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IV.NATIONAL PARKS IN THE PACIFIC NORTHWEST, CLASS I AREAS

A. CRATER LAKE NATIONAL PARK

1. Description

Crater Lake National Park was established in 1902 as America's sixth national park. Under the enabling legislation, Congress identified the need to preserve the "natural objects", including Crater Lake and the associated land.

> *Sec. 2. That the reservation established by this act shall be under the control and custody of the Secretary of the Interior, whose duty it shall be to establish rules and regulations and cause adequate measures to be taken for the preservation of the natural objects within said park, and also for the protection of the timber from wanton depredation, the preservation of all kinds of game and fish, the punishment of trespassers, the removal of unlawful occupants and intruders, and the prevention and extinguishment of forest fires. (U.S.C., title 16, sec. 122)*

Referred to as the "Jewel of the Cascades", Crater Lake resulted from an enormous volcanic eruption and collapse that occurred almost 6800 years ago. This pristine lake is now the central feature of Crater Lake National Park, situated along the crest of the Cascades in southern Oregon. With a depth of 589 m, it is the deepest lake in the United States, and the seventh deepest in the world. The vivid blue color of the lake results from the extreme depth, low organic matter, and low productivity. Hydrologic inputs occur primarily as snow and rain directly on the lake surface and springs on the side of the caldera. Water is lost only through evaporation and seepage. Park elevation varies from 1340 m at the south entrance to 2720 m at Mount Scott, a volcanic cone east of the lake.

a. Geology and Soils

The High Cascades are geologically young, with some lava flows being only several hundred years old. The most extensive deposits are gray olivine basalts and olivine-bearing andesites with subordinate amounts of dense porphyritic pyroxene andesites. Scattered over the area are younger flows comprised of andesites and basalts which are dated as upper Pleistocene and Recent epochs. The larger peaks generally are made of olivine-bearing andesite from the Pleistocene. The smaller cones, or cinder cones, are comprised of gray to red basaltic and andesitic pyroclastic rocks. Bedrock usually is obscured by a mantle of pumice and ash from several volcanic eruptions, the most recent of which was the eruption of Mount Mazama 6,600 years ago. Glacial deposits are locally abundant near the higher peaks.

Crater Lake began forming when Mount Mazama erupted, leaving a caldera from the imploded volcano. The primary rock types in the caldera are andesitic basalt. Although the volcano is not active, low-volume geothermal springs are believed to contribute to the ionic composition of Crater Lake (Larson et al. 1993). Much of the area outside the caldera is covered in ash and pumice deposited during multiple previous eruptions.

The High Cascades are dominated by immature soils developed in volcanic ejecta, and by more developed soils in glacially deposited materials. Soils on glacial till are more abundant to the north, and volcanic types are more abundant to the south.

b. Climate

The climate of Crater Lake is dominated by long winters with high snowfall, and brief, warm and sunny summers. Moist Pacific air masses moving eastward across the Cascades contribute to the prodigious snowfall, averaging 15 m annually. Long-term variations in the precipitation/evaporation regime are believed to contribute to changes in the stage of Crater Lake and may lead to other effects on the lake (Larson et al. 1993). There is a pronounced decrease in precipitation across the lake from west to east. This climatic variation across the lake complicates efforts to develop hydrologic and chemical mass balances of the lake.

c. Biota

Excluding the Pumice Desert in the northern part of the park, conifer forests blanket most of the landscape. Four general vegetation zones are recognized within the park. The lowest elevations on the west side, in the mixed conifers vegetation zone, is dominated by ponderosa pine (*Pinus ponderosa*), with variable proportions of sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), and Douglas-fir (*Pseudotsuga menziesii*). At higher elevations are found mixed forests of Shasta red fir (*Abies magnifica*), lodgepole pine (*Pinus contorta*), and mountain hemlock (*Tsuga mertensiana*). Near the crater rim, dense stands of mountain hemlock and Shasta red fir are found. Still higher on the northern rim and the summit of Mount Scott, are the gnarled whitebark pines (*Pinus albicaulis*) of the subalpine zone. Occasional deciduous trees include big leaf maple (*Acer macrophyllum*) and aspen (*Populus tremuloides*). Wildflowers in meadows and snowfields in forest openings offer a spectacular, but brief, show at higher elevations. Nearly all of the 600 plant species that have been inventoried in the Park have colonized the area since the volcanic eruption. A comprehensive listing of park flora is available through the NPFLORA database (Waggoner 1989). There are currently no plant species in Crater Lake listed as Threatened or Endangered by the USFWS. Species that are under consideration for Federal listing include pumice grapefern (*Botrychium pumicola*), Mount Mazama collomia (*Collomia mazama*), and Crater Lake rockcress (*Arabis suffrutencens* var. *horizontalis*). Species listed by the State as Threatened include Tepson's monkeyflower (*Mimulus jepsonii*), Cascade fleabane (*Erigeron cascadensis*), sticky arnica (*Arnica viscosa*). Wetmore (1983) made a cursory survey of lichens in the park. Additional herbarium collections are made periodically by park personnel.

Sixty mammal species are present in the park, the largest being black bear and elk. Other common mammal species include marmots, pikas, and chipmunks. Many bird species visit the park seasonally, but only a few of the hardiest species such as jays, grouse, and chickadees are year-round residents. Golden and bald eagles are seen occasionally near the caldera rim, though sightings are becoming less frequent.

d. Aquatic Resources

The primary aquatic resource of CRLA is Crater Lake itself. The lake is renowned for its deep blue apparent color resulting from its tremendous clarity. Secchi disk transparency values of 40 m have been recorded, although more typical values range from 25 to 35 m (Larson et al. 1993). There are no surface outlets from Crater Lake, although over 40 ephemeral inlets are present in the caldera.

Table 7. Emissions for counties adjacent to Crater Lake National Park in 1992 (see Figure 6 for county locations). Units are in tons/yr.

County	PM_{10}	SO_x	NO_x	CO	VOC
Douglas	12,409	2,404	16,006	76,654	9,464
Jackson	8,227	2,742	10,183	81,352	11,760
Klamath	10,118	1,849	9,325	76,267	7,508
Josephine	2,902	1,278	5,247	28,473	4,243
Coos	5,424	1,310	4,921	47,240	4,901
Southwest Oregon	39,080	9,583	45,682	309,986	37,876

Source: ODEQ (1993)

2. Emissions

Emissions of air pollutants throughout Oregon are low and are particularly low in the southwestern portion of the State (Table 7, Figure 6). Three of the four cities in the region (Grants Pass, Medford, and Klamath Falls) are nonattainment areas because of exceedances of PM_{10}. No other air quality violations were recorded in the region. Carbon monoxide standards were exceeded in Medford and Grants Pass during the 1980s but were within acceptable levels in 1992. In summary, the emissions within the vicinity of Crater Lake are comparatively low and widely dispersed.

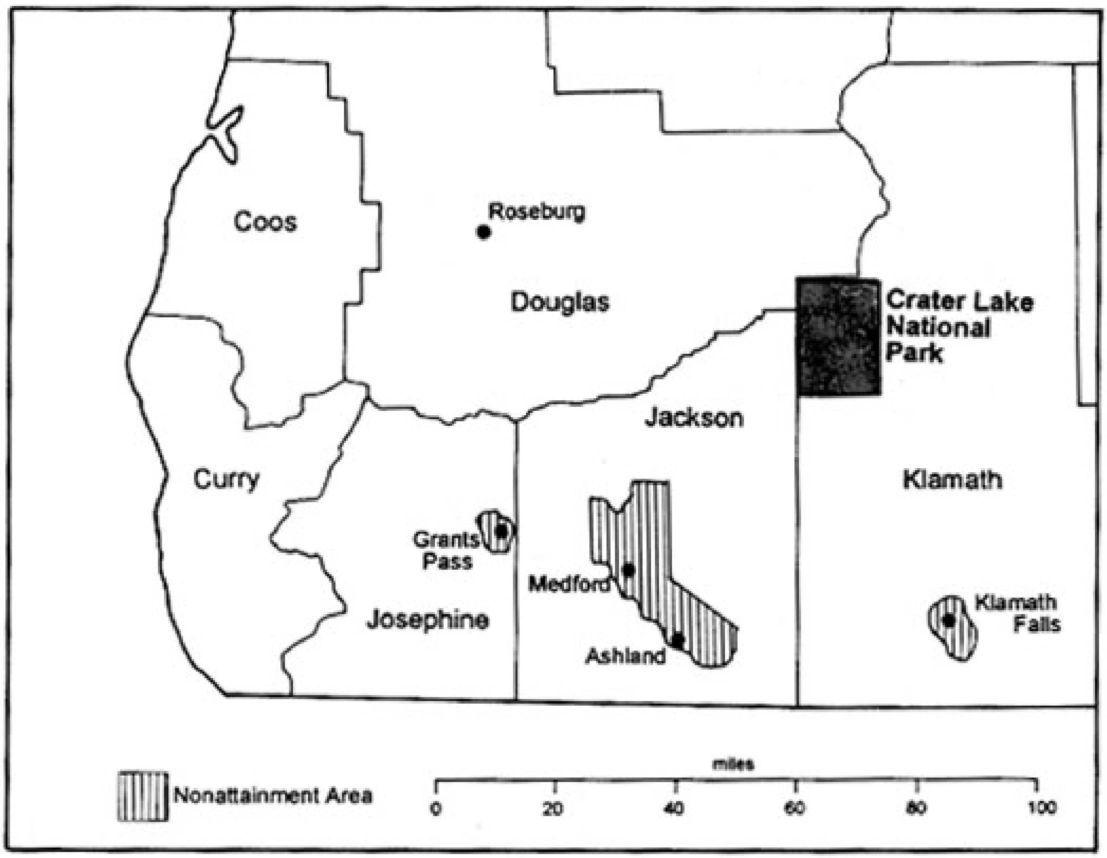

Figure 6. Crater Lake National Park and urban areas in southwestern Oregon. Nonattainment areas outside the park are shaded with vertical lines (redrafted from ODEQ 1993).

Figure 6.Crater Lake National Park and urban areas in southwestern Oregon. Nonattainment areas outside the park are shaded with vertical lines (redrafted from ODEQ 1993).

3. Current Monitoring and Research Activities

a. <u>Air Quality/Deposition</u>

(i) Wet Deposition

The closest NADP/NTN monitoring site to Crater Lake is located at Silver Lake Ranger Station about 80 km east of CRLA, although the Silver Lake site is arid (measured precipitation in 1990 was 19.9 cm). The H.J. Andrews Experimental Station about 120 km to the northwest is more representative of conditions at CRLA.

Precipitation chemistry at the H.J. Andrews site is low in concentrations of sulfate, nitrate, ammonium, and hydrogen ion (Table 8). These data reflect the low-population density and minimal industrial activity in central and southwestern Oregon. The monitoring site is over 1400 m lower in elevation than Crater Lake. Consequently, there is reasonable uncertainty regarding estimates of deposition chemistry at the lake that are derived from the H.J. Andrews monitoring site.

The only deposition chemistry measured to date at Crater Lake is bulk deposition collected at the caldera rim just north of the park headquarters from January 1987 through September 1988 (Reilly 1989). The results of analyses of these data show low concentrations of nitrogen but much higher concentrations of sulfate than that measured at H.J. Andrews (Table 9). The Cl^- concentrations also are surprisingly high in these samples, given the elevation of the site, the distance from the ocean, and the comparatively low Na^+ values. The predicted [Na^+] for these Cl^- data would be 8.9 μeq/L. Reilly (1989) noted some analytical uncertainty in these data that may explain the discrepancies.

Table 9. Solute component concentrations (mg/L) for precipitation, Crater Lake. Microequivalents per liter are shown in parentheses for major ions (Source: Reilly 1989)

Parameter	Concentration[a]
TKN	0.066
NH_3-N	0.025 (1.8)
NO_3-N	0.036 (2.6)
P	0.005
PO_4-P	0.005
SO_4	0.362 (7.5)
Cl	0.375 (10.6)
Ca	0.093 (4.6)
Mg	0.024 (2.0)
K	0.067 (1.7)
Na	0.072 (3.1)
Si	0
B	0
HCO_3	0
SO_4^*	(6.4)

[a] Annual volume-weighted mean

Snow samples collected at three locations in the park by Laird et al. (1986) showed lower concentrations of most analytes (Table 10), as compared with the data of Reilly (1989). Snow chemistry is expected to be more dilute than rainfall at a given site; however, the magnitude of the difference between the snow data and the bulk deposition data suggests that the concentrations of major ions reported by Reilly (1989) may be slightly overestimated.

Table 10. Snow chemistry (µeq/L) for CRLA based on an average of data from three sites sampled by Laird et al. (1986).

Parameter	Concentration
H^+	2.5
Ca^{2+}	2.3
Mg^{2+}	0.2
K^+	0.3
Na^+	2.6
NH_4^-	1.0[a]
NO_3^-	1.3
Cl^-	1.5
SO_4^{2-}	1.5
SO_4^*	1.3

[a] NH_4^+ was reported at concentrations much greater than could be supported on the basis of regional sources of NH_3 emissions (Eilers 1991). The NH_4^+ value was set to 1 µeq/L for this presentation.

(ii) Occult/Dry Deposition

Dry deposition was not measured directly but was included in the bulk deposition container for those periods that did not receive precipitation (Reilly 1989). The results are probably an underestimate of dry deposition because of the method of collection, but they provide some insight into the potential importance of dry deposition at this site (Table 9). For example, precipitation-weight SO_4^{2-} concentrations at the H.J. Andrews Experimental Forest NADP/NTN site for 1990-1992 ranged from 3.5 to 4.0 µeq/L compared to 7.5 µeq/L for SO_4^{2-} measured in bulk deposition at Crater Lake.

(iii) Gaseous Monitoring

No gaseous monitoring is being conducted in the park. The nearest gaseous monitoring station is located at Medford, Oregon. At this site, 5% of the hourly O_3 values were at 60 ppb or higher; 1% were > 80 ppb. These data, however, probably do not reflect ambient O_3 values at CRLA (ODEQ 1993).

Table 11 (also see Figures 7 and 8) summarizes gaseous monitoring data from the EPA AIRS monitoring sites in Oregon during 1985-1992. Ozone concentrations throughout the region were

Table 11.Summary of ozone data from the EPA AIRS (Aerometric Information Retrieval System) monitoring sites within 100 km of the class I national park in Oregon during the period 1985-1992. Sites are identified in Figures 7 and 8.

	1-hour Maximum (ppb)							
Site #	1985	1986	1987	1988	1989	1990	1991	1992
41-029-0010	98	105	94	122	91	97	73	115
41-029-0201	-	-	-	-	-	-	-	115
41-039-0060	89	93	120	146*1	84	-	89	99
41-039-1007	103	107	114	118	89	92	94	103

*(#) - Number of exceedances of primary standards (NAAQS) for a pollutant (see Table 1).

generally low. One exceedance of the primary ozone standards was recorded near Eugene in 1988. No data were available on sulfur dioxide, and limited data on nitrogen dioxide did not exceed the primary standard from 1985-1987. These data do not indicate a significant threat to CRLA from gaseous pollutants at the present time.

(iv) Particulates

Crater Lake is an IMPROVE site, and for the period March 1988-February 1991, the concentrations of coarse particle mass, fine sulfate aerosols, and fine nitrate aerosols were the lowest among the sites in the contiguous United States (Sisler et al. 1993). Organic carbon contributed most of the fine particle mass. Fine soil aerosol concentrations were moderate at CRLA.

(v) Trace Metals/Toxics Deposition

No information regarding deposition of trace contaminants has been reported for the park, although lake sediment samples have been collected and are available for analysis (G. Larson, pers. comm.). Recent data on Hg concentrations in fish from Paulina and East Lakes in the Newberry Crater (located about 100 km NE of Crater Lake) show that axial muscle tissue in older

Figure 7. Location of EPA AIRS monitoring sites within the states of Washington, Oregon, and Idaho.

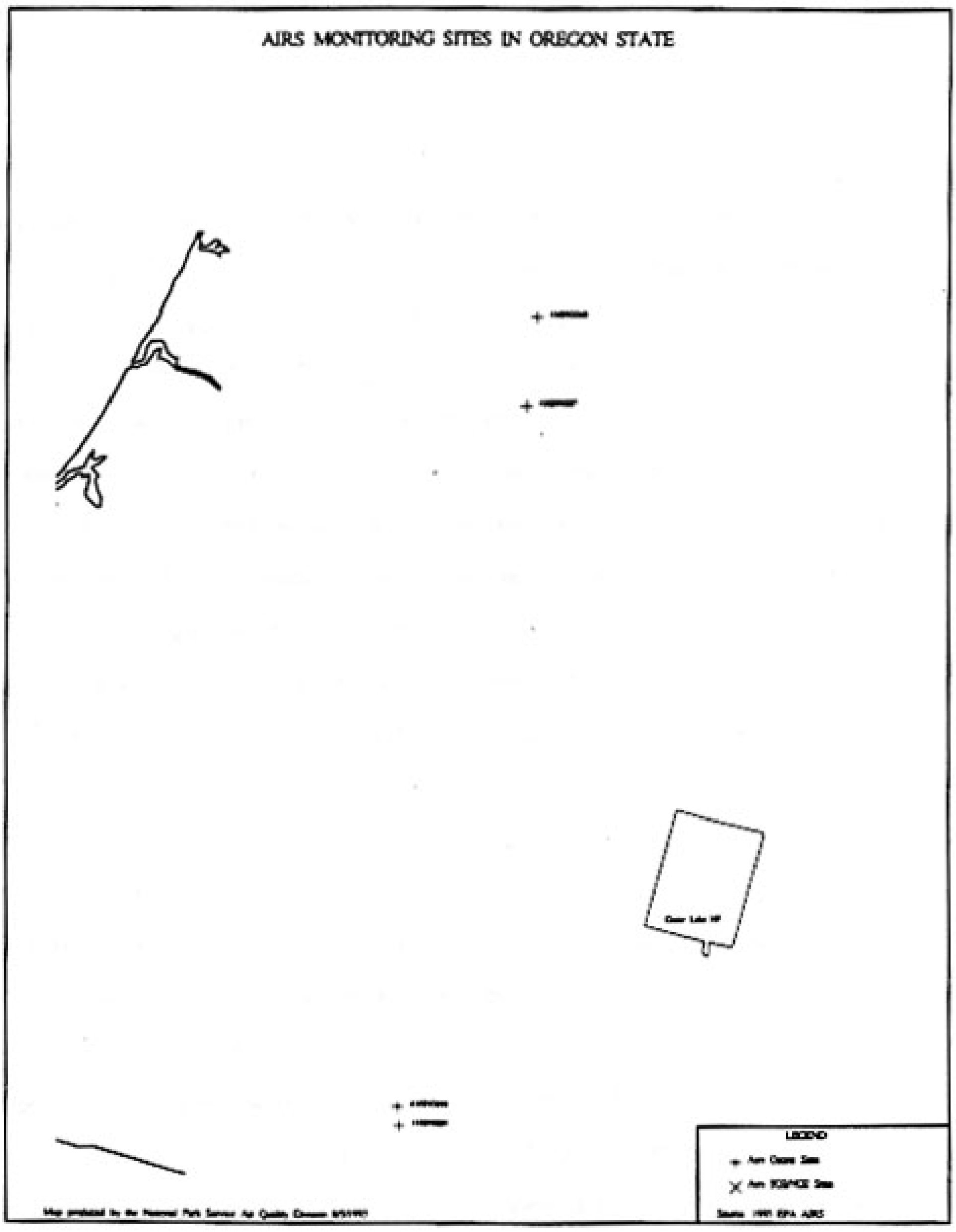

Figure 8. Location of EPA AIRS monitoring sites within the state of Oregon.

Figure 8.Location of EPA AIRS monitoring sites within the state of Oregon.

fish exceed recommended values for human consumption (USGS, unpublished data). The relation between deposition of Hg and the concentrations of Hg in the fish at Newberry Crater is unknown.

b. Water Quality

Crater Lake is the site of a 10-year research program (1982-1992) designed to assess status and trends in water quality (Larson et al. 1993). Crater Lake, relative to other lakes in the Cascades, is a high alkalinity system (ANC = 700 μeq/L) that is extremely well buffered against any realistic future acidic deposition scenario. Analyses of nutrient profiles, however, reveal a depletion of nitrogen in the water column, thereby suggesting that Crater Lake is nitrogen-limited (Larson et al. 1993) and thus may be sensitive to increased loading of nitrogen. The lake area represents about 80% of the watershed, and thus most of the nitrogen inputs are not lost to terrestrial systems as is the case in many other lakes in the forested ecosystems. Atmospheric deposition currently represents the majority of N input to the lake, and relatively small changes in N concentrations in the deposition could conceivably increase the productivity of the lake. Increased lake productivity would cause a decrease in lakewater transparency, which is an important resource value of the park.

c. Terrestrial

A partial species inventory of the park vascular flora is maintained on the NPFLORA database (Waggoner 1989). Lichen and bryophyte diversity is partially documented in an herbarium collection.

Species lists for park fauna are fairly complete and periodically updated. On-going projects include amphibian surveys and monitoring of peregrine falcon populations. Planned studies include monitoring of T&E species and surveys of small mammals and spotted owls.

The geology of the area was discussed in detail by Harris (1990). Specific information on soils of the park is not currently available. No studies of air quality effects on terrestrial ecosystems have been conducted or are currently underway.

4.Sensitive Receptors

The review of relevant literature that formed the basis for these recommendations is presented in Appendix D.

a. Aquatic

The most sensitive receptor for the aquatic component of CRLA resources is the transparency of Crater Lake. The lake is well-buffered from changes in acid-base chemistry, and acidification from atmospheric sources is not a concern. The lake transparency is influenced to a large degree by primary productivity, and an increase in nutrient loading (especially N) would therefore be cause for concern.

b. Terrestrial

With regard to ambient air quality in the Pacific Northwest, sulfur and nitrogen deposition presently are too low to cause much concern about effects on terrestrial resources. Regionally, the highest potential for air quality to impact terrestrial resources is associated with ozone near industrialized urban areas and rural areas downwind. To date, there has been no research to determine the effects of ozone on terrestrial resources in CRLA. Consequently, this assessment of potentially sensitive species in the park is based on research conducted in other ecosystems, on related species or taxa of organisms.

Much of the research effort over the past 50 years to document air quality effects on terrestrial vegetation has focussed on documenting forest growth and physiological condition in relation to "forest decline", and on establishing dose-response functions for economically important tree species (Smith 1990). Less effort has been directed to the study of mosses and lichens, except near heavily polluted areas of Great Britain, Europe and Canada (Bates and Farmer 1992). There are only a few studies of the effects of pollutants on lichens in the Pacific Northwest (Denison and Carpenter 1973, Hoffman 1974, Denison et al. 1977, Johnson 1979, Taylor and Bell 1983, Blesdoe et al. 1985, Rhoades 1988). Physiological studies of dose-response functions have yielded the most conclusive results, but the high cost of these studies has limited their applicability.

More information is available on ozone effects than on N and S effects. The most comprehensive ozone research has been conducted in the mixed-conifer forest and other vegetation types of California, on the dominant, commercially important tree species (Miller et al. 1989; Peterson et al. 1987, 1991, 1992 a,b; Horner and Peterson 1993). Few data are available to relate ozone dose or exposure to mature trees, and almost no data for herbaceous species are available.

A provisional list of potentially sensitive vascular plant species indigenous to CRLA is presented in Table 12. A listing for lichen and moss species is provided in Table 13. This list of potentially sensitive species is only a preliminary compilation of known or suspected sensitive plants. The information should be viewed as largely preliminary, due to the limited database. Sensitivity classes for vascular plants, lichens, and bryophytes have been developed to summarize the high variability in response to different pollutants that has been documented within plant species. The wide range of variability in plant responses to pollutants is attributable to differences in research methodology, environmental conditions, and to natural variability in species sensitivity. Specific values for pollutant sensitivity are listed where data exist. The application of much of this sensitivity data to the Pacific Northwest must be undertaken with caution because the data are mostly from laboratory fumigation experiments on seedlings and have not been field tested on mature trees. The reliability of extrapolating pollutant responses from the laboratory to the field and from seedlings to mature trees is questionable, and studies

Table 12. Partial list of potentially sensitive plant species in CRLA.

		Sensitivity[a]		
Common Name	Scientific Name	Ozone[b]	Sulfur	Nitrogen
White fir *Abies concolor*	L/M	M/H	H	
Rocky Mountain maple	*Acer glabrum*	X	M	UK
Bigtooth maple	*Acer macrophyllum*	X	UK	UK
Alders *Alnus* species	L/M (120-300 ppb)	H	UK	
Junipers *Juniperus* species	L	L	UK	
Incense cedar	*Libocedrus decurrens*	L/M	UK	UK
Honeysuckle (twinberry)	*Lonicera involucrata*	L	UK	UK
(Utah honeysuckle)	*Lonicera utahensis*	X	UK	UK
Lupines	*Lupinus* species	X	UK	UK
Engelmann spruce	*Picea engelmannii*	UK	M	UK
Lodgepole pine	*Pinus contorta*	M (100 ppb)	M (SO_2 40 ppb)	H
Limber pine	*Pinus flexilis*	UK	L	UK
Sugar pine *Pinus lambertiana*	X	UK	UK	
W. white pine	*Pinus monticola*	M (100 ppb)	M	UK
Ponderosa pine	*Pinus ponderosa*	H (80-100 ppb)	M/H (SO_2, 40 ppb)	H
Balsam poplar	*Populus balsamifera trichocarpa*	H	M	UK
Quaking aspen	*Populus tremula tremuloides*	H (40 ppb)	H	UK
Choke cherry	*Prunus virginiana*	X	M	UK
also *Prunus emarginata*	X	M	UK	
Douglas-fir *Pseudotsuga menziesii*	L/M (100 ppb)	M/H SO_2,	H 65 ppb)	
Golden currant	*Ribes cereum*	X	UK	UK
Blueberried elder	*Sambucus caerulea*	X	UK	UK
Pacific yew	*Taxus brevifolia*	UK	L	UK
Western hemlock	*Tsuga heterophylla*	UK	M	UK
Mountain hemlock	*Tsuga mertensiana*	UK	H	UK
Big huckleberry	*Vaccinium membranaceum*	X	UK	UK
Western bog blueberry	*Vaccinium occidentale*	X	UK	UK

[a]X = known or suspected; H = high; M = moderate; L = low; UK = unknown sensitivity.
[b]A general range of sensitivities to ozone is 60-90 ppb for conifers, 70-120 ppb for hardwoods, 7-h growing season means.

Source: Esserlieu and Olson (1986); Lefohn 1992; Peterson et al. (1992a,b); Horner and Peterson (1993); Forest Health Monitoring Program (1993)

Table 13. Partial list of lichen and moss species that have documented responses to pollutants.

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Alectoria sarmentosa*	L	O_3 (H) PAN	F	CA, USA	3,5	Sigal and Nash (1983)
- *Bryoria abbreviata* *B. fremontii* *B. oregana*	L	O_3 (H) PAN	F	CA, USA	1,2,3,4 1,2,3,4,5 1,3	Sigal and Nash (1983)
- *Calicium viride*	L	O_3 (H) PAN SO_2 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
- *Cetraria islandica*	L	NH_4 NO_3 O_3 (H) SO_2 (M) F (M)	F	SWED	1,2,3,4,5	Gerhardt and Kellner (1986)
C. canadensis	L	O_3 (H) PAN	F	CA, USA	2,4	Sigal and Nash (1983)
- *Cladina portentosa*	L	NO_x	F	NETH	1	Sochting and Johnsen (1990)
C. rangiferina	L	NH_4 SO_2 (M-H) F (M) NO_3	F	SWED	1,3,4,5	Gerhardt and Kellner (1986)
		HNO_3	F	FRG, USA CAN		Scott and Hutchinson (1989)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
C. stellaris	L	H^+	L		4	Lechowicz (1982)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
- *Evernia prunastri*	L	O_3 (H)	F	CA, USA	1,3,4,5	Sigal and Nash (1983)
		PAN F (H)	L, F	CA, USA		Nash (1988)
		S	F			
		SO_2 (3.0 ppb,	F	USA		Johnson (1979)

		L-M)				
- *Hylocomium splendens*	M	H^+ SO_2 (H) F (M)	F	UK	1,3,4,5	Farmer et al. (1992a)
- *Hypogymnia enteromorpha*	L	O_3 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
		PAN	L, F			Nash (1988)
		O_3 (800 ppb, L-M) SO_2 (L-M)	L			Nash and Sigal (1979)

Table 13. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Isothecium myosuroides*	M	H^+	F	UK	1,3,4,5	Pitkin (1975)
- *Lobaria pulmonaria*	L	O_3 (L-M) H^+	F	UK	1,2,3,4,5	Gilbert (1986)
		H_2SO_4 SO_2 (H)				Denison et al. (1977)
- *Nephroma arcticum*	L	NH_4^+ O_3 (H) SO_2 (H) NO_x PAN (H)	L, F	SWED	3	Nohrstedt et al. (1988)
- *Parmelia caperata*	L	SO_2	F	UK	1,2,3,4,5	Gilbert (1992)
		O_3 (800 ppb) PAN	L			Nash and Sigal (1979)
		O_3 (200 ppb)				Ross and Nash (1983)
P. sulcata	L	NO_x PAN (M-H) SO_2 (70 ppb, L-H) F (M-H)	L, F	SWED	1,2,3,4,5	von Arb et al. (1990)
		O_3 (500 ppb, M-H)	L			Nash and Sigal (1979)
- *Peltigera aphthosa polydactyla*	L	H^+ O_3 (H) SO_2 (M) NO_x/PAN (M-H)	L		1,2,3,4,5	Fritz-Sheridan (1985)
	L	NH_4^+ SO_2 (M)	L, F	SWED		Nohrsted et al. (1988)
- *Physodes* species	L	SO_2 SO_4 NO TM		FRG, USA CAN	1,2,3,4,5	Scott and Hutchinson (1989)
- *Platismatia glauca*	L	O_3 (H)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)

		PAN				
		SO_2 (10 ppb,M)	F	EST		Trass (1973)
- *Pleurozium schreberi*	M	H^+	F		3,4,5	Kellner and Marshagen (1991)
		SO_2 (700 ppb, M-H)	L	CAN		Winner and Bewley (1983)
						Winner (1988)

Table 13. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Pseudevernia* species	L	SO_2 SO_4 NO_3 TM	F F F F	FRG, USA, CAN	4	Scott and Hutchinson (1989)
- *Rhytidiadelphus triquetrus*	M	H^+	F	UK	1,3,4,5	Farmer et al. (1992b)
- *Sphagnum* species	M	SO_2 (H) F (H) bisulphite	F	UK	1,3,4,5	Ferguson and Lee (1983)
- *Tortula ruralis*	M	H^+ SO_2 (L)	L		1,2,3,4,5	Sheridan and Rosentreter (1973)
- *Usnea* species	L	O_3 (H) S	L, F	CA, USA	1,2,3,4,5	Nash (1988)
		SO_2 (3.0 ppb)	F	USA		Johnson (1979)
		(10.0 ppb, M-H)	F	EST		Trass (1973)

Footnotes:

[a] L = lichen, M = moss.

[b] Pollutant type: O_3 = ozone; NO_3 = nitrate; H^+ = acidity; SO_4 = sulfate; H_2SO_4 = sulfuric acid; PAN = peroxyacetyl nitrate; NH_4 = ammonium; NO_x = nitrogen oxides; SO_2 = sulfur dioxide; TM = trace metals; HNO_3 = Nitric acid

Values in parentheses include the pollutant concentration used in the study. Letters in parentheses refer to ratings of low (L), medium (M), or high (H) sensitivity to a specific pollutant, as listed by Peterson et al. (1992a), Appendix B.

[c] Study type: F = field; L = Laboratory; blank = unknown.

[d] Source: location where study was performed.

[e] Species occurrence in a class I national park. 1 = CRLA, 2 = CRMO, 3 = MORA, 4 = NOCA, 5 = OLYM.

are currently underway at EPA, Corvallis to compare results (Bates and Farmer 1992; Peterson et al. 1992a,b; Stolte et al. 1993a,b).

In general, reliable data on the sensitivities of vascular plants, bryophytes, and lichen flora to air quality in CRLA are lacking. Limitations of the existing data on terrestrial vegetation include (1) lack of park-specific or regional data, (2) lack of testing for laboratory dose-response functions under field conditions, (3) poor correspondence between visual injury estimates and dose-response functions, and (4) lack of information on noncommercial species. Esserlieu and Olson (1986) attempted to rank the vulnerability of national parks to atmospheric pollutants by evaluating the potential sensitivities of park flora and surface waters to pollutants. However, limitations of the emissions and deposition data, as well as the plant sensitivity data compromised the validity of the conclusions. Therefore, we have not included this study in the present analysis. For a general overview of ecosystems and plants that exhibit general sensitivities to various pollutants, see Appendix D.2.

Relatively little information is available on the effects of air quality on wildlife. Most studies have focused on the hazards of toxic contaminants, mainly trace metals and industrial solvents in water (Kilkelly Environmental Associates 1989). Furthermore, there are few data with which to assess specific impacts of air quality on wildlife in the class I national parks, with the exception of Frenzel and Starkey (1987). They examined concentrations of trace metals in goat hair from MORA, NOCA, and OLYM. Concentrations were considered low and were not indicative of potentially toxic accumulations.

Based on the data evaluated in this report, we conclude that there are currently no air pollutants posing significant risks to terrestrial resources in CRLA.

5.Monitoring and Research Needs

The primary monitoring need for CRLA is to characterize deposition at the park (Table 14).

a. Deposition

The deposition chemistry for Crater Lake is believed to be relatively unpolluted, but this assessment is based on data from a distant NADP/NTN site (H.J. Andrews Experimental Forest) and limited on-site bulk deposition and snow chemistry sampling. Because atmospheric inputs constitute the major source of nutrients to Crater Lake, it is extremely important to measure these inputs at the park. We recommend installing an NADP/NTN compatible station near the caldera rim. Because of the high volume of snow, it is likely that monitoring of winter deposition will need to be collected as bulk deposition or as snow pack sampling. Rainfall could be collected using a standard Aerochem metric sampler.

b. Aquatics

Crater Lake is a moderately hardwater lake and is not susceptible to acidification from atmospheric sources. The only potential atmospheric threat to the lake is accelerated inputs of N into this N-limited system. The continuing monitoring program proposed for Crater Lake will measure the nutrient status of the lake (G. Larson, pers. comm.). No additional lake monitoring activities related to atmospheric effects are required at this time for Crater Lake.

c. Terrestrial

Inventory of the vascular flora, lichen, and bryophyte species should be continued. Additional inventory and archiving of lichens and bryophytes is especially needed at Crater Lake. Monitoring and inventory of T&E plant and animal species could be expanded. A basic inventory of soils would be useful in future assessments of air quality effects on vegetation. Soil cation exchange capacity and mineral weathering figures into the determination of critical loads, especially for S. Soil survey data is used in the MAGIC model to calculate critical loads of sulfur for forest soils (Frogner et al. 1992). In the event that air quality problems (primarily ozone) develop in the future, dose-response studies for major tree species would be helpful. Due to inherent limitations in the methods, however (see Appendix D), lichen chemistry studies may be used more effectively to determine the source or cause of severe N or S pollution (isotope analysis) than to detect gradual deterioration in air quality before significant impacts occur to ecosystems. These studies are not currently critical for CRLA.

We offer a general approach to study ozone effects on terrestrial vegetation in class I national parks, based primarily on information presented in Olson et al. (1992), Bates and Farmer (1992), and Stolte et al. (1993a,b). Key points include the selection of (1) sensitive receptor(s), and (2) study methods.

Given funding limitations, it would be more efficient to focus efforts on the most sensitive organism or component of an ecosystem. This can also save time and money in the design of monitoring programs. Candidate species should be selected based on ozone sensitivities and plant geographic distribution in relation to known pollutant exposures in class I areas. These decisions should be based on exhaustive reviews of existing literature by technical experts.

Physiological studies of plant dose-response usually provide the most quantitative results, although they are more expensive and time-consuming, and thus too costly to implement at many field locations. Plant physiological processes are usually affected first by pollutants, but visible symptoms are easier to measure. On the other hand, although descriptive studies such as injury surveys are easier to implement on a large scale, they are more subjective and easily confounded by factors other than air quality (especially in natural ecosystems).

In our opinion, the best approach for studying vegetation response to ozone would be to combine quantitative dose-response and descriptive approaches beginning with carefully controlled physiological studies in both the laboratory and field (for trees, include seedlings and larger trees). Descriptive data on morphological symptoms of plant injury due to pollutant exposure should also be collected. Once dose-response functions have been established and injury symptoms have been documented, the findings should be tested using natural gradients in pollutant exposure in the field. If the experimentally measured dose-response functions and visual symptoms of injury agree in the lab and field, the data can then be manipulated through modeling to test individual species responses at population and landscape levels.

The primary monitoring needs to protect terrestrial vegetation int he Pacific Northwest at the present time include improved monitoring of ozone at rural locations near class I areas, and cloud chemistry at higher elevations in the Cascade Range. Protocols should be established for data collection and analysis to ensure high-quality results.

Additional needs for research and monitoring also include the dispersion of pollutants in relation to the complex meteorology and terrain of the Cascades. Local conditions in the Cascades generally result in elevated ozone south and east of major metropolitan areas below elevations of 1200 m. Exceptions occur when a temperature inversion dissipates with a marine frontal intrusion that pushes pollutants over the Cascades. This event is less common than pollution episodes at lower elevations, but there is the potential for high ozone levels (> 100 ppb) in class I areas when it happens. Additional research and monitoring of these meteorological events is needed to determine which geographic areas may be at highest risk from ozone damage.

6. References for Crater Lake National Park

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

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.

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.

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

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.

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

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

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.

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.

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.

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

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.

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

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

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. of Forest Research 21:733-738.

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.

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.

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.

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.

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

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.

Nash, T.H. III. 1988. Correlating fumigation studies with field effects. In: Lichens, Bryophytes, and Air Quality. Bibl. Lichenol. 30:201-216. J. Cramer, Berlin.

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

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

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.

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.

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. 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.

Ross, L.J. and T.H. Nash III. 1983. Effect of ozone on gross photosynthesis of lichens. Environmental and Experimental Botany 23:171-177.

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 Phytologist 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.

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.

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.

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.

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.

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 Science 57(3):157-166.

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

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.

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.

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

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 Botany 61:1456-1461.

B. CRATERS OF THE MOON NATIONAL MONUMENT

1. Description

Craters of the Moon National Monument is the smallest class I area in the Pacific Northwest, covering 21669 ha at the northern edge of the Snake River Plain, about 29 km southwest of Arco, Idaho. On May 2, 1924, President Calvin Coolidge established a 10100 ha area as Craters of the Moon National Monument; the area was later expanded to 21500 ha. The proclamation establishing the monument recognized the scientific and educational value of the area, even though its beauty was considered unusual:

> *Whereas, there is located in townships one south, one and two north, ranges twenty-four and twenty-five east of the Boise Meridian, in Butte and Blaine Counties, Idaho, an area which contains a remarkable fissure eruption together with its associated volcanic cones, craters, rifts, lava flows, caves, natural bridges, and other phenomena characteristic of volcanic action which are of unusual scientific value and general interest; and*
>
> *Whereas, this area contains many curious and unusual phenomena of great educational value and has a weird and scenic landscape peculiar to itself;*

In 1962, an additional 21650 ha were added to protect the Cary Kipuka, a unique undisturbed expanse of sagebrush grasslands, for scientific study. In 1970, 17500 ha were set aside as the Craters of the Moon Wilderness Area. Only the Wilderness Area is designated as Class I.

a. Geology

Geologically recent cinder cones, vents, lava flows, and other volcanic features are abundant throughout the Great Rift Zone, an 85-km-long volcanic rift zone traversing the monument in a north-northwest series of fissures across the Snake River Plain. The age of the most recent lava flows has been estimated from tree ring cores and radio carbon dating of buried wood to be around 2,000 years (Stearns 1963, Kuntz et al. 1986b).

The northern portion of the monument, north of Highway 93, includes foothills of the Pioneer Mountains. The elevational range within the monument varies from 1625 to 2355 m. The tallest cinder cone, Big Cinder Butte, rises more than 200 m above the surrounding plain and is one of the largest purely basaltic cinder cones in the world (Stearns 1928).

The geologic features of the region are dominated by volcanism. The term "plains volcanism" was coined by Greeley (1977) to describe the central Snake River Plain, with low shield volcanoes, tube-fed lava flows, fissure-fed flows, and intracanyon flows. The individual flows average 10 m thick from central vents and short fissures. The Craters of the Moon lava field covers 160000 ha, contains more than 30 km^3 of lava flows and pyroclastic deposits, and is the largest predominantly Holocene flow in the conterminous United States (Kuntz et al. 1986a). Other interesting volcanic features include lava caves, arches, and stalactites. The geology of Craters of the Moon National Monument has been described via ground mapping (Murtaugh 1961, Sidle 1979), and by remote sensing using LANDSAT and airborne radar (Lefebvre 1975). Studies on the chemical composition of Craters of the Moon lavas have been reviewed in detail by Blakesley and Wright (1988). Soil development generally is restricted to accumulated organics and particulates in depressions and fissures in the lava. No studies describing or mapping soils are known.

b. Climate

The continental climate of the region is characterized by hot, dry summers, and cold winters. Temperatures range from an average -1.7 ^{o}C in January to 28.7 ^{o}C in July. Annual precipitation averages 42.6 cm total, falling mostly as snow in December-January, and as rain in May. Water and ice in the monument may persist in (1) depressions which collect snow in winter, (2) lava caves or tubes where water that percolates inside freezes, and (3) in deep inverted funnels of scatter cones. Persistent water is always perched on bodies of ice. Groundwater is at least 306 m below the soil surface.

c. Biota

Fifty-eight percent of the monument consists of relatively barren lava flows with less than 15% plant cover. Sagebrush communities (*Artemisia* species) cover more than 30% of the area. Limber pine (*Pinus flexilis*) grows on cinder cones, and cinder gardens cover 7% of the monument. Cooler north-facing slopes of older cinder cones support Douglas-fir (*Pseudotsuga menziesii*) on about 1% of the total land area. Riparian areas occupy less than 0.5% of the monument

(Day and Wright 1985). Despite the limited vegetative cover, Craters of the Moon National Monument supports a surprising diversity of plant communities and species. A comprehensive listing of monument flora is available through the NPFLORA database (Waggoner 1989). Day and Wright (1985) identified and mapped 26 vegetation types, and Wunner (1967) and Urban (1968) documented 304 plant species. A listing of the rare vascular flora of Idaho is given by Moseley et al. (1992). Partial lists of the lichen flora are found in Pearson (1990) and Wetmore (1983).

Vegetation development on lava flows is determined primarily by the amount of soil present. The youngest lava flows support only lichens, but vascular plants establish in depressions, herbs in shallow crevices, and shrubs in deeper crevices. As soils accumulate over the flow surface, plants are eliminated from deeper crevices and replaced by grass-sedge climax communities. The vegetation communities of cinder cones, concentrated on the cooler and moister northeast slopes, include pioneer communities of herbs, trees, and shrubs.

A comprehensive inventory of the vertebrate and invertebrate fauna of the monument has been compiled by Blakesley and Wright (1988). Insect diversity includes at least 20 orders, 248 families, 1,144 genera, and 2,064 species and subspecies. A checklist compiled from observations of personnel and visitors at the monument lists one amphibian and seven reptile species. An annotated list of birds, compiled by Carter (1970) includes about 150 species. Mammals include six species of bat (Chiroptera), six species of rodents (Rodenta), three species of lagomorphs (Lagomorpha), mule deer, pronghorn, coyote, and rarely black bear, lynx, cougar, and red fox. Though wolves and grizzly bear were formerly present within the monument, they are now absent. Three mammal species are unique to the lava fields of the monument and vicinity--the Great Basin pocket mouse, yellow pine chipmunk, and a dark race of pika.

d. Aquatic Resources

The aquatic resources in CRMO are limited to two streams on the north side of the monument and ice in several caves. The streams pass through mine tailings from abandoned mining operations and the water quality is being characterized in a NPS-funded study. There are no lakes or ponds present in the monument.

2. Emissions

Emissions of air pollutants are low in Idaho (Table 6), and air quality problems have been restricted to local effects adjacent to some industrial sources (IDHW 1991). A current, reliable emissions inventory is not available on a county basis for Idaho (D. Collins, pers. comm.), although there are no major emission sources within 50 km of the monument (Figure 9). The closest major emission source to CRMO is the Idaho National Engineering Laboratory about 100 km east of the monument.

Industrial development began near Craters of the Moon National Monument in the mid- 1800s. The north end of the monument is in the Lava Creek Mining District which contained high levels of silver mining during the early 1900s. Rights to the Martin Mine, also on monument property, were transferred to the monument in 1963, and most mining structures were removed. Today, mining continues on a small scale outside the monument, in the Lava Creek District. Also, a phosphate fertilizer plant is located about 100 km from the monument, in Pocatello.

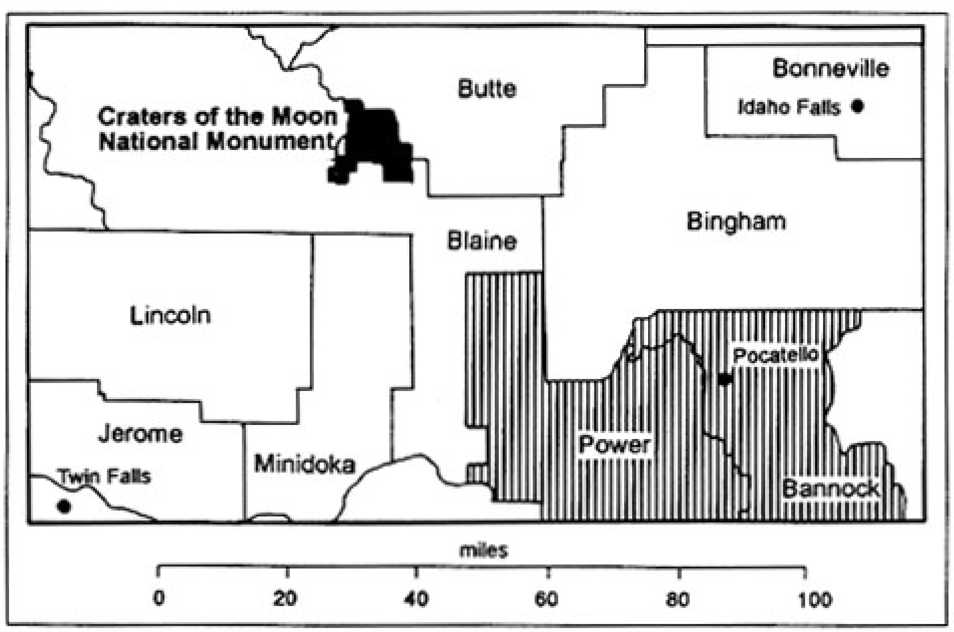

Figure 9. Craters of the Moon National Monument and proximity of urban areas in southern Idaho. Nonattainment areas for PM_{10} outside the monument are shaded with vertical lines.

Figure 9.Craters of the Moon National Monument and proximity of urban areas in southern Idaho. Nonattainment areas for PM_{10} outside the monument are shaded with vertical lines.

3. Current Monitoring and Research Activities

a. Air Quality/Deposition

(i) Wet Deposition

A NADP/NTN site is located at the Craters of the Moon headquarters near the monument entrance. The site has operated since August 1980. A NOAA weather site is also operating at CRMO. Precipitation is extremely low at CRMO, and because of its arid climate, the atmospheric pollutants can become highly concentrated. Furthermore, wind-entrained soil particles often can precede or be incorporated into convective thunderstorms or major frontal systems. A storm in February 1990 (2.5 cm) was the major contributor to the high annual precipitation-weighted concentrations observed in the year (Table 15). Median values for 1990 were typical of the annual precipitation-weighted means for 1991 and 1992. Both NO_3^- and NH_4^+ concentrations are much higher than observed in precipitation in the national parks of western Oregon and Washington. The comparatively high N concentration in the precipitation at CRMO is indicative of agricultural regions where use of fertilizer and large livestock populations contribute to volatilization of N. Natural production of NH_3 is also higher in the alkaline soils of the region.

(ii) Occult/Dry Deposition

Data on cloudwater chemistry has not been collected at the monument.

(iii) Gaseous Monitoring

An ozone monitor is operating at the monument, and since September 1992 wind speed and direction are also monitored. Tables 16 and 17 (also see Figures 10 and 11) summarize gaseous monitoring data from the EPA AIRS monitoring sites in Idaho during 1985-1992. Ozone concentrations (Table 16) throughout the region generally were low. There were no exceedances of the primary ozone standard in Idaho during that period, but the data were limited to one location for one year. Sulfur dioxide values (Table 17) also were low, although one exceedance for the 24-hour maximum standard occurred in 1985. No data were available on NO_2. These data do not currently indicate a significant threat to CRMO from gaseous pollutants.

Table 16.Summary of ozone data from the EPA AIRS (Aerometric Information Retrieval System) monitoring sites within 100 km of the class I national monument in Idaho during the period 1985-1992. Sites are identified in Figures 10 and 11.

	1-hour Maximum (ppb)							
Site #	1985	1986	1987	1988	1989	1990	1991	1992
16-023-0101	-	-	-	-	-	-	-	51

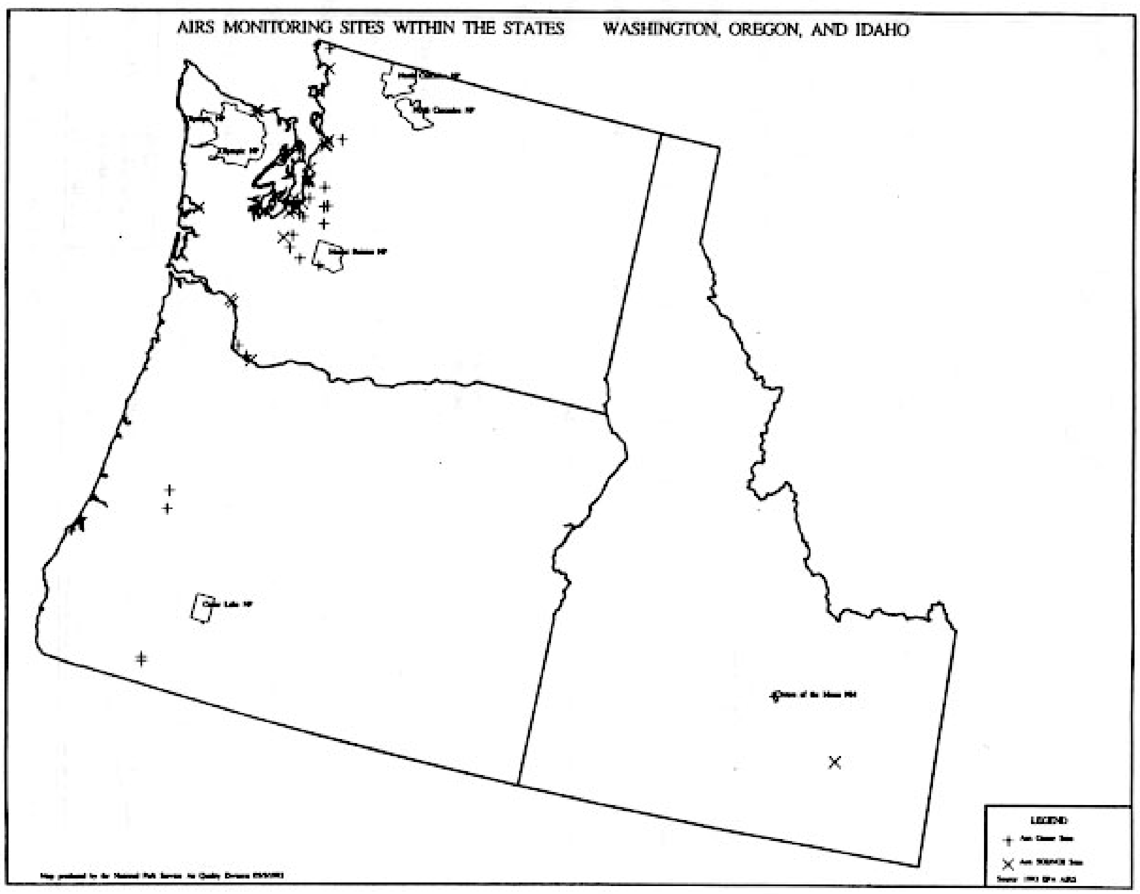

Figure 10. Location of EPA AIRS monitoring sites within the states of Washington, Oregon, and Idaho.

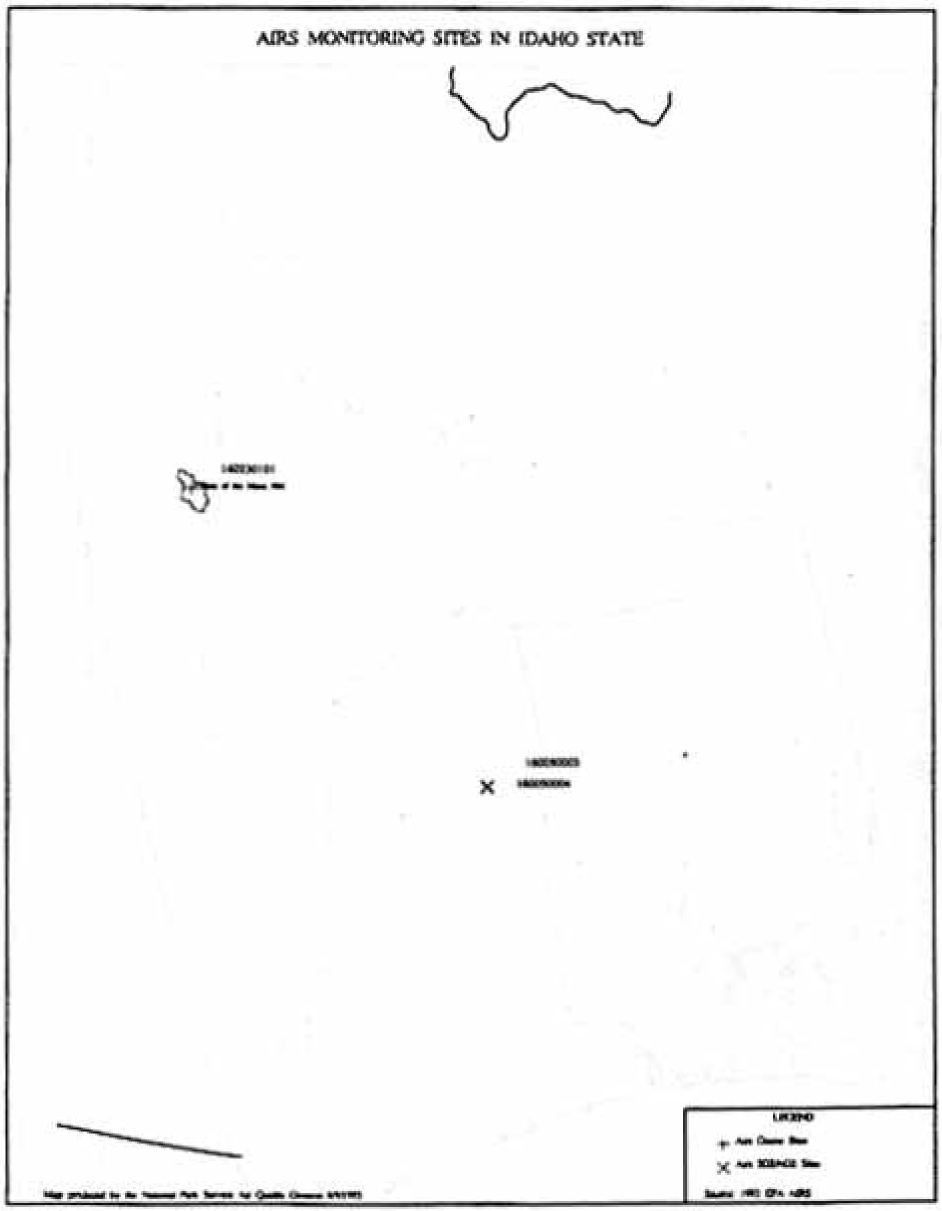

Figure 11. Location of EPA AIRS monitoring sites within the state of Idaho.

Figure 11.Location of EPA AIRS monitoring sites within the state of Idaho.

(iv) Particulates

A HiVOL sampler was replaced in 1991 with an IMPROVE site for collection of aerosols and fine particulates.

(v) Trace Metals

Trace metal samples in deposition have been collected by staff from the Idaho National Engineering Laboratory. A report describing these data was not available.

b. Water Quality

The aquatic resources at CRMO consist of two streams on the north end of the monument and ice in several lava caves. Analyses of these resources is being conducted by the University of Idaho under the direction of Dr. Michael Falter. Mine tailings from the Martin Mine, adjacent to one of the streams, is being investigated by Larry Martin and Mike Martin with the NPS, Water Resources Division. Preliminary analyses indicated that the streams are well-buffered systems (M. Falter, pers. comm.).

c. Terrestrial

A partial species inventory of the vascular flora of CRMO is maintained on the NPFLORA database (Waggoner 1989). Vegetation communities have been delineated on 1:24,000 scale topographic maps (Day 1984, Day and Wright 1985). Successional processes in plant communities have been reviewed by Blakesley and Wright (1988). An incomplete listing of the lichen flora was provided by Pearson (1990). An herbarium collection of lichens has been compiled. An inventory of vertebrate and invertebrate fauna was presented by Blakesley and Wright (1988), although it is not complete. A site inspection in 1985 by NPS AQD staff suggested that some vegetation was exhibiting damage possibly associated with high O_3 or F^- deposition (Bennett 1985). No data are available to support this claim. One study of fluoride concentrations in pine needles at CRMO was inconclusive regarding accumulation of F and its source. A possible source of fluoride was from a phosphate fertilizer plant in Pocatello, 100 km from the monument.

A detailed synthesis of the geology of the national monument is presented in Blakesley and Wright (1988). Very little information is available on soils in the monument.

4. Sensitive Receptors

The review of relevant literature that formed the basis for these recommendations is presented in Appendix D.

a. Aquatics

There are no sensitive receptors for aquatics in CRMO.

b. Terrestrial

With regard to ambient air quality in the vicinity of CRMO, sulfur and nitrogen deposition presently are too low to cause much concern about effects on terrestrial resources. Regionally, the highest potential for air quality to impact terrestrial resources is associated with ozone near industrialized urban areas of western Oregon and Washington and rural areas downwind. Limited data do not indicate a current threat to terrestrial resources in CRMO from ozone. To date, there has been no research to determine the effects of ozone on terrestrial resources in CRMO. Consequently, this assessment of potentially sensitive species in the monument is based on research conducted in other ecosystems, on related species or taxa of organisms.

Much of the research effort over the past 50 years to document air quality effects on terrestrial vegetation has focussed on documenting forest growth and physiological condition in relation to "forest decline", and on establishing dose-response functions for economically important tree species (Smith 1990). Less effort has been directed to the study of mosses and lichens, except near heavily-polluted areas of Great Britain, Europe and Canada (Bates and Farmer 1992). There are only a few studies of the effects of pollutants on lichens in the Pacific Northwest (Denison and Carpenter 1973, Hoffman 1974, Denison et al. 1977, Johnson 1979, Taylor and Bell 1983, Bledsoe et al. 1985, Rhoades 1988). Physiological studies of dose-response functions have yielded the most conclusive results, but the high cost of such studies has limited their applicability.

More information is available on ozone effects than on N and S effects. The most comprehensive ozone research has been conducted in the mixed conifer forest and other vegetation types of California, on the dominant, commercially important tree species (Miller et al. 1989; Peterson et al. 1987, 1991, 1992 a,b; Horner and Peterson 1993). Few data are available to relate ozone dose or exposure to mature trees, and almost no data for herbaceous species.

A provisional list of potentially sensitive vascular plant species indigenous to CRMO are presented in Table 18. A listing for lichen and moss species is provided in Table 19. This list of potentially sensitive species is only a preliminary compilation of known or suspected sensitive plants. The information should be viewed as largely preliminary, due to the limited database. Sensitivity classes for vascular plants, lichens, and bryophytes have been developed to summarize the high variability in response to different pollutants that has been documented within plant species. The wide range of variability in plant responses to pollutants is attributable to differences in research methodology, environmental conditions, and to natural variability in species sensitivity. Specific values for pollutant sensitivity are listed where data exist. The application of much of this sensitivity data to the Pacific Northwest must be undertaken with caution because the data are mostly from laboratory fumigation experiments on seedlings and have not been field tested on mature trees. The reliability of extrapolating pollutant responses from the laboratory to the field and from seedlings to mature trees is questionable, and studies are currently underway at EPA, Corvallis to compare results (Bates and Farmer 1992; Peterson et al. 1992a,b; Stolte et al. 1993a,b). In general, reliable data on the sensitivities of vascular plants,

Table 18. Partial list of potentially sensitive vascular plant species in CRMO.

		Sensitivity[a]		
Common Name	Scientific Name	Ozone[b]	Sulfur	Nitrogen
Rocky Mountain maple	*Acer glabrum*	X	M	UK
Alders	*Alnus* species	L/M (120-300 ppb)	H	UK
Big sagebrush	*Artemisia tridentata*	L	L	UK
Junipers *Juniperus* species	L	L	UK	
Lupines *Lupinus* (species)	X	UK	UK	
Limber pine	*Pinus flexilis*	UK	L	UK
Balsam poplar	*Populus balsaifera trichocarpa*	H	M	UK
Aspen	*Populus tremuloides*	S	UK	UK
Quaking aspen	*Populus tremula tremuloides*	H (40 ppb)	H	UK
Choke cherry	*Prunus emarginata*	X	M	UK
Choke cherry	*Prunus virginiana*	X	M	UK
Douglas-fir	*Pseudotsuga menziesii*	L/M (100 ppb)	M/H (SO_2 65 ppb)	H
Golden currant	*Ribes aureum*	X	UK	UK
also *Ribes cereum*	X	UK	UK	
Wild rose *Rosa woodsii*	X	UK	UK	
Western thimbleberry	*Rubus parviflorus*	X	UK	UK
Scouler willow	*Salix scouleriana*	X	UK	UK

[a] X = known or suspected; H = high; M = moderate; L = low; UK = unknown sensitivity.
[b]A general range of sensitivities to ozone is 60-90 ppb for conifers, 70-120 ppb for hardwoods, 7-h growing season means.

Source:Esserlieu and Olson (1986); Lefohn 1992; Peterson et al. (1992a,b); Horner and Peterson (1993); Forest Health Monitoring Program (1993)

Table 19. Partial list of lichen and moss species that have documented responses to pollutants.

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Alectoria sarmentosa*	L	O_3 (H) PAN	F	CA, USA	3,5	Sigal and Nash (1983)
- *Bryoria abbreviata* *B. fremontii* *B. oregana*	L	O_3 (H) PAN	F	CA, USA	1,2,3,4 1,2,3,4,5 1,3	Sigal and Nash (1983)
- *Calicium viride*	L	O_3 (H) PAN SO_2 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
- *Cetraria islandica*	L	NH_4 NO_3 O_3 (H) SO_2 (M) F (M)	F	SWED	1,2,3,4,5	Gerhardt and Kellner (1986)
C. canadensis	L	O_3 (H) PAN	F	CA, USA	2,4	Sigal and Nash (1983)
- *Cladina portentosa*	L	NO_x	F	NETH	1	Sochting and Johnsen (1990)
C. rangiferina	L	NH_4 SO_2 (M-H) F (M) NO_3	F	SWED	1,3,4,5	Gerhardt and Kellner (1986)
		HNO_3	F	FRG, USA CAN		Scott and Hutchinson (1989)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
C. stellaris	L	H^+	L		4	Lechowicz (1982)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
- *Evernia prunastri*	L	O_3 (H)	F	CA, USA	1,3,4,5	Sigal and Nash (1983)
		PAN F (H) S	L, F F	CA, USA		Nash (1988)
		SO_2 (3.0 ppb, L-M)	F	USA		Johnson (1979)
- *Hylocomium splendens*	M	H^+	F	UK	1,3,4,5	Farmer et al. (1992a)

		SO_2 (H) F (M)				
- *Hypogymnia enteromorpha*	L	O_3 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
		PAN	L, F			Nash (1988)
		O_3 (800 ppb, L-M) SO_2 (L-M)	L			Nash and Sigal (1979)

Table 19. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Isothecium myosuroides*	M	H^+	F	UK	1,3,4,5	Pitkin (1975)
- *Lobaria pulmonaria*		O_3 (L-M)				
	L	H^+	F	UK	1,2,3,4,5	Gilbert (1986)
		H_2SO_4				Denison et al. (1977)
		SO_2 (H)				
- *Nephroma arcticum*	L	NH_4^+ O_3 (H) SO_2 (H) NO_x PAN (H)	L, F	SWED	3	Nohrstedt et al. (1988)
- *Parmelia caperata*	L	SO_2	F	UK	1,2,3,4,5	Gilbert (1992)
		O_3 (800 ppb) PAN	L			Nash and Sigal (1979)
		O_3 (200 ppb)				Ross and Nash (1983)
P. sulcata	L	NO_x PAN (M-H) SO_2 (70 ppb, L-H) F (M-H)	L, F	SWED	1,2,3,4,5	von Arb et al. (1990)
		O_3 (500 ppb, M-H)	L			Nash and Sigal (1979)
- *Peltigera aphthosa polydactyla*	L	H^+ O_3 (H) SO_2 (M) NO_x/PAN (M-H)	L		1,2,3,4,5	Fritz-Sheridan (1985)
	L	NH_4^+ SO_2 (M)	L, F	SWED		Nohrsted et al. (1988)
- *Physodes* species	L	SO_2 SO_4 NO TM		FRG, USA CAN	1,2,3,4,5	Scott and Hutchinson (1989)
- *Platismatia glauca*	L	O_3 (H) PAN	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
		SO_2 (10 ppb,M)	F	EST		Trass (1973)

- *Pleurozium schreberi*	M	H^+	F		3,4,5	Kellner and Marshagen (1991)
		SO_2 (700 ppb, M-H)	L	CAN		Winner and Bewley (1983) Winner (1988)

Table 19. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Pseudevernia* species	L	SO_2 SO_4 NO_3 TM	F F F F	FRG, USA, CAN	4	Scott and Hutchinson (1989)
- *Rhytidiadelphus triquetrus*	M	H^+	F	UK	1,3,4,5	Farmer et al. (1992b)
- *Sphagnum* species	M	SO_2 (H) F (H) bisulphite	F	UK	1,3,4,5	Ferguson and Lee (1983)
- *Tortula ruralis*	M	H^+ SO_2 (L)	L		1,2,3,4,5	Sheridan and Rosentreter (1973)
- *Usnea* species	L	O_3 (H) S	L, F	CA, USA	1,2,3,4,5	Nash (1988)
		SO_2 (3.0 ppb)	F	USA		Johnson (1979)
		(10.0 ppb, M-H)	F	EST		Trass (1973)

Footnotes:

[a] L = lichen, M = moss.

[b] Pollutant type: O_3 = ozone; NO_3 = nitrate; H^+ = acidity; SO_4 = sulfate; H_2SO_4 = sulfuric acid; PAN = peroxyacetyl nitrate; NH_4 = ammonium; NO_x = nitrogen oxides; SO_2 = sulfur dioxide; TM = trace metals; HNO_3 = Nitric acid

Values in parentheses include the pollutant concentration used in the study. Letters in parentheses refer to ratings of low (L), medium (M), or high (H) sensitivity to a specific pollutant, as listed by Peterson et al. (1992a), Appendix B.

[c] Study type: F = field; L = Laboratory; blank = unknown.

[d] Source: location where study was performed.

[e] Species occurrence in a class I national park. 1 = CRLA, 2 = CRMO, 3 = MORA, 4 = NOCA, 5 = OLYM.

bryophytes, and lichen flora to air quality in CRMO are lacking. Limitations of the existing data on terrestrial vegetation include: (1) lack of park-specific or regional data, (2) lack of testing for laboratory dose-response functions under field conditions, (3) poor correspondence between visual injury estimates and dose-response functions, and (4) lack of information on noncommercial species. Esserlieu and Olson (1986) attempted to rank the vulnerability of national parks to atmospheric pollutants by evaluating the potential sensitivities of monument flora and surface waters to pollutants. However, limitations of the emissions and deposition data, as well as the plant sensitivity data compromised the validity of the conclusions. Therefore, we have not included this study in the present analysis. For a general overview of ecosystems and plants that exhibit general sensitivities to various pollutants, see Appendix D.2.

Information on the effects of air quality on wildlife is scarce. Most studies have focused on the hazards of toxic contaminants, mainly heavy metals and industrial solvents in water (Kilkelly Environmental Associates 1989). Furthermore, few data exist with which to assess specific impacts of air quality on wildlife in the class I national parks.

Based on the data evaluated in this report, we conclude that there are currently no air pollutants posing significant risks to terrestrial resources in CRMO.

5. Monitoring and Research Needs

The monitoring and research needs at CRMO are summarized in Table 20. Research needs relative to air pollution effects are limited to terrestrial effects.

a. Deposition

No additional monitoring activities are required at CRMO.

b. Aquatics

No additional monitoring activities relative to atmospheric impacts on aquatic resources are required at CRMO.

c. Terrestrial

Additional inventory of vascular flora, lichen, and bryophyte species is needed as well as a more complete inventory of T&E species. A basic inventory of soil types would be useful to any future assessments of air quality effects on terrestrial resources. Soil cation exchange capacity and mineral weathering figures into the determination of critical loads, especially for S. Soil survey data is used in the MAGIC model to calculate critical loads of sulfur for forest soils (Frogner et al. 1992). Dose-response information on dominant tree species also would be valuable and should be initiated if regional values for ambient ozone increase. Due to inherent limitations in the methods, however (see Appendix D), lichen chemistry studies may be used more effectively to determine the source or cause of severe N or S pollution (isotope analysis) than to detect gradual deterioration in air quality before significant impacts occur to ecosystems.

We offer a general approach to study ozone effects on terrestrial vegetation in class I national parks, based primarily on information presented in Olson et al. (1992), Bates and Farmer (1992), and Stolte et al. (1993a,b). Key points include the selection of (1) sensitive receptor(s), and (2) study methods.

Given funding limitations, it would be more efficient to focus efforts on the most sensitive organism or component of an ecosystem. This can also save time and money in the design of monitoring programs. Candidate species should be selected based on ozone sensitivities and plant geographic distribution in relation to known pollutant exposures in class I areas. These decisions should be based on exhaustive reviews of existing literature by technical experts.

Physiological studies of plant dose-response usually provide the most quantitative results, although they are more expensive and time-consuming, and thus too costly to implement at many field locations. Plant physiological processes are usually affected first by pollutants, but visible symptoms are easier to measure. On the other hand, although descriptive studies such as injury surveys are easier to implement on a large scale, they are more subjective and easily confounded by factors other than air quality (especially in natural ecosystems).

In our opinion, the best approach for studying vegetation response to ozone would be to combine quantitative dose-response and descriptive approaches beginning with carefully controlled physiological studies in both the laboratory and field (for trees, include seedlings and larger trees). Descriptive data on morphological symptoms of plant injury due to pollutant exposure should also be collected. Once dose-response functions and injury symptoms have been documented, the findings should be tested using natural gradients in pollutant exposure in the field. If the experimentally measured dose-response functions and visual symptoms of injury agree in the lab and field, the data can then be manipulated through modeling to test individual species responses at population and landscape levels.

These studies are not currently critical for CRMO. The primary monitoring need near CRMO at the present time is to continue monitoring of ozone.

6. References for Craters of the Moon National Monument

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

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.

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.

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.

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.

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.

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

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.

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

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

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.

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.

Greeley, R. 1977. Basaltic plains volcanism. Pages 23-44 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.

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.

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

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

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

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. of Forest Research 21:733-738.

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.

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.

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.

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.

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

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

Nash, T.H. III. 1988. Correlating fumigation studies with field effects. In: Lichens, Bryophytes, and Air Quality. Bibl. Lichenol. 30:201-216. J. Cramer, Berlin.

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

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

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.

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

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.

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.

Ross, L.J. and T.H. Nash III. 1983. Effect of ozone on gross photosynthesis of lichens. Environmental and Experimental Botany 23:171-177.

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 Phytologist 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.

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.

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

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.

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.

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.

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.

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 Science 57(3):157-166.

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

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.

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.

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.

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

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 Botany 61:1456-1461.
National Park Service, GIS Div., Denver, CO.

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.

C. MOUNT RAINIER NATIONAL PARK

1. Description

Mount Rainier National Park was established as the nation's fifth national park in 1899. Enabling legislation reads as follows:

...preservation from injury or spoilation of all timber, mineral deposits, natural curiosities or wonders within said park and retention in their natural condition...

The southern Washington Cascades are characterized by generally accordant ridge crests separated by steep, deeply dissected valleys. The average ridge elevation runs about 2000 m in the northern section and 1200 m in the southern. An extensive area around Mount Adams is composed of recent lava flows, with a gently sloping plateau to 900-1500 m in elevation, differing markedly from the rest of the region. Three major volcanoes dominate the landscape: Mount Rainier (4392 m), Mount Adams (3801 m), and Mount St. Helens (2948 m). At 4392 m, Mount Rainier is the fifth tallest peak in the contiguous 48 states. The massive mountain occupies more than one-fourth of the park's 98000 ha area. Sixty miles southeast of Seattle, Washington, Mount Rainier is the highest in the chain of volcanoes comprising the Cascade Range. The 27 major glaciers on its slopes form the largest mass of year-round ice in the United States outside Alaska.

a. Geology and Soils

The geology of Mount Rainier reflects the opposing forces of volcanic eruptions building the mountain and glacial erosion slowly grinding it away. Although intermittently active for hundreds of thousands of years, and last erupting only 150 years ago, Mount Rainier is currently quiescent. Deep canyons, lava flows, mud flows, landslides and pumice/ash deposits testify to the mountain's explosive past.

Andesite and basalt are the dominant rock types with minor amounts of igneous intrusive, sedimentary, and metamorphic rocks present. More geologic investigations have been carried out near Mount Rainier than on any other dormant volcano (Crandell 1969a,b; 1971). At least 90% of the area is comprised of andesite and basalt flows with their associated breccias and tuffs. Areas adjacent to the three volcanic peaks generally are mantled with pumice deposits of variable age, origin, and thickness. The most recent pumice deposit near Mount Rainier was deposited 100-150 years ago during the last eruption. Pleistocene glacial activity was widespread in this portion of the Cascades, although most of these alpine glaciers were small.

Compared to areas to the north, few soils are developed in glacial materials, and because of the less rugged topography, there are small areas of rocky and stony skeletal soils. The most widespread soils are derived from a combination of parent materials consisting of both pumice and basalt and andesite. Surface layers may consist of a series of unmixed aeolian sand and pumice overlying residual materials. An accounting of different soil types by vegetation zone, is provided by Franklin and Dyrness (1988).

b. Climate

Orographic effects of the Cascade Range produce dramatic patterns of precipitation along an east-west gradient through the park. Rain and snowfall are abundant on the west side, averaging about 250 cm per year at Paradise. Most of this precipitation falls as snow, accumulating to depths of 4.5 to 6 m during normal years, and up to 9 m during heavy winters. Snow may fall during any month, but July, August and early September usually are warm. The abundant precipitation also produces many lakes, streams, and glaciers, which contribute to an abundant and diverse floral and faunal assemblage.

c. Biota

Vegetation distribution patterns are strongly influenced by edaphic and climatic factors, primarily the east-west precipitation gradient and conditions associated with increasing elevation from valley bottom to ridgetop-shallow soil, reduced air temperature, steep slopes, and shorter growing season. On the western side, lower elevation forests of deep valleys support giant stands of western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Douglas-fir (*Pseudotsuga menziesii*) to about 550 m. Pacific silver fir (*Abies amabilis*) replaces western red cedar (*Thuja plicata*) in the western hemlock-silver fir zone, which grades to mountain hemlock (*Tsuga mertensiana*), subalpine fir (*Abies lasiocarpa*), and Alaskan yellow cedar (*Chamaecyparis nootkatensis*) in the subalpine zone and extends up to the alpine zone, about 1800 m above sea level. Understory shrubs and herbs are most abundant in open forests. Riparian areas also support a rich diversity of shrubs and herbs. At higher elevations, alpine and subalpine habitats support lush wildflower meadows, for which the park is renown.

On the eastern slopes of the park, larch (*Larix* species) and white bark pine (*Pinus albicaulis*) grow in subalpine meadows above stunted Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*). Douglas-fir dominates at the mid elevations on the east side, whereas hemlock and silver fir occur on the west side. On the driest sites of the lowest eastern foothills, ponderosa pine (*Pinus ponderosa*) predominates. A comprehensive listing of park flora is available through the NPFLORA database (Waggoner 1989). Vegetation communities have been plotted on a 1:100,000 scale topographic map, using Landsat MSS data. These maps are available at park offices. Lichens of MORA are listed in Wetmore (1983).

Vegetation types as discussed by Franklin and Dyrness (1988) include the western hemlock zone, the Pacific silver fir zone, and the mountain hemlock zone. In the western hemlock zone (to 1000 m elevation), large areas are dominated by forests of Douglas-fir often in mixture with western red cedar and mountain hemlock. The climate of this zone is wet, mild, and maritime, but varies widely with elevation, latitude, and orographic influences. Precipitation averages 150-300 cm and occurs mainly during the winter. The Pacific silver fir zone lies between the temperate mesophytic western hemlock zone and the subalpine mountain hemlock zone at about 900-1300 m in elevation. Species composition differs widely depending on stand conditions and history. This zone is cooler and wetter than lower elevations and receives considerably more precipitation as snow. The mountain hemlock zone is the highest forested zone along the western slope of the Cascades to elevations of 1300-1700 m. It consists of a lower subzone of closed forest and an upper parkland subzone. *Tsuga mertensiana* predominates in the lower subzone, and a mosaic of forest patches and tree groups interspersed with shrub and herbaceous plants forms the upper subzone. This zone is the coolest and the wettest of the forested types in western Washington, and has the highest snow accumulation.

Large mammals such as mountain goats, black-tailed deer, mule deer, elk, and black bear comprise some of the more than 50 mammal species found in the park. Though many of the 140 bird species identified in the park are migrants, many species such as the gray jay and Clark's nutcracker are residents. A listing of the flora and fauna of MORA is presented by the Sierra Club (1985).

d. Aquatic Resources

Mount Rainier National Park has an extensive network of rivers radiating from the mountain and the glacial activity has created nearly 200 lakes and ponds. The glaciers that remain on the mountain feed the rivers and some of the lakes with meltwaters. The lakes are distributed around the face of the mountain and extend from montane to alpine settings. The lakes at the higher elevations may remain ice-free only three to four months of the year.

2. Emissions

Mount Rainier National Park is within 40 km of the Puget Sound urban zone and is downwind of the largest SO_2 source in Washington, the Centralia power plant. The four counties adjacent to MORA emit 56% of the State's SO_2 and 21% of the NO_x (Figure 12, Table 21). The SO_2 emissions from these four Washington counties exceed SO_2 emissions from the entire state of Oregon. In addition, most of the populated and industrialized areas in Washington are located along the Puget trough, which at times probably contributes to deterioration of air quality at MORA. As a consequence of these emissions, air quality standards are not met in portions of Puget Sound for

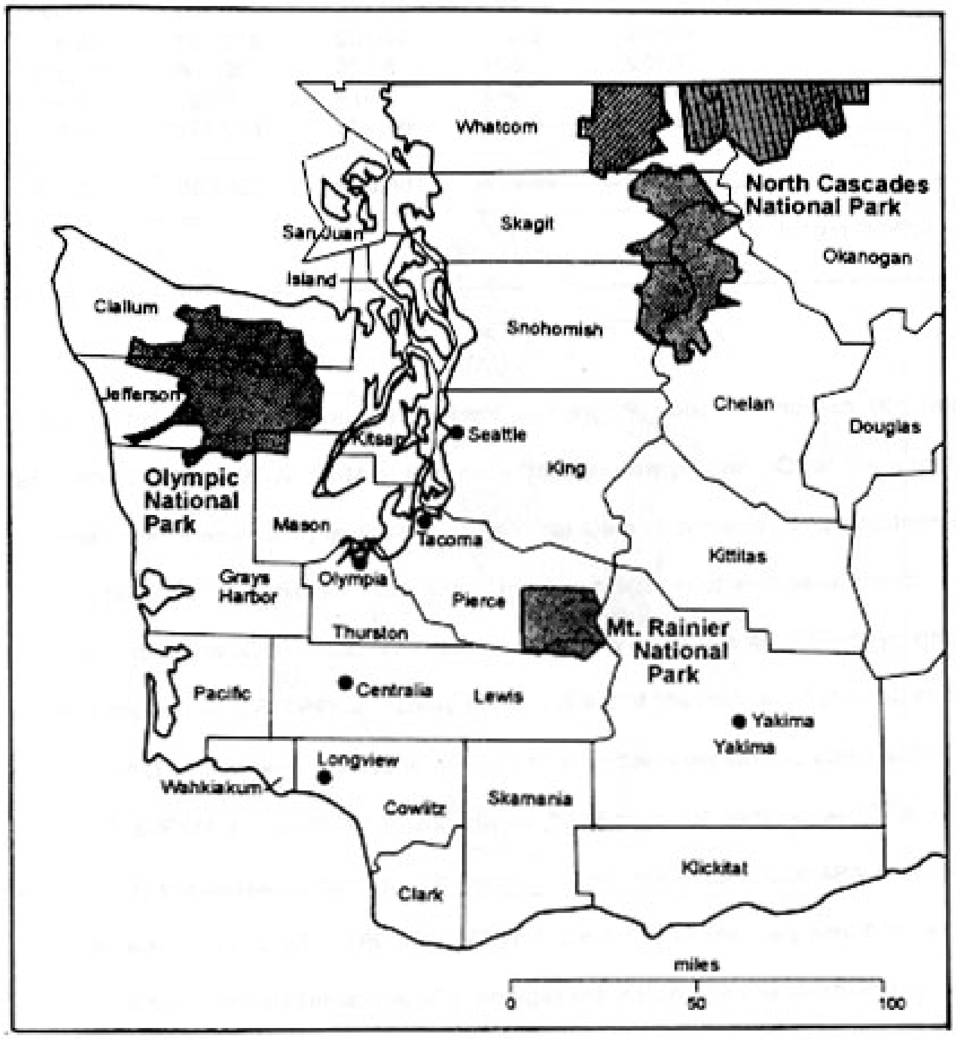

Figure 12. Mount Rainier National Park and proximity of urban areas in Washington.

Figure 12.Mount Rainier National Park and proximity of urban areas in Washington.

Table 21. Emissions in the counties adjacent to MORA. Units are in tons/yr.

County	PM_{10}	SO_x	NO_x	CO	VOC
Lewis	8,099	69,991	27,719	71,863	7,992
Pierce	30,439	6,877	30,102	312,697	48,307
Thurston	7,952	524	8,125	89,086	14,323
Yakima	8,942	842	10,974	90,269	14,849
King	72,828	8,683	87,108	719,141	124,667
TOTAL	128,260	86,917	164,028	1,283,056	210,138

Source: WDOE (1993)

ozone (Figure 13), carbon monoxide (Figure 14), and PM_{10} (Figure 15). Attainment plans for the nonattainment areas for CO and O_3 were submitted to EPA in 1992 (WDOE 1993). Additional state implementation plan revisions to meet the remaining Federal requirements are being developed. Additional actions to reduce emissions in the state are expected to result in continued improvement in air quality. Two major events have caused SO_2 emissions in Washington to decrease substantially in the last 10-15 years. In 1980, SO_2 emissions from Mount St. Helens in Skamania County were estimated by USGS at 222,000 metric tons (244,000 tons), but by 1988 emissions declined to about 3,000 metric tons (3,300 tons) (M. McGee, pers. comm.). Also, the ASARCO copper smelter in Tacoma discontinued operation in 1984, thereby eliminating over 100,000 tons per year of SO_2 emissions. Thus, while the current emissions of air pollutants are a concern, the emissions trends seem to be declining.

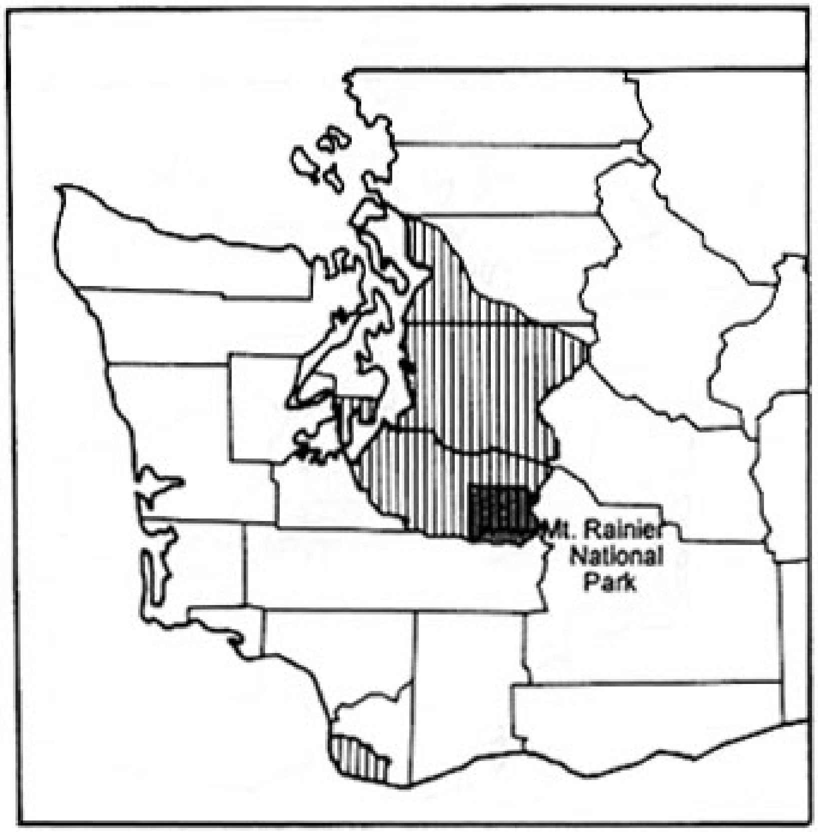

Figure 13. Nonattainment areas (lined areas) for O_3 in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

Figure 13.Nonattainment areas (lined areas) for O_3 in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

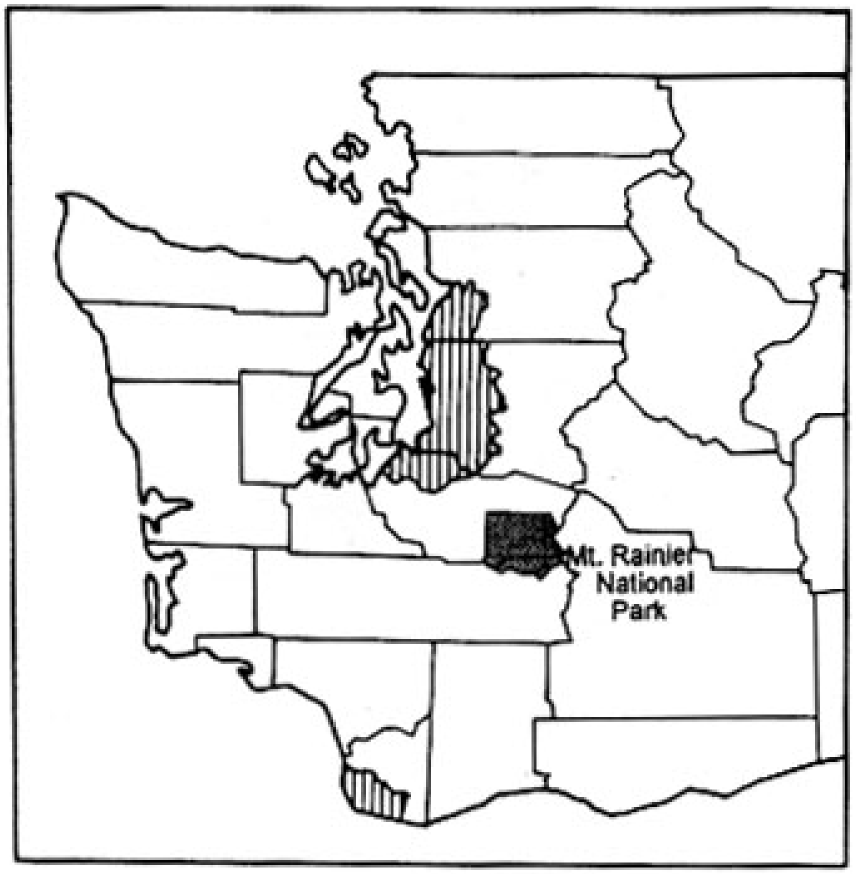

Figure 14. Nonattainment areas (lined areas) for CO in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

Figure 14.Nonattainment areas (lined areas) for CO in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

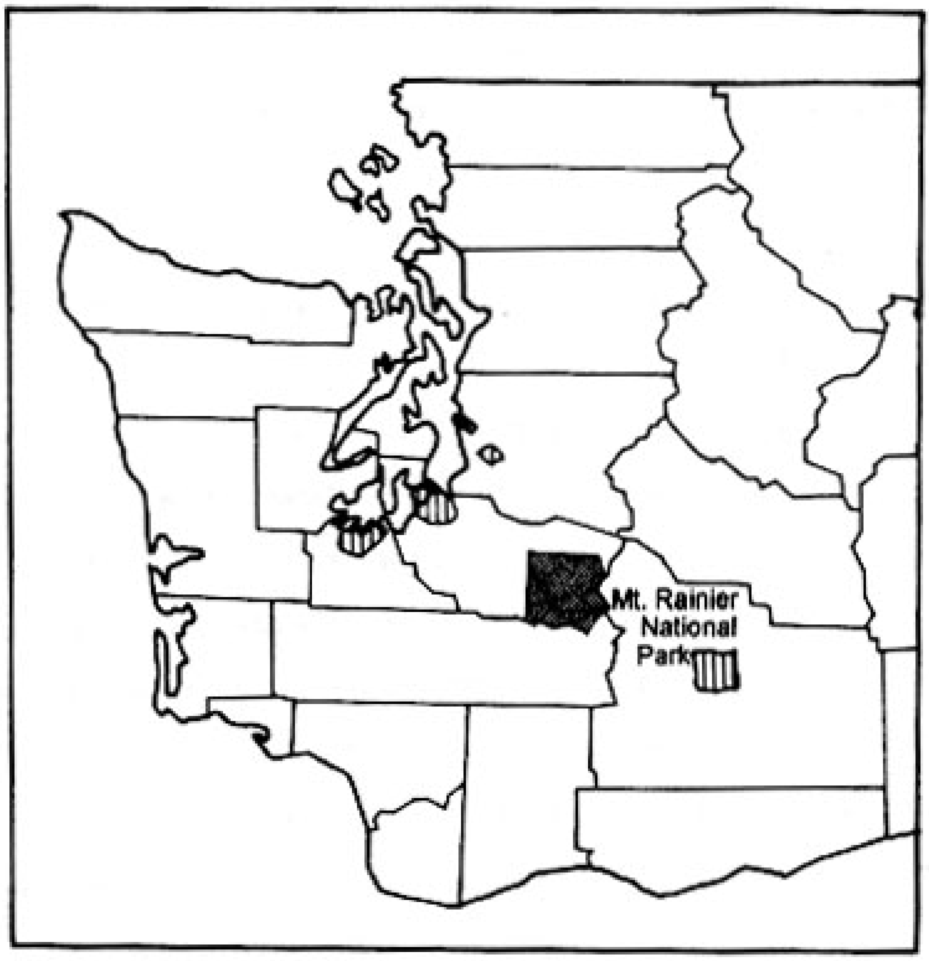

Figure 15. Nonattainment areas (lined areas) for PM_{10} in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

Figure 15.Nonattainment areas (lined areas) for PM_{10} in Washington State relative to Mount Rainier National Park (redrafted from WDOE 1993).

3. Current Monitoring and Research Activities

a. Air Quality/Deposition

(i) Wet Deposition

The closest NADP/NTN site is located 25 km from the park near La Grande in the University of Washington Pack Forest. The collector is located at an elevation of 616 m and has been in operation since April 1984. The wet deposition at the La Grande site (Table 22) shows sulfate concentrations significantly greater than that observed at the other parks in the Pacific Northwest (excluding CRMO). The greater concentrations of SO_4^{2-} near MORA may reflect its proximity to emission sources of SO_2 in western Washington. In particular, the single largest emission source in the Pacific Northwest, the Centralia PP&L coal-fired power generation station, is located about 75 km west of MORA and 50 km west of the NADP/NTN monitoring site. Nitrate concentrations at La Grande are similar to those observed at NOCA but are twice as large as those observed in the central Oregon Cascades at H.J. Andrews Experimental Forest. Ammonium concentrations in the precipitation at La Grande are greater than those observed at both NOCA and H.J. Andrews. The contribution of the acid anions, SO_4^{2-} and NO_3^-, to the precipitation at La Grande causes the precipitation to be more acidic (pH ~ 5.0) than observed at other sites in western Washington and Oregon where the pH generally is near 5.4.

Sampling of bulk deposition was initiated in the park at Paradise starting in 1987. Field measurements are collected for sample volume, temperature, pH, and conductivity. Samples originally were mailed to WDOE for analysis, although analyses of the samples are currently contracted to Central Washington University.

Winter bulk deposition samples have been collected at Snoqualmie Pass from 1984-1991 (Duncan 1992; Table 23). The collection site is about 40 km north of MORA. Duncan et al. (1992) reported no temporal trends in SO_4^{2-} or NO_3^- deposition for the study period and concluded:

> "The sulfate, nitrate, and ammonium concentrations in the winter precipitation at Stevens Pass and Snoqualmie Pass are low when compared to precipitation concentrations observed in other parts of the United States."

Table 23. Volume-weighted average precipitation concentrations and deposition at Snoqualmie Pass for the period January 1 to July 18, 1991 (Duncan 1992).

	Concentration (µeq/L)	Load (kg/ha)
SO_4^{2-}	8.4	9.5 (3.2 as S)
NO_3^-	6.1	8.9 (2.0 as N)
NH_4^+	2.7	1.2 (0.9 as N)

Snow samples also were collected by Laird et al. (1986) from sites in and near MORA. Concentrations of acid anions were higher in the area, and metals such as Pb were elevated with respect to other sites, presumably as a consequence of sources in the Puget Sound area. Average concentrations of SO_4^{2-} measured at four sites on the west side of the park (5.7 µeq/L) were nearly double those at Paradise and Tatoosh Lakes on the south side of the park (3.3 µeq/L).

Concentrations of ions measured in the snow at Mount Rainier in 1983 by Laird et al. (1986) (Table 24) were considerably lower than those measured by Duncan (1992) at Snoqualmie Pass. Nitrogen deposition was not significantly different between the western and southern sites.

Table 24. Snow chemistry for MORA based on an average of seven sites sampled by Laird et al. (1986). Units are in micro-equivalents per liter.

Parameter	Concentration
H^+	3.6
Ca^{2+}	2.0
Mg^{2+}	0.3
K^+	0.3
Na^+	5.6
NH_4^+	0.8
NO_3^-	1.1
Cl^-	7.2
SO_4^{2-}	4.9
SO_4^*	4.1

(ii) Occult/Dry Deposition

Fog and cloud chemistry were measured in the park at Sunrise and Paradise in MORA, and Burley Mountain to the south of the park in 1987-1988 (Basabe et al. 1989a). The three sites ranged in elevation from 1618 to 1950 m. Cloudwater pH values < 4 were commonly measured at MORA and these three sites exhibited the highest concentrations of SO_4^{2-},

NO_3^-, NH_4^+, and H^+ measured among the 12 stations in the study (Basabe et al. 1989a).

(iii) Gaseous

Of the four monitoring stations near MORA (King County, Pack Forest, Pierce County, and Stampede Pass), Pack Forest and Stampede Pass have the highest ozone levels. Mean hourly values of ozone over the growing season (May-October, 1980-1988) were relatively low (30-35 ppb) at these two sites. These values were higher, however, than the "cleanest" site on the Olympic Peninsula (5-16 ppb). Peak hourly values for ozone at Pack Forest and Stampede Pass can exceed 100 ppb. At Pack Forest, 8% of the hourly ozone values were equal to or greater than 60 ppb, 3% were equal to or greater than 80 ppb, and 1% were equal to or greater than 100 ppb. At Stampede Pass, 7% of the hourly ozone values were between 60-80 ppb. In addition, Edmonds and Basabe (1989) measured hourly ozone concentrations in excess of 120 ppb at Cedar River. Basabe et al. (1989a) also reported high ozone values from 90-196 ppb at locations near MORA (WDOE 1993).

Tables 25-27 (see also Figures 16 and 17) summarize gaseous monitoring data from the EPA AIRS monitoring sites in Washington during 1985-1992. Ozone concentrations (Table 25) throughout the region generally were low. Washington State, however, had several exceedances of the primary ozone standard (maximum 1-hour average = 125 ppb) with a range of 126-149 ppb, to the east and southeast of Seattle. An ozone monitoring station is currently operating at MORA, and in 1993, hourly maximum values for ozone ranged from 75-87 ppb during most of the growing season (May-September). These ozone values were well above regional background values.

Table 25.Summary of ozone data from the EPA AIRS (Aerometric Information Retrieval System) monitoring sites within 100 km of the class I national parks in Washington during the period 1985-1993. Sites are identified in Figures 16-17.

	1-hour Maximum (ppb)								
Site #	1985	1986	1987	1988	1989	1990	1991	1992	1993
53-009-0012	-	-	70	40	65	64	56	63	
53-011-0011	-	-	-	120	98	124	102	121	
53-011-1001	100	100	-	-	-	-	-	-	
53-033-0010	120	130	110	140*1	90	126*1	109	94	
53-033-0018	-	-	-	-	100	119	-	-	
53-033-0088	-	-	-	-	-	102	101	-	
53-033-2001	90	80	-	-	-	-	-	-	
53-033-7001+	100	120*1	140	110	100	149*3	112	108	
53-053-0004	90	100	-	-	-	-	-	-	
53-053-0005+	100	110	100	110	-	-	-	-	
53-053-1001+	110	100	110	110	-	-	-	-	
53-053-1008+	-	-	110	110	103	130*2	99	103	
53-053-1009+	-	100	110	110	-	-	-	-	
53-053-1010+	-	-	-	-	-	-	-	-	87
53-061-2001	110	90	-	-	-	-	-	-	
53-073-0005	-	-	-	-	52	83	82	72	

*(#) - Number of exceedances of primary standards (NAAQS) for a pollutant (see Table 1).
\+ - Indicates ozone monitors in closest proximity to MORA.

Nitrogen dioxide (Table 26) and sulfur dioxide (Table 27) generally were low throughout the region, although one exceedance of the 24-hour maximum standard for sulfur dioxide occurred to the northeast of MORA in 1989. No exceedances occurred for the annual arithmetic mean standard for sulfur dioxide.

Table 26.Summary of nitrogen dioxide data from the EPA AIRS (Aerometric Information Retrieval System) Monitoring Sites within 100 km of the class I national parks in Washington during the period 1985-1992. Sites are identified in Figures 16 and 17.

	Annual Arithmetic Mean (ppb)		
Site #	1985	1986	1987
53-033-0080	19	18	13
53-033-0082	34	32	35

These data indicate that currently, ozone is the primary gaseous pollutant posing a threat to vegetation in MORA. With the rapidly growing urban population nearby, future problems with elevated ozone may increase.

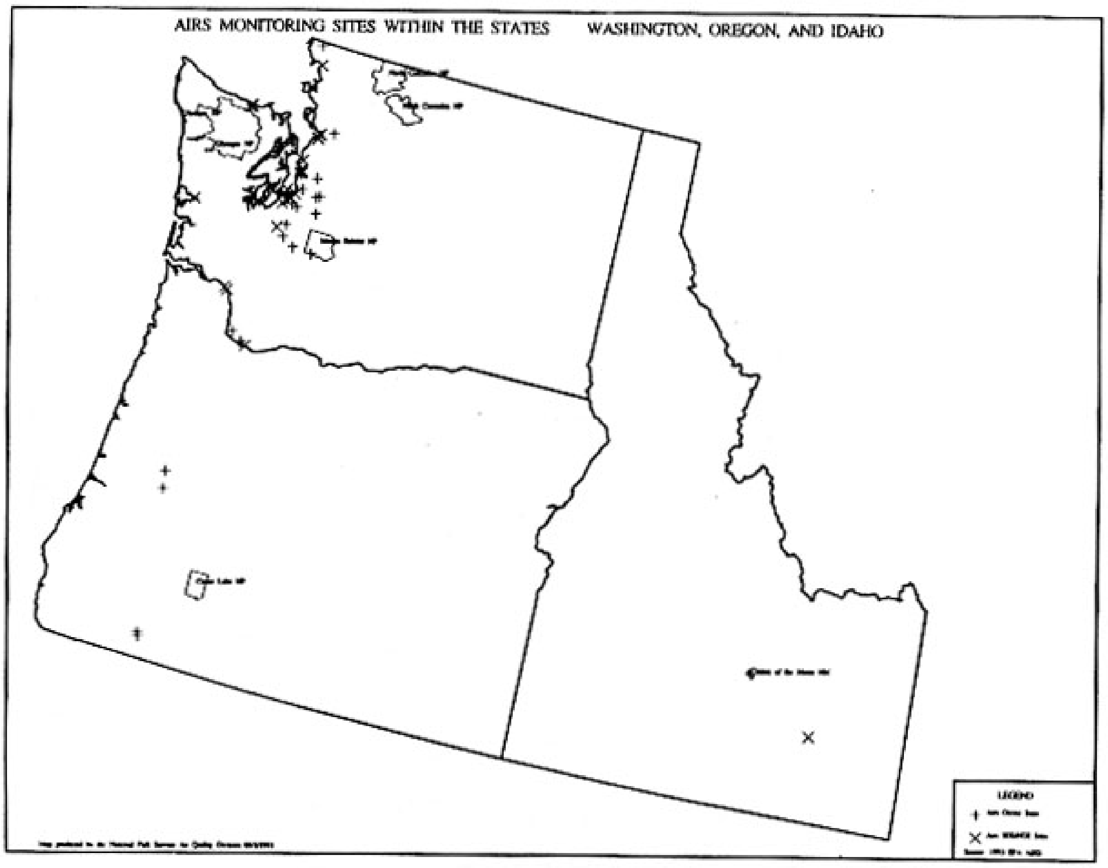

Figure 16. Location of EPA AIRS monitoring sites within the states of Washington, Oregon, and Idaho.

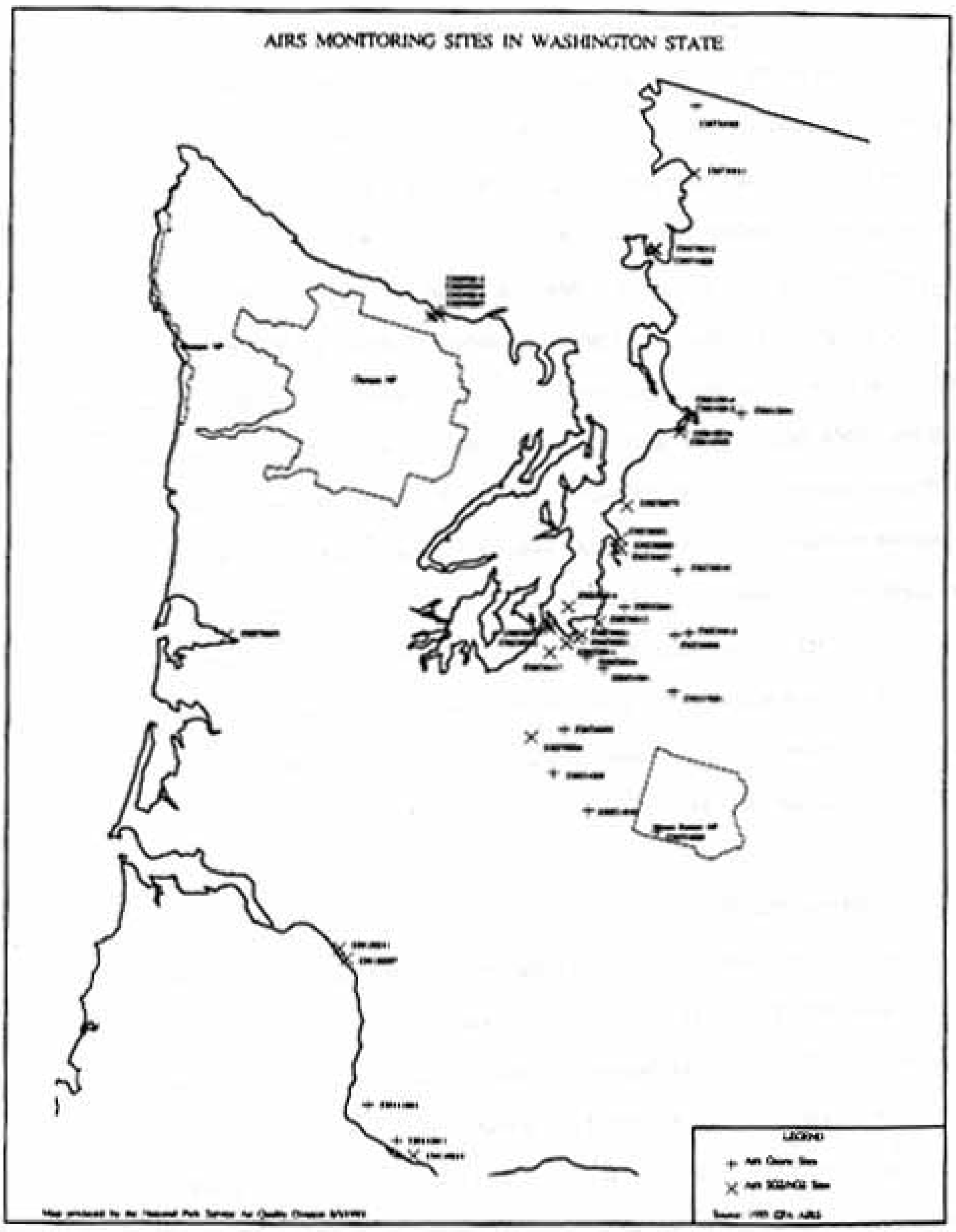

Figure 17. Location of EPA AIRS monitoring sites within the state of Washington.

Figure 17.Location of EPA AIRS monitoring sites within the state of Washington.

(iv) Particulates

Fine particulates are measured as part of the IMPROVE network. During the period 1988-1991 (Sisler et al. 1993), aerosols at MORA were identified as acidic primarily due to sulfate. The overall concentration of aerosols was high for the western United States, but less than half as much as values on the east coast. Light extinction due to coarse particles was low. The component of light extinction was high for organic carbon and low for nitrate.

MORA was also a PREVENT site (Malm et al. 1993 [in review]). PREVENT was a short-term study conducted to apportion atmospheric aerosols to scattering/extinction and to source types at MORA (Tahoma Woods, Paradise) and at NOCA (Marblemount). During the measurement period (summer 1990), fine mass concentrations were relatively high at MORA, compared to other locations in the western United States. About 60% of the fine mass was associated with carbon compared to 20-30% in most rural areas elsewhere in the United States. About 30% of the mass was attributed to sulfates, 5% to nitrates, and 5% to soils. The standard visual range was about 45 km. Precision models indicated that about 50% of the organics at Mount Rainier had an urban-origin, 10% was associated with fire activity, and 40% was attributed to soil. Nitrate input at Mount Rainier, measured in particulate and acid vapor forms in 1986 by Pankratz and Zwicker (1987), was determined to be quite low.

(v) Trace Metals/Contaminants

Hair shed by mountain goats was collected in MORA and analyzed for Pb and As (Frenzel and Starkey 1987). Concentrations of these trace contaminants (suspected origin was presumed to be the ASARCO smelter) were lowest in MORA compared to samples collected from OLYM and NOCA. The presumption was that most of the metals were deposited close to the smelter. Concentrations were considered low and did not indicate potentially toxic accumulations. A sample of lichen species from MORA and NOCA (Frenzel et al. 1990) indicated that the northwest portion of MORA might have accelerated deposition of As, Zn, Cu, and Cd. The concentration of trace metals, however, generally was similar to values reported for remote, and underdeveloped areas. Therefore, more comprehensive data are needed before valid conclusions can be drawn.

b. Water Quality

The water quality in MORA has been characterized in many studies. The Western Lake Survey (WLS) sampled five lakes in the park (Landers et al. 1987, Eilers et al. 1987). One of the lakes sampled was a dilute, low-ANC system that was among the most sensitive lakes sampled in the survey. The SW Golden Lake (4B1-069), located on the west side of the park, had SO_4^{2-} and ANC concentrations of 12 μeq/L with an extractable Al concentration of 37 μg/L, one of the highest values measured in the region. The lake is small (2 ha), relatively shallow (6 m), and is the type of lake that would be expected to respond quickly to changes in atmospheric deposition. Before the WLS survey, lakes adjacent to the park were sampled as part of the WDOE High Alpine Lake Sampling in 1983-85. The 11 lakes east of the park in the south-central Cascades were quite sensitive with almost half the sample lakes having ANC $\leq$ 50 μeq/L (WDOE 1988). Nitrate concentrations in this lake group were the lowest (x = 2.9 μeq/L) among the five groups of lakes summarized in the water quality report.

Additional studies of lakes in MORA were conducted by Turney et al. (1986), Nelson and Baumgartner (1986), and Larson et al. (1992). Neither Turney et al. (1986) nor Nelson and Baumgartner (1986) found evidence for lake acidification in the MORA lakes. Nelson and Baumgartner (1986) found that the 16 lakes sampled were "highly susceptible to acidification due to their diluteness and poor buffering capacity." Sulfate concentrations in the lakes averaged nearly 23 μeq/L, but Nelson and Baumgartner (1986) did not attribute these concentrations to watershed sources. The minimum ANC of their sampled lakes was 17 μeq/L.

The analysis by Larson et al. (1992) included chemical and biological sampling of 27 lakes in MORA. The principal focus of the study was to test interactions between watershed and lake features. Sulfate was not measured although pH, alkalinity, nitrate, and nutrients were measured. Cursory examination of these data is consistent with the findings of the previously cited studies for MORA about lack of evidence of acidification. Two lakes, St. Andrews and GO2, were reported to have alkalinity values of 10 and 12 μeq/L, respectively.

Park staff have been monitoring up to 19 lakes since 1988 (Table 28). Of these lakes, Eunice, Green, and Mowich Lakes are located in the northwest corner of the park and Crescent, James, and Ethel Lakes are in the north-central portion of the park. Sampling includes vertical profiles of temperature and DO; top (1 m) and bottom (1 m off bottom) samples for pH, ANC, and conductivity; vertical tows for zooplankton; 1 m (or 2 m for Mowich) phytoplankton sample; chlorophyll samples at 1 m and at the light compensation depth; and nutrients and ions at 1 m

Table 28. Benchmark lakes sampled during the period from 1988 through 1993. The numbers represent the frequency of lake sampling per year.

Location	1988	1989	1990	1991	1992	1993
Bench	3	1	2	2	2	2
Clover	2	1	2	3	2	2
Louise	2	1	3	3	2	2
Mowich[a]	8	1	2	3	12	8
Reflection	2	1	3	3	2	4
Snow	2	1	3	3	2	2
Green	2	0	3	2	2	2
U. Palisades	2	0	2	3	2	2
Eleanor	2	0	0	0	2	2
Eunice	2	1	0	0	2	2
James[b]	2	2	0	0	1	1
Shadow[b]	2	0	2	0	1	1
Sunrise[c]	2	0	1	0	0	2
Shriner	2	0	0	0	2	2
Tipsoo[b]	2	0	0	0	1	1
George	2	0	0	0	2	2
Ethel[b]	1	0	0	0	1	1
L. Palisades[c]	0	1	0	0	0	2
Hidden[c]	0	1	0	0	0	2

[a] Mowich sampled biweekly from late June through end of October
[b] Lakes will continue to be sampled once in summer (August or early September)
[c] Lakes to be sampled again in 1994 as part of a separate project

(several different depths for Mowich), and 1 m off bottom once during the summer (August or early September) (B. Samora, pers. comm.).

Studies of individual lakes in the park include Larson (1969) and Hall (1973). Mowich Lake, first studied by Larson (1969), was resampled in 1988-1989 (M. Hurley unpublished data). Subalpine ponds in the Reflection Lakes area were recently studied as part of a graduate research project (S. Girdner, MS Thesis, In Prep); baseline information on the Reflection Lakes was gathered by Funk et al. (1985).

Studies of large streams in the park were initiated by Larson et al. (1990) who sampled the water quality in both glacial and nonglacial streams. In general, the larger streams in the park are relatively well buffered and are not expected to be sensitive to effects from atmospheric deposition. It is unknown if this sample can be extrapolated to the smaller streams.

c. Terrestrial

A partial species inventory of the park vascular flora is maintained on the NPFLORA database (Waggoner 1989). More information is available on the native flora for MORA than for any other park in the Pacific Northwest. A fairly complete collection of lichens and bryophytes is stored in an herbarium collection. Species listings of mushrooms, fungi, and slime molds are available for several park locations. A partial listing of threatened, endangered, sensitive, and rare plant species have been compiled by Tanaka (1979), Rochefort (1986), NPS (1991), and Kertis and Agee (1985). There are no Federally listed plant species, but several species are on the state T&E list. Lists of endangered, threatened, and sensitive vascular plants of Washington State, by county, are also available from the Washington State Department of Natural Resources.

Animal species periodically are inventoried, but the inventory is incomplete. Little information exists on the gray wolf, several species of salamander, and frog, goshawk, or wolverine. Only one animal, the northern spotted owl, is on the USFWS threatened and endangered list. Bald eagles and peregrine falcons migrate through the park, but have not been recorded as nesting in the park.

The geology of the area is described in detail by Harris (1990). Soil temperatures were studied by Greene and Klopsch (1985). Hobson (1976) developed a soil classification system for the park, but soil maps of the park are not yet available.

Frenzel et al. (1990) examined heavy metal concentrations in one arboreal lichen species collected 50 km SE of a copper smelter in Tacoma, Washington. They found significantly higher concentrations of several heavy metals in lichens at MORA, compared to a more pristine area. Yet, overall concentrations of heavy metals were still far below toxic levels. They concluded that there might be potential for contamination by heavy metals in the park in the future with the increasing industrialization and human development of the Puget Sound area.

Bledsoe et al. (1985) documented S and As in vegetation and soils near industrial sources of pollutants in Tacoma and Centralia, but pollution was not detected as far as MORA. Xue and Harrison (1991) looked at the fate of sulfate in forest soils and the relation to soil Al, Fe, and pH. Recently, three old growth stands in MORA were part of a study to determine if forests in the Puget Sound area exhibited radial growth reductions due to ozone (Brubaker and Ford 1993). Growth patterns did not exhibit an ozone effect, however, we consider the results to be inconclusive. A new study for monitoring ozone and effects on vegetation is underway in the Goat Rocks Wilderness (Horner and Peterson 1993). Additional studies of ozone effects on vegetation are soon to be initiated in MORA by Dr. David Peterson, Cooperative Park Studies Unit, University of Washington, Seattle.

4. Sensitive Receptors

The review of relevant literature that formed the basis for these recommendations is presented in Appendix D.

a. Aquatics

There are clearly sensitive aquatic receptors in MORA. Lakes throughout the park, especially those on the west side, would be considered highly sensitive receptors to atmospheric deposition. The MORA staff have recognized the importance of developing a systematic data set on selected lakes around the park. It may be prudent to ensure that one or more of the low-ANC lakes (e.g., ~10 µeq/L) be added to those lakes sampled routinely or substituted for higher ANC lakes currently being monitored.

Within the low-ANC lakes, populations of amphibians would be among the biota most sensitive to acid stress. Again, NPS staff have already initiated an investigation of amphibian distribution and reproductive success in selected lakes and ponds. To the extent possible, the geographic emphasis should be placed on conducting these studies on the west side of the park.

b. Terrestrial

With regard to ambient air quality near MORA, sulfur and nitrogen deposition presently are too low to cause much concern about effects on terrestrial resources. Regionally, the highest potential for air quality to impact terrestrial resources is associated with ozone near industrialized urban areas and rural areas downwind. Until recently, there has been no research to determine the effects of ozone on terrestrial resources in MORA. Consequently, this assessment of potentially sensitive species in the park is based on research conducted in other ecosystems, on related species or taxa of organisms.

Much of the research effort over the past 50 years to document air quality effects on terrestrial vegetation has focussed on documenting forest growth and physiological condition in relation to "forest decline", and on establishing dose-response functions for economically important tree species (Smith 1990). Less effort has been directed to the study of mosses and lichens, except near heavily-polluted areas of Great Britain, Europe and Canada (Bates and Farmer 1992). There are only a few studies of the effects of pollutants on lichens in the Pacific Northwest (Denison and Carpenter 1973, Hoffman 1974, Denison et al. 1977, Johnson 1979, Taylor and Bell 1983, Rhoades 1988). Physiological studies of dose-response functions have yielded the most conclusive results, but the high cost of these studies has limited their applicability.

More information is available on ozone effects than on N and S effects. The most comprehensive ozone research has been conducted in the mixed-conifer forest and other vegetation types of California, on the dominant, commercially important tree species (Miller et al. 1989; Peterson et al. 1987, 1991, 1992 a,b; Horner and Peterson 1993). Few data are available to relate ozone dose or exposure to mature trees, and almost no data exist for herbaceous species.

Provisional lists of potentially sensitive vascular plant species indigenous to MORA are presented in Table 29. A listing for lichen and moss species is provided in Table 30. This list of potentially sensitive species is only a preliminary compilation of known or suspected sensitive plants. The information should be viewed as largely preliminary, due to the limited database. Sensitivity classes for vascular plants, lichens, and bryophytes have been developed to summarize the high variability in response to different pollutants that has been documented within plant species. The wide range of variability in plant responses to pollutants is attributable to differences in research methodology, environmental conditions, and to natural variability in species sensitivity. Specific values for pollutant sensitivity are listed where data exist. The application of much of this sensitivity data to the Pacific Northwest must be undertaken with caution because the data are mostly from laboratory fumigation experiments on seedlings and have not been field tested on mature trees. The reliability of extrapolating pollutant responses from the laboratory to the field and from seedlings to mature trees is questionable, and studies are currently underway at EPA, Corvallis to compare results (Bates and Farmer 1992; Peterson et al. 1992a,b; Stolte et al. 1993a,b).

In general, reliable data on the sensitivities of vascular plants, bryophytes, and lichen flora to air quality in MORA are lacking. Limitations of the existing data on terrestrial vegetation include:

Table 29. Partial list of potentially sensitive vascular plant species in MORA.

		Sensitivity[a]		
Common Name	Scientific Name	Ozone	Sulfur	Nitrogen
Pacific silver fir	*Abies amabilis*	UK	L	UK
Rocky Mountain maple	*Acer glabrum*	X	M	UK
Bigtooth maple	*Acer macrophyllum*	X	UK	UK
Alders	*Alnus* species	M (120-300)	H	UK
Serviceberry	*Amelanchier alnifolia*	X	UK	UK
Ceanothus	*Ceanothus velutinus*	UK	L	UK
Dogwood *Corylus cornuta*	UK	H	UK	
Junipers *Juniperus* species	UK	L	UK	
Honeysuckle (twinberry)	*Lonicera involucrata*	L	L	UK
Lupines *Lupinus* (any species)	X	UK	UK	
Engelmann spruce	*Picea engelmanni*	UK	M	UK
Sitka spruce	*Picea sitchensis*	UK	M	UK
Whitebark pine	*Pinus albicaulis*	UK	UK	UK
Lodgepole pine	*Pinus contorta*	M (100 ppb)	M (SO_2 40 ppb)	H
W. white pine	*Pinus monticola*	M (100 ppb)	M	UK
Ponderosa pine	*Pinus ponderosa*	H (80-100)	M/H (SO_2 40 ppb)	H
Balsam poplar	*Populus balsamifera trichocarpa*	H	M	UK
Quaking aspen	*Populus tremula tremuloides*	H (40 ppb)	H	UK
Aspen	*Populus* species	H	H	UK
Choke cherry	*Prunus emarginata*	X	M	UK
Douglas-fir	*Pseudotsuga menziesii*	L/M (100 ppb)	M/H (SO_2 65 ppb)	H
Golden currant	*Ribes divaricatum*	X	UK	UK
Western thimbleberry	*Rubus parviflorus*	X	UK	UK
Blueberried elder	*Sambucus caerulea*	X	UK	UK
Western hemlock	*Tsuga heterophylla*	UK	M	UK
Mountain hemlock	*Tsuga mertensiana*	UK	H	UK
Big huckleberry	*Vaccinium membranaceum*	X	UK	UK
Bog blueberry	*Vaccinium occidentale*	X	UK	UK

[a] X = known or suspected; H = high; M = moderate; L = low; UK = unknown.

[b]A general range of sensitivities to ozone is 60-90 ppb for conifers, 70-120 ppb for hardwoods, 7-h growing season means.

Source:Esserlieu and Olson (1986); Lefohn 1992; Peterson et al. (1992a,b); Horner and Peterson (1993); Forest Health Monitoring Program (1993)

Table 30. Partial list of lichen and moss species that have documented responses to pollutants.

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Alectoria sarmentosa*	L	O_3 (H) PAN	F	CA, USA	3,5	Sigal and Nash (1983)
- *Bryoria abbreviata* *B. fremontii* *B. oregana*	L	O_3 (H) PAN	F	CA, USA	1,2,3,4 1,2,3,4,5 1,3	Sigal and Nash (1983)
- *Calicium viride*	L	O_3 (H) PAN SO_2 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
- *Cetraria islandica*	L	NH_4 NO_3 O_3 (H) SO_2 (M) F (M)	F	SWED	1,2,3,4,5	Gerhardt and Kellner (1986)
C. canadensis	L	O_3 (H) PAN	F	CA, USA	2,4	Sigal and Nash (1983)
- *Cladina portentosa*	L	NO_x	F	NETH	1	Sochting and Johnsen (1990)
C. rangiferina	L	NH_4 SO_2 (M-H) F (M) NO_3	F	SWED	1,3,4,5	Gerhardt and Kellner (1986)
		HNO_3	F	FRG, USA CAN		Scott and Hutchinson (1989)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
C. stellaris	L	H^+	L		4	Lechowicz (1982)
		H_2SO_4/HNO_3 pH 2.5-3.0	L			Scott and Hutchinson (1987)
- *Evernia prunastri*	L	O_3 (H)	F	CA, USA	1,3,4,5	Sigal and Nash (1983)
		PAN F (H) S	L, F F	CA, USA		Nash (1988)
		SO_2 (3.0 ppb,	F	USA		Johnson (1979)

		L-M)				
- *Hylocomium splendens*	M	H^+ SO_2 (H) F (M)	F	UK	1,3,4,5	Farmer et al. (1992a)
- *Hypogymnia enteromorpha*	L	O_3 (L-M)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)
		PAN	L, F			Nash (1988)
		O_3 (800 ppb, L-M) SO_2 (L-M)	L			Nash and Sigal (1979)

Table 30. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Isothecium myosuroides*	M	H^+	F	UK	1,3,4,5	Pitkin (1975)
- *Lobaria pulmonaria*		O_3 (L-M)				
	L	H^+	F	UK	1,2,3,4,5	Gilbert (1986)
		H_2SO_4 SO_2 (H)				Denison et al. (1977)
- *Nephroma arcticum*	L	NH_4^+ O_3 (H) SO_2 (H) NO_x PAN (H)	L, F	SWED	3	Nohrstedt et al. (1988)
- *Parmelia caperata*	L	SO_2	F	UK	1,2,3,4,5	Gilbert (1992)
		O_3 (800 ppb) PAN	L			Nash and Sigal (1979)
		O_3 (200 ppb)				Ross and Nash (1983)
P. sulcata	L	NO_x PAN (M-H) SO_2 (70 ppb, L-H) F (M-H)	L, F	SWED	1,2,3,4,5	von Arb et al. (1990)
		O_3 (500 ppb, M-H)	L			Nash and Sigal (1979)
- *Peltigera aphthosa polydactyla*	L	H^+ O_3 (H) SO_2 (M) NO_x/PAN (M-H)	L		1,2,3,4,5	Fritz-Sheridan (1985)
	L	NH_4^+ SO_2 (M)	L, F	SWED		Nohrsted et al. (1988)
- *Physodes* species	L	SO_2 SO_4 NO TM		FRG, USA CAN	1,2,3,4,5	Scott and Hutchinson (1989)
- *Platismatia glauca*	L	O_3 (H)	F	CA, USA	1,2,3,4,5	Sigal and Nash (1983)

		PAN				
		SO_2 (10 ppb,M)	F	EST		Trass (1973)
- *Pleurozium schreberi*	M	H^+	F		3,4,5	Kellner and Marshagen (1991)
		SO_2 (700 ppb, M-H)	L	CAN		Winner and Bewley (1983)
						Winner (1988)

Table 30. Continued

Species	ID[a]	Pollutant[b]	Study Type[c]	Source[d]	Park[e]	Reference
- *Pseudevernia* species	L	SO_2 SO_4 NO_3 TM	F F F F	FRG, USA, CAN	4	Scott and Hutchinson (1989)
- *Rhytidiadelphus triquetrus*	M	H^+	F	UK	1,3,4,5	Farmer et al. (1992b)
- *Sphagnum* species	M	SO_2 (H) F (H) bisulphite	F	UK	1,3,4,5	Ferguson and Lee (1983)
- *Tortula ruralis*	M	H^+ SO_2 (L)	L		1,2,3,4,5	Sheridan and Rosentreter (1973)
- *Usnea* species	L	O_3 (H) S	L, F	CA, USA	1,2,3,4,5	Nash (1988)
		SO_2 (3.0 ppb)	F	USA		Johnson (1979)
		(10.0 ppb, M-H)	F	EST		Trass (1973)

Footnotes:

[a] L = lichen, M = moss.

[b] Pollutant type: O_3 = ozone; NO_3 = nitrate; H^+ = acidity; SO_4 = sulfate; H_2SO_4 = sulfuric acid; PAN = peroxyacetyl nitrate; NH_4 = ammonium; NO_x = nitrogen oxides; SO_2 = sulfur dioxide; TM = trace metals; HNO_3 = Nitric acid

Values in parentheses include the pollutant concentration used in the study. Letters in parentheses refer to ratings of low (L), medium (M), or high (H) sensitivity to a specific pollutant, as listed by Peterson et al. (1992a), Appendix B.

[c] Study type: F = field; L = Laboratory; blank = unknown.

[d] Source: location where study was performed.

[e] Species occurrence in a class I national park. 1 = CRLA, 2 = CRMO, 3 = MORA, 4 = NOCA, 5 = OLYM.

(1) lack of park-specific or regional data, (2) lack of testing for laboratory dose-response data under field conditions, (3) poor correspondence between visual injury estimates and dose-response functions, and (4) lack of information on non-commercial species. Esserlieu and Olson (1986) attempted to rank the vulnerability of national parks to atmospheric pollutants by evaluating the potential sensitivities of park flora and surface waters to pollutants. However, limitations of the emissions and deposition data, as well as the plant sensitivity data compromised the validity of the conclusions. Therefore, we have not included this study in the present analysis. For a general overview of ecosystems and plants that exhibit general sensitivities to various pollutants, see Appendices D.2.

Information on the effects of air quality on wildlife is scarce. Most studies have focused on the hazards of toxic contaminants, mainly heavy metals and industrial solvents in water (Kilkelly Environmental Associates 1989). Furthermore, few data exist with which to assess specific impacts of air quality on wildlife in the class I national parks.

Based on the data evaluated in this report, we conclude that at present, air pollutants posing a significant threat to terrestrial resources in MORA include ozone and, potentially, acid deposition in cloud water or fog. Ozone values above 60-80 ppb can be assumed to effect many plant species (Peterson et al. 1992a,b; Horner and Peterson 1993). Acidic fog (< pH 4.0) due primarily to SO_4^{2-}, can potentially harm vegetation in the park, although data on exposure and dose-response functions for plants are not adequate to assess current risk.

5.Monitoring and Research Needs

Although MORA is probably one of the best characterized parks in the region, there still remains a considerable need for monitoring and research because of the sensitivity of the resources and the park's proximity to air pollution sources. These recommended monitoring and research needs are summarized in Table 31 and discussed in greater detail below.

a.Deposition

Wet deposition is monitored 25 km west of MORA near La Grande at an elevation of 617 m. The westward orientation of the site is appropriate given the location of emission sources to the west, but it is uncertain how well the site characterizes deposition at the higher elevations in the park. We recommend that one or more snow sites be sampled on the west side of the park for two or more years to determine the relation between pollutant concentrations at the NADP/NTN site and the snow chemistry on the west side of the park.

A dry deposition monitoring station is currently planned for implementation at Paradise in 1995 on the south side of the park. Most of the air masses of concern seem to enter the park from the west and northwest; thus, the location of the Paradise site may underestimate maximum pollutant exposures in the park. Locating monitoring stations at Paradise is understandable because of favorable access considerations, but it is also likely that this site is not optimal with respect to measuring maximum pollutant loadings to the park. Snowpack accumulations of sulfur and nitrogen or measurements of bulk deposition on both the northern and southern sides of the park could be compared with dry deposition monitoring data to resolve this issue.

b. Aquatics

Several studies have been conducted on the chemistry of lakes in MORA during summer and fall. Several lakes were sampled that had ANC < 20 μeq/L. Likely the ANC values of these lakes would be lower during the spring and early summer snowmelt period (cf. Loranger and Brakke 1988, Smayda 1986). Consideration should be given to conducting research on episodic effects on the west side of the park. In particular, the northwest quadrant of the park is of concern because of the recent recognition of the chemistry in Summit Lake, located about 10 km from the NW park boundary in the Clearwater Wilderness of the Mount Baker-Snoqualmie National Forest. Summit has an ANC near 1 μeq/L and a nonmarine SO_4^{2-} concentration of over 7 μeq/L (Eilers and Bernert, unpublished data). Most of the base cations in the lake can be accounted for on the basis of precipitation and evaporation. Thus, nearly all of the SO_4^{2-} in Summit Lake may have originated from atmospheric sources. If this is the case, it would be prudent to conduct a thorough baseline characterization of lakes on the west side of the park. One or more low-ANC lake on the west side of the park might be an appropriate site to conduct more thorough analyses of both chronic and episodic acidification. We believe that the NPS should give high priority to investigating lake chemistry in MORA, particularly on the west side. The small, shallow lakes not receiving runoff from glaciers would be the most likely candidates for first showing a chemical response to acidification.

Although no acidic lakes have been sampled in the park to date (excluding one lake with watershed contributions of SO_4^{2-}), we believe that it is important to further investigate this issue because of:

1. Proximity of the park to major emission sources, including the largest SO_2 source in the region.

2. Deposition chemistry at LaGrande which suggests slightly elevated SO_4^{2-} deposition.

3. Presence of low-alkalinity lakes in the park.

4. Recent indication of possible acidification of a lake immediately outside the park.

c. Terrestrial

Additional inventory is needed for bryophytes and lichens as well as for T&E plant and animal species. A detailed soils inventory combined with data on vegetation communities in a GIS format also would be useful in future assessments of air quality effects on terrestrial resources. Soil cation exchange capacity and mineral weathering figures into the determination of critical loads, especially for S. Soil survey data is used in the MAGIC model to calculate critical loads of sulfur for forest soils (Frogner et al. 1992). Soils information is particularly useful for modeling aquatic response to acidic deposition. The need for additional monitoring and research is especially urgent to assess effects of acid deposition and acid fog, as well as ozone, particularly on high-elevation forests in the western portion of this park. Due to inherent limitations in the methods, however (see Appendix D), lichen chemistry studies may be used more effectively to determine the source or cause of severe N or S pollution (isotope analysis) than to detect gradual deterioration in air quality before significant impacts occur to ecosystems.

We offer a general approach to study ozone effects on terrestrial vegetation in class I national parks, based primarily on information presented in Olson et al. (1992), Bates and Farmer (1992), and Stolte et al. (1993a,b). Key points include the selection of (1) sensitive receptor(s) and (2) study methods.

Given funding limitations, it is practical to focus efforts on the most sensitive organism or component of an ecosystem. This can also save time and money in the design of monitoring programs. Candidate species should be selected based on ozone sensitivities and plant geographic distribution in relation to known pollutant exposures in class I areas. These decisions should be based on exhaustive reviews of existing literature by technical experts.

Physiological studies of plant dose-response usually provide the most quantitative results, although they are more expensive and time-consuming, and thus too costly to implement at many field locations. Plant physiological processes are usually affected first by pollutants, but visible symptoms are easier to measure. On the other hand, although descriptive studies such as injury surveys are easier to implement on a large scale, they are more subjective and easily confounded by factors other than air quality (especially in natural ecosystems).

In our opinion, the best approach for studying vegetation response to ozone would be to combine quantitative dose-response and descriptive approaches beginning with carefully controlled physiological studies in both the laboratory and field (for trees, include seedlings and larger trees). Descriptive data on morphological symptoms of plant injury due to pollutant exposure should also be collected. Once dose-response functions and injury symptoms have been documented, the findings should be tested using natural gradients in pollutant exposure in the field. If the experimentally measured dose-response functions and visual symptoms of injury agree in the lab and field, the data can then be manipulated through modeling to test individual species responses at population and landscape levels.

The primary monitoring needs to protect terrestrial vegetation in the Pacific Northwest at the present time include improved monitoring of ozone at rural locations near class I areas, and cloud chemistry at higher elevations in the Cascade Range. Protocols should be established for data collection and analysis to ensure high-quality results. With regard to injury surveys, problems, opportunities to improve field-level research.

Additional needs for research and monitoring also include the dispersion of pollutants in relation to the complex meteorology and terrain of the Cascades. Local conditions in the Cascades generally result in elevated ozone south and east of major metropolitan areas below elevations of 1200 m. Exceptions occur when a temperature inversion dissipates with a marine frontal intrusion that pushes pollutants over the Cascades. This event is less common than pollution episodes at lower elevations, but there is the potential for high ozone levels (> 100 ppb) in class I areas of western Washington when it happens. Additional research and monitoring of these meteorological events is needed to determine which geographic areas may be at highest risk from ozone damage.

6. References for Mount Rainier National Park

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

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.

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.

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.

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

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.

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.

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.

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.

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

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.

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

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

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.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.

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.

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.

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.

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.

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

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.

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

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

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. of Forest Research 21:733-738.

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.

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.L., 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., 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.

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

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.

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.

Nash, T.H. III. 1988. Correlating fumigation studies with field effects. In: Lichens, Bryophytes, and Air Quality. Bibl. Lichenol. 30:201-216. J. Cramer, Berlin.

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

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

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.

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

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.

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.

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.

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.

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

Ross, L.J. and T.H. Nash III. 1983. Effect of ozone on gross photosynthesis of lichens. Environmental and Experimental Botany 23:171-177.

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 Phytologist 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.

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.

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.

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, 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.

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.

Tanaka, W. 1979. Rare, endangered, threatened, and endemic plant species in designated places of developed areas of Mount Rainier National Park, Washington.

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 Science 57(3):157-166.

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

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.

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.

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.

Washington Department of Ecology. 1988. Air Quality Program 1993 Annual Report. Olympia, WA.

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

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

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 Botany 61:1456-1461.

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.