



Air Quality Related Values (AQRVs) for Sonoran Desert Network (SODN) Parks

Effects from Ozone; Visibility Reducing Particles; and Atmospheric Deposition of Acids, Nutrients and Toxics (Revised, 2019)

Natural Resource Report NPS/SODN/NRR—2019/1929



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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(Revised, 2019)*

Natural Resource Report NPS/SODN/NRR—2019/1929

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Note that this Sonoran Desert Network specific report was originally published in 2016. The 2019 update reflects an error correction to estimated park rankings for nutrient nitrogen pollutant exposure and ecosystem sensitivity to nutrient nitrogen enrichment in the third paragraph on page 16 and in Table 3 on page 17.

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Executive Summary

Note that this Sonoran Desert network specific report was originally published in 2016. The 2019 update reflects an error correction to estimated park rankings for nutrient nitrogen pollutant exposure and ecosystem sensitivity to nutrient nitrogen enrichment in the third paragraph on page 16 and in Table 3 on page 17.

This report describes the Air Quality Related Values (AQRVs) of the parks in the Sonoran Desert Network (SODN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The 11 SODN national park units that are included in the NPS Inventory and Monitoring (I&M) Program and discussed in this report are Casa Grande Ruins National Monument (CAGR), Chiricahua National Monument (CHIR), Coronado National Memorial (CORO), Fort Bowie National Historic Site (FOBO), Gila Cliff Dwellings National Monument (GICL), Montezuma Castle National Monument (MOCA), Organ Pipe Cactus National Monument (ORPI), Saguaro National Park (SAGU), Tonto National Monument (TONT), Tumacácori National Historic Park (TUMA), and Tuzigoot National Monument (TUZI). CHIR and SAGU are Class I air quality areas; the rest of the parks are Class II areas. Risk assessments are reported here for acidification, eutrophication and ozone (O_3) for all of the SODN parks. However, because most of the air quality and AQRV data have been collected in the two Class I areas, those parks are the main focus of this report. This report also describes air pollutant emissions and air quality within the SODN region and their effects on AQRVs. 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).

The SODN generally receives relatively low levels of both S and N atmospheric deposition. Nevertheless, the Phoenix area is an N deposition hotspot that is not well represented in coarse scale atmospheric deposition modeling using models such as the Community Multiscale Air Quality (CMAQ) model. In the most exposed desert and forested areas downwind of Phoenix, N deposition can be many times higher than is estimated from the CMAQ simulations used to estimate regional N deposition for this assessment (Fenn et al. 2003b; <http://www.wrapair2.org/WestJumpAQMS.aspx>).

Little work has been done on the ecological effects of acidification on arid land ecosystems in the SODN, and it is unlikely that such effects have occurred to any significant degree, except perhaps near large urban areas such as Phoenix and Tucson. Acidification effects have not been demonstrated in acid addition experiments at the Central Arizona-Phoenix Long Term Ecological Research (LTER) site within the SODN region, despite the very high levels of added acid deposition (almost 30 kg N/ha/yr). Similarly, there is no information available regarding the possible effects of acidic deposition on aquatic resources in the SODN. Such effects are unlikely in a desert environment.

Nitrogen pollutants can also cause undesirable nutrient enrichment of natural ecosystems, leading to changes in plant species distribution and diversity. Nitrogen deposition to arid and semi-arid lands

has a heightened potential to increase plant growth, enhance denitrification, alter plant community composition, and increase fire risk. Such changes could alter key ecosystem processes. The two largest parks in the SODN (SAGU and ORPI) are both desert parks. The predominant vegetation types within these parks that are known to be especially sensitive to nutrient N enrichment are arid and semi-arid vegetation, including grasslands and shrublands (Pardo et al. 2011).

Levels of atmospheric N deposition to the forests northeast of Phoenix may be locally high, above 13 kg N/ha/yr (Fenn and Geiser 2011) at some places. Such high levels of N deposition may have substantial effects on terrestrial ecosystems, especially on lichen and herbaceous/grass understory species composition. The potentially affected terrestrial ecosystems are likely spatially limited, however, and it has not been determined if such effects have occurred.

Model simulations using the Patch Arid Land Simulator (PALS) suggested that plant biomass in the desert near Phoenix can increase with only a small increase in N supply. The issue of increased plant biomass with increased N input is further confounded by the presence of nonnative invasive grass species, including buffelgrass (*Pennisetum ciliare*), which are common in portions of the SODN, including throughout much of SAGU. Increased prevalence of buffelgrass is also linked to increased fire frequency and intensity.

Ozone pollution can harm human health, reduce plant growth, and cause visible injury to foliage. Ambient O₃ exposure to plants in the parks in the SODN varies by park. Exposure is high in the majority of SODN parks, but the risk of foliar injury was judged to be low (eight parks) to moderate (three parks) due to the influence of dry conditions on stomatal opening and consequent O₃-uptake into foliage. In general, ambient O₃ exposure is relatively high in all the parks in the SODN. Nevertheless, foliar symptoms from O₃ exposure have not been reported.

Particulate pollution can cause haze, reducing visibility. Haze has been estimated by the Interagency Monitoring of Protected Visual Environments (IMPROVE) program for five parks within the SODN, including the two largest parks, ORPI and SAGU. SAGU contained two monitoring stations with individual estimated values, one in the East unit and one in the West unit of the park. The large number of visibility monitoring stations in the SODN reflects the importance placed on visibility for visitor enjoyment of parks in this network. Visibility in all the parks in the SODN is considered impaired by haze, even though haze levels are relatively low. The majority of the total particulate light extinction (b_{ext}) in all of the monitored parks is attributable to SO₄²⁻ (which largely originates from coal-burning power plants), coarse mass (from dust), organics (including from fires), and natural sources.

Background

The 11 parks in the Sonoran Desert Network (SODN) are located in Arizona and New Mexico. Two parks in the SODN are larger than 100 square miles, Organ Pipe Cactus National Monument (ORPI) and Saguaro National Park (SAGU). The other nine smaller parks are Casa Grande Ruins National Monument (CAGR), Chiricahua National Monument (CHIR), Coronado National Memorial (CORO), Fort Bowie National Historic Site (FOBO), Gila Cliff Dwellings National Monument (GICL), Montezuma Castle National Monument (MOCA), Tonto National Monument (TONT), Tumacácori National Historic Park (TUMA), and Tuzigoot National Monument (TUZI). 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.

Most of the population centers of any magnitude (i.e., larger than 50,000 people) in this network region are located in and around Phoenix and Tucson. Map 1 shows the network boundary along with locations of each park and population centers with greater than 10,000 people around the network. The two SAGU units are located on the east and west sides of Tucson.

Atmospheric Emissions and Deposition

Annual county-level sulfur (S) emissions in the SODN region in 2002 were generally less than 1 ton of sulfur dioxide (SO₂) per square mile per year, with one area having emissions between 1 and 5 tons per square mile per year (tons/mi²/yr). There were relatively few point source emissions of SO₂ within the network geographic boundary shown in Map 1. Most were centered around Phoenix and emitted less than 5,000 tons of SO₂ per year. Emissions near CHIR have included those from power plants and industrial smelting facilities in Mexico. However, SO₂ emissions declined after about 1999 in response to closure of smelters in Playas, New Mexico and Cananea, Sonora (Fenn and Allen 2011).

Annual county-level nitrogen (N) emissions within the network region in 2002 were higher than SO₂ emissions, ranging from less than 1 ton/mi²/yr to between 5 and 20 tons/mi²/yr. Nevertheless, annual county N emissions were generally less than 5 tons per square mile throughout most of the network region. There were few N point sources of any magnitude (i.e., larger than about 500 tons per year) in this region. Of the N point sources that did occur, the larger ones were sources of oxidized, rather than reduced, N. The major source of N emissions in this network region is vehicular traffic (Fernando et al. 2001). Because CHIR lies in close proximity to the border with Mexico, it is a good location for evaluating the potential effects of cross-border atmospheric transport of emissions into the SODN of SO₂ and N from Mexico.

County-level emissions near the SODN, based on data from the EPA's National Emissions Inventory (NEI) during a recent time period (2011), are depicted in Maps 2 through 4 for SO₂, oxidized N (NO_x), and reduced N (NH₃), respectively. Some counties to the north of SODN parks had relatively high SO₂ emissions (> 5 tons/mi²/yr; Map 2). Spatial patterns in NO_x emissions were generally

similar, with highest values to the west of most of the SODN parks (Map 3). Emissions of NH_3 near SODN parks were low, with most counties showing emissions levels below 2 tons/mi²/yr (Map 4).

Total estimated S deposition in 2002 in the SODN was uniformly less than 2 kg S/ha/yr (Sullivan et al. 2011b). Total N deposition within the network was generally between 2 and 5 kg N/ha/yr, though there were areas of both lower and higher N deposition. Estimated total N deposition was less than 5 kg N/ha/yr throughout all of the areas that contain I&M parks.

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

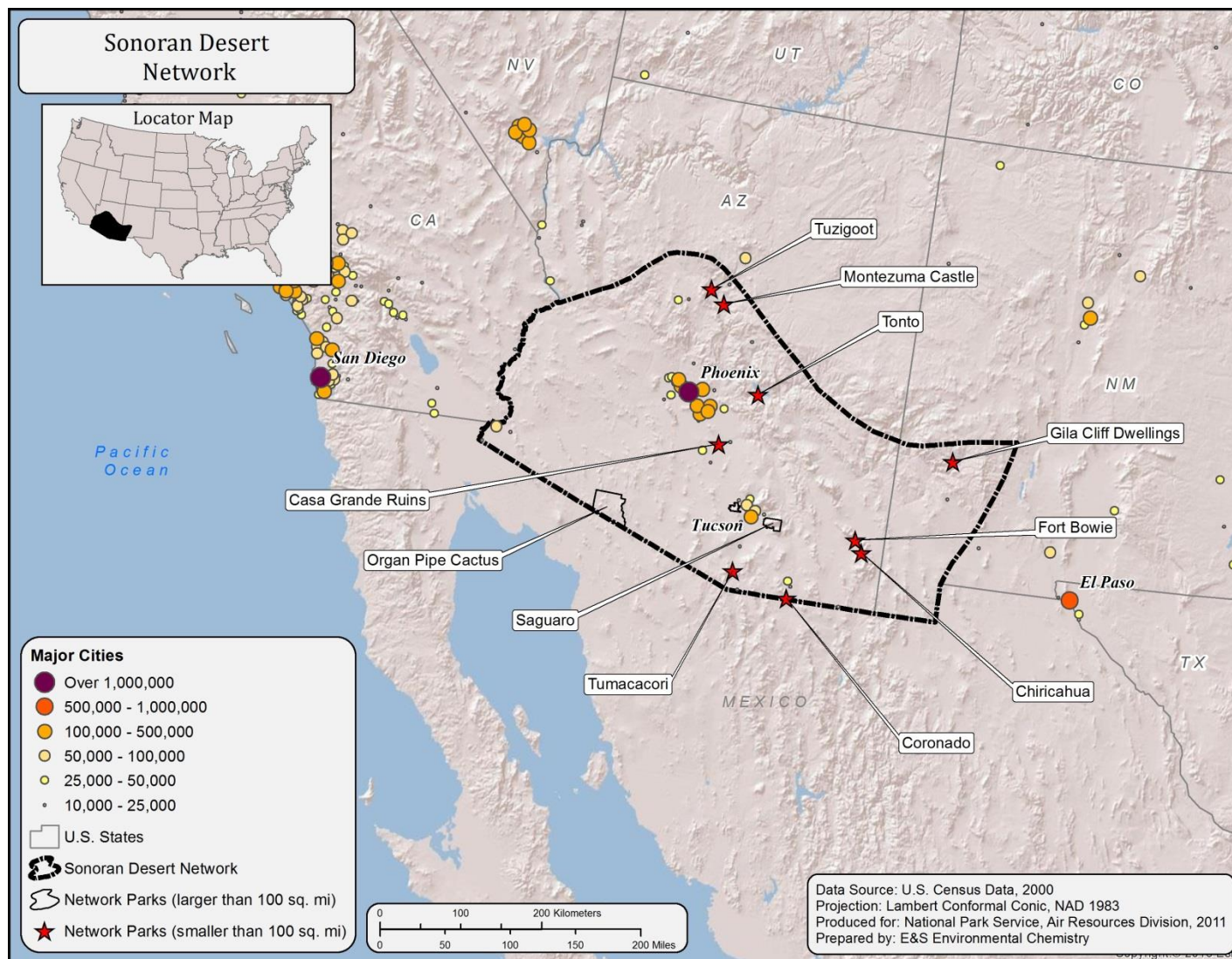
Atmospheric S and N deposition levels have decreased at some SODN parks and increased at others since 2001, based on TDEP estimates (Table 1). Most changes were relatively small. Oxidized and reduced N showed opposite patterns, with oxidized N generally decreasing and reduced N generally increasing at all of the parks in the network since the monitoring period 2000-2002. In many cases, the increases in reduced N deposition were substantial (> 50%).

Total S deposition in and around SODN for the period 2010-2012 was generally highest (> 2 kg S/ha/yr) to the north and lowest (< 2 kg S/ha/yr) to the southwest of 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 land within the SODN (Map 6). Most areas received less than 2 kg N/ha/yr of reduced inorganic N from atmospheric deposition during this same period (Map 7); a few areas received higher amounts. Total N deposition was higher than 5 kg N/ha/yr at some of the park locations (Map 8).

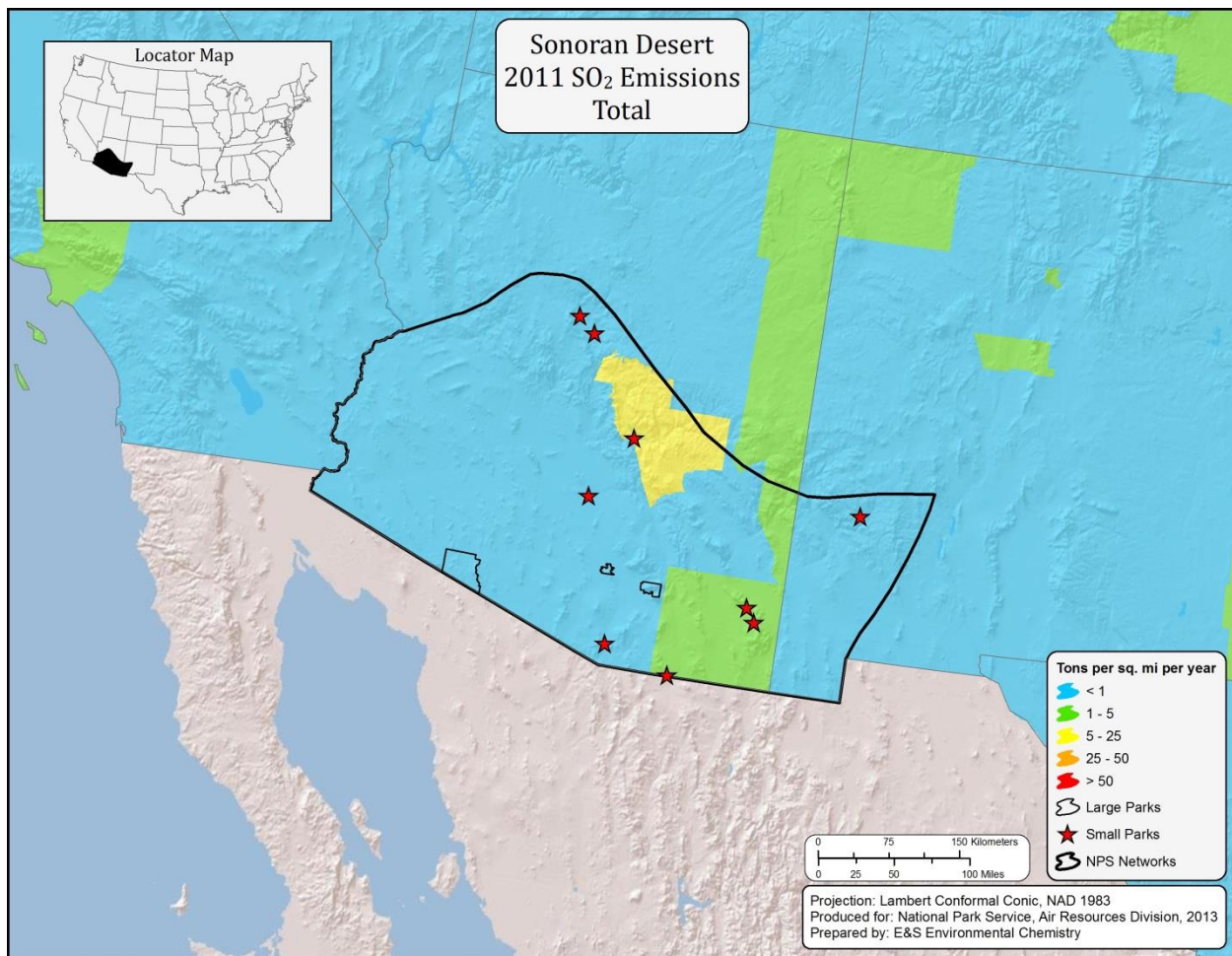
Rainfall in the arid southwest is infrequent. There is relatively little wet deposition of S or N in arid ecosystems, such as are prevalent in the SODN, and dry deposition predominates (Fenn et al. 2003b). Dry deposition is difficult to quantify, however, in large part because the deposition flux is 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 amount of nitrate (NO_3^-) in the surface soil decreased as NO_3^- was leached down the soil profile (Padgett et al. 1999, Padgett and Bytnerowicz 2001).

The Phoenix area is an N deposition hotspot that is not well represented in coarse scale atmospheric deposition modeling using CMAQ (Fenn et al. 2009). In the most exposed desert and forested areas downwind of Phoenix, N deposition can be as high as 29 kg/ha/yr (Fenn et al. 2003b), about five times higher than is estimated from the 36-km CMAQ simulations.

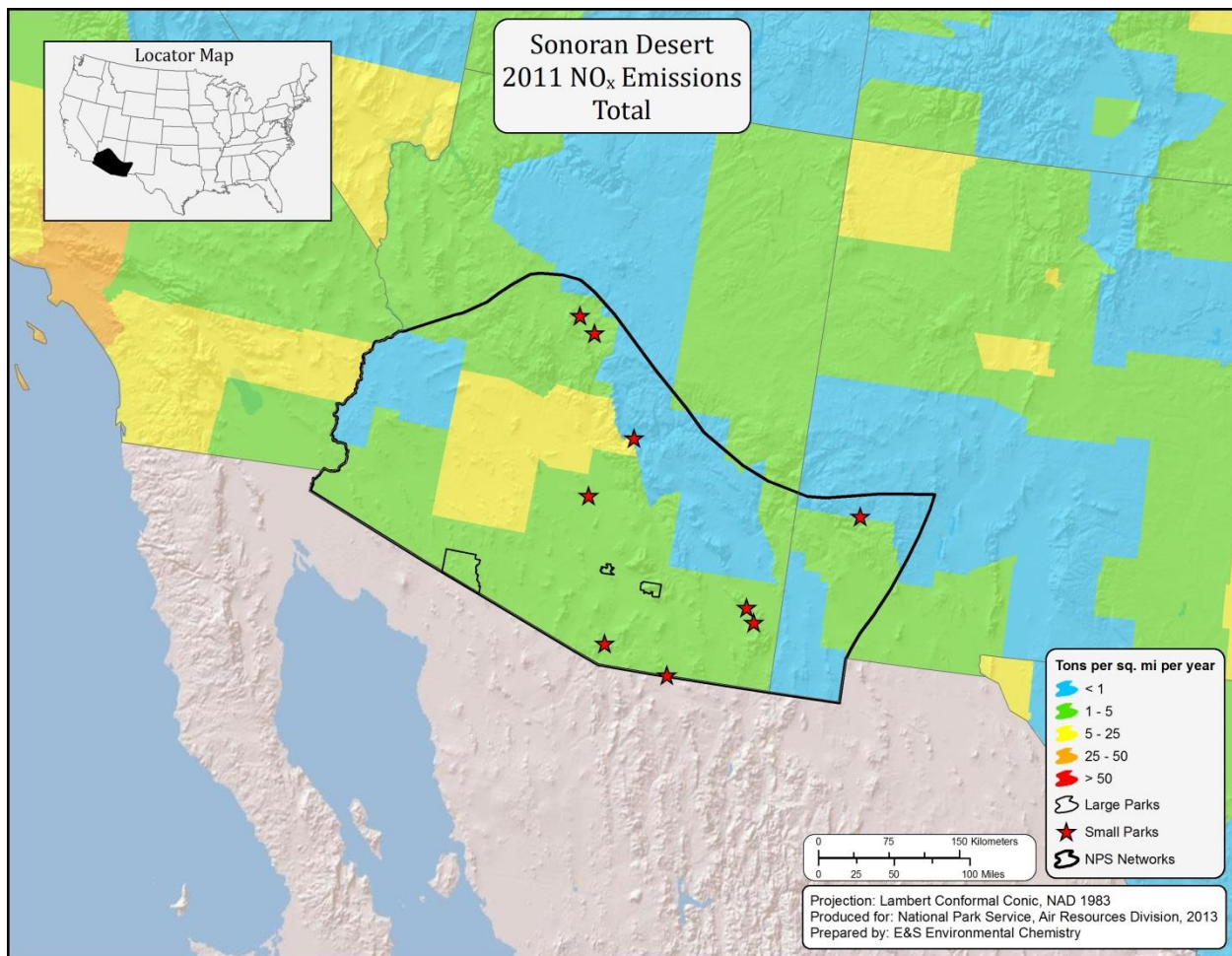
Based on wet deposition collected at 29 national park locations, and reported by NPS (2010), concentrations of NO_3^- in wet deposition during the period 1989 to 2008 decreased by statistically significant ($p \leq 0.05$) amounts at four locations. A statistically significant increase in NO_3^- concentration in wet deposition was only reported for one SODN park, GICL (0.47 $\mu\text{eq/L/yr}$). GICL also showed a significant ($p \leq 0.01$) increase in the concentration of ammonium (NH_4^+) in precipitation (0.35 $\mu\text{eq/L/yr}$), the second largest increase among monitored parks. Lehmann et al (2007) found that NH_4^+ in wet precipitation increased significantly (>50%) throughout the Intermountain West from 1985 to 2004. This increase is probably due to increases in ammonia (NH_3) emissions from agriculture and feedlots and to wildland fire emissions.



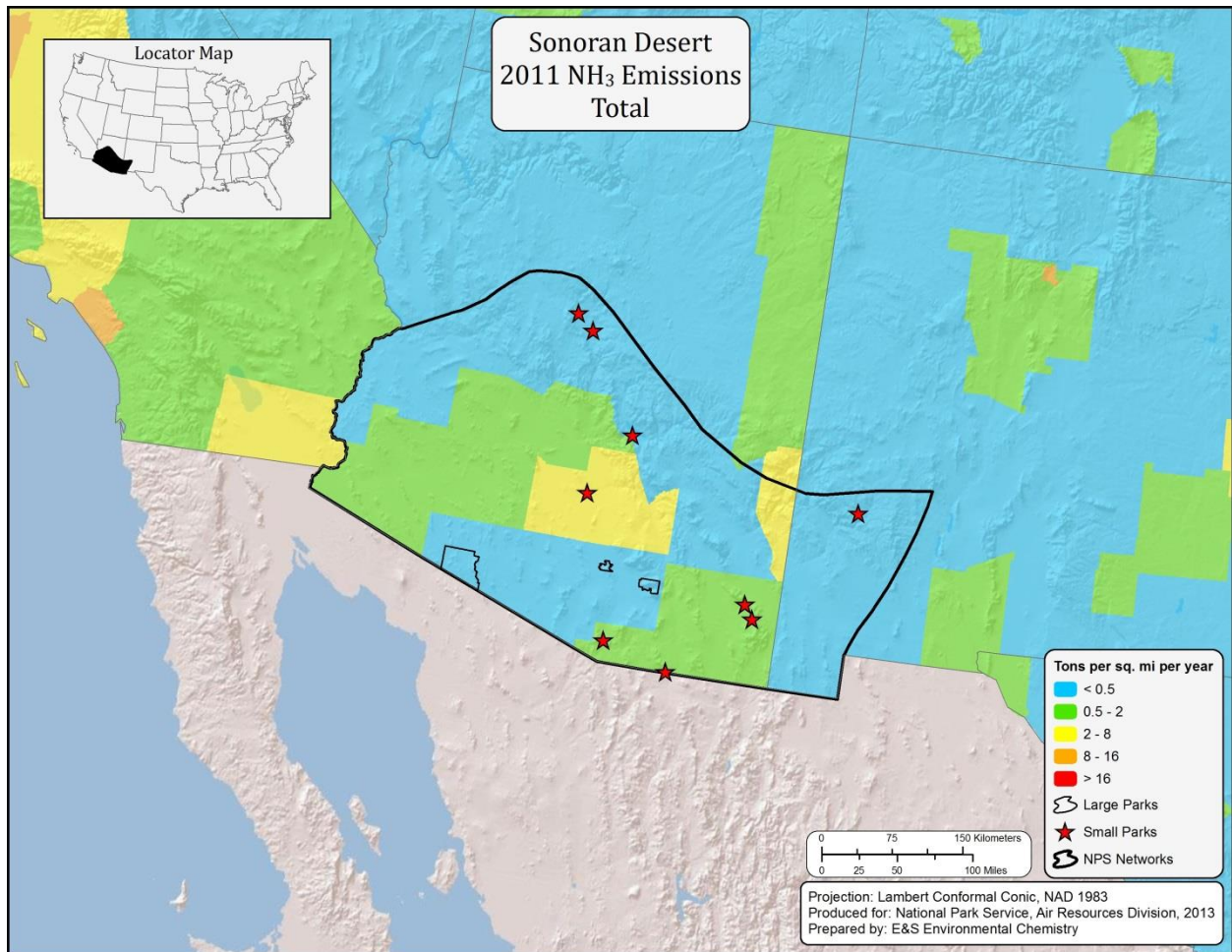
Map 1. Network boundary and locations of national parks and population centers with more than 10,000 people near the SODN.



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



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



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

Table 1. Average changes in S and N deposition between 2001 and 2011 across park grid cells at SODN 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.

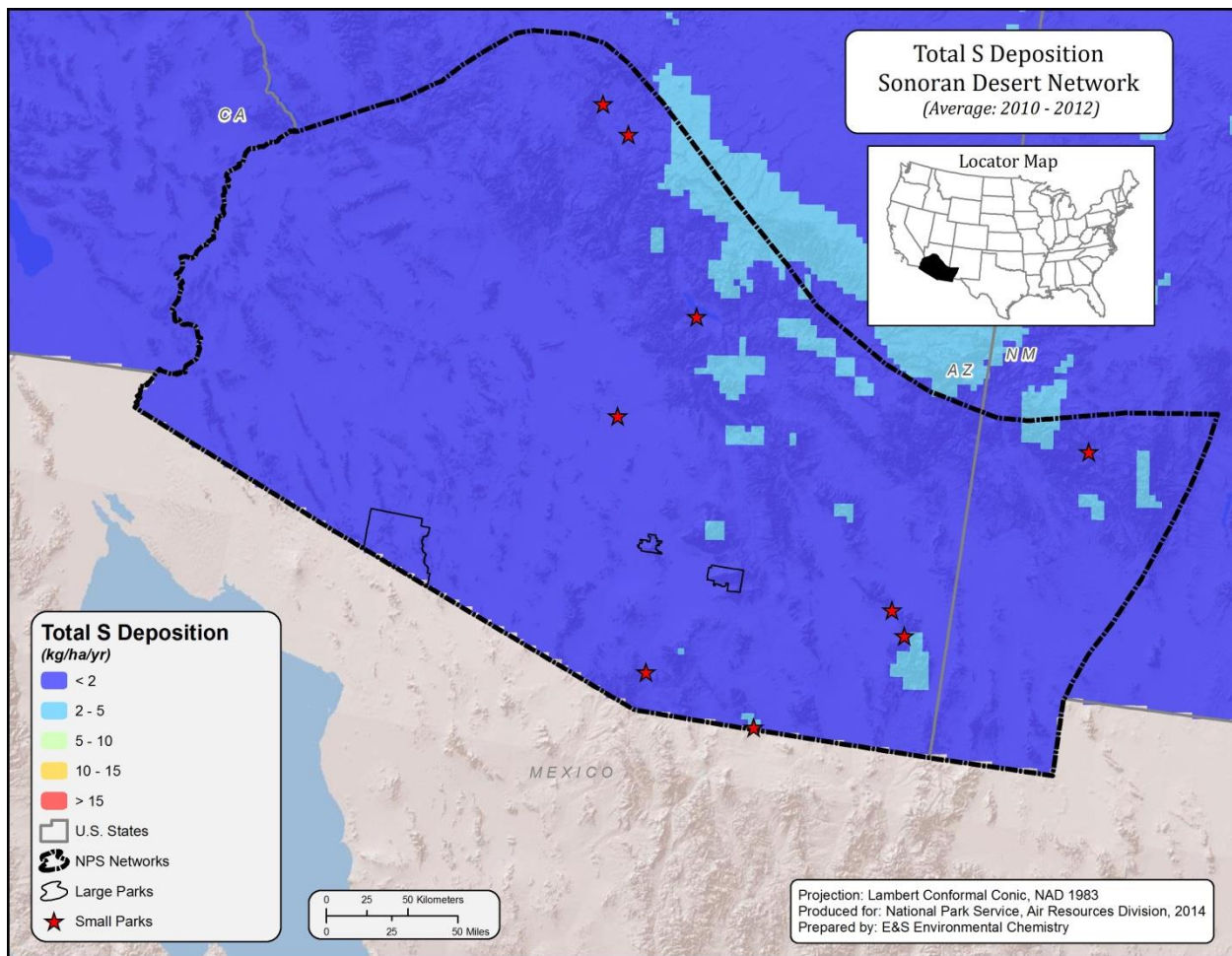
Park Code/Name	Parameter	2001 Average (kg/ha/yr)	2011 Average (kg/ha/yr)	Absolute Change (kg/ha/yr)	Percent Change	2011 Minimum (kg/ha/yr)	2011 Maximum (kg/ha/yr)	2011 Range (kg/ha/yr)
CAGR/Casa Grande Ruins	Total S	1.00	0.77	-0.22	-22.2%	0.77	0.77	0.00
	Total N	4.71	5.04	0.33	6.9%	5.04	5.04	0.00
	Oxidized N	2.99	2.24	-0.75	-25.2%	2.24	2.24	0.00
	Reduced N	1.72	2.80	1.08	62.9%	2.80	2.80	0.00
CHIR/Chiricahua	Total S	1.59	1.59	0.00	-0.2%	1.40	2.19	0.79
	Total N	3.61	5.22	1.60	44.4%	4.71	7.07	2.36
	Oxidized N	2.36	2.28	-0.09	-3.7%	2.08	3.29	1.21
	Reduced N	1.24	2.94	1.69	136.1%	2.63	3.77	1.14
CORO/Coronado	Total S	1.81	1.76	-0.05	-2.7%	1.41	2.15	0.74
	Total N	4.23	4.67	0.44	9.7%	3.71	5.70	1.99
	Oxidized N	2.60	2.74	0.14	4.6%	2.13	3.36	1.23
	Reduced N	1.64	1.94	0.30	17.9%	1.58	2.34	0.76
FOBO/Fort Bowie	Total S	1.36	1.26	-0.11	-7.7%	1.24	1.26	0.02
	Total N	3.30	4.27	0.97	29.3%	4.15	4.29	0.14
	Oxidized N	2.22	2.04	-0.18	-8.0%	1.96	2.06	0.09
	Reduced N	1.08	2.23	1.15	106.0%	2.19	2.23	0.05
GICL/Gila Cliff Dwellings	Total S	1.32	1.46	0.15	11.1%	1.43	1.46	0.03
	Total N	3.24	3.56	0.32	9.9%	3.49	3.57	0.07
	Oxidized N	2.33	2.28	-0.05	-2.3%	2.25	2.28	0.03
	Reduced N	0.91	1.28	0.38	41.4%	1.25	1.29	0.04

Table 1 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at SODN 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.

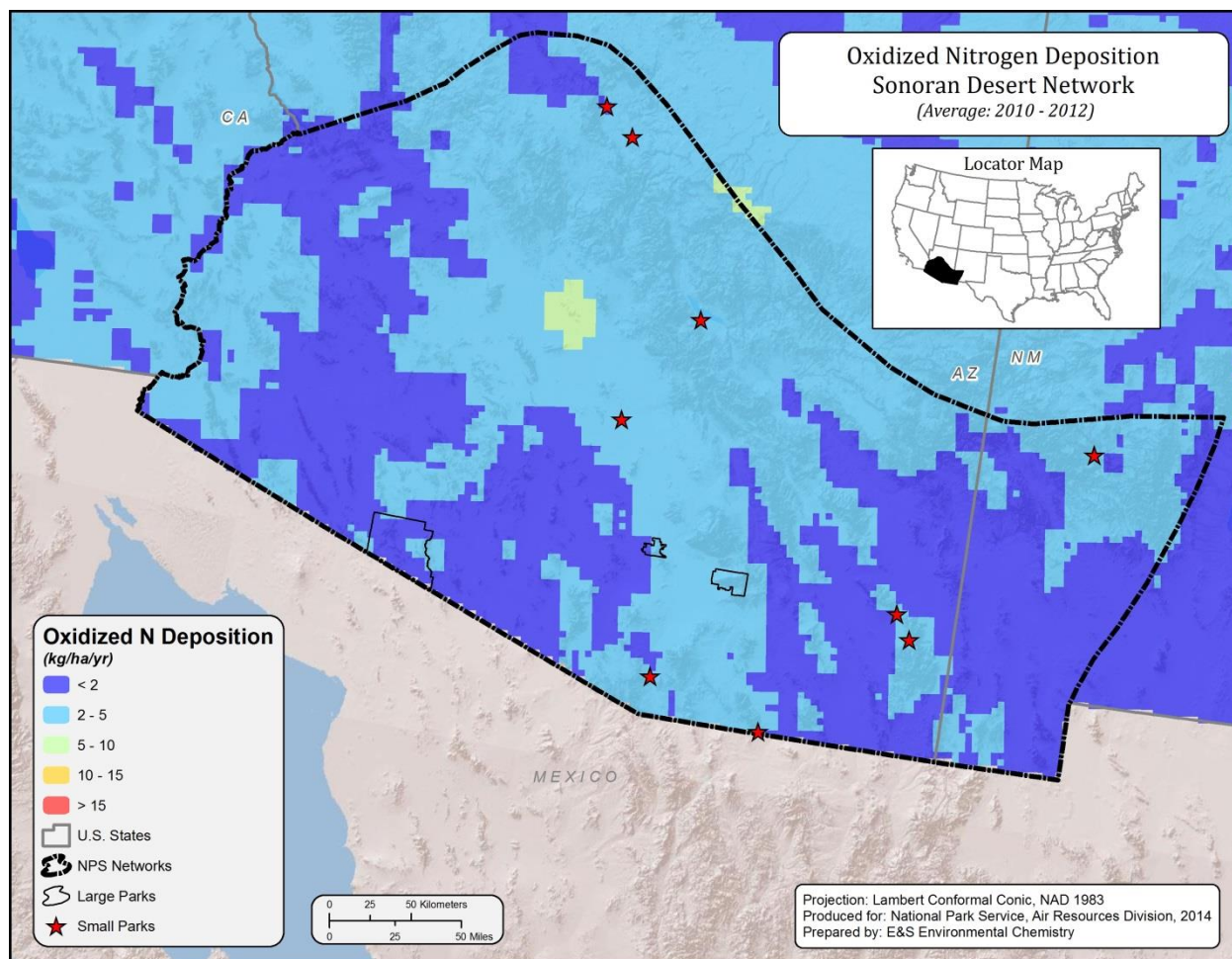
Park Code/Name	Parameter	2001 Average (kg/ha/yr)	2011 Average (kg/ha/yr)	Absolute Change (kg/ha/yr)	Percent Change	2011 Minimum (kg/ha/yr)	2011 Maximum (kg/ha/yr)	2011 Range (kg/ha/yr)
MOCA/Montezuma Castle	Total S	0.95	0.98	0.03	3.0%	0.90	1.12	0.22
	Total N	3.74	3.86	0.12	3.2%	3.69	4.18	0.49
	Oxidized N	2.83	2.42	-0.41	-14.7%	2.25	2.74	0.49
	Reduced N	0.90	1.44	0.53	58.9%	1.44	1.44	0.00
ORPI/Organ Pipe Cactus	Total S	0.73	0.81	0.08	11.1%	0.70	0.98	0.29
	Total N	2.87	2.60	-0.26	-9.1%	2.40	2.94	0.54
	Oxidized N	2.33	1.95	-0.38	-16.3%	1.76	2.14	0.38
	Reduced N	0.53	0.65	0.12	22.5%	0.57	0.80	0.22
SAGU/Saguaro	Total S	1.45	1.23	-0.22	-15.2%	0.76	1.66	0.89
	Total N	4.38	3.97	-0.41	-8.3%	2.84	4.73	1.89
	Oxidized N	3.21	2.55	-0.66	-19.2%	1.92	2.90	0.99
	Reduced N	1.17	1.42	0.25	22.2%	0.93	1.83	0.90
TONT/Tonto	Total S	1.16	1.19	0.04	3.3%	1.17	1.27	0.10
	Total N	4.13	3.95	-0.18	-4.2%	3.91	4.15	0.24
	Oxidized N	3.13	2.54	-0.59	-18.8%	2.49	2.71	0.21
	Reduced N	1.00	1.42	0.42	41.8%	1.41	1.44	0.03

Table 1 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at SODN 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.

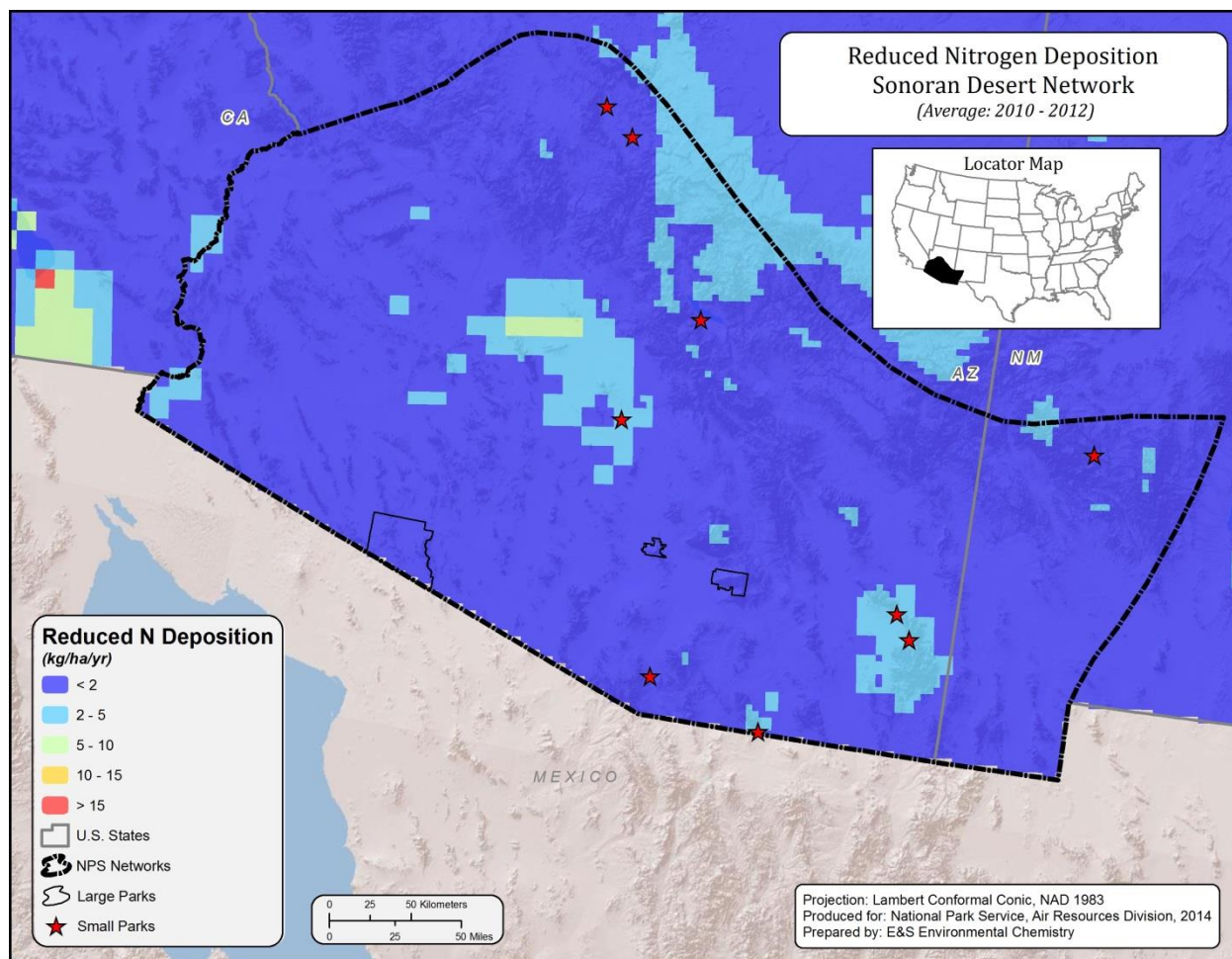
Park Code/Name	Parameter	2001 Average (kg/ha/yr)	2011 Average (kg/ha/yr)	Absolute Change (kg/ha/yr)	Percent Change	2011 Minimum (kg/ha/yr)	2011 Maximum (kg/ha/yr)	2011 Range (kg/ha/yr)
TUMA/Tumacacori	Total S	1.33	1.20	-0.13	-10.0%	1.12	1.23	0.11
	Total N	3.75	3.57	-0.18	-4.5%	3.46	3.90	0.44
	Oxidized N	2.47	2.15	-0.32	-12.9%	2.06	2.19	0.13
	Reduced N	1.28	1.42	0.14	11.7%	1.27	1.84	0.57
TUZI/Tuzigoot	Total S	0.80	0.81	0.01	1.2%	0.81	0.81	0.00
	Total N	3.41	3.15	-0.26	-7.6%	3.15	3.15	0.00
	Oxidized N	2.58	1.98	-0.60	-23.1%	1.98	1.98	0.00
	Reduced N	0.83	1.17	0.34	40.5%	1.17	1.17	0.00



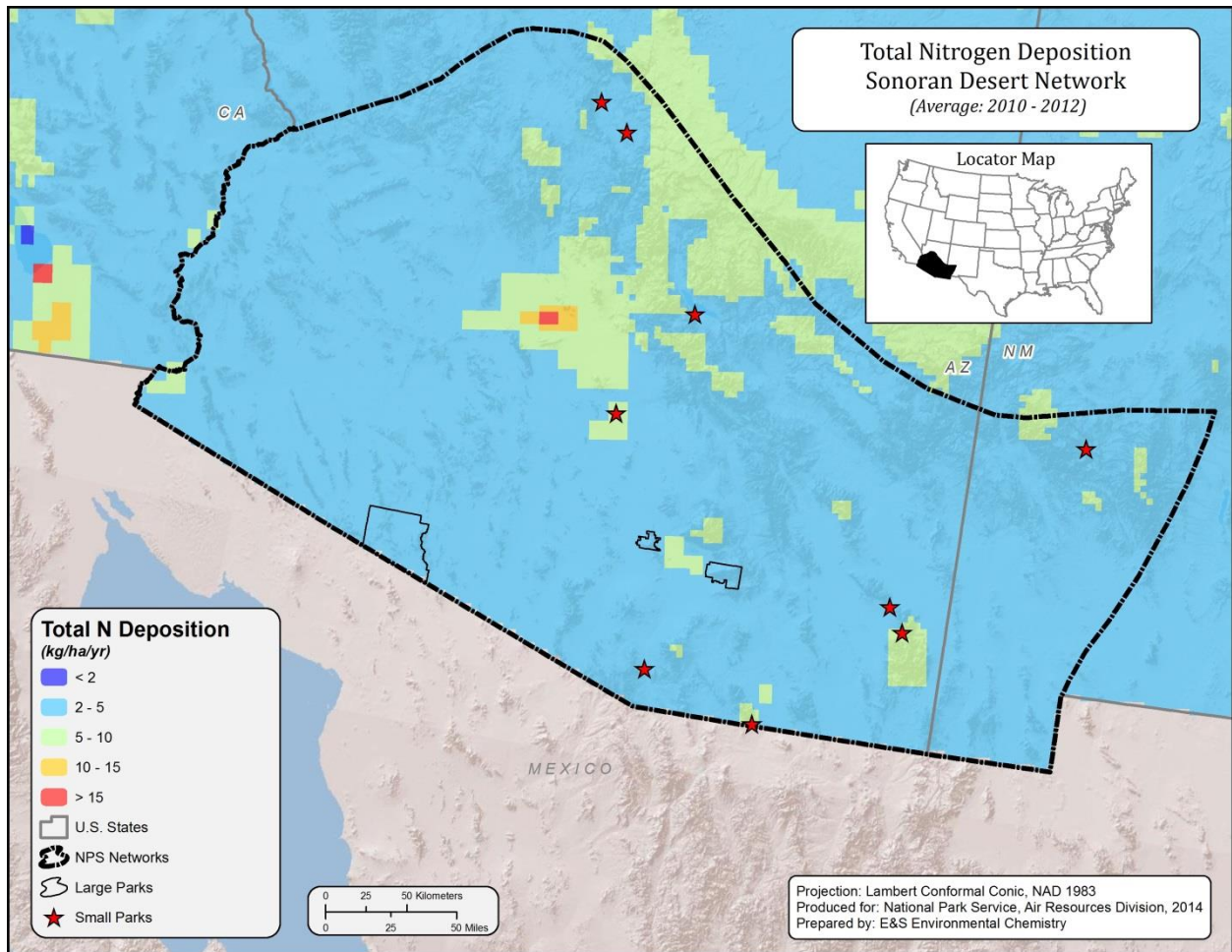
Map 5. Total S deposition for the three-year period centered on 2011 in and around the SODN. (Source: Schwede and Lear 2014)



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



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



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

Acidification

The network rankings developed 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 SODN that was near the middle of the distribution among all networks. The overall level of concern for acidification effects on I&M parks within this network was judged by Sullivan et al. (2011b) to be moderate. While rankings are an indication of risk, park-specific data, particularly data on ecosystem sensitivity, are needed to fully evaluate risk from acidification.

Two parks (TONT and CAGR) in the SODN were ranked in the middle quintile in acid Pollutant Exposure by Sullivan et al. (2011b; Table 2). The acid Pollutant Exposure rankings for the other parks were lower, with four parks (including SAGU) ranked Low and five parks (including ORPI) ranked Very Low. Ecosystem Sensitivity to acidification for the parks in this network varied from Very Low to High (Table 2). Ecosystem sensitivity to acidification rankings take into

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
Casa Grande Ruins	CAGR	Moderate	Very Low
Chiricahua	CHIR	Very Low	High
Coronado	CORO	Very Low	Low
Fort Bowie	FOBO	Very Low	Low
Gila Cliff Dwellings	GICL	Very Low	Moderate
Montezuma Castle	MOCA	Low	Low
Organ Pipe Cactus²	ORPI	Very Low	Moderate
Saguaro²	SAGU	Low	High
Tonto	TONT	Moderate	Moderate
Tumacácori	TUMA	Low	Very Low
Tuzigoot	TUZI	Low	Low

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

² Parks larger than 100 mi² (also in bold).

account land slope, which often influences the degree of acid neutralization provided by soils and bedrock within the watershed. Land slope within the parks in this network varies considerably, from less than 10° in some parks to over 40°, especially in some portions of SAGU, suggesting increased potential for acid sensitivity of aquatic resources.

Little work has been done on the effects of acidification on arid land ecosystems in the SODN or elsewhere in the southwestern United States, and it is unlikely that such effects have occurred to any significant degree. As reviewed by Fenn et al. (2003a), acidification effects have not been

demonstrated at the Central Arizona-Phoenix LTER site within the SODN region, despite the almost 30 kg N/ha/yr of deposition added in the long-term experiment. Similarly, no information is available regarding the possible effects of acidic deposition on aquatic resources in the SODN. Such effects are unlikely.

Nutrient Nitrogen Enrichment

The network rankings developed by Sullivan et al. (2011a) for 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 in the middle of the second highest 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 High. 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 two I&M parks in the Sonoran Desert Network that are larger than 100 square miles (SAGU and ORPI) were ranked by Sullivan et al. (2011a) in the second lowest or lowest quintile in nutrient N Pollutant Exposure. The nutrient N Pollutant Exposure rankings for the smaller parks were more variable, ranging from the lowest quintile (four parks) to the middle quintile (two parks; Table 3). Nutrient N pollutant exposure locally near Phoenix is much higher (Fenn et al. 2009). Dry N deposition in and around Tucson might also be expected to be higher than is indicated by regional or national model projections. This is relevant because the East unit of SAGU is located on the outskirts of Tucson, in close proximity to vehicular emissions sources.

Ecosystem Sensitivity to nutrient N enrichment for parks in this network was in nearly all cases ranked as Very High (including SAGU and ORPI) or High (Table 3).

The Chiricahua Mountains in Arizona and New Mexico are located near the intersection of the Sonoran and Chihuahuan deserts, the Rocky Mountains, and the Sierra Madre Mountains (CEC 1997). Desert grassland and desert scrub vegetation occur at lower elevations, oak and juniper occur at middle elevations, and coniferous forests are found at higher elevations. Experimental studies have not been conducted in this region to determine sensitivity to, or effects of, atmospheric N addition. In the lowland areas throughout the SODN, N deposition would be expected to contribute to increased cover of non-native grasses and increased fire frequency and severity (Fenn and Allen 2011). Non-native grass invasion is an important management issue in SAGU. Buffelgrass is an invasive grass of particular concern in southern Arizona and Sonoran Desert ecosystems. Inputs of N favor buffelgrass over native species, as buffelgrass is able to efficiently absorb and assimilate N (Lyons et al. 2013). Increased cover of exotic grasses, such as buffelgrass, has been shown to increase fire risk in arid areas (Rao et al. 2010). Interactions among N, invasive annual grasses, and fire have profound implications for changes to biodiversity of ecosystems that were not historically adapted to frequent fire (such as those commonly found in the Sonoran Desert). Increased plant uptake of N may also exacerbate water use in plants like big sagebrush (Inouye 2006).

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

Park Name	Park Code	Estimated Nutrient N Pollutant Exposure	Estimated Ecosystem Sensitivity to Nutrient N Enrichment
Casa Grande Ruins	CAGR	Moderate	Very High
Chiricahua	CHIR	Very Low	High
Coronado	CORO	Very Low	Very High
Fort Bowie	FOBO	Very Low	High
Gila Cliff Dwellings	GICL	Very Low	Very High
Montezuma Castle	MOCA	Low	Very High
Organ Pipe Cactus²	ORPI	Low	Very High
Saguaro²	SAGU	Low	Very High
Tonto	TONT	Moderate	Very High
Tumacacori	TUMA	Low	High
Tuzigoot	TUZI	Low	Moderate

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 Parks larger than 100 mi² (also in bold).

The two largest parks in this network (ORPI and SAGU) are both desert parks. The predominant vegetation types within these parks that are presumed to be especially sensitive to nutrient N enrichment are arid and semi-arid vegetation. Nitrogen deposition has the potential to increase plant growth, enhance denitrification, and alter plant community composition in arid environments (Allen et al. 2005, Egerton-Warburton and Allen 2000). Such changes could alter key ecosystem processes.

Levels of atmospheric N deposition to the forests northeast of Phoenix may be locally high (Fenn and Geiser 2011). Such high levels of N deposition may have substantial effects on terrestrial ecosystems, especially on lichen community composition and herbaceous/grass understory species composition. The potentially affected forest ecosystems are likely spatially limited, however, and it has not been determined if such effects have occurred in forest communities within the SODN (Fenn and Geiser 2011).

Total N deposition at CHIR has been estimated by different studies to be in the range of about 4 to 5 kg N/ha/yr (Fenn and Allen 2011) and about 4 to 7 kg N/ha/yr (Byun and Schere 2006). Such levels of atmospheric N deposition may be high enough to cause changes in lichen community composition or the distribution and abundance of annual plant species (Fenn et al. 2003a, Fenn and Allen 2011). These vegetation communities may also have been affected in the past by emissions from copper smelters in this region (Fenn and Allen 2011).

Marler et al. (2001) evaluated the potential impacts of experimentally elevated stream water nutrient concentrations on three plant species in riparian areas in the SODN: Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii*), and non-native saltcedar (*Tamarix ramosissima*) collected from the riparian zone of the Salt River near Phoenix. The results from this 43-day

experiment showed that growth of all three riparian plant species responded positively to increased nutrient supply. Only slight increases in biomass were observed between the lowest N treatments. The exotic and invasive saltcedar showed the greatest increases in biomass at high N supply. Other studies have also found that exotic plant species often respond more than native vegetation to increased nutrient supply (Milberg et al. 1999, Paschke et al. 2000). The Marler et al. (2001) experiment was conducted to simulate impacts of wastewater effluent on riparian zones, and N additions were therefore very large. Elevated nutrient supply to riparian systems via atmospheric N deposition is more typically in the range of the two lowest N treatments in this study, which showed only minimal response to N addition.

Model simulations using the Patch Arid Land Simulator (PALS) suggested that plant biomass in the desert near Phoenix can increase with only a small increase in N supply (Shen et al. 2008). This can dramatically increase fire risk. The issue of increased plant biomass with increased N input is further confounded by the presence of nonnative invasive grass species.

Pardo et al. (2011) 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 compiled by Pardo et al. (2011) suggest that ambient N deposition may exceed the lower limit of the expected CL to protect against nutrient enrichment effects in two parks in the SODN: CAGR and SAGU. These potential exceedances were reported for the protection of lichens and herbaceous plants (Table 4). In contrast, Marsh and Nash (1979) did not find effects on lichens near the Four Corners Power Plant on the Colorado Plateau. Desert lichens may be sensitive to N addition. Lichens near a large coal-fired plant in Page, Arizona showed chlorophyll degradation and reduced N fixation (Belnap 1991).

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

NPS Unit	Ecoregion	N Deposition (kg N/ha/yr)	Critical Load (kg N/ha/yr)				
			Mycorrhizal Fungi	Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Casa Grande NM	North American Deserts	3.8	NA	3.0*	3 - 8.4*	NA	NA
Chiricahua NM	Southern Semi - Arid Highlands	2.4	NA	NA	NA	NA	NA
Coronado NMem	Southern Semi - Arid Highlands	2.4	NA	NA	NA	NA	NA
Fort Bowie NHS	Southern Semi - Arid Highlands	2.3	NA	NA	NA	NA	NA
Gila Cliff Dwellings NM	Temperate Sierras	2.6	NA	4 - 7	NA	NA	NA
Montezuma Castle NM	Temperate Sierras	2.7	NA	4 - 7	NA	NA	NA
Organ Pipe Cactus NM	North American Deserts	1.8	NA	3.0	3 - 8.4	NA	NA
Saguaro NP	North American Deserts	3.6	NA	3.0*	3 - 8.4*	NA	NA
Saguaro NP	Southern Semi - Arid Highlands	3.6	NA	NA	NA	NA	NA
Tonto NM	Temperate Sierras	3.6	NA	4 - 7	NA	NA	NA
Tumacacori NM	Southern Semi - Arid Highlands	2.3	NA	NA	NA	NA	NA
Tuzigoot NM	Temperate Sierras	2.6	NA	4 - 7	NA	NA	NA

Ozone Injury to Vegetation

The O₃-sensitive plant species that are known or thought to occur within the I&M parks in the SODN are listed in Table 5. Those considered to be bioindicators, because they exhibit distinctive symptoms when injured (e.g., dark stipple), are designated by an asterisk. One park in this network, CAGR, did not contain any sensitive and/or bioindicator species. Each of the other parks in this network contained at least three O₃-sensitive and/or bioindicator species. For the large parks, CHIR contained 15 sensitive species, (8 bioindicators), SAGU contained 14 sensitive species (10 bioindicators), and ORPI contained 3 sensitive species (2 bioindicators). 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 NPS and Kohut ranking systems differ. The NPS (2010) ranking system is a quick assessment of O₃ condition that ranks O₃ exposure levels according to injury thresholds from the literature (Heck and Cowling 1997), using a 5-year average of either the W126 or SUM06 index. The former is a measure of cumulative O₃ exposure that preferentially weights higher concentrations; the latter is a measure of cumulative O₃ exposure that includes only hourly concentrations over 60 ppb. Both metrics are calculated over a 3-month period. The W126 was classified as Moderate exposure at values between 7 and 13 ppm-hr, as defined by NPS (2010). Values higher than 13 ppm-hr were classified as High exposure, and values lower than 7 ppm-hr were classified as Low exposure. 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 SODN parks for 2005-2009 are rated Moderate to High. The W126 index was ranked Moderate in four parks (including SAGU) and High in seven parks in the SODN, including ORPI. The SUM06 index was ranked Moderate in two parks (GICL and TUMA) and High in nine parks. Kohut's (2007) ranking was Low in eight parks (including SAGU) and Moderate in three parks (MOCA, ORPI, and TONT). Although O₃ exposures are relatively high at most parks in the SODN, the low availability of soil moisture at these parks would be expected to limit O₃ uptake into vegetation.

Table 5. Ozone-sensitive and bioindicator plant species known or thought to occur in the I&M parks of the SODN (represented by an “X”). (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										
		CAGR	CHIR	CORO	FOBO	GICL	MOCA	ORPI ¹	SAGU ¹	TONT	TUMA	TUZI
<i>No Species Present</i>	N/A	X	—	—	—	—	—	—	—	—	—	—
<i>Ailanthus altissima</i> ²	Tree-of-heaven	—	—	X	—	—	X	—	—	—	X	X
<i>Apocynum androsaemifolium</i> ²	Spreading dogbane	—	X	—	—	—	—	—	X	—	—	—
<i>Apocynum cannabinum</i>	Dogbane, Indian hemp	—	X	—	—	X	X	—	X	—	—	—
<i>Artemisia ludoviciana</i> ²	Silver wormwood	—	X	X	X	X	X	X	X	X	X	X
<i>Fraxinus pennsylvanica</i>	Green ash	—	X	X	—	—	—	—	—	—	—	—
<i>Oenothera elata</i> ²	Evening primrose	—	X	—	X	X	X	—	X	—	—	—
<i>Parthenocissus quinquefolia</i>	Virginia creeper	—	X	—	—	X	—	—	X	—	—	—
<i>Pinus ponderosa</i> ²	Ponderosa pine	—	X	—	—	X	—	—	X	—	—	—
<i>Populus tremuloides</i> ²	Quaking aspen	—	X	—	—	—	—	—	X	—	—	—
<i>Prunus serotina</i> ²	Black cherry	—	X	X	—	X	—	—	X	—	—	—
<i>Prunus virginiana</i>	Choke cherry	—	X	—	—	—	—	—	X	—	—	—
<i>Rhus trilobata</i> ²	Skunkbush	—	X	X	X	X	X	X	X	X	X	X
<i>Rubus parviflorus</i>	Thimbleberry	—	X	—	—	—	—	—	—	—	—	—
<i>Rudbeckia laciniata</i> ²	Cutleaf coneflower	—	X	—	—	X	—	—	X	—	—	—
<i>Salix gooddingii</i>	Gooding's willow	—	X	X	X	—	X	X	X	—	X	X
<i>Salix scouleriana</i> ²	Scouler's willow	—	—	—	—	—	—	—	X	—	—	—
<i>Sambucus nigra</i> ²	Blue elderberry	—	—	X	—	—	—	—	X	X	X	—
<i>Solidago canadensis</i>	Goldenrod	—	X	X	—	—	X	—	—	—	—	—

¹ Parks larger than 100 mi².

² Bioindicator species

Table 6. Ozone assessment results for I&M parks in the SODN 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	
Casa Grande Ruins	CAGR	15.68	High	20.30	High	Low
Chiricahua	CHIR	13.18	High	17.59	High	Low
Coronado	CORO	11.87	Moderate	15.39	High	Low
Fort Bowie	FOBO	13.32	High	17.85	High	Low
Gila Cliff Dwellings	GICL	9.97	Moderate	11.47	Moderate	Low
Montezuma Castle	MOCA	18.13	High	28.52	High	Moderate
Organ Pipe Cactus	ORPI	14.05	High	16.13	High	Moderate
Saguaro	SAGU	11.91	Moderate	15.52	High	Low
Tonto	TONT	17.89	High	28.08	High	Moderate
Tumacacori	TUMA	11.34	Moderate	14.19	Moderate	Low
Tuzigoot	TUZI	18.03	High	27.61	High	Low

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

² Parks larger than 100 mi² (also in bold).

Kohut's approach constitutes a rigorous assessment of potential risk to plants. It considers both O₃ exposure and environmental conditions (soil moisture). Kohut also used injury thresholds from the literature, but evaluated a different O₃ metric (after Lefohn et al. 1997), the W126 over a 5-month period in conjunction with the N100 (number of hours over 100 ppb O₃). The rationale for the N100 statistic is that higher O₃ concentrations are most likely to cause plant injury. Kohut examined five individual years of O₃ exposure and soil moisture data and considered the effects of low soil moisture on O₃ uptake each year when assigning risk. Soil moisture is important because dry conditions induce stomatal closure in plants, which has the effect of limiting O₃ uptake and injury. In areas where low soil moisture levels correspond with high O₃ exposure, uptake and injury are limited by stomatal closure even when exposures are relatively high. Kohut's (2007) ranking was Low across all parks in this network.

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. The NPS approach considers more recent O₃ conditions, but not environmental conditions.

Visibility Impairment

Natural Background and Ambient Visibility Conditions

The Clean Air Act set a specific goal for visibility protection in Class I areas: “the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I federal areas which impairment results from manmade air pollution” (42 U.S.C. 7491). In 1999, EPA passed the Regional Haze Rule (RHR), which requires each state to develop a plan to improve visibility in Class I areas, with the goal of returning visibility to natural conditions in 2064. CHIR and SAGU are Class I parks; the other SODN parks are Class II parks but are expected to benefit from visibility improvements at Class I areas.

Natural background visibility 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 (IMPROVE) Network. IMPROVE samplers use filters to collect the fine particles of air pollution that cause haze and impair visibility. Visibility conditions are estimated based on the types and amounts of fine particles and are typically reported using the haze index deciview (dv)¹.

IMPROVE monitors are located in CHIR (monitor CHIR1, operated by NPS), GICL (GICL1 – U.S. Forest Service), ORPI (ORPI1- Arizona Department of Environmental Quality), SAGU (SAGU East – SAGU1 – NPS; SAGU West – SAWE1 – Arizona Department of Environmental Quality), and TONT (TONT1 - U.S. Forest Service). Data are also available that are considered to be representative of visibility conditions in three of the other parks, CAGR (monitor PHOE1), FOBO (monitor CHIR1), and TUMA (monitor SAGU1). 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. The large number of visibility monitoring stations in the SODN reflect the importance placed on visibility for visitor enjoyment of parks in this network.

Current visibility estimates reflect current air pollution levels and provide park managers with information on spatial differences in visibility and air pollution. Data from IMPROVE show that visibility impairment caused by air pollution is widespread at most national park and wilderness area monitoring stations. To evaluate visibility conditions over time and space, IMPROVE compares conditions on two groups of days, the 20% clearest and the 20% haziest days. Tables 7a and 7b give estimated natural haze levels and recent, or current, levels on the 20% clearest, 20% haziest, and average days. Current haze levels at SODN parks are substantially elevated above estimated natural haze levels.

¹ The *deciview* visibility metric expresses uniform changes in haziness in terms of common increments across the entire range of visibility conditions, from pristine to extremely hazy conditions. Because each unit change in deciview represents a common change in perception, the deciview scale is like the decibel scale for sound. A one deciview change in haziness is a small but noticeable change in haziness under most circumstances when viewing scenes in Class I areas.

Table 7a. Estimated natural haze in I&M parks averaged over the period 2004 through 2008.

Park Name	Park Code	Site ID	Estimated Natural Haze (dv)		
			20% Clearest Days	20% Hazeiest Days	Average Days
Casa Grande Ruins ²	CAGR	PHOE1	3.31	7.16	4.92
Chiricahua	CHIR	CHIR1	1.83	7.20	3.95
Coronado	CORO	No Site	—	—	—
Fort Bowie ²	FOBO	CHIR1	1.83	7.20	3.95
Gila Cliff Dwellings	GICL	GICL1	0.52	6.66	3.04
Montezuma Castle	MOCA	No Site	—	—	—
Organ Pipe Cactus¹	ORPI	ORPI1	3.01	7.26	4.78
Saguaro - East¹	SAGU	SAGU1	2.23	6.46	4.05
Saguaro - West¹	SAGU	SAWE1	2.50	6.24	4.12
Tonto	TONT	TONT1	2.03	6.54	3.99
Tumacácori ²	TUMA	SAGU1	2.23	6.46	4.05
Tuzigoot	TUZI	No Site	—	—	—

¹ Parks larger than 100 mi² (also in bold).

² Data are borrowed from a nearby IMPROVE site. 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.

Table 7b. Measured ambient haze in I&M parks averaged over the period 2004 through 2008.

Park Name	Park Code	Site ID	Measured Ambient Haze (dv; For Years 2004 through 2008)		
			20% Clearest Days	20% Hazeiest Days	Average Days
Casa Grande Ruins ²	CAGR	PHOE1	12.61	24.47	17.73
Chiricahua	CHIR	CHIR1	4.40	12.33	8.08
Coronado	CORO	No Site	—	—	—
Fort Bowie ²	FOBO	CHIR1	4.40	12.33	8.08
Gila Cliff Dwellings	GICL	GICL1	2.86	12.52	7.05
Montezuma Castle	MOCA	No Site	—	—	—
Organ Pipe Cactus¹	ORPI	ORPI1	6.79	13.83	10.23
Saguaro - East¹	SAGU	SAGU1	6.77	13.59	10.27
Saguaro - West¹	SAGU	SAWE1	8.11	14.91	11.60
Tonto	TONT	TONT1	5.80	13.86	9.83
Tumacácori ²	TUMA	SAGU1	6.77	13.59	10.27
Tuzigoot	TUZI	No Site	—	—	—

¹ Parks larger than 100 mi² (also in bold).

² Data are borrowed from a nearby IMPROVE site. 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.

In addition to the IMPROVE samplers, cameras have been used to illustrate visibility conditions. Representative photos of selected vistas under differing visibility conditions are shown in Figures 1a and 1b for CHIR and TONT. 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 these parks.

IMPROVE data allow estimation of visual range (VR), a measurement more easily understood by many park visitors than d_v or b_{ext} . Data indicate that in CHIR (site CHIR1), air pollution has reduced average VR from 160 to 95 miles (258 to 153 km). On the haziest days, VR has been reduced from 110 to 60 miles (177 to 97 km). Severe haze episodes occasionally reduce visibility to 20 miles. At GICL (site GICL1) 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 12 miles (19 km). At ORPI (site ORPI1), air pollution has reduced average VR from 150 to 85 miles (241 to 137 km). On the haziest days, VR has been reduced from 120 to 55 miles (193 to 89 km). Severe haze episodes occasionally reduce visibility to 20 miles (32 km). At SAGU (site SAGU1), air pollution has reduced average VR from 160 to 80 miles (258 to 129 km). On the haziest days, VR has been reduced from 130 to 50 miles (209 to 81 km). Severe haze episodes occasionally reduce visibility to 22 miles (35 km). At TONT (site TONT1), air pollution has reduced average VR from 160 to 85 miles (258 to 137 km). On the haziest days, VR has been reduced from 120 to 55 miles (193 to 89 km). Severe haze episodes occasionally reduce visibility to 14 miles (23 km).

20% Clearest Days

Taken: 9:00 AM

Haze = 4 dv

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

VR = 275 km

**20% Haziest Days**

Taken: 9:00 AM

Haze = 12 dv

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

VR = 115 km

**Average Days**

Taken: 9:00 AM

Haze = 8 dv

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

VR = 180 km



Figure 1a. Three representative photos of the same view in Chiricahua (CHIR) illustrating the 20% clearest visibility (top), the 20% haziest visibility (middle), and the annual average visibility (bottom) in deciviews (dv). 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 light extinction 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. Top: 20% clearest days, taken at 9:00 AM., haze = 4dv, $B_{\text{ext}} = 14 \text{ Mm}^{-1}$, VR = 275 km. Middle: 20% haziest days, taken at 9:00 AM, haze = 12 dv, $B_{\text{ext}} = 34 \text{ Mm}^{-1}$, VR = 115 km. Bottom: average days, haze = 8 dv, $B_{\text{ext}} = 22 \text{ Mm}^{-1}$, VR = 180 km.

20% Clearest Days

Taken: 9:00 AM

Haze = 5 dv

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

VR = 240 km



20% Haziest Days

Taken: 9:00 AM

Haze = 14 dv

$B_{\text{ext}} = 39 \text{ Mm}^{-1}$

VR = 100 km



Average Days

Taken: 9:00 AM

Haze = 10 dv

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

VR = 150 km



Figure 1b. Three representative photos of the same view in Tonto (TONT) illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility in deciviews (dv). 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 light extinction 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. Top: 20% clearest days, taken at 9:00 AM., haze = 5dv, $B_{\text{ext}} = 16 \text{ Mm}^{-1}$, VR = 240 km. Middle: 20% haziest days, taken at 9:00 AM, haze = 14 dv, $B_{\text{ext}} = 39 \text{ Mm}^{-1}$, VR = 100 km. Bottom: average days, haze = 10 dv, $B_{\text{ext}} = 26 \text{ Mm}^{-1}$, VR = 150 km.

Composition of Haze

Various pollutants make up the haze that causes visibility impairment². IMPROVE measures these pollutants and reports them as ammonium sulfate, ammonium nitrate, elemental carbon, 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, and fires. Organic compounds are emitted from a variety of both natural (biogenic) and anthropogenic sources, including agriculture, industry, oil and gas development, and fires. Atmospheric sea salt concentrations are higher in coastal areas. Soil can enter the atmosphere through both natural processes and human disturbance.

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

The major contributors to the total particulate b_{ext} in most of these parks were sulfate, nitrate, coarse mass and organics (Figures 2a-2g).

² *Visibility impairment* means any humanly perceptible change in visibility (light extinction, visual range, contrast, coloration) from that which would have existed under natural conditions.

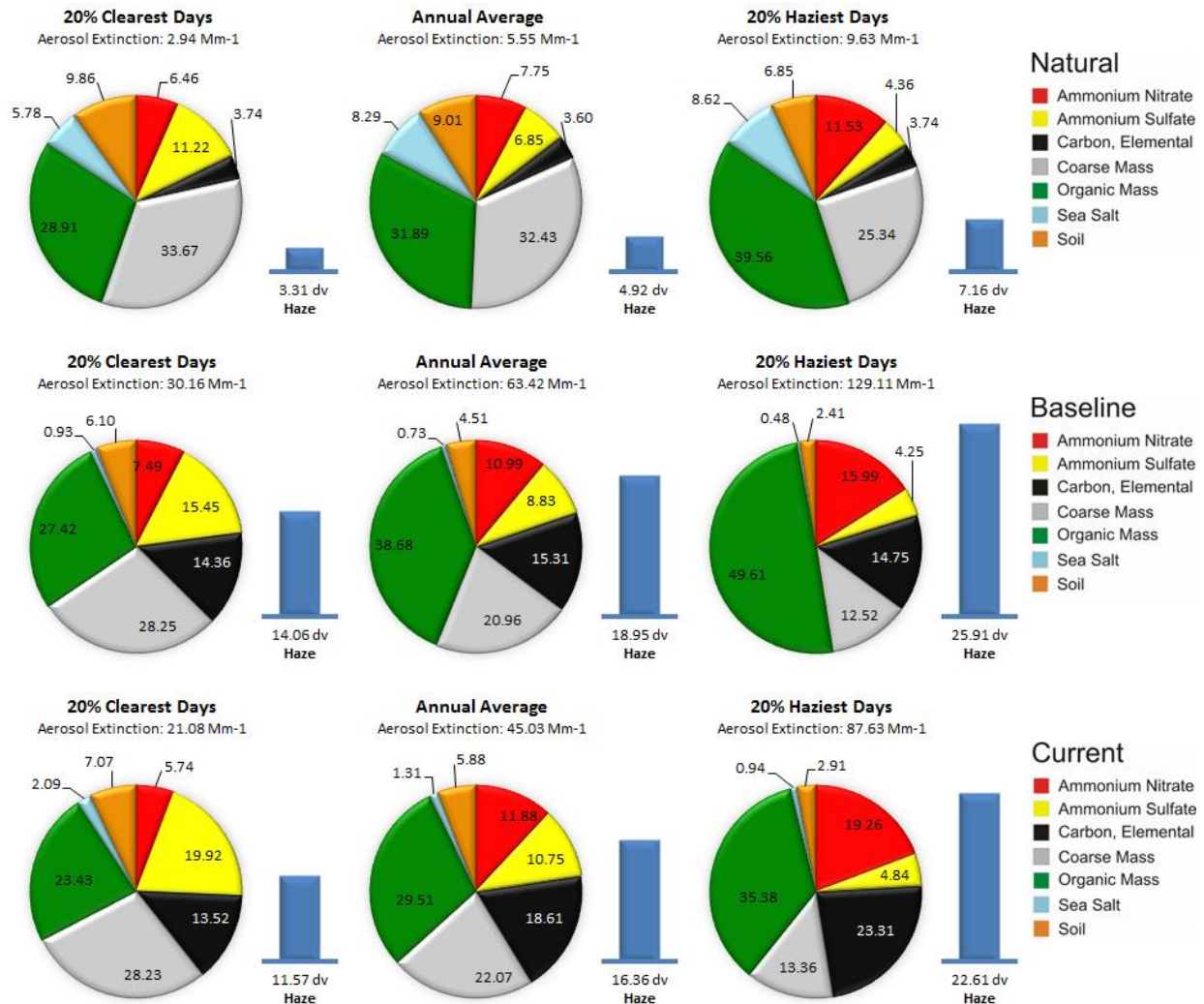


Figure 2a. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for CAGR (PHOE1). Data for CAGR, FOBO, and TUMA were taken from nearby sites. (Data Source: NPS-ARD)

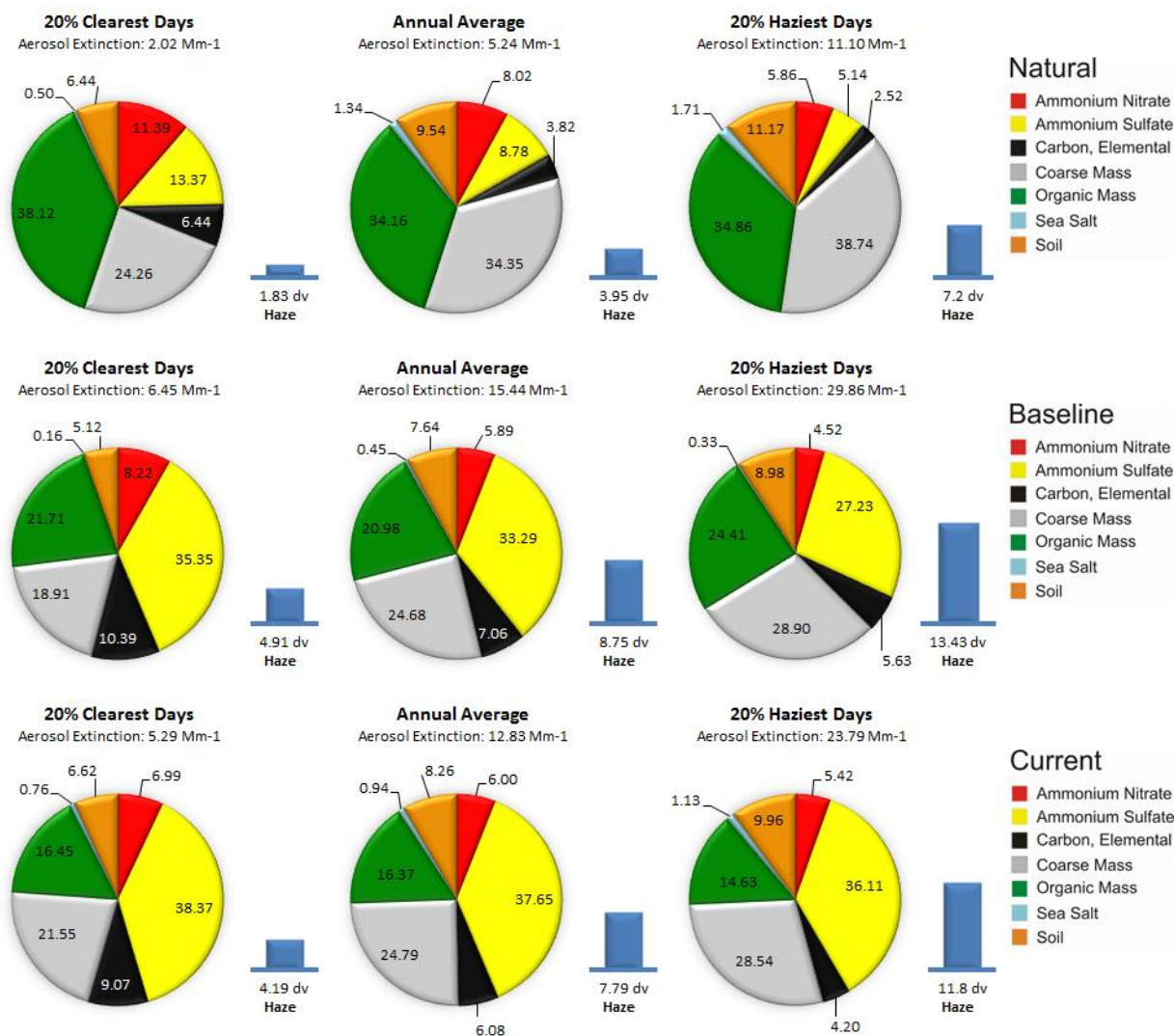


Figure 2b. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for CHIR and FOBO. Data for CAGR, FOBO, and TUMA were taken from nearby sites. (Data Source: NPS-ARD)

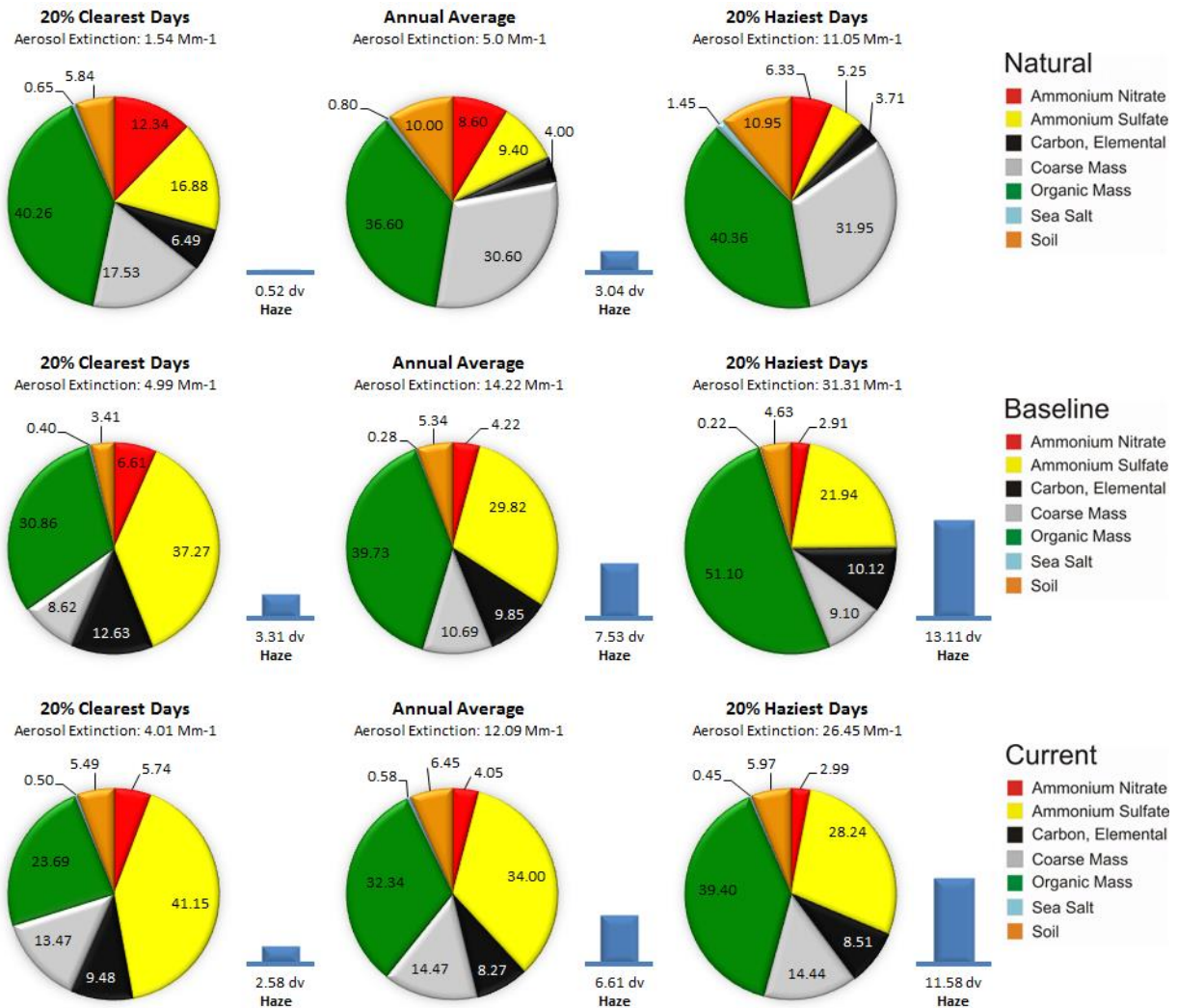


Figure 2c. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for GICL. (Data Source: NPS-ARD)

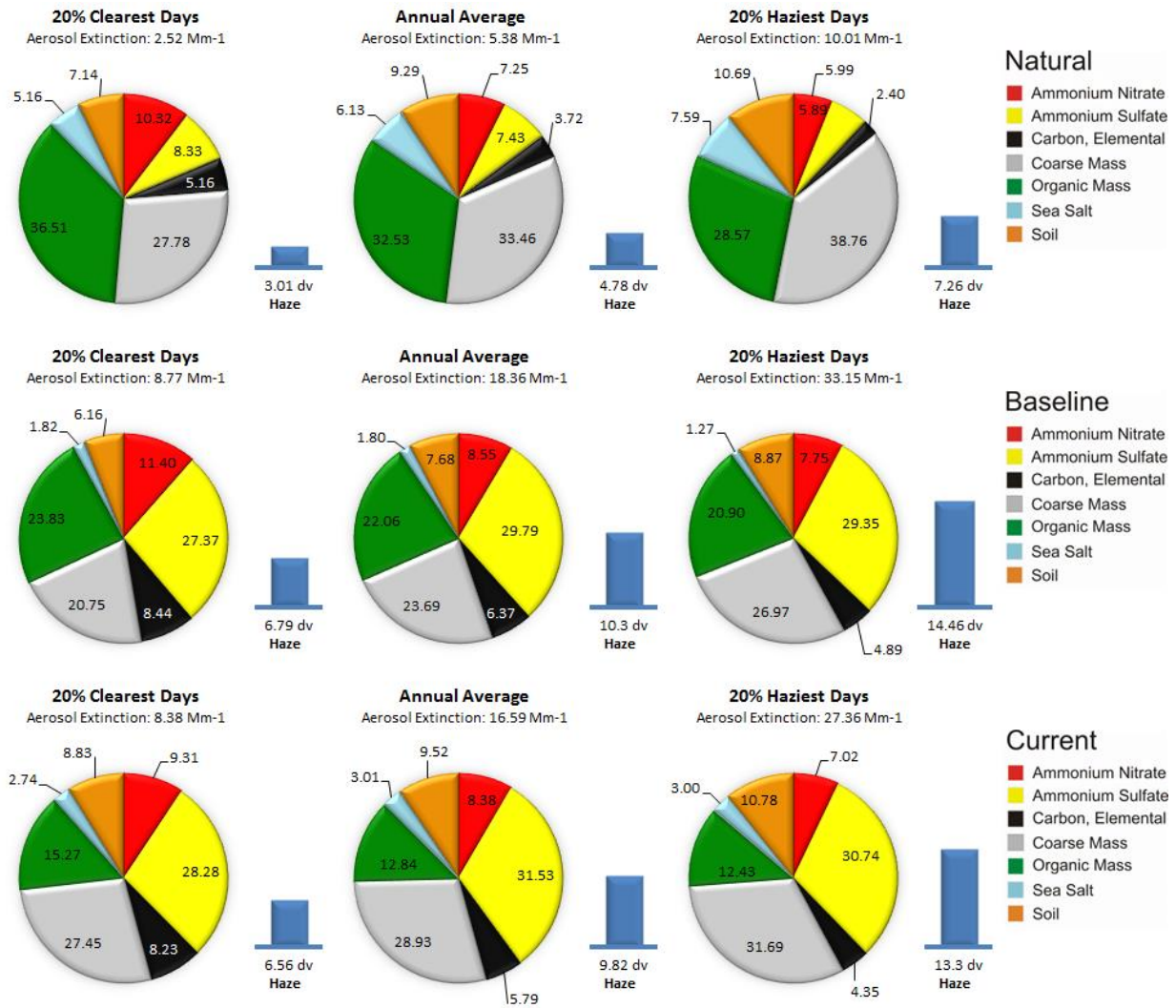


Figure 2d. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for OPRI. (Data Source: NPS-ARD)

SAGU-East (SAGU1; also TUMA)

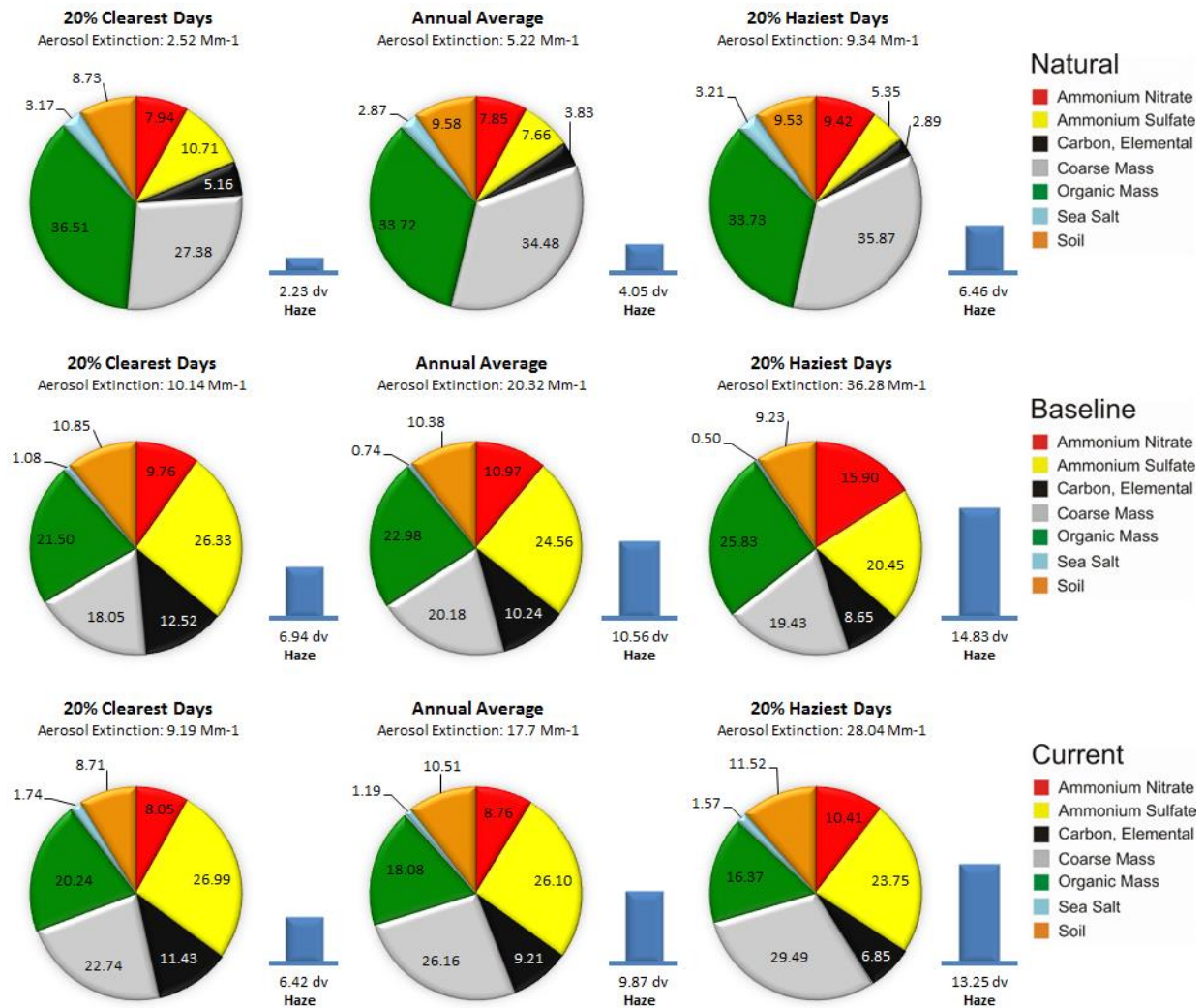


Figure 2e. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for SAGU-East (SAGU1) and TUMA. Data for CAGR, FOBO, and TUMA were taken from nearby sites. (Data Source: NPS-ARD)

SAGU-West (SAWE1)

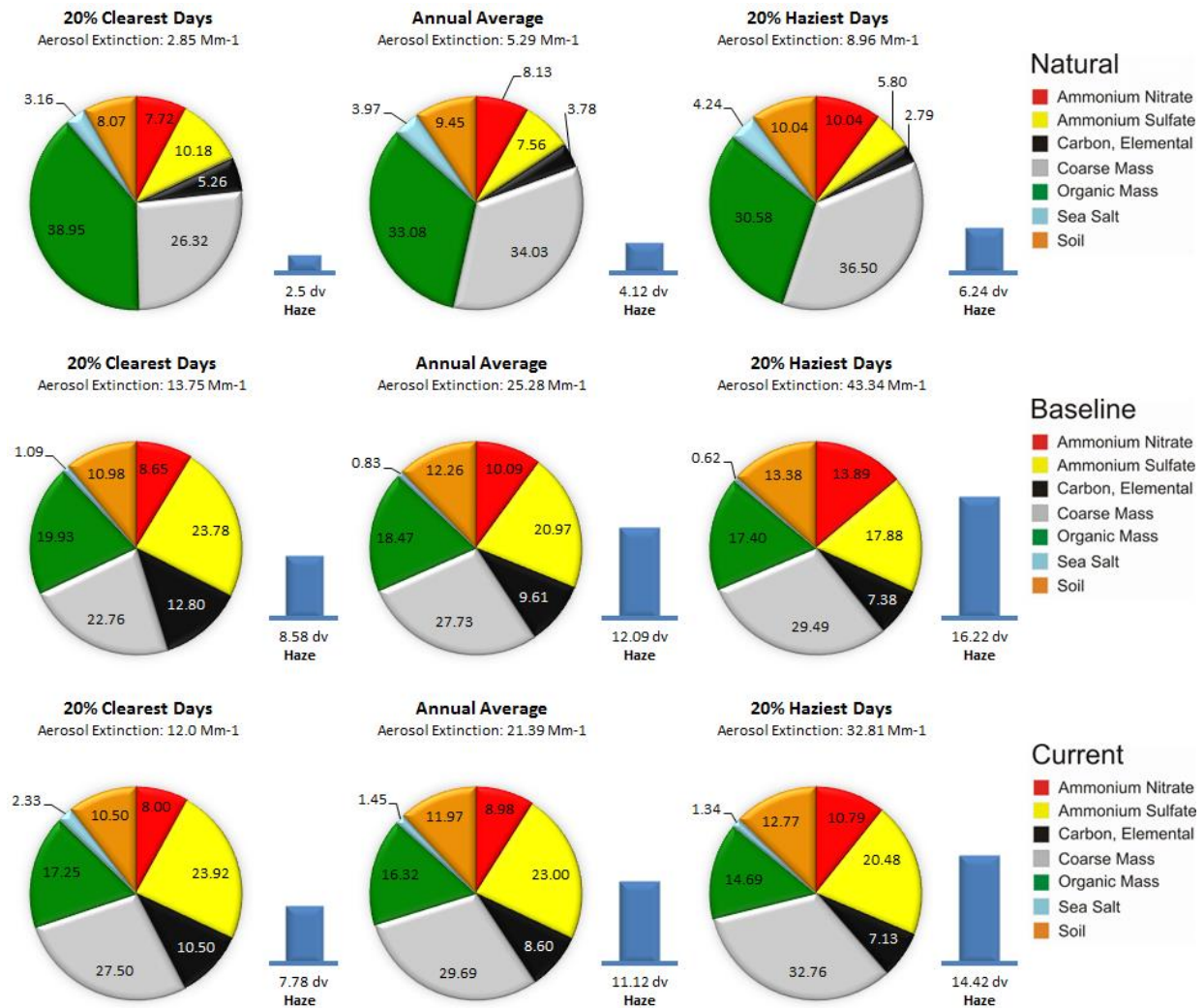


Figure 2f. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for SAGU-West (SAWE1). (Data Source: NPS-ARD)

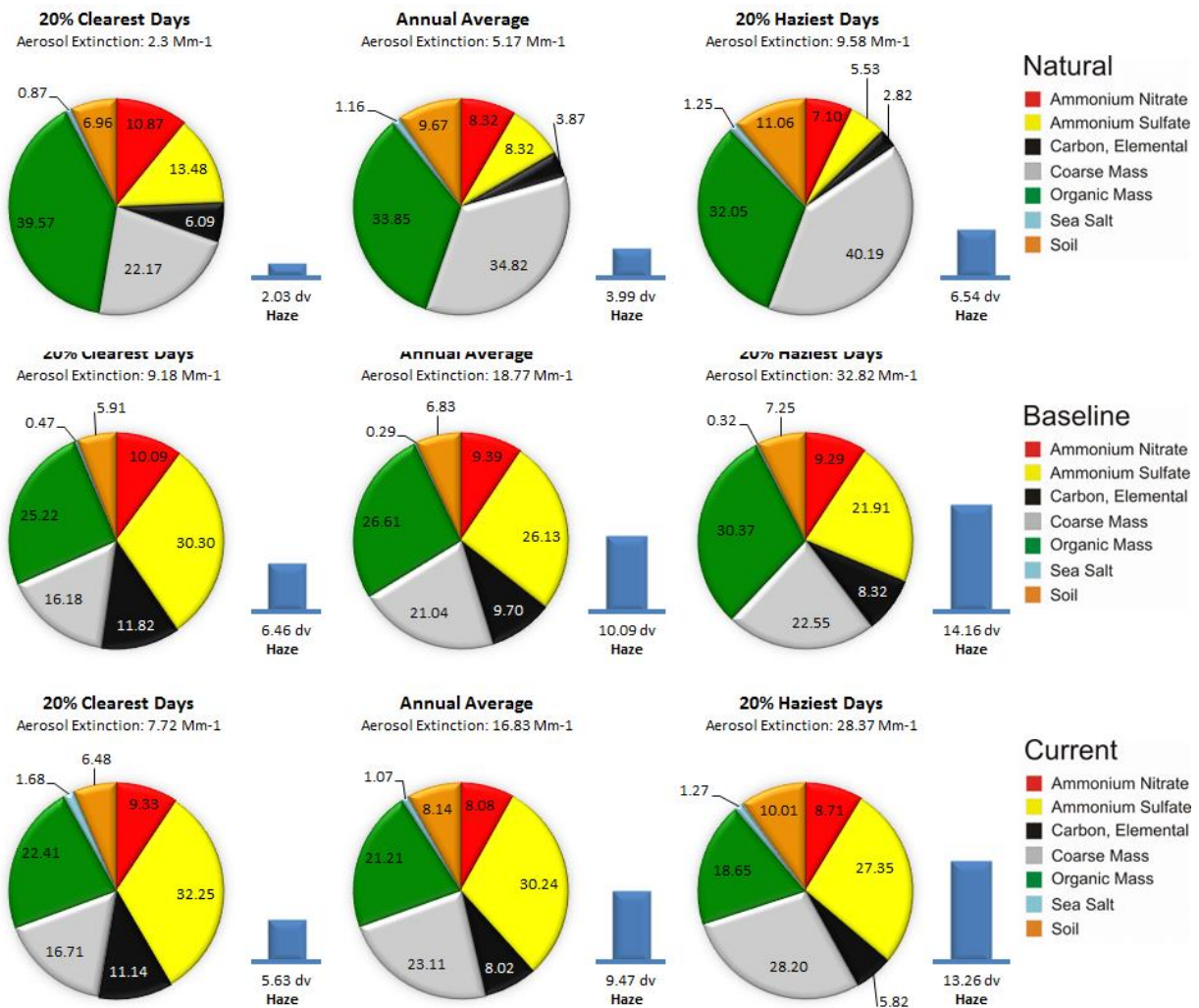


Figure 2g. Estimated natural (pre-industrial), baseline (2000-2004), and more recent (2006-2010) levels of haze in deciviews (dv - blue columns) and light extinction (aerosol extinction) in inverse megameters (Mm⁻¹) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for TONT. (Data Source: NPS-ARD)

Sources of Visibility Impairment in the SODN

Analyses conducted by the Western Regional Air Partnership (WRAP) indicated that a variety of air pollution sources, both anthropogenic and natural, contribute to visibility impairment throughout the western United States, including within the SODN. In addition to many sources in the U.S., air pollution sources outside the western U.S., 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).

The WRAP has provided technical assistance for Western states in developing their plans to meet the requirements of the Regional Haze Rule. The WRAP has conducted regional modeling to identify what type of pollution sources are affecting visibility in Class I areas, and where that pollution is coming from. Source regions include WRAP (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., powerplants, smelters), Area (e.g., oil and gas development), Mobile (e.g., vehicles), Anthropogenic Fires (prescribed burns), and Natural Fires and Biogenic Sources. The following sections show regional contributions to atmospheric 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 SODN, 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 2018. Although WRAP also modeled contributions for the best 20% visibility days, this assessment focuses 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 reductions at some point sources and increases due to activities like oil and gas exploration, development, and production. Updates to emissions inventories are underway and will be used to improve current estimates and to improve modeled projections of future conditions.

The West-Wide Jump-Start Air Quality Modeling Study (WestJump) updated the 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 in the following sections. 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 significant, and in some cases major, contributors at times to haze and visibility impairment in the SODN 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 problematical for States and Federal Land Managers, as prescribed burns, while contributing to visibility impairment, are needed to improve and maintain forest health and to avoid more catastrophic wildfires.

Chiricahua NM

Figure 3a shows regional contributions to sulfate on the worst 20% of days at CHIR 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 Mexico and the area outside the modeling domain identified as major source regions.

Figure 3b shows source type by region, including each of the WRAP States. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Point sources (e.g., power plants) contribute most to sulfate at CHIR. Mexico, the Eastern U.S., the Central U.S., and the Pacific Offshore region are significant source regions within the modeling domain.

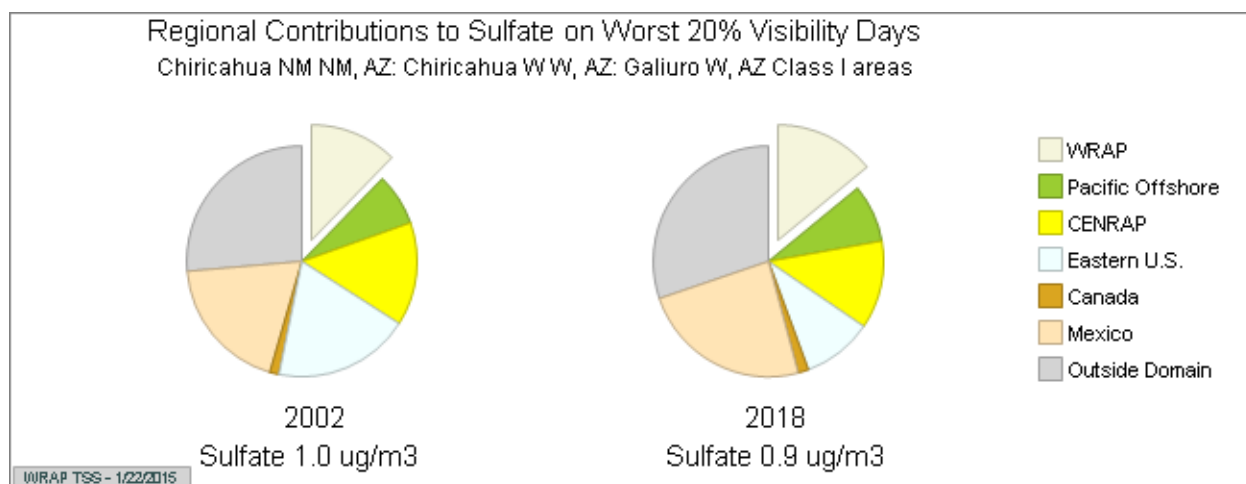


Figure 3a. Regional contributions to sulfate on worst 20% visibility days for CHIR. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

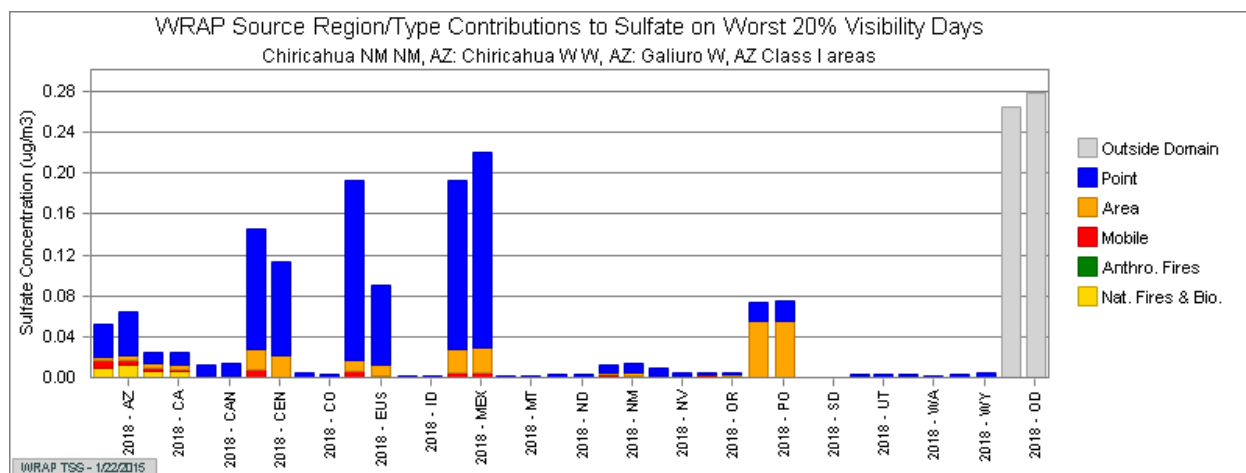


Figure 3b. WRAP source region/type contributions to sulfate on worst 20% visibility days for CHIR. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

Figure 4a shows that nitrate concentrations are projected to decrease from 2002 to 2018 at CHIR, and that sources in the WRAP region are primarily responsible for nitrate at CHIR. Figure 4b shows that mobile, point, and area sources all contribute to nitrate at CHIR, with sources in CA and AZ dominating. Each region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018.

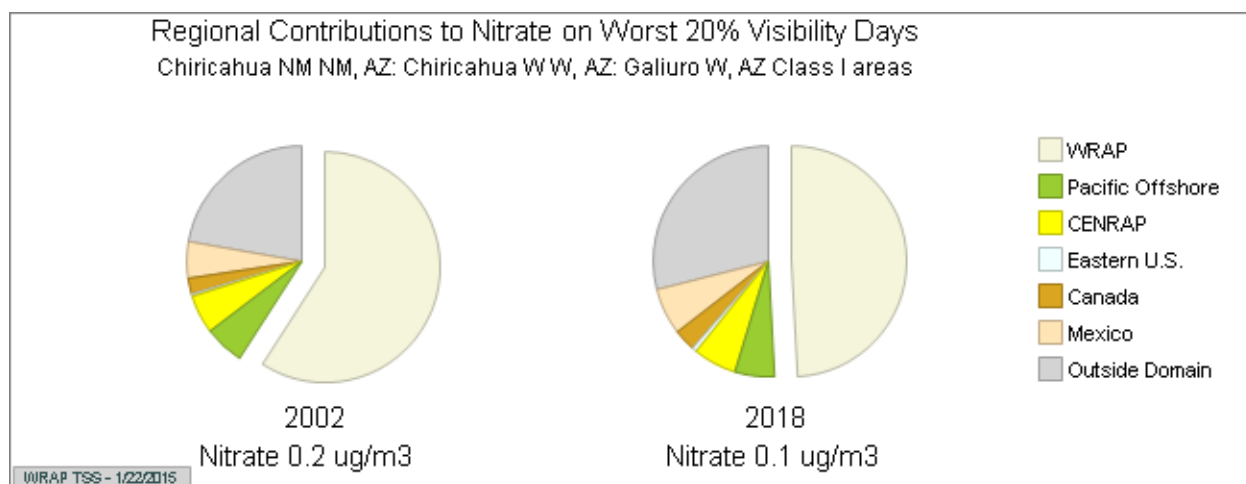


Figure 4a. Regional contributions to nitrate on worst 20% visibility days for CHIR. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

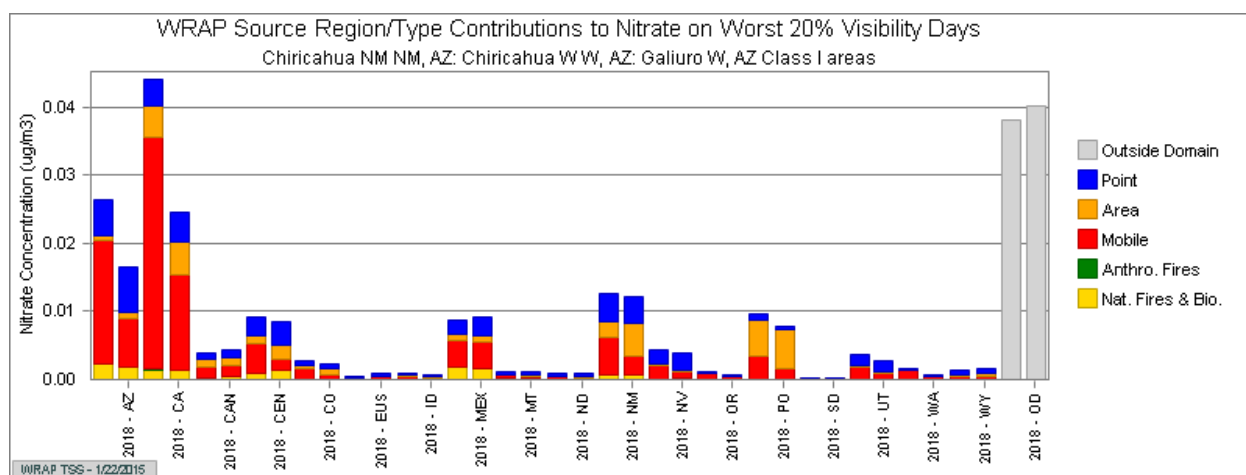


Figure 4b. WRAP source region/type contributions to nitrate on worst 20% visibility days for CHIR. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

Data from the WestJump emissions inventory found that about 70 percent of the pollutants that reduced visibility in CHIR in 2008 came from sources within the WRAP region. Although AZ was the largest contributor overall, TX contributed most to sulfate. Sulfate and nitrate contributed about equally, and in addition to organic and elemental carbon from prescribed fires and other sources, were the major controllable pollutants reducing visibility in CHIR (ENVIRON et al. 2013, Appendix O).

Saguaro NP

The SAGU1 IMPROVE monitor, located in the more remote eastern portion of the park (the Rincon Mountain District) is considered by IMPROVE to be the representative monitor for SAGU. Figure 5a shows regional contributions to sulfate on the worst 20% of days at SAGU1 in the base year of 2002 and the projected contributions in 2018. Sulfate in SAGU is attributed primarily to sources from both within the WRAP region, outside the modeling area (Outside Domain – OD), and in Mexico.

Figure 5b shows source type by region, including each of the WRAP States. Each source region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018. Point sources (e.g., power plants) within Mexico, the WRAP region, the Eastern and Central U.S., and the Pacific Offshore region are important contributors to sulfate at SAGU.

Figure 6a shows that sources within the WRAP region are primarily responsible for nitrate at SAGU. Figure 6b shows that mobile and point sources, primarily from AZ, are major contributors to nitrate at SAGU. Each source region is represented by two columns, one for 2002 (unlabeled) followed by one for 2018.

Data from the 2008 WestJump emissions inventory found that about 80 percent of the pollutants that reduced visibility at SAGU came from sources within the WRAP region, mainly AZ. Nitrate was a larger contributor to haze than sulfate, but together with organic and elemental carbon from prescribed fires and other sources were the major controllable pollutants reducing visibility in SAGU (WRAP 2013).

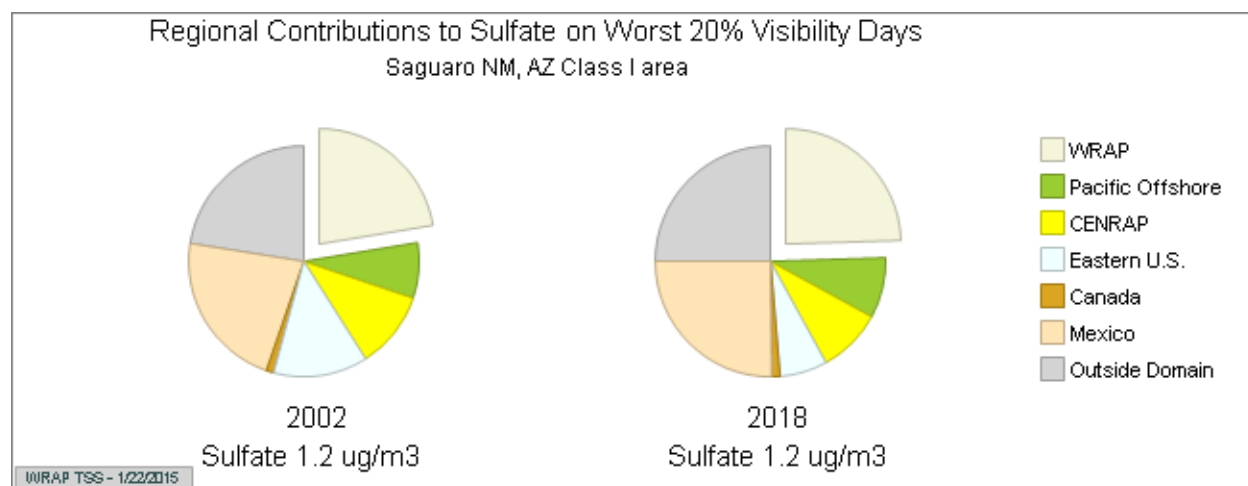


Figure 5a. Regional contributions to sulfate on worst 20% visibility days for SAGU. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

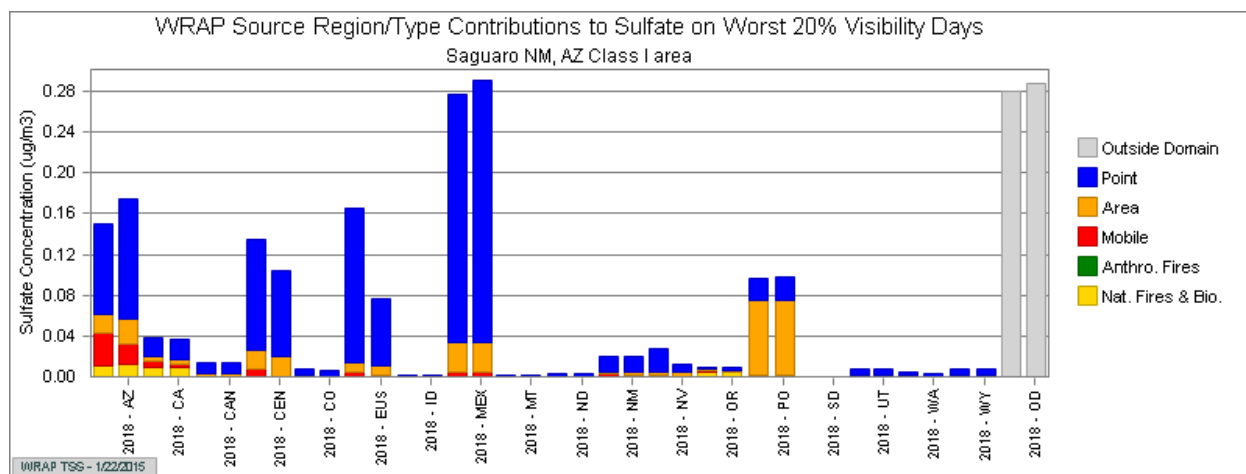


Figure 5b. WRAP source region/type contributions to sulfate on worst 20% visibility days for SAGU. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

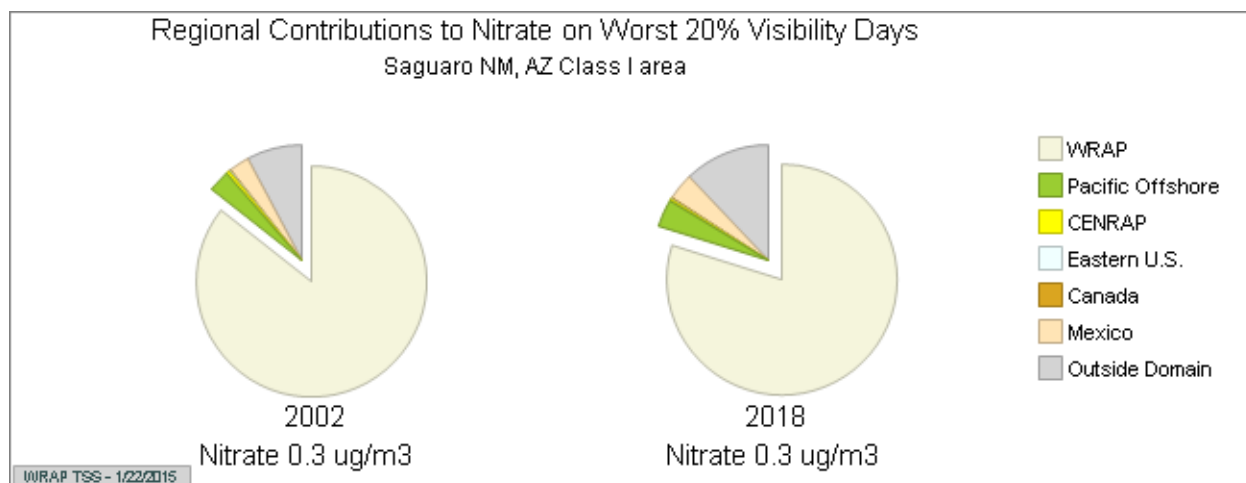


Figure 6a. Regional contributions to nitrate on worst 20% visibility days for SAGU. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

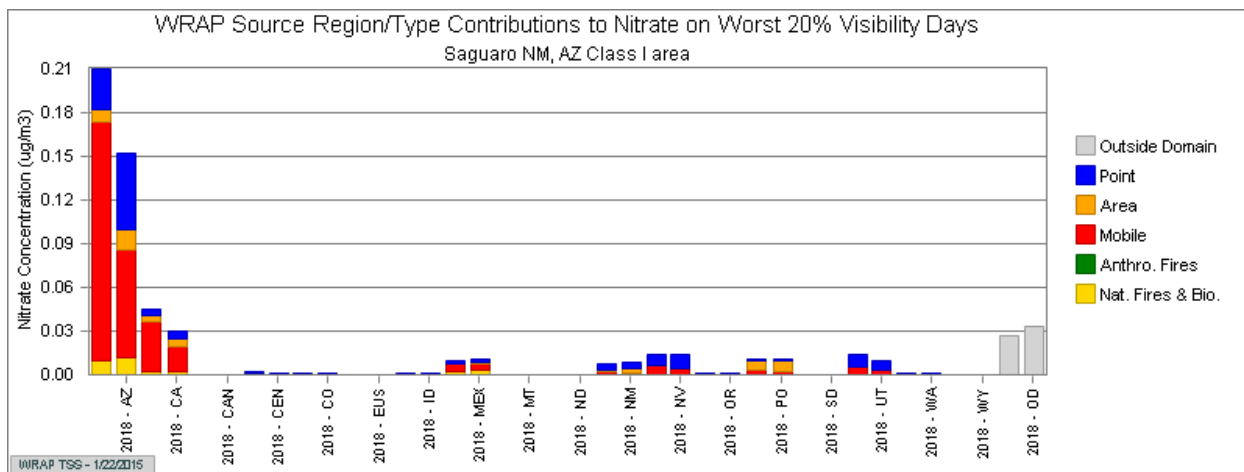


Figure 6b. WRAP source region/type contributions to nitrate on worst 20% visibility days for SAGU. (Source: WRAP TSS (technical support system) at vista.cira.colostate.edu/tss)

Trends in Visibility

IMPROVE long-term trend data are available for CHIR (1990-2013) and SAGU (SAGU1, 1990-2013). Trends are shown in Figures 7a-7d for the 20 percent clearest and haziest days. Visibility improved significantly on both the 20 percent clearest days and the haziest days at both parks.

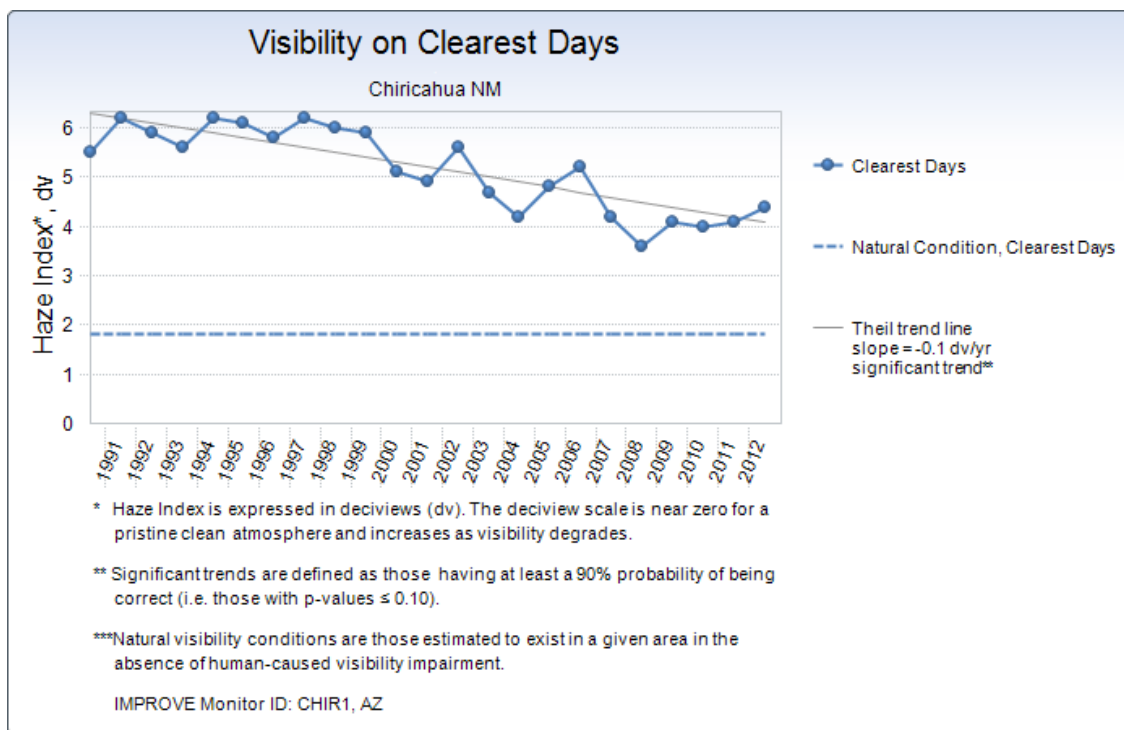


Figure 7a. Trends in ambient haze levels at CHIR, based on IMPROVE measurements on the 20% clearest days over the monitoring period of record. (Source: at <http://views.cira.colostate.edu/fed/AgrVMenu.aspx>)

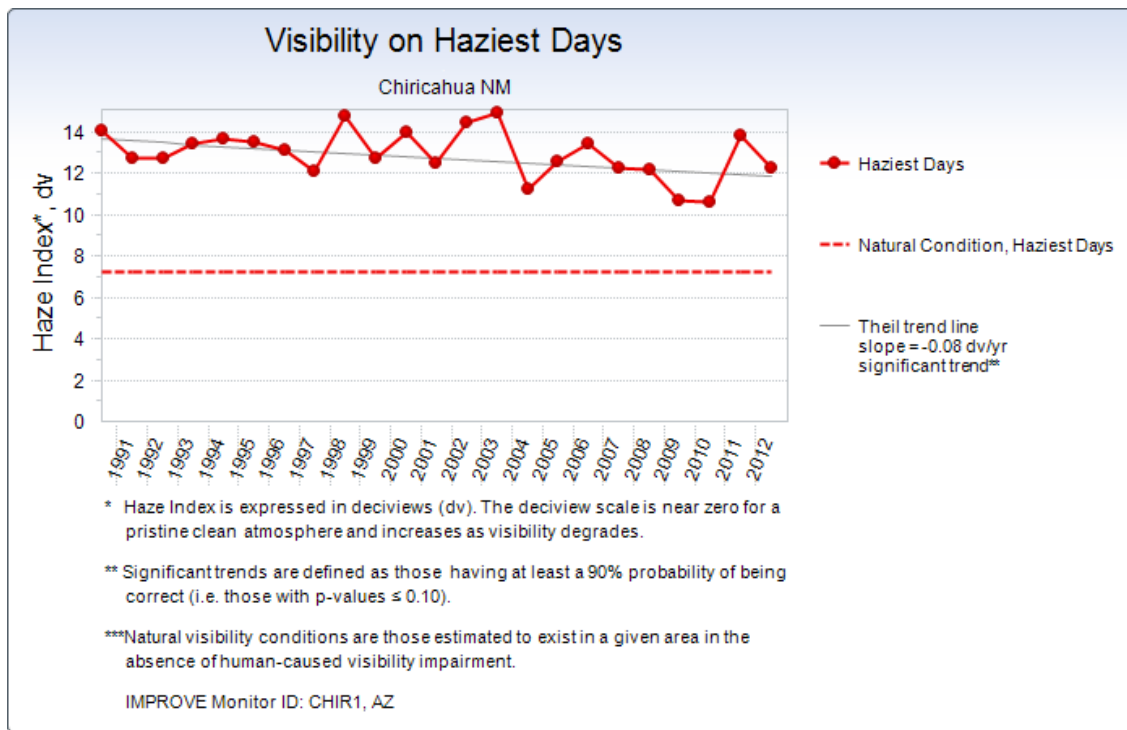


Figure 7b. Trends in ambient haze levels at CHIR, based on IMPROVE measurements on the 20% haziest days over the monitoring period of record. (Source: at <http://views.cira.colostate.edu/fed/AqrvMenu.aspx>)

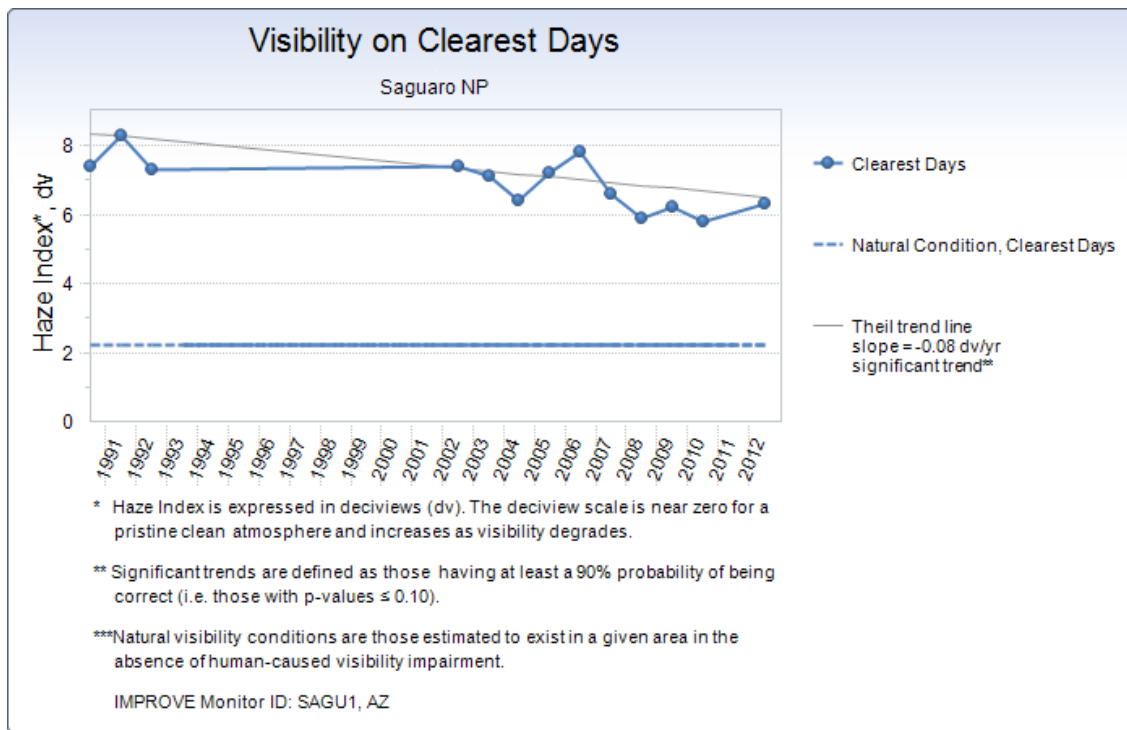


Figure 7c. Trends in ambient haze levels at SAGU, based on IMPROVE measurements on the 20% clearest days over the monitoring period of record. (Source: at <http://views.cira.colostate.edu/fed/AgrvMenu.aspx>)

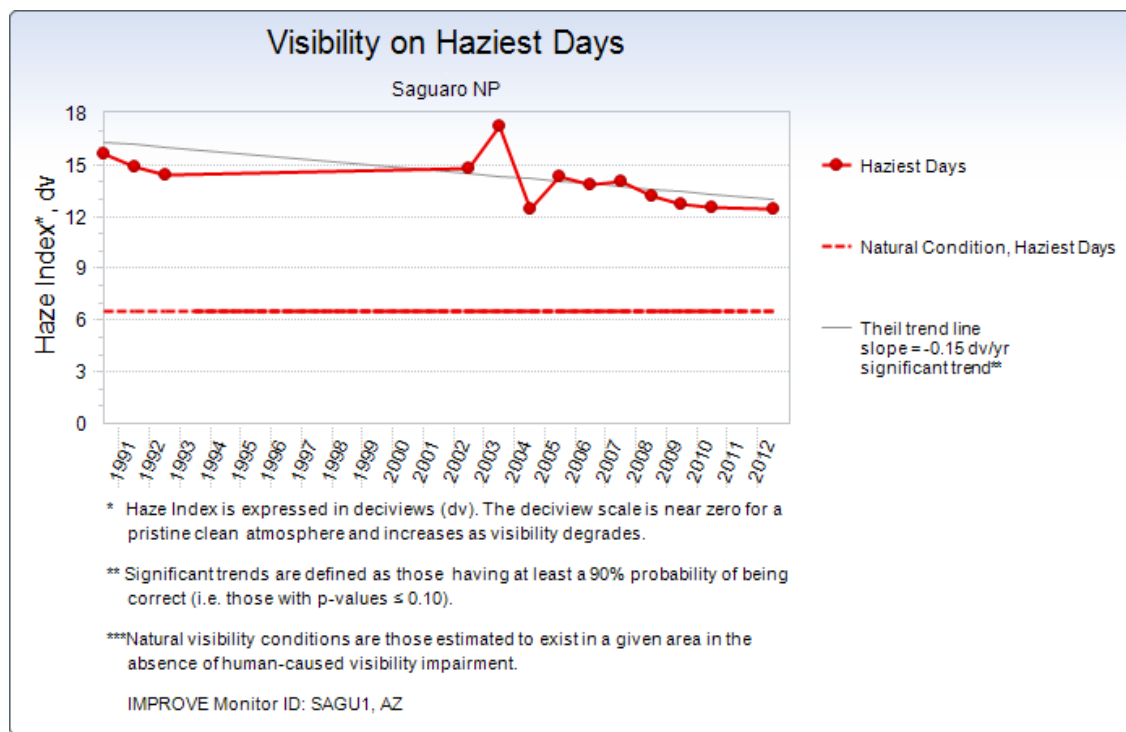


Figure 7d. Trends in ambient haze levels at SAGU, based on IMPROVE measurements on the 20% haziest days over the monitoring period of record. (Source: at <http://views.cira.colostate.edu/fed/AgrvMenu.aspx>)

Development of State Implementation Plans

According to the RHR, promulgated in 1999, 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 in 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 requirement of the RHR. Because of this requirement, major emissions reductions have been made by power plants (electric generating units), and many more are anticipated from sources impacting the SODN region. Figures 8a and 8b shows trends in SO_2 and NO_x emissions from two large power plants (generating stations) in AZ including the Apache Generating Station (Arizona Electric Power Cooperative), west of CHIR, and the Irvington Generating Station (Tucson Electric Power), west of SAGU. The moderate reductions seen from 2000-2014 will 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.

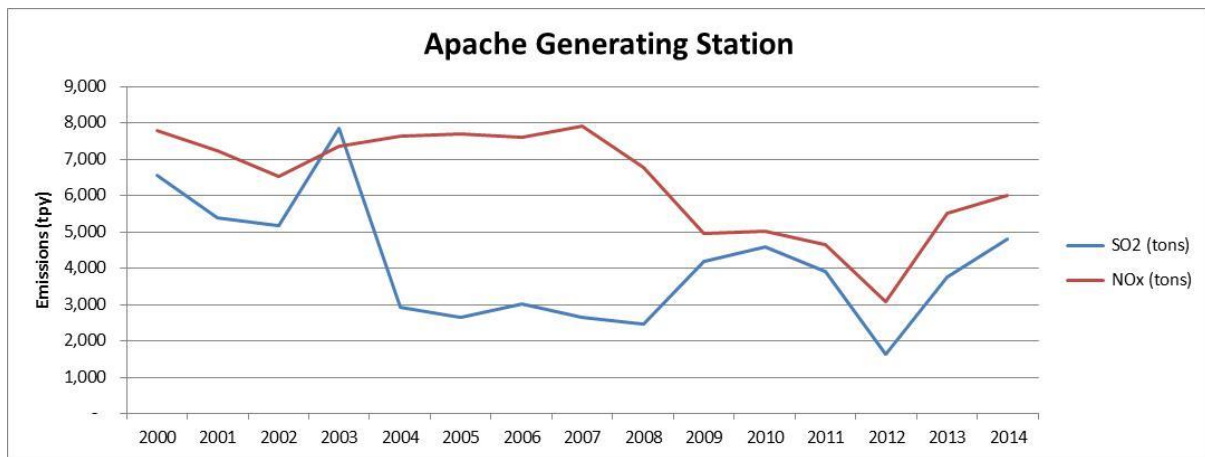


Figure 8a. Trends in sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions (in tons per year – tpy) at the Apache Generating Station in southern Arizona from 2000-2014 (pers. comm. Don Shepherd, NPS ARD 2015).

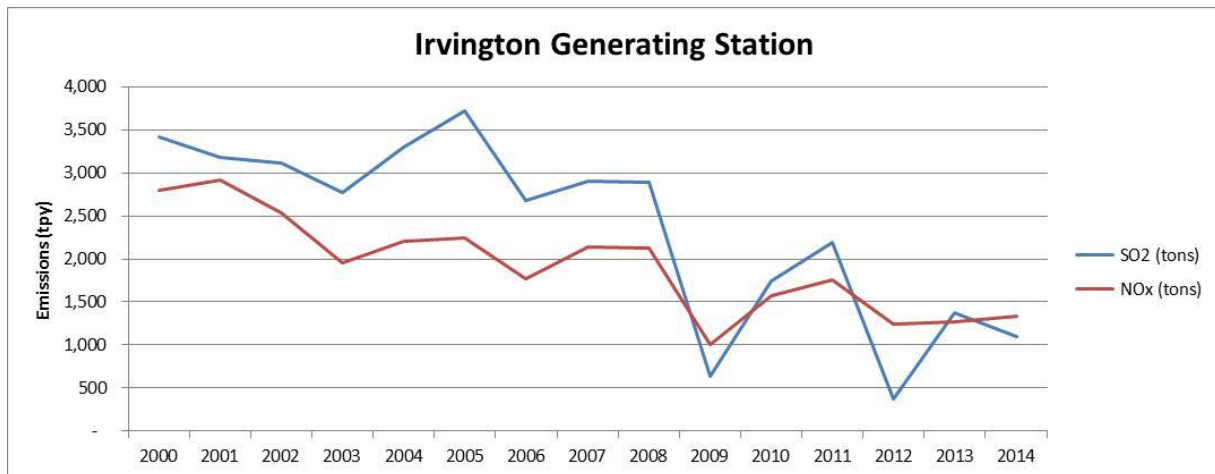


Figure 8b. Trends in sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions (in tons per year – tpy) at the Irvington Generating Station in southern Arizona from 2000-2014 (pers. comm. Don Shepherd, NPS ARD 2015).

Table 8 gives estimates of visibility at CHIR and SAGU 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 has estimated that, for these two parks, natural conditions will not be reached for hundreds of years, suggesting that additional reductions from many sources will be needed (U.S. EPA 2014) .

Table 8. Estimates of natural and baseline (2000-2004) and projected 2018 visibility on the 20% clearest and haziest days at Chiricahua NM and Saguaro NP (East and West Units), as well as the estimated years to natural conditions on the haziest days given actual and anticipated emissions reductions in the region (Data for natural, baseline, and projected 2018 visibility from WRAP at <http://vista.cira.colostate.edu/tss/Results/HazePlanning.aspx>; estimated years to natural conditions from U.S. EPA (2014).

Park Name	20% Clearest Days (dv)			20% Haziest Days (dv)			Years to Natural Conditions
	Baseline	2018	Natural	Baseline	2018	Natural	
Chiricahua	4.91	4.77	1.83	13.43	13.19	7.20	367
Saguaro East	6.94	6.93	2.23	14.83	14.68	6.46	767
Saguaro West	8.58	8.23	2.50	16.22	15.87	6.24	397

Toxic Airborne Contaminants

Airborne toxics include heavy metals, such as mercury (Hg), and semivolatile organics, such as industrial byproducts and pesticides. When deposited into ecosystems, these chemicals can accumulate in organisms and reach toxic levels in fish and wildlife.

When Hg is deposited to an ecosystem, ecosystem conditions may facilitate methylation of Hg from its inorganic form to the more toxic organic form, methylmercury. Methylmercury readily bioaccumulates in food chains, reaching toxic levels in fish and wildlife. Methylation most commonly occurs in wetlands, reservoirs, and riverine systems. Atmospheric deposition of Hg from coal-burning power plants has been identified as a major source of Hg to remote ecosystems (Landers et al. 2008). Because of the size and number of coal-burning power plants in the SODN region, Hg poses a potential threat to ecosystems in the parks, and may affect amphibians, invertebrates, and/or other wildlife that depend on rock pools, springs, and riparian areas. Although Hg is not monitored in the SODN parks, data from the Mercury Deposition Network for other southwestern U.S. areas suggest that concentrations of Hg in rainfall are relatively high in the region. Eagles-Smith et al. (2014) examined fish from 21 national parks in the western U.S., including Capitol Reef NP and Zion NP in Utah. In those two parks, speckled dace contained levels of Hg exceeding levels associated with biochemical and reproductive effects in fish and reproductive impairment in birds (Eagles-Smith et al. 2014).

Other airborne contaminants pose risks to biota in SODN parks. These include persistent organic pollutants and other semivolatile organic compounds (SOCs) such as pesticides, industrial and urban use compounds, and polycyclic aromatic hydrocarbon combustion products (Landers et al. 2010). Information regarding the levels of SOC contaminants in SODN parks is not available.

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