W. Bassett. 1990. Emissions involved in acidic deposition processes. State of Science and Technology Report 1, National Acid Precipitation Assessment Program, Washington, DC.

Pronos, J. and D.R. Vogler. 1981. Assessment of ozone injury to pines in the southern Sierra Nevada, 1979-1980. USDA Forest Service Southwest Regional Forest Pest Management Report 81-20. Pacific Southwest Region, U.S. Forest Service, San Francisco, CA.

Pronos, J., D.V. Vogler, and R.S. Smith. 1978. An evaluation of ozone injury to pines in the southern Sierra Nevada. USDA Forest Service, Pacific Southwest Region Forest Pest Management Report 78-1. San Francisco, CA.

Reich, P.B. 1987. Quantifying plant response to ozone: a unifying theory. Tree Phys. 3:63-91.

Reilly, J.F. 1989. A chemical mass balance of Crater Lake, Oregon. Master's Project, Dept. of Civil Engineering, Oregon State University, Corvallis, OR.

Rhoades, F.M. 1985. Re-examination of baseline plots to determine effects of air quality on lichens and bryophytes in Olympic National Park. CX-0001-4-0057. Northrop Services, Inc., Research Triangle Park, NC.

Rhoades, F.M. 1988. Re-examination of baseline plots to determine effects of air quality on lichens and bryophytes in Olympic National Park. SP-4450-88-13. Northrop Services, Inc., Research Triangle Park, NC.

Richards, J.H. 1989. Evaluation of root growth and functioning of trees exposed to air pollutants. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 169-181.

Richardson, C.J., R.T. DiGiulio, and N.E. Tandy. 1989. Free radical processes as markers of air pollution stress in trees. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 251-260.

Richardson, D.H.S., and E. Nieboer. 1983. Ecophysiological responses of lichens to sulphur dioxide. Journal of the Hattori Botanical Laboratory 54:331-351.

RMCC. 1986. Assessment of the state of knowledge on the long-range transport of air pollutants and acid deposition. Part 3. Aquatic effects. Federal-Provincial Research and Monitoring Coordinating Committee, Ottawa, Ontario.

RMCC. 1990. Report of the Federal-Provincial Research and Monitoring Coordinating Committee, Ottawa, Ontario.

Rochefort, R.M. 1986. Mount Rainier Rare Plant Program. Intraagency Memo.

Rock, B.N., J.E. Vogelmann, and N.J. Defoe. 1989. The use of remote sensing for the study of air pollution effects in forests. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 183-194.

Rosén, K., P. Gundersen, L. Tagnhammar, M. Johansson, and T. Frogner. 1992. Nitrogen enrichment of Nordic forest ecosystems. The concept of critical loads. Ambio 21(5):364-368.

Ross, L.J. and T.H. Nash III. 1983. Effect of ozone on gross photosynthesis of lichens. Environ. and Exper. Bot. 23:171-177.

Ruggiero, L. 1991. Wildlife and vegetation of unmanaged Douglas-fir forests. Pacific Northwest Research Station, USDA-Forest Service, General Technical Report PNW-GTR-285.

Ruggiero, L.F., K.B. Aubrey, A.B. Carey, and M.H. Huff. 1991. Wildlife and vegetation of unmanaged Douglas-fir forests. USDA Forest Service Pacific Northwest Research Station, General Technical Report GTR-285. 533 pp.

Rundel, P.W. 1978. The ecological role of secondary lichen substances. Biochem. Syst. Ecol. 6:157-170.

Schermerhorn, V. 1967. Relations between topography and annual precipitation in western Oregon and Washington. Wat. Resour. Res. 3:707-711.

Schofield, W.B. 1992. Bryophyte distribution patterns. In: Bates, J.W. and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Clarendon Press, New York. pp. 103-130.

Schulze, E.-D., W. de Vries, M. Hauhs, K. Rosén, L. Rasmussen, C.O. Tamm, and J. Nilsson. 1989. Critical loads for nitrogen deposition on forest ecosystems. Water Air Soil Pollut. 48:451-456.

Schuster, R. M. 1984. Evolution, phylogeny and classification of the Hepaticae. In: Schuster, R.M. (ed.). New Manual of Bryology, Vol. 2. Hattori Botanical Laboratory, Nichinan. pp. 892-1070.

Schutt, P. 1989. Symptoms as bioindicators of decline in European forests. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 119-126.

Schwoegler, B. and M. McClintock. 1981. Weather and Energy. McGraw-Hill, Inc. 230 pp.

Scott, B.C. 1981. Sulfate washout ratios in winter storms. J. Appl. Meteor. 20:619-625.

Scott, J.M., F. Davis, B. Csuti, B. Butterfield, R. Noss, S. Caicco, H. Anderson, J. Ulliman, F. D'Erchia, and C. Groves. 1990. Gap Analysis: Protecting Biodiversity Using Geographic Information Systems. Handbook prepared for a workshop held at the University of Idaho, October 29-31, 1990. USFWS, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho.

Scott, M.G. and T.C. Hutchinson. 1987. Effects of a simulated acid rain episode on photosynthesis and recovery in the caribou-forage lichens, *Cladina stellaris* (Opiz.) Brodo. and *Cladina rangiferina* (L.) Wigg. New Phytol. 107:567-575.

Scott, M.G. and T.C. Hutchinson. 1989. Experiments and observations of Epiphytic lichens as early warning sentinels of forest decline. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 205-216.

Seaward, M.R.D. 1988. Contributions of lichens to ecosystems. In: Galun, M. (ed.). CRC Handbook of Lichenology, II, CRC Press Boca Raton , Florida, USA. pp. 107-129.

Sehmel, G.A. 1980. Particle and gas dry deposition: a review. Atmos. Environ. 14:983-1011.

Sharpe, P.J.H. and R.D. Spence. 1989. Biologic markers: new and emerging techniques. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 81-88.

Sheridan, R.P. and R. Rosentreter. 1973. The effect of hydrogen ion concentration in simulated rain on the moss Tortula ruralis (Hedw.) Sm. The Bryologist 76:168-173.

Shortle, W.C. 1989. Metals in roots, stem, and foliage of forest trees. Biologic markers. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 275-279.

Showman, R.E. 1973. The foliose and fruticose lichen flora of the Ohio River Valley between Gallipolis, Ohio and Parkersburg, West Virginia. Ohio Journal of Science 73:357-363.

Showman, R.E. 1975. Lichens as indicators of air quality around a coal-fired power generating plant. The Bryologist 78:1-6.

Showman, R.E. 1981. Lichen recolonization following air quality improvement. The Bryologist 84:492-497.

Showman, R.E. 1988. Mapping air quality with lichens, the North American experience. In: Nash, T.H. and V. Wirth (eds.). Lichens, Bryophytes and Air Quality. Bibliotheca Lichenologica 30. J. Cramer, Berlin. pp. 67-89.

Showman, R.E. 1990. Lichen recolonization in the upper Ohio River Valley. The Bryologist 93:427-428.

Shugart, H. H. 1984. A theory of forest dynamics. Springer-Verlag, New York.

Sidle, W.C. 1979. Geology of north Craters of the Moon National Monument, Idaho. M.S. Thesis, Portland State University, Portland, OR. 65 pp.

Sierra Club. 1985. Guide to the National Parks. Stewart, Tabori, and Chang, New York.

Sigal, L.L. and T.H. Nash. 1983. Lichen communities on conifers in southern California mountains: an ecological survey relative to oxidant air pollution. Ecology 64:1343-1354.

Sisler, J.F., D. Huffman, and D.A. Latimer. 1993. Spatial and temporal patterns and the chemical composition of the haze in the United States: An analysis of data from the IMPROVE Network, 1988-1991. Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins.

Sisterson, D.L., V.C. Bowersox, T.P. Meyers, A.R. Olsen, and R.J. Vong. 1990. Deposition Monitoring: Methods and Results. State of Science and Technology Report 6. National Acid Precipitation Assessment Program, Washington, DC.

Skeffington, R.A. and E.J. Wilson. 1988. Excess nitrogen deposition: issues for consideration. Environ. Pollut. 54:159-184.

Smayda, T.J. 1986. Acid precipitation and Cascade Mountain Lakes: effect of lake flushing rate on temporal variation in chemical content. M.S.E. Thesis, University of Washington, Seattle. 104 pp.

Smith, B.C. and J.A. Henderson. 1986. Baseline vegetation survey of the Hoh and Dosewallips drainages, Olympic National Park, Washington. Report to the National Park Service, contract CY-9000-7-0063. 439 pp.

Smith, C., L. Geiser, L. Gough, B. McCune, B. Ryan, and R. Showman. 1993. Species and communities. In: Huckaby, L.S. (ed.). Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 41-66.

Smith F.B. and A.D. Hunt. 1978. Meteorological aspects of the transport of pollution over long distances. Atmos. Environ. 12:461-478.

Smith, W.H. 1984. Ecosystem pathology: a new perspective for phytopathology. For. Ecol. and Mgmt. 9:193-219.

Smith, W.H. 1990. Air Pollution and Forests - Interactions Between Air Contaminants and Forest Ecosystems. Springer-Verlag, New York. 618 p.

Sochting, U. and I. Johnsen. 1990. Overvagning af de danske likenheder. URT 14. argang. 1990:4-9.

Soderstrom, L. 1992. Invasions and range expansions and contractions of bryophytes. In: Bates, J.W. and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Clarendon Press, New York, USA. pp. 131-158.

Stanosz, G.R., V.L. Smith, and R.I. Bruck. 1987. Effect of ozone on colonization of disturbed forest soil by moss. Phytopathology 77:1727-1728.

Starkey, E.E., J.F. Franklin, and J.W. Matthews. 1982. Ecological Research in National Parks of the Pacific Northwest. Forest Research Laboratory, Oregon State University, Corvallis, Oregon.

Stearns, H.T. 1928. Craters of the Moon National Monument, Idaho. Idaho Bur. of Mines and Geol. Bull. No. 13. 57 pp.

Stearns, H.T. 1963. Geology of the Craters of the Moon National Monument, Idaho. Craters of the Moon Natural History Assoc., Arco, ID. 34 pp.

Stoddard, J.L. 1994. Long-term changes in watershed retention of nitrogen: its causes and aquatic consequences. In: Baker, L.A. (ed.). Environmental Chemistry of Lakes and Reservoirs. Advances in Chemistry Series, No. 237, American Chemical Society, Washington, DC. pp. 223-284.

Stolte, K., R. Doty, K. Tonnessen, and R. Fisher. 1993a. Lessons from several case studies. In: Huckaby, L.S. (ed.). Lichens as Bioindicators of Air Quality. USDA Forest Service, General Technical Report RM-224. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 116-127.

Stolte, K., S. Pittam, and R. Rosentreter. 1993b. Site Characterization. In: Stolte, K. et al. (eds.). Lichens as bioindicators of air quality. Rocky Mountain Forest and Range Experiment Station, USDA Forest Service. General Tech. Rept. RM-GTR-224. Fort Collins, CO. pp. 16-40.

Sullivan, T.J. 1990. Historical Changes in Surface Water Acid-Base Chemistry in Response to Acidic Deposition. State of the Science, SOS/T 11, National Acid Precipitation Assessment Program. 212 pp.

Sullivan, T.J. 1993. Whole ecosystem nitrogen effects research in Europe. Environ. Sci. Technol. 27:1482-1486.

Sullivan, T.J. and J.A. Bernert. 1990. Steady-state water chemistry methods. Critical loads calculations for selected ELS-I lakes. Report prepared for U.S. Environmental Protection Agency, Environmental Research Laboratory-Corvallis. E&S Environmental Chemistry, Inc., Corvallis, OR.

Sullivan, T.J. and J.M. Eilers. 1992. Nitrogen Effects Studies in Europe: An Evaluation of Recent and On-going Aquatic and Terrestrial Effects Research Projects. Final report to the National Acid Precipitation Assessment Program. E&S Environmental Chemistry, Inc., Corvallis, OR.

Sullivan, T.J., D.F. Charles, J.P. Smol, B.F. Cumming, A.R. Selle, D.R. Thomas, J.A. Bernert, and S.S. Dixit. 1990b. Quantification of changes in lakewater chemistry in response to acidic deposition. Nature 345:54-58.

Sullivan, T.J., B.J. Cosby, C.T. Driscoll, D.F. Charles, and H.F. Hemond. In review. Long-term environmental change: intercomparisons among paleolimnological and process-based model hindcasts of lake acidification.

Sullivan, T.J., C.L. Rose, R.E. Gilfilian, J.M. Eilers, N. van Breemen, J.A. Bernert, D. Hanson, and B.E. Queitzsch. 1990a. Nikiski Vegetation Impact Assessment. Executive Summary Report. Prepared for the Alaska Department of Environmental Conservation, Juneau, Alaska.

Sveinbjornsson, B. and W.C. Oechel. 1992. Controls on growth and productivity of bryophytes: environmental limitations under current and anticipated conditions. In: Bates, J.W. and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Clarendon Press, New York, USA. pp. 77-102.

Sverdrup, H., W. de Vries, and A. Henriksen. 1990. Mapping critical loads. Nordic Council of Ministers, Copenhagen.

Syers, J.K. and I.K. Iskandar. 1973. Pedogenetic significance of lichens. In: Amadjian, V. and M.E. Hale (eds.). The Lichens. Academic Press, New York. pp. 225-248.

Tabor, R.W. 1987. Geology of Olympic National Park. Pacific Northwest National Parks and Forests Association. Seattle.

Tanaka, W. 1979. Rare, endangered, threatened, and endemic plant species in designated places of developed areas of Mount Rainier National Park, Washington. Report to the National Park Service, Mount Rainier National Park. 11 pp.

Taylor, R.J. and M.A. Bell. 1983. Effects of SO_2 on the lichen flora in an industrial area of northwest Whatom County, Washington. Northwest Sci. 57(3):157-166.

Thomas, M.D. 1951. Gas damage to plants. Ann. Rev. Plant Physiol. 2:293-322.

Thomas, T.B. and R.L. Edmonds. 1990a. Nutrient cycling in a temperate old-growth rainforest, Hoh River, Washington. Northwest Environ. J. 6(2):436-438.

Thomas, T.B. and R.L. Edmonds. 1990b. Species influence on throughfall and stemflow chemistry in a temperate rainforest, Hoh Valley, Washington. Bull. Ecol. Soc. Amer. 71(2):61. Supplement.

Thomas, T., J.J. Rhodes, R.L. Edmonds, and T.W. Cundy. 1988. Precipitation chemistry and ecosystem function in Olympic National Park: baseline research and precipitation studies. 1987 Annual Report to the National Park Service, Seattle, WA. Coop. Agreement No. CA-9000-3-0004, subagreement No. 3, Coll. For. Res., Univ. Washington, Seattle, WA.

Thornton, K., D. Marmorek, and P. Ryan. 1990. Methods for Projecting Future Changes in Surface Water Acid-Base Chemistry. State of the Science, SOS/T 14, National Acid Precipitation Assessment Program.

Tingey, D.T. 1989. Bioindicators in air pollution research -- applications and constraints. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 73-80.

Trass, H. 1973. Lichen sensitivity to air pollution and index of paleotolerance. Folia Cryptogamica Estonia, Tartu 3:19-22.

Treshow, M., ed. 1984. Air Pollution and Plant Life. John Wiley & Sons, New York.

Turner, R.S., R.B. Cook, H. van Miegroet, D.W. Johnson, J.W. Elwood, O.P. Bricker, S.E. Lindberg, and G.M. Hornberger. 1990. Watershed and Lake Processes Affecting Chronic Surface Water Acid-Base Chemistry. State of the Science, SOS/T 10. National Acid Precipitation Assessment Program.

Turney, G.L., N.P. Dion, and S.S. Sumioka. 1986. Water quality of selected lakes in Mount Rainier National Park, Washington with respect to lake acidification. U.S. Geological Survey, Water Resources Investigations Report 85-4254. Tacoma, WA.

Ugolini, F.C. and R.L. Edmonds. 1983. Soil Biology. In: Wilding, L.P., N.E. Smeck, and G.F. Hall (eds.). Pedogenesis and Soil Taxonomy. I. Concepts and Interactions, Elsevier, Amsterdam. pp. 193-231.

Unsworth, M.H. and J.C. Wilshaw. 1989. Wet, occult, and dry deposition of pollutants on forests. Agr. and For. Meteor. 47:221-238.

Urban, D.L. 1990. A versatile model to simulate forest pattern. A user's guide to ZELIG, version 1.0. University of Virginia, Charlottesville, Virginia.

Urban, K.A. 1968. A revised checklist of plants. Craters of the Moon National Monument. Craters of the Moon Natural History Association, Arco, Idaho. 13 pp.

Urban, K.A. 1971. Common plants of Craters of the Moon National Monument. Craters of the Moon Natural History Assoc., Arco, ID. 13 pp.

U.S. Geological Survey. March 1994. News Release.

Van Haren, F. 1987. Characterization of ozone at four rural sites in western Washington. National Council for Air and Stream Improvement. Technical Bull. 495.

Vitousek, P.M. 1977. The regulation of element concentrations in mountain streams in the northeastern United States. Ecol. Monogr. 47:65-87.

Vitt, D.H. 1984. Classification of the Bryopsida. In: Schuster, R.M. (ed.). New Manual of Bryology, Vol. 2., Hattori Botanical Laboratory, Nichinan. pp. 696-759.

Vitt, D.H., J.E. Marsh, and R.B. Bovey. 1988. Mosses, Lichens, & Ferns of Northwest North America. Lone Pine Publ., Edmonton, Alberta. 296 p.

Voldner, E.C., L.A. Barrie, and A. Sirois. 1986. A literature review of dry deposition of oxides of sulfur and nitrogen with emphasis on long-range transport modeling in North America. Atmos. Environ. 20:2101-2123

von Arb, C., C. Mueller, K. Ammann, and C. Brunold. 1990. Lichen physiology and air pollution. II. Statistical analysis of the correlation between SO_2, NO_2, NO, and O_3, and chlorophyll content, net photosynthesis, sulphate uptake and protein synthesis of *Parmelia sulvata* Taylor. New Phytol. 115(3):431-437.

Vong, R.J. and P. Guttorp. 1991. Co-occurence of ozone and acidic cloudwater in high elevation forests. Environ. Sci. Tech. 25:1325-1329.

Waggoner, G. 1989. NPFLORA User's Manual for the National Park System Vascular Flora Database. Natural Resources Report. NPS-BR-89-02. National Park Service, GIS Div., Denver, CO.

Waldman, J.M., J.W. Munger, D.J. Jacob, and M.R. Hoffman. 1985. Chemical characterization of straus cloudwater and its role as a vector for pollutant deposition in a Los Angeles pine forest. Tellus 37B:91-108.

Warfvinge, P., M. Holmberg, M. Posch, and R.F. Wright. 1992. The use of dynamic models to set target loads. Ambio 21(5):369-376.

Wasem, R. 1989. Endangered, threatened & sensitive vascular plants of the North Cascades Region of Washington. North Cascades National Park Service Complex. Sedro Woolley, WA.

Washington Department of Ecology. 1988. Air Quality Program 1988 Annual Report. Olympia, WA.

Washington Department of Ecology. 1993. Air Quality Program 1993 Annual Report. Olympia, WA. 74 pp.

Washington Department of Ecology. 1994. County Emissions of Selected Sources, March 24, 1994. (Update to WDOE 1993).

Weinstein, D.A., R.M. Beloin, R.D. Yanai, and C.G. Zollweg. 1990. The response of plants to interacting stresses: TREGRO simulates the carbon, water, and nutrient balances of a plant-soil system. Vol. 1: Model version 1.73. Description and parameter requirements. Report to the Electric Power Research Institute. 46 pp.

Weinstein, L.H. 1977. Fluoride and plant life. J. Occup. Med. 19:49-78.

Weinstein, L.H. and J.A. Laurence. 1989. Indigenous and cultivated plants as bioindicators. In: Grossblatt, N. (ed.). Biological Markers of Air-Pollution Stress and Damage in Forests. National Academy Press, Washington, DC. pp. 195-204.

Westman, W.E., K.P. Preston, and L.B. Weeks. 1985. SO_2 effects on the growth of native plants, In: Winner, W.E., H.A. Mooney, and R.A. Goldstein, eds. Sulfur dioxide and vegetation. Stanford University Press, Stanford, CA.

Wetmore, C.M. 1983. Lichens of the air quality class I national parks. Report to the National Park Service. 158 pp.

Wetmore, C. 1988. Lichen floristics and air quality. In: Nash, T.H. III and V. Wirth (eds.). Lichens, bryophytes, and air quality. Bibliotheca Lichenologica. Vol. 30. J. Cramer, Berlin. pp. 55-56.

Wiersma, G.B., M.E. Harmon, G.A. Baker, and S.E. Greene. 1987. Elemental composition of *Hylocomium splendens*, Hoh Rainforest, Olympic National Park, Washington, USA. Chemosphere 16:2631-2645.

Wigington, P.J., Jr., T.D. Davies, M. Tranter, and K.N. Eshleman. 1990. Episodic acidification of surface waters due to acidic deposition. State of Science and Technology Report No. 12, National Acid Precipitation Assessment Program, Washington, DC.

Williams, M.W. and J.M. Melack. 1991a. Precipitation chemistry in and ionic loading to an alpine basin, Sierra Nevada. Water Resour. Res. 27:1563-1574.

Williams, M.W. and J.M. Melack. 1991b. Solute chemistry of snowmelt and runoff in an alpine basin, Sierra Nevada. Water Resour. Res. 27:1575-1588.

Winner, W.E. 1988. Responses of bryophytes to air pollution. In: Nash, T.H. and V. Wirth (eds). Lichens, Bryophytes, and Air Quality, Cramer, Berlin. pp. 141-173.

Winner, W.E. and J.D. Bewley. 1983. Photosynthesis and respiration of feather mosses fumigated at different hydration levels with SO2. Can. J. of Bot. 61:1456-1461.

Winner, W.E., J.D. Bewley, H.R. Krause, and H.M. Brown. 1978. Stable sulfur isotope analysis of SO_2 pollution impact on vegetation. Oecologia 36:351-361.

Woodman, J.M. and E.B. Cowling. 1987. Airborne chemicals and forest health. Environ. Sci. Tech. 21(2):120-126.

Wright, R.F., B.J. Cosby, R.C. Ferrier, A. Jenkins, and R. Harriman. In review. Changes in acidification of lochs in Galloway, southwestern Scotland. I. Regional surveys in 1979 and 1988 and evaluation of the MAGIC model.

Wright, R.F., B.J. Cosby, M.B. Flaten, and J.O. Reuss. 1990. Evaluation of an acidification model with data from manipulated catchments in Norway. Nature 345:53-55.

Wright, R.F., B.J. Cosby, G.M. Hornberger, and J.N. Galloway. 1986. Comparison of paleolimnological with MAGIC model reconstructions of water acidification. Water Air Soil Pollut. 30:367-380.

Wright, R.F., E. Lotse, and A. Semb. 1988. Reversibility of acidification shown by whole-catchment experiments. Nature 334:670-675.

Wunner, R.C. 1967. A flora of Craters of the Moon National Monument. Unpublished Report, Craters of the Moon National Monument Library. B-13. 97 pp.

Wyodoski, R.S. and R.R. Whitney. 1979. Inland Fishes of Washington. Univ. of Washington Press, Seattle, WA. 220 pp.

Xue, D. and R.B. Harrison. 1991. Sulfate, aluminum, iron, and pH relationships in four Pacific Northwest forest subsoil horizons. Soil Sci. Soc. Amer. J. 55:837-840.

VII. ACKNOWLEDGEMENTS

This report was funded through a cooperative agreement between the National Park Service and the Pacific Northwest Research Station, USDA Forest Service. The project coordinator for the project was Tonnie Maniero, National Park Service Air Quality Division. The authors thank Ms. Maniero and staff with the AQD in Denver, Colorado, for providing information on emissions in the region and constructive comments at various stages in the project. Shirley Clark, NPS, Seattle, was very helpful in coordinating local reviews with the individual parks. The NPS librarians Nancy Hori, Richard Aroksaar, and Mary Ellen Bartholomew provided assistance in locating reports and documents at the NPS regional library. Resource managers in the five study sites were very helpful in reviewing park activities related to air pollution studies and in providing comments on progress reports. The principal park contacts were Mark Buktenica (CRLA), Vicki Snitzler-Neeck (CRMO), Barbara Samora (MORA), Reed Glesne and Bob Koonce (NOCA), Shelly Sparhawk (OLYM), and Cat Hoffman (OLYM). Researchers with the Cooperative Park Studies Units were generous in supplying information on their studies and include Dr. Gary Larson (CPSU-OSU Corvallis), Dr. Gerald Wright, Jr. (CPSU-Univ. Idaho), and Dr. Dave Peterson (CPSU-UW). Dr. Kathy Tonnessen, now with the NBS, was instrumental in formulating the project scope and providing comments on progress reports.

We are indebted to a large number of scientists and agency officials through the region and Europe for sharing information on work in progress.

Jayne Charles provided the word processing support, Susan Binder assisted with preparation of figures, and data analysis runs were conducted by Joseph Bernert, all of E&S. Technical editing was kindly provided by Sandra Ernst.