



Air Quality Related Values (AQRVs) for Klamath Network (KLMN) Parks

*Effects from Ozone; Visibility Reducing Particles; and
Atmospheric Deposition of Acids, Nutrients and Toxics*

Natural Resource Report NPS/KLMN/NRR—2016/1160



ON THE COVER

Photograph of air quality related values within various National Park units. Wildflowers, clear views, aquatic species, and lichens may all be threatened by air pollution.

Photographs courtesy of the National Park Service

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Natural Resource Report NPS/KLMN/NRR—2016/1160

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Summary

This report describes the Air Quality Related Values (AQRVs) of the Klamath Network (KLMN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The KLMN parks that are included in the National Park Service (NPS) Inventory and Monitoring (I&M) Program and discussed in this report are Crater Lake National Park (CRLA), Lassen Volcanic National Park (LAVO), Lava Beds National Monument (LABE), Oregon Caves National Monument (ORCA), Redwood National Park (REDW), and Whiskeytown National Recreation Area (WHIS). Crater Lake NP, LABE, LAVO and REDW are Class I air quality areas and receive special protection against air quality impacts under the Clean Air Act (CAA); the other two parks are Class II areas.

Sullivan et al. (2011a, 2011b) and Kohut (2007) conducted risk assessments for acidification, eutrophication, and ozone (O_3) for the KLMN parks; their results are described in this report. This report also describes air pollutant emissions and air quality, and their effects on AQRVs in the KLMN. The primary pollutants likely to affect AQRVs include nitrogen (N) and sulfur (S) compounds (nitrate [NO_3^-], ammonium [NH_4^+], and sulfate [SO_4^{2-}]); ground-level O_3 ; haze-causing particles; and airborne toxics. Background for this section can be found in “Air Quality Related Values (AQRVs) in National Parks: Effects from Ozone; Visibility Reducing Particles; and Atmospheric Deposition of Acids, Nutrients and Toxics” (Sullivan 2016).

Air quality in the portions of California and Oregon within the KLMN region is among the best in the United States, in particular in remote sections of the Cascade Mountain Range, northern portions of the Sierra Nevada, and at some near-coastal locations (Sullivan et al. 2001). This is because the principal air masses that influence these areas are largely derived from the atmosphere over the Pacific Ocean. Air quality generally deteriorates further to the south in California, especially in the southern Sierra Nevada and near Los Angeles.

Sulfur and N pollutants can cause acidification of streams, lakes and soils. Park lands in the KLMN vary in their sensitivity to acidification. In a coarse screening assessment that evaluated relative risk of acidification in all I&M parks nationwide, CRLA and LAVO ranked as very sensitive (Sullivan et al. 2011) while REDW and WHIS ranked as sensitive. Differences in Ecosystem Sensitivity to acidification within KLMN parks were largely due to differing slopes and to the presence of high-elevation lakes and streams in some of the parks. Acid-sensitive waters are often located at relatively high elevation, on steep slopes having shallow, base-poor (having low amounts of adsorbed base cations) soils. All of the streams in LAVO and CRLA are low-order¹, which increases their potential sensitivity to acidification. A very high percentage of the lakes in LAVO are highly sensitive. Such lakes tend to be small, are situated in rather small watersheds, and are almost devoid of buffering capacity because of a combination of factors, including steep slopes, the predominance of base-poor bedrock that is resistant to weathering, thin soils, large amounts of precipitation, deep seasonal

¹ Low-order streams are the small tributary streams located at relatively high elevation, designated by Strahler Order, generally as first, second, or third order.

snowpacks, coniferous vegetation and extremely dilute waters. Current modeled and monitored acidic deposition levels in the KLMN are very low, however, and are not likely to have caused acidification impacts to aquatic ecosystems.

Nitrogen pollutants can cause undesirable nutrient enrichment of natural ecosystems, leading to changes in plant species distribution and diversity. A coarse screening assessment that evaluated relative risk of N enrichment effects in all I&M parks nationwide (Sullivan et al. 2011) found that ecosystem sensitivity to nutrient N enrichment was variable throughout the KLMN, with LABE ranked as very highly sensitive and LAVO as highly sensitive. Differences in ecosystem sensitivity among parks were due to differing coverage of vegetation types thought to be most sensitive to N deposition, and also to the presence of high-elevation lakes, which are often N-limited and therefore sensitive to increased N. The most sensitive indicator for aquatic ecosystems at CRLA is the transparency of Crater Lake. Transparency is influenced to a large degree by primary productivity. An increase in N contribution to the lake might increase algal growth and decrease transparency.

Ozone pollution can harm vegetative health, reduce plant growth, and cause visible injury to foliage. In 2012, LAVO experienced several exceedances of the O₃ National Ambient Air Quality Standard (NAAQS). However, because O₃ concentrations did not exceed the NAAQS during the two previous years, LAVO was not in violation of the standard and has not been designated as nonattainment. Ozone-induced foliar injury was documented at LAVO as part of the Forest Ozone Response Study (FOREST) in the early 1990s (Arbaugh et al. 1998), but the amount of plant injury was relatively low compared to national parks in the southern Sierra Nevada (Sullivan et al. 2001). Nevertheless, this injury represented a significant impact of air pollution at a location quite remote from urban air pollution sources in California.

Particulate pollution can cause haze, reducing visibility. Monitoring indicates that haze impairs visibility at all KLMN parks.

Atmospherically deposited toxic substances were evaluated at KLMN as part of the Western Airborne Contaminant Assessment Project (WACAP; Landers et al. 2010). Concentrations of semivolatile organic compounds (SOCs) were generally comparable to those in other surveyed parks in the western United States. Potential effects on park biota are not known.

Background

There are six parks in the Klamath Network (KLMN): Crater Lake National Park (CRLA), Lassen Volcanic National Park (LAVO), Lava Beds National Monument (LABE), Oregon Caves National Monument (ORCA), Redwood National Park (REDW), and Whiskeytown National Recreation Area (WHIS). Crater Lake NP, LABE, LAVO and REDW are Class I air quality areas and receive special protection against air quality impacts under the Clean Air Act (CAA); the other two parks are Class II areas. The KLMN contains three parks larger than 100 square miles: CRLA, LAVO, and REDW. Larger parks generally have more available data with which to evaluate air pollution sensitivities and effects. In addition, the larger parks generally contain more extensive resources in need of protection against the adverse impacts of air pollution.

Air quality in the KLMN is generally very good compared to most other areas of the United States (Eilers et al. 1994). The principal air masses that affect this region are largely derived from the atmosphere over the Pacific Ocean, and as a consequence, accumulated air pollutant levels are low. Emissions of air pollutants within the KLMN region are also generally low (Sullivan et al. 2001).

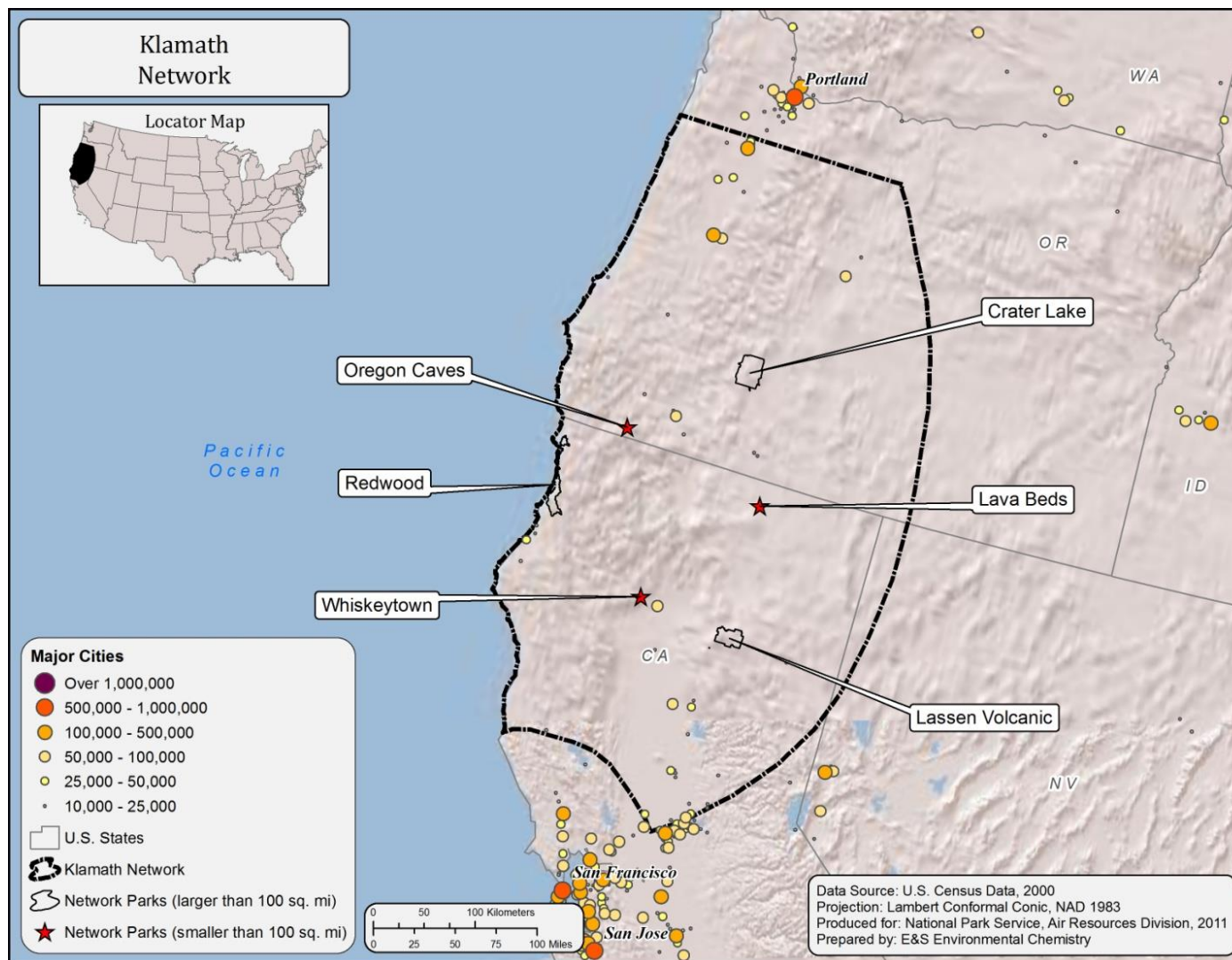
There are no population centers in the KLMN region larger than 500,000 people, and only two larger than 100,000. However, within a 300-mile radius around the network boundary are the large cities of San Francisco, San Jose and Sacramento to the south, and Portland and Seattle to the north. Map 1 shows the KLMN region, indicating locations of each park and of population centers with more than 10,000 people.

Given REDW's location in remote coastal northern California, combined with the prevailing northwesterly winds, the park is generally upwind of most emission sources. A portion of the monitored S deposition at REDW is derived from natural marine aerosols. Lassen Volcanic NP is located further inland than REDW in northern California, but is also relatively remote from urban areas. Nevertheless, emissions from the adjacent Sacramento Valley may affect air quality in LAVO (Sullivan et al. 2001). Lava Beds NM is also located in a remote region of northern California. Substantial transport of air pollutants to LABE from adjacent, more heavily developed areas in California is not expected (Sullivan et al. 2001). Based on a review of NPS Class I areas in California, Sullivan et al. (2001) concluded that there were no significant air pollution concerns in LABE or REDW at that time. Monitored and estimated pollutant exposures were uniformly low, and there were no known or suspected adverse effects on sensitive AQRVs.

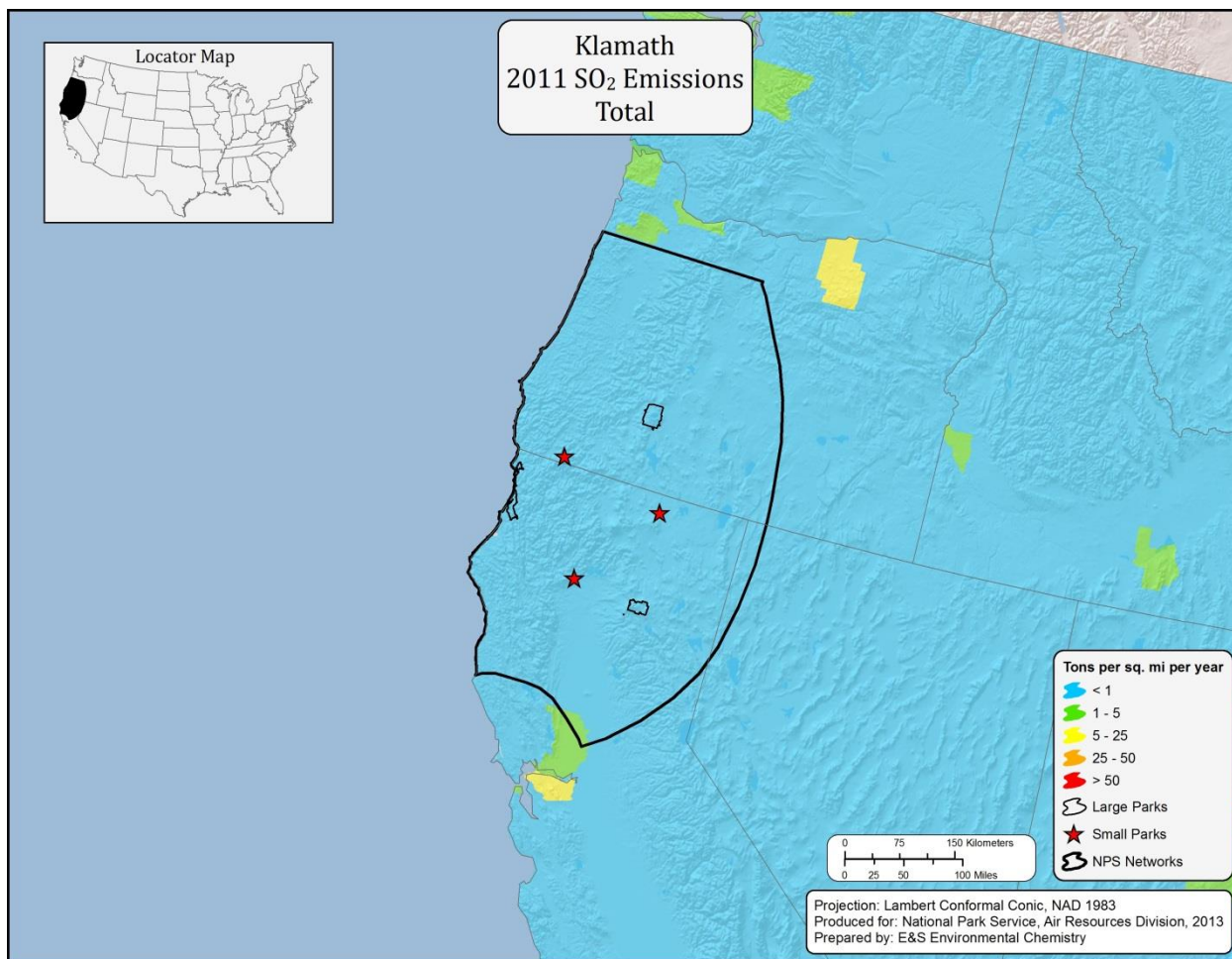
Atmospheric Emissions and Deposition

County-level sulfur (S) emissions within and near the KLMN region reported by Sullivan et al. (2011b) were generally less than 1 ton of sulfur dioxide (SO₂) per square mile per year (ton/mi²/yr), with only two counties having higher emissions, in the range 1 to 5 tons/mi²/yr. There were no SO₂ point sources greater than 5,000 tons/mi²/yr within the KLMN region. The majority of the relatively small SO₂ point sources were located in the Central Valley of California, in the southern half of the network region.

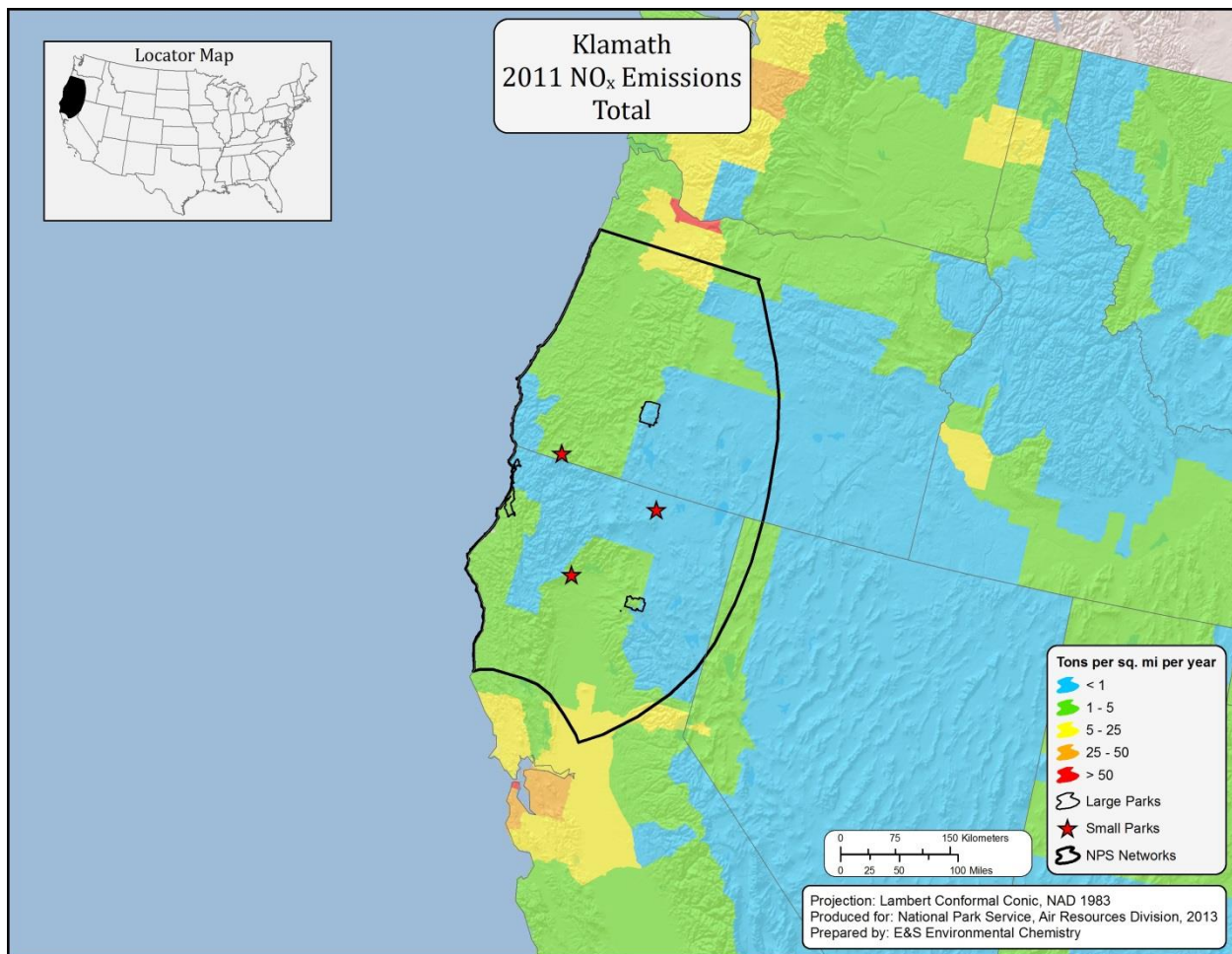
County-level nitrogen (N) emissions within the KLMN region ranged from less than 1 ton/mi²/yr to between 5 and 20 tons/mi²/yr. There were no large N point sources in the KLMN region (Sullivan et al. 2011b). The major sources of N emissions in the western United States, including the KLMN region, are transportation, agriculture, power plants and industry. Trans-Pacific transport of N from southeast Asia is also a source, but the amount is uncertain (Fenn et al. 2003b). According to data compiled by the state of California and the U.S. Environmental Protection Agency's (EPA) National Emissions Trends database, California was the only western state that had a decrease in oxidized N (NO_x) emissions during the period 1985 to 1999 (Fenn et al. 2003b).



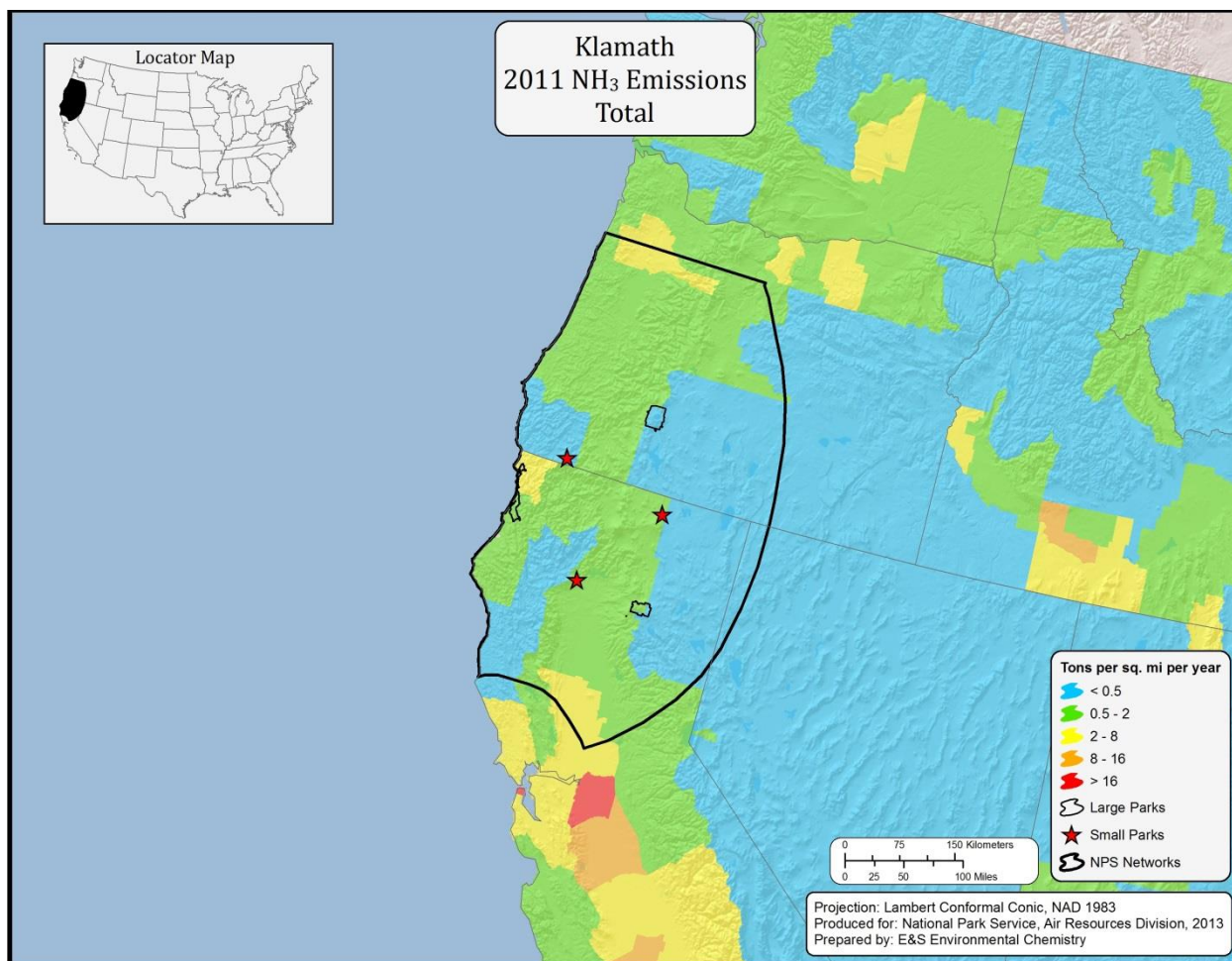
Map 1. Network boundary and locations of parks and population centers greater than 10,000 people within the KLMN region.



Map 2. Total SO₂ emissions, by county, near KLMN for the year 2011. Data from EPA's National Emissions Inventory.



Map 3. Total NO_x emissions, by county, near KLMN for the year 2011. Data from EPA's National Emissions Inventory.



Map 4. Total NH₃ emissions, by county, near KLMN for the year 2011. Data from EPA's National Emissions Inventory.

County-level emissions near KLMN, based on data from the EPA's National Emissions Inventory (NEI) during a recent time period (2011), are depicted in Maps 2 through 4 for SO₂, NO_x, and reduced N (NH₃), respectively. Throughout the network region, SO₂ emissions were < 1 ton/mi²/yr (Map 2). Spatial patterns in NO_x emissions showed somewhat higher values, in many places between 1 and 5 tons/mi²/yr (Map 3). Emissions of NH₃ near KLMN parks were between 0.5 and 2 tons/mi²/yr at many locations (Map 4).

Both SO₂ emissions and atmospheric sulfate (SO₄²⁻) concentrations measured at Interagency Monitoring of Protected Visual Environments (IMPROVE) sites decreased during the 1990s throughout much of the western United States (Malm et al. 2002). Decreases in emissions ranged from -37% in California to -8% in Idaho. Most of the NPS IMPROVE sites investigated by Malm et al. (2002) showed decreasing atmospheric SO₄²⁻ concentrations on the 20 percent haziest days during the period 1989 to 1999, but the trends were statistically significant at only 6 of 30 sites. The reduction was about 29% in REDW. In contrast, LAVO was one of only two sites that showed a statistically significant increase in atmospheric SO₄²⁻ concentrations on the clearest days. Atmospheric SO₄²⁻ concentrations on the 20 percent clearest days decreased at nearly all NPS

IMPROVE sites west of the Rocky Mountains. The only statistically significant increase was at LAVO (Malm et al. 2002).

Emissions of N and S in Asia are higher than in North America (Fenn et al. 2003b) and have increased dramatically in recent decades (Akimoto and Narita 1994). Emissions of N can be transported across the Pacific Ocean from Asia as peroxyacetyl nitrate (PAN), which has a lifetime in the atmosphere of days to weeks. Because of the comparatively short lifetime of NO_x in the atmosphere (generally less than 24 hr), conversion of NO_x to a longer-lived form (such as PAN) is necessary for long-range transport of N. Once in the troposphere, PAN can be transported long distances over a period of many days and then moved back into the boundary layer of the atmosphere, where it regenerates NO_x and nitric acid (HNO_3 ; Kotchenruther et al. 2001). Long-range transport of PAN from Asia to North America is well documented (Jaffe et al. 1999). Thus, it is likely that NO_x emissions in Asia contribute some, albeit an unknown amount of, N deposition to the western United States, including KLMN. If Asian NO_x emissions continue to increase as predicted (cf., Klimont et al. 2001, Streets and Waldhoff 2000), trans-Pacific sources of N may become more important to west coast locations of the United States in the future.

Total modeled S deposition throughout most of the KLMN region was less than 2 kg S/hectare/year (kg S/ha/yr) in 2002 (Sullivan et al. 2011b). Some portions of the KLMN region, mainly along the coastline, had S deposition values in the range of 2 to 5 kg S/ha/yr. Part of the coastal S deposition is undoubtedly of marine origin. Total modeled N deposition ranged from less than 2 kg N/ha/yr in the eastern portion of the KLMN region to as high as 5 to 10 kg N/ha/yr at scattered locations (Sullivan et al. 2011b). Atmospheric deposition in the Sierra Nevada and Cascade Mountains is largely influenced by local emissions (Sullivan et al. 2001). Wet N deposition in the Pacific Northwest is lower than in most of the rest of the conterminous United States (<http://nadp.sws.uiuc.edu/ntn/>). Based on National Atmospheric Deposition Program (NADP) data, wet N deposition has been less than 1.6 kg/ha/yr at 8 of 10 monitoring sites in the Pacific Northwest since the 1980s. Higher values (up to 3.2 kg N/ha/yr) have been recorded at the NADP sites just east of Seattle, WA and Portland, OR (Fenn et al. 2003b). Wet ammonium (NH_4^+) deposition, largely of agricultural origin, has been increasing at NADP sites in Washington and Oregon since 1980 when monitoring began.

Recently, Schwede and Lear (2014) documented a hybrid approach developed by the National Atmospheric Deposition Program (NADP) Total Deposition (TDEP) Science Committee for estimating total N and S deposition. This approach combined monitoring and modeling data. Modeling was accomplished using the Community Multiscale Air Quality (CMAQ) model (Byun and Schere 2006). Priority was given to measured data near the locations of the monitors and to modeled data where monitoring data were not available. In addition, CMAQ data were used for N species that are not routinely measured in the monitoring programs: PAN, N_2O_5 , NO, NO_2 , HONO, and organic NO_3 . The total deposition estimates are considered to be dynamic, with updates planned as new information becomes available. TDEP data reported here were developed in late 2013 and are designated version 2013.02.

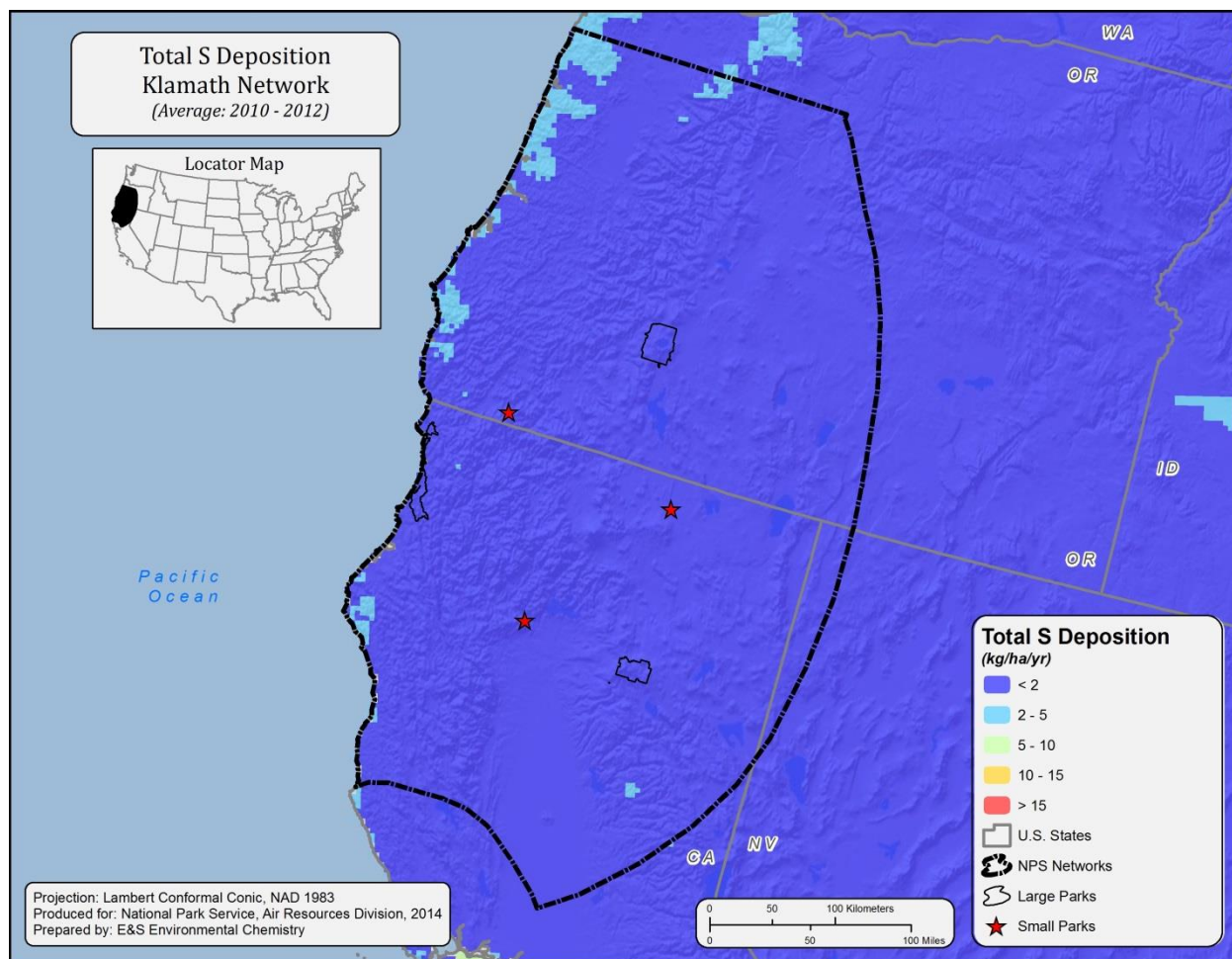
Table 1. Average changes in S and N deposition between 2001 and 2011 across park grid cells at KLMN parks. Deposition estimates were determined by the Total Deposition Project, TDEP, based on three-year averages centered on 2001 and 2011 for all ~4 km grid cells in each park. The minimum, maximum, and range of 2011 S and N deposition within each park are also shown.

Park Code	Park Name	Parameter	2001 Average (kg/ha/yr)	2011 Average (kg/ha/yr)	Absolute Change (kg/ha/yr)	Percent Change	2011 Minimum (kg/ha/yr)	2011 Maximum (kg/ha/yr)	2011 Range (kg/ha/yr)
CRLA	Crater Lake	Total S	0.68	0.91	0.23	34.5%	0.54	1.19	0.66
		Total N	2.88	2.94	0.06	1.6%	2.04	3.68	1.64
		Oxidized N	1.59	1.17	-0.42	-26.3%	0.87	1.44	0.57
		Reduced N	1.29	1.76	0.47	36.0%	1.17	2.40	1.23
LABE	Lava Beds	Total S	0.27	0.29	0.02	6.9%	0.23	0.58	0.35
		Total N	1.77	1.56	-0.22	-10.3%	1.34	2.33	0.99
		Oxidized N	1.07	0.68	-0.40	-37.2%	0.55	1.11	0.56
		Reduced N	0.70	0.88	0.18	36.0%	0.74	1.22	0.48
LAVO	Lassen Volcanic	Total S	1.16	1.27	0.11	14.0%	0.76	1.73	0.97
		Total N	4.46	4.75	0.29	9.6%	2.90	6.23	3.33
		Oxidized N	2.34	1.86	-0.48	-19.1%	1.33	2.31	0.98
		Reduced N	2.11	2.89	0.78	43.1%	1.57	3.92	2.35
ORCA	Oregon Caves	Total S	0.58	1.02	0.44	74.9%	1.01	1.02	0.01
		Total N	3.55	3.82	0.27	7.5%	3.81	3.82	0.01
		Oxidized N	2.15	1.72	-0.43	-20.1%	1.71	1.72	0.01
		Reduced N	1.40	2.10	0.70	49.8%	2.10	2.10	0.00
REDW	Redwood	Total S	0.86	1.42	0.56	65.5%	1.15	1.70	0.55
		Total N	3.90	4.30	0.40	10.7%	3.26	5.73	2.47
		Oxidized N	2.19	1.82	-0.37	-16.1%	1.46	2.21	0.76
		Reduced N	1.71	2.48	0.76	45.2%	1.80	3.76	1.95
WHIS	Whiskeytown	Total S	1.01	1.06	0.05	5.4%	0.91	1.27	0.36
		Total N	4.66	3.97	-0.69	-14.8%	3.40	4.46	1.06
		Oxidized N	2.75	1.75	-1.00	-36.2%	1.58	1.97	0.39
		Reduced N	1.92	2.22	0.30	15.9%	1.80	2.82	1.01

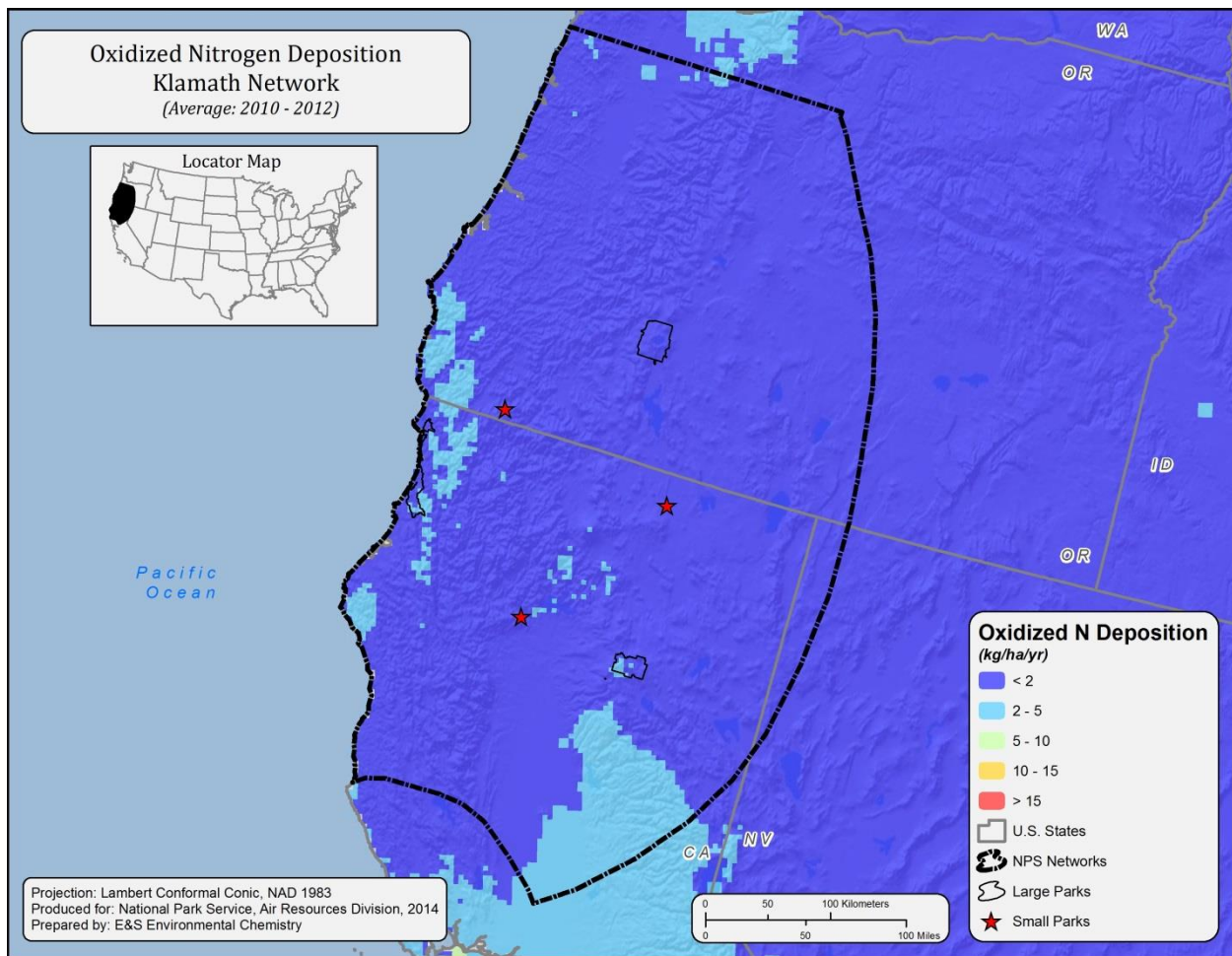
Atmospheric S deposition levels have increased at all KLMN parks since 2001, based on TDEP estimates (Table 1). Increases in total S deposition over the previous decade for the parks in this network were in several cases larger than 30%. Estimated total N deposition over that same time period decreased at some parks and increased at others. Reduced N deposition increased at all parks in the network, in most cases by more than 30%. Oxidized and reduced N showed opposite patterns, with oxidized N decreasing in all parks, usually by more than 20%, since the monitoring period 2000-2002.

Total S deposition for the period 2010-2012 was low (< 2 kg S/ha/yr) at park locations within the KLMN; some areas in the network region received 2-5 kg N/ha/yr (Map 5). Oxidized inorganic N deposition for the period 2010-2012 was less than 2 kg N/ha/yr throughout some of the park lands within KLMN (Map 6). Most areas received less than 2 kg N/ha/yr of reduced inorganic N from atmospheric deposition during this same period (Map 7); some areas to the south of LAVO received higher amounts. Total N deposition was less than 10 kg N/ha/yr at park locations (Map 8).

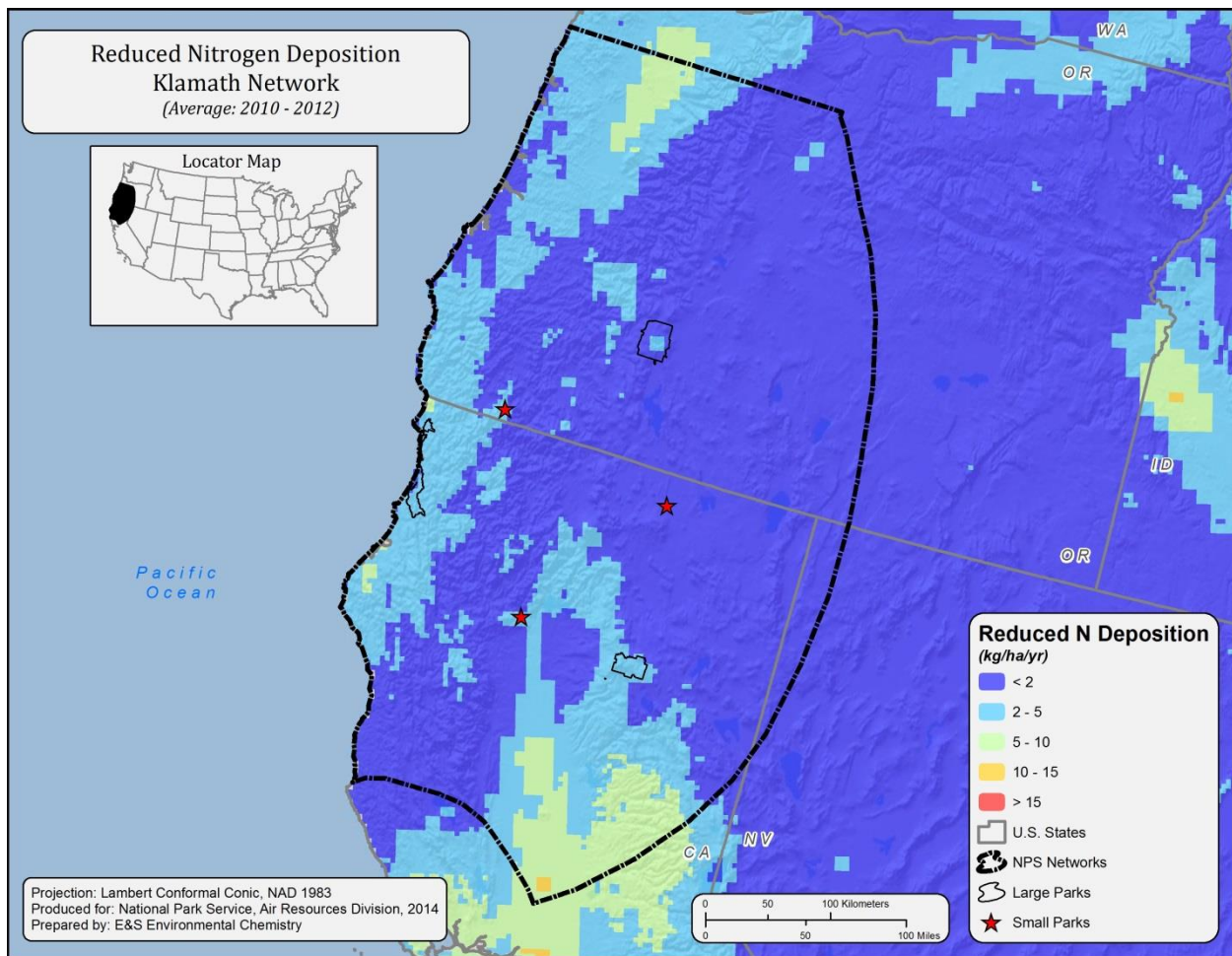
The Western Airborne Contaminants Assessment Project (WACAP) studied airborne contaminants in a number of national parks of the western United States from Alaska to southern California, including two parks in the KLMN (CRLA and LAVO) from 2002 to 2007. Pollutant concentrations detected in the air at CRLA were moderate compared with other WACAP parks for most semivolatile organic compounds (SOCs) detected. These included dacthal, endosulfans, hexachlorocyclohexane- γ , hexachlorocyclohexane- α , and polycyclic aromatic hydrocarbons (PAHs). Concentrations of hexachlorobenzene were relatively high (Landers et al, 2010). Except for PAHs, all SOC detected in air in LAVO (trifluralin, dacthal, hexachlorocyclohexane- γ , endosulfans, hexachlorobenzene, hexachlorocyclohexane- α , and chlordanes) were above median values for WACAP parks.



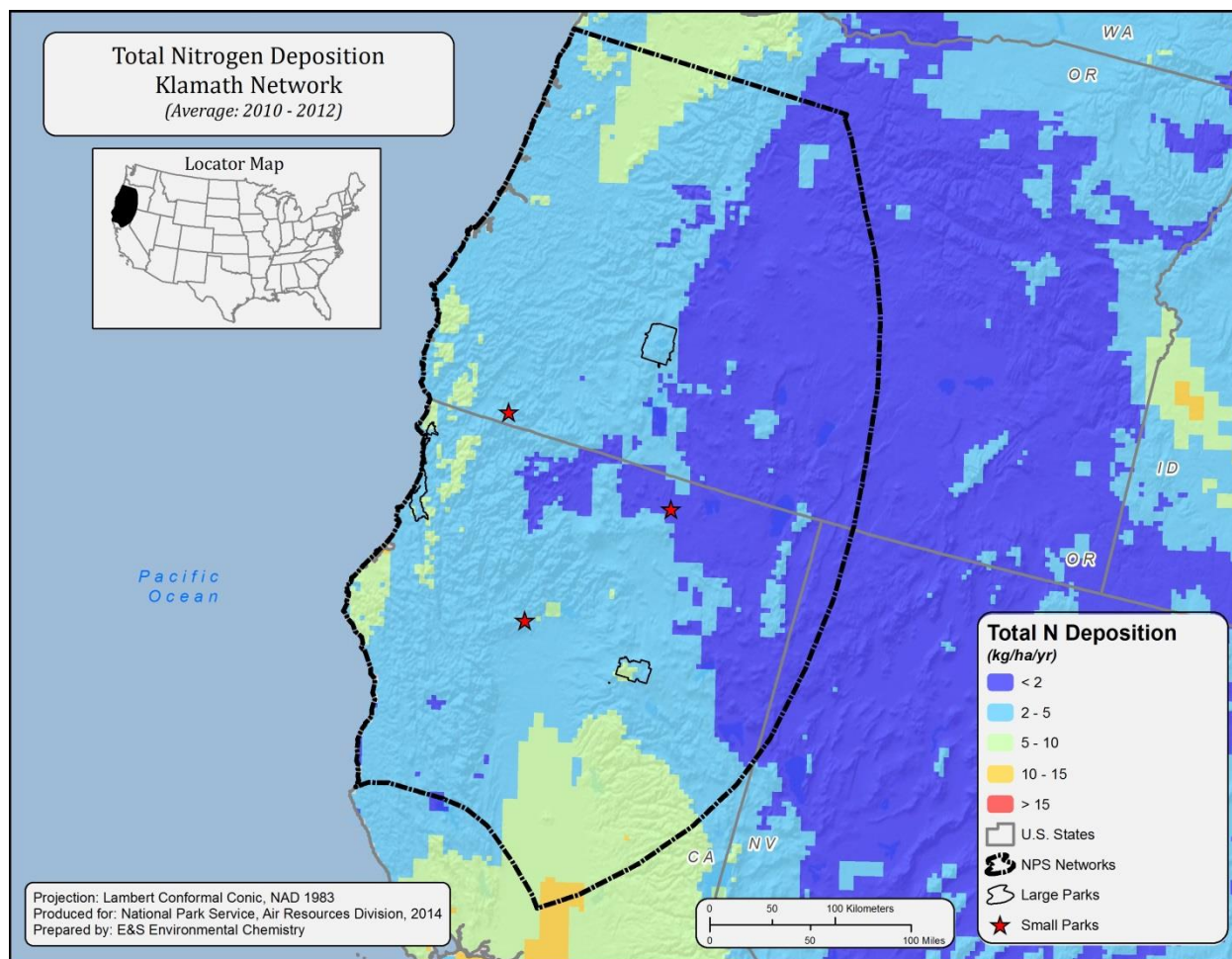
Map 5. Total S deposition for the three-year period centered on 2011 in and around KLMN. (Source: Schwede and Lear 2014)



Map 6. Total oxidized inorganic N deposition for the three-year period centered on 2011 in and around KLMN. (Source: Schwede and Lear 2014)



Map 7. Reduced inorganic N deposition for the three-year period centered on 2011 in and around KLMN.
(Source: Schwede and Lear 2014)



Map 8. Total N deposition for the three-year period centered on 2011 in and around KLMN. (Source: Schwede and Lear 2014)

Acidification

Sullivan et al. (2011) conducted a coarse screening assessment of relative risk of acidification for all I&M networks nationwide. The network rankings for acid Pollutant Exposure, Ecosystem Sensitivity to acidification and Park Protection yielded an overall acidification Summary Risk ranking for the KLMN that was near the median among all networks. The overall level of concern for acidification effects on KLMN parks was judged to be Moderate.

Acid pollutant exposure for KLMN parks ranked from Low to Very Low (Table 2). Ecosystem Sensitivity to acidification was more variable, with CRLA and LAVO ranking in the highest quintile and REDW and WHIS in the second highest quintile (High), but ORCA ranking in the second lowest quintile (Low) and LABE ranking in the lowest quintile (Very Low; Table 2). Differences among parks in Ecosystem Sensitivity to acidification were partly due to the presence of high-elevation lakes and streams in some of the parks (Sullivan et al. 2011b). Land slope also often influences the degree of acid neutralization provided by soils and bedrock within the watershed. Average slope in CRLA and LAVO ranges from 10° to 40°. REDW and WHIS are predominately in the 30° to 40° range, and average slope in ORCA exceeds that, reaching slopes up to 40° to 50°. In contrast, LABE has very low relief, with slopes less than 10° throughout the park. The occurrence of high-elevation lakes and streams in CRLA and LAVO contributes to acidification sensitivity in these parks. While rankings are an indication of risk, park-specific data, particularly data on ecosystem sensitivity, are needed to fully evaluate risk from acidification.

Acidification of Terrestrial Ecosystems

Portions of the KLMN, including some of the high-elevation areas of LAVO and CRLA, contain areas of exposed bedrock, with little soil or vegetative cover to neutralize acidic inputs (Sullivan and Eilers 1994). It is likely that soils in some areas within these parks are sensitive to acidification. However, monitored and modeled acidic deposition to KLMN parks is very low, and is not likely to increase substantially in the near future. Therefore, the overall risk of acidification of terrestrial resources in KLMN parks seems to be very small.

Table 2. Estimated I&M park rankings¹ according to risk of acidification impacts on sensitive receptors (Source: Sullivan et al. 2011b)

Park Name ²	Park Code	Estimated Acid Pollutant Exposure	Estimated Ecosystem Sensitivity to Acidification
<i>Crater Lake</i>	CRLA	Low	Very High
<i>Lassen Volcanic</i>	LAVO	Low	Very High
Lava Beds	LABE	Very Low	Very Low
Oregon Caves	ORCA	Low	Low
<i>Redwood</i>	REDW	Low	High
Whiskeytown	WHIS	Low	High

¹ Relative park rankings are designated according to quintile ranking, among all I&M Parks, from the lowest quintile (Very Low risk) to the highest quintile (Very High risk).

² Park names are printed in bold italic for parks larger than 100 mi².

Acidification of Aquatic Ecosystems

The Sierra Nevada and Cascades are the mountain ranges with the greatest number of acid-sensitive aquatic resources in the western United States (Landers et al. 1987). Portions of the KLMN occur in both of these mountain ranges. Lakes (and presumably also streams) in mountainous portions of the KLMN are especially sensitive to potential impacts from acid deposition because of the predominance of base-poor bedrock, thin soils, large amounts of precipitation, coniferous vegetation and dilute nature of the lakes (McColl 1981, Melack et al. 1985, Melack and Stoddard 1991). The hydrologic cycle is dominated by the annual accumulation and melting of a dilute, mildly acidic snowpack (Melack et al. 1997, Nelson 1991). In most lakes in the KLMN region, concentrations of SO_4^{2-} are low, although watershed sources of S are substantial in some cases (Sullivan 2000).

High-elevation lakes are considered potentially more susceptible to atmospheric S and N input than are low-elevation lakes. Crater Lake is at high elevation and LAVO contains numerous high-elevation lakes. Both parks also contain a moderate length of first through third order streams at high elevation (Sullivan et al. 2011b). Low-order, high-elevation streams on steep terrain are often particularly sensitive to acidification impacts from both S and N deposition.

The available information on acid-base chemistry of surface waters in LAVO and CRLA is based mostly on synoptic data from the Western Lakes Survey (WLS; Landers et al. 1987) and some more localized studies. Data from intensive study sites elsewhere in the mountainous West suggested that episodic depression of stream pH may be more pronounced than that of lakes. There are no data with which to assess sensitivity of streams to acid deposition in KLMN parks.

Crater Lake is well buffered from changes in acid-base chemistry, and acidification from atmospheric sources is not a concern (Eilers et al. 1994). Lassen Volcanic NP contains over 200 lakes and ponds and 15 perennial streams. Most of the lakes in the park are less than 1 ha in area, and many of those contain water only in spring and early summer. Lakes in the park are generally of glacial origin, although a few of the smaller ones are found in the craters of extinct volcanoes. Inlet and outlet streams are generally swift-flowing and intermittent, flowing primarily during the spring runoff period. Some lake and stream waters in LAVO are almost devoid of any buffering capacity (Sullivan et al. 2001). They are especially sensitive to potential acid deposition. Even moderate amounts of N or S deposition could lead to chronic, and especially episodic, acidification, with significant adverse effects on in-lake and in-stream biota (Sullivan et al. 2001). Current modeled and monitored acid deposition levels are very low, however, and are not likely to have caused adverse impacts to aquatic ecosystems. It appears that chronic acidification has not occurred to any significant degree. It is possible, however, that limited episodic effects may occur under current deposition regimes (Sullivan et al. 2001).

The WLS sampled seven lakes within LAVO, plus an additional nine lakes within 25 km of the park (Landers et al. 1987). Five of the seven LAVO lakes had acid neutralizing capacity (ANC) $< 50 \mu\text{eq/L}$, and four of those had ANC values between 18 and $27 \mu\text{eq/L}$. These four lakes are highly sensitive to potential acidification. Fewer of the lakes sampled outside the park were highly sensitive, although there were two lakes with ANC $< 50 \mu\text{eq/L}$. The sensitive lakes were small ($< 8 \text{ ha}$) and had small watershed areas (between 31 and 114 ha). All had pH approximately equal to 6.5 and dissolved

organic carbon (DOC) ≤ 2.1 mg/L. Sulfate concentrations in the sensitive lakes ranged from 2 to 6 $\mu\text{eq/L}$, confirming the very low levels of S deposition that LAVO receives. Lakewater NO_3^- concentrations were also very low, less than 1 $\mu\text{eq/L}$ in all of the lakes sampled in and around the park. Concentrations of calcium (Ca^{2+}) and other base cations were very low (sum of base cation concentrations < 35 $\mu\text{eq/L}$) in the most sensitive lakes.

Data from over 12,500 streams and lakes were used by the Critical Loads of Atmospheric Deposition Science Committee (CLAD) of the NADP (<http://nadp.sws.uiuc.edu/committees/clad/>) to develop steady-state critical loads for acidity of surface waters based on multiple approaches for estimating base cation weathering; modified F-factor, regional regression model, and MAGIC model. Water quality data were obtained from a variety of sources including EPA Long Term Monitoring (LTM) sites, lake surveys, EMAP Assessments, and National Stream Surveys; USGS; NPS Vital Signs program; and USFS air program. The average water quality measurements from the most recent five years of data were used for sites with long-term water monitoring records. The CLAD database included CL estimates for seven sites in LAVO. The median estimate was 0 eq S/ha/yr, suggesting a high degree of acid sensitivity in the surface waters of this park.

A survey of water chemistry in 101 high-altitude lakes in seven national parks in the western United States was conducted by the U. S. Geological Survey during the fall of 1999 (Clow et al. 2000). Seventy-two of the lakes had previously been sampled as part of the WLS, including the seven lakes in LAVO. Water chemistry was generally similar to the results of the WLS. There was not a consistent pattern of change in ANC between the two surveys. Nitrate concentration was 0 $\mu\text{eq/L}$ in all of the lakes surveyed in LAVO by the U.S. Geological Survey.

On the whole, the lakes sampled by the WLS and the U.S. Geological Survey within LAVO reflected slightly greater acid-sensitivity than did the lakes sampled further south. Sampled lakes in LAVO are among the most acid-sensitive in the National Park system (Sullivan et al. 2001). In view of the extreme sensitivity of many of the lakes that have been studied, relatively little research has been conducted in LAVO on the response of aquatic ecosystems to atmospheric S and/or N deposition. More complete characterization of these resources is needed to better establish baseline conditions and determine if and when future impacts might occur.

Surface water resources are lacking at LABE, so air pollution impacts on water quality are not a concern at that park (Sullivan et al. 2001). In REDW, streams are moderately dilute and some may be somewhat sensitive to acidification. Atmospheric inputs of N and S are very low, however, and there appears to be no real risk of future adverse aquatic effects unless deposition increases substantially (Sullivan et al. 2001).

Temporal Variability in Water Chemistry

Decreases in pH with increases in flow are common in drainage waters throughout the United States, especially in mountainous terrain such as is prevalent in the KLMN region (Wigington et al. 1990). Chemical changes during episodes are controlled in part by acid deposition and in part by natural processes. Episodic acid pulses may last for hours to weeks, and sometimes result in depletion of ANC in acid-sensitive streams and lakes, such as those that occur in LAVO, to negative values with

concomitant increases in inorganic aluminum in solution to toxic levels. Limited data collected during snowmelt suggest that spring concentrations in surface waters of SO_4^{2-} , NO_3^- , and DOC throughout most of the KLMN could be several times higher than concentrations in the fall (e.g., Reuss et al. 1995).

The mechanisms that produce acidic episodes can include dilution of base cations by spring meltwater and flushing of NO_3^- , SO_4^{2-} and/or organic acids from soils to drainage water (Kahl et al. 1992, Lawrence 2002, Wigington, 1999, Wigington et al. 1996). Acid deposition can contribute to episodic acidification of surface water by supplying N which can produce pulses of NO_3^- during high flow periods, contributing hydrologically mobile SO_4^{2-} and by lowering baseline pH and ANC, so that episodes are sufficient to produce biologically harmful conditions (Stoddard et al. 2003).

In the KLMN, episodic acidification has the potential to be an especially important issue for surface waters throughout high-elevation areas. A number of factors predispose watersheds in LAVO and to a lesser extent CRLA to potential episodic effects (Peterson et al. 1998, Sullivan 2000), including:

1. the abundance of dilute to ultra-dilute lakes which exhibit very low concentrations of base cations, and therefore ANC, throughout the year;
2. large seasonal snowpack accumulations at the high-elevation sites, thus causing substantial episodic acidification via the natural process of base cation dilution; and
3. short hydraulic retention times for many of the high-elevation drainage lakes, thus enabling snowmelt to rapidly flush lake basins with highly dilute meltwater.

One of the most important factors governing watershed sensitivity to episodic acidification is the pathway followed by snowmelt water and stormflow water through the watershed. These water flow paths largely determine the extent of acid neutralization provided by the soils and bedrock in that watershed. High-elevation watersheds with steep topography, extensive areas of exposed bedrock, deep snowpack accumulation, and shallow, base-poor soils tend to be most sensitive to episodic acidification. Such conditions are widespread in LAVO and CRLA.

Most research on episodic processes has been conducted on stream systems, which tend to be more susceptible to such effects than lakes. Spatial variability can be considerable in lakes, and this complicates efforts to quantify the magnitude of episodic effects (Gubala et al. 1991). Moreover, synoptic lake surveys are typically conducted during the summer or autumn "index period", during which time lakewater chemistry exhibits low temporal variability. Although the index period is an ideal time for surveying lakewater chemistry in terms of minimizing variability, lakewater samples collected during low-flow conditions provide little relevant data on episodic processes, and in particular on the dynamics or importance of N as an agent of acidification. Nitrate concentrations in lakewater are elevated during the summer or autumn seasons only in lakes having watersheds that exhibit fairly advanced symptoms of N saturation (Stoddard 1994).

The weight of evidence suggests that high-elevation lakes in the KLMN receive N deposition sufficiently high to cause some minimal NO_3^- leaching, and likely some degree of associated acidification (Sullivan 2000). However, the effects, if they occur, are not thought to be large, and the

data that would be needed for determining the extent and magnitude of episodic acidification have not been collected to a sufficient degree in acid-sensitive areas of the KLMN to support regional assessment of episodic acidification (Sullivan 2000).

Effects on Aquatic Biota

During hydrologic episodes, both discharge and water chemistry change, sometimes dramatically. This is important because some lakes and streams may in some cases exhibit chronic chemistry that is suitable for aquatic biota, but nevertheless experience occasional episodic acidification with lethal consequences (cf., Wigington et al. 1993). Episodic acidification is often the limiting condition for aquatic organisms in streams that can be suitable for aquatic life under baseflow conditions. If there are any effects of acidification on aquatic biota in the KLMN, they most likely occur episodically. Given the very low levels of S and N deposition, however, such biological effects are unlikely at the present time.

In acid-sensitive lakes in the western United States, the focus of potential acidification effects research is often mainly on native trout. It is important to note, however, that many high-elevation lakes and streams in the KLMN were probably historically fishless. The top predators in such aquatic ecosystems were often amphibians or crustaceans. Thus, even though trout might be considered native to some waters in this network, they were not necessarily native to a particular lake or stream that might be acid-sensitive.

Serious declines and extirpation of frogs and toads have been documented in many areas of the United States. National parks in California have been affected, including LAVO. Possible causes for these declines include acid deposition, disease, habitat loss, increased ultra-violet light, or a combination of such factors (Sullivan et al. 2001). The decline and extinction of amphibians has also apparently been aggravated in many parks by the introduction of non-native fish. Historically, it was possible for amphibians to use streams as dispersal corridors. However, the presence of introduced fish in many of the Sierran and Cascade lakes and streams has greatly reduced or eliminated this possibility (Bradford et al. 1993).

Redwood NP contains an abundant and diverse amphibian fauna, which could be sensitive to acidification. This park also contains an important anadromous fisheries resource, which is highly sensitive to acidification damage (Sullivan et al. 2001).

Nutrient Nitrogen Enrichment

Sullivan et al. (2011) conducted a coarse screening assessment to evaluate relative risk of nutrient enrichment from N deposition for all I&M networks nationwide. The network rankings for nutrient N Pollutant Exposure, Ecosystem Sensitivity to nutrient N enrichment, and Park Protection yielded an overall network nutrient N Summary Risk ranking for the KLMN that was in the highest quintile among all networks. This suggests that parks in the KLMN may be highly susceptible to effects from nutrient enrichment caused by atmospheric N deposition.

The six parks in the KLMN contain a wide diversity of habitats from wetlands and wet forests along the Pacific coast to desert conditions inland. Vegetation monitoring within the network includes permanent plots that are sampled every three years. Proportionately more sampling occurs at high elevation and in riparian communities, as these are the habitats expected to be most sensitive to human impacts (Odion et al. 2011).

Table 3. Estimated park rankings¹ according to risk of nutrient enrichment impacts on sensitive receptors (Source: Sullivan et al. 2011a)

Park Name ²	Park Code	Estimated Nutrient N Pollutant Exposure	Estimated Ecosystem Sensitivity to Nutrient N Enrichment
Crater Lake	CRLA	Low	Moderate
Lassen Volcanic	LAVO	Low	High
Lava Beds	LABE	Very Low	Very High
Oregon Caves	ORCA	Moderate	Very Low
Redwood	REDW	Low	Very Low
Whiskeytown	WHIS	Low	Low

¹ Relative park rankings are designated according to quintile ranking, among all I&M Parks, from the lowest quintile (Very Low risk) to the highest quintile (very high risk).

² Park names are printed in bold italic for parks larger than 100 mi².

Nutrient N Pollutant Exposure rankings for KLMN parks ranged from Very Low (LABE) to Moderate (ORCA; Table 3). Ecosystem Sensitivity to nutrient N enrichment was more variable, however, with LABE ranked in the highest quintile (Very High) and LAVO in the second highest quintile (High); CRLA was ranked in the middle quintile (Moderate), WHIS in the second lowest quintile (Low), and REDW and ORCA in the lowest quintile (Very Low; Table 3). Although rankings provide an indication of risk, park-specific data, particularly regarding nutrient-enrichment sensitivity, are needed to fully evaluate risk from nutrient N addition.

Differences in Ecosystem Sensitivity were due to differing coverages of vegetation types thought to be most sensitive to N enrichment, and also to the presence in some cases (especially LAVO) of high-elevation lakes. The vegetation types within KLMN parks that are thought to be most sensitive to N enrichment effects from atmospheric deposition include alpine, wetland, grassland and meadow,

and arid and semi-arid. Lava Beds NM was ranked especially high with regards to sensitive vegetation types due to the widespread coverage of arid and semi-arid vegetation.

Aquatic Ecosystem Nutrient Enrichment

Some freshwater aquatic ecosystems in the United States are sensitive to nutrient enrichment effects from atmospheric N deposition. In order to be sensitive to such effects, the lake or stream must be N limited. Conventional wisdom previously held that most lakes and streams in the United States are phosphorus (P)-, rather than N-limited. However, new research suggests that this may not always be the case. Surveys of the literature of fertilization experiments and lake studies found that oligotrophic waters are commonly N limited, especially undisturbed northern temperate or boreal lakes that receive low levels of atmospheric N deposition (Bergström et al. 2005, Elser et al. 2009a, Elser et al. 2009b). Such lakes are common in the KLMN region. In more productive and less remote fresh waters, nutrient enrichment from N deposition does not necessarily stimulate productivity or algal community changes because P is more commonly the limiting nutrient. Also, in many places with even minor levels of human disturbance, nutrient enrichment with both N and P from non-atmospheric human-caused sources is common.

Lassen Volcanic NP has 37 high-elevation lakes. Many may be N-sensitive. Crater Lake is a high-elevation lake. The most sensitive aquatic indicator for Crater Lake is lake transparency, which is influenced to a large degree by primary productivity. An increase in N to the lake might increase algal growth and decrease transparency.

An examination of EPA's WLS data (Eilers et al. 1987) found higher N concentrations in high-elevation lakes adjacent to and downwind from urban centers (Fenn et al. 2003a). A survey of 62 lakes that were the subject of N enrichment studies across a variety of regions reported a mean increase in phytoplankton biomass of 79% in response to N enrichment (average of 46.3 $\mu\text{eq/L N}$; Elser et al. 1990). Long-term measurements at Lake Tahoe, CA show that primary productivity doubled, while water clarity declined, mostly as a result of atmospheric N deposition (Goldman 1988, Jassby et al. 1994). A meta-analysis of lakes from 42 regions of Europe and North America concluded that atmospheric N deposition was responsible at many locations for increased concentrations of N in lake water, and elevated phytoplankton biomass (Bergström and Jansson 2006). Bergström and Jansson (2005) found a consistent pattern of N limitation at atmospheric deposition levels below approximately 2.5 kg N/ha/yr, co-limitation of N and P at N deposition between ~2.5 and 5.0 kg N/ha/yr, and P limitation in areas with N deposition greater than 5.0 kg N/ha/yr. Throughout most of the KLMN, total modeled N deposition is less than 5 kg/ha/yr.

Terrestrial Ecosystem Nutrient Enrichment

Monitored wet N deposition in the western portion of the Pacific Northwest region, including parts of the KLMN, increased from generally less than 1 kg N/ha/yr in the mid-1980s to the range of 1 to 3 kg N/ha/yr in many locations in more recent years, mainly due to increased NH_4^+ deposition (NADP/NTN Geiser and Neitlich 2007, 2006). Lichen communities in the region show evidence of changes in response to increased N pollution. The Pacific Northwest retains widespread populations of air pollution-sensitive lichens (Fenn et al. 2003a). However, in urban areas, intensive agricultural zones, and downwind of major urban and industrial centers in the Pacific Northwest, there are few air

pollution-sensitive lichen species and relatively high N concentrations have been measured in lichen tissue (Fenn et al. 2003a). Air pollution has been mainly associated with effects on community composition of lichens, rather than species richness. With N enrichment, especially around urban and agricultural areas, there is a shift towards weedy, nitrophilous lichen species (Fenn et al. 2003a). Replacement of sensitive lichens by nitrophilous species has undesirable ecological consequences. In late-successional, naturally N-limited forests of the Oregon Coast Range and western Cascade Mountains, for example, epiphytic lichens make important contributions to mineral cycling and soil fertility (Pike 1978, Sollins et al. 1980). Together with other large, pollution-sensitive lichens, they constitute integral parts of the food web for mammals, insects, and birds (McCune and Geiser 1997, U.S. Environmental Protection Agency 2005). Sensitive lichen species appear to be negatively affected by total N inputs as low as 3 to 8 kg/ha/yr (Fenn et al. 2003a), which occur in parts of the KLMN region.

Lichen taxa recommended as indicators of clean sites and polluted sites were used by Geiser and Neitlich (2007) to create six lichen zones of air quality within the Pacific Northwest region, from worst (all sensitive species absent) to best (all sensitive species present). The zone of worst air quality was associated with an absence of sensitive lichens; enhancement of nitrophilous lichens; mean wet NH_4^+ deposition > 0.06 mg N/L; lichen tissue N and S concentrations > 0.6% and 0.07 %, respectively, and SO_2 levels harmful to sensitive lichens. The strongest relationship was with wet NH_4^+ deposition, consistent with findings in California (Jovan and McCune 2005) and Europe (van Dobben et al. 2001).

Geiser et al. (2010) developed critical loads (CLs) for nutrient N deposition to protect epiphytic lichen communities in maritime forests of western Washington and Oregon. They were based on observed relationships between epiphytic lichens and total N deposition estimates derived from the CMAQ model. Estimated total N deposition values equal to 3 to 9 kg N/ha/yr were associated with 20 to 40% declines in sensitive lichen species. A model was developed with which to predict N CLs at any desired lichen community composition, expressed as the percent composition represented by oligotrophic (those adapted to low nutrient availability) versus eutrophic (nitrophilous [nitrogen-loving]) lichen species. The estimated CL increased with increasing precipitation amounts. Oligotrophic lichens decreased in abundance and eutrophic lichens increased in abundance in response to higher N deposition (Jovan 2008, McCune and Geiser 2009). Geiser et al. (2010) concluded that no single lichen CL was appropriate across land areas in this region that receive varying amounts of precipitation.

Despite the presumed high sensitivity of resources in LABE and LAVO to nutrient enrichment effects on both terrestrial (LABE and LAVO) and aquatic (LAVO) ecosystems, data are not available with which to fully assess nutrient enrichment effects on receptors other than lichens. Given the observed low levels of N emissions and deposition in the KLMN region, ecological effects are expected to be relatively minor at the present time.

Pardo et al. (2011b) identified the CLs that would protect sensitive resources in Level I ecoregions across the conterminous United States against effects caused by atmospheric N deposition. If current deposition is lower than the CL for a given receptor, one would not expect harmful effects to occur.

If current deposition exceeds the CL, the risk of harmful effects increases. Some parks may be included in more than one ecoregion, so CLs for the same receptor may vary within a park. Based on the Pardo et al. (2011b) report, most KLMN parks may exceed the CL for protecting lichens, and CRLA and WHIS may exceed the N CL for other terrestrial AQRVs (Table 4). In view of the apparent high degree of resource sensitivity, monitoring of nutrient-sensitive terrestrial and aquatic receptors in KLMN is recommended.

Ellis et al. (2013) estimated the CL for nutrient-N deposition to protect the most sensitive ecosystem receptors in 45 national parks. Changes to lichen communities may signal the beginning of other changes to the ecosystem that might affect structure and function (Pardo et al. 2011a). Ellis et al. (2013) estimated the N CL in the range of 2.5-7.1 kg N/ha/yr for protection of lichens in CRLA and LAVO and 2.7-9.2 for protection of lichens in REDW.

Table 4. Critical loads for nitrogen in the KLMN, determined by ecoregion and receptor from Pardo et al. (2011b). Current N deposition is compared to the lowest critical load for a receptor to identify exceedances, indicated by graying. A critical load exceedance indicates that the receptor is at increased risk for harmful effects.

NPS Unit	Ecoregion	Modeled N Deposition (kg N/ha/yr)	Critical Load (kg N/ha/yr)				
			Mycorrhizal Fungi	Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Crater Lake NP	Northwestern Forested Mountains	4.43	5-10	2.5-7.1	4-10	4-17	4-17
Lava Beds NM	Northwestern Forested Mountains	1.86	5-10	2.5-7.1	4-10	4-17	4-17
Lassen Volcanic NP	Northwestern Forested Mountains	3.85	5-10	2.5-7.1	4-10	4-17	4-17
Oregon Caves NM	Northwestern Forested Mountains	2.81	5-10	2.5-7.1	4-10	4-17	4-17
Redwood NP	Marine West Coast Forests	3.30	5-5	2.7-9.2	NA	5-5	NA
Redwood NP	Northwestern Forested Mountains	3.30	5-10	2.5-7.1	4-10	4-17	4-17
Whiskeytown NRA	Mediterranean California	6.23	7.8-9.2	3.1-6	6-33	17-39	10-17
Whiskeytown NRA	Northwestern Forested Mountains	6.23	5-10	2.5-7.1	4-10	4-17	4-17

Ozone Injury to Vegetation

The ozone (O₃)-sensitive plant species that are known or thought to occur within the KLMN parks are listed in Table 5. Those considered to be bioindicators, because they exhibit distinctive symptoms when injured (e.g., dark stipple), are designated by an asterisk. Each park within the network, except ORCA, contains at least five O₃ sensitive and/or bioindicator species.

Ozone Exposure Indices and Levels

The W126 and SUM06 exposure indices calculated by NPS staff are given in Table 6, along with Kohut's (2007) O₃ risk ranking. The NPS and Kohut ranking systems differ. The NPS ranking system (NPS 2010) is a quick assessment of O₃ condition that ranks O₃ exposure levels according to injury thresholds from the literature (Heck and Cowling 1997), using a 5-year average of either the W126 or SUM06 index. The former is a measure of cumulative O₃ exposure that preferentially weights higher concentrations; the latter is a measure of cumulative O₃ exposure that includes only hourly concentrations over 60 ppb. Both metrics are calculated over a 3-month period. NPS (2010) classified the W126 as Moderate at values between 7 and 13 parts per million-hours (ppm-hr). Values higher than 13 ppm-hr were classified as High, and values lower than 7 ppm-hr were classified as Low. The SUM06 was classified as Moderate at values between 8 and 15 ppm-hr. Higher and lower values were classified as High and Low.

Table 5. Ozone-sensitive and bioindicator plant species known or thought to occur in KLMN parks. (Source: E. Porter, National Park Service, pers. comm., August 30, 2012; lists are periodically updated at <https://irma.nps.gov/NPSpecies/Report>)

Species	Common Name	Park ¹					
		<i>CRLA</i>	<i>LABE</i>	LAVO	ORCA	<i>REDW</i>	WHIS
No Species Present							
<i>Ailanthus altissima</i> *	Tree-of-heaven						x
<i>Alnus rubra</i> *	Red alder				x	x	x
<i>Amelanchier alnifolia</i>	Saskatoon serviceberry				x	x	
<i>Apocynum androsaemifolium</i> *	Spreading dogbane	x		x	x	x	x
<i>Apocynum cannabinum</i>	Dogbane, Indian hemp		x				
<i>Artemisia douglasiana</i> *	Mugwort			x	x	x	x
<i>Liquidambar styraciflua</i>	Sweetgum						x
<i>Physocarpus capitatus</i> *	Ninebark				x	x	x
<i>Pinus jeffreyi</i> *	Jeffrey pine		x	x	x	x	x
<i>Pinus ponderosa</i> *	Ponderosa pine	x	x	x	x		x
<i>Pinus radiata</i>	Monterey pine					x	
<i>Populus tremuloides</i> *	Quaking aspen		x	x	x		
<i>Prunus virginiana</i>	Choke cherry		x				
<i>Quercus kelloggii</i>	California black oak			x	x	x	x
<i>Rhus trilobata</i> *	Skunkbush						x
<i>Robinia pseudoacacia</i>	Black locust					x	x
<i>Rubus parviflorus</i>	Thimbleberry			x	x	x	x
<i>Salix scouleriana</i> *	Scouler's willow		x	x	x		x
<i>Sambucus mexicana</i> *	Blue elderberry		x	x	x	x	x
<i>Sambucus racemosa</i> *	Red elderberry	x			x	x	
<i>Symphoricarpos albus</i> var. <i>laevigatus</i> *	Common snowberry				x		x
<i>Symphoricarpos albus</i> *	Common snowberry	x					
<i>Vaccinium membranaceum</i> *	Huckleberry	x			x		x

¹ Park names are printed in bold italic for parks larger than 100 mi².

* Bioindicator species

Kohut's approach constitutes a more rigorous assessment of potential risk to plants. It considers both O₃ exposure and environmental conditions (soil moisture). Kohut also used injury thresholds from the literature, but evaluated a different O₃ metric (after Lefohn et al. 1997), the W126 over a 5-month period in conjunction with the N100 (number of hours over 100 ppb O₃). The rationale for the N100 statistic is that higher O₃ concentrations are most likely to cause plant injury). Kohut examined five individual years of O₃ exposure and soil moisture data and considered the effects of low soil moisture on O₃ uptake each year when assigning risk. Soil moisture is important because dry conditions induce stomatal closure in plants, which has the effect of limiting O₃ uptake and injury. In areas where low soil moisture levels correspond with high O₃ exposure, uptake and injury are limited by stomatal closure even when exposures are relatively high. Ozone condition, as rated by NPS, ranges from Low to High in the KLMN parks. Kohut's evaluation of risk to plants also ranged from Low to High, but with differences. In LAVO, he assessed risk as Low, while the NPS system rated exposure as High. Kohut found that, during the period that he reviewed, very few hours had concentrations exceeding 100 ppb, and therefore he concluded that risk was Low. The results of both ranking systems should be considered when evaluating the potential for O₃ injury to park vegetation. The Kohut approach considered environmental conditions that significantly affect plant response to O₃, but exposures have likely changed since the time of the assessment (1995-1999). The NPS approach considers more recent O₃ conditions (2005-2009), but not environmental conditions.

Table 6. Ozone assessment results for I&M parks in the KLMN based on estimated average 3-month W126 and SUM06 ozone exposure indices for the period 2005-2009 and Kohut's (2007) ozone risk ranking for the period 1995-1999¹.

Park Name ²	Park Code	W126		SUM06		Kohut O ₃ Risk Ranking
		Value (ppm-hr)	Ranking	Value (ppm-hr)	Ranking	
<i>Crater Lake</i>	CRLA	5.70	Low	7.41	Low	Moderate
<i>Lassen Volcanic</i>	LAVO	13.19	High	22.20	High	Low
Lava Beds	LABE	9.66	Moderate	14.64	Moderate	Moderate
Oregon Caves	ORCA	6.66	Low	8.80	Moderate	Moderate
<i>Redwood</i>	REDW	5.36	Low	7.32	Low	Moderate
Whiskeytown	WHIS	11.90	Moderate	18.45	High	High

¹ Parks are classified into one of three ranks (Low, Moderate, High), based on comparison with other I&M parks.

² Park names are printed in bold italic for parks larger than 100 mi².

Ozone Formation

The O₃ exposure in the KLMN region is partly due to trans-Pacific transport of pollutant emissions from Asia. The coastal O₃ monitoring site at Trinidad Head in northern California is well suited to evaluate O₃ and O₃-precursor transport from Asia to the west coast of the United States (Oltmans et al. 2008). During the O₃ seasonal maximum in the spring, measurements of O₃ concentration at the Trinidad Head coastal location often exceeded 50 ppb in air that had not been influenced by emission sources in North America. During daytime hours, air that arrives at this headland site is nearly

exclusively off the Pacific Ocean during the spring months. The average daytime O₃ concentrations at Trinidad Head exceeded 40 ppb for the period 2002-2005 (Oltmans et al. 2008).

Jaffe et al. (2003) demonstrated that the concentration of O₃ in air masses reaching the west coast of the United States from Asia increased by about 30% (10 ppb) from the mid-1980s to 2002. The study included sites in LAVO and REDW. The measured increase in O₃ at these parks was correlated with increasing N emissions in Asia.

Forest fires emit considerable quantities of NO_x and hydrocarbons, and therefore can contribute to O₃ formation in the KLMN region. The concentration of O₃ in the atmosphere in the nonurban western United States has increased since the late 1980s by about 5 ppb (Jaffe and Ray 2007). The summer burned area was significantly correlated with O₃ concentration at atmospheric chemistry monitoring sites, including sites within LAVO and five other parks in the western United States (Jaffe et al. 2008). Increasing temperature in the future will likely further influence the effects of fire on O₃ formation.

Ozone Exposure Effects

Field Survey Results

Forests of the central and eastern regions of the KLMN are primarily Rocky Mountain types where the dominant species include ponderosa pine (*Pinus ponderosa*) at lower elevations and subalpine fir (*Abies amabilis*) at higher elevations. Ponderosa pine (var. *ponderosa*) is an excellent bioindicator of O₃ exposure; the Rocky Mountain variety (var. *scopularum*) is less sensitive to O₃ and is not recommended for use in O₃ injury surveys (Aitken et al. 1984). Lower montane forests on the west side of the KLMN region, including at LAVO, are dominated by ponderosa pine (var. *ponderosa*) on xeric sites. At higher elevations, mixed conifer forest is prevalent and includes ponderosa pine along with several other coniferous tree species. Jeffrey pine (*Pinus jeffreyi*), also a good bioindicator tree species, replaces ponderosa pine within the mixed conifer forest at higher elevations and on shallow soils. In addition to Jeffrey pine and ponderosa pine, there are other potential O₃ bioindicators in LAVO and elsewhere within the KLMN, including quaking aspen (*Populus tremuloides*). Foliar injury detected in these bioindicators in the KLMN was moderate (Arbaugh et al. 1998, Sullivan et al. 2001).

High O₃ exposure along the western edge of the Sierra Nevada Mountains throughout late spring and summer provides sufficient stress in ponderosa pine and Jeffrey pine to induce a gradient in foliar injury from north to south; injury has been shown to be very severe at Sequoia and Kings Canyon National Parks, severe at Yosemite National Park, and moderate at LAVO (Sullivan et al. 2001). Sullivan et al. (2001) reported that LAVO experienced seasonal to chronic periods of poor air quality, especially relatively high O₃. Among the parks in the KLMN, LAVO had the highest monitored or interpolated W126 and SUM06 O₃ exposure during the period 2005-2009 (Table 6).

There has been very limited research on, or monitoring of, the potential effects of air pollution on vegetation in LABE (Sullivan et al. 2001). This is despite the fact that the park has three good O₃ bioindicators (Jeffrey pine, ponderosa pine [var. *ponderosa*], and quaking aspen) and that some O₃ injury has been documented at LAVO, which is only 120 km to the south. Ozone weekly averages

were measured at a single passive O₃ monitoring site within LABE during the period 1995-1998. Ozone measurements from this sampler were amongst the lowest of all parks in California (Sullivan et al. 2001) and do not support the likelihood of appreciable risk to vegetation at LABE.

The Forest Ozone Response Study (FOREST), conducted during the period 1991 to 1994, quantified the distribution of O₃ injury to forest species throughout California (Arbaugh et al. 1998, Cahill et al. 1996, Rocchio et al. 1993), including at some national park locations. This study was linked to the Sierra Cooperative Ozone Impact Assessment Study (SCOIAS), another regional study that focused primarily on monitoring of ambient O₃ and associated weather variables in the Sierra Nevada (Van Ooy and Carroll 1995). The FOREST study added to the spatial resolution of long-term research and monitoring of O₃ effects in southern California by Miller (1992) and Miller and McBride (1999) and to extensive surveys of injury and growth patterns in the Sierra Nevada by Peterson et al. (1987, 1991) and Peterson and Arbaugh (1988, 1992).

The FOREST data included results of O₃-injury surveys at 11 sites (all with associated O₃ monitoring data), ranging from LAVO in northern California to San Bernardino National Forest in southern California, with sites distributed throughout the western Sierra Nevada within the elevational range of mixed conifer forest. Visible O₃ injury to ponderosa pine and Jeffrey pine was detected at all sites, ranging from 26.8% of trees at the northernmost site in LAVO to 100% at the southernmost. The Ozone Injury Index (OII; Schilling and Duriscoe 1996) ranged from 6.3 in the north to 65.1 in the south. There were significant correlations between OII and various O₃ indices over the geographic range of the study, which suggested that (1) O₃-monitoring data could be used to predict O₃ injury in sensitive pine species and (2) conversely, injury data for pines (much less expensive to collect than O₃ exposure data) provide a reasonable indication of the level of O₃ exposure at a particular geographic location. The FOREST study was one of the first field studies to demonstrate a quantitative relationship between tree injury and cumulative O₃ exposure (SUM06).

The FOREST study corroborated results from a previous analysis of O₃ injury (presence of chlorotic mottling and needle retention) to ponderosa pine in the Sierra Nevada (Peterson et al. 1991, Peterson and Arbaugh 1992), which found a gradient of injury, ranging from low injury at northern sites (Tahoe National Forest) to high injury at southern sites (Sequoia National Park and Sequoia National Forest). Strong correlations were found between injury level and O₃ exposure. Because essentially the same results were obtained by two studies that used different methods at different points in time, confidence is high in the inference that O₃ injury increases from north to south in the Sierra Nevada and that the injury is directly proportional to ambient O₃ exposure (Sullivan et al. 2001). Nevertheless, foliar injury is only one manifestation of injury. Effects in growth and relative abundance are also possible.

Model Responses

Weinstein et al. (2005) simulated the effects on growth and competitive success of white fir (*Abies concolor*) and ponderosa pine at three sites in California, including LAVO, from O₃ exposures of 0.5, 1.5, 1.75, and 2.0 times ambient. The response of individual trees was modeled using the TREGRO model (Weinstein et al. 1991), based on results obtained in controlled chamber studies. These results were then extrapolated to the overall forest using the ZELIG model (Urban 1990, Urban et al. 1991),

which considers the effects of competition. Model results suggested little growth impact of O₃ on white fir up to two times ambient exposure, but substantial growth reduction for ponderosa pine, mainly in southern California. Continued O₃ exposure for 100 years at ambient levels at LAVO was not projected to decrease ponderosa pine abundance (Weinstein et al. 2005).

Visibility Degradation

Natural Background Visibility and Monitored Visibility Conditions

The Clean Air Act set a specific goal for visibility protection in Class I areas: “the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I federal areas which impairment results from manmade air pollution” (42 U.S.C. 7491). In 1999, EPA passed the Regional Haze Rule (RHR), which requires each state to develop a plan to improve visibility in Class I areas, with the goal of returning visibility to natural conditions by 2064. Visibility is monitored by the Interagency Monitoring of Protected Visual Environments (IMPROVE) Program and typically reported using the haze index called the deciview² (dv). Lower dv values correspond with better visibility conditions.

Natural background visibility, the goal of the Clean Air Act, assumes no human-caused pollution, but varies with natural processes such as windblown dust, wildfire, volcanic activity and biogenic emissions from vegetation. Natural background visibility has been estimated for IMPROVE sites located in CRLA, LAVO, LABE, and REDW for the 20% clearest visibility days, the 20% haziest visibility days, and average days, in order to establish goals for visibility improvement. Data are also available that are considered to be representative of visibility conditions at WHIS, based on measured values taken from the Trinity IMPROVE site (TRIN1) located within 60 mi (100 km) and 425 ft (130 m) elevation of WHIS. Estimated natural background and monitored visibility for KLMN parks are given in Table 7.

Current visibility estimates reflect current pollution levels and were used to rank conditions at parks in order to provide park managers with information on spatial differences in visibility and air pollution. Rankings range from very low haze (very good visibility) to very high haze (very poor visibility). Only parks with on-site IMPROVE monitors, or parks with representative data from a nearby monitoring site, were used in generating the baseline visibility ranking.

REDW experienced much higher levels of natural haze than did the other parks within KLMN, with natural haze values that were nearly twice as high as other parks in this network. Natural haze is not an important feature at most of the monitored parks within KLMN, with the exception of REDW, which experiences considerable natural haze.

Other Class I national parks in KLMN (LAVO, LABE) have relatively good monitored visibility compared with Class I areas in other parts of California because the northern parks are far-removed from large urban population centers. Similarly, CRLA is very remote from human air pollution

² The *deciview* visibility metric expresses uniform changes in haziness in terms of common increments across the entire range of visibility conditions, from pristine to extremely hazy conditions. Because each unit change in deciview represents a common change in perception, the deciview scale is like the decibel scale for sound. A one deciview change in haziness is a small but noticeable change in haziness under most circumstances when viewing scenes in Class I areas.

sources and is not in close proximity to the ocean. It generally experiences the best visibility among all monitored KLMN parks (Table 7).

Table 7. Estimated natural background visibility and monitored visibility in KLMN parks averaged over the period 2004 through 20081.

Park Name ²	Park Code	Site ID	Estimated Natural Background Visibility (dv)					
			20% Clearest Days		20% Haziest Days		Average Days	
Crater Lake	CRLA	CRLA1	0.10		7.62		3.26	
Lassen Volcanic	LAVO	LAVO1	1.00		7.31		3.77	
Lava Beds	LABE	LABE1	1.29		7.85		4.13	
Oregon Caves	ORCA	No Site						
Redwood	REDW	REDW1	3.46		13.91		8.11	
Whiskeytown ³	WHIS	TRIN1	1.16		7.90		3.94	
Park Name	Park Code	Site ID	Measured Visibility (For Years 2004 through 2008)					
			20% Clearest Days		20% Haziest Days		Average Days	
			dv		dv		dv	
Crater Lake	CRLA	CRLA1	1.58		13.74		6.72	
Lassen Volcanic	LAVO	LAVO1	2.61		15.32		8.01	
Lava Beds	LABE	LABE1	2.95		14.29		8.06	
Oregon Caves	ORCA	No Site						
Redwood	REDW	REDW1	5.76		19.08		12.26	
Whiskeytown ³	WHIS	TRIN1	3.37		18.10		9.15	

¹ Parks are classified into one of five ranks (Very Low, Low, Moderate, High, Very High).

² Park names are printed in bold italic for parks larger than 100 mi².

³ Data from a nearby site (TRIN1) are used to represent conditions at WHIS. A monitoring site is considered by IMPROVE to be representative of an area if it is within 60 mi (100 km) and 425 ft (130 m) in elevation.

Although REDW had the highest ambient haze values among the monitored parks within KLMN, the difference between natural and ambient haze on the haziest 20% days was actually smaller for REDW than it was for any of the other monitored parks in KLMN. Thus, the human-caused contribution to haze on the poorest visibility days appears to be lower in REDW than in the other parks.

LAVO showed the greatest difference among monitored KLMN parks between natural background and monitored visibility (a difference of 8 dv on the 20% haziest days; Table 7). The 1988 to 1998 data showed the worst visibility at LAVO occurred during summer when the seasonal average visual range (VR; i.e., how far a person can see) was only 73 miles (118 km). The best visibility occurred during winter when the seasonal average visual range was 139 miles (223 km).

Representative photos of selected vistas under three different visibility conditions are shown in Figure 1 for CRLA, LAVO and REDW. Photos were selected to correspond with the clearest 20% of

visibility conditions, haziest 20% of visibility conditions, and annual average visibility conditions at each location. IMPROVE data from CRLA show that pollution has reduced average VR from 160 miles (257 km) to 100 miles (161 km). On the haziest days, VR has been reduced from 100 miles (161 km) to 50 miles (80 km). Severe haze episodes occasionally reduce visibility to 5 miles. At LAVO, air pollution has reduced average VR from 160 miles (257 km) to 100 miles (161 km). On the haziest days, VR has been reduced from 120 miles (193 km) to 55 miles (89 km). Severe haze episodes occasionally reduce visibility to 7 miles. At LABE, air pollution has reduced average VR from 150 miles (241 km) to 90 miles (145 km). On the haziest days, VR has been reduced from 110 (177 km) to 50 miles (80 km). Severe haze episodes occasionally reduce visibility to 11 miles (18 km). At REDW, air pollution has reduced average VR from 100 miles (161 km) to 65 miles (105 km). On the haziest days, VR has been reduced from 60 miles (97 km) to 40 miles (64 km). Severe haze episodes occasionally reduce visibility to 15 miles (24 km). At the Trinity IMPROVE site (representative of WHIS), air pollution has reduced average VR from 160 miles (257 km) to 80 miles (129 km). On the haziest days, VR has been reduced from 100 miles (161 km) to 35 miles (56 km). Severe haze episodes occasionally reduce visibility to 3 miles (5 km).

Composition of Haze

Various pollutants make up the haze that causes visibility degradation. IMPROVE measures these pollutants and reports them as ammonium SO_4^{2-} , ammonium NO_3^- , elemental carbon, coarse mass, organic mass, sea salt, and soil. Sulfates form in the atmosphere from SO_2 emissions from coal-burning power plants, smelters, and other industrial facilities. Nitrates form in the atmosphere from NO_x emissions from combustion sources including vehicles, power plants, industry, and fires. Organic compounds are emitted from a variety of both natural (biogenic) and human-caused sources, including agriculture, industry, and fires. Atmospheric sea salt concentrations are higher in coastal areas, such as in portions of REDW. Soil can enter the atmosphere through both natural processes and human disturbance.

At IMPROVE sites throughout the interior Columbia River basin, from North Cascades NP and Glacier NP in the north to LAVO and Yellowstone NP in the south, carbon in various forms, including fine particulate organics and soot, contributes most to visibility impairment³ (Schoettle et al. 1999). The second most important contributor is SO_4^{2-} . Savig and Morse (2001) reported that visibility impairment at LAVO in the 1990s was largely due to organics and sulfates. The clearest 20% days at LAVO probably approach natural conditions (GCVTC 1996). Historically, visibility varied with patterns in weather, wind (and the effects of wind on coarse particles), and smoke from fires.

³ *Visibility impairment* means any humanly perceptible change in visibility (light extinction, visual range, contrast, coloration) from that which would have existed under natural conditions.

Crater Lake

20% Clearest Days

Taken: 9:00 AM

Haze = 3 dv

VR = 290 km



20% Haziest Days

Taken = 9:00 AM

Haze = 12 dv

VR = 120 km



Average Days

Taken = 9:00 AM

Haze = 6 dv

VR = 210 km



Figure 1a. Three representative photos of the same view in CRLA illustrating the 20% clearest visibility (Group 10), the 20% haziest visibility (Group 90) and the annual average visibility (Group 100). VR is visual range.

Lassen Volcanic

20% Clearest Days

Taken: 3:00 PM

Haze = 3 dv

VR = 300 km



20% Haziest Days

Taken = 3:00 PM

Haze = 15 dv

VR = 90 km



Average Days

Taken = 3:00 PM

Haze = 8 dv

VR = 180 km



Figure 1b. Three representative photos of the same view in LAVO illustrating the 20% clearest visibility (Group 10), the 20% haziest visibility (Group 90) and the annual average visibility (Group 100). VR is visual range.

Redwood

20% Clearest Days

Taken: 3:00 PM

Haze = 6 dv

VR = 220 km



20% Haziest Days

Taken = 3:00 PM

Haze = 21 dv

VR = 50 km



Average Days

Taken = 3:00 PM

Haze = 13 dv

VR = 110 km



Figure 1c. Three representative photos of the same view in REDW illustrating the 20% clearest visibility (Group 10), the 20% haziest visibility (Group 90) and the annual average visibility (Group 100). VR is visual range.

Lightning is the most important source of wildfire ignition in the Pacific Northwest (McKenzie et al. 2006, Rorig and Ferguson 1999). Managers of protected areas, such as national parks and wilderness, have adopted a policy whereby naturally ignited fires are allowed to burn unless they threaten structures or ambient air quality (McKenzie et al. 2006, Miller and Landres 2004). Prescribed fire is also widely used throughout the western United States, including in the KLMN region, for restoring and maintaining vegetation communities (Allen et al. 2002, Brockway et al. 2002, Fulé et al. 1997, McKenzie et al. 2006, Stephenson 1999).

A substantial component of regional haze in the Pacific Northwest is caused by prescribed and wildland fires. Smoke plumes can contribute to visibility impairment downwind from the fire locations (Malm 1999). In recent years, fires have become more severe than they were historically, because of more extreme weather and buildup of fuel from fire suppression (Agee 1997, Allen et al. 2002, Covington 2000, Flannigan et al. 1998, McKenzie et al. 2006). This pattern may continue into the future in response to climate change. Both empirical (McKenzie et al. 2004) and process (Lenihan et al. 1998) models suggest that the area burned by wildfires is likely to increase in the western United States in response to a warming climate.

Data from IMPROVE monitors in the northern and central coastal locations in California, including at REDW, for the baseline period of 2000 to 2004, suggested that visibility-degrading pollutants on the 20% haziest days were primarily SO_4^{2-} , NO_3^- , and sea salt (Suarez-Murias et al. 2009). Sulfate was the most important cause of haze on the haziest days at all of the coastal IMPROVE monitoring sites, except on the haziest winter days at Point Reyes NS to the south of the KLMN, when NO_3^- predominated (Suarez-Murias et al. 2009). The SO_4^{2-} contribution to haze exhibited some seasonality at REDW, with highest contributions during summer. High contributions from sea salt occurred throughout the year at REDW. Emissions of SO_4^{2-} from ocean vessels also constitute an important contributor to visibility impairment at coastal California Class I areas (Suarez-Murias et al. 2009).

Visibility modeling results reported by Suarez-Murias et al. (2009) for the IMPROVE sites in northern California suggested that a 48% improvement would be required on the haziest visibility days in order to meet RHR goals by 2064 at LABE and LAVO. A somewhat smaller improvement (25%) would be required for REDW (Table 8).

Figure 2 shows estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze and its composition for CRLA, LAVO, LABE, REDW, and WHIS. The RHR requires at least three years of valid data out of a five-year period to calculate the five-year average for the baseline period (2000-2004). Sites having fewer than three years of valid data required use of the RHR_VS algorithm substitution to calculate the baseline. This process entailed using substituted valid data for incomplete years. WHIS has no valid measured data for the years 2000 and 2002; RHR2_VS substituted data were used for 2002. For more information on this process, see http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm.

Table 8. IMPROVE monitors and Visibility at Class I Areas in Northern California. (Source: Suarez-Murias et al. 2009)

			Current Conditions (2000-2004 Baseline)		Future Natural Conditions (2064 Goals)		
Improve Monitor (name and elevation in meters)		Class I Area(s)	Haziest Days	Clearlest Days (maintain in future years)	Natural Haziest Days	Deciview Hurdle (baseline to 2064)	Improvement Required from Current Visibility on Haziest Days
TRIN (1014 m)	Trinity	Marble Mountain Wilderness Yolla Bolly-Middle Eel Wilderness	17.4	3.4	7.9	9.5	55%
LABE (1460 m)	Lava Beds	Lava Beds National Monument South Warner Wilderness	15.1	3.2	7.9	7.2	48%
LAVO	Lassen Volcanic	Lassen Volcanic National Park Caribou Wilderness Thousand Lakes Wilderness	14.1	2.7	7.3	6.8	48%
REDW (244 m)	Redwood	Redwood National Park	18.5	6.1	13.9	4.6	25%

On the 20% haziest days and average days, the majority of the impairment in all parks except REDW was attributable to organics, followed by SO_4^{2-} (Figure 2). On the clearest 20% visibility days, the major contribution was from SO_4^{2-} . The contributors to impairment at REDW differed from the other monitored KLMN parks (Figure 2). Sea salt played a much larger role, contributing the most to haze on the 20% haziest days, followed closely by SO_4^{2-} . On the 20% clearest and average days, SO_4^{2-} was the largest contributor, followed closely by sea salt. Consistent with the findings presented here, Savig and Morse (2001) found that organics contributed the most to visibility impairment, on an annual basis, at parks in the Sierra-Humboldt area (including LAVO), whereas SO_4^{2-} generally contributed the most to impairment in the Pacific Coastal Mountain parks (including REDW).

During the 2000-2004 baseline period, the 20% haziest days at the IMPROVE sites in LAVO and LABE were dominated by organic aerosols. These organic aerosols showed distinct seasonality, with peak values occurring during the summer, correlating with the prevalence of wildfire and increased natural biogenic emissions from vegetation (Suarez-Murias et al. 2009).

Visibility conditions during the period 1988 to 1998 at REDW varied by season and were strongly influenced by weather, winds, and coastal fog (Savig and Morse 2001). Reconstructed extinction generated from aerosol data showed that the annual average VR was 49 miles (79 km), and the worst seasonal average VR was 45 miles (73 km), which occurred in the autumn. The best seasonal average VR at REDW was 86 miles (139 km), which occurred during winter (Savig and Morse 2001).

Dust storms commonly occur during the spring season in eastern Asia. With westerly air flows, fine dust particles can be transported to the western United States. Asian dust can also be mixed with human-caused air pollutants emitted in industrial areas of China. Liu et al. (2003) determined Asian dust contributed an estimated 16% and 11% of the fine particulate mass measured at CRLA and LAVO IMPROVE sites, respectively.

CRLA

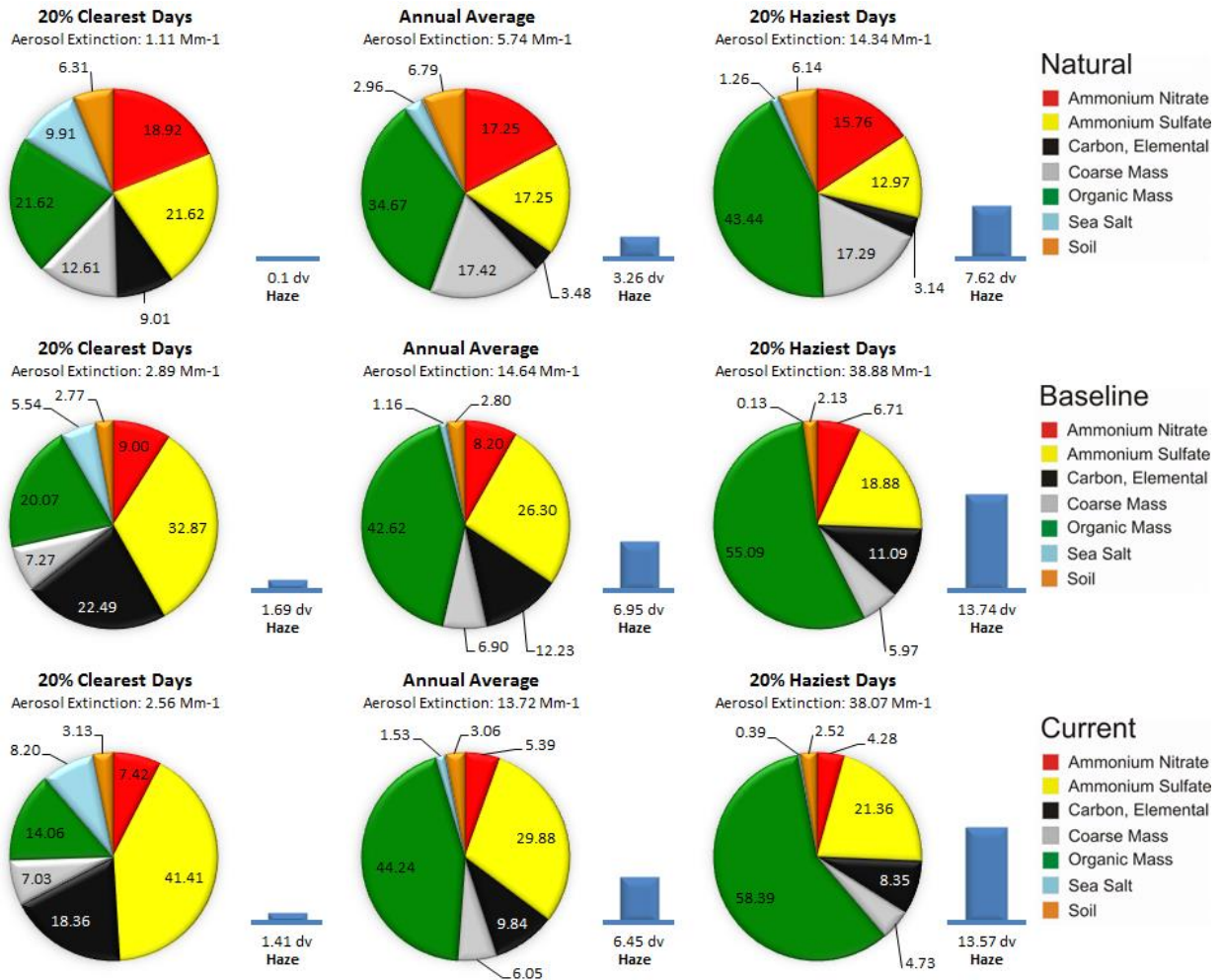


Figure 2a. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% hazeiest visibility days for CRLA. Data for WHIS are based on a nearby site (TRIN1). LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid measured data for the years 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: Scott Copeland, USDA Forest Service, Lander, WY, Pers. Comm.); and REDW has no measured data for the year 2010. Source: NPS-ARD

LAVO

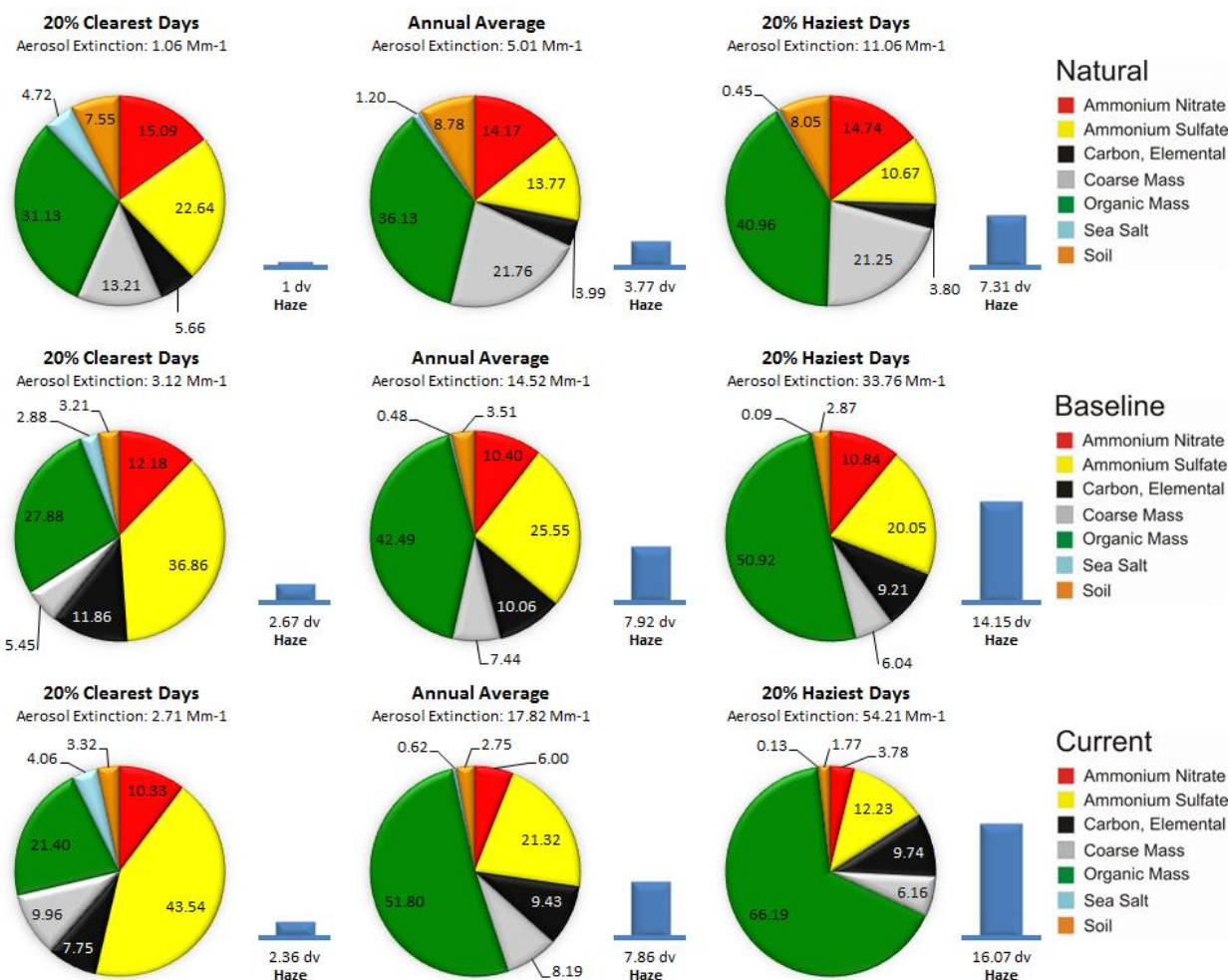


Figure 2b. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for LAVO. Data for WHIS are based on a nearby site (TRIN1). LAVE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid measured data for the years 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: Scott Copeland, USDA Forest Service, Lander, WY, Pers. Comm.); and REDW has no measured data for the year 2010. Source: NPS-ARD

LABE

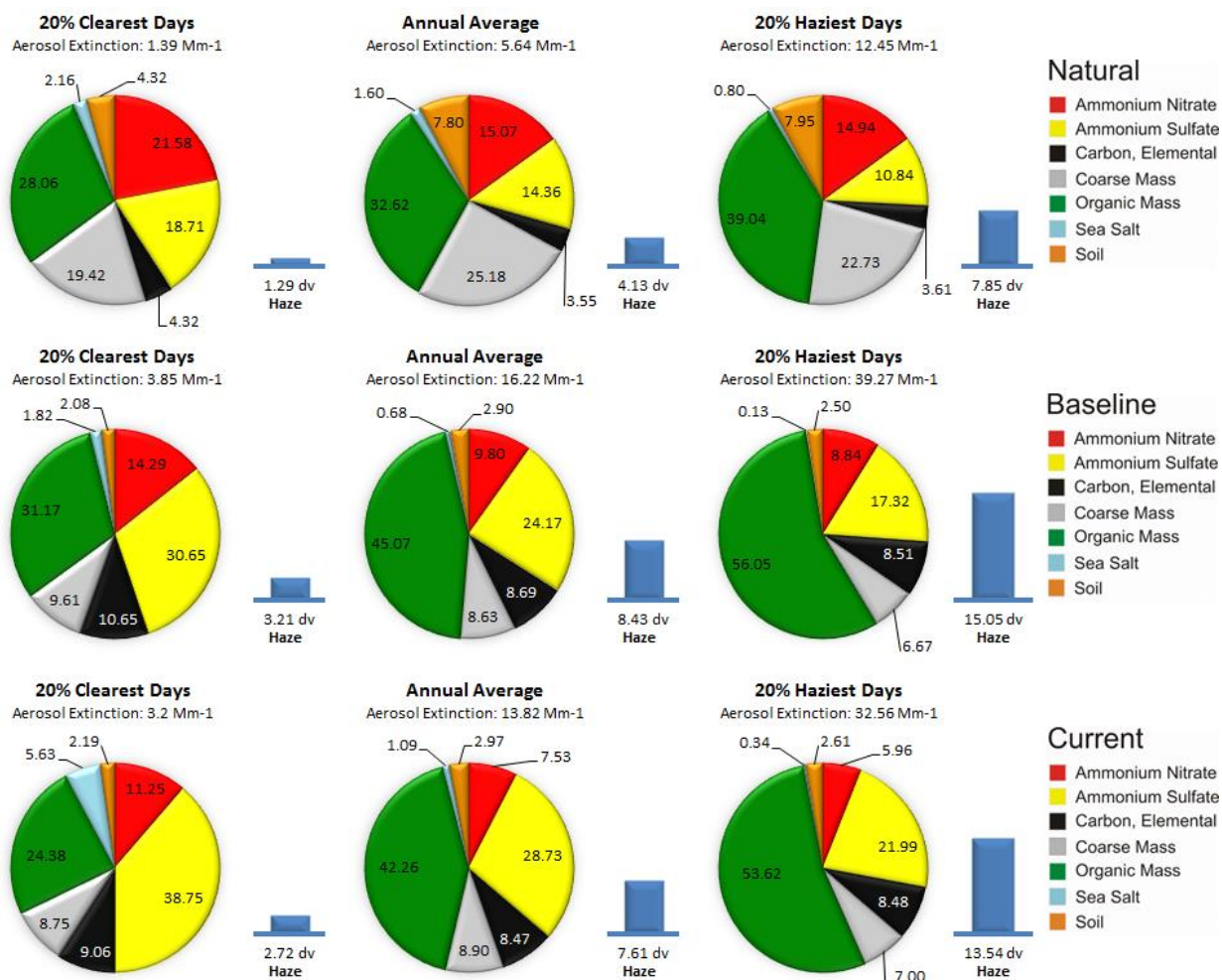


Figure 2c. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for LABE. Data for WHIS are based on a nearby site (TRIN1). LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid measured data for the years 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: Scott Copeland, USDA Forest Service, Lander, WY, Pers. Comm.); and REDW has no measured data for the year 2010. Source: NPS-ARD

REDW

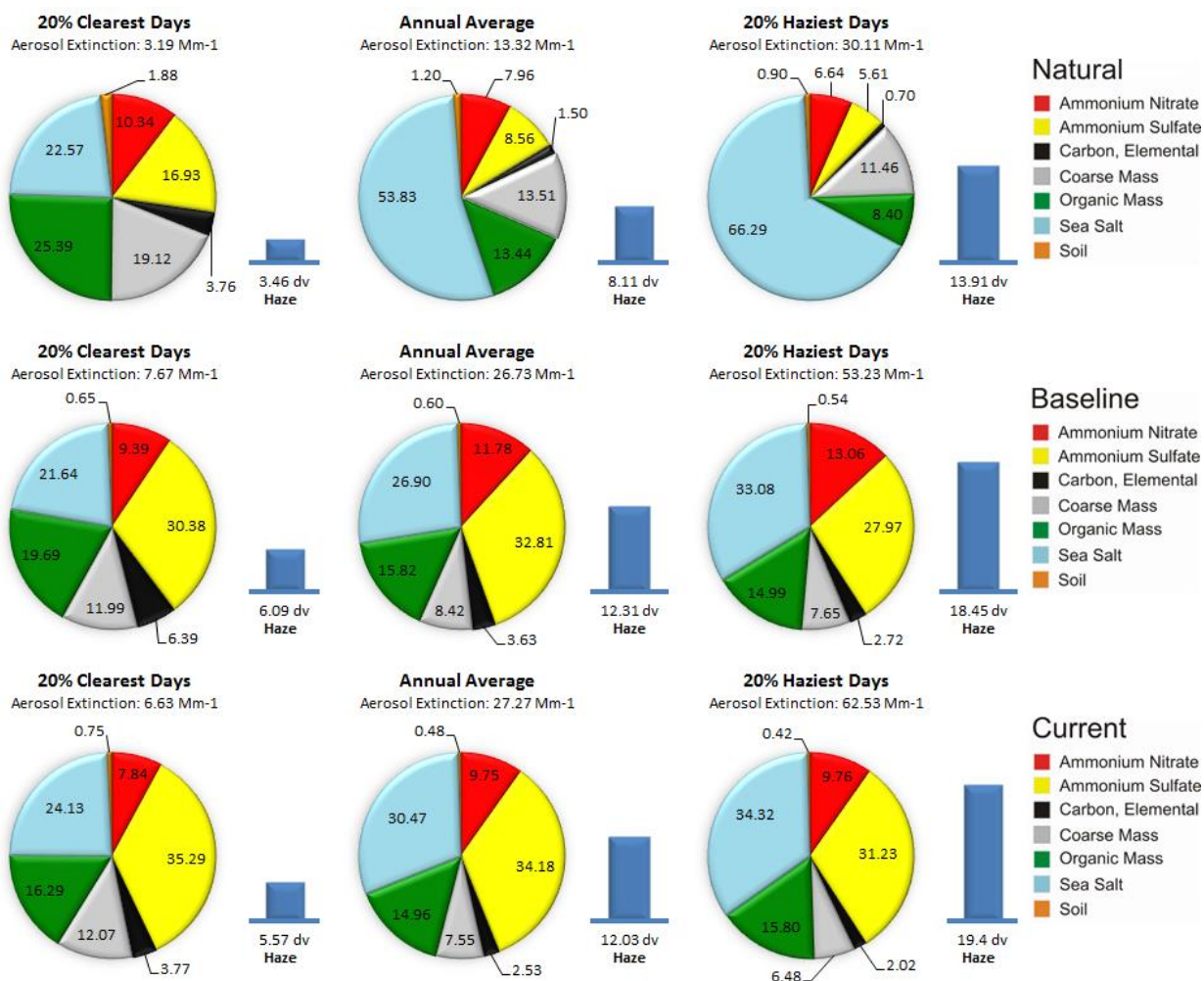


Figure 2d. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for REDW. Data for WHIS are based on a nearby site (TRIN1). LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid measured data for the years 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: Scott Copeland, USDA Forest Service, Lander, WY, Pers. Comm.); and REDW has no measured data for the year 2010. Source: NPS-ARD

Trinity (for WHIS)

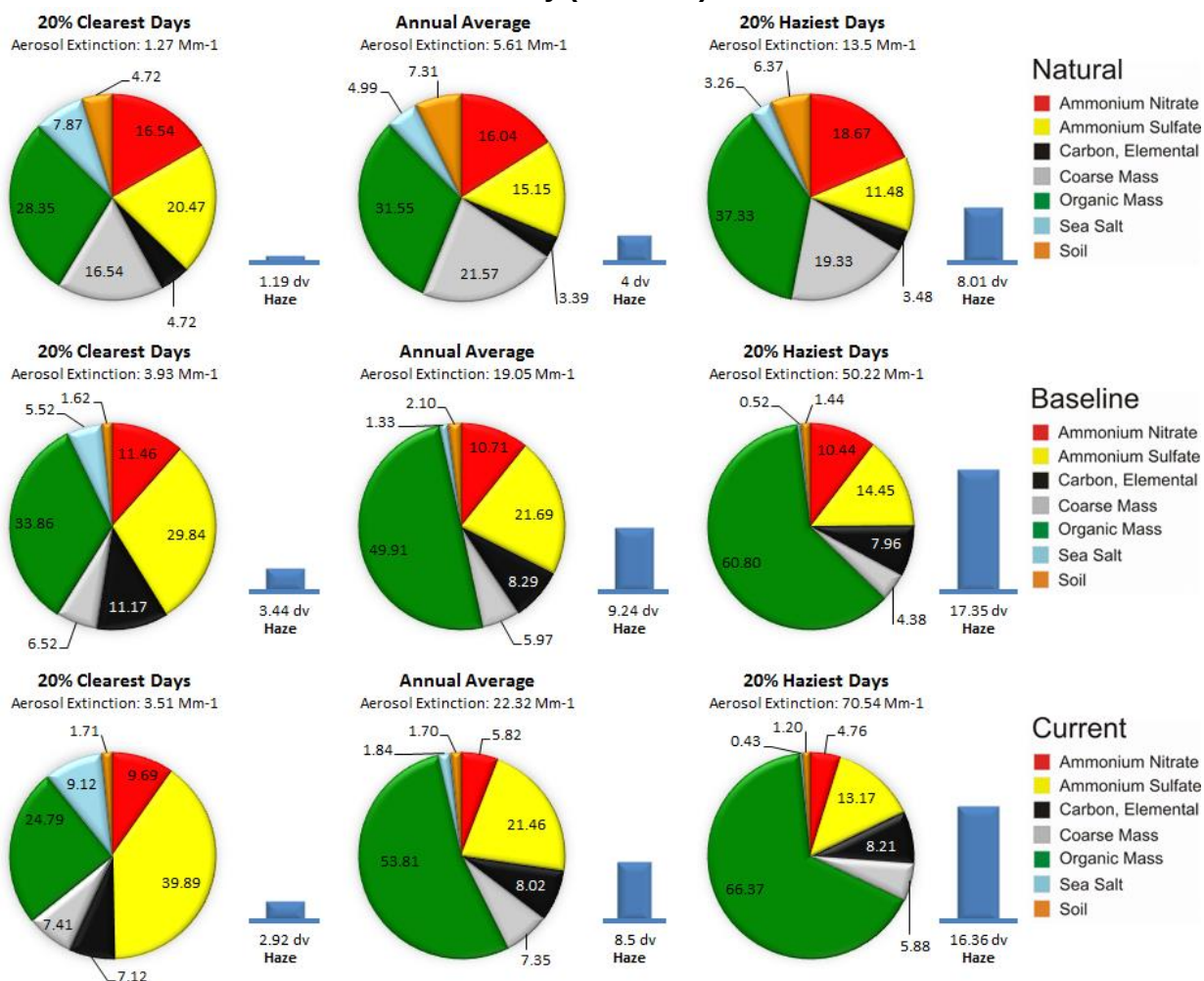


Figure 2e. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for WHIS. Data for WHIS are based on a nearby site (TRIN1). LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid measured data for the years 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: Scott Copeland, USDA Forest Service, Lander, WY, Pers. Comm.); and REDW has no measured data for the year 2010. Source: NPS-ARD

Analyses conducted by the Western Regional Air Partnership (WRAP) indicated that organics from natural emissions sources, including wildfire and biogenic sources (vegetation), contribute to substantial visibility impairment throughout the western United States, including within the KLMN region. In addition, air pollution sources outside the WRAP domain, including international off-shore shipping and sources from Mexico, Canada, and Asia, can in some cases be substantial contributors to haze (Suarez-Murias et al. 2009).

Source appointment analyses were conducted for the California Regional Haze Plan (Suarez-Murias et al. 2009), using regional-scale, three-dimensional air quality models that simulate emissions, chemical transformations, and transport of criteria air pollutants and fine particulate matter. Effects

on visibility in Class I areas in California were then evaluated for organic C, SO_4^{2-} , and NO_3^- , which are the three major drivers of haze in California. The PM Source Appointment Technology (PSAT) algorithm was used for WRAP model analysis. Directly emitted human-caused organic C was estimated to contribute half or less of the organic C in most areas of California. Human-caused sources of NO_x contributed at least half of the NO_3^- in all Class I areas in California except REDW (where it only contributed 7%). The human-caused SO_4^{2-} contribution ranged from 1 to 35% at various Class I areas, with highest contributions in southern California. Important drivers of haze in California derive from natural sources (organic C), mobile sources (NO_3^-), and off-shore and non-WRAP regional sources of SO_4^{2-} (Suarez-Murias et al. 2009).

Trends in Visibility

Over the full period of monitoring data for the parks in the KLMN region, there is only limited evidence of improvement in haze levels (Figure 3). Nevertheless, the most recent three years of monitoring data (2008-2010) do suggest consistent improvement in visibility on the 20% haziest days at each of the monitored parks.

Development of State Implementation Plans

According to the RHR, states and tribes must establish and meet reasonable progress goals for each federal Class I area to improve visibility on the 20% haziest days and to prevent visibility degradation on the 20% clearest days. The national goal is to return visibility in Class I areas to natural background levels by 2064. States must evaluate progress by 2018 (and every 10 years thereafter) based on a baseline period of 2000 to 2004 (Air Resource Specialists 2007).

The Class I parks in California requiring the least amount of visibility improvement to meet the national goal specified by the RHR are REDW in the KLMN and Point Reyes NS to the south. These two parks are coastal and are relatively (compared with other parks in California) unaffected by land-based emissions sources in California. Sea salt provides an important natural cause of haze at these locations.

Progress to date in meeting the national visibility goal is illustrated in Figure 4 using a uniform rate of progress glideslope. Although some progress has been made since the baseline period (2000-2004), substantial additional visibility improvement is needed to eliminate human-caused haze by 2064. More data will be needed to evaluate compliance with requirements of the RHR.

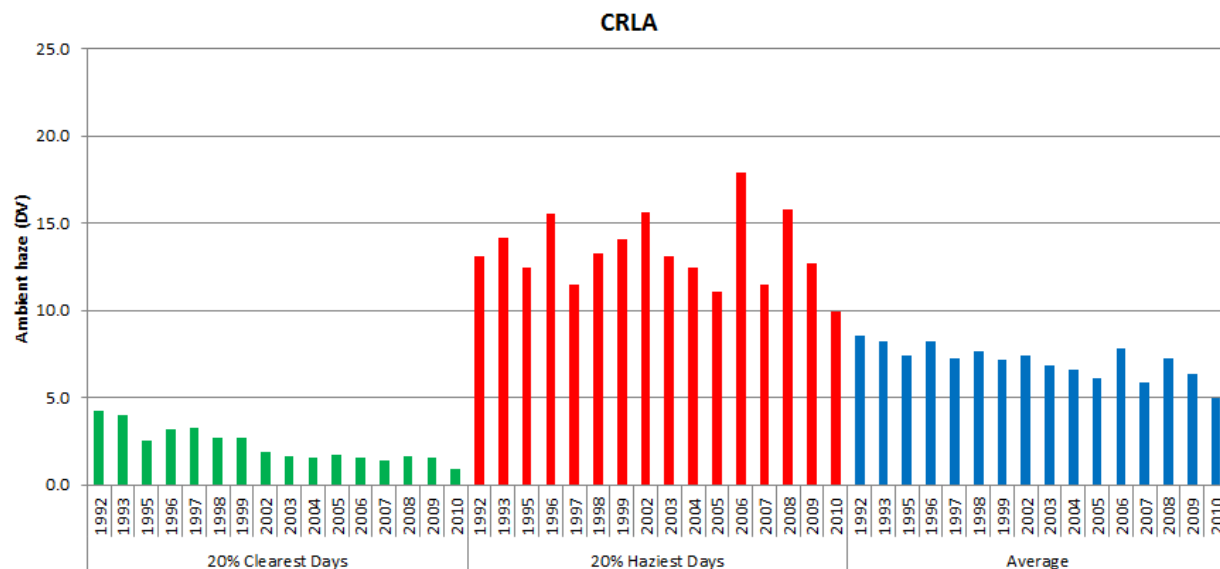


Figure 3a. Trends in monitored visibility at CRLA, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for TRIN1 are used to represent conditions at WHIS. TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

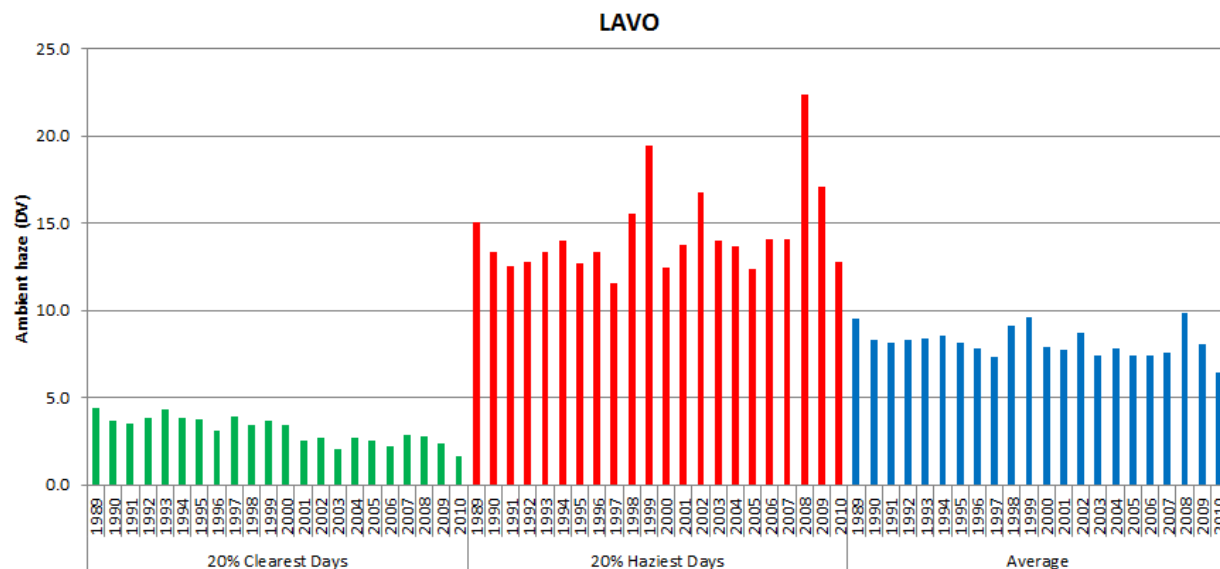


Figure 3b. Trends in monitored visibility at LAVO, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for TRIN1 are used to represent conditions at WHIS. TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

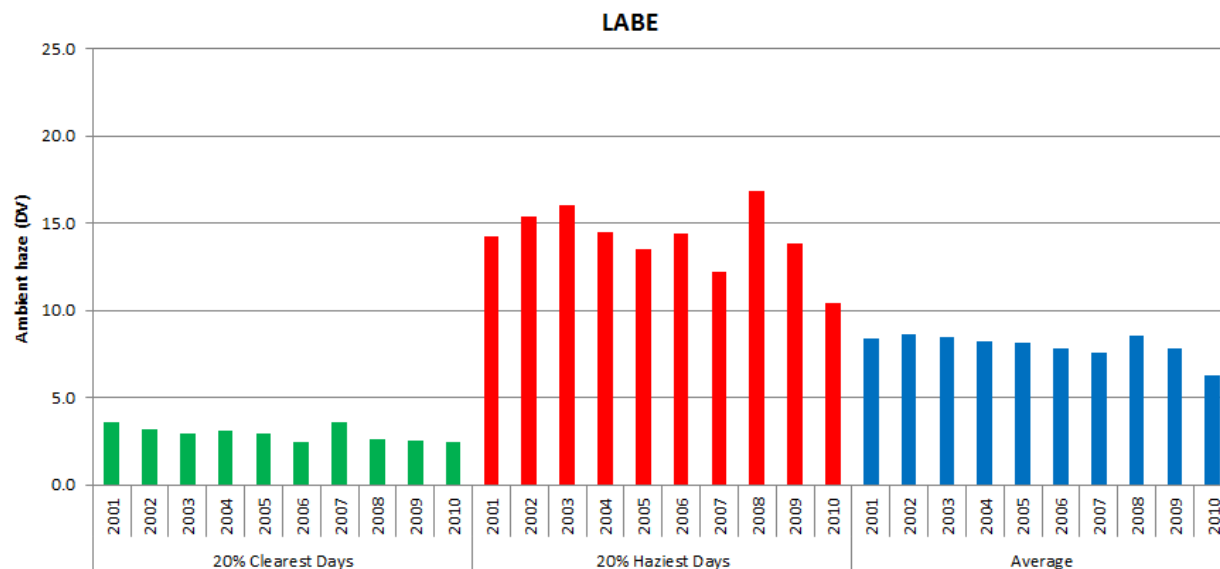


Figure 3c. Trends in monitored visibility at LABE, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for TRIN1 are used to represent conditions at WHIS. TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

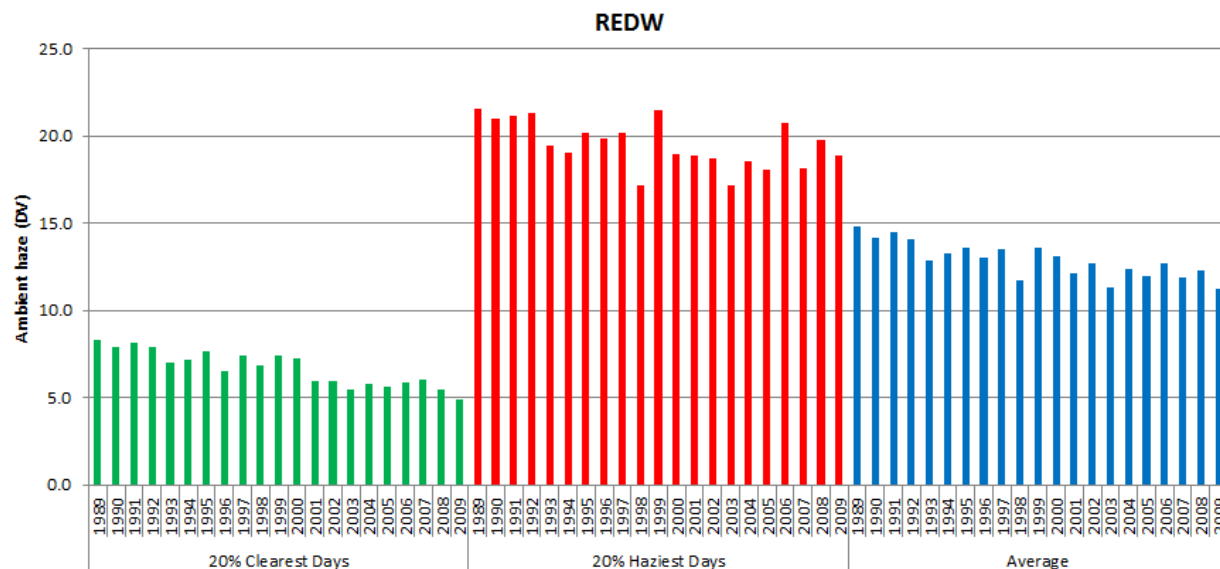


Figure 3d. Trends in monitored visibility at REDW, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for TRIN1 are used to represent conditions at WHIS. TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

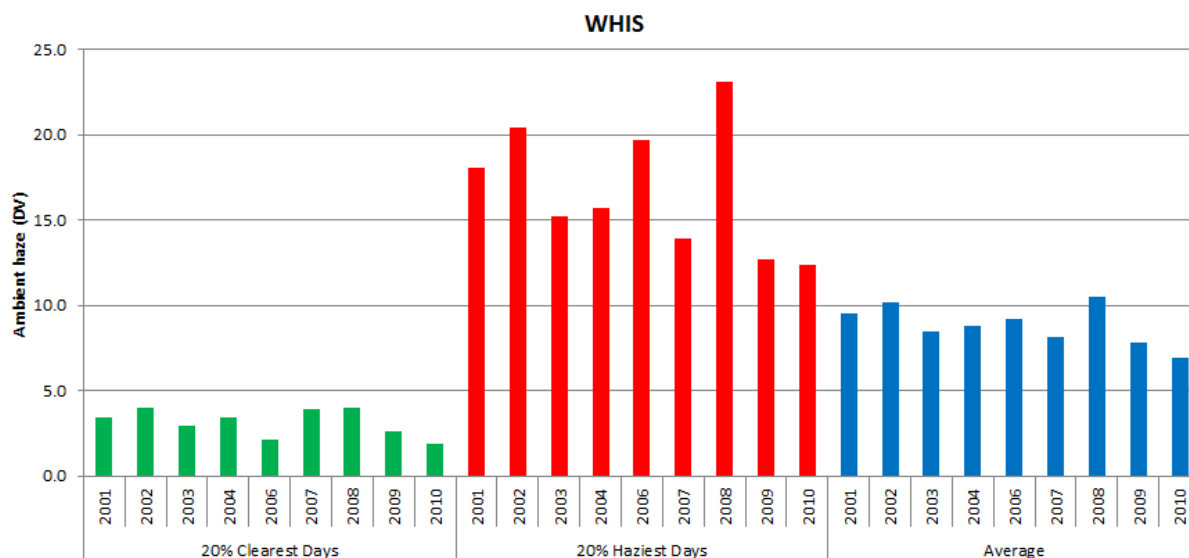


Figure 3e. Trends in monitored visibility at TRIN1, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for TRIN1 are used to represent conditions at WHIS. TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

Toxic Airborne Contaminants

Data are limited on the effects of atmospherically deposited toxic substances on resources in KLMN parks. Concentrations of SOCs detected in CRLA vegetation were generally at or above medians for all WACAP parks studied in the western United States. In vegetation in CRLA, dominant SOCs detected were endosulfans and dacthal, followed by PAHs, hexachlorobenzene, hexachlorocyclohexane- α , chlordanes, and dichlorodiphenyltrichloroethane (DDT). In LAVO, concentrations of SOCs detected in vegetation were relatively high, and closely approached or exceeded medians for WACAP parks. Dominant SOCs detected in vegetation at LAVO were endosulfans and dacthal, followed by PAHs, hexachlorobenzene, hexachlorocyclohexane- α , chlordanes, and DDT. The extent to which these potentially toxic airborne contaminants actually impact biota in the parks within the KLMN is not known.

Krabbenhoft et al. (2002) sampled 90 lakes in seven national parks in the western United States, including LAVO, and analyzed their mercury (Hg) and methylmercury (MeHg) concentrations. Levels of MeHg were similar in most parks (~ 0.05 ng/L), including LAVO. USGS (Last modified February 20, 2015) estimated MeHg concentrations in surface waters throughout the conterminous United States. Estimates for the KLMN region were low to moderate compared with other regions.

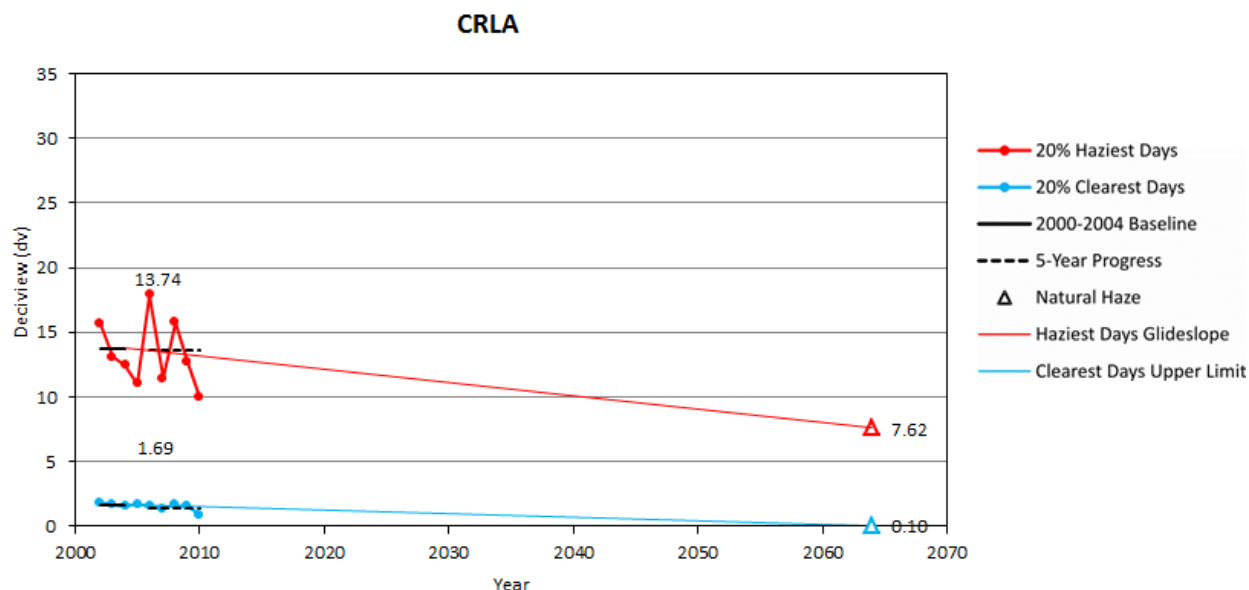


Figure 4a. Glideslopes to achieving natural visibility conditions by 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in CRLA. In the RHR, the clearest days do not have a uniform rate of progress glideslope; the Rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. LAVE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm)

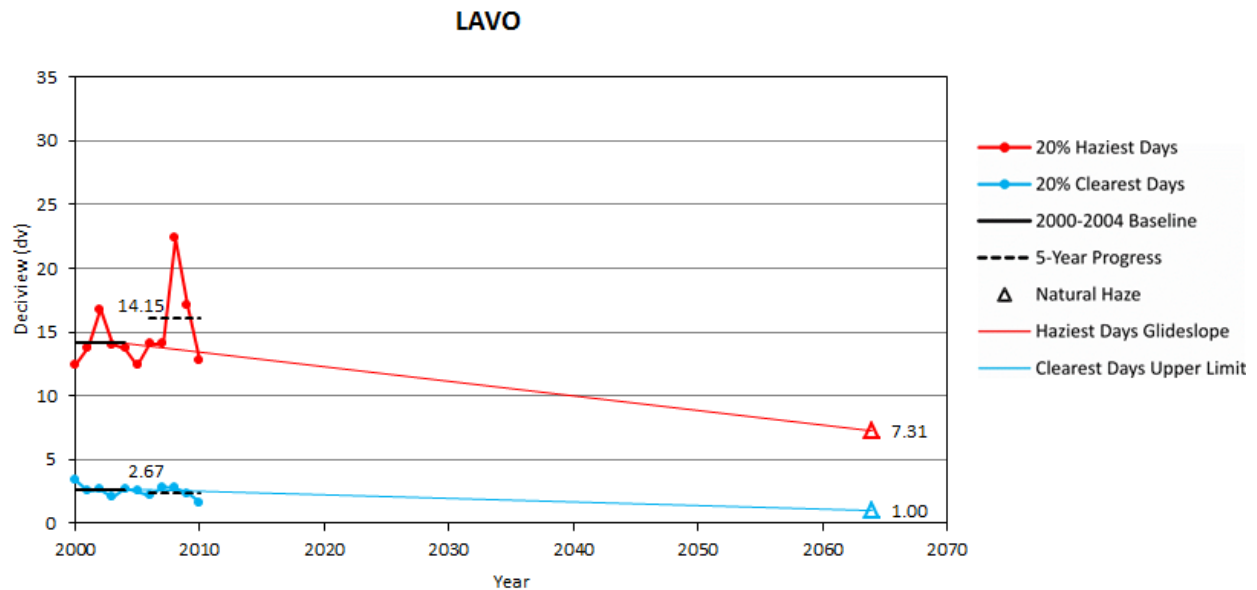


Figure 4b. Glideslopes to achieving natural visibility conditions by 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in LAVO. In the RHR, the clearest days do not have a uniform rate of progress glideslope; the Rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. LAVE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm)

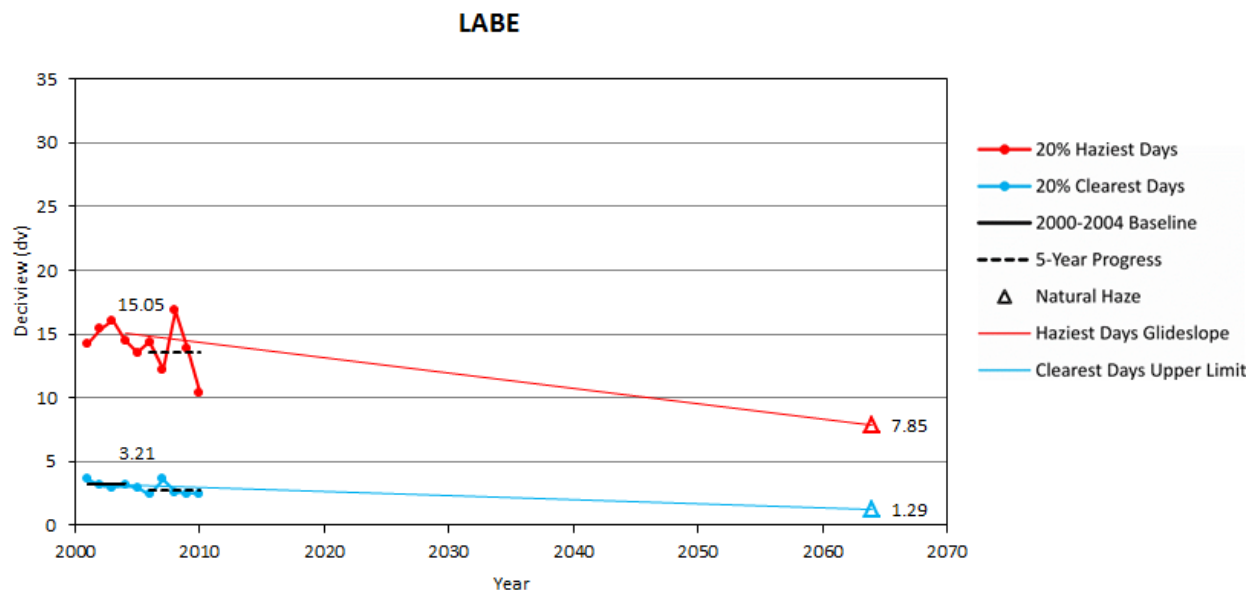


Figure 4c. Glideslopes to achieving natural visibility conditions by 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in LABE. In the RHR, the clearest days do not have a uniform rate of progress glideslope; the Rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm)

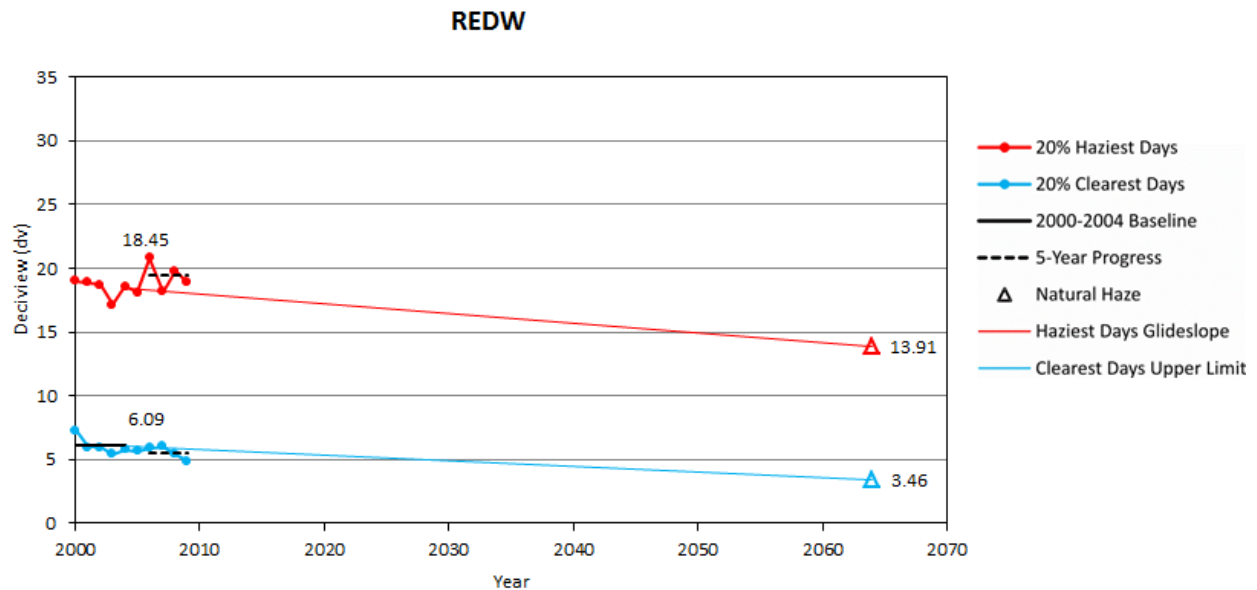


Figure 4d. Glideslopes to achieving natural visibility conditions by 2064 for the 20% hazeiest (red line) and the 20% clearest (blue line) days in REDW. In the RHR, the clearest days do not have a uniform rate of progress glideslope; the Rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm)

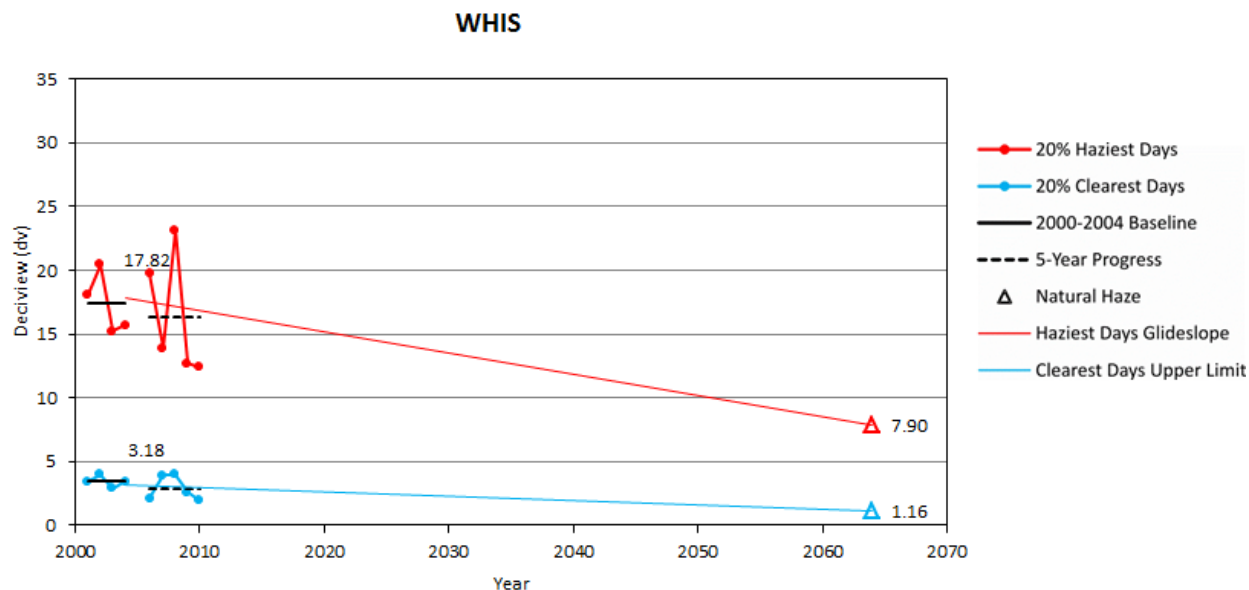


Figure 4e. Glideslopes to achieving natural visibility conditions by 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in TRIN1 (used to represent WHIS). In the RHR, the clearest days do not have a uniform rate of progress glideslope; the Rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. LABE has no data for the year 2000; CRLA has no data for the years 2000 and 2001; TRIN1 has no valid, measured data for the year 2000 and 2002, but has RHR2_VS substituted data for the year 2002 (Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm)

Eagles-Smith et al. (2014) sampled fish in 21 national parks and analyzed them for Hg concentrations in tissue. Results varied substantially by park and by water body. The concentrations of Hg in brook trout (*Salvelinus fontinalis*) sampled in three lakes in LAVO were variable. Risk to fish and wildlife appeared to be limited to fish from Summit Lake. However, Hg concentrations in brook trout from Horseshoe Lake were estimated to reach concentrations of concern for tissue-based toxicity to fish and for protection of human health.

Kokanee (*Oncorhynchus nerka*) and rainbow trout (*Oncorhynchus mykiss*) were sampled from two locations in CRLA. These fish had among the lowest Hg concentrations recorded in the survey. There was no evidence that piscivorous predators were at risk from Hg contamination in this park.

Organochlorine chemicals can be estrogenic (Garcia-Reyero et al. 2007), contributing to the occurrence of intersex fish, and can accumulate in the aquatic food chains of remote mountain ecosystems (Blais et al. 1998). Biomarkers of exposure to estrogenic chemicals suggest the likelihood of reproductive dysfunction (Harries et al. 1997). Organochlorines are likely transported as atmospheric contaminants to high-elevation sites (Hageman et al. 2006). Work by Schreck and Kent (2013) followed up on some of the work performed in the WACAP Study. They expanded the range of coverage to additional western parks, including CRLA and LAVO within KLMN. No intersex fish were found in CRLA; in LAVO, 1 out of 45 sampled male fish was intersex. The low observed frequency of intersex fish in these parks and water bodies may be a natural phenomenon

(Schwindt et al. 2009). The extent to which human-caused contaminants contribute to an increased frequency is difficult to determine (Schreck and Kent 2013).

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