



Air Quality Related Values (AQRVs) for Southern Colorado Plateau Network (SCPN) Parks

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

Natural Resource Report NPS/SCPN/NRR—2016/1157



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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Summary

This chapter describes the Air Quality Related Values (AQRVs) of the Southern Colorado Plateau Network (SCPN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The SCPN parks that are included in the NPS Inventory and Monitoring (I&M) Program and discussed in this report are Aztec Ruins National Monument (AZRU), Bandelier National Monument (BAND), Canyon de Chelly National Monument (CACH), Chaco Culture National Historical Park (CHCU), El Malpais National Monument (ELMA), El Morro National Monument (ELMO), Glen Canyon National Recreation Area (GLCA), Grand Canyon National Park (GRCA), Hubbell Trading Post National Historic Site (HUTR), Mesa Verde National Park (MEVE), Navajo National Monument (NAVA), Petrified Forest National Park (PEFO), Petroglyph National Monument (PETR), Rainbow Bridge National Monument (RABR), Salinas Pueblo Missions National Monument (SAPU), Sunset Crater National Monument (SUCR), Walnut Canyon National Monument (WACA), Wupatki National Monument (WUPA), and Yucca House National Monument (YUHO). BAND, GRCA, MEVE, and PEFO are designated as Class I, giving them a heightened level of protection against harm caused by poor air quality under the Clean Air Act (CAA).

Sullivan et al. (2011a, 2011b) and Kohut (2007) conducted risk assessments for acidification, eutrophication, and ozone (O_3) for the SCPN parks; their results are described in this report. This report also describes regional air pollutant emissions and air quality, and their effects on AQRVs in the SCPN. 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).

Although the SCPN parks are located in relatively remote areas, they experience air pollutants from regional and local sources, including large power plants, urban areas, agriculture, oil and gas development, and fires. There are few human population centers within the SCPN; only Albuquerque is larger than 100,000 people.

Based on EPA’s National Emissions Inventory for 2011, most counties in the vicinity of the SCPN had relatively low levels of sulfur dioxide (SO_2) emissions (< 5 tons per square mile per year [$tons/mi^2/yr$]). Emissions of oxidized N were generally slightly higher (up to $5 tons/mi^2/yr$ or even higher), and emissions of reduced N were lower ($< 2 tons/mi^2/yr$). Total S deposition at the locations of SCPN parks during the period 2010-2012 was generally less than $2 kg S/ha/yr$. Total N deposition was less than $5 kg N/ha/yr$ at most park locations.

The arid conditions that prevail throughout much of the SCPN do not contribute to acid sensitivity, which tends to be enhanced by high precipitation due to the leaching by precipitation of base cations from watershed soils. At the higher elevations within parklands in the SCPN that receive greater amounts of precipitation, which leaches base cations, it is possible that there are some acid-sensitive surface waters. Ecosystem sensitivity to acidification is also influenced by land slope, which often

affects the degree of acid neutralization provided by soils and bedrock within the watershed. Land slope varies considerably among the parks in the SCPN, but is most pronounced in GRCA, suggesting increased potential for acid sensitivity of aquatic ecosystems. However, stream acidification has not been documented in any of the SCPN parks and is considered unlikely in this network.

Preliminary testing has suggested that the sandstone masonry of the Anasazi dwellings in MEVE might be vulnerable to deterioration from acidic deposition. Experiments in the 1980s on test walls similar in composition to ruins at MEVE found that rates of acid deposition at that time did not seem to accelerate sandstone deterioration beyond natural rates of erosion, but investigators postulated that if acid deposition inputs increased (in response to increasing regional emissions in the region of N and S), chemical erosion could be increased, especially in structures more openly exposed (Dolske et al. 1991).

In addition to contributing to acidification, N deposition can also cause undesirable nutrient enrichment of natural ecosystems, leading to changes in plant species composition and diversity and soil nutrient cycling. The predominant vegetation types within these parks that are known to be sensitive to nutrient N enrichment are arid and semi-arid plant communities. Nitrogen inputs in the form of atmospheric deposition can promote the growth of annual grasses, such as buffelgrass (*Pennisetum ciliare*) and cheatgrass (*Bromus tectorum*), with gradual loss of native forbs and shrubs. Increases in annual grasses can also increase fuel loading, leading to greater fire risk.

Ozone pollution can harm human health, reduce plant growth, and cause visible injury to foliage. Although O₃ concentrations and long-term exposures are somewhat elevated at times in the SCPN region, risk to plants has been rated as low to moderate. Relatively dry soil conditions that predominate in the region tend to limit gas exchange in plants, including O₃ uptake. However, plants growing in well-watered riparian areas may be more vulnerable to O₃ damage.

Particulate pollution can cause haze, reducing visibility. Clean, clear skies are typical of the SCPN parks, although all suffer some impairment of visibility. Most parks in the network afford magnificent vistas, with massive landforms, unique geology, and vivid rock colors. The panoramic views evident at many locations in parklands within this network provide unique visual experiences for visitors, and high air quality is central to full enjoyment of those experiences. Because the Colorado Plateau has some of the best visual air quality in the conterminous United States, reduced air quality that might go relatively unnoticed elsewhere is acutely evident on the Plateau.

The park in the SCPN in which specific visibility concerns are best understood is GRCA. Because of the importance of visibility to visitors at GRCA, the sources of atmospheric aerosols that impair that visibility, even by a relatively minor amount, has been subject of considerable research. The most important canyon locations for visibility are located at and slightly below the canyon rim. Visibility at these locations is most strongly affected by atmospheric conditions between the viewer's vantage point and the geological formations on the opposite side of the canyon.

Visibility in GRCA varies with the seasons. It is worse in the spring and summer than in the winter. Regardless of season, visibility is typically worse inside the canyon than on the rim. Average atmospheric concentrations of SO_4^{2-} , organics, and elemental carbon (C) are highest in summer, whereas NO_3^- concentrations are generally highest in winter and spring, reflecting seasonal differences in atmospheric chemistry and pollutant emissions.

Much of the work on the sources of visibility degradation in GRCA has focused on long-range transport from the Pacific coast and local transport from two large point sources, the Navajo Generating Station (NGS) and the Mohave Power Project (MPP). In 1990, NGS agreed to reduce SO_2 emissions by 90%. Three scrubbers were installed at NGS in 1997 to 1999. Reducing NGS emissions had a beneficial effect by decreasing winter haze and improving visibility in GRCA. Visibility on the haziest days, having highest fine particulate SO_4^{2-} , improved markedly following the reduction in NGS emissions. During summer, however, when NGS impacts on GRCA were minimal, there was only a small decrease in fine particulate SO_4^{2-} .

MPP elected to shut down operations in 2005 rather than scrub its SO_2 emissions in response to a law suit by environmental groups. As predicted by NPS studies, the closure of MPP improved air quality in the Grand Canyon but not by a substantial amount. Mean haze and extinction (b_{ext}) levels did not respond to the closure in a statistically significant way. Aerosol SO_4^{2-} concentrations did decrease, but not by enough to induce a measureable improvement in b_{ext} or haze.

Tracer experiments conducted during both winter and summer have demonstrated the importance of air flow channeling within valleys and canyons along the Colorado River to visibility in GRCA. Three situations have most commonly been associated with poor air quality in GRCA: 1) regional haze from southern California, 2) high humidity and cloud cover from summer monsoons, and 3) slow moving anticyclones over the Great Basin that traps pollutants in the planetary boundary layer. Other studies have identified Las Vegas and urban areas in the Baja California and Imperial Valley regions as likely primary sources of atmospheric SO_4^{2-} in the park. Northwestern Mexico was identified as a significant source of haze-producing particulates during one extreme event of unusually high SO_4^{2-} concentrations in the Grand Canyon.

Airborne toxics, including mercury (Hg) and other heavy metals, can accumulate in food webs, reaching toxic levels in top predators. Several reservoirs in southwestern Colorado near MEVE have fish consumption advisories because of elevated Hg levels. Concentrations of Hg in rainfall are relatively high in the region, but Hg deposition is relatively low because precipitation amounts are low (deposition is a function of the concentration of Hg in the precipitation and the precipitation amount). A pilot study examining Hg bioaccumulation in birds and aquatic biota in MEVE and vicinity did not find high levels of Hg, but recommended additional study focused on the top predators in aquatic ecosystems that would be most likely to accumulate toxic levels of Hg.

Background

There are five parks in the SCPN that are larger than 100 square miles: Canyon de Chelly National Monument (CACH), El Malpais National Monument (ELMA), Glen Canyon National Recreation Area (GLCA), Grand Canyon National Park (GRCA), and Petrified Forest National Park (PEFO). In addition, there are 14 smaller parks: Aztec Ruins National Monument (AZRU), Bandelier National Monument (BAND), Chaco Culture National Historical Park (CHCU), El Morro National Monument (ELMO), Hubbell Trading Post National Historic Site (HUTR), Mesa Verde National Park (MEVE), Navajo National Monument (NAVA), Petroglyph National Monument (PETR), Rainbow Bridge National Monument (RABR), Salinas Pueblo Missions National Monument (SAPU), Sunset Crater National Monument (SUCR), Walnut Canyon National Monument (WACA), Wupatki National Monument (WUPA), and Yucca House National Monument (YUHO). 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.

There are few human population centers within the network; only Albuquerque is larger than 100,000 people. Map 1 shows the network boundary and the location of each national park along with human population centers with more than 10,000 people.

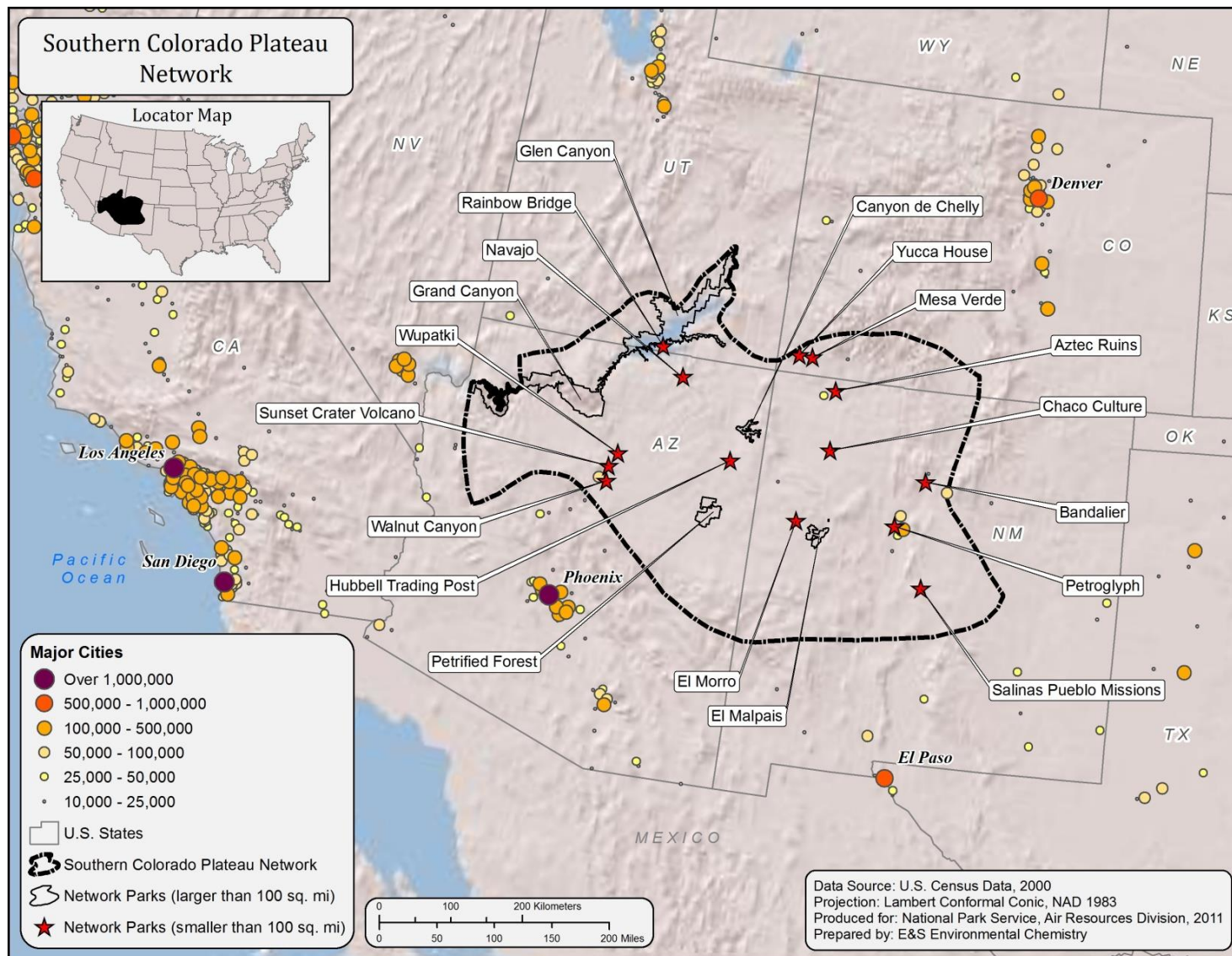
Atmospheric Emissions and Deposition

Annual county-level emissions of both sulfur dioxide (SO₂) and nitrogen (N) within the SCPN in 2002 ranged from less than 1 ton per square mile per year (ton/mi²/yr) to between 5 and 20 tons/mi²/yr. In general, annual county emissions of SO₂ and N were each less than 5 tons/mi²/yr throughout most of the network region. Most SO₂ point sources in the SCPN emitted less than 5,000 tons per year, although there were several that emitted between 5,000 and 20,000 tons per year. There are also several relatively large (larger than 5,000 tons per year) point sources of oxidized N (NO_x) in this network.

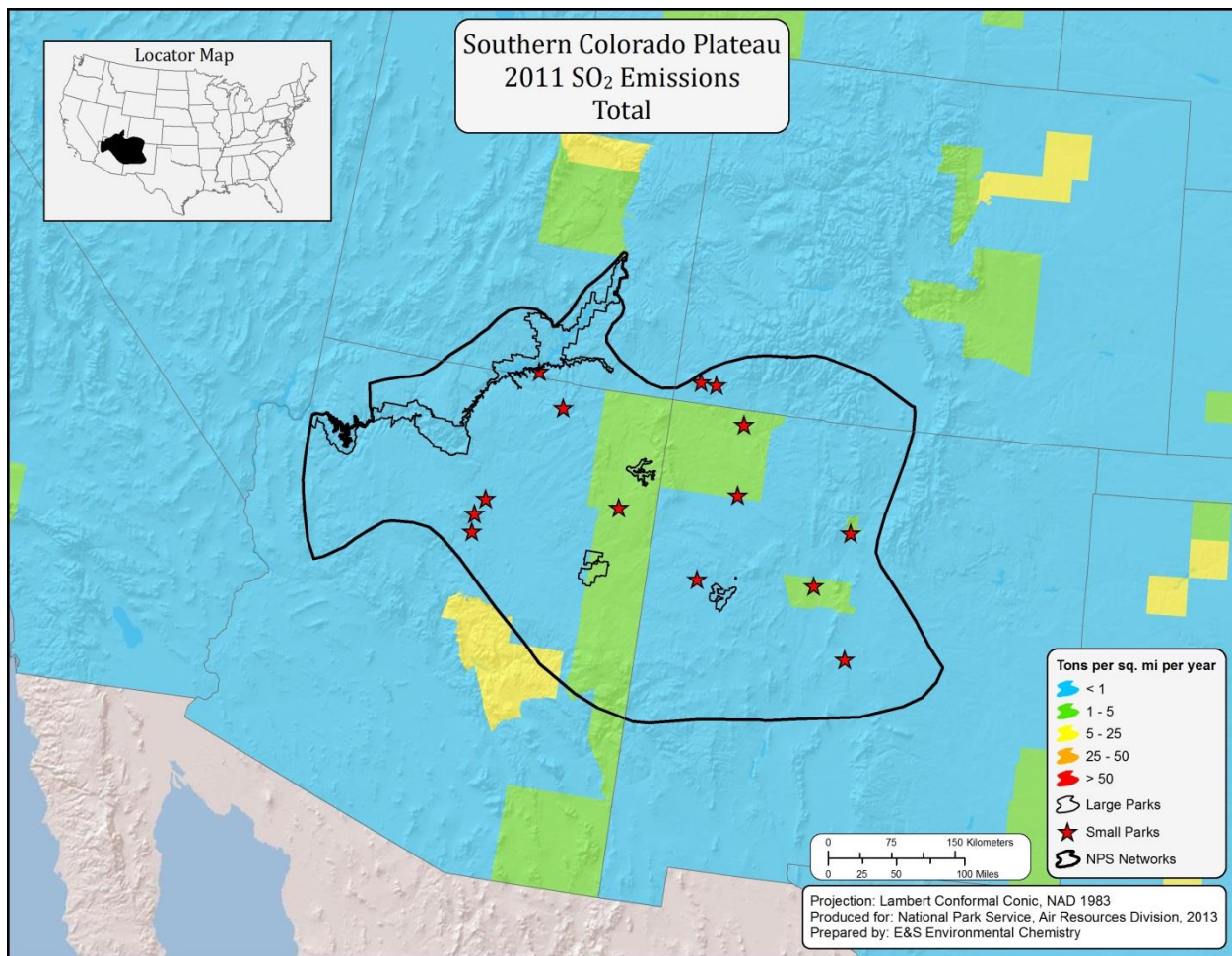
Total NO_x emissions in counties south of MEVE are relatively high compared with the surrounding area, in the range of 25,000 to 50,000 tons per year (Sullivan and McDonnell 2014). In that area, oil and gas (O&G) emissions comprised an estimated 20% to 40% of NO_x emissions from all source types. To the east and southeast of MEVE, that percentage was higher than 60%. The proportional contribution of O&G emissions to total NO_x emissions was somewhat lower around GRCA (Sullivan and McDonnell 2014).

County-level emissions near the SCPN, 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 sulfur dioxide (SO₂), NO_x, and reduced N (NH₃), respectively. Most counties near SCPN parks had relatively low SO₂ emissions (<5 tons/mi²/yr; Map 2). Spatial patterns in NO_x emissions showed more counties in the range of 1 to 5 tons/mi²/yr or higher (Map 3). Emissions of NH₃ near SCPN parks were somewhat lower, with most counties showing emissions levels below 2 tons/mi²/yr (Map 4).

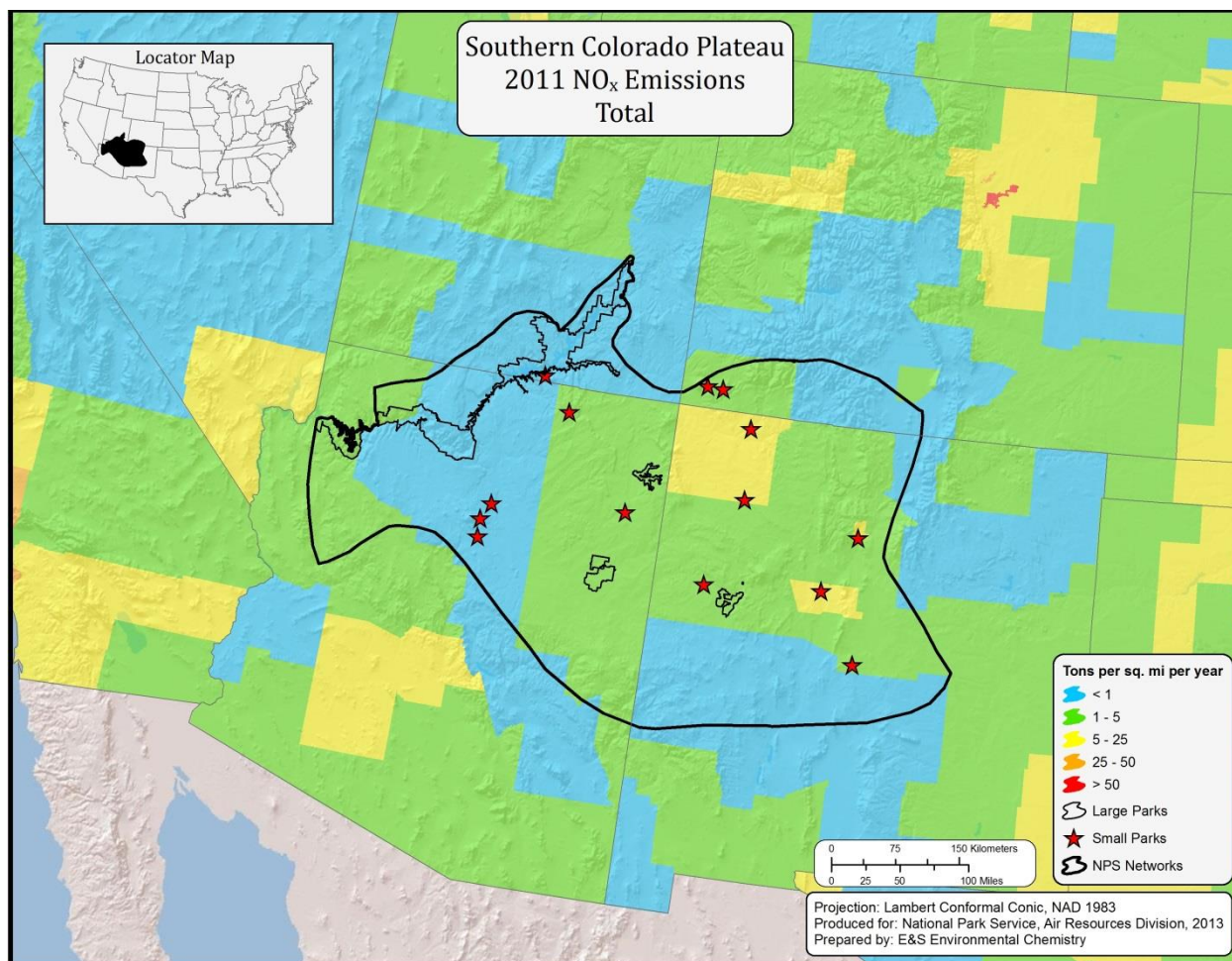
Recently, Schwede and Lear (2014) documented a hybrid approach developed by the NADP Total Deposition (TDEP) Science Committee for estimating total N and S deposition. This approach combined monitoring and modeling data. Modeling was accomplished using the Community



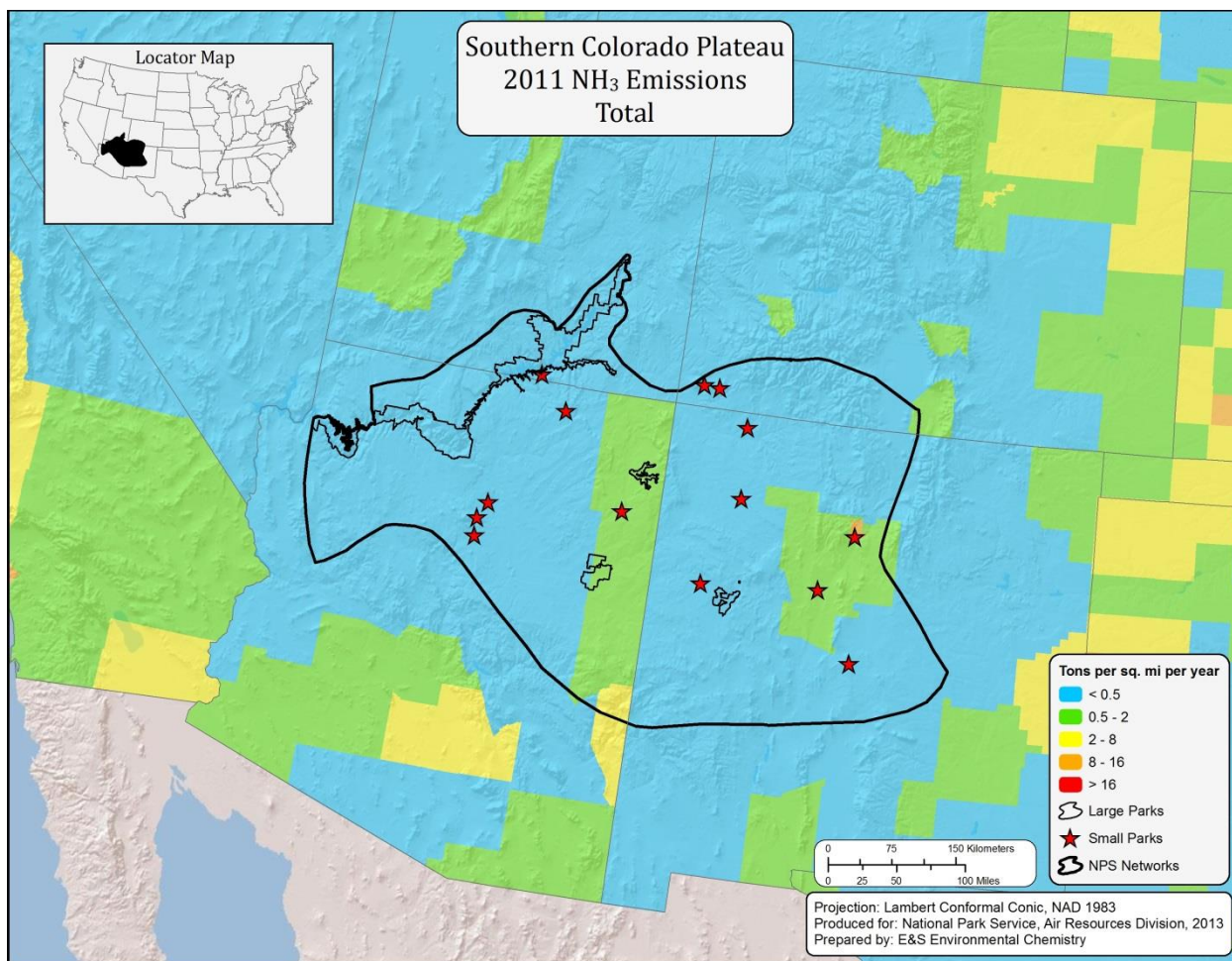
Map 1. Network boundary and locations of national parks and human population centers within the SCPN.



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



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



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

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: peroxyacetyl nitrate (PAN), N₂O₅, NO, NO₂, HONO, and organic NO₃. 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.

Deposition estimates from TDEP were used to evaluate changes in deposition of S and N at park locations over a recent 10-year period. From 2001 to 2011, total S deposition in the SCPN decreased slightly (median -0.1 kg S/ha/yr). Total NO_x deposition decreased by a larger amount (median -0.3 kg N/ha/yr), but that was balanced by an increase in total NH₃ deposition of the same magnitude. Table 1 gives three-year average changes in atmospheric deposition of S and N components in each SCPN park between 2001 and 2011.

Table 1. Average changes in S and N deposition between 2001 and 2011 across park grid cells at SCPN 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)
AZRU	Aztec Ruins	Total S	1.16	0.87	-0.29	-25.1%	0.87	0.89	0.02
		Total N	3.43	4.20	0.76	22.3%	3.75	4.22	0.47
		Oxidized N	2.88	2.17	-0.71	-24.5%	2.17	2.31	0.14
		Reduced N	0.55	2.03	1.47	266.8%	1.43	2.05	0.61
BAND	Bandelier	Total S	1.11	0.95	-0.15	-14.5%	0.68	1.48	0.80
		Total N	3.33	3.28	-0.05	-2.2%	2.51	4.65	2.13
		Oxidized N	2.44	2.17	-0.27	-11.6%	1.67	2.94	1.28
		Reduced N	0.89	1.11	0.22	23.6%	0.84	1.70	0.86
CACH	Canyon de Chelly	Total S	1.04	1.20	0.16	15.5%	0.84	1.61	0.77
		Total N	2.63	3.35	0.72	27.3%	2.64	4.37	1.73
		Oxidized N	2.06	2.33	0.27	13.2%	1.70	3.01	1.31
		Reduced N	0.57	1.02	0.45	78.0%	0.83	1.36	0.53
CHCU	Chaco Culture	Total S	1.05	0.85	-0.20	-18.7%	0.82	1.16	0.34
		Total N	2.66	2.53	-0.13	-4.8%	2.48	3.08	0.60
		Oxidized N	2.15	1.85	-0.29	-13.7%	1.81	2.25	0.44
		Reduced N	0.52	0.68	0.17	32.2%	0.64	0.83	0.19
ELMA	El Malpais	Total S	1.21	1.46	0.25	20.3%	0.94	1.89	0.96
		Total N	3.07	3.50	0.43	13.7%	2.65	4.60	1.94
		Oxidized N	2.29	2.40	0.11	4.9%	1.86	3.20	1.34
		Reduced N	0.78	1.09	0.31	39.8%	0.77	1.40	0.63
ELMO	El Morro	Total S	1.46	1.56	0.10	7.0%	1.54	1.57	0.03
		Total N	3.38	3.72	0.34	10.1%	3.65	3.74	0.09
		Oxidized N	2.47	2.38	-0.09	-3.5%	2.36	2.39	0.03
		Reduced N	0.91	1.34	0.43	46.8%	1.29	1.35	0.06
GLCA	Glen Canyon	Total S	0.72	0.56	-0.16	-23.0%	0.36	0.99	0.63
		Total N	2.56	1.97	-0.59	-23.3%	1.33	3.28	1.95
		Oxidized N	2.03	1.36	-0.67	-32.8%	0.90	2.19	1.29
		Reduced N	0.53	0.61	0.07	13.4%	0.42	1.08	0.67

Table 1 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at SCPN 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)
GRCA	Grand Canyon	Total S	0.84	0.75	-0.08	-8.9%	0.39	1.70	1.31
		Total N	2.91	2.65	-0.25	-8.9%	1.54	5.16	3.62
		Oxidized N	2.24	1.63	-0.61	-27.5%	1.05	3.02	1.97
		Reduced N	0.67	1.03	0.36	55.8%	0.49	2.14	1.64
HUTR	Hubbell Trading Post	Total S	1.16	1.21	0.06	4.9%	1.21	1.22	0.01
		Total N	3.02	3.13	0.11	3.5%	3.12	3.15	0.02
		Oxidized N	2.35	2.13	-0.23	-9.6%	2.12	2.14	0.02
		Reduced N	0.67	1.00	0.33	49.9%	1.00	1.01	0.01
MEVE	Mesa Verde	Total S	1.76	1.42	-0.33	-17.6%	1.25	1.54	0.29
		Total N	3.75	4.28	0.53	15.7%	3.87	4.90	1.03
		Oxidized N	2.72	2.59	-0.13	-4.0%	2.35	2.88	0.53
		Reduced N	1.02	1.69	0.66	69.9%	1.50	2.01	0.51
NAVA	Navajo	Total S	0.74	0.88	0.14	18.6%	0.62	0.93	0.31
		Total N	2.53	2.93	0.40	15.4%	2.11	3.09	0.97
		Oxidized N	2.01	2.09	0.08	3.6%	1.51	2.19	0.68
		Reduced N	0.52	0.84	0.32	61.1%	0.60	0.90	0.29
PEFO	Petrified Forest	Total S	1.50	1.26	-0.24	-14.9%	1.17	1.30	0.13
		Total N	3.45	3.11	-0.34	-9.6%	2.88	3.57	0.69
		Oxidized N	2.58	2.00	-0.58	-22.4%	1.91	2.09	0.18
		Reduced N	0.86	1.11	0.24	29.7%	0.97	1.64	0.67
PETR	Petroglyph	Total S	1.15	0.66	-0.49	-42.3%	0.62	0.71	0.09
		Total N	4.57	3.13	-1.44	-31.4%	2.51	3.80	1.29
		Oxidized N	3.61	2.25	-1.36	-37.7%	1.82	2.74	0.92
		Reduced N	0.96	0.88	-0.07	-7.4%	0.68	1.08	0.40
RABR	Rainbow Bridge	Total S	0.66	0.53	-0.13	-19.3%	0.53	0.53	0.00
		Total N	2.47	1.95	-0.52	-21.1%	1.95	1.95	0.00
		Oxidized N	1.98	1.44	-0.54	-27.1%	1.44	1.44	0.00
		Reduced N	0.49	0.50	0.02	3.3%	0.50	0.50	0.00

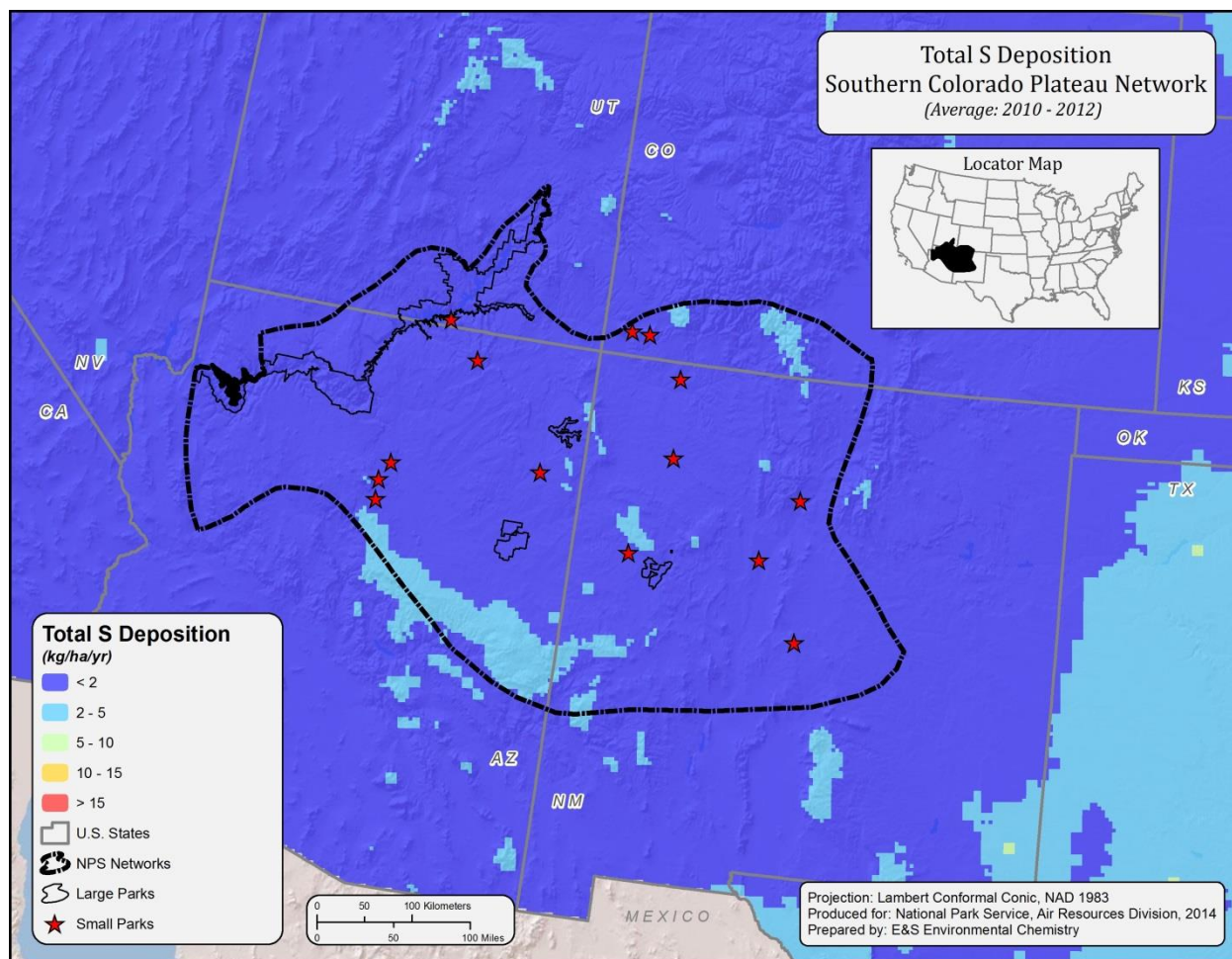
Table 1 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at SCPN parks. Deposition estimates were determined by the Total Deposition Project, TDEP, based on three-year averages centered on 2001 and 2011 for all ~4 km grid cells in each park. The minimum,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

Park Code	Park Name	Parameter	2001	2011	Absolute	Percent	2011	2011	2011
			Average (kg/ha/yr)	Average (kg/ha/yr)	Change (kg/ha/yr)		Minimum (kg/ha/yr)	Maximum (kg/ha/yr)	Range (kg/ha/yr)
SAPU	Salinas Pueblo Missions	Total S	1.29	1.04	-0.25	-18.5%	0.98	1.10	0.11
		Total N	3.49	3.00	-0.48	-13.5%	2.93	3.38	0.44
		Oxidized N	2.43	1.99	-0.44	-17.9%	1.93	2.22	0.28
		Reduced N	1.06	1.01	-0.05	-3.2%	0.98	1.16	0.18
SUCR	Sunset Crater Volcano	Total S	1.05	1.23	0.18	17.4%	1.18	1.38	0.20
		Total N	3.47	4.03	0.56	16.0%	3.86	4.45	0.59
		Oxidized N	2.64	2.55	-0.09	-3.3%	2.46	2.78	0.32
		Reduced N	0.83	1.48	0.65	77.6%	1.41	1.67	0.26
WACA	Walnut Canyon	Total S	1.11	1.62	0.51	46.3%	1.38	1.79	0.41
		Total N	3.86	5.53	1.68	43.6%	4.62	6.01	1.38
		Oxidized N	2.91	3.56	0.65	22.5%	3.03	3.81	0.79
		Reduced N	0.95	1.97	1.03	108.3%	1.60	2.20	0.60
WUPA	Wupatki	Total S	0.63	0.56	-0.07	-11.1%	0.48	0.67	0.19
		Total N	2.49	2.10	-0.40	-15.9%	1.78	2.46	0.68
		Oxidized N	1.98	1.38	-0.59	-30.0%	1.21	1.60	0.39
		Reduced N	0.52	0.71	0.20	37.7%	0.57	0.88	0.30
YUHO	Yucca House	Total S	1.42	1.15	-0.26	-18.6%	1.15	1.15	0.00
		Total N	3.30	3.59	0.29	8.7%	3.59	3.59	0.00
		Oxidized N	2.55	2.21	-0.34	-13.4%	2.21	2.21	0.00
		Reduced N	0.75	1.38	0.63	83.5%	1.38	1.38	0.00

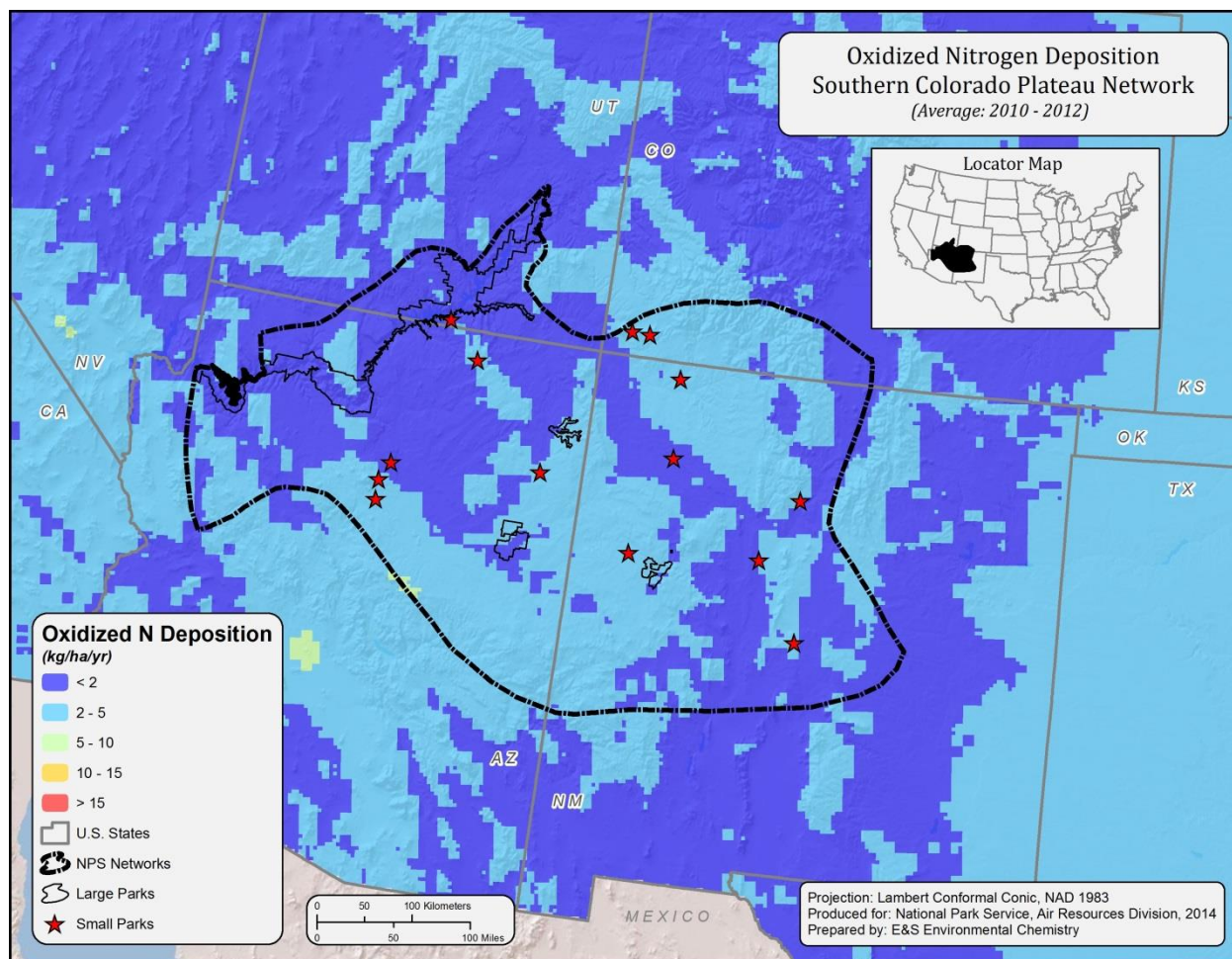
Total S deposition in and around the SCPN for the period 2010-2012 was generally less than 2 kg S/ha/yr at park locations within the network area (Map 5). Oxidized inorganic N deposition for the period 2010-2012 was less than 5 kg N/ha/yr throughout the park lands within SCPN (Map 6). Most areas received less than 2 kg N/ha/yr of NH_3 from atmospheric deposition during this same period (Map 7); a few areas received higher amounts. Total N deposition was less than 5 kg N/ha/yr at most park locations (Map 8); some areas received higher amounts.

Rainfall in the arid southwest is infrequent and most N deposition occurs as dry inputs (Fenn et al. 2003). The major source of N emissions at many locations is vehicular traffic (Fernando et al. 2001). Dry deposition is difficult to quantify, in large part because the deposition flux is influenced by a multitude of factors, including the mix of air pollutants present, surface characteristics of soil and vegetation, and meteorological conditions (Weathers et al. 2006). Because the vegetation is sparse in arid ecosystems, soil surfaces are potentially exposed to substantial direct dry deposition of atmospheric pollutants. Padgett et al. (1999) found that inorganic N can accumulate on the soil surface of coastal sage scrub vegetation communities in southern California during dry smoggy periods. Upon onset of the rainy season, the concentration of NO_3^- in the surface soil decreased and was leached down the soil profile (Padgett et al. 1999, Padgett and Bytnerowicz 2001).

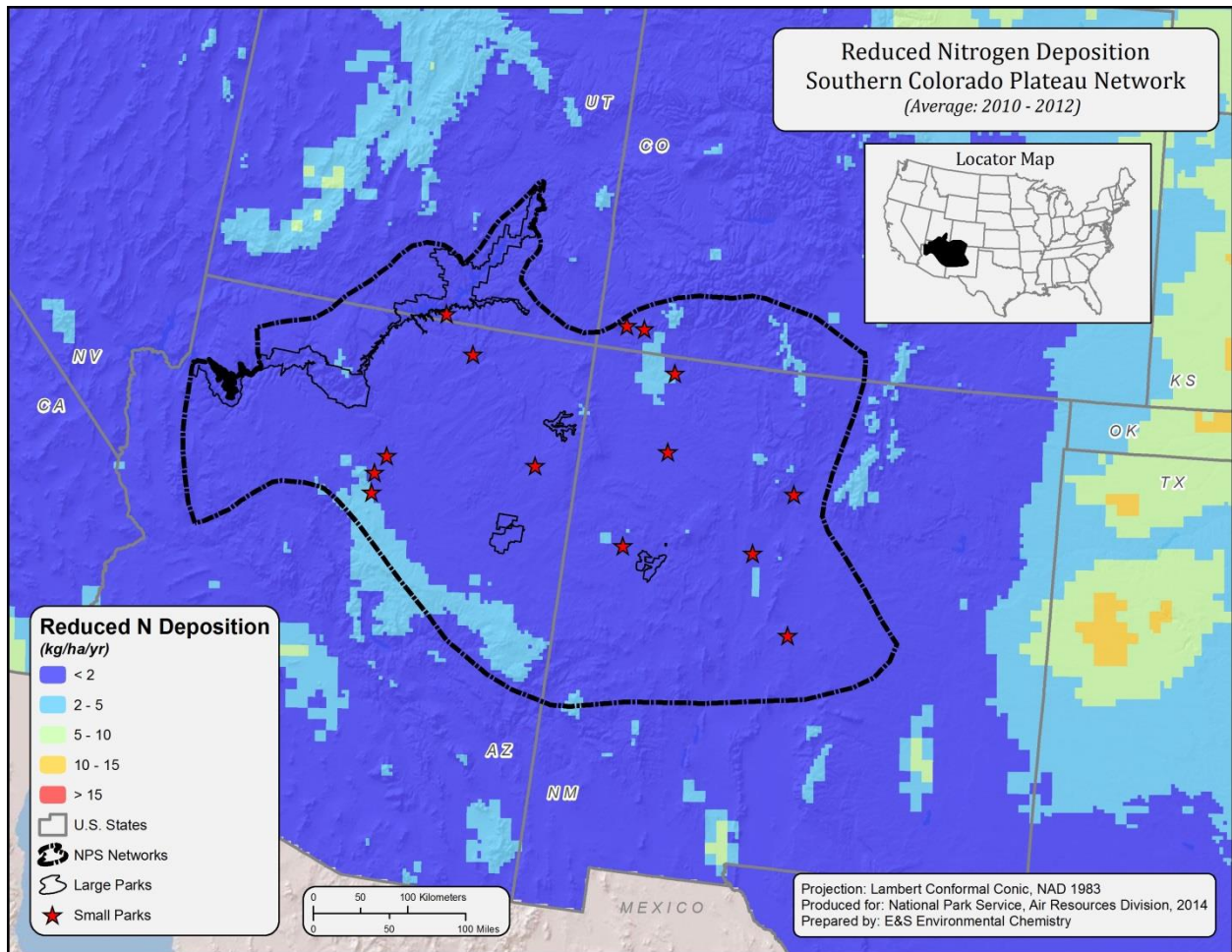
From 2002 to 2007, the Western Airborne Contaminant Assessment Project (WACAP) studied airborne contaminants in a number of national parks of the western United States from Alaska to southern California, including BAND in the SCPN. Semivolatile organic compounds in the air at BAND were mainly the current use pesticides (CUPs) endosulfan, dacthal, and trifluralin and the historic use pesticides (HUPs) hexachlorobenzene, hexachlorocyclohexane- α , and chlordanes.



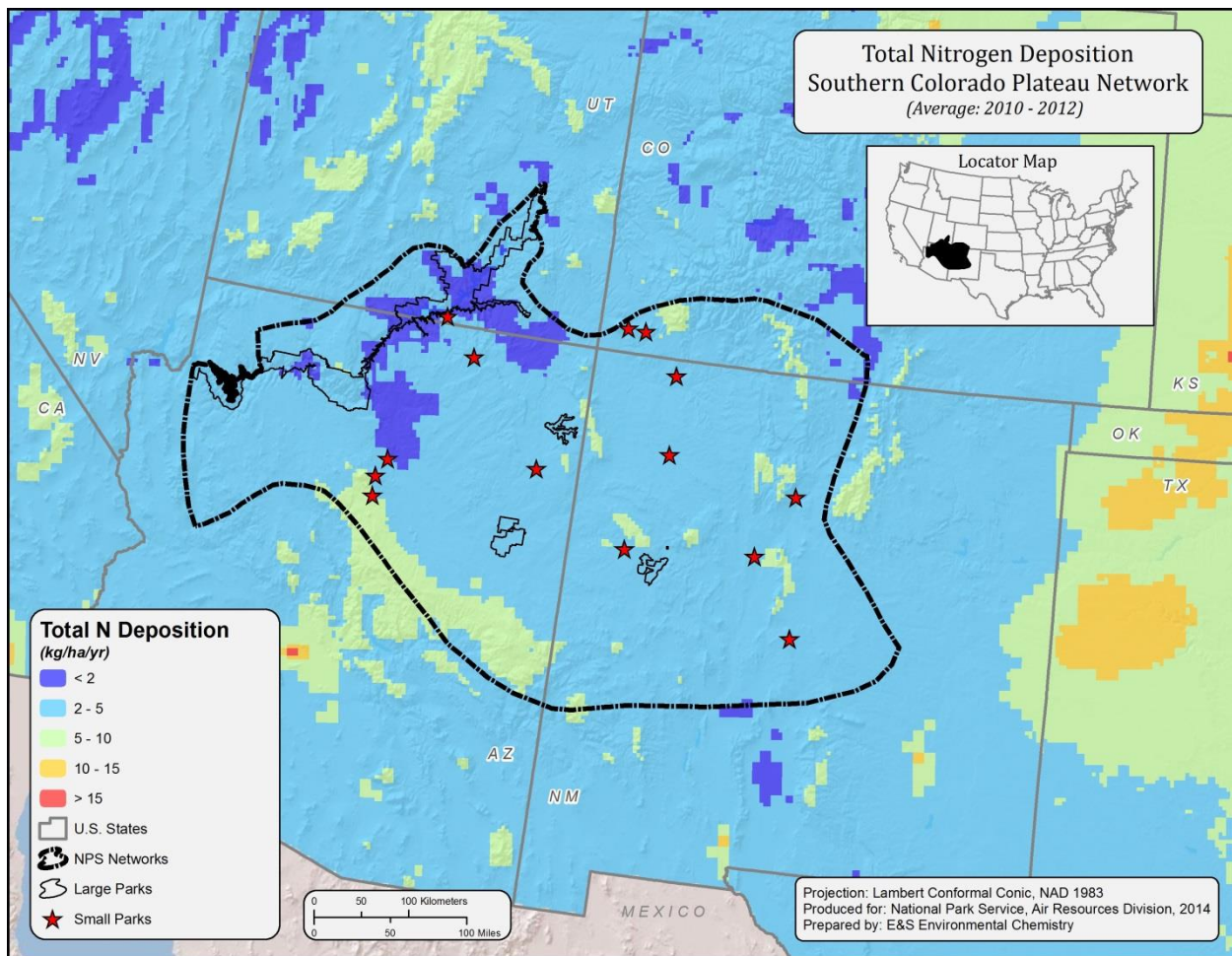
Map 5. Total S deposition for the three-year period centered on 2011 in and around the SCPN. (Source: Schwede and Lear 2014)



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



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



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

Acidification

Effects on Natural Ecosystems

The network rankings developed in a coarse national assessment by Sullivan et al. (2011b) for acid Pollutant Exposure, Ecosystem Sensitivity to acidification, and Park Protection yielded an overall network acidification Summary Risk ranking for the SCPN that was Moderate, in the middle of the distribution among networks.

The five I&M parks within the SCPN that are larger than 100 square miles were all ranked in the lowest or second lowest quintile among parks in acid Pollutant Exposure (Table 2). For the smaller parks, four were ranked Very Low, six were ranked Low, and the other four were ranked Moderate for this theme. There was considerable variation in the Ecosystem Sensitivity to acidification ranking. One park (GRCA) was ranked in the highest quintile, while four parks (AZRU, ELMO, HUTR and YUHO) were ranked in the lowest quintile. The remaining parks varied in their rankings from Low to High (Table 2). While rankings are an indication of risk, park-specific data, particularly data on ecosystem sensitivity, are needed to fully evaluate risk from acidification.

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
Aztec Ruins	AZRU	Moderate	Very Low
Bandelier	BAND	Low	High
<i>Canyon de Chelly</i>	CACH	Low	High
Chaco Culture	CHCU	Low	Moderate
<i>El Malpais</i>	ELMA	Low	Low
El Morro	ELMO	Moderate	Very Low
<i>Glen Canyon</i>	GLCA	Very Low	High
<i>Grand Canyon</i>	GRCA	Low	Very High
Hubbell Trading Post	HUTR	Low	Very Low
Mesa Verde	MEVE	Moderate	High
Navajo	NAVA	Very Low	Moderate
<i>Petrified Forest</i>	PEFO	Low	Moderate
Petroglyph	PETR	Low	Low
Rainbow Bridge	RABR	Very Low	Moderate
Salinas Pueblo Missions	SAPU	Very Low	Low
Sunset Crater Volcano	SUCR	Low	Low
Walnut Canyon	WACA	Low	Moderate
Wupatki	WUPA	Very Low	Moderate
Yucca House	YUHO	Moderate	Very 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.

Ecosystem sensitivity to acidification rankings take into account elevation and land slope, which often influence the degree of acid neutralization provided by soils and bedrock within the watershed. Land slope varies considerably among the parks in the SCPN. Two of the larger parks (ELMA and PEFO) have average slope less than 10°, whereas terrain in the remainder of the larger parks is steeper, with average slope ranging from 10° to 20° in some areas to more than 40° in GRCA. The steep slopes in GRCA suggest increased potential for acid sensitivity of aquatic ecosystems. The average slope within the smaller parks ranges from less than 10° in some areas to the range of 30° to 40° in others. Nevertheless, there is no information available regarding the sensitivity of terrestrial resources in the SCPN to soil acidification. Given the low levels of N, and especially S, deposition in this network and the low precipitation, it is very unlikely that any appreciable soil acidification has occurred to date.

Large rivers, such as the Colorado River that flows through the Grand Canyon, typically contain high solute concentrations and are not acid-sensitive. The arid conditions that prevail throughout much of the SCPN also do not contribute to acid sensitivity, which tends to be enhanced by high precipitation amounts. At the higher elevations within parklands in the SCPN that receive greater amounts of precipitation, it is possible that there are acid-sensitive surface waters. Data are not available to substantiate that possibility, however.

There are a number of amphibian species living GRCA and other parks within the SCPN, but they do not appear to be threatened by acidification caused by air pollution. Many of these species—including the Great Basin spadefoot toad (*Scaphiopus intermontanus*), the red-spotted frog (*Bufo punctatus*), and the canyon treefrog (*Hyla arenicolor*)—breed in small pools in sandstone. The tiger salamander (*Ambystoma tigrinum*) and the Chiricahua leopard frog (*Rana chiricahuensis*), both found in GRCA, are on the State of Arizona threatened list. However, Binkley et al. (1997) reported that the main threat to these species is habitat loss, and that there is no evidence indicating risk from acidic deposition.

Binkley et al. (1997) additionally concluded that it is unlikely that fish in the Colorado River in GRCA are affected by air pollution; they again cite habitat elimination as the greatest risk to native species in the river. The Colorado River was transformed from a warm, muddy river to a cold, relatively clear river as a result of construction of the Glen Canyon Dam. Operation of the dam resulted in loss of habitat for native species such as the Colorado squawfish (*Ptychocheilus lucius*), bonytail chub (*Gila elegans*), humpback chub (*Gila cypha*), razorback sucker (*Xyrauchen texanus*), roundtail chub (*Gila robusta*) and flannelmouth sucker (*Catostomus insignis*; Binkley et al. 1997).

Effects on Historic Structures

In the 1980s, the NPS became increasingly concerned that archeological resources, specifically sandstone masonry structures, in the Four Corners region were at risk from anthropogenic stressors, including air pollution. To evaluate potential air pollution impacts, sandstone masonry deterioration was monitored at MEVE over three years. Investigators found that, during this time, the environment did not seem to be sufficiently wet or acidic to accelerate sandstone deterioration beyond what would be expected from natural erosion processes. However, they noted that in more exposed areas (e.g.,

mesa top sites) chemical erosion due to acidic deposition could be more pronounced. Increases in acidic deposition inputs in the future might further increase erosion (Dolske et al. 1991).

Nutrient Nitrogen Enrichment

The network rankings determined by Sullivan et al. (2011a) in a coarse national assessment of nutrient N Pollutant Exposure, Ecosystem Sensitivity to nutrient N enrichment, and Park Protection yielded an overall network nutrient N enrichment Summary Risk ranking that was near the median, in the middle quintile among all networks. The overall level of concern for nutrient N enrichment effects on I&M parks within this network was judged by Sullivan et al. (2011a) to be Moderate. 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.

The five I&M parks within the SCPN that are larger than 100 square miles were all ranked in the lowest or second lowest quintile among parks in nutrient N Pollutant Exposure (Table 3). Similarly, all of the smaller parks, except AZRU (which was ranked in the middle quintile), were ranked in one of the two lowest quintiles for nutrient N Pollutant Exposure. Ecosystem Sensitivity to nutrient N enrichment was relatively high, however, within the two highest quintiles among I&M parks, for three of the larger parks (GLCA, GRCA, and PEFO) and 11 of the smaller parks (Table 3). In general, the predominant vegetation types within these parks that are presumed to be especially sensitive to nutrient N enrichment are arid and semi-arid plant communities.

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
Aztec Ruins	AZRU	Moderate	High
Bandelier	BAND	Low	High
<i>Canyon de Chelly</i>	CACH	Low	Moderate
Chaco Culture	CHCU	Low	Very High
<i>El Malpais</i>	ELMA	Low	Low
El Morro	ELMO	Low	High
<i>Glen Canyon</i>	GLCA	Very Low	High
<i>Grand Canyon</i>	GRCA	Very Low	Very High
Hubbell Trading Post	HUTR	Low	Moderate
Mesa Verde	MEVE	Low	High
Navajo	NAVA	Very Low	Moderate
<i>Petrified Forest</i>	PEFO	Low	Very High
Petroglyph	PETR	Low	Very High
Rainbow Bridge	RABR	Very Low	High
Salinas Pueblo Missions	SAPU	Very Low	Very High
Sunset Crater Volcano	SUCR	Low	Low
Walnut Canyon	WACA	Low	High
Wupatki	WUPA	Very Low	High
Yucca House	YUHO	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.

Response of desert vegetation communities to N addition have been shown to include change in plant species composition, increase in biomass of non-native invasive species, and decrease in relative abundance and richness of native herbaceous species (Allen and Geiser 2011). The abundance of invasive non-native plant species has increased in desert ecosystems, likely due in part to N deposition at some locations (Allen et al. 2009, Brooks 2003). Increases in N have been found to promote invasions of fast-growing exotic annual grasses (e.g., cheatgrass [*Bromus tectorum*]) and forbs (e.g., Russian thistle [*Salsola kali*]) at the expense of native species (Allen et al. 2009, Brooks 2003, Schwinning et al. 2005). Nitrogen addition favors buffelgrass (*Pennisetum ciliare*) over native species in arid ecosystems, as buffelgrass is able to rapidly absorb and assimilate N (Lyons et al. 2013). Increased cover of exotic grasses can increase fire risk and frequency (Balch et al. 2013, Rao et al. 2010) and affect plant biodiversity. Inputs of N may also decrease water use efficiency in plants like big sagebrush (Inouye 2006).

Limited experimental data are available. Biomass of native blue grama grass (*Bouteloua gracilis*) in desert grassland at the Sevilleta Long-Term Ecological Research (LTER) site in New Mexico increased in response to N addition at a rate of 20 kg N/ha/yr (Báez et al. 2007). In contrast, a change in ambient N deposition at the control plot during the 16-year experiment from 1.7 to 2.4 kg N/ha/yr did not cause a change in blue grama biomass.

Experimental N addition reduced the soil moisture in Sagebrush steppe. This would be expected to decrease herbaceous plant productivity (Inouye 2006). Experimental fertilization with N at very high levels (72 kg N/ha/yr) at the Jornada LTER site in New Mexico caused increased growth of native annual forbs during winter, but decreases during summer (Gutierrez and Whitford 1987). This variable response may have been due, at least in part, to water limitation during summer. Barker et al. (2006) determined that water availability, rather than N supply, was the most important limiting factor for productivity of creosote bush.

Pardo et al. (2011b) compiled data on empirical critical loads (CL) for protecting sensitive resources in Level I ecoregions across the conterminous United States against nutrient enrichment effects caused by atmospheric N deposition. Data on empirical CL for nutrient N deposition in the parks in the SCPN are limited. Pardo et al. (2011b) mainly reported empirical CL values in the North American Deserts ecoregion for the protection of lichens and herbaceous plants (Table 4). The lower end of the reported range was 3 kg N/ha/yr for both of these sensitive receptors. Ambient N deposition reported by Pardo et al. (2011b) was higher than the lower end of the CL range at four desert parks in the SCPN: AZRU, MEVE, PETR, and YUHO. This suggests CL exceedance for protection against nutrient enrichment at these parks. The CL for protection of lichens in forested portions of BAND was also exceeded.

Table 4. Empirical critical loads for nitrogen in the SCPN, by ecoregion and receptor from Pardo et al. (2011b). Ambient N deposition reported by Pardo et al. (2011b) is compared to the lowest critical load for a receptor to identify potential exceedance, indicated by graying. A critical load exceedance suggests that the receptor is at increased risk for harmful effects.

NPS Unit	Ecoregion	N Deposition (kg N/ha/yr)	Mycorrhizal Fungi	Critical Load (kg N/ha/yr)			
				Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Aztec Ruins NM	North American Deserts	3.7	NA	3	3 - 8.4	NA	NA
Bandelier NM	North American Deserts	2.9	NA	3	3 - 8.4	NA	NA
Bandelier NM	Northwestern Forested Mountains	2.9	5 - 10	2.5 - 7.1	4 - 10	4 - 17	4 - 17
Canyon de Chelly NM	North American Deserts	2.2	NA	3	3 - 8.4	NA	NA
Canyon de Chelly NM	Temperate Sierras	2.2	NA	4 - 7	NA	NA	NA
Chaco Culture NHP	North American Deserts	2.4	NA	3	3 - 8.4	NA	NA
El Malpais NM	North American Deserts	2.5	NA	3	3 - 8.4	NA	NA
El Malpais NM	Temperate Sierras	2.5	NA	4 - 7	NA	NA	NA
El Morro NM	North American Deserts	2.5	NA	3	3 - 8.4	NA	NA
Glen Canyon NRA	North American Deserts	2.5	NA	3	3 - 8.4	NA	NA
Grand Canyon NP	North American Deserts	2.9	NA	3	3 - 8.4	NA	NA
Grand Canyon NP	Temperate Sierras	2.9	NA	4 - 7	NA	NA	NA
Hubbel Trading Post NHS	North American Deserts	2.0	NA	3	3 - 8.4	NA	NA
Mesa Verde NP	North American Deserts	3.4	NA	3	3 - 8.4	NA	NA
Navajo NM	North American Deserts	1.7	NA	3	3 - 8.4	NA	NA
Petrified Forest NP	North American Deserts	2.8	NA	3	3 - 8.4	NA	NA
Petroglyph NM	North American Deserts	3.7	NA	3	3 - 8.4	NA	NA
Rainbow Bridge NM	North American Deserts	2.0	NA	3	3 - 8.4	NA	NA
Salinas Pueblo Missions NM	Great Plains	2.6	12 - 12	NA	5 - 25	NA	10 - 25
Sunset Crater NM	Temperate Sierras	2.8	NA	4 - 7	NA	NA	NA
Walnut Canyon NM	Temperate Sierras	3.0	NA	4 - 7	NA	NA	NA
Wupatki NM	North American Deserts	2.1	NA	3	3 - 8.4	NA	NA
Wupatki NM	Temperate Sierras	2.1	NA	4 - 7	NA	NA	NA
Yucca House NM	North American Deserts	3.1	NA	3	3 - 8.4	NA	NA

Ellis et al. (2013) estimated the CL for nutrient-N deposition to protect the most sensitive ecosystem receptors in 45 national parks. The lowest terrestrial CL of N is generally estimated for protection of lichens (Geiser et al. 2010). 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 for GRCA, MEVE, and PEFO in the range of 3-8.4 kg N/ha/yr for protection of herbaceous plants and 3 kg N/ha/yr for protection of lichens. Sullivan and McDonnell (2014) analyzed nutrient-N deposition and CL at selected national parks in the Intermountain West, including MEVE and GRCA in SCPN. Most of MEVE received ambient N deposition in excess of the lower estimate of the nutrient-N CL reported by Allen and Geiser (2011). None of GRCA was reported to be in exceedance, although much of the park was within 1 kg N/ha/yr of exceedance (Sullivan and McDonnell 2014).

Most of MEVE received ambient N deposition estimated using the Comprehensive Air Quality Model with Extensions (CAM_x) that was in exceedance of the lower estimate of the nutrient-N empirical CL reported by Allen and Geiser (2011); the remainder was largely below, but within 1 kg N/ha/yr of, exceedance. Although none of GRCA was in exceedance, most of the western third of the park and scattered portions of the remainder of the park were close (within 1 kg N/ha/yr) to exceedance (Sullivan and McDonnell 2014). Thus, it is likely that nutrient effects caused by N deposition may occur under ambient N loading at MEVE, and significant portions of GRCA may be at risk if N emissions from electricity generating units (EGUs), O&G exploration and production, or other sources increase appreciably over 2008 levels.

Ozone Injury to Vegetation

The O₃-sensitive plant species that are known or thought to occur within the I&M parks in the SCPN are listed in Table 5. Those considered to be bioindicators, because they exhibit distinctive symptoms when injured by O₃ (e.g., dark stipple), are designated by an asterisk. One park in this network, PETR, has not documented the presence of any O₃-sensitive and/or bioindicator species. The other parks in this network contained at least 1 and as many as 12 O₃-sensitive and/or bioindicator plant species.

The W126 and SUM06 O₃ exposure indices calculated by NPS staff are given in Table 6, along with Kohut's (2007) O₃ risk ranking. The two ranking systems differ. The NPS ranking system (NPS 2010) is a quick assessment of O₃ condition and simply ranks O₃ exposure levels according to injury thresholds from the literature (Heck and Cowling 1997), using a 5-year average of the W126 (a measure of cumulative O₃ exposure that preferentially weights higher O₃ concentrations) or the SUM06 (a measure of cumulative O₃ exposure that includes only hourly concentrations over 60 ppb) metrics over a 3-month period. The W126 was classified as Moderate at values between 7 and 13 ppm-hr, as defined by NPS (2010). 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, respectively, as defined by NPS (2010). Using these criteria, O₃ levels at the SCPN parks are rated Moderate to High.

Kohut's approach is a rigorous assessment of potential risk to plants that considers both O₃ exposure and soil moisture. Kohut also used injury thresholds from the literature, but evaluated a different O₃ metric (after Lefohn 1997), the W126 over a 5-month period in conjunction with the N100 (number of hours over 100 ppb ozone, i.e., higher O₃ concentrations most likely to cause plant injury). Kohut examined five individual years (1995-1999) 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. Kohut's (2007) ranking was Low for all except four parks (PEFO, SUCR, WACA, and WUPA), which were all ranked Moderate.

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 5. Ozone-sensitive and bioindicator plant species known or thought to occur in the I&M parks of the SCPN. (Data 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																	
		AZRU	BAND	CACH	CHCU	ELMA	ELMO	GLCA	GRCA	HUTR	MEVE	NAVA	PEFO	PETR	RABR	SAPU	SUCR	WACA	WUPA
No Species													x						
<i>Ailanthus altissima</i> *	Tree-of-heaven		x						x				x						
<i>Amelanchier alnifolia</i>	Saskatoon serviceberry										x								
<i>Amelanchier utahensis</i>	Saskatoon serviceberry							x											
<i>Apocynum androsaemifolium</i> *	Spreading dogbane		x						x		x								
<i>Apocynum cannabinum</i>	Dogbane, Indian hemp		x	x				x	x		x			x			x		
<i>Artemisia ludoviciana</i> spp. <i>Mexicana</i> *	Silver wormwood			x															
<i>Artemisia ludoviciana</i> *	Silver wormwood				x	x		x	x		x	x	x	x			x	x	
<i>Liriodendron tulipifera</i> *	Yellow-poplar																	x	
<i>Oenothera elata</i> *	Evening primrose							x	x		x	x							
<i>Parthenocissus quinquefolia</i>	Virginia creeper	x			x	x				x				x	x		x		
<i>Parthenocissus vitacea</i>	Virginia creeper			x															
<i>Pinus ponderosa</i> *	Ponderosa pine			x		x	x	x	x		x						x		
<i>Populus tremuloides</i> *	Quaking aspen			x		x			x		x	x				x	x	x	
<i>Prunus virginiana</i>	Choke cherry			x	x				x		x	x					x		
<i>Rhus trilobata</i> *	Skunkbush	x		x	x				x		x	x	x	x	x	x	x	x	
<i>Robinia pseudoacacia</i>	Black locust	x	x																
<i>Rubus parviflorus</i>	Thimbleberry			x															
<i>Rudbeckia laciniata</i> *	Cutleaf coneflower			x															
<i>Salix gooddingii</i>	Gooding's willow	x		x	x				x	x			x	x	x				
<i>Salix scouleriana</i> *	Scouler's willow					x			x							x		x	
<i>Solidago canadensis</i> var. <i>scabra</i>	Goldenrod									x									

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

* Bioindicator species

Table 6. Ozone assessment results for I&M parks in the SCPN 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	
Aztec Ruins	AZRU	12.91	Moderate	17.74	High	Low
Bandelier	BAND	11.94	Moderate	15.16	High	Low
Canyon de Chelly	CACH	13.80	High	19.35	High	Low
Chaco Culture	CHCU	12.92	Moderate	17.55	High	Low
El Malpais	ELMA	13.19	High	17.79	High	Low
El Morro	ELMO	13.41	High	18.19	High	Low
Glen Canyon	GLCA	15.12	High	21.56	High	Low
Grand Canyon	GRCA	17.78	High	26.22	High	Low
Hubbell Trading Post	HUTR	14.59	High	20.96	High	Low
Mesa Verde	MEVE	13.96	High	19.62	High	Low
Navajo	NAVA	14.83	High	21.61	High	Low
Petrified Forest	PEFO	16.14	High	23.69	High	Moderate
Petroglyph	PETR	12.90	Moderate	17.27	High	Low
Rainbow Bridge	RABR	15.12	High	21.82	High	Low
Salinas Pueblo Missions	SAPU	13.01	High	17.49	High	Low
Sunset Crater Volcano	SUCR	17.88	High	27.43	High	Moderate
Walnut Canyon	WACA	18.02	High	27.83	High	Moderate
Wupatki	WUPA	17.71	High	27.18	High	Moderate
Yucca House	YUHO	14.38	High	20.40	High	Low

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.

Summer peaks of ground-level O₃ in the SCPN could result in part from natural stratospheric intrusions (Diem 2004). However, in remote locations, including GRCA and perhaps other park lands within the SCPN, ground-level O₃ concentrations tend to peak earlier, in the springtime. Diem (2004) concluded that stratospheric intrusions had relatively little overall effect on O₃ concentrations in GRCA. Rather, Diem (2004) suggested that NO_x and VOCs originating in southern California were being transported to the park and were largely responsible for the observed high O₃ concentrations in GRCA in the spring. In more recent years, O&G emissions have increased substantially and may affect O₃ formation.

Between 1983 and 1994, average hourly O₃ concentrations in GRCA were measured at around 25 to 50 ppb, with a peak one-hour concentration of up to 80 ppb. Although there were no reports of O₃ damage to park plants, these values are likely high enough to cause visible or growth effects on sensitive plant species (Binkley et al. 1997).

NPS (2010) evaluated the fourth-highest 8-hour O₃ concentrations for national parks that have consistently been at or above the standard of 75 ppb, based on 11-20 years of monitoring data

running through 2008. There were six parks that routinely had such high concentrations. Six additional parks had O₃ levels that were typically below the 75 ppb standard, but were within the EPA's proposed range for a possible new standard (60-70 ppb; NPS 2010). These parks included GRCA. NPS (2010) reported long-term trends in annual fourth highest 8-hour daily maximum O₃ concentration for 31 monitoring sites in 27 national parks having more than 10 years of data through 2008. Statistically significant increases were reported for four parks, including MEVE in the SCPN.

Visibility Impairment

The southern Colorado Plateau landscape includes massive landforms, unique geology, and vivid rock colors (Grand Canyon Visibility Transport Commission [GCVTC] 1996). The panoramic views evident at many locations in parklands within this network provide exceptional visual experiences for visitors, and high air quality is central to full enjoyment of those experiences. In general, the best visibility in the conterminous United States typically occurs in the Great Basin, Colorado Plateau, and Rocky Mountains (Hand et al. 2011, Savig and Morse 1998). Because the Colorado Plateau has some of the best visual air quality in the conterminous United States, reduced air quality that might go relatively unnoticed elsewhere is acutely evident on the Plateau (GCVTC, 1996).

Air pollution causes haze and visibility impairment¹ in all of the SCPN parks at times. Regional and local pollution sources that appear to contribute to visibility impairment include automobiles, coal- and oil-fired power plants, smelters, O&G production, wildfires, and urban emissions.

Natural Background and Ambient Visibility Conditions

Four of the parks in the SCPN are classified as Class I under the Clean Air Act: BAND, GRCA, MEVE, and PEFO. The other SCPN parks are classified as Class II. 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 in 2064. Natural background visibility, or natural haze, assumes no human-caused pollution, but varies with natural processes such as windblown dust, fire, volcanic activity and biogenic emissions. Visibility is monitored by the Interagency Monitoring of Protected Visual Environments Network (IMPROVE). IMPROVE samplers use filters to collect the fine particles of pollution that cause haze and impair visibility. Visibility is estimated based on the types and amounts of fine particles and typically reported using the haze index, deciview (dv^2).

IMPROVE monitors are located at BAND, GRCA, MEVE, and PEFO in the SCPN. Data are also available that are considered by IMPROVE to be representative of visibility conditions in three of the other parks, GLCA, SUCR, and WACA. A monitoring site is considered to be representative of an area if it is within 60 mi (100 km) and 425 ft (130 m) in elevation of that area. GLCA is represented

¹ *Visibility impairment* means any humanly perceptible change in visibility (light extinction, visual range, contrast, coloration) from that which would have existed under natural conditions. The EPA believes that visibility changes of less than one deciview are likely to be perceptible in some cases, especially where the scene being viewed is highly sensitive to small amounts of pollution.

² This 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.

by a monitor at Capitol Reef NP (CAPI1); SUCR by GRCA2 at GRCA; WACA by SYCA1 at the Sycamore Canyon Wilderness.

Current visibility estimates reflect current pollution levels and provide park managers with information on spatial differences in visibility and air pollution. To evaluate visibility conditions over time and space, IMPROVE compares conditions on two groups of days, the 20% clearest and the 20% haziest days. Data from IMPROVE show that visibility impairment caused by air pollution occurs virtually all the time at most national park and wilderness area monitoring stations. Table 7 gives the estimated natural (i.e., no man-made impairment) conditions and degree of impairment on the average of the 20% clearest and 20% haziest days. Measured ambient haze values for the RHR baseline period 2000 through 2004 were several times higher than the estimated natural condition on both the clearest and haziest days.

In addition to the IMPROVE samplers, cameras have been used to illustrate visibility conditions. Representative photos of selected vistas under three different visibility conditions are shown in Figure 1 for BAND, GRCA, and MEVE. In addition to expressing visibility in dv , visibility is expressed in terms of light extinction (b_{ext}) in inverse megameters (Mm^{-1}) and visual range (VR) in kilometers (km). Deciview and b_{ext} are most closely related to the amounts and types of fine pollution particles in the air, whereas visual range can be influenced by meteorological conditions. 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. This series of photos provides a graphic illustration of the visual effect of these differences in haze level on a representative vista in each of these parks.

IMPROVE data allow estimation of visual range (VR). Data indicate that in BAND, air pollution has reduced average VR from 170 to 95 miles (274 to 153 km). On the haziest days, VR has been reduced from 120 to 60 miles (193 to 97 km). Severe haze episodes occasionally reduce visibility to 4 miles (6 km). At GRCA (with the monitor also representative of SUCR), pollution has reduced average VR from 170 to 120 miles (274 to 193 km). On the haziest days, VR has been reduced from 120 to 70 miles (193 to 113 km). Severe haze episodes occasionally reduce visibility to 14 miles (23 km). At MEVE, air pollution has reduced average VR from 170 to 100 miles (274 to 161 km). On the haziest days, VR has been reduced from 120 to 60 miles (193 to 97 km). Severe haze episodes occasionally reduce visibility to 10 miles (16 km). At PEFO, air pollution has reduced average VR from 170 to 95 miles (274 to 153 km). On the haziest days, VR has been reduced from 120 to 60 miles (193 to 97 km). Severe haze episodes occasionally reduce visibility to 10 miles (16 km). At the CAPI1 site, representative of GLCA, air pollution has reduced average VR from 170 to 110 miles (274 to 177 km). On the haziest days, VR has been reduced from 130 to 80 miles (209 to 129 km). Severe haze episodes occasionally reduce visibility to 21 miles (34 km). At the SYCA1 site, representative of WACA, air pollution has reduced average VR from 170 to 80 miles (274 to 129 km). On the haziest days, VR has been reduced from 120 to 50 miles (193 to 80 km). Severe haze episodes occasionally reduce visibility to 15 miles (24 km).

Bandelier

20% Clearest Days

Taken: 3:00 PM

Haze = 4 dv

$B_{\text{ext}} = 16 \text{ Mm}^{-1}$

VR = 250 km



20% Haziest Days

Taken: 3:00 PM

Haze = 12 dv

$B_{\text{ext}} = 34 \text{ Mm}^{-1}$

VR = 115 km



Average Days

Taken: 3:00 PM

Haze = 8 dv

$B_{\text{ext}} = 22 \text{ Mm}^{-1}$

VR = 180 km



Figure 1a. Three representative photos of the same view in each of BAND, illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility in deciviews (dv), light extinction (B_{ext}) in inverse megameters (Mm^{-1}), and visual range (VR) in kilometers (km).

Grand Canyon

20% Clearest Days

Taken: 12:00 PM

Haze = 2 dv

$B_{\text{ext}} = 12 \text{ Mm}^{-1}$

VR = 320 km



20% Haziest Days

Taken: 12:00 PM

Haze = 11 dv

$B_{\text{ext}} = 30 \text{ Mm}^{-1}$

VR = 130 km



Average Days

Taken: 12:00 PM

Haze = 7 dv

$B_{\text{ext}} = 20 \text{ Mm}^{-1}$

VR = 195 km



Figure 1b. Three representative photos of the same view in each of GRCA, illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility in deciviews (dv), light extinction (B_{ext}) in inverse megameters (Mm^{-1}), and visual range (VR) in kilometers (km).

Mesa Verde

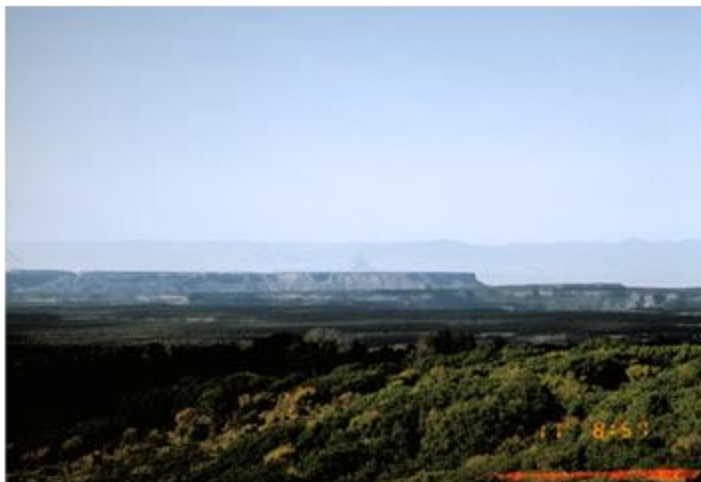
20% Clearest Days

Taken: 9:00 AM

Haze = 3 dv

$B_{\text{ext}} = 14 \text{ Mm}^{-1}$

VR = 280 km



20% Haziest Days

Taken: 9:00 AM

Haze = 10 dv

$B_{\text{ext}} = 26 \text{ Mm}^{-1}$

VR = 150 km



Average Days

Taken: 9:00 AM

Haze = 7 dv

$B_{\text{ext}} = 21 \text{ Mm}^{-1}$

VR = 190 km



Figure 1c. Three representative photos of the same view in each of MEVE, illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility in deciviews (dv), light extinction (B_{ext}) in inverse megameters (Mm^{-1}), and visual range (VR) in kilometers (km).

Table 7. Estimated natural haze and measured current baseline haze in I&M parks in the SCPN averaged over the RHR Baseline period 2000 through 2004.

Park Name ²	Park Code	Site ID	Measured Baseline and Estimated Natural Haze			
			20% Clearest Days (dv)		20% Haziest Days (dv)	
			Baseline	Natural	Baseline	Natural
Aztec Ruins	AZRU	No Site				
Bandelier	BAND	BAND1	4.95	1.29	12.22	6.26
<i>Canyon de Chelly</i>	CACH	No Site				
Chaco Culture	CHCU	No Site				
<i>El Malpais</i>	ELMA	No Site				
El Morro	ELMO	No Site				
<i>Glen Canyon</i> ³	GLCA	CAP11		1.25		6.03
<i>Grand Canyon</i>	GRCA	GRCA2	2.16	0.31	11.66	7.04
Hubbell Trading Post	HUTR	No Site				
Mesa Verde	MEVE	MEVE1	4.32	1.01	13.03	6.81
Navajo	NAVA	No Site				
<i>Petrified Forest</i>	PEFO	PEFO1	5.02	1.07	13.21	6.49
Petroglyph	PETR	No Site				
Rainbow Bridge	RABR	No Site				
Salinas Pueblo Missions	SAPU	No Site				
Sunset Crater Volcano ³	SUCR	GRCA2		0.31		7.04
Walnut Canyon ³	WACA	SYCA1		0.98		6.65
Wupatki	WUPA	No Site				
Yucca House	YUHO	No Site				

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

² Data are borrowed from nearby IMPROVE sites. 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 of that area.

Composition of Haze

Various pollutants make up the haze that causes visibility degradation. IMPROVE measures these pollutants and reports them as ammonium sulfate, ammonium nitrate, elemental C, coarse mass, organic mass, sea salt, and soil. Sulfates form in the atmosphere from SO₂ 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, O&G production, and fires. Organic compounds are emitted from a variety of both natural (biogenic) and anthropogenic sources, including agriculture, industry, O&G production, and fires. Soil can enter the atmosphere through both natural processes and human soil disturbance.

Figure 2 shows the composition and levels of estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) haze for the monitored parks in the SCPN. 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). For more information on this process, see http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm.

The majority of the visibility impairment in these parks was typically attributable to sulfate, coarse mass, and organics. In some cases, light absorbing carbon, soils, and nitrate were also quantitatively important. On the 20% clearest days in all of the monitored parks, sulfate was the largest contributor

to visibility impairment, followed by organics. Sulfate particles can remain suspended in the atmosphere for many days to weeks and be transported long distances (Hall 1981). For the annual average, sulfate, followed by organics, were responsible for the largest contributions to haze in all of these parks except WACA; in WACA (using data from SYCA1), organics and coarse mass both exceeded sulfate as contributors to visibility impairment. On the 20% haziest days, sulfate contributed the most to b_{ext} in only one park, BAND. In MEVE, coarse mass was responsible for the most haze on the 20% haziest days, and in the other five monitored parks, organics was the largest contributor (Figure 2).

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 SCPN. 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).

In a study of air composition conducted during summer at Meadview, AZ, just west of GRCA, Eatough et al. (2006) determined that reduced visibility was most strongly influenced by suspended fine particulate organic material, which contributed 19% of b_{ext} , on average, followed by fine particulate sulfate, which contributed an average of 14%. When b_{ext} was highest, these species, along with light-absorbing carbon, were the dominant contributors to the b_{ext} . During periods of highest b_{ext} , sulfate and associated water were responsible for 33% of b_{ext} (Eatough et al. 2006). These were also the periods of highest humidity. Coarse particles (e.g., dust) were also important contributors to visibility impairment, and were judged to be responsible for 18% of the b_{ext} on average and 19% during periods of the highest b_{ext} (Eatough et al. 2006). In a study of coarse particle species composition at nine sites chosen to be representative of the continental United States, Malm et al. (2007) found that crustal materials accounted for 76% of coarse material at GRCA, which was the highest percentage among all study sites. Contribution to coarse material from organic mass was 8.6% at GRCA, which was the lowest among the study sites (along with San Geronio wilderness area in southern California; Malm et al. 2007).

Sources of Visibility Impairment in the SCPN

The WRAP has provided technical assistance for western states in developing plans to meet the requirements of the Regional Haze Rule. As part of this effort, the WRAP conducted regional modeling to identify pollution sources that are affecting visibility in Class I areas, and where these sources are located. Source regions include the WRAP region (AZ, CA, CO, ID, MT, ND, NM, NV, OR, SD, UT, WA, and WY), Pacific Offshore (PO), CENRAP (AL, AR, IA, KS, MN, MO, NE, OK, and TX), Eastern U.S., Canada, Mexico, and Outside Domain (OD-outside the modeling domain). Source types identified include Outside Domain (OD-undefined), Point (e.g., power plants, smelters), Area (e.g., O&G development), Mobile (e.g., vehicles), Anthropogenic Fires (prescribed burns), and Natural Fires and Biogenic Sources. Presented here are estimates of regional contributions to sulfate and nitrate, two of the primary controllable anthropogenic pollutant species responsible for visibility impairment, on the worst 20% visibility days for each of the Class I areas in the SCPN, for the base

year 2002 and projected contributions for the year 2018. Also shown are the contributions, by region and source type, to atmospheric sulfate and nitrate on the worst 20% visibility days for 2002 and projections for 2018. Although WRAP also modeled contributions for the best 20% visibility days, the focus here is on the worst days when visibility is most impaired by human activities. Projections for 2018 were modeled using 2008 and earlier data. Projections therefore do not include emissions changes unforeseen at the time of the modeling, including emissions reductions at some point sources and increases due to activities like O&G exploration, development, and production. Updates to emissions inventories are underway and will be used to improve emissions estimates and modeled projections of future conditions.

The West-Wide Jump-Start Air Quality Modeling Study (WestJump) updated the previous WRAP work with emissions inventories for the year 2008 (ENVIRON et al. 2013, Appendix O). The WestJump results for nitrate and sulfate are described and compared to the WRAP data below. WestJump data have some of the same limitations as the WRAP data in that they do not include recent emissions reductions and increases occurring since 2008. The WestJump data agree with the WRAP data in that they also show that organic and elemental carbon from prescribed burns and other anthropogenic sources are at times significant, and in some cases major, contributors to haze and visibility impairment in the SCPN parks. Ongoing work continues to improve emissions inventories, particularly for fires (both wildfires and prescribed burns) through the WRAP and the Joint Fire Science Program (JFSP 2014). Carbon from prescribed burns is, at present, considered controllable by EPA. This can be problematic for States and Federal Land Managers because prescribed burns, while causing visibility impairment, are needed to improve and maintain forest health and to avoid more catastrophic wildfires in the future.

BAND

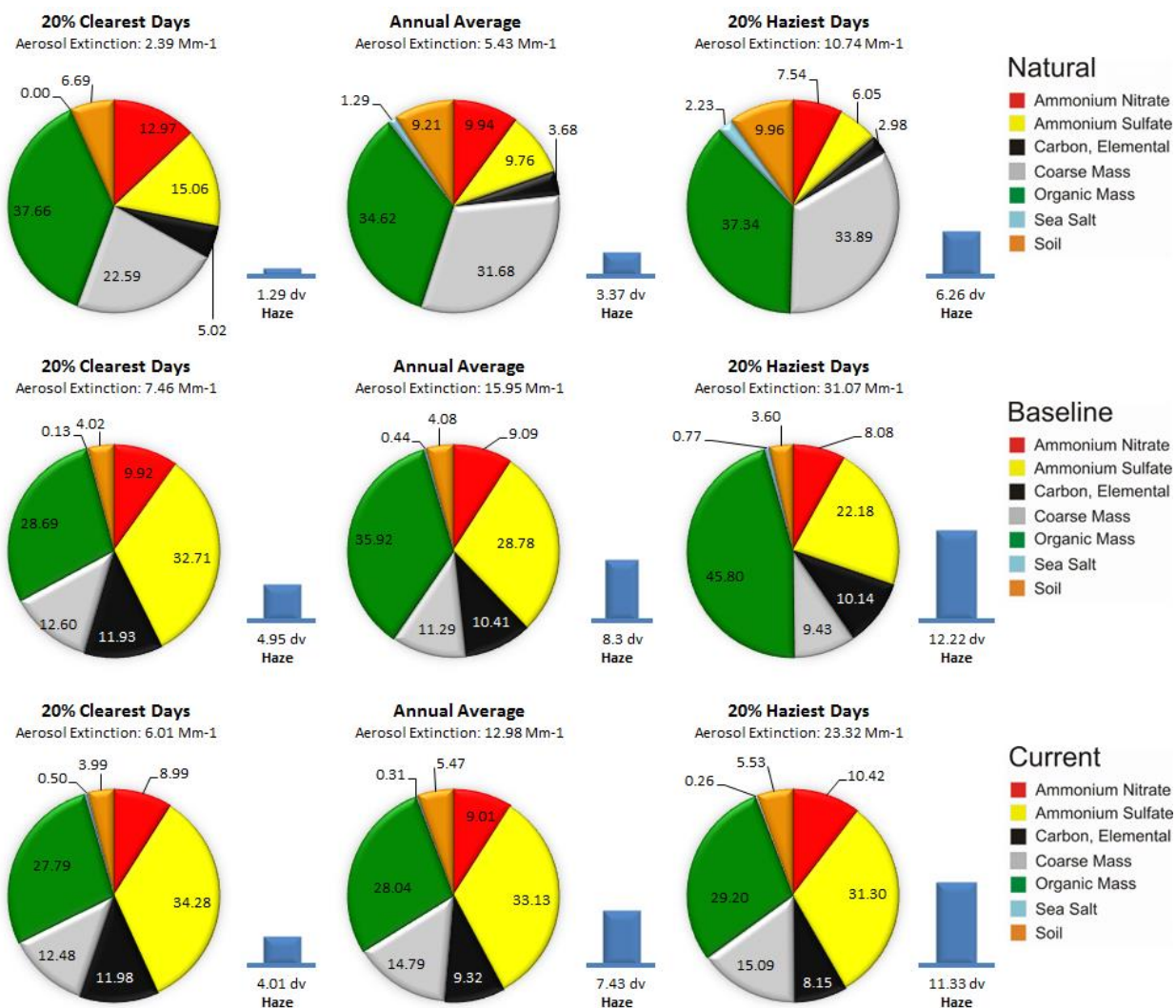


Figure 2a. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for BAND. Data Source: NPS-ARD.

CAP11 (representing GLCA)

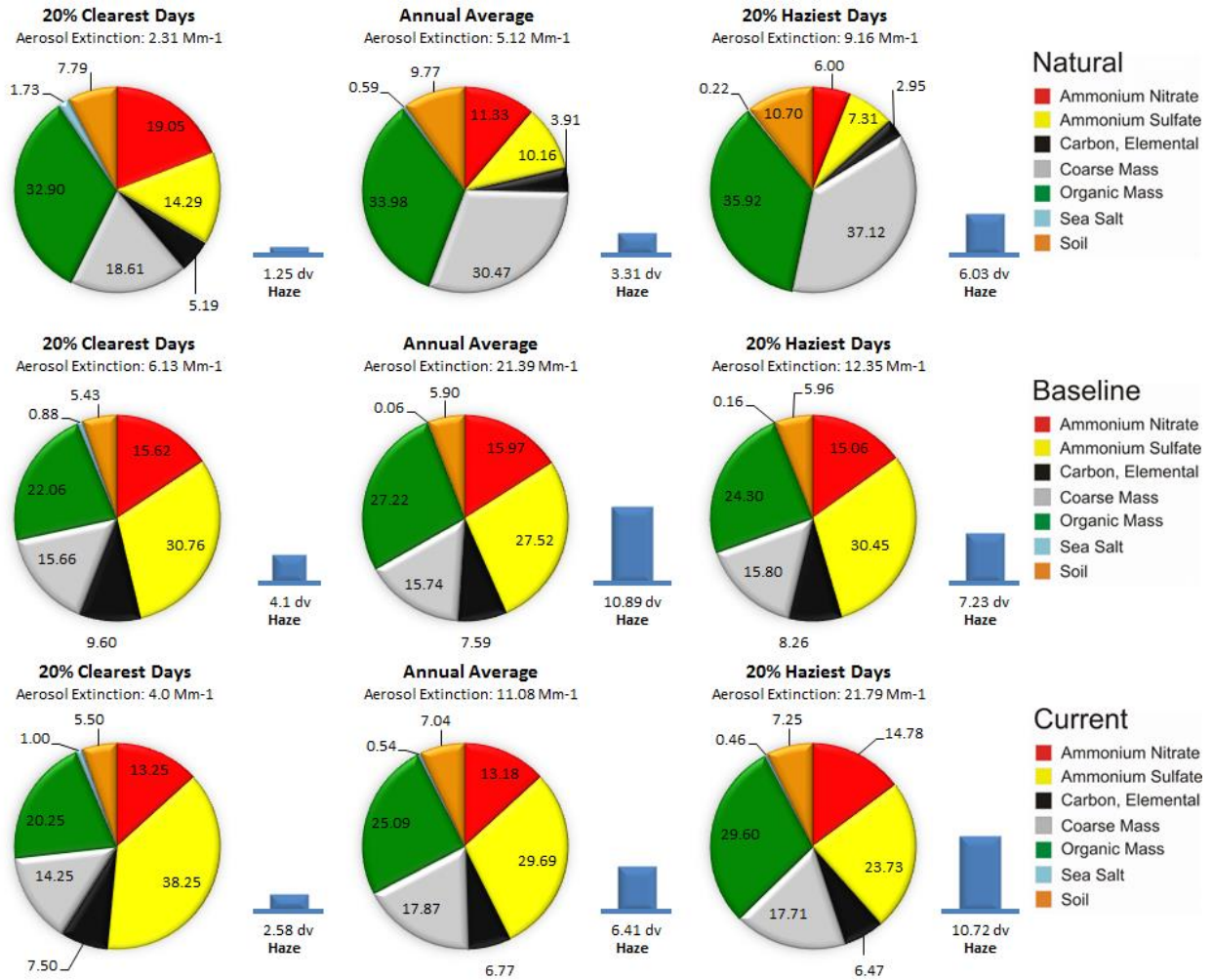


Figure 2b. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for GLCA. GLCA has no valid, measured data for the years 2000-2002 and 2006,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

GRCA (also representing SUCR)

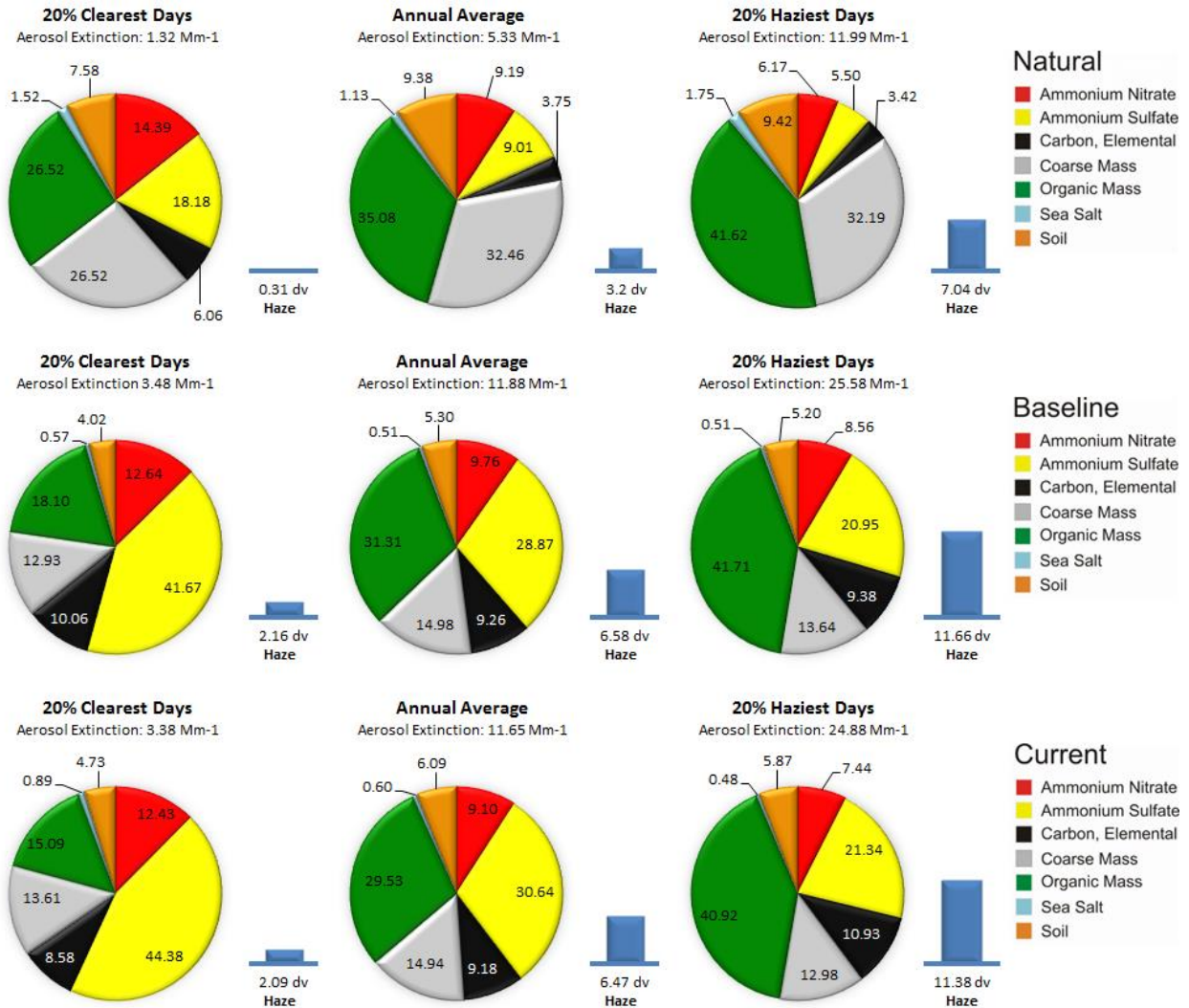


Figure 2c. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for SUCR. GRCA and SUCR have no data for the year 2001. Data Source: NPS-ARD.

MEVE

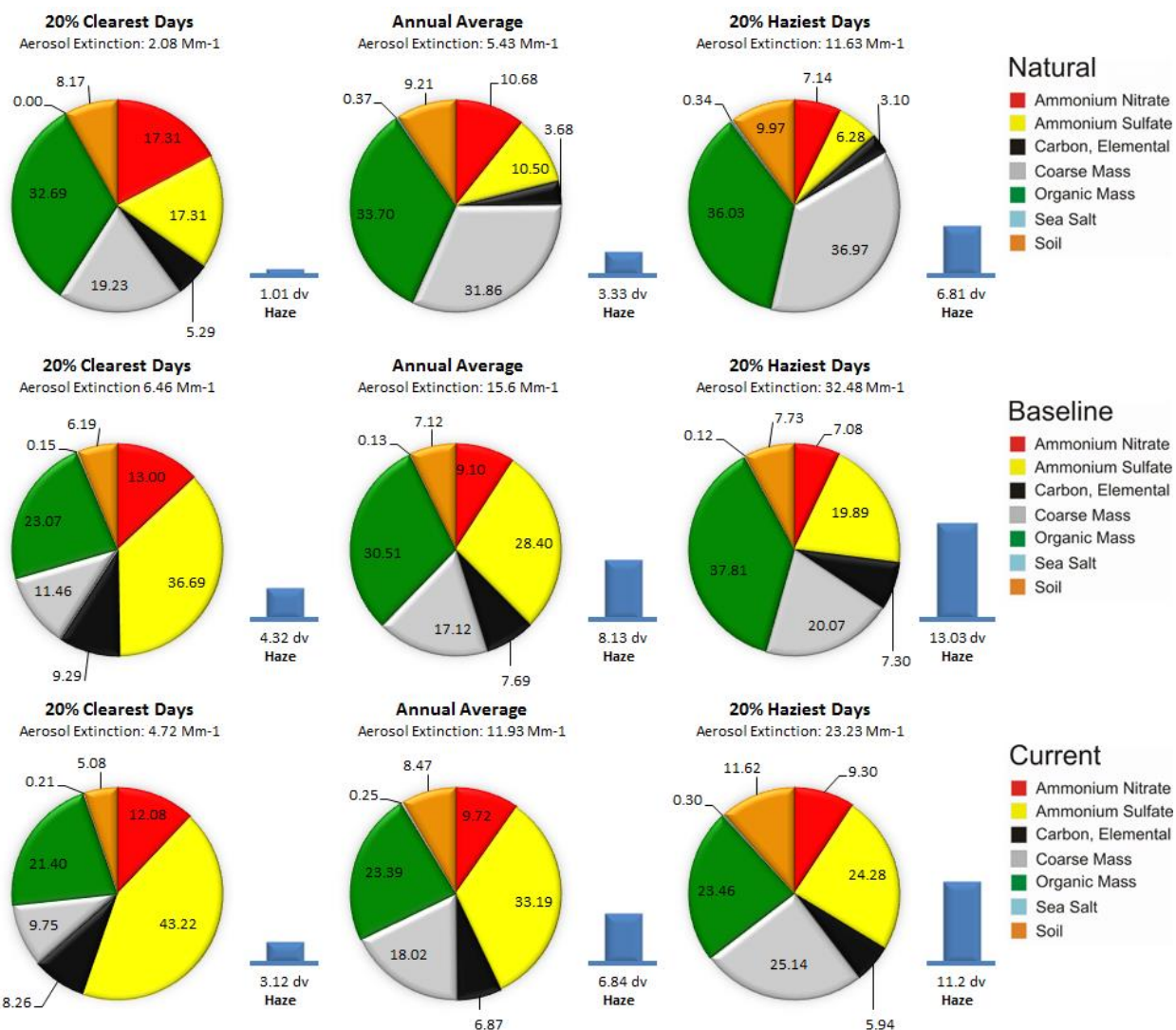


Figure 2d. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% hazeiest visibility days for MEVE. Data Source: NPS-ARD.

PEFO

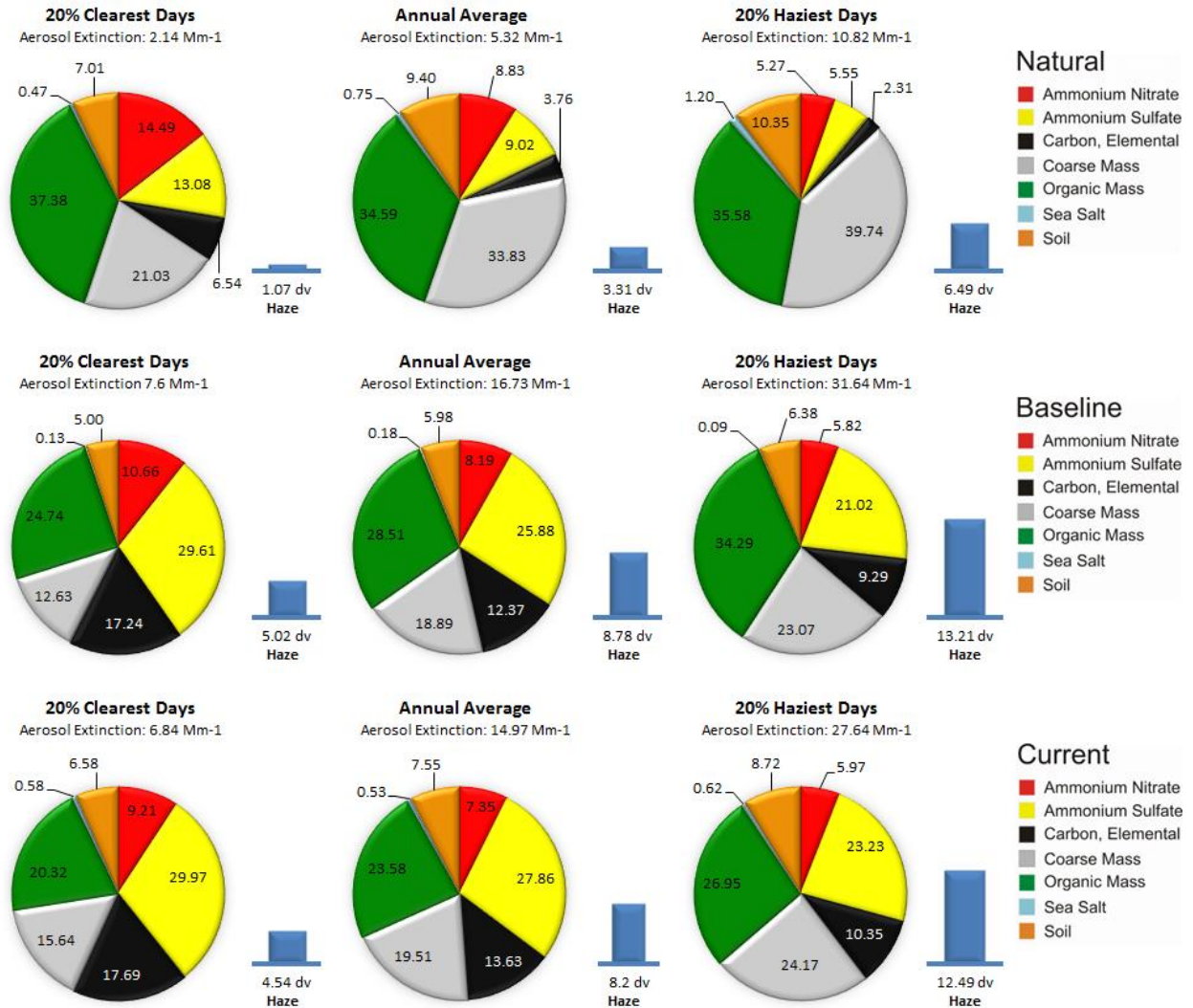


Figure 2d. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for PEFO. Data Source: NPS-ARD.

SYCA1 (representing WACA)

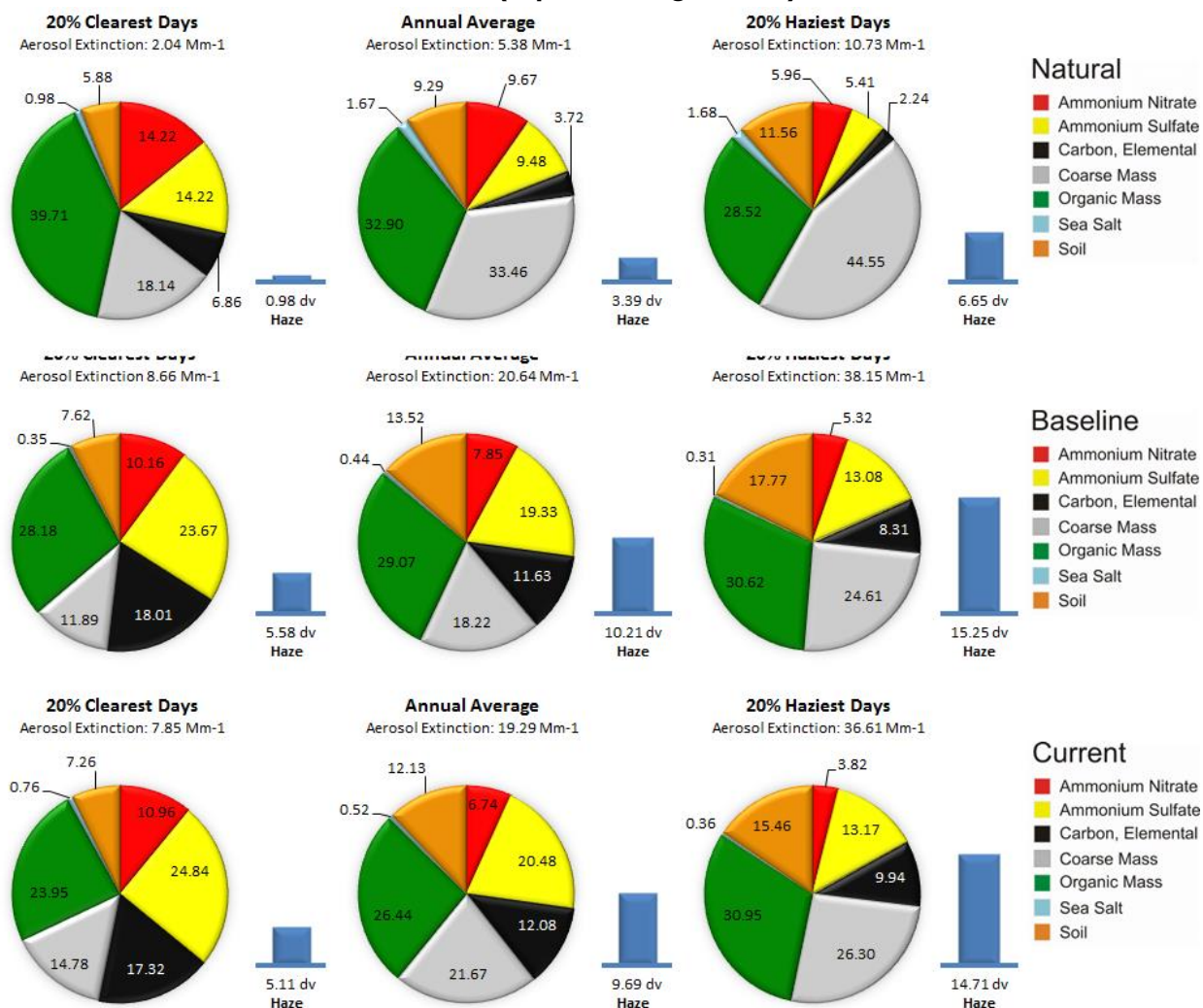


Figure 2e. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for WACA. WACA has no data for the year 2000. Data Source: NPS-ARD.

Bandelier National Monument

Figure 3a shows regional contributions to sulfate on the worst 20% of days at BAND in the base year 2002 and the projected contributions in 2018. Sulfate concentrations are projected to be unchanged by 2018, and the regional contribution profile remains similar, with the WRAP region as the dominant source area.

Figure 3b shows source type contributions to BAND by region, including each of the WRAP States. Point sources (e.g., power plants) contribute most to atmospheric sulfate at BAND, with several source regions in the modeling domain, including NM, CENRAP, and Mexico contributing significantly.

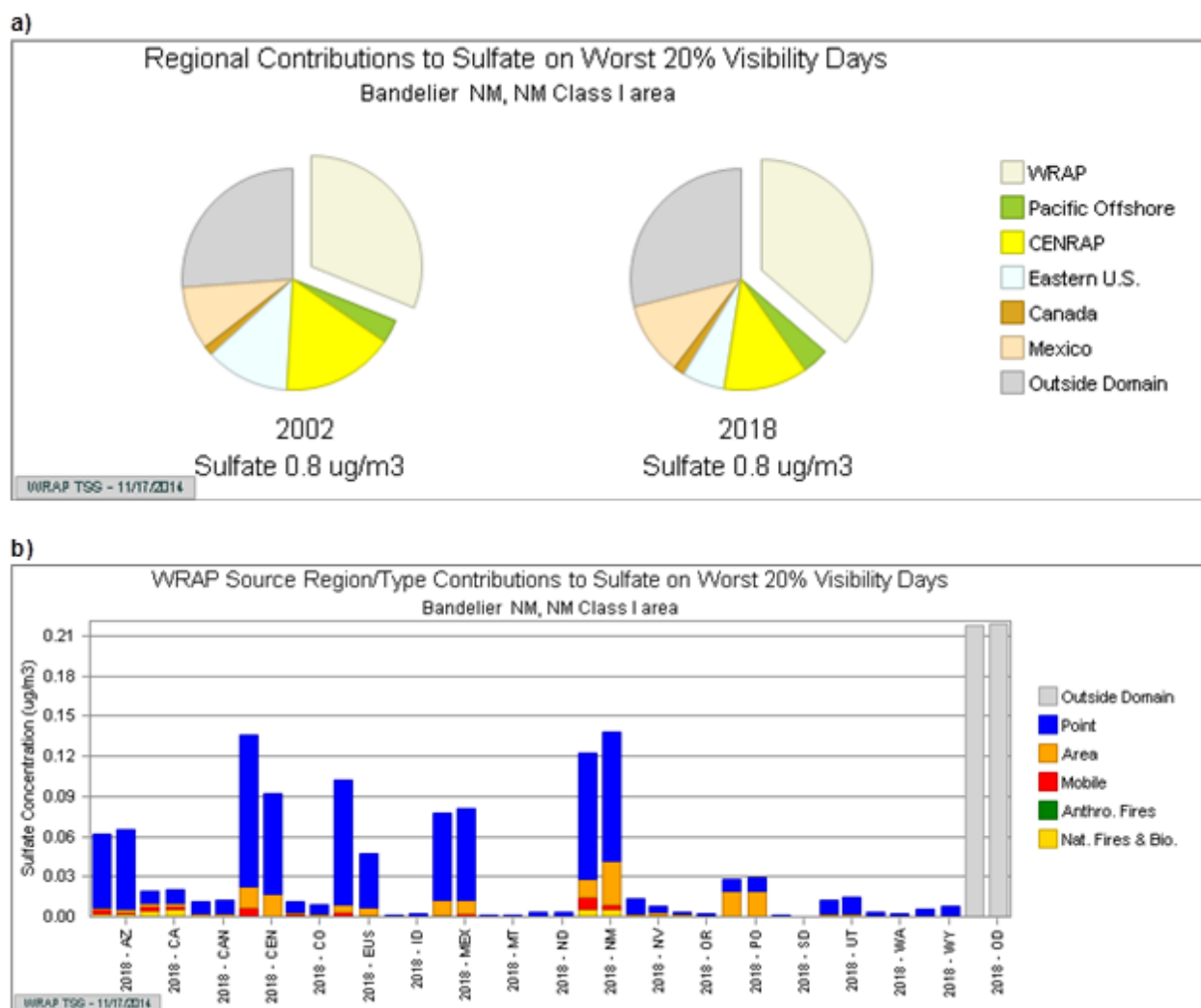


Figure 3. Regional contributions to sulfate on worst 20% visibility days (a) and WRAP source region/type contributions to sulfate on worst 20% visibility days (b) for BAND. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Figure 4a shows that nitrate concentrations are projected to remain steady from 2002 to 2018 at BAND, and that sources in the WRAP region are primarily responsible for nitrate at BAND. Figure 4b shows that point, area, and mobile sources all contribute to nitrate at BAND, with sources in NM dominating. Projections for 2018 show emissions from NM area sources, including O&G development, increasing significantly.

Data from the WestJump emissions inventory found that most of the pollutants that reduced visibility in BAND in 2008 came from sources within the WRAP region, mainly New Mexico. Nitrate was a somewhat larger contributor to haze than sulfate, but organic and elemental carbon from prescribed fires and other sources, primarily in New Mexico, were the major controllable pollutants reducing visibility in BAND (ENVIRON et al. 2013, Appendix O).

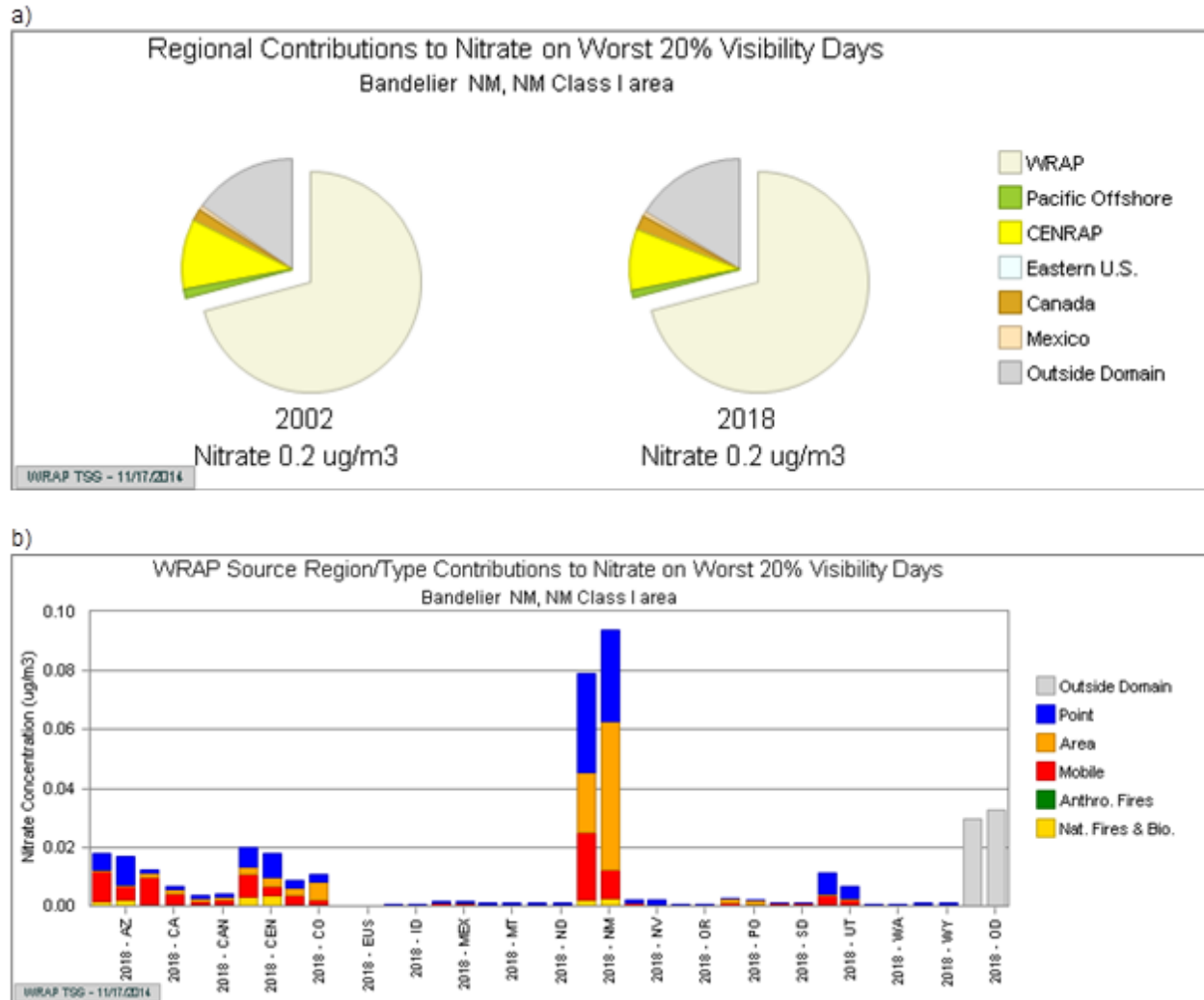


Figure 4. Regional contributions to nitrate on worst 20% visibility days (a) and WRAP source region/type contributions to nitrate on worst 20% visibility days (b) for BAND. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Grand Canyon NP

Figure 5a shows regional contributions to sulfate on the worst 20% of days at GRCA in the base year 2002 and the projected contributions in 2018. Sulfate concentrations are projected to decrease somewhat by 2018, but the regional contribution profile remains similar, with emissions from outside the modeling area (Outside Domain – OD) and from the WRAP region significantly contributing to sulfate at GRCA.

Figure 5b shows source type by region, including each of the WRAP States. Point sources (e.g., power plants) within the WRAP region, as well as sources outside the modeling domain (international sources) are important contributors to sulfate at GRCA.

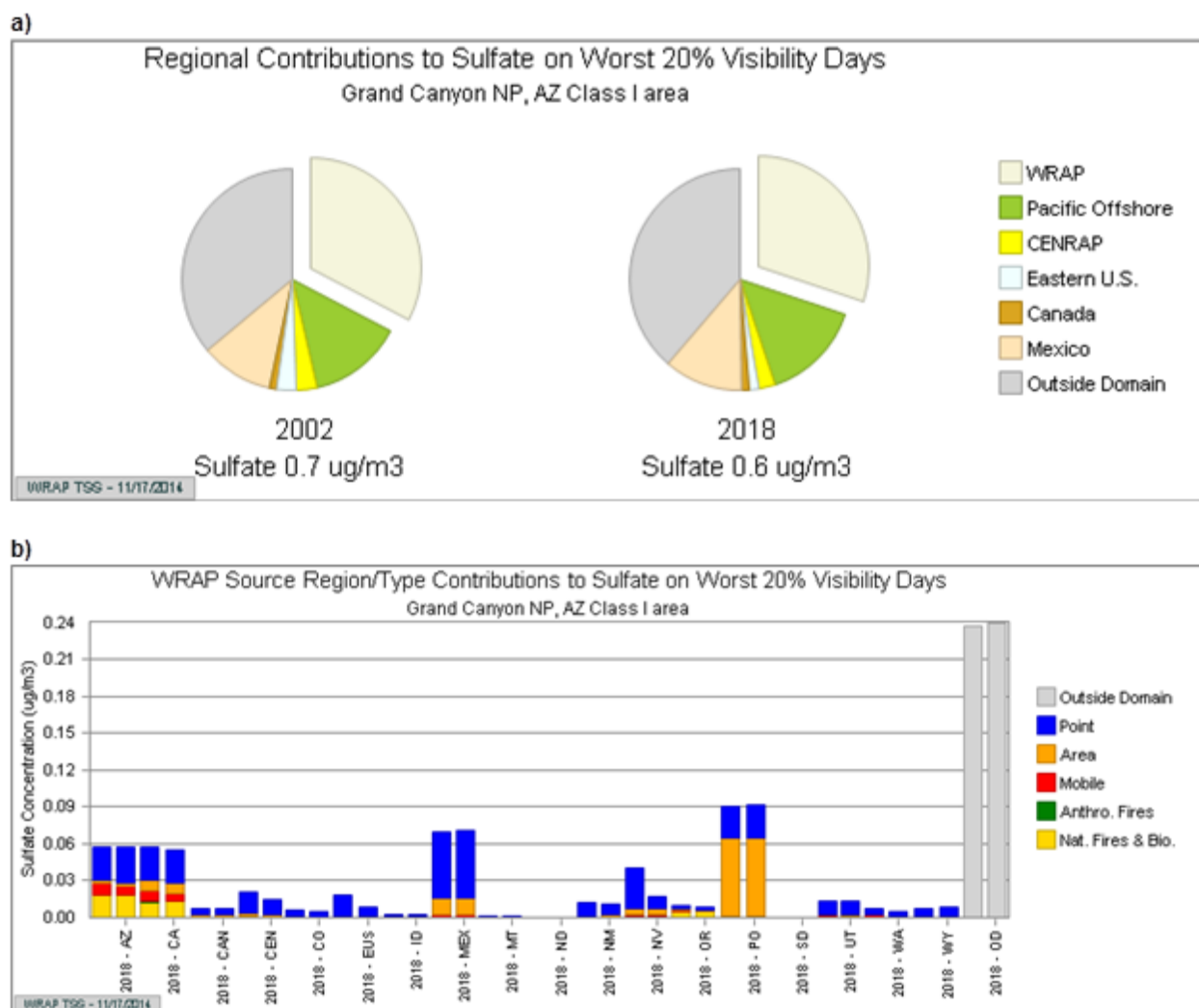


Figure 5. Regional contributions to sulfate on worst 20% visibility days (a) and WRAP source region/type contributions to sulfate on worst 20% visibility days (b) for GRCA. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Figure 6a shows that nitrate concentrations are projected to remain steady from 2002 to 2018 at GRCA, and that sources in the WRAP region are primarily responsible for nitrate at GRCA. Figure 6b shows that mobile sources from AZ and CA are primary contributors to nitrate at GRCA.

Data from the 2008 WestJump emissions inventory found that about two-thirds of the pollutants that reduced visibility in GRCA came from sources within the WRAP region, mainly AZ and CA. Nitrate was a somewhat larger contributor to haze than sulfate, but organic and elemental carbon from prescribed fires and other sources, primarily in AZ, were the major controllable pollutants reducing visibility in GRCA (ENVIRON et al. 2013, Appendix O).

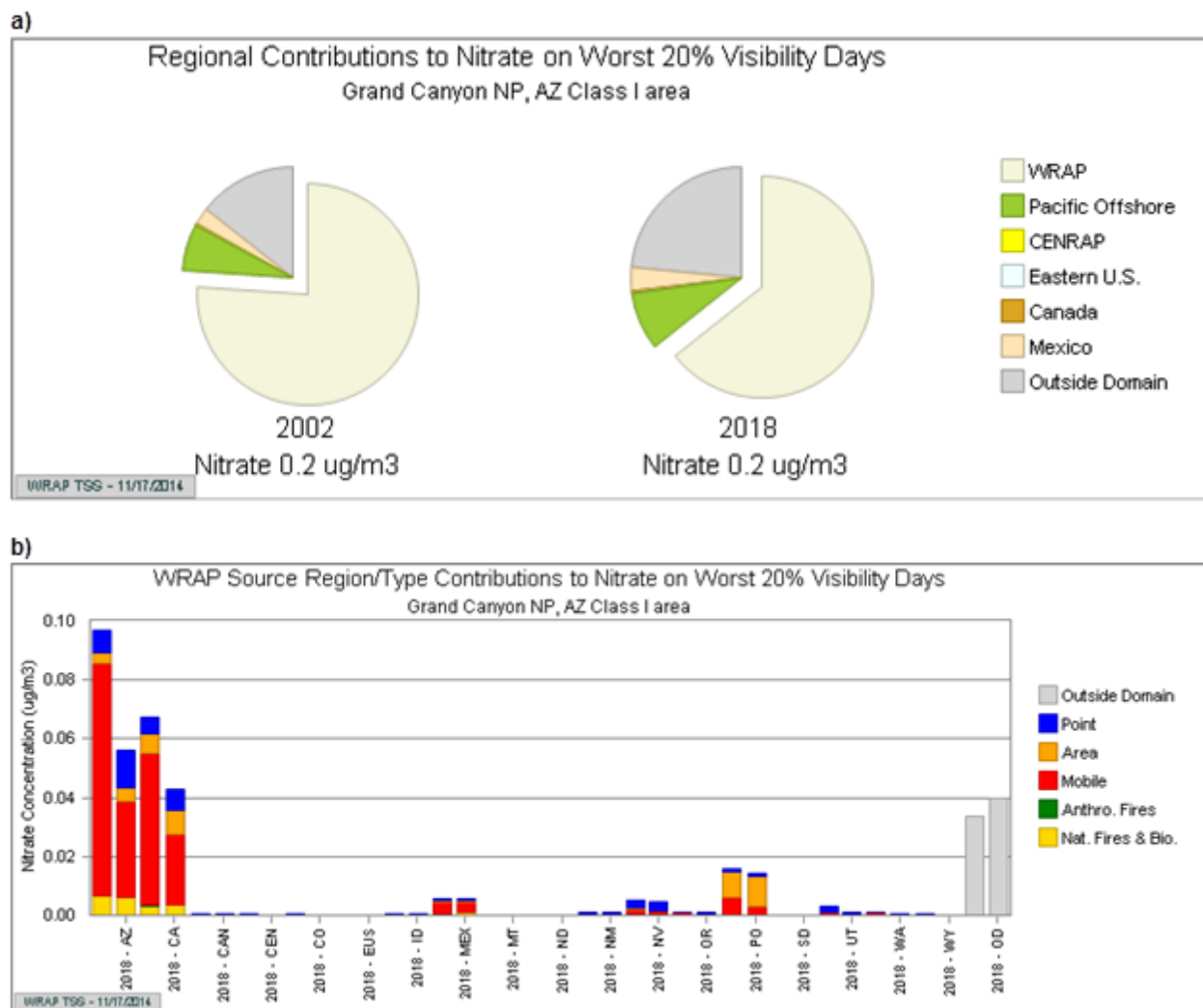


Figure 6. Regional contributions to nitrate on worst 20% visibility days (a) and WRAP source region/type contributions to nitrate on worst 20% visibility days (b) for GRCA. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Mesa Verde NP

Figure 7a shows regional contributions to sulfate on the worst 20% of days at MEVE in the base year of 2002 and the projected contributions in 2018. Sulfate concentrations are projected to decrease somewhat by 2018, but the regional contribution profile remains similar, with emissions from outside the modeling area (Outside Domain – OD) and from the WRAP region significantly contributing to sulfate at MEVE.

Figure 7b shows source type by region, including each of the WRAP States. Point sources such as power plants within the WRAP region and sources outside WRAP and outside the modeling domain (international sources) are important contributors to sulfate at MEVE.

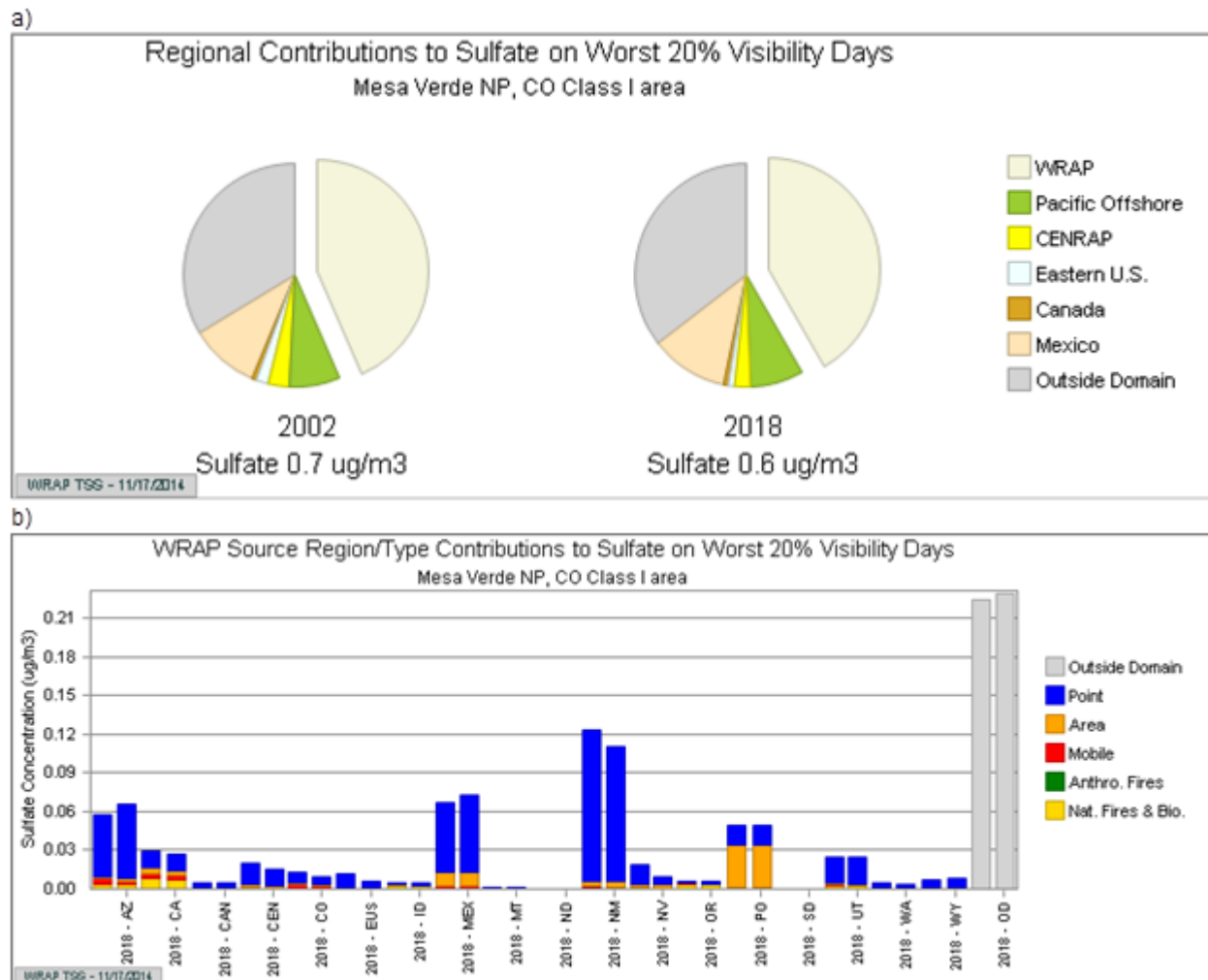


Figure 7. Regional contributions to sulfate on worst 20% visibility days (a) and WRAP source region/type contributions to sulfate on worst 20% visibility days (b) for MEVE. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Figure 8a shows that nitrate concentrations are projected to remain steady from 2002 to 2018 at MEVE, and that sources in the WRAP region are primarily responsible for nitrate at MEVE. Figure 8b shows that point and area sources, primarily from NM, are primary contributors to nitrate at MEVE.

Data from the 2008 WestJump emissions inventory found that about two-thirds of the pollutants that reduced visibility in MEVE came from sources within the WRAP region, mainly NM, CO, AZ, and CA. Nitrate was a somewhat larger contributor to haze than sulfate. For controllable pollutants, organic and elemental carbon from prescribed fires and other sources were roughly equivalent to nitrate and sulfate in terms of impairing visibility in MEVE (ENVIRON et al. 2013, Appendix O).

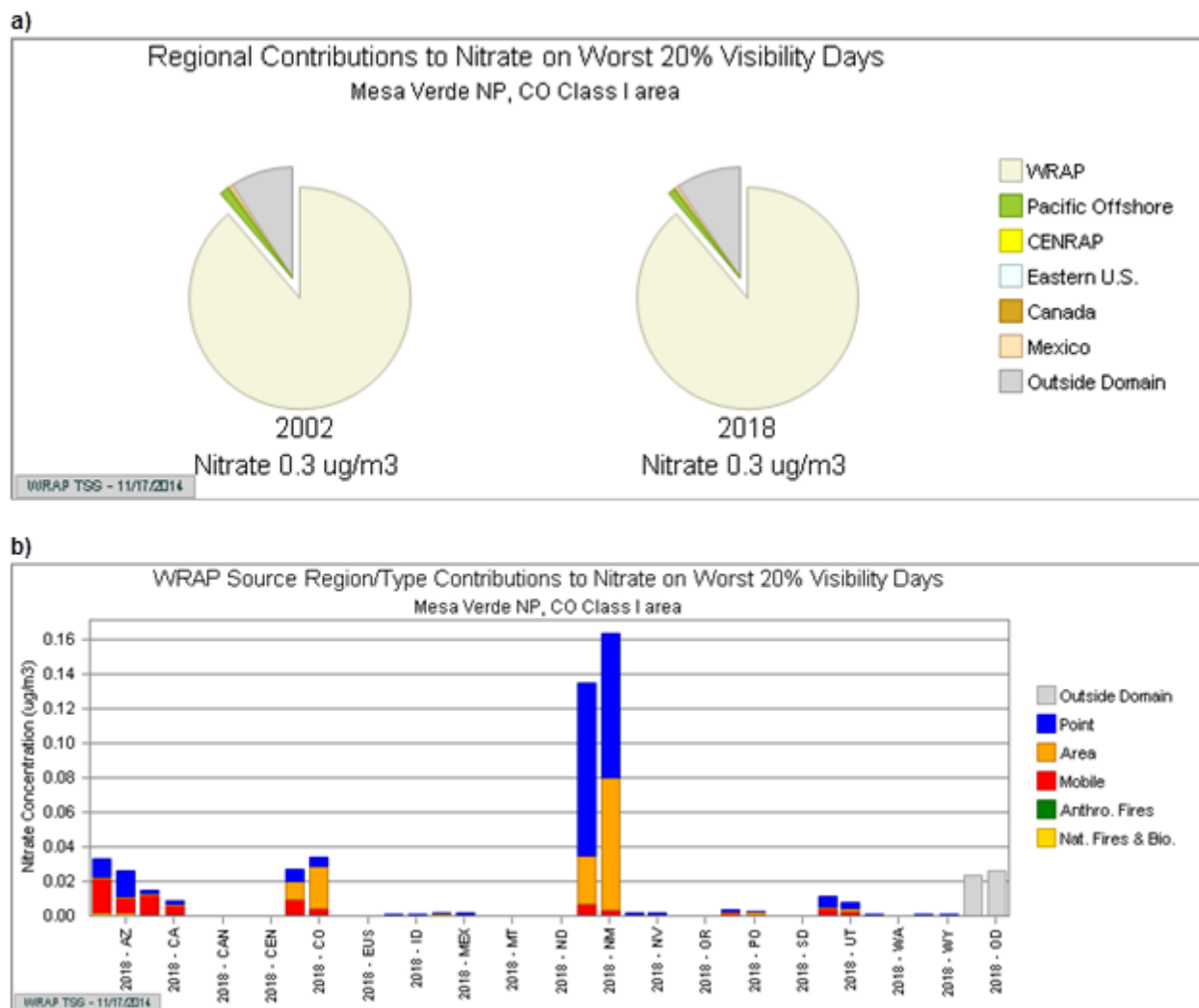


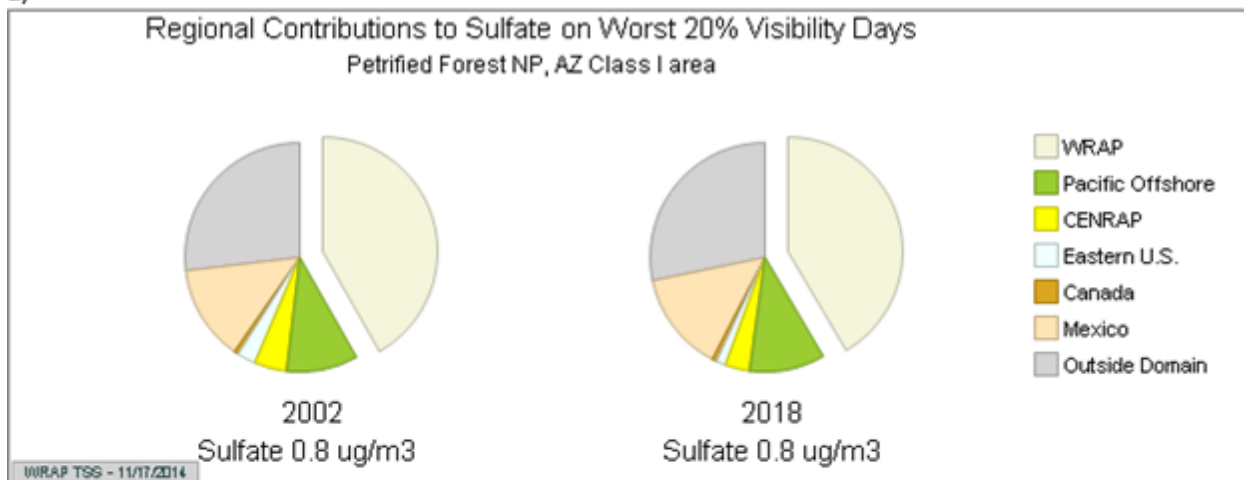
Figure 8. Regional contributions to nitrate on worst 20% visibility days (a) and WRAP source region/type contributions to nitrate on worst 20% visibility days (b) for MEVE. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Petrified Forest National Park

Figure 9a shows regional contributions to sulfate on the worst 20% of days at PEFO in the base year of 2002 and the projected contributions in 2018. Sulfate concentrations are projected to remain unchanged by 2018, and the regional contribution profile remains similar, with the WRAP region as the dominant source area.

Figure 9b shows source type by region, including each of the WRAP States. Point sources (e.g., power plants) contribute most to sulfate at PEFO, with point sources in AZ and Mexico dominating. Area emissions from shipping in the Pacific Offshore region are also important.

a)



b)

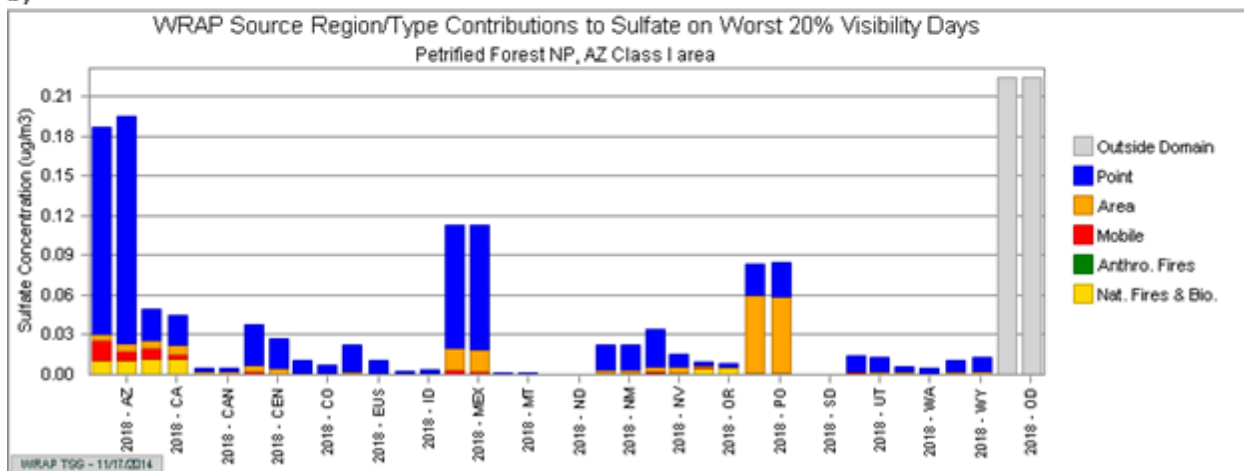


Figure 9. Regional contributions to sulfate on worst 20% visibility days (a) and WRAP source region/type contributions to sulfate on worst 20% visibility days (b) for PEFO. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Figure 10a shows that nitrate concentrations are projected to remain steady from 2002 to 2018 at PEFO, and that sources in the WRAP region are primarily responsible for nitrate at PEFO. Figure 10b shows that point, area, and mobile sources all contribute to nitrate at PEFO, with sources in AZ dominating the total. Projections for 2018 show nitrate emissions relatively unchanged from 2002.

Data from the 2008 WestJump emissions inventory found that about two-thirds of the pollutants that reduced visibility in PEFO came from sources within the WRAP region, mainly AZ. Nitrate was a somewhat larger contributor to haze than sulfate, but organic and elemental carbon from prescribed fires and other sources, primarily in AZ, were the major controllable pollutants reducing visibility in PEFO (ENVIRON et al. 2013, Appendix O).

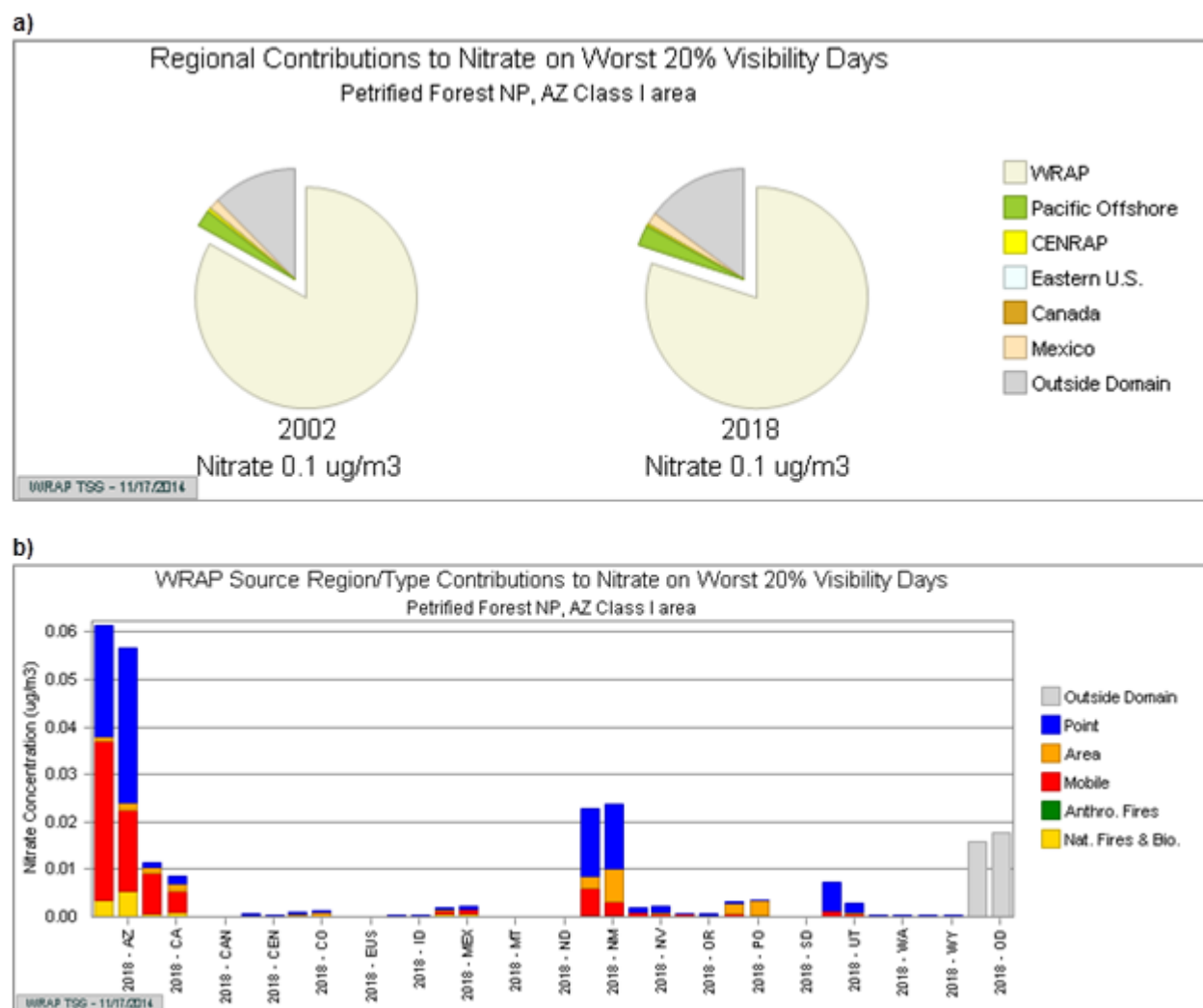


Figure 10. Regional contributions to nitrate on worst 20% visibility days (a) and WRAP source region/type contributions to nitrate on worst 20% visibility days (b) for PEFO. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

Visibility Research at GRCA

GRCA became the focus of considerable visibility research several decades ago. It was recognized that the most important canyon levels for visibility are located at and slightly below the canyon rim. Visibility at these locations is most strongly affected by atmospheric conditions between the viewer's vantage point and the geological formations on the opposite side of the canyon (Banta et al. 1999). As a consequence, effectiveness of pollutant vertical transport down into and within the canyon is a key component of visibility degradation central to the visitor experience in this park. These issues were studied by Banta et al. (1999) using Doppler lidar. They focused on three wind flow patterns that occurred during winter: flow reversal, coupled flow inside and above the canyon, and thermally forced up-and-down-canyon winds. Other studies have focused on how the vertical transport of haze-producing aerosols is affected by the flow structure within the canyon as well as the dynamics of

advectations of clean air into the canyon that can flush out pollutants (e.g., McKee and O'Neal 1989, Steinacker 1984, Whiteman et al. 1999a, Whiteman et al. 1999b).

Mazurek et al. (1997) used gas chromatography to examine the composition of aerosol organics collected in GRCA in August, 1989, and compared them with the components of diluted, aged air samples from the Los Angeles area. The researchers found that certain characteristics of the samples were very different based on sample origin. They therefore concluded that significant organic aerosols in GRCA likely originated from sources other than Los Angeles. Nevertheless, atmospheric tracer studies have demonstrated some summer pollutant transport from the Los Angeles basin to GRCA (Hering et al. 1981, Macias et al. 1981, Pitchford et al. 1981). Summer long-range pollutant transport from the LA basin initiates with prevailing westerlies that are enhanced during summer by formation of thermal lows over the interior California deserts. Pollutants are ejected vertically by passage of the air mass over the San Gabriel Mountains, and are then transported to the southwest towards the SCPN with winds from the Pacific High (Chen et al. 1999). Southwesterly flows have also been shown to advect pollution from southern Arizona smelters into the GRCA region (Chen et al. 1999).

Xu et al. (2006) identified major source regions of the atmospheric sulfate aerosols measured at Class I areas throughout the western United States. Airmass back-trajectories were calculated using the NOAA HYSPLIT v4.6 model for each of 84 Class I areas every three hours over the period 2000 to 2002. Results for a site on the south rim of the Grand Canyon suggested that air flows that reached GRCA most commonly followed a southeasterly path along the Pacific coast before turning inland and approaching GRCA from the southwest. A secondary flow regime included air flows to GRCA from the southeast. The identified top five source regions that contributed sulfate to GRCA were the Pacific Ocean, Pacific Coast, southwestern Arizona, Mexico, and California (Xu et al. 2006). The sulfate originating from southwest Arizona and Mexico was likely from coal-burning power plants. The sulfate originating from the Pacific Ocean and Pacific Coast source regions was from sources including ocean shipping and aerosol transport from Asia.

A substantial portion of winter anthropogenic visibility impairment at GRCA has been attributed to emissions from the coal-burning units at the Navajo Generating Station (NGS) power plant (NRC 1990), located at the eastern end of the Grand Canyon, about 6 mi east of Page, Arizona. The NGS impacts on GRCA visibility were generally highest from December to February. This was likely a result of SO₂ interactions with humidity, which is most prevalent at GRCA during the winter (Green et al. 2005). This finding was further supported by modeling results based on the 1990 winter NGS visibility field study (Gray et al. 1991). Chen et al. (1999) used data from that study as input to several models to analyze transport of the NGS plume during a four-day period. Results revealed that complex terrain features dramatically affected wind flow patterns during winter in the GRCA area.

Chen et al. (1999) determined the path taken by the NGS emissions plume to GRCA and evaluated the resulting effects on winter visibility in the park. Analysis of data collected during the 1990 NGS Visibility Field Study showed that terrain complexity influences wind flow patterns during winter, and creates such local effects as channeling, decoupled canyon winds, and slope and valley flows. Both direct and indirect plume transport occurred from the NGS to GRCA, resulting from

northeasterly winds or from wind direction shifts caused by passing synoptic weather systems, respectively (Chen et al. 1999).

A field program associated with the project SCENES air quality and visibility assessment around GRCA evaluated the contribution of emissions from the coal-fired power plant at the NGS to winter visibility impairment in GRCA, Canyonlands National Park in the Northern Colorado Plateau Network, and GLCA (1989, Malm et al. 1988). During the 1990 NGS winter visibility study of surface and upper air meteorological measurement systems were operated in and around GRCA from January 10 to March 31, 1990. The network included surface monitoring stations, balloon sounding stations, Doppler radar wind profilers, and Doppler sodars (Lindsey et al. 1999). Results suggested atmospheric transport of NGS emissions to GRCA, followed by buildup over multiple days, and then advection out of the area by frontal passages.

Lindsey et al. (1999) summarized the knowledge gained from analyses of the 1990 NGS data, highlighting the mechanisms responsible for emissions transport to GRCA. They determined that the primary mode of transport was synoptic-scale winds driven by pressure gradients associated with passing storms, creating a ridge of high pressure following the passage of a low-pressure system. The topographical features of the region channel these winds and also influence mesoscale circulation, another mechanism for emissions transport that forms during light wind conditions. Short-distance transport of emissions can also occur due to slope and valley flows, which are directed by the regional topography but driven by the diurnal heating cycle. However, these flows are disrupted by passing storms, and may not play a significant role in overall emissions transport from the NGS to GRCA (Lindsey et al. 1999).

In 1990, NGS agreed to reduce SO₂ emissions by 90%. Three scrubbers were installed at NGS in 1997 to 1999, and the IMPROVE Aerosol Network monitored air quality in GRCA to evaluate the effects of emissions reductions. Previously, NGS emitted about 200 tons per day (t/day) of SO₂. Post-scrubber concentrations of particulate sulfate were significantly reduced (by ~33%) during the winter as compared with concentrations before scrubbers were installed at NGS. Reducing NGS emissions had a beneficial effect by decreasing winter haze and improving visibility in GRCA. Visibility on the haziest days having highest particulate sulfate improved markedly following the reduction in NGS emissions (Green et al. 2005). During summer, however, when NGS impacts on GRCA were minimal, there was only a small decrease in particulate sulfate (Green et al. 2005).

Installation of combustion controls to reduce NO_x began in 2009 and has resulted in a decline from 35,000 tons per year to around 16,000 tons per year. Remaining plant-wide emissions of SO₂ and NO_x are expected to drop by one-third in 2019 due to decisions by the Los Angeles Department of Water and Power and by Nevada Energy to eliminate coal-fired electricity from their generation portfolios. In 2014, the U.S. EPA finalized a rule to reduce air pollutants from NGS. When fully implemented by 2030, the plan will reduce NO_x emissions by about 80% and the visual impairment caused by NGS by about 73%.

Project MOHAVE (Measurement of Haze and Visual Effects) was a large U.S. EPA air quality and visibility research program conducted between 1990 and 1999 to evaluate causes of visibility

impairment in and surrounding GRCA. The MOHAVE project was particularly comprehensive, and included tracer/receptor field experiments in 1992, source emissions simulations, and extensive statistical analyses (Pitchford et al. 1999). The Mohave Power Project (MPP) was identified by MOHAVE as the single emissions source of haze-producing aerosols most likely to decrease visibility in GRCA (Pitchford et al. 1999). The MPP was a large coal-fired power plant located 90 miles southeast of Las Vegas in Laughlin, Nevada. The link between MPP emissions and air quality in GRCA had been subject of debate and study for over two decades (cf., Pitchford et al. 1999).

The Project MOHAVE final report (Pitchford et al. 1999) concluded that field measurements did not directly link elevated sulfate concentrations in GRCA with MPP emissions. Rather, concentrations of all visibility impairing species were affected by regional sources and regional meteorology. The dominant sources of GRCA visibility impairment were area sources in Southern California, Arizona, northern Mexico and, to some extent, the Las Vegas area.

Eatough et al. (2001) found that, although MGS was the major source of sulfate at Meadview, AZ, only 4.3 to 5.5% of total atmospheric sulfate in GRCA appeared to be derived from MPP emissions. They identified Las Vegas and urban areas in the Baja California and Imperial Valley regions as likely primary sources of atmospheric SO_4^{2-} in the park (Eatough et al. 2001). They identified northwestern Mexico as a significant source of haze-producing particulates in an extreme event of unusually high SO_4^{2-} concentrations in the Grand Canyon in 1992, and as the largest contributor of SO_4^{2-} aerosols to the sample site at Hopi Point in GRCA during Project MOHAVE. Subsequent analyses of Project MOHAVE extinction data and mass balance analyses of sulfur oxide sources by Eatough et al. (2006) also suggested that Los Angeles, CA, and Las Vegas, NV, were likely the largest anthropogenic contributors to b_{ext} in GRCA.

As a result of Project MOHAVE, MGS and stakeholders entered into a consent decree in 1999 that required MGS to install pollution control equipment by 2006 in order to address concerns about the impacts of plant emissions on GRCA visibility and ongoing violations of the plant's opacity emission limits (67 FR 6130 (February 8, 2002)). MPP opted to not install the equipment and, in 2005, elected to close the plant. The permanent closure of the MPP facility provided an opportunity to ascertain the level of impact on GRCA visibility that had been due to the operation of MPP. In advance of and following this permanent power plant closure, analyses were conducted using the IMPROVE Aerosol Network database to predict the resulting changes in atmospheric SO_2 concentrations and visibility in GRCA. Project MOHAVE's analysis of these data and tracer studies concluded that, although low levels of particulate sulfate originating in MPP emissions were reaching GRCA, there were negligible correlations between tracer concentration and measurements of b_{ext} in the park, suggesting that other aerosol sources also contributed to haze (Pitchford et al. 1999). Terhorst and Berkman (2010) analyzed pre- and post-closure visibility in GRCA in order to evaluate whether visibility improved after the closure of the plants and to identify the level of visibility degradation that could be attributed solely to MPP. Their analyses found a 3 to 10% drop in atmospheric fine sulfate concentrations in GRCA following the MPP closure, but no statistically significant change in visibility as measured by the haze index. Based on this finding, they concluded that the closure of the plant did not improve visibility in the Grand Canyon. White et al. (2012) found that conclusion to be

misleading, noting that the analysis of Terhorst and Berkman actually confirmed the results of Project MOHAVE which predicted that fine sulfate concentrations in GRCA would decrease if MPP sulfur emissions were controlled. White et al. (2012) also noted that Terhorst and Berkman based their conclusion of no improvement in visibility on haze estimates derived directly from the IMPROVE filter concentrations of sulfate and other chemical species, an accounting framework in which lower sulfate concentrations necessarily implies better visibility if other species are held constant. However, other chemical species fluctuated during the time period examined, likely masking the effect of the relatively small decreases in sulfate (White et al. 2012). White et al. (2012) commented that scientists had recognized for some time that visibility in GRCA is impaired by a combination of emissions from diverse sources over a large region, and that imperceptible increments, such as from MPP, can add up to perceptible haze.

Trends in Visibility

Visibility at 12 locations in the GRCA area declined from the 1950s to the 1970s by an estimated 10 to 30% (Trijonis 1979). IMPROVE long-term trend data are available for BAND (1992-2012), GRCA (1999-2012), MEVE (1990-2012), and PEFO (1990-2012; Figure 11). Trends analyses indicate that visibility has significantly improved in all four parks on the 20 percent clearest days, but only in BAND has visibility improved significantly on the 20% haziest days.

Development of State Implementation Plans

According to the Regional Haze Rule, 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). Strategies for meeting the requirements of the RHR are detailed in State-specific Implementation Plans, which must be approved by the EPA. Included in those Plans are the major emissions reductions achieved or expected as a result of the Best Available Retrofit Technology (BART) requirement of the Regional Haze Rule. Because of this BART requirement, major emissions reductions have been made by power plants (electric generating units - EGUs), and many more are anticipated from sources impacting the SCPN region. Figure 12 shows trends in SO₂ and NO_x emissions from power plants (electric generating units-EGU) in AZ, NM, and NV. From 2000-2014, very large emissions reductions occurred in these three states that are most likely to affect visibility in the SCPN parks. These reductions will be expected to result in visibility improvements if other visibility-reducing pollutants do not increase. However, as noted previously, organics and carbon fine particles also are major contributors to visibility impairment in the region.

Table 8 gives estimates of visibility at four SCPN Class I areas on the 20 percent clearest and haziest days. Haze is significantly elevated over natural conditions on both clear and hazy days for both the baseline (2000-2004) period and 2018. Natural conditions on the haziest days are not expected to be achieved by 2064. EPA estimates that for these parks, natural conditions will not be reached for many years (101-261 years), suggesting that reductions in addition to those illustrated by Figure 12 will be needed.

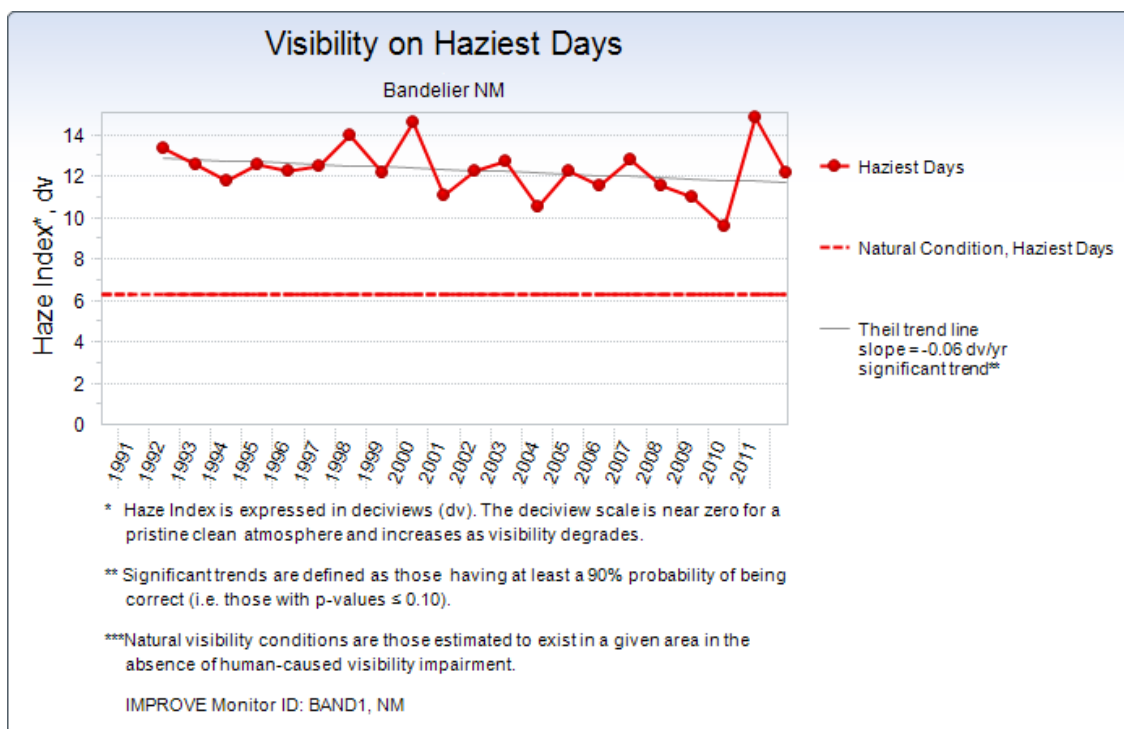
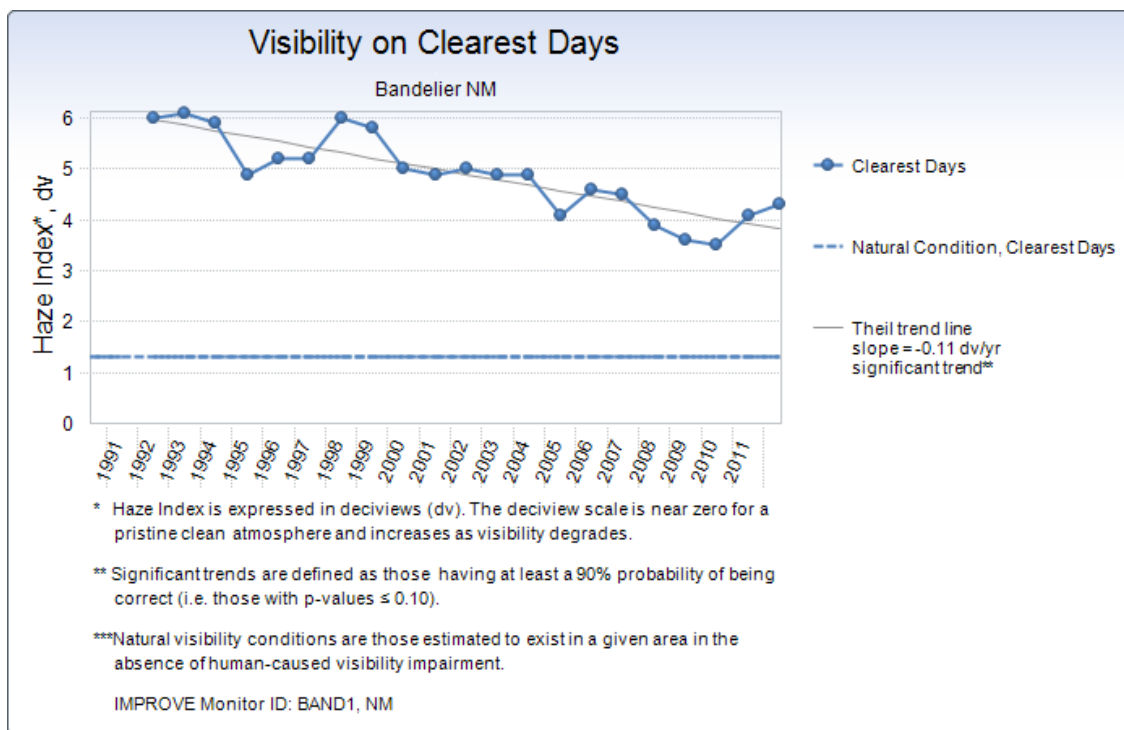


Figure 11a. Trends in ambient haze levels at BAND, based on IMPROVE measurements on the 20% clearest and 20% haziest days over the monitoring period of record. Data Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

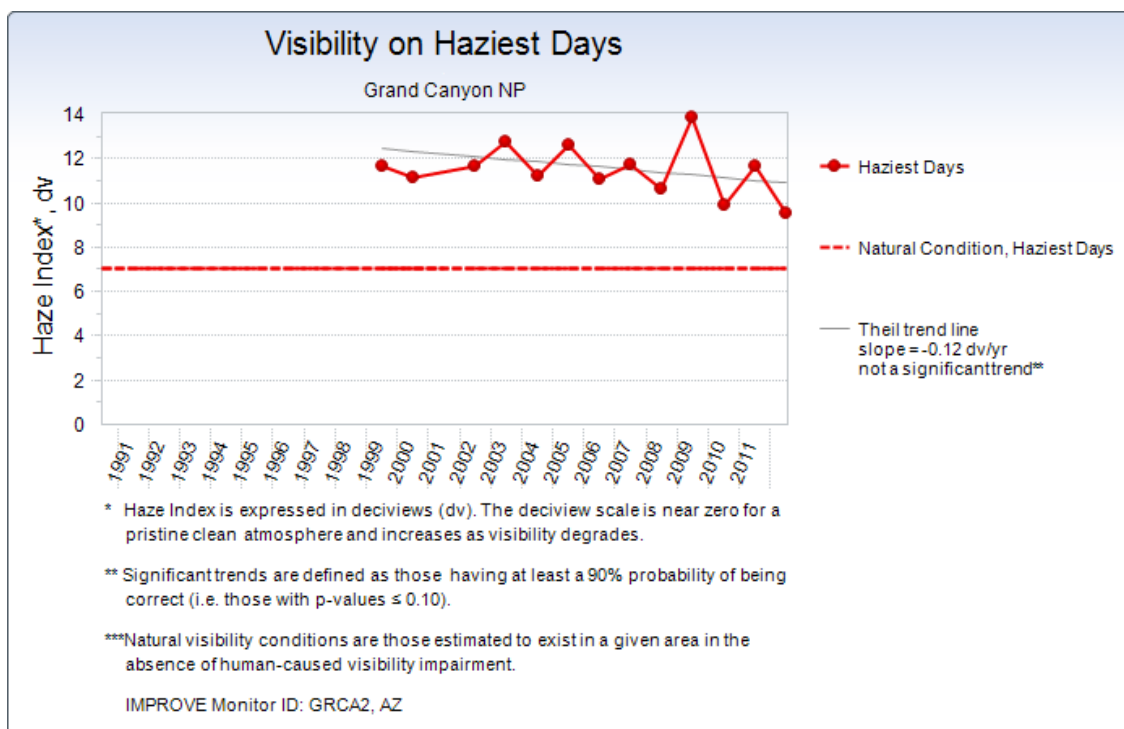
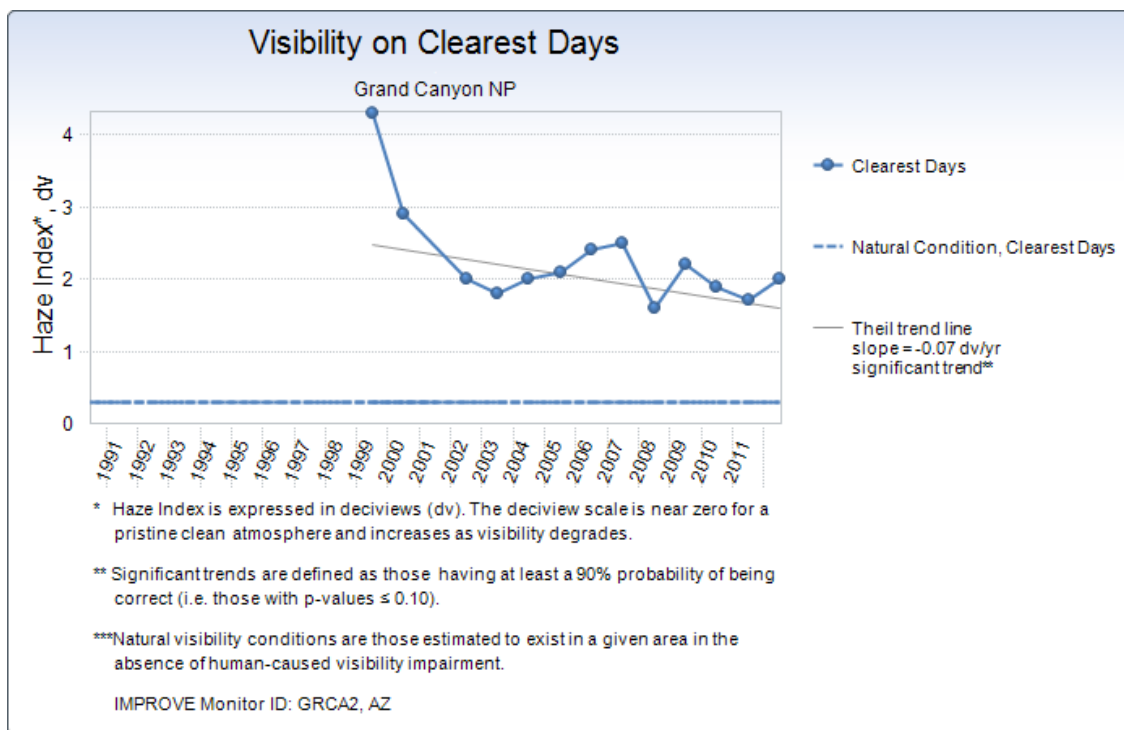


Figure 11b. Trends in ambient haze levels at GRCA, based on IMPROVE measurements on the 20% clearest and 20% haziest days over the monitoring period of record. Data Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

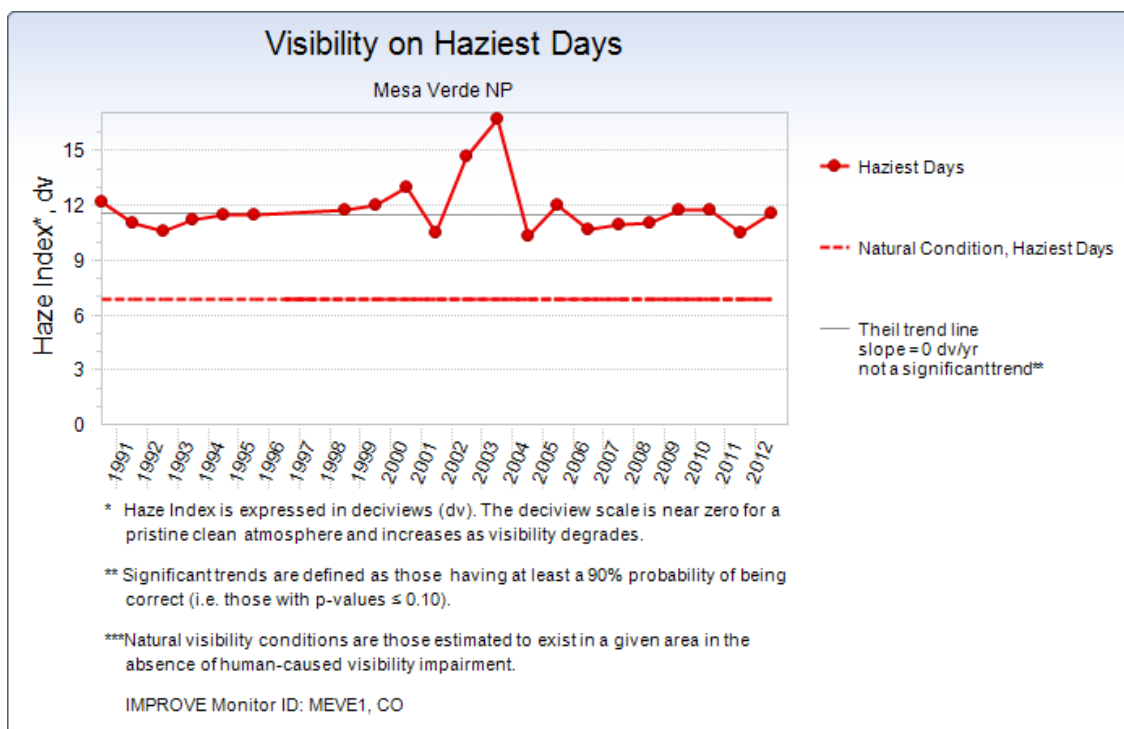
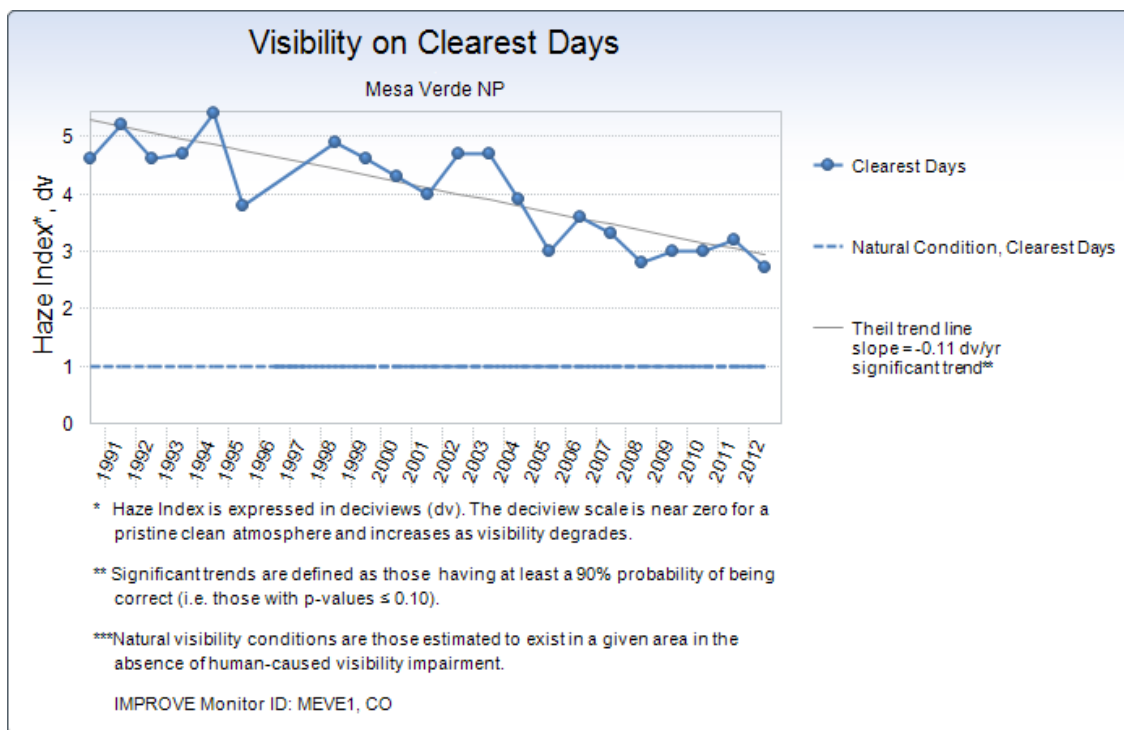


Figure 11c. Trends in ambient haze levels at MEVE, based on IMPROVE measurements on the 20% clearest and 20% haziest days over the monitoring period of record. Data Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

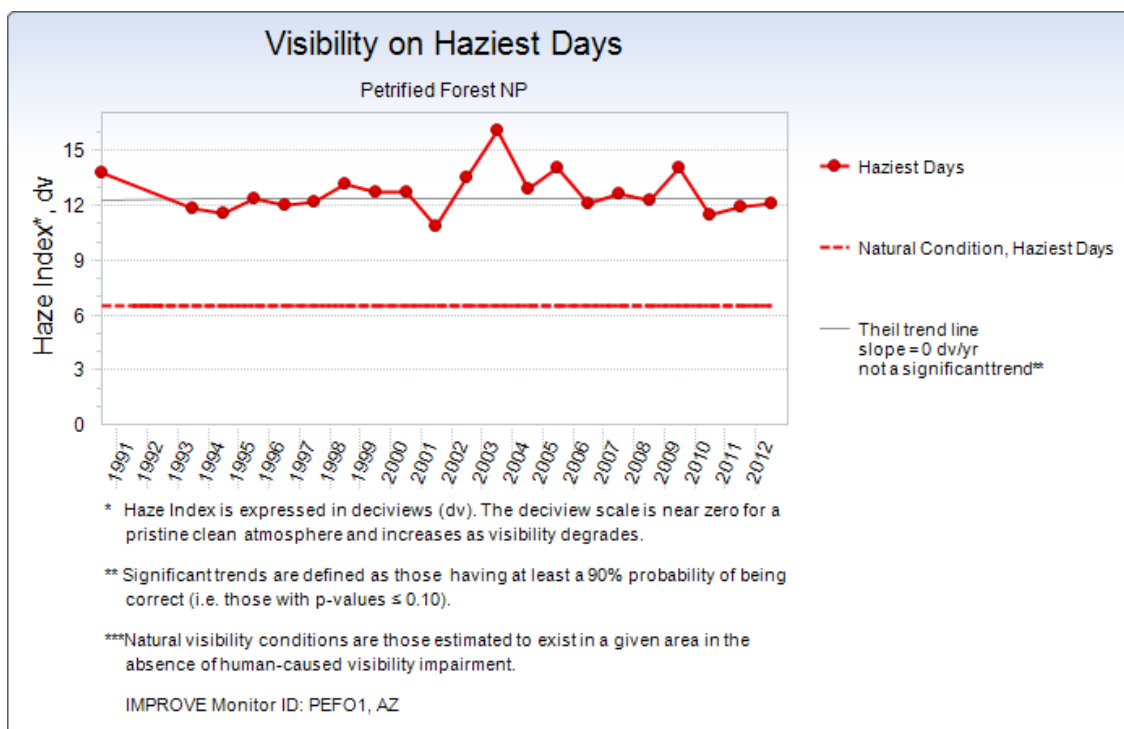
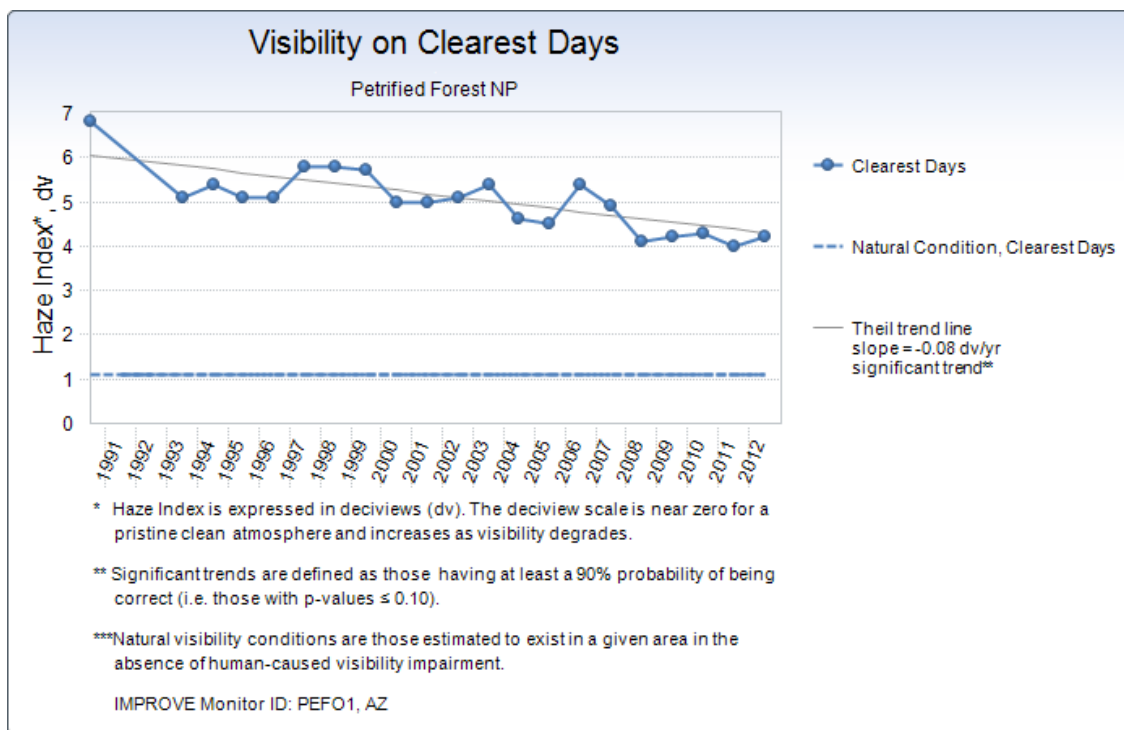


Figure 11d. Trends in ambient haze levels at PEFO, based on IMPROVE measurements on the 20% clearest and 20% haziest days over the monitoring period of record. Data Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss.

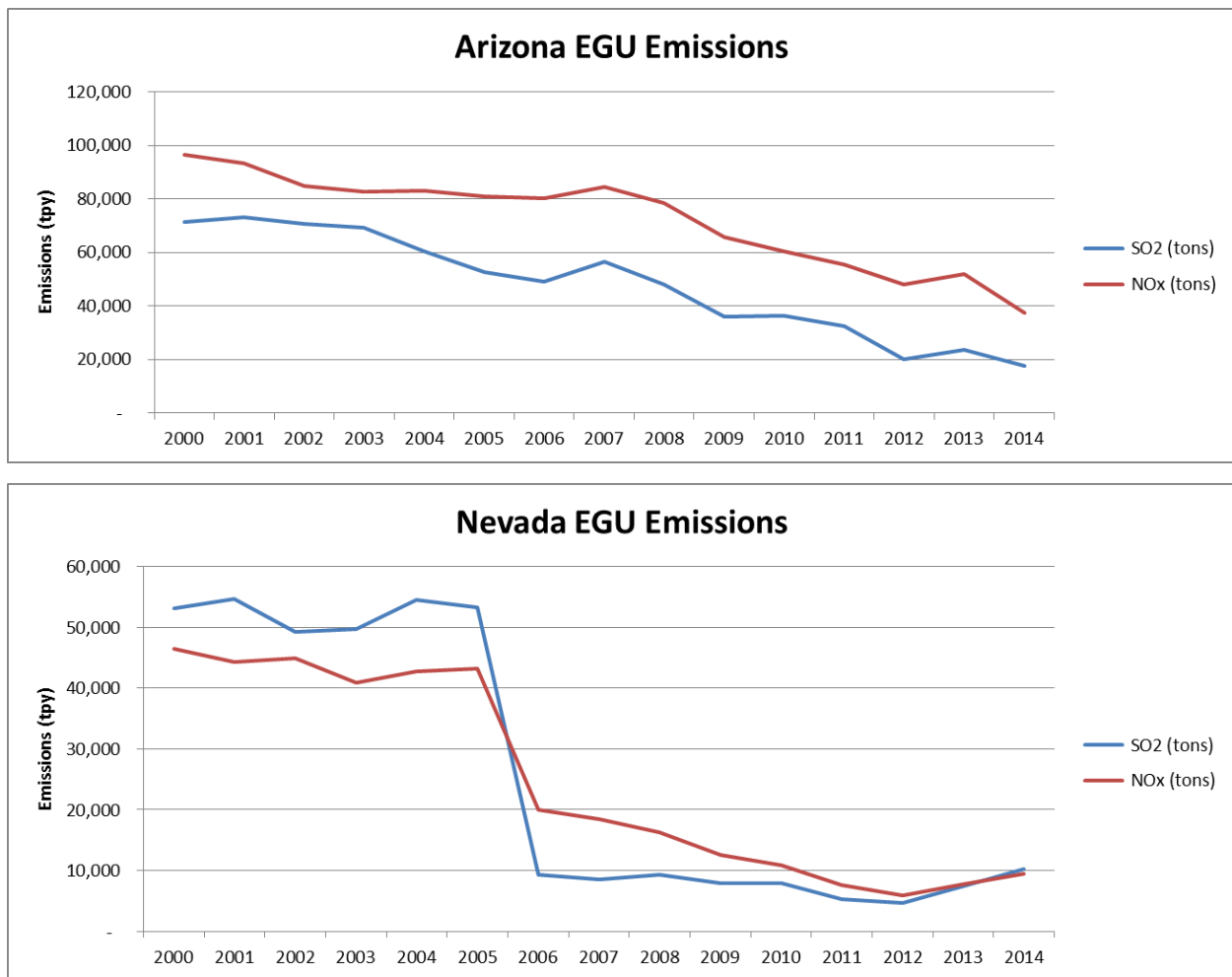


Figure 12. Sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions reductions in tons per year (tpy) at Electric Generating Units (EGU) in Arizona, New Mexico, and Nevada (NPS ARD 2015).

Table 8. Estimates of natural and baseline (2000-2004) and projected 2018 visibility on the 20% clearest and haziest days at Bandelier NM, Grand Canyon NP, Mesa Verde NP, and Petrified Forest NP, as well as the estimated years to natural conditions on the haziest days given actual and anticipated emissions reductions in the region.

Park Name	Measured Baseline, Projected 2018, and Estimated Natural Haze						Years to Natural Conditions
	20% Clearest Days (dv)			20% Haziest Days (dv)			
	Baseline	2018	Natural	Baseline	2018	Natural	
Bandelier ¹	4.95	4.89	1.29	12.22	11.90	6.26	261
Grand Canyon ²	2.16	2.02	0.31	11.66	10.58	7.04	101
Mesa Verde ³	4.32	4.10	1.01	13.03	12.50	6.81	164
Petrified Forest ²	5.02	4.62	1.07	13.21	12.64	6.49	165

¹ EPA, 40 CFR Part 52, [EPA-R06-OAR-2009-0050; FRL-9683-9], Approval and Promulgation of State Implementation Plans; New Mexico; Regional Haze Rule Requirements for Mandatory Class I Areas Agency (EPA). ACTION: Proposed rule. June 15, 2012

² EPA, 40 CFR Part 52, [EPA-R09-OAR-2013-0588; FRL-9912-97-OAR], Promulgation of Air Quality Implementation Plans; Arizona; Regional Haze and Interstate Visibility Transport Federal Implementation Plan, ACTION: Final rule. September 3, 2014

³ EPA, 40 CFR Part 52, [EPA-R08-OAR-2011-0770, FRL-9650-7], Approval and Promulgation of Implementation Plans; State of Colorado; Regional Haze State Implementation Plan, ACTION: Proposed rule. March 26, 2012

Toxic Airborne Contaminants

Because of the size and number of coal-burning power plants in the SCPN region, mercury (Hg) is a potential problem for ecosystems in the SCPN parks. Burning coal releases Hg, which can be transported long distances in the atmosphere. It is routinely monitored in rain at MEVE and levels at the park are among the highest of western U.S. sites (NADP 2010). A pilot study at the park did not find elevated mercury levels in songbirds, invertebrates, stream fish, or crayfish (Nydick and Williams 2010). Sample sizes were very small, however, and the study did not preclude the possibility of Hg accumulation in park wildlife.

Eagles-Smith et al. (2014) examined fish from 21 national parks in the western U.S., including two SCPN parks, GRCA and MEVE. In GRCA, brown trout and rainbow trout were sampled (n=42) and mean total Hg concentrations (76 nanograms per gram wet weight – ng/g ww) were similar to the average across all fish in the study (77.7 ng/g ww). However, size adjusted total Hg concentrations were among the highest in the size class (101.2 ng/g ww) across all parks. Moreover, size-adjusted total Hg concentrations in Shinumo Creek (178.8 ng/g ww) were more than 2-fold higher than those in the other two sites (71.5 and 81.0 ng/g ww) in GRCA, suggesting that Hg exposure within the park is variable. None of the fish exceeded EPA's criterion for human consumption (300 ng/g ww), but 10 percent of the fish exceeded toxicity thresholds for birds considered to be highly sensitive to Hg, including osprey (*Pandion haliaetus*) and snowy egret (*Egretta thula*). In MEVE, speckled dace were sampled (n=10). Their total mean Hg concentration (74.9 ng/g ww) was comparable to the study-wide mean value (77.7 ng/g ww), but much lower than concentrations measured in dace from nearby Capitol Reef and Zion National Parks. These differences may reflect differences in environmental processes occurring in the parks. None of the fish in MEVE exceeded toxicity thresholds for birds. Human health thresholds were not applied, as speckled dace is a very small fish, not consumed by humans (Eagles-Smith et al. 2014).

Data on other airborne toxics in SCPN ecosystems are very limited. Pesticide levels in air samples in BAND were near the median for all WACAP parks. Relative to other WACAP parks, BAND vegetation had medium to high concentrations of CUPs (endosulfans, dacthal, and chlorpyrifos) and medium to low concentrations of HUPs (hexachlorobenzene and hexachlorocyclohexane- α).

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