



Air Quality Related Values (AQRVs) for Greater Yellowstone Network (GRYN) Parks

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

Natural Resource Report NPS/GRYN/NRR—2016/1168



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

Air Quality Related Values (AQRVs) for Greater Yellowstone Network (GRYN) Parks

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

Natural Resource Report NPS/GRYN/NRR—2016/1168

Timothy J. Sullivan
P.O. Box 609
Corvallis, OR 97339

January 2016

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the E&S Environmental Chemistry website (www.esenvironmental.com) and the Natural Resource Publications Management website (<http://www.nature.nps.gov/publications/nrpm/>). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Sullivan, T. J. 2016. Air quality related values (AQRVs) for Greater Yellowstone Network (GRYN) parks: Effects from ozone; visibility reducing particles; and atmospheric deposition of acids, nutrients and toxics. Natural Resource Report NPS/GRYN/NRR—2016/1168. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures.....	iv
Tables.....	iv
Maps.....	v
Summary	vi
Background.....	1
Atmospheric Emissions and Deposition	2
Acidification	8
Acidification of Terrestrial Ecosystems	13
Acidification of Aquatic Ecosystems	13
Temporal Variability in Water Chemistry.....	16
Effects on Aquatic Biota	17
Nutrient Enrichment.....	18
Ozone Injury to Vegetation.....	21
Visibility Degradation.....	24
Natural Background and Ambient Visibility Conditions	24
Composition of Haze	25
Trends in Visibility.....	28
Development of State Implementation Plans	28
Toxic Airborne Contaminants.....	29
References Cited	36

Figures

	Page
Figure 1 Three representative photos of the same view in YELL illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility. B_{ext} is total particulate light extinction; VR is the visual range.....	27
Figure 2a. Estimated natural, baseline; and current levels of haze and its composition on the 20% clearest, annual average, and 20% haziest visibility days for BICA	30
Figure 2b. Estimated natural, baseline; and current levels of haze and its composition on the 20% clearest, annual average, and 20% haziest visibility days for GRTE.	31
Figure 2c. Estimated natural, baseline; and current levels of haze and its composition on the 20% clearest, annual average, and 20% haziest visibility days for YELL.....	32
Figure 3. Trends in ambient haze levels at BICA, GRTE, and YELL, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record.....	33
Figure 4. Glideslopes to achieving natural visibility conditions in 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in BICA, GRTE, and YELL.....	34

Tables

	Page
Table 1. Average changes in S and N deposition between 2001 and 2011 across park grid cells at GRYN parks	12
Table 2. Estimated I&M park rankings ¹ according to risk of acidification impacts on sensitive receptors.....	12
Table 3. Estimated park rankings ¹ according to risk of nutrient enrichment impacts on sensitive receptors.....	19
Table 4. Empirical critical loads for nitrogen in the GRYN, by ecoregion and receptor from Pardo et al. (2011b).....	19
Table 5. Ozone sensitive and bioindicator plant species known or thought to occur in the I&M parks of the GRYN	22
Table 6. Ozone assessment results for I&M parks in the GRYN based on estimated average 3-month W126 and SUM06 ozone exposure indices for the period 2005-2009 and Kohut's (2007a) ozone risk ranking for the period 1995-19991.....	22
Table 7. Estimated natural haze and measured ambient haze in I&M parks in the GRYN averaged over the period 2004 through 2008 ¹	25

Maps

	Page
Map 1. The GRYN network boundary and locations of parks and population centers greater than 10,000 people near the network.	3
Map 2. Total SO ₂ emissions, by county, near the GRYN for the year 2011.....	4
Map 3. Total NO _x emissions, by county, near the GRYN for the year 2011	5
Map 4. Total NH ₃ emissions, by county, near the GRYN for the year 2011	6
Map 5. Total S deposition for the three-year period centered on 2011 in and around the GRYN. (Source: Schwede and Lear 2014).....	8
Map 6. Total oxidized inorganic N deposition for the three-year period centered on 2011 in and around the GRYN. (Source: Schwede and Lear 2014).....	9
Map 7. Reduced inorganic N deposition for the three-year period centered on 2011 in and around the GRYN. (Source: Schwede and Lear 2014)	10
Map 8. Total N deposition for the three-year period centered on 2011 in and around the GRYN. (Source: Schwede and Lear 2014).....	11

Summary

This report describes the Air Quality Related Values (AQRVs) of the Greater Yellowstone Network (GRYN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The GRYN parks that are included in the NPS Inventory and Monitoring (I&M) Program, and discussed in this report, are Bighorn Canyon National Recreation Area (BICA) and Grand Teton (GRTE) and Yellowstone (YELL) national parks. GRTE and YELL 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 (2007a) conducted risk assessments for acidification, eutrophication, and ozone (O_3) for all of the NCCN parks; their results are described in this report.

This report also describes air pollutant emissions and air quality, 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 ozone (O_3); haze-causing particles; and airborne toxics. Background for this section can be found in “Air Quality Related Values (AQRVs) in the Inventory and Monitoring (I&M) National Parks: Status of Visibility Degradation, Ozone Effects on Vegetation, and the Effects on Natural Resources of Atmospheric Acid, Nutrient, and Toxics Deposition” (Sullivan 2016).

In general, air quality in GRYN is excellent, largely because the area is not heavily developed, and has limited emissions sources and good air dispersion (Story et al. 2006). Nevertheless, regional emissions from power plants, agricultural sources, oil and gas (O&G) development, and on-road and off-road vehicles affect air quality in GRYN parks. In addition, geothermal sources in YELL are natural sources of S. The largest air quality concerns in the Greater Yellowstone Area (GYA) include gas development in southwestern Wyoming and emissions from energy-related industries (Story et al. 2006).

Atmospheric S and N pollutants can cause acidification of streams, lakes, and soils. The GRYN area receives relatively low levels of S and N deposition. However, many Rocky Mountain lakes, including within GRTE, are highly sensitive to potential acidic deposition effects. Although it does not appear that chronic surface water acidification has occurred to any significant degree in the Rocky Mountain region, episodic acidification has been reported for lakes in the Colorado Front Range in the Rocky Mountain Network (ROMN) and probably occurs in the most acid-sensitive lakes and streams in GRTE as well. Episodic acidification is an especially important issue for surface waters throughout high-elevation areas such as occur within GRTE. A number of factors pre-dispose such watersheds to potential episodic effects, including (1) the dilute nature of the lakes, which exhibit low concentrations of base cations, and therefore acid neutralizing capacity (ANC), throughout the year; (2) large snowpack accumulations at the high-elevation sites, thus causing substantial episodic acidification via the natural process of base cation dilution during snowmelt; and (3) short hydraulic retention times for many of the high-elevation drainage lakes, thus enabling snowmelt to rapidly flush lake basins with highly dilute meltwater.

Nitrogen deposition can also cause undesirable nutrient enrichment of natural ecosystems, leading to changes in plant species composition and diversity and soil nutrient cycling. Parks in the GRYN receive generally low levels of N deposition, but sensitive aquatic and terrestrial ecosystems, including those at high elevation and those containing plant communities that are very sensitive to nutrient N input, may be affected by current levels of N deposition.

Ozone pollution can harm human health, reduce plant growth, and cause visible injury to plant foliage. Although elevated levels of O₃ have been measured in southern Wyoming, O₃ levels in the GRYN area are usually relatively low and unlikely to induce plant injury.

Particulate pollution can cause haze, reducing visibility. For most visitors, scenic vistas are an important reason for their visit to the GRYN area parks. Some of the regional and local pollution sources that likely contribute to visibility impairment include on-road and off-road vehicles, coal- and oil-fired power plants, agricultural activities, O&G development activities, and particulates from unpaved roads. Visibility may also be affected by prescribed fires and wildfires, with the specific effects of fire on visibility varying interannually depending on climatic conditions and the frequency and intensity of fires in and adjacent to a specific park. Seasonal increases in carbon monoxide (CO) and particulates associated with woodburning stoves in Jackson, WY (40 km south of GRTE) and high snowmobile use in YELL and GRTE are also recognized as important air pollution concerns.

Airborne toxics, including mercury (Hg) and other heavy metals, can accumulate in food webs, reaching toxic levels in top predators. Sampling and analyses conducted in the Western Airborne Contaminant Project (WACAP) documented deposition and bioaccumulation of airborne toxics in several western national parks, including GRTE. Semivolatile organic compounds (SOC) in GRTE were dominated by polycyclic aromatic hydrocarbons (PAH) and two current use pesticides. The former derive from combustion, including forest fire. The latter derive from agriculture.

Background

There are three national parks in the Greater Yellowstone Network (GRYN): Bighorn Canyon National Recreation Area (BICA) and Grand Teton (GRTE) and Yellowstone (YELL) national parks. All of the GRYN parks are larger than 100 square miles. 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.

Map 1 shows the network boundary, along with locations of each park and the population centers with more than 10,000 people around the network. Although there are no human population centers of any magnitude near GRYN, Salt Lake City, Boise, and Denver are all within 300 miles of the network boundary.

Atmospheric Emissions and Deposition

In general, air quality in GRYN is considerably better than in most other areas of the United States. This is partly due to the absence of high levels of fossil fuel combustion associated with power plants and metropolitan areas. Although current air quality is good in most areas, resource sensitivity is generally high, and some pollutants may have potential impacts on national park resources in both the short- and long-term.

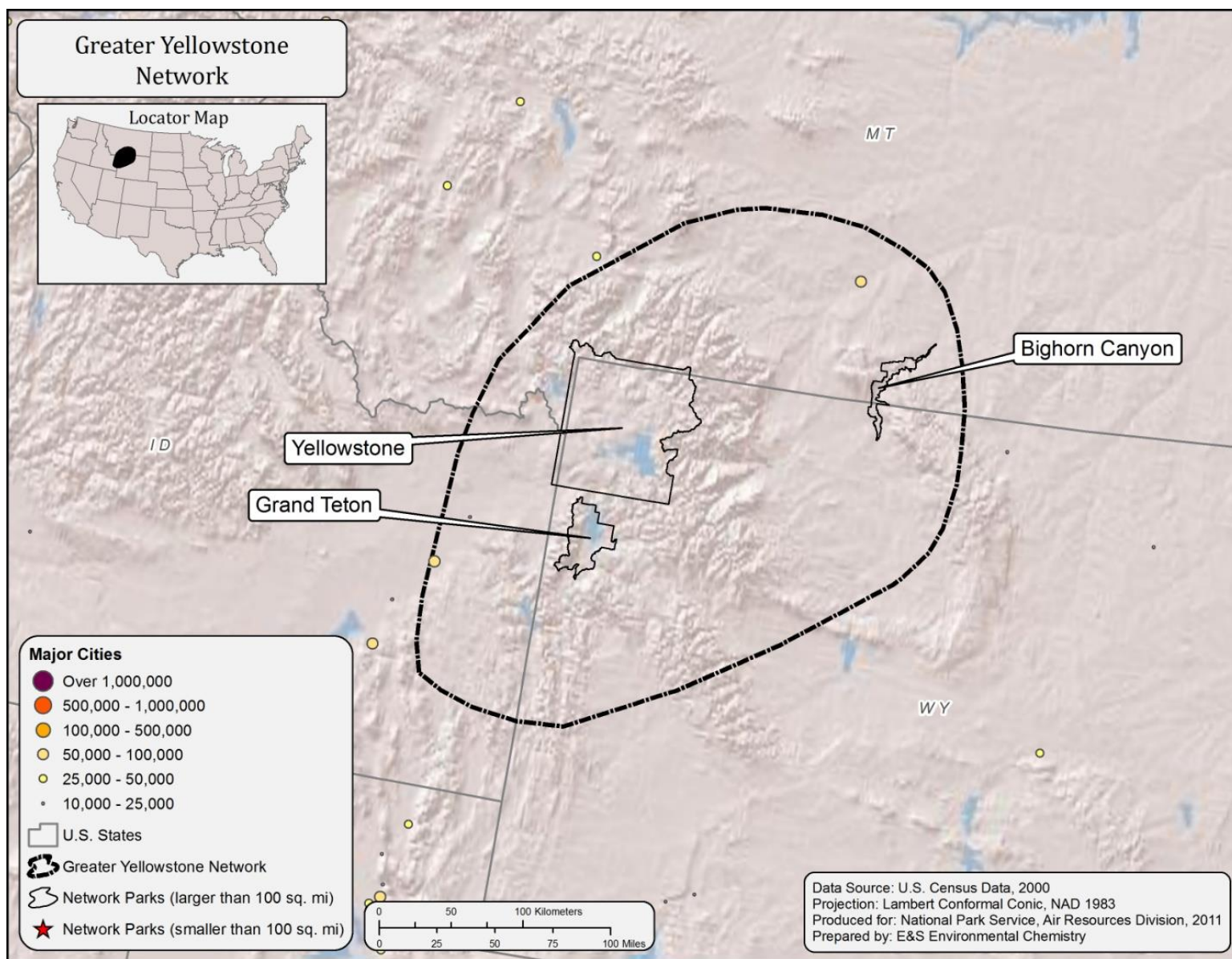
In 2006, the Greater Yellowstone Area Clean Air Partnership (GYACAP) updated its earlier (1999) assessment of air quality in the GYA. The focus was on new information regarding 1) urban and industrial emissions, 2) oil and gas (O&G) development in southwestern Wyoming, 3) smoke from prescribed fire and wildfire, and 4) snowmobile emissions. Urban and industrial emissions were identified as important concerns. They consisted largely of industrial, petroleum refinery, gas transmission, agricultural processing, wood processing, mining, power generation, sand and gravel, and mining emissions sources. The O&G development, in particular, has been rapidly expanding in southwestern Wyoming, including in the Upper Green River Basin. Wildfire smoke was identified as having the most dramatic air quality impact.

Emissions of carbon (C) and particulate matter (PM) from prescribed fire and wildfire contribute to periodic visibility impairment¹. The increased popularity of snowmobiles in the GYA during the late 1980s and 1990s raised concerns about air pollution and other impacts on natural resources and the visitor experience. By 2000, visitors were making about 75,000 snowmobile trips and 1,300 snowcoach trips into YELL during the 90-day winter season. The majority entered the park through the West Entrance from West Yellowstone. A recent Natural Resource Condition Assessment is available for GRTE and the John D. Rockefeller, Jr. Memorial Parkway (Ramsey et al. 2012). It provides a synthesis of available data regarding resource condition, including air quality.

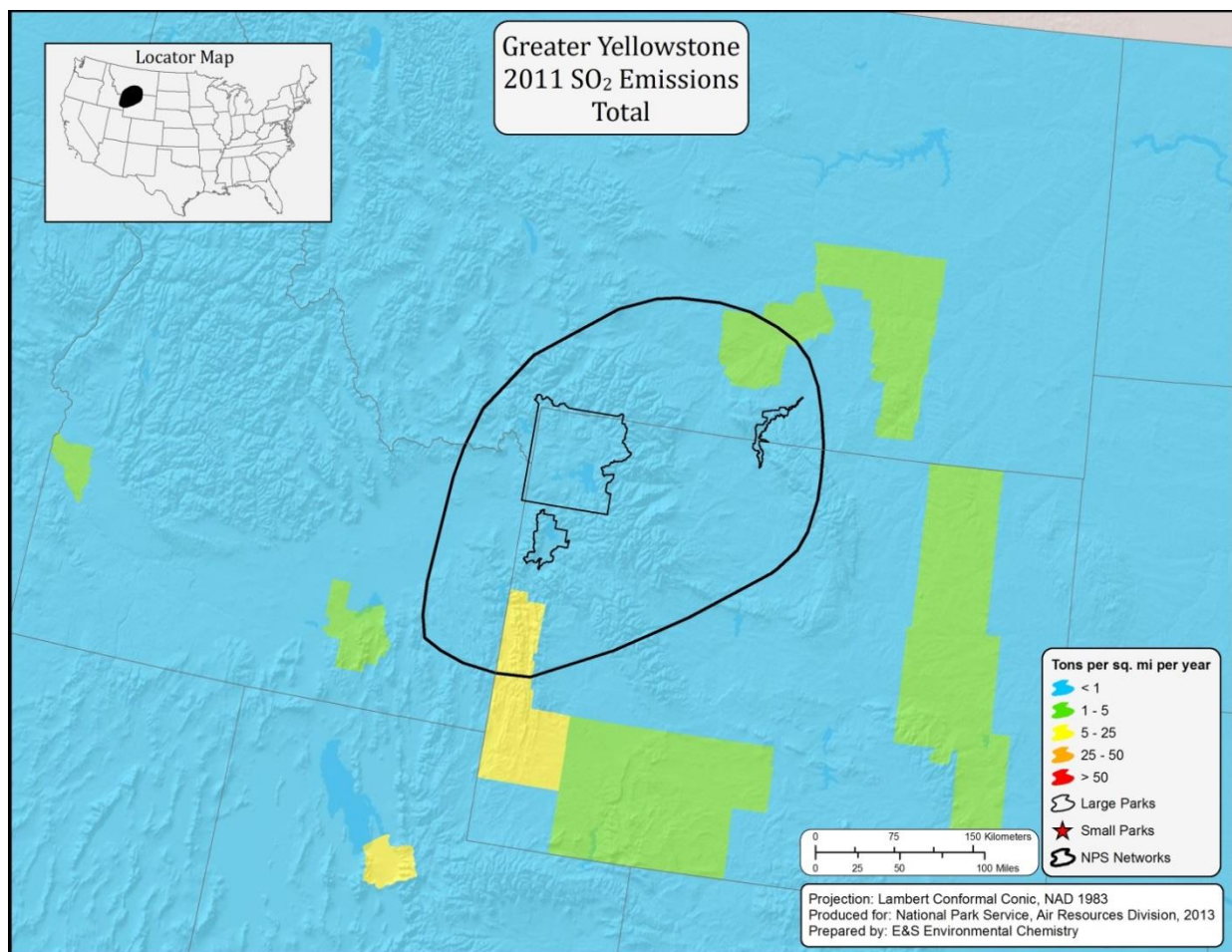
Sullivan et al. (2011b) reported that, in general, annual sulfur dioxide (SO₂) and nitrogen (N) emissions across the network region in 2002 were both less than 1 ton per square mile, although emissions were higher close to GRTE and YELL as compared with other portions of the GRYN region. There were no large SO₂ point sources in close proximity to GRYN parks, although there were two point sources located to the south of YELL and GRTE that emitted S in the range of 5,000 to 20,000 tons per year. In the central part of the United States from Texas to North Dakota, SO₂ emissions increased during the 1990s, with statistically significant increases in several states, including Wyoming (31%; Malm et al. 2002). Nevertheless, all parks within the network had S

deposition values less than 2 kg S/ha/yr in 2002. Total N deposition within the network region ranged from below 2 kg N/ha/yr in the southeast to over 5 kg N/ha/yr in and around portions of GRTE and the southwestern portion of YELL (Sullivan et al. 2011b). There were few N emissions point sources

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.



Map 1. The GRYN network boundary and locations of parks and population centers greater than 10,000 people near the network.

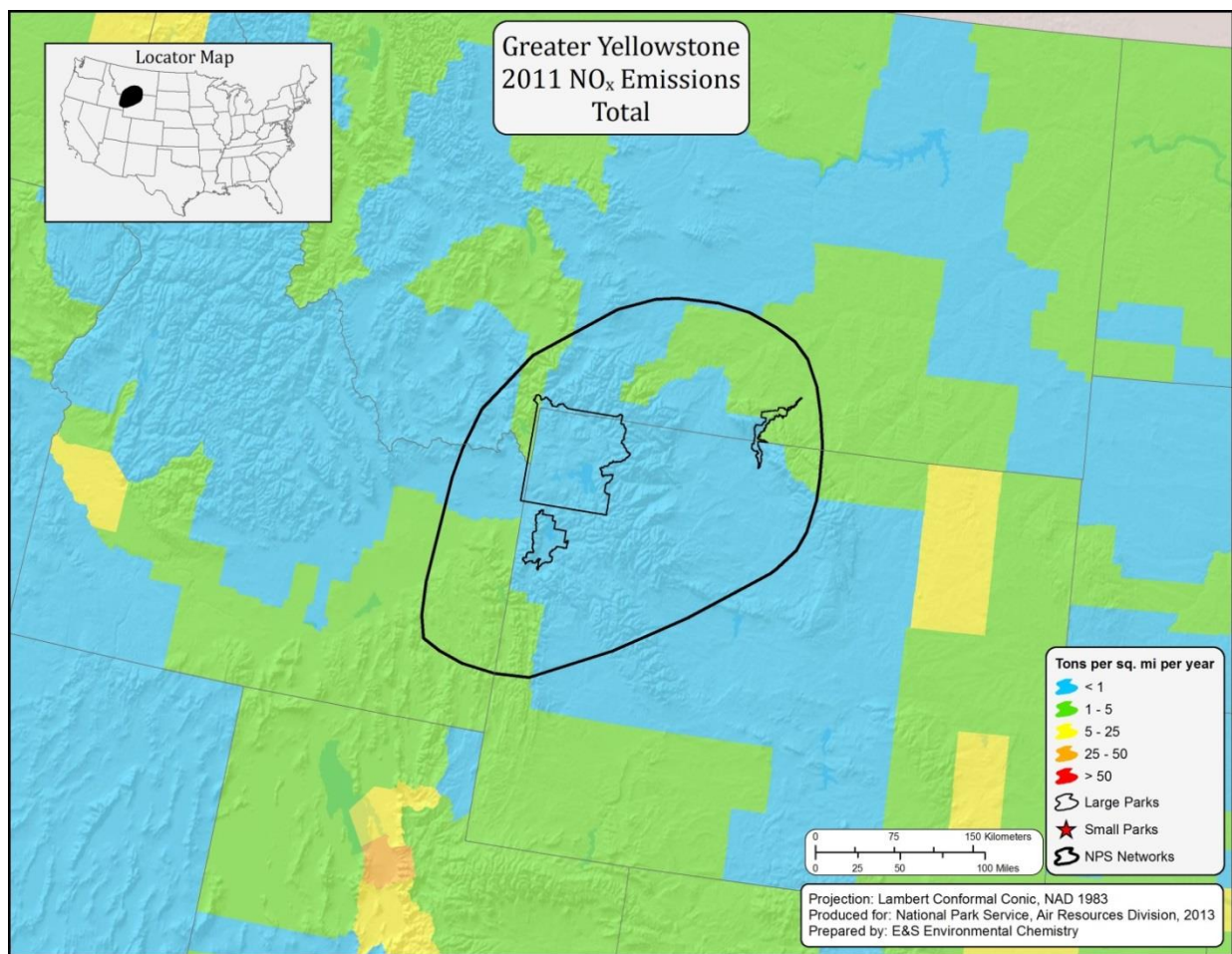


Map 2. Total SO₂ emissions, by county, near the GRYN for the year 2011. Data from EPA's National Emissions Inventory.

of any magnitude near this network. The few relatively large point sources that did exist were sources of oxidized N (NO_x).

County-level emissions near the GRYN, based on data from the EPA's National Emissions Inventory (NEI) during a recent time period (2011), are depicted in Maps 2 through 4 for SO₂, NO_x, and reduced N (NH₃), respectively. Most counties near GRYN parks had relatively low SO₂ emissions (< 1 ton/mi²/yr; Map 2), although higher emissions occurred in some areas, especially south of YELL and GRTE. Patterns in NO_x emissions were generally higher, especially to the southwest of GRYN parks (Map 3). Emissions of NH₃ near GRYN parks were somewhat lower, with most counties showing emissions levels below 2 tons/mi²/yr (Map 4).

Most S and N deposition in this network is due to long-distance transport from emissions sources to the west. Industrial and electric utility facilities in Idaho produce NO_x and volatile organic compounds that can contribute to O₃ formation in or upwind from the GRYN. The Salt Lake City, Utah, region to the southwest may also contribute O₃ precursors to the YELL/GRTE region. Most emissions of NO_x and SO₂ in Wyoming are from industrial and power-generation facilities located to

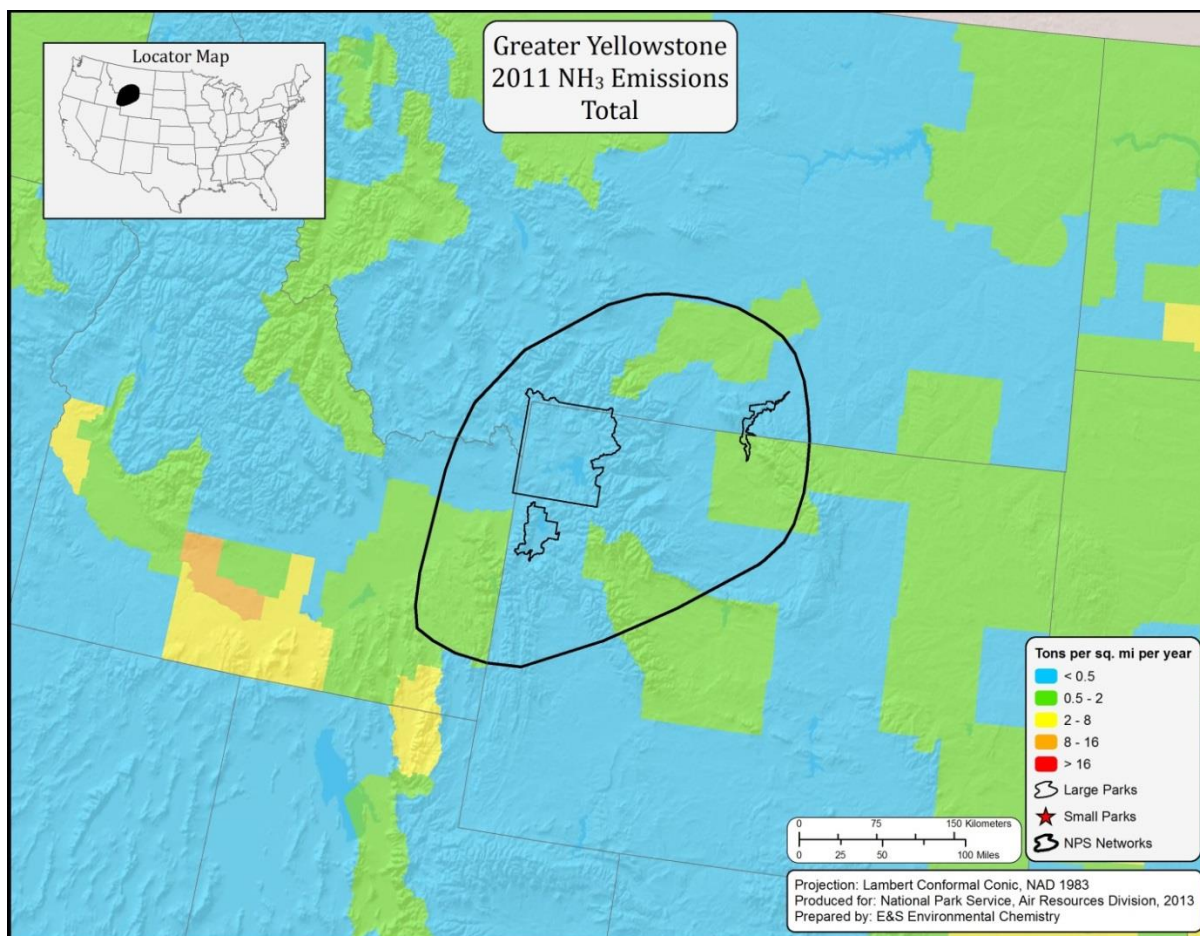


Map 3. Total NO_x emissions, by county, near the GRYN for the year 2011. Data from EPA's National Emissions Inventory.

the east of YELL and GRTE; only relatively uncommon easterly winds would transport these pollutants into the parks in GRYN.

Grenon and Story (2009) reported increasing trends in wet deposition of ammonium (NH_4^+) within at least one season of the year since the 1980s for all monitoring sites in the northern Rocky Mountains region. This result agreed with analyses reported by Ingersoll et al. (2008) and Lehmann et al. (2005). This trend of increasing NH_4^+ wet deposition has likely been due in part to increased agricultural emissions of reduced N (NH_x). The concentrations of NO_3^- in precipitation at National Atmospheric Deposition Program (NADP) monitoring sites in the Rocky Mountains have also generally increased over time, especially near urban areas (Fenn et al. 2003, Lehmann et al. 2005). In contrast, wet S deposition decreased between 1985 and 2002 at NADP sites throughout the western United States (Lehmann et al. 2005), likely due in large part to reductions in power plant emissions required by the Clean Air Act.

The Grand Teton Reactive Nitrogen Deposition study investigated atmospheric concentrations and deposition of various reactive N constituents in and around GRTE. Wet deposition of NH_4^+ and dry



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

deposition of NH₃ were the main reactive N species, together accounting for about 60% of the N deposition in GRTE (Benedict et al. 2013). The GRTE is closer to N emissions source regions than YELL. These include agricultural activities in the Snake River Valley and northern Utah, O&G extraction and power plants in Wyoming, and both wildfire and prescribed fire. Benedict et al. (2013) estimated total N deposition at the NOAA Climate Center in 2010-2011 at 2.5 kg N/ha/yr.

The Western Airborne Contaminant Assessment Project (WACAP) studied airborne contaminants in a number of national parks of the western United States, including GRTE, from 2002 to 2007. Concentrations of dacthal, endosulfans, hexachlorocyclohexane- γ , hexachlorobenzene, hexachlorocyclohexane- α , and chlordanes in the air sampled at GRTE were relatively high among western parks and exceeded the median for the 20 WACAP parks.

Snowfall that accumulates in the seasonal snowpack generally accounts for about 50-70% of the annual precipitation in headwater areas of the Rocky Mountains, including within the GRYN (Ingersoll et al. 2005, Western Regional Climate Center 2004). Atmospherically deposited pollutants accumulate in these snowpacks and are released to surface waters during the snowmelt. The U.S. Geological Survey (USGS) monitors the chemistry of the snowpack at multiple mountain locations

from New Mexico to Montana. Concentrations of NH_4^+ in snow are highest in the vicinity of YELL and GRTE. Nitrate and SO_4^{2-} concentrations in snow tend to be highest to the south of the GRYN (Ingersoll et al. 2005, Ingersoll et al. 2011). These contaminants can contribute episodic pulses of pollutants to surface waters.

Snowmobile use in YELL has led to concern about possible effects of snowmobile emissions on snowpack chemistry and air quality. Ingersoll (1999) sampled the snowpack at approximately the time of maximum snow accumulation at a variety of locations in and near YELL to determine the association between snowmobile use and snowpack chemistry. Concentrations of NH_4^+ , NO_3^- , SO_4^{2-} , benzene, and toluene were positively correlated with snowmobile use. Concentrations decreased rapidly, however, with distance from roadways. These pollutants are generally dispersed into surrounding areas at concentrations below levels likely to threaten ecosystem health, although local episodic effects might be possible (Ingersoll 1999). The two most-common air pollutants emitted by snowmobiles are carbon monoxide (CO) and fine PM (PM_{2.5}). Winter-time air quality monitoring has found that, over time, concentrations of CO and PM_{2.5} have decreased at the West Entrance, where most snowmobiles enter the park, and at Old Faithful, a popular destination for the snowmobiles. The decreases are likely due to the implementation of Best Available Technology (BAT) regulation for snowmobiles, and a decrease in the number of snowmobiles entering the park. The BAT regulation was introduced in winter 2002-2003 and has significantly reduced snowmobile emissions, with many machines now having cleaner four-stroke engines as compared to two-stroke engines. Air quality in the park meets EPA's health standards for CO and PM_{2.5} (Ray 2012).

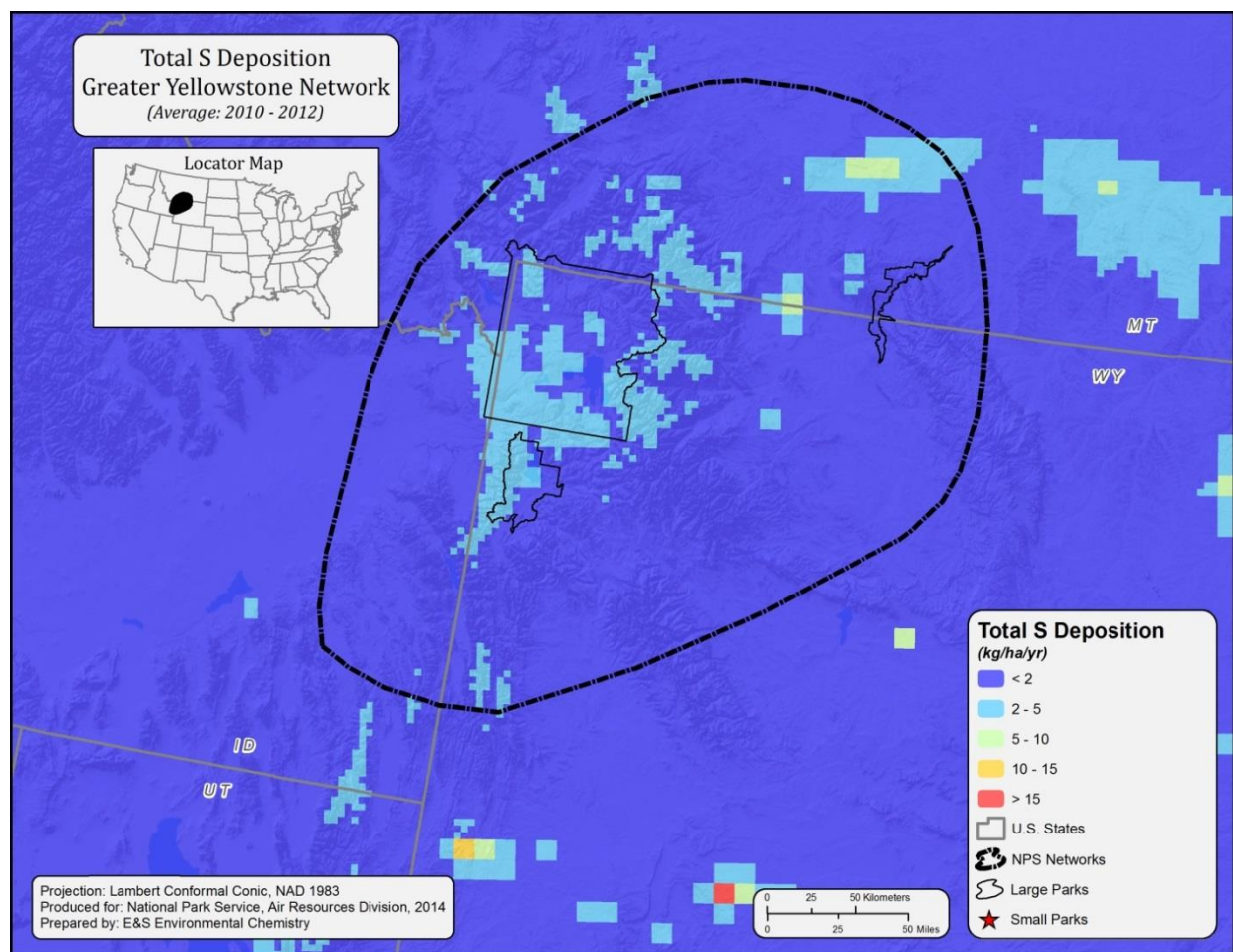
Schwede and Lear (2014) recently developed by the National Atmospheric Deposition Program (NADP) Total Deposition (TDEP) Science Committee for estimating total N and S deposition. This approach combined monitoring and modeling data. Modeling was accomplished using the CMAQ model (Byun and Schere 2006). 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. The TDEP data reported here were developed in late 2013 and are designated version 2013.02.

Total S deposition in and around the GRYN for the period 2010-2012 was generally < 5 kg S/ha/yr (Map 5). Oxidized inorganic N deposition for the period 2010-2012 was less than 5 kg N/ha/yr throughout the park lands within the GRYN (Map 6). Most areas received 2 to 5 kg N/ha/yr of reduced inorganic N from atmospheric deposition during this same period (Map the 7). Total N deposition was generally in the range of 2 to 5 kg N/ha/yr, although higher values were estimated for portions of YELL and GRTE (Map 8).

Atmospheric S deposition levels have increased at all GRYN parks since 2001, based on TDEP estimates (Table 1). Total S deposition over the previous decade increased in BICA by almost one third. Estimated total N deposition decreased over that same time period by 7.7% at BICA, but increased at YELL (9.6%) and GRTE (15.3%). At all parks in the network, oxidized N decreased and reduced N deposition increased over that time period.

Acidification

The network rankings for acid Pollutant Exposure, Ecosystem Sensitivity to acidification, and Park Protection developed by Sullivan et al. (2011b) in a coarse screening analysis yielded an overall network acidification Summary Risk ranking for the GRYN that was relatively high among networks. This network is known to contain acid-sensitive waters and geology, and there are numerous high-elevation lakes and streams and low-order streams, especially in GRTE, that might be sensitive to acidification effects. The overall level of concern for acidification effects on Inventory and Monitoring (I&M) parks within this network was judged by Sullivan et al. (2011b) to be High.

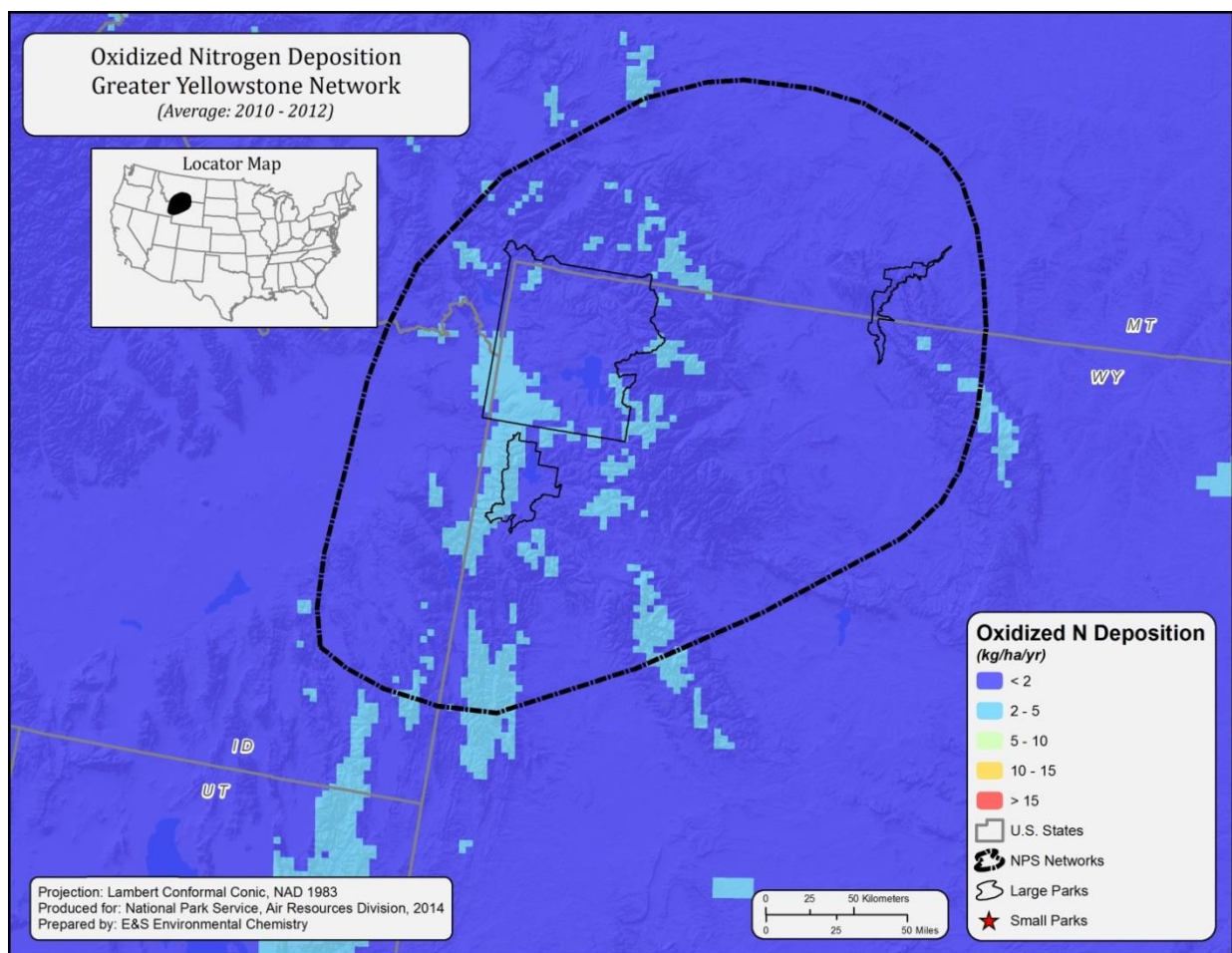


Map 5. Total S deposition for the three-year period centered on 2011 in and around the GRYN. (Source: Schwede and Lear 2014)

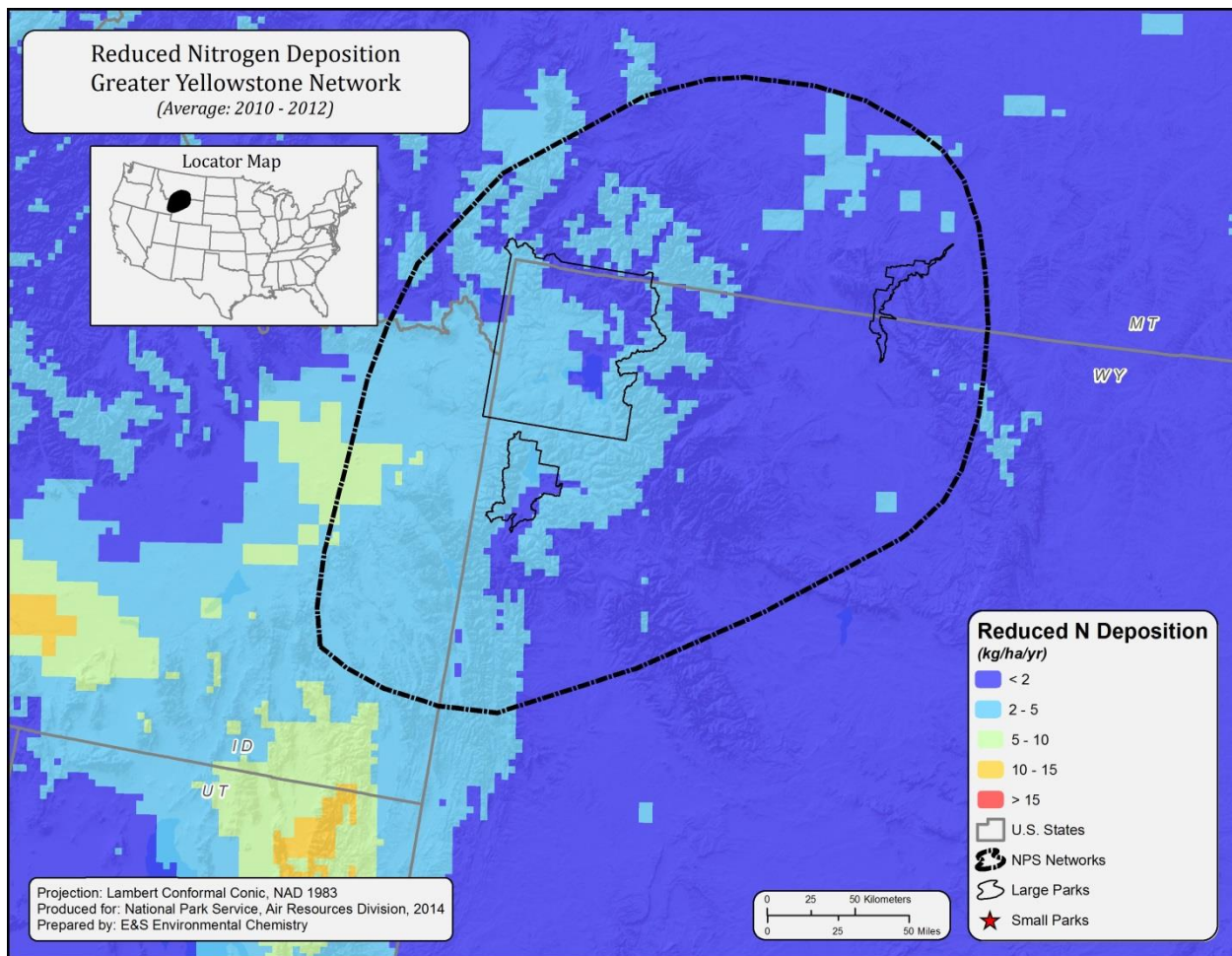
While rankings are an indication of risk, park-specific data, particularly data on ecosystem sensitivity, are needed to fully evaluate risk from acidification.

Acid Pollutant Exposure was ranked Low for GRTE and YELL, and Very Low for BICA (Table 2; Sullivan et al. 2011b). However, GRTE and YELL were ranked Very High for Ecosystem Sensitivity to acidification (Sullivan et al. 2011a; Table 2). This ranking is due in part to the incidence of high-

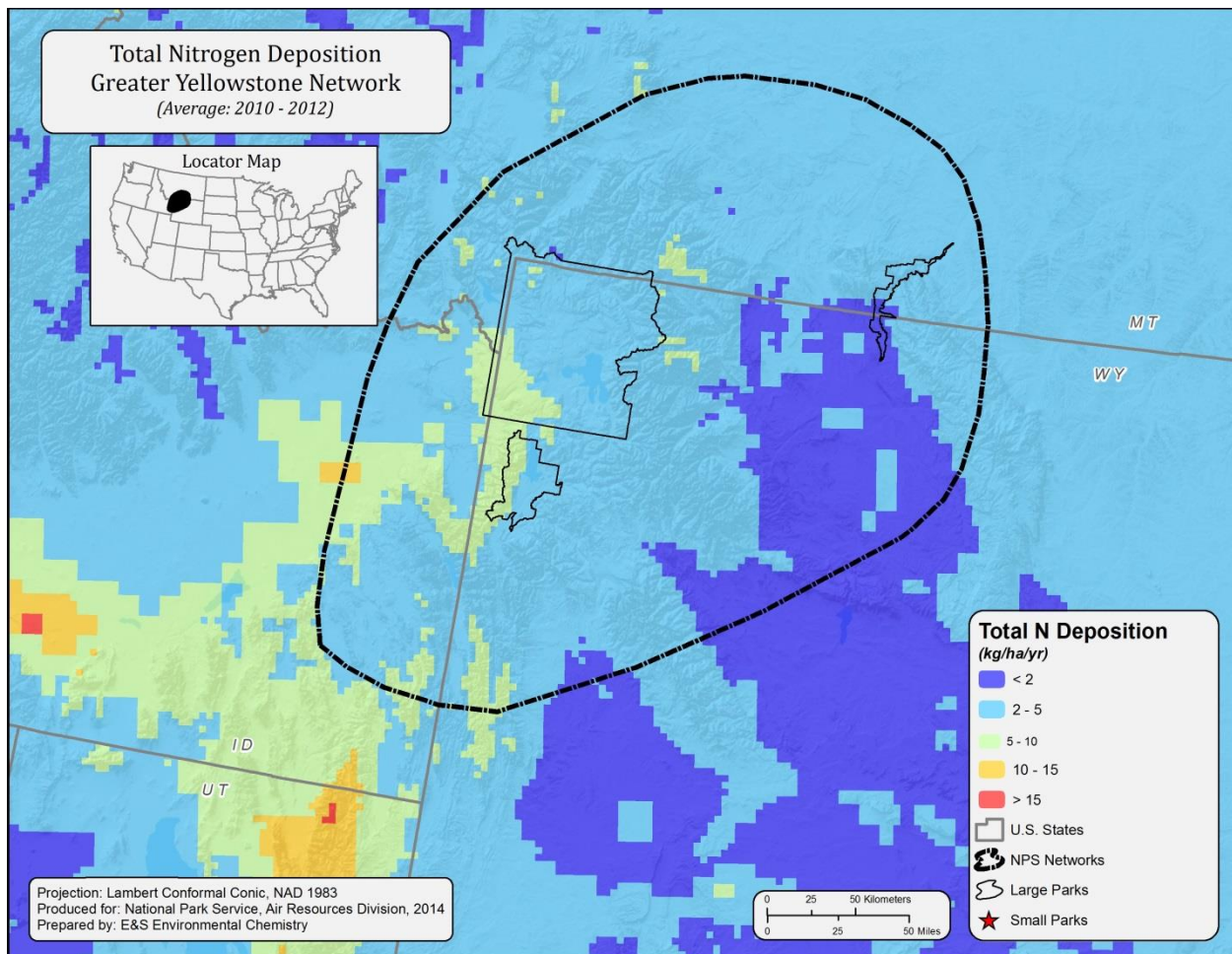
elevation lakes and streams in both GRTE and YELL. In GRTE in particular, many high-elevation, low-order streams, especially in GRTE, are found above 2,500 m elevation in the Teton Range, which runs north to south along the western border of the park. YELL contains numerous high-elevation, low-order streams, especially along the eastern border of the park and in the northwest. These high-elevation water bodies might be more prone than lakes and streams at lower elevation to acidification effects, and therefore are potentially more susceptible to acidification in response to atmospheric S and N inputs. Additionally, ecosystem sensitivity to acidification rankings also take into account land slope, which often influences the degree of acid neutralization provided by soils and bedrock within the watershed. Land slope within the GRYN tends to be highly variable and ranges from less than 10° to between 40° and 50° in parts of YELL and GRTE. BICA was ranked High in acid sensitivity in the screening assessment of Sullivan et al. (2011b). However, there are no available empirical data to suggest that aquatic or terrestrial resources in this park are either sensitive to or impacted by acidic deposition. Komp et al. (2012) compiled data on pH measurements in BICA (2,268 measurements at 159 sites sampled between 1947 and 1987). Stream pH measurements were almost all above 6.5. Data for seven monitoring sites collected over five years showed mean pH values near 8.0, with minimum measured values equal to or higher than 7.25 (Komp et al. 2012).



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



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



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

Table 1. Average changes in S and N deposition between 2001 and 2011 across park grid cells at GRYN 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)
BICA	Bighorn Canyon	Total S	0.97	1.25	0.28	29.9%	0.78	1.61	0.82
		Total N	2.53	2.37	-0.16	-7.7%	1.47	3.15	1.68
		Oxidized N	1.43	1.16	-0.27	-19.5%	0.75	1.57	0.82
		Reduced N	1.11	1.21	0.10	7.9%	0.70	1.86	1.16
GRTE	Grand Teton	Total S	1.74	2.01	0.27	16.1%	0.94	3.24	2.30
		Total N	4.07	4.70	0.63	15.3%	2.58	7.79	5.22
		Oxidized N	2.28	1.94	-0.33	-15.6%	1.17	3.33	2.16
		Reduced N	1.79	2.76	0.97	56.2%	1.41	4.47	3.06
YELL	Yellowstone	Total S	1.78	1.94	0.16	8.9%	1.09	2.76	1.67
		Total N	3.71	4.08	0.37	9.6%	1.89	6.78	4.89
		Oxidized N	2.03	1.73	-0.30	-15.2%	0.86	2.65	1.79
		Reduced N	1.68	2.36	0.68	40.1%	1.03	4.13	3.10

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

Park Name ²	Park Code	Estimated Acid Pollutant Exposure	Estimated Ecosystem Sensitivity to Acidification
<i>Bighorn Canyon</i>	BICA	Very Low	High
<i>Grand Teton</i>	GRTE	Low	Very High
<i>Yellowstone</i>	YELL	Low	Very High

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

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

Acidification of Terrestrial Ecosystems

There is no information available on the possibility of terrestrial acidification attributable to acidic deposition in the GRYN. Sensitivity to soil acidification is probably relatively high. However, given the generally low levels of S and N deposition to this network, such effects are unlikely under current deposition levels.

Acidification of Aquatic Ecosystems

The sensitivity of the Rocky Mountains to adverse aquatic effects from acidic deposition varies widely since the mountain ranges are discontinuous, with highly variable geological composition. For that reason, assessments of the sensitivity of Rocky Mountain aquatic resources to acidification should be specific to individual ranges (Sullivan and Eilers 1994, Turk and Spahr 1991).

Portions of the mountainous West, including parts of the GRYN, contain large areas of exposed bedrock, with little soil or vegetative cover to neutralize acidic inputs. However, the percentage of exposed bedrock in a watershed does not always indicate acid sensitivity of surface waters. If the bedrock contains even small deposits of calcareous minerals or if physical weathering such as that caused by glaciers causes a high production of base cations within the watershed (Drever and Hurcomb 1986), surface waters may be neutral to alkaline, and would not be sensitive to acidification from acidic deposition.

Some of the aquatic resources in the Rocky Mountains that are potentially sensitive to acidification were identified by the U.S. EPA (1995) as occurring in the Idaho Batholith region of Idaho and Montana and in mountainous areas of northwestern Wyoming in the vicinity of the GRYN. Many of the low-ANC lakes and streams in these areas are susceptible to episodic acidification associated with snowmelt or rainstorms (Schoettle et al. 1999).

The available information on acid-base chemistry of surface waters in the GRYN is based in part on synoptic data from EPA's Western Lakes Survey (WLS; Landers et al. 1987) and some more localized studies. Acid anion concentrations tend to be low during fall, but can be higher during snowmelt (Melack et al. 1989, Williams and Melack 1991). Concentrations of SO_4^{2-} in lake waters are generally low, although watershed sources of S are substantial in some cases. Nitrate concentrations in most WLS lakes in the GRYN were near 0 during fall sampling (Landers et al. 1987), although fall NO_3^- concentrations were high in some areas. For example, nearly one fourth of the lakes in northwest Wyoming had NO_3^- greater than 5 $\mu\text{eq/L}$ and almost 10% had NO_3^- greater than 10 $\mu\text{eq/L}$ (Sullivan and Eilers 1994).

The 1990 NAPAP State of Science and Technology Reports and the Integrated Assessment (NAPAP 1991) provided only a cursory treatment of aquatic effects issues in the GRYN and elsewhere in the Rocky Mountains, largely because it was well known that atmospheric deposition of S and N were generally low compared to highly affected areas in the East (Sullivan 2000) and because results from the WLS (Landers et al. 1987) indicated that there were virtually no acidic (ANC # 0) lakes in the West. NAPAP (1991) indicated, however, that high-elevation areas of the West contained many of the watersheds most sensitive to the potential effects of acidic deposition.

High-elevation lakes constitute an important sensitive aquatic resource of concern in the GRYN, especially within GRTE. There are about 90 alpine and subalpine lakes and ponds in GRTE located above about 2,700 m elevation. Many lakes in the park were formed behind the terminal moraines of glaciers. The majority are in remote areas that are difficult to access (Gulley and Parker 1985). Most are less than 10 ha in area. Larger lakes are found at lower elevation, and are not expected to be acid-sensitive. Surface water ANC values tend to be high throughout most of the low elevation areas of GRTE. Lakes and streams with ANC less than 400 $\mu\text{eq/L}$ are generally restricted to the high mountain areas near the western border of the park (Peterson et al. 1998). Alpine lakes in GRTE exhibit a range of characteristics that contribute to their sensitivity to potential acidic deposition impacts (cf, Marcus et al. 1983): bedrock resistant to weathering, shallow soil, steep slope, low watershed to lake surface area ratio, high lake flushing rate, high precipitation, high snow accumulation, and short growing season.

The WLS sampled six lakes in YELL and nine lakes in surrounding areas (Landers et al. 1987). One of the lakes in the park was acidic (ANC = -24 $\mu\text{eq/L}$). This acidity was attributable to geothermal inputs as evidenced by the extremely high concentrations of SO_4^{2-} (818 $\mu\text{eq/L}$) and sum of base cations (1,330 $\mu\text{eq/L}$). One lake had an ANC of 139 $\mu\text{eq/L}$; its pH was also relatively low (6.6), mainly as a consequence of high concentration of dissolved organic carbon (11 mg/L). Several of the lakes in surrounding areas surveyed by the WLS were more acid-sensitive than those in the park; four of the nine surrounding lakes had ANC less than 100 $\mu\text{eq/L}$ and one was below 50 $\mu\text{eq/L}$. Most of these had low base cation concentrations and low SO_4^{2-} concentrations (~ 8 to 10 $\mu\text{eq/L}$) that could reasonably be attributed to atmospheric inputs.

Peterson et al. (1998) summarized data collected by M. Williams and K. Tonnessen in August, 1996 for 17 high-elevation headwater lakes throughout and adjacent to GRTE. Although none were acidic, about half had ANC values near 50 $\mu\text{eq/L}$, and almost all had ANC below 200 $\mu\text{eq/L}$. About one-third had pH in the range of 5.8 to 6.0. These data do not suggest that chronic lakewater acidification has occurred to any significant degree, but do suggest sensitivity, especially to episodic acidification. Of particular importance were the observed concentrations of NO_3^- , which were relatively high in many of the lakes sampled. Six had NO_3^- concentrations in the range of 5 to 10 $\mu\text{eq/L}$ and three had NO_3^- concentrations higher than 10 $\mu\text{eq/L}$ (to a maximum of 13 $\mu\text{eq/L}$). Given that the lakes were sampled at the end of the growing season, these data suggested that the capacity for biological uptake of N may have been reached in response to ambient N inputs. It is likely that future increase in N deposition to these watersheds would contribute to higher lakewater NO_3^- concentrations and possible chronic acidification. Furthermore, the observed relatively high NO_3^- concentrations suggested that additional water quality data should be collected during early summer, during the snowmelt period, when concentrations might be substantially higher (Peterson et al. 1998).

Of the lakes sampled in GRTE by Williams and Tonnessen, those having the lowest ANC were Surprise and Amphitheater lakes (ANC=50 and 63 $\mu\text{eq/L}$, respectively). These were also the two lakes having the lowest specific conductance (5 and 6 $\mu\text{S/cm}$, respectively), further suggesting acid sensitivity. Both had very low concentrations of SO_4^{2-} (6 $\mu\text{eq/L}$) and no measurable NO_3^- . There were also, however, some relatively low-ANC (< 100 $\mu\text{eq/L}$) lakes that had $\text{NO}_3^- > 5$ $\mu\text{eq/L}$ (Delta and

Holly lakes). Peterson et al. (1998) recommended that any of these four lakes might be good candidates for inclusion in future monitoring efforts.

Peterson et al. (1998) analyzed an NPS database of water quality and flow data for YELL, based on retrievals from five of EPA's national databases, mostly from STORET. Measured values of pH were available in this database on one or more sampling occasions from 201 sites, 5 of which had pH < 5.5. However, none of the lakes or streams having pH < 5.5 exhibited other data that reflected sensitivity to acidification from acidic deposition. For example, SO_4^{2-} concentrations ranged from 18 mg/L to 191 mg/L in the low-pH waters, much higher than would be attributable to atmospheric deposition caused by air pollution. Chloride (Cl^-) concentrations were also high in most of these low-pH surface waters, ranging from 1 mg/L to 121 mg/L. Four of the five lakes with pH < 5.5 had Cl^- concentration > 57 mg/L. It is likely that all of these low-pH surface waters were impacted by geothermal discharge that caused the water to be low in pH.

Gibson et al. (1983) reported the chemistry of 106 lakes in YELL. Data were evaluated by Peterson et al. (1998); lakes were included from every region of the park and from every major geological formation. A spatial sensitivity map was created for the park based on measurements of ANC. Excluding lakes located in the midst of major geothermal areas, the lowest ANC measured was 40 $\mu\text{eq/L}$. Most of the lakes with ANC less than 200 $\mu\text{eq/L}$ occurred within a large rhyolite flow which rose from the southwest and spread along the westcentral and central portions of the park. The greatest proportion of high pH and high ANC lakes were found in the northern portions of the park (Gibson et al. 1983).

In 1999, the USGS resampled many of the lakes that had been surveyed as part of EPA's WLS, including six lakes in YELL and one lake in GRTE. Most had high ANC, although one lake sampled in YELL was acidic as a consequence of geothermal influence (Clow et al. 2002). Corbin and Woods (2004) sampled nine high-elevation lakes in GRTE plus three in the adjacent Targhee National Forest in 2002. The focus of the study was on status and trends in lake water quality and development of a predictive model to identify lakes likely to be sensitive to acidification. Three of the sampled lakes (Amphitheater, Surprise, and Delta Lakes) had ANC < 50 $\mu\text{eq/L}$. Presence of limestone and granite bedrock were the strongest predictors of lake ANC and explained 86.5% of the variance in the ANC prediction (Corbin and Woods 2004).

Nanus et al. (2005) assessed the sensitivity of 400 lakes in GRTE and YELL to acidification from atmospheric deposition of S and N using measured lake chemistry at 52 lakes in GRTE and 23 lakes in YELL. Lakes were classified into three general acidification classes (0-50, 0-100, and 0-200 $\mu\text{eq/L}$). They considered a range of potential explanatory predictor variables, including atmospheric deposition (inorganic N, S, H), basin characteristics (elevation, slope, aspect, area), bedrock type, soil type, vegetation type, precipitation, and lake area. The data were fit to logistic regression models and applied to lake watersheds larger than 1 ha (106 in GRTE and 294 in YELL). Lake acid sensitivity was higher in GRTE than in YELL. In GRTE, 36% of lakes were estimated to have ANC ≤ 100 $\mu\text{eq/L}$, compared with only 13% in YELL. In GRTE, 7% of the lakes had greater than a 60% probability of having ANC less than 50 $\mu\text{eq/L}$, compared with 0% in YELL. For both parks, elevation was the principal predictor variable; for GRTE, the watershed area facing to the northeast

was also a statistically significant predictor variable. Lakes that exceeded the 60% probability of having $\text{ANC} \leq 100 \mu\text{eq/L}$ were located above 2,790 m in GRTE and above 2,590 m in YELL (Nanus et al. 2005). Lakes predicted to have $\text{ANC} \leq 50 \mu\text{eq/L}$ ($n = 7$ lakes) with a probability greater than 60% were located at high elevation in the southern half of GRTE.

Nanus et al. (2009) described the sensitivity of high mountain lakes to acidification in Glacier National Park (GLAC), Rocky Mountain National Park (ROMO), and Great Sand Dunes National Park and Preserve (GRSA) within the Rocky Mountain Network and of YELL and GRTE within the GRYN. They developed statistical relationships between lake ANC and basin characteristics for 151 surveyed lakes. Results were confirmed through lake sampling in 2004 at 58 lakes. Lakes having ANC below $100 \mu\text{eq/L}$ were generally located in watersheds above 3000 m elevation, with $< 30\%$ of the watershed area having NE aspect, and with $> 80\%$ of the watersheds having bedrock with low buffering capacity. The most acid-sensitive lakes were generally located in ROMO and GRTE (Nanus et al. 2009).

Data from over 12,500 streams and lakes were used by the Critical Loads of Atmospheric Deposition Science Committee (CLAD) of the NADP (<http://nadp.sws.uiuc.edu/committees/clad/>) to develop steady-state critical loads for acidity of surface waters based on multiple approaches for estimating base cation weathering; modified F-factor, regional regression model, and MAGIC model. Water quality data were obtained from a variety of sources including EPA Long Term Monitoring (LTM) sites, lake surveys, EMAP Assessments, and National Stream Surveys; USGS; NPS Vital Signs program; and USFS air program. The average water quality measurements from the most recent five years of data were used for sites with long-term water monitoring records. The CLAD database included CL estimates for 12 sites in GRTE and 16 sites in YELL. Most estimates were high ($> 1000 \text{ eq S/ha/yr}$). However, GRTE did contain CL estimates as low as 64 eq S/ha/yr . The lowest estimate in YELL was 784 S/ha/yr .

Temporal Variability in Water Chemistry

The weight of evidence suggests that many high-elevation lakes in the Rocky Mountains receive N deposition sufficiently high to cause some degree of episodic water acidification. The mechanisms that produce acidic episodes can include dilution of base cations and flushing of NO_3^- , SO_4^{2-} and/or organic acids from soils or snowpack to drainage water (Kahl et al. 1992, Lawrence 2002, Wigington 1999, Wigington et al. 1996). Acidic deposition can contribute to episodic acidification of surface water both by supplying N which can produce pulses of NO_3^- during high flow periods, contributing hydrologically mobile SO_4^{2-} , and by lowering baseline pH and ANC, so that episodes are sufficient to produce biologically harmful conditions (Stoddard et al. 2003).

There has not been sufficient data collected for the GRYN to support a regional assessment of episodic acidification. It is important to note that even low to moderate concentrations of NO_3^- in many GRYN lakes might be significant in view of (1) the low base cation concentrations in many lakes, (2) the potential for continuing N deposition to eventually exhaust natural assimilative capabilities, and (3) the fact that these distributions are often based on fall data and are therefore insufficient to make a conclusive determination (Sullivan 2000). Time-intensive discharge and chemical data for alpine streams located elsewhere in the Rocky Mountains identified strong seasonal

control on streamwater NO_3^- concentrations (cf., Campbell et al. 1995). Limited data collected during snowmelt suggested that spring NO_3^- concentrations in Rocky Mountain surface waters could be several times higher in a given water body than samples collected during the fall (e.g., Reuss et al. 1995).

Episodic surface water acidification is most commonly associated with N deposition, and effects tend to be most pronounced during snowmelt. Snowmelt can flush into surface waters N that was deposited from the atmosphere to the snowpack as well as N that was mineralized within the soil under the snowpack during winter (Campbell et al. 1995). A substantial component of the NO_3^- flux may have been derived from mineralization of organic N (Ley et al. 2004). Much of the N released from the snowpack during the melting period is retained in underlying soils, and only a portion of that is flushed to surface waters. Where soils are sparse, as in alpine regions of the GRYN, much of the snowpack N is likely flushed to surface waters. Snowpack N has been reported to cause temporary acidification of alpine streams (Campbell et al. 2002, Williams and Tonnessen 2000).

Effects on Aquatic Biota

In acid-sensitive lakes in the Rocky Mountains, some of the focus of research on the biological effects of acidification has been on native cutthroat trout (*Oncorhynchus clarkia*; Sullivan 2000). It is important to note, however, that many high-elevation western lakes and streams were historically fishless. The top predators in such aquatic ecosystems were often amphibians or crustaceans. Thus, even though cutthroat trout might be considered native to the region, they were not necessarily native to a particular lake or stream.

It is unlikely that aquatic biota in the GRYN have experienced adverse impacts to date from acidic deposition. This is because deposition of S and N are low, and the available lake water chemistry data are not indicative of chronic acidification. However, in view of the high sensitivity of lakewater chemistry to future increases in acidic deposition, aquatic biota in the GRYN constitute important AQRVs, especially within GRTE.

Nutrient 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 for the GRYN that was in the highest quintile among all national park networks. Based on a coarse screening assessment, the overall level of concern for nutrient N enrichment effects on I&M parks within this network was considered by Sullivan et al. (2011a) to be Very High.

Nutrient N Pollutant Exposure was ranked Low for GRTE and YELL, and Very Low for BICA (Table 3). However, all three were ranked High (BICA) or Very High (GRTE, YELL) for Ecosystem Sensitivity to nutrient N enrichment. Many of the high-elevation lakes and streams that are common in YELL, and especially GRTE, might be N-limited, and therefore might be highly sensitive to eutrophication from atmospheric N deposition. 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.

In general, the predominant vegetation types within the I&M parks in the GRYN thought to be most responsive to nutrient N enrichment effects include grassland and meadow, alpine, and arid and semi-arid vegetation types. There are also extensive wetland areas in GRTE and YELL. In GRTE, alpine vegetation is abundant at the higher elevations of the Grand Teton Mountains. Arid and semi-arid land is found at the lower elevations to the southeast. Meadow and wetland vegetation types are scattered throughout the park. A large proportion of GRTE is covered by these vegetation types thought to be most sensitive to nutrient N enrichment effects (Sullivan et al. 2011a). A relatively high proportion of YELL is also covered with sensitive vegetation types, with a broad mix of meadow, arid and semi-arid, alpine, and wetland vegetation types. Although the parks in the GRYN contain extensive coverage of vegetation community types expected to be highly sensitive to eutrophication caused by atmospheric N inputs, the extent to which such effects have actually occurred under ambient N deposition load rates is not known. It is likely that future changes in atmospheric N deposition will interact with changes in temperature and precipitation caused by climate change at alpine sites in GRYN parks (cf., McDonnell et al. 2014). Alpine plant community monitoring has begun in YELL and GRTE through the Global Observation Research Initiative in Alpine Environments (GLORIA; <http://www.gloria.ac.at/?a=2>). This monitoring effort has been initiated by the Colorado National Heritage Program and the NPS.

Pardo et al. (2011b) compiled data on empirical CL for protecting sensitive vegetative resources in Level I ecoregions across the conterminous United States against nutrient enrichment effects caused by atmospheric N deposition. Pardo et al. (2011b) determined that the lower end of the empirical CL range is generally near 2.5 kg N/ha/yr for protecting lichens and 4-5 kg N/ha/yr for protecting mycorrhizal fungi, herbaceous plants, and forests and for preventing NO₃⁻ leaching in most parks in the GRYN (Table 4). Ambient N deposition reported by Pardo et al. (2011b) was consistently above these levels in GRTE and YELL, but not (except the CL to protect lichens at BICA) at the smaller

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
<i>Bighorn Canyon</i>	BICA	Very Low	High
<i>Grand Teton</i>	GRTE	Low	Very High
<i>Yellowstone</i>	YELL	Low	Very 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.

parks in this network. Thus, within the GRYN, exceedance of empirical CL seems to be widespread for protecting different sensitive resources, but this is mainly limited to GRTE and YELL.

Algal communities in high-elevation lakes within the GRYN are also sensitive to potential eutrophication. *In situ* N enrichment experiments in lakes within YELL stimulated the growth of the diatom *Fragilaria crotonensis*. Maximum algal species diversity in lakes in the YELL region occurred at experimental NO₃⁻ concentrations < 3 µeq/L (Interlandi and Kilham 1998). More recently, N addition experiments found that *Asterionella formosa* reached a maximum growth rate at 0.5 µeq/L (Nanus et al. 2012). This finding suggests that lakes in this network having NO₃⁻ concentration higher than 0.5 µeq/L may be experiencing changes in algal diversity due to nutrient N enrichment. Nanus et al. (2012) used a geostatistical approach to map surface water NO₃⁻ concentration in lakes throughout the Rocky Mountain region, using basin characteristics, climate, N deposition, and other factors. They mapped regional N CL and exceedance.

Table 4. Empirical critical loads for nitrogen in the GRYN, 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)	Critical Load (kg N/ha/yr)				
			Mycorrhizal Fungi	Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Bighorn Canyon NRA	Great Plains	2.7	12	NA	5 - 25	NA	10 - 25
Bighorn Canyon NRA	North American Deserts	2.7	NA	3	3 - 8.4	NA	NA
Bighorn Canyon NRA	Northwestern Forested Mountains	2.7	5 - 10	2.5 - 7.1	4 - 10	4 - 17	4 - 17
Grand Teton NP	Northwestern Forested Mountains	5.3	5 - 10	2.5 - 7.1	4 - 10	4 - 17	4 - 17
Yellowstone NP	Northwestern Forested Mountains	5.3	5 - 10	2.5 - 7.1	4 - 10	4 - 17	4 - 17

The lowest CL estimates (< 1.5 kg N/ha/yr) were for high-elevation watersheds having steep slopes, sparse vegetation, and abundant exposed rock and talus, such as predominate in GRTE. Many such areas were estimated to be in exceedance of the CL to protect aquatic biota.

Saros et al. (2011) used fossil diatom remains in lake sediment cores to determine changes in diatom species abundance over the last century. Observed changes were suggestive of N enrichment in the Greater Yellowstone Ecosystem, starting in about 1980 and in the Sierra Nevada starting in the early 1960s. They modeled wet N deposition for the period during which diatom species shifts first occurred. From these analyses, a CL of N deposition to prevent changes in diatom species assemblages was estimated to be about 1.4 kg N/ha/yr.

Ellis et al. (2013) estimated the CL for 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 GRTE and YELL in the range of 2.5-7.1 kg N/ha/yr for protection of lichens.

Ozone Injury to Vegetation

The O₃-sensitive plant species that are known or thought to occur within the I&M parks found in the GRYN 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. Each park within the network contains at least seven O₃-sensitive and/or bioindicator species.

The W126 and SUM06 O₃ exposure indices calculated by NPS staff are given in Table 6, along with Kohut's (2007a) O₃ risk ranking. The two ranking systems differ. The NPS ranking system (NPS 2010) is a quick assessment of O₃ condition that ranks O₃ exposure levels according to injury thresholds from the literature (Heck and Cowling 1997), using a 5-year average of either the W126 or SUM06 index. The former is a measure of cumulative O₃ exposure that preferentially weights higher concentrations; the latter is a measure of cumulative O₃ exposure that includes only hourly concentrations over 60 ppb. Both metrics are calculated over a 3-month period. 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 NPS criteria, O₃ exposure risk at the GRYN parks is rated Moderate.

Kohut's approach constituted a more rigorous assessment of potential risk to plants. It considered 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.

The levels of O₃ exposure in this network were considered by Kohut (2007b) to be unlikely to injure vegetation. In general, soil moisture was low when O₃ exposure was high in BICA and YELL, but the pattern was not consistent. In BICA and YELL, low soil moisture constrains O₃ uptake into foliage during higher exposure years. In GRTE, soil moisture conditions were generally favorable for O₃ uptake, but the O₃ exposure was low enough that there was not a substantial risk of O₃ injury. Kohut (2007b) classified all three of these parks as having Low risk of foliar injury in response to O₃ exposure.

Table 5. Ozone sensitive and bioindicator plant species known or thought to occur in the I&M parks of the GRYN. (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		
		<i>BICA</i>	<i>GRTE</i>	<i>YELL</i>
<i>Amelanchier alnifolia</i>	Saskatoon serviceberry		x	
<i>Amelanchier alnifolia</i> var. <i>alnifolia</i>	Saskatoon serviceberry	x		
<i>Apocynum androsaemifolium</i> *	Spreading dogbane	x	x	x
<i>Apocynum cannabinum</i>	Dogbane, Indian hemp	x	x	
<i>Artemisia ludoviciana</i> var. <i>ludoviciana</i> *	Silver wormwood	x		
<i>Artemisia ludoviciana</i> *	Silver wormwood		x	
<i>Asclepias incarnata</i>	Swamp milkweed	x		
<i>Fraxinus pennsylvanica</i>	Green ash	x		
<i>Physocarpus malvaceus</i> *	Pacific ninebark		x	x
<i>Pinus ponderosa</i> *	Ponderosa pine	x		
<i>Populus tremuloides</i> *	Quaking aspen	x	x	x
<i>Rhus aromatica</i> var. <i>trilobata</i> *	Skunkbush	x		x
<i>Rubus parviflorus</i>	Thimbleberry	x	x	
<i>Rubus parviflorus</i> var. <i>parviflorus</i>	Thimbleberry			x
<i>Rudbeckia laciniata</i> var. <i>ampla</i> *	Cutleaf coneflower	x		
<i>Salix scouleriana</i> *	Scouler's willow		x	x
<i>Sambucus racemosa</i> *	Red elderberry		x	
<i>Symphoricarpos albus</i> var. <i>albus</i> *	Common snowberry	x		
<i>Symphoricarpos albus</i> *	Common snowberry		x	
<i>Vaccinium membranaceum</i> *	Huckleberry		x	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 GRYN based on estimated average 3-month W126 and SUM06 ozone exposure indices for the period 2005-2009 and Kohut's (2007a) ozone risk ranking for the period 1995-19991.

Park Name ²	Park Code	W126		SUM06		Kohut O ₃ Risk Ranking
		Value (ppm-hr)	Ranking	Value (ppm-hr)	Ranking	
<i>Bighorn Canyon</i>	BICA	7.93	Moderate	8.70	Moderate	Low
<i>Grand Teton</i>	GRTE	10.78	Moderate	12.97	Moderate	Low
<i>Yellowstone</i>	YELL	9.40	Moderate	10.19	Moderate	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.

In YELL, the levels of O₃ exposure reported by Kohut (2007b) generally increased over the 10-year monitoring period (1995-2004). However, there were more months of drought stress during the second half of the period of record, thereby constraining the uptake of O₃ into foliage and reducing the likelihood of injury (Kohut 2007b).

In general, air quality with respect to O₃ in the GRYN is considerably better than in most other areas of the conterminous United States. Nevertheless, natural background O₃ concentrations can be above 40 ppb at YELL under appropriate atmospheric conditions. For example, a high-elevation site at YELL exhibited the largest number of coincidences (more than 19 days in one month) of average O₃ concentration in excess of 50 ppb and the occurrence of stratospheric intrusions (Lefohn 2011). This finding suggests that naturally occurring stratospheric intrusion can be an important source of elevated O₃ levels at YELL. The maximum daily 8-hr average concentrations mostly ranged from about 50 to 60 ppb at this site (Lefohn 2011).

Forest fires can also be an important source of O₃ precursors in the GRYN (Jaffe et al. 2008). The recent increase in fire frequency in the western United States has been identified as an important cause of increased O₃ concentrations. This trend may continue in response to global warming.

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. Six parks, including YELL, 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).

Visibility Degradation

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. 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 Network (IMPROVE) and typically reported using the haze index deciview (dv)².

Haze is monitored at YELL. In addition, data from the NOCH1 (Northern Cheyenne, Rosebud County) IMPROVE site is considered representative of BICA, and data from the BRID1 (Bridger Wilderness, Sublette County) site is considered representative of GRTE. 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. Natural and ambient haze levels are estimated for the 20% clearest visibility days, the 20% haziest visibility days, and average days.

Natural haze levels are estimated to be low in GRYN parks (Table 7). Ambient visibility estimates reflect current pollution levels and were used to rank conditions at parks in order to provide park managers with information on spatial differences in visibility and air pollution. Rankings range from very low haze (very good visibility) to very high haze (very poor visibility). Only parks with on-site or representative IMPROVE monitors were used in generating the baseline visibility ranking. Table 7 gives the relative park haze rankings on the 20% clearest, 20% haziest, and average days.

Measured ambient haze values for the period 2004 through 2008 were higher than the estimated natural condition. Nevertheless, measured ambient haze rankings were ranked Very Low for GRTE and YELL and Low for BICA (Table 7). However, because of the importance of scenic views to the visitor experience in GRYN parks, visibility remains an important AQRV concern in this network.

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

Table 7. Estimated natural haze and measured ambient haze in I&M parks in the GRYN averaged over the period 2004 through 2008¹.

			Estimated Natural Haze					
Park Name ²	Park Code	Site ID	20% Clearest Days		20% Haziest Days		Average Days	
			dv		dv		dv	
<i>Bighorn Canyon</i> ³	BICA	NOCH1	1.47		7.91		4.03	
<i>Grand Teton</i> ³	GRTE	BRID1	0.28		6.45		2.89	
<i>Yellowstone</i>	YELL	YELL2	0.43		6.44		2.93	
			Measured Ambient Haze (For Years 2004 through 2008)					
Park Name	Park Code	Site ID	20% Clearest Days		20% Haziest Days		Average Days	
			dv	Ranking	dv	Ranking	dv	Ranking
<i>Bighorn Canyon</i> ³	BICA	NOCH1	3.52	Low	14.64	Low	8.46	Low
<i>Grand Teton</i> ³	GRTE	BRID1	1.62	Very Low	10.96	Very Low	5.79	Very Low
<i>Yellowstone</i>	YELL	YELL2	2.18	Very Low	11.76	Very Low	6.50	Very Low

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

² Park names are printed in bold italic for parks larger than 100 m².

³ Data are borrowed from a nearby 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.

Representative photos of the same vista under different visibility conditions are shown in Figure 1 for YELL. Photos were selected to correspond with the clearest 20% of visibility conditions, haziest 20% of visibility conditions, and annual average visibility conditions at that location. This series of photos provides a graphic illustration of the visual effect of these differences in haze level on a representative vista in this park. IMPROVE data allow estimation of visual range (VR). Data indicate that at the BRID1 site representative of GRTE, air pollution has reduced average VR from 180 to 120 miles (290 to 193 km). On the haziest days, VR has been reduced from 120 to 75 miles (193 to 121 km). Severe haze episodes occasionally reduce visibility to 14 miles (23 km). At the NOCH1 site representative of BICA, air pollution has reduced average VR from 160 to 90 miles (258 to 145 km). On the haziest days, VR has been reduced from 110 to 50 miles (177 to 81km). Severe haze episodes occasionally reduce visibility to 8 miles (13 km). At the YELL2 site in YELL, air pollution has reduced average VR from 180 to 120 miles (290 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 13 miles (21 km).

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 carbon, coarse mass, organic mass, sea salt, and soil. Sulfates form in the atmosphere from SO₂ emissions from coal-burning power plant, smelters, and other industrial facilities. Nitrates form in the atmosphere from NO_x emissions from combustion sources including vehicles, power plant, industry, and fires. Organic compounds are emitted from a variety of both natural (biogenic) and anthropogenic sources, including agriculture, industry, and fires. Soil can enter the atmosphere through both natural processes and human disturbance.

At IMPROVE sites throughout the interior Columbia River basin, from North Cascades National Park and GLAC in the north to Lassen Volcanic National Park and YELL in the south, carbon in various forms, including fine particulate organics and soot, dominates the light extinction budget (Schoettle et al. 1999). The second most important contributor to extinction is SO_4^{2-} . Extinction charts are shown for BICA, GRTE, and YELL in Figure 2. The largest share of the annual average total particulate light extinction (b_{ext}) in GRTE and YELL was attributable to organics (32.5% and 41.7%, respectively), followed closely by SO_4^{2-} (Figure 2). For BICA, organics contributed about the same amount of extinction as SO_4^{2-} on average days. On the 20% haziest days, organics contributed over 40% to light extinction in all three parks. In contrast, on the clearest 20% visibility days, SO_4^{2-} accounted for more than 40% of b_{ext} in these parks. 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 GRYN. 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).=

Yellowstone

20% Clearest Days

Taken: 3:00 PM

Haze = 2 dv

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

VR = 320 km



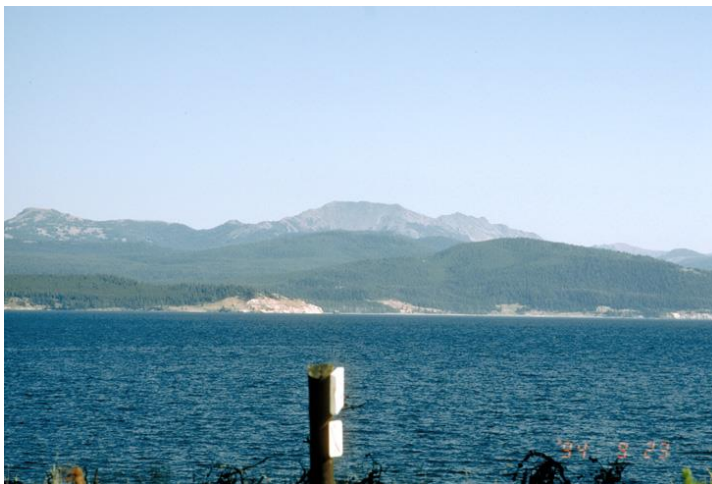
20% Haziest Days

Taken = 3:00 PM

Haze = 11 dv

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

VR = 130 km



Average Days

Taken = 3:00 PM

Haze = 7 dv

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

VR = 200 km



Figure 1 Three representative photos of the same view in YELL illustrating the 20% clearest visibility, the 20% haziest visibility, and the annual average visibility. B_{ext} is total particulate light extinction; VR is the visual range.

Trends in Visibility

There are not clear trends in haze at any of the GRYN parks on the 20% clearest, 20% haziest, or average days over the full period of available monitoring data. However, in each of the three monitored parks, the haze level shows some evidence of decreasing over the last several years (Figure 3).

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).

The glideslope analysis shows some evidence of decreasing haze over the last several years (Figure 4). Measured values are generally close to following the glideslope required for conformance with the RHR goal of zero human-caused visibility impairment in 2064. More data will be needed for determining the extent of improvement.

Toxic Airborne Contaminants

Pesticide and other semivolatile organic compound burdens in vegetation at GRTE, as measured by WACAP, were dominated by polycyclic aromatic hydrocarbons (PAH) and the current use pesticides endosulfan and dacthal. Likely sources of PAH to these parks include forest fires and perhaps woodburning stoves. Lichen data reported by WACAP parks in GRTE showed relatively high SOC concentrations. Some work has been done on the presence of polychlorinated biphenyls (PCBs) and organochlorine insecticides and their metabolites in and near YELL as part of the USGS National Water Quality Assessment (NAWQA; Peterson and Boughton 2000), although the connection to atmospheric deposition is unclear. They found dichlorodiphenyltrichloroethane (DDT), and its metabolites dichlorodiphenyldichloroethane (DDD) and dichlorodiphenyldichloroethylene (DDE), in fish collected in YELL, probably reflecting residual effects from historical DDT spraying for spruce budworm in and near the park. Fish appeared to be more sensitive indicators of contamination than river bed sediment in YELL, likely due to the lipophilic nature of these compounds, chemical partitioning, and bioaccumulation (Peterson and Boughton 2000).

Krabbenhoft et al. (2002) sampled 90 lakes in seven national parks in the western United States and analyzed their Hg and methylmercury (MeHg) concentrations. YELL and GRTE were included in the study. Levels of MeHg were similar among YELL, GRTE, and most of the other surveyed parks (~ 0.05 ng/L), but somewhat lower (0.02 ng/L) in GLAC in the Rocky Mountain Network. Data are available regarding Hg in lake trout (*Salvelinus namaycush*) in Yellowstone Lake, but much of that Hg is probably attributed to geothermal, rather than atmospheric, sources.

NOCH1 (for BICA)

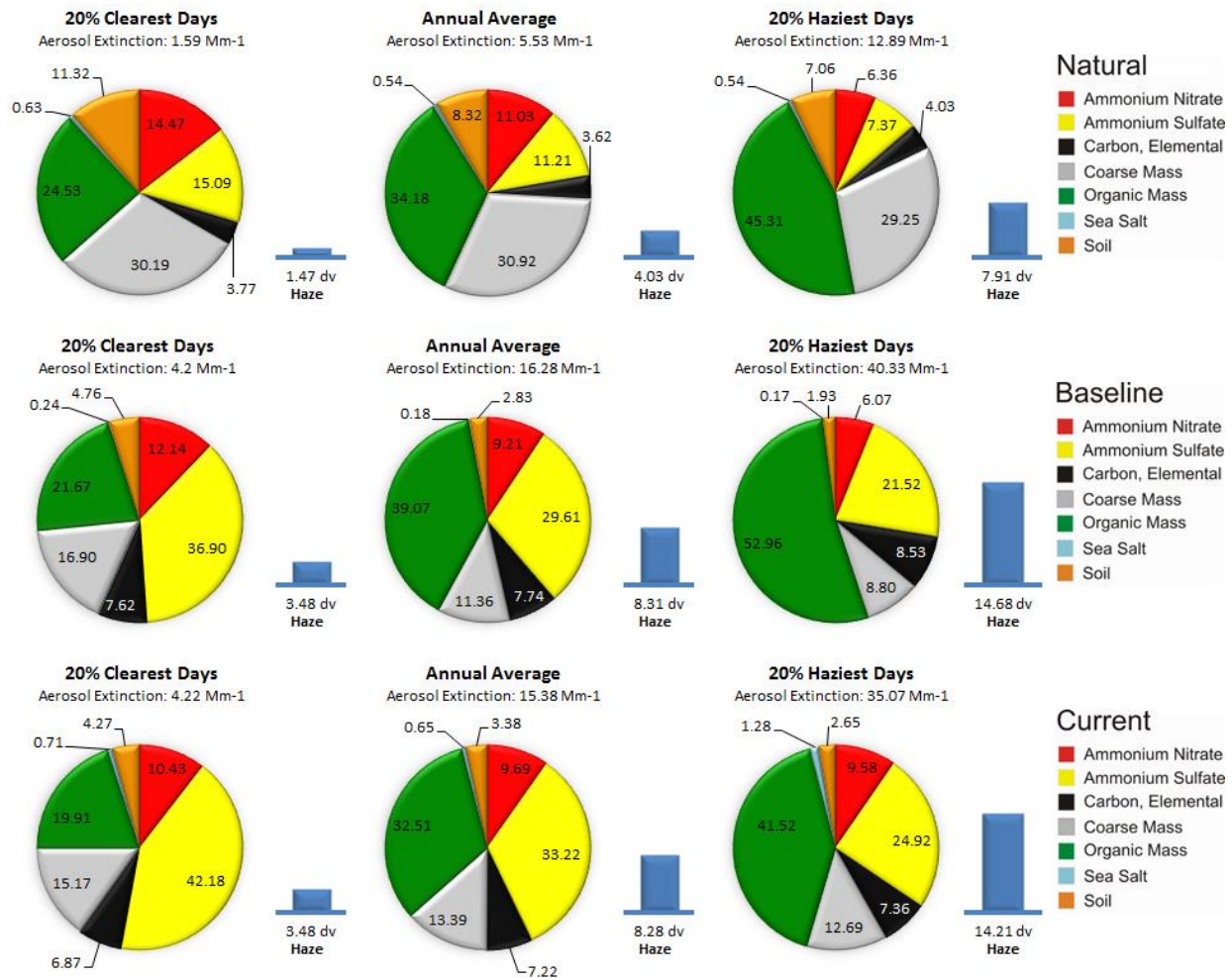


Figure 2a. Estimated natural (pre-industrial), baseline (2000-2004); and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for BICA. Data for BICA were taken from nearby site NOCH1. BICA has no valid, measured or substituted data for the years 2000-2002. Data Source: NPS-ARD.

BRID1 (for GRTE)

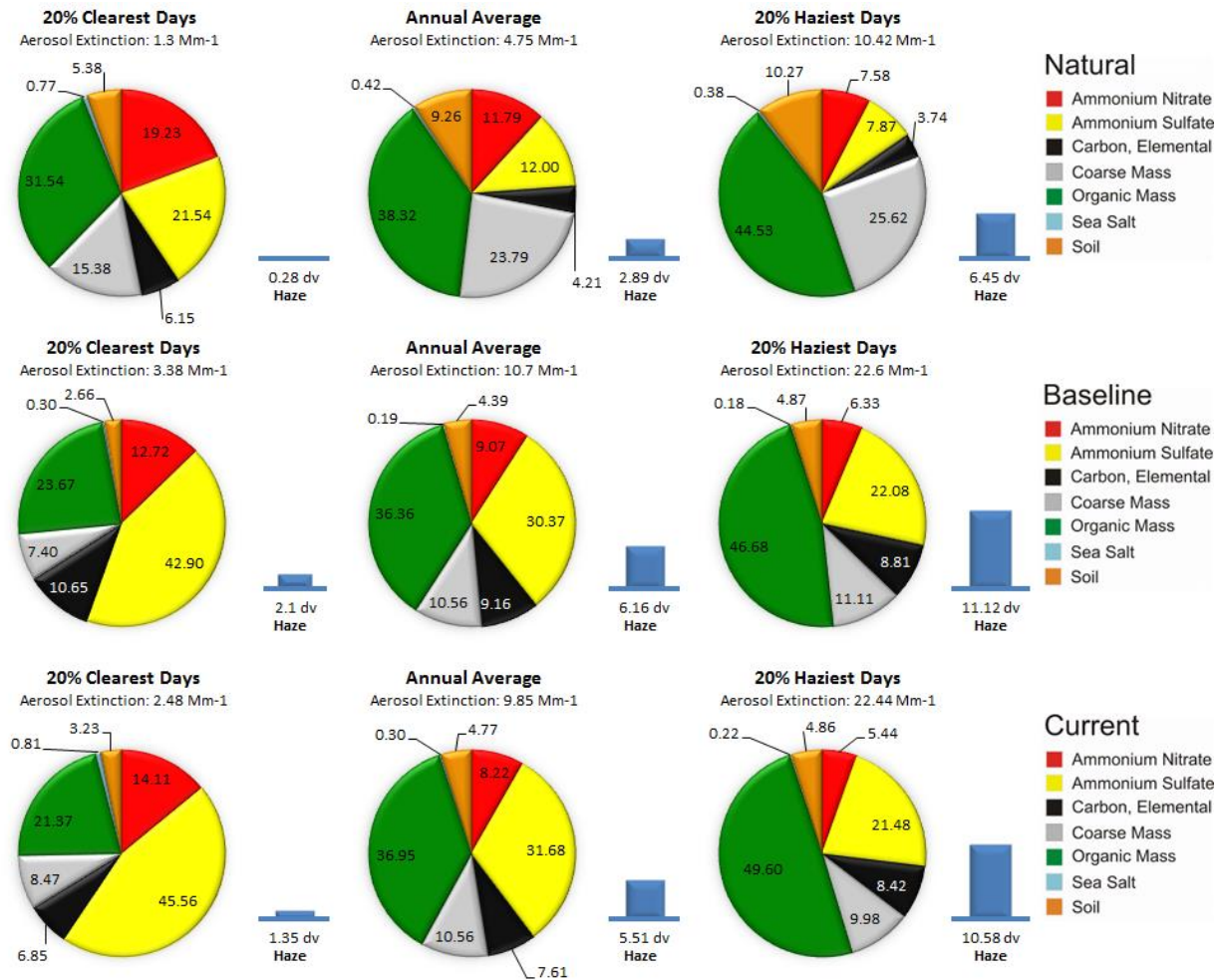


Figure 2b. Estimated natural (pre-industrial), baseline (2000-2004); and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for GRTE. Data for GRTE were taken from nearby site BRID1. Data Source: NPS-ARD.

YELL

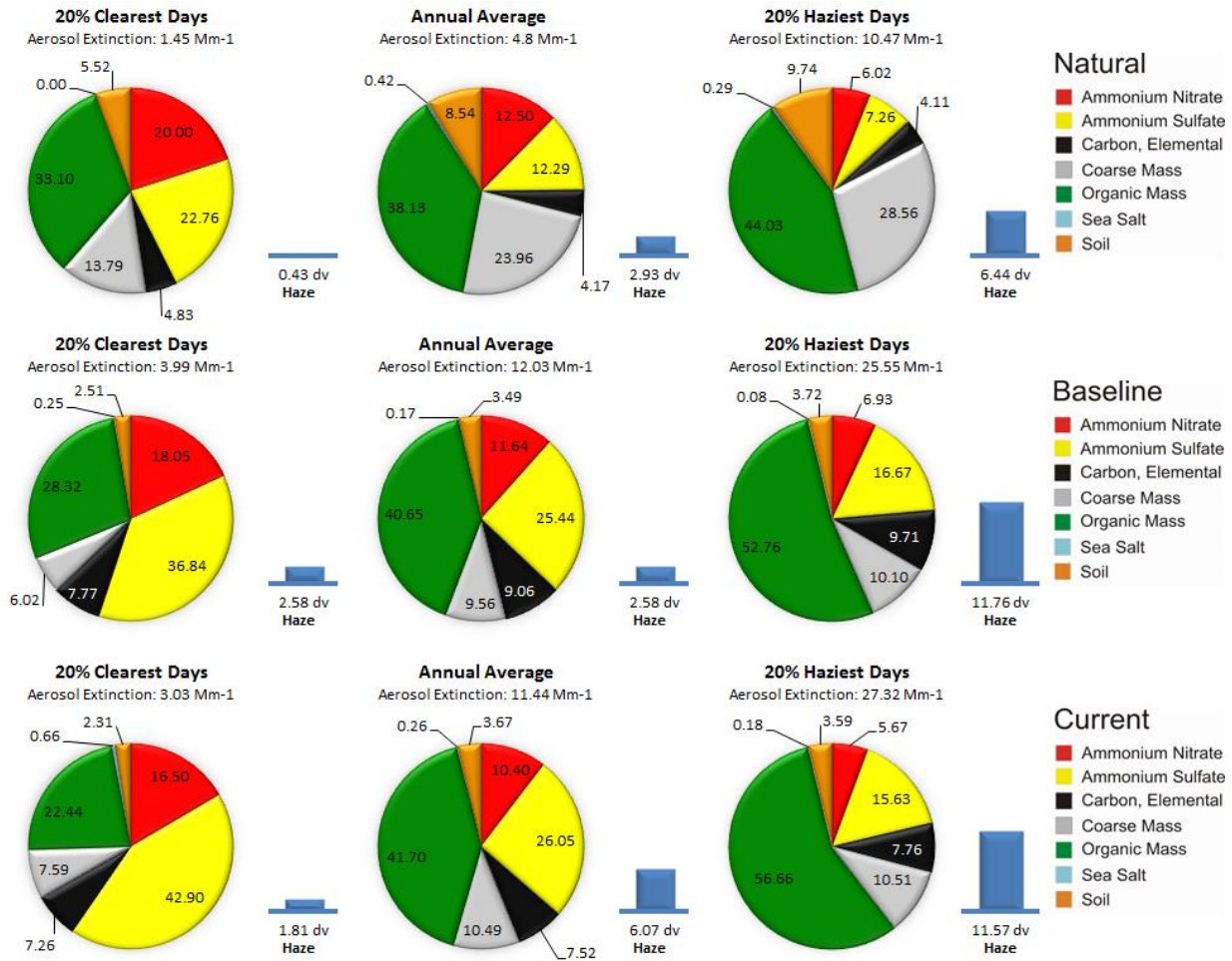


Figure 2c. Estimated natural (pre-industrial), baseline (2000-2004); and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for YELL. Data Source: NPS-ARD.



Figure 3. Trends in ambient haze levels at BICA, GRTE, and YELL, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for BICA and GRTE were taken from nearby sites (NOCH1 and BRID1, respectively). BICA has no valid, measured or substituted data for the years 2000-2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

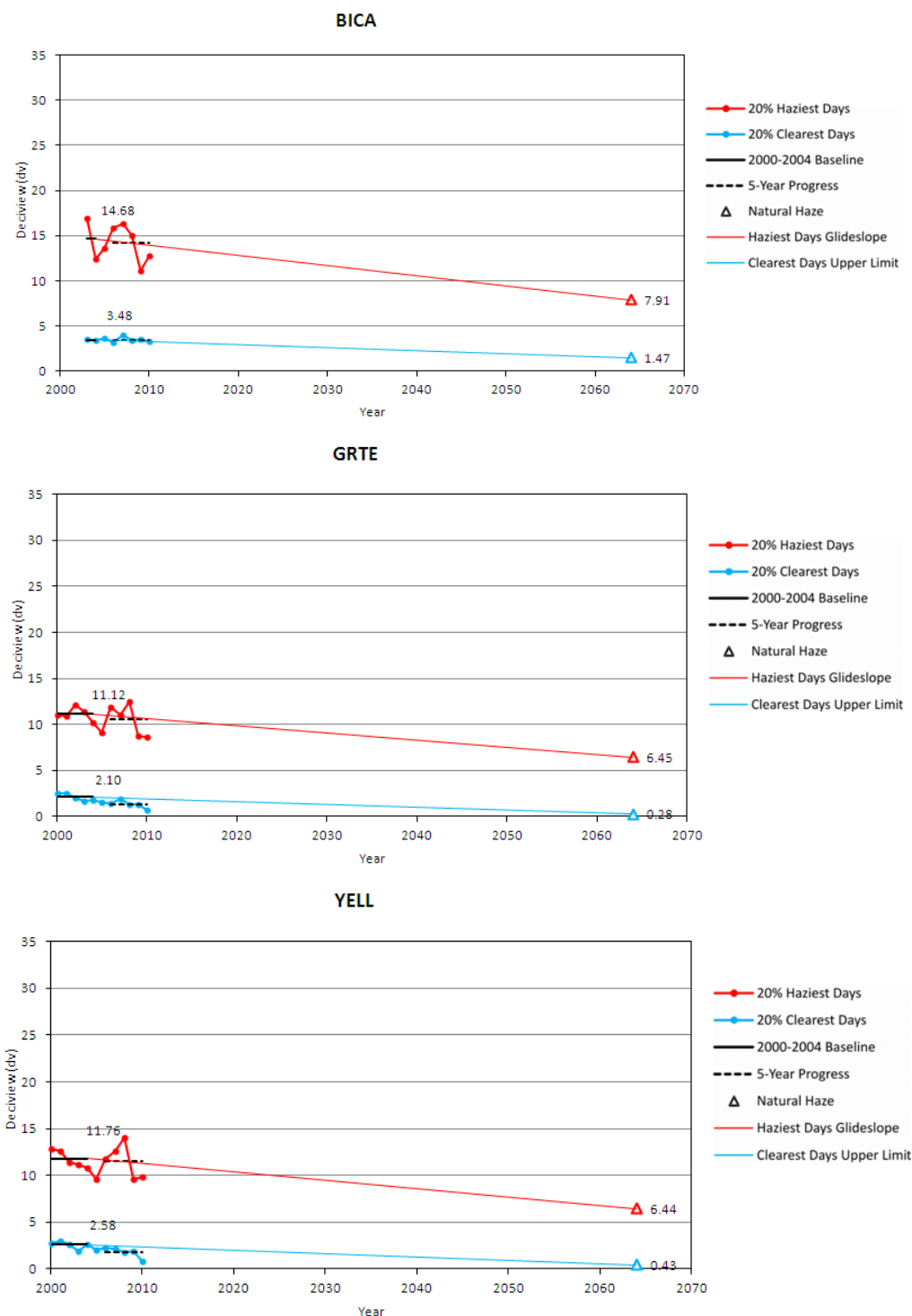


Figure 4. Glideslopes to achieving natural visibility conditions in 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in BICA, GRTE, and YELL. In the regional haze rule, the clearest days do not have a uniform rate of progress glideslope; the rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. Data for BICA and GRTE were taken from nearby sites (NOCH1 and BRID1, respectively). BICA has no valid, measured or substituted data for the years 2000-2002. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

Eagles-Smith et al. (2014) sampled fish in 21 national parks and analyzed them for Hg concentrations in tissue. Results varied substantially by park and by water body. Mean fish Hg concentrations in YELL (101 ng/g ww) were higher than the mean across all study parks. The size-adjusted values were among the highest measured in this study. However, natural geothermal concentrations of Hg might play a role in this observation. Concentrations of Hg in fish collected from two lakes and one stream in GRTE were very low, compared with other study parks.

Lake whitefish (*Coregonus clupeaformis*) and bull trout (*Salvelinus confluentus*), sampled from Lake McDonald in GLAC exhibited high Hg concentrations compared with other species and parks. Levels approached or exceeded the EPA criterion for protection of human health and the level at which reproductive impairment could occur in piscivorous birds (Eagles-Smith et al. 2014). Toxicity of Hg in fish is a particular concern because bull trout is federally listed as a threatened species. In contrast, Landers et al. (2008) found low Hg concentrations in fish from two other lakes in GLAC, suggesting substantial lake-to-lake variability.

Keteles (2011) collected surface water samples from high-elevation areas of ROMO, GRSA, GRTE, and GLAC during the summer, 2009 and analyzed them for pesticides. High levels of contaminant deposition can occur at high elevation in the Rocky Mountains due to high precipitation, upslope winds, and the process of cold condensation, whereby chemicals volatilize in warm locations (i.e., low-elevation agricultural areas) and subsequently condense when they reach colder areas in the mountains (Blais et al. 1998). Concentrations of pesticides in water were compared with EPA Office of Pesticide Programs Aquatic life benchmarks for freshwater species and to toxicity values determined in other programs (Kegley et al. 2011). The measured concentrations in this screening study suggested low pesticide concentration values in these national parks, far below the aquatic life benchmarks (Keteles 2011).

References Cited

- Air Resource Specialists. 2007. VISTAS Conceptual Description Support Document. Report prepared for Visibility Improvement State and Tribal Association of the Southeast. Fort Collins, CO.
- Benedict, K.B., C.M. Carrico, S.M. Kreidenweis, B. Schichtel, W.C. Malm, and J.L. Collett. 2013. A seasonal nitrogen deposition budget for Rocky Mountain National Park. *Ecol. Appl.* 23(5):1156-1169. 10.1890/12-1624.1.
- Blais, J.M., D.W. Schindler, D.C.G. Muir, L.E. Kimpe, D.B. Donald, and B. Rosenberg. 1998. Accumulation of persistent organochlorine compounds in mountains of Western Canada. *Nature* 395:585-588.
- Byun, D. and K.L. Schere. 2006. Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. *Applied Mechanics Reviews* 59:51-77.
- Campbell, D.H., D.W. Clow, G.P. Ingersoll, M.A. Mast, N.E. Spahr, and J.T. Turk. 1995. Nitrogen deposition and release in alpine watersheds, Loch Vale, Colorado, USA. *In* K.A. Tonnessen, M.W. Williams and M. Tranter (Eds.). *Biogeochemistry of seasonally snow covered catchments. Proceedings of a Boulder Symposium July 1995.* IAHS Pub. No. 228. pp. 243-253.
- Campbell, D.H., C. Kendall, C.C.Y. Chang, S.R. Silva, and K.A. Tonnessen. 2002. Pathways for nitrate release from an alpine watershed: determination using $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$. *Water Resour. Res.* 31:2811-2821.
- Clow, D.W., R. Striegl, L. Nanus, M.A. Mast, D.H. Campbell, and D.P. Krabbenhoft. 2002. Chemistry of selected high-elevation lakes in seven national parks in the Western United States. *Water, Air, & Soil Pollution Focus* 2(2):139-164.
- Corbin, J.A. and S.W. Woods. 2004. Effects of Atmospheric Deposition on Water Quality in High Alpine Lakes of Grand Teton National Park, Wyoming. University of Montana.
- Drever, J.I. and D.R. Hurcomb. 1986. Neutralization of atmospheric acidity by chemical weathering in an alpine drainage basin in the North Cascade Mountains. *Geology* 14:221-224.
- Eagles-Smith, C.A., J.J. Willacker, Jr., and C.M. Flanagan Pritz. 2014. Mercury in Fishes from 21 National Parks in the Western United States - Inter- and Intra-Park Variation in Concentrations and Ecological Risk. U.S. Geological Survey Open-File Report 2014-1051. <http://dx.doi.org/10.3133/ofr20141051>.
- Ellis, R.A., D.J. Jacob, M.P. Sulprizio, L. Zhang, C.D. Holmes, B.A. Schichtel, T. Blett, E. Porter, L.H. Pardo, and J.A. Lynch. 2013. Present and future nitrogen deposition to national parks in the

- United States: critical load exceedances. *Atmos. Chem. Phys.* 13(17):9083-9095. 10.5194/acp-13-9083-2013.
- Fenn, M.E., R. Haeuber, G.S. Tonnesen, J.S. Baron, S. Grossman-Clark, D. Hope, D.A. Jaffe, S. Copeland, L. Geiser, H.M. Rueth, and J.O. Sickman. 2003. Nitrogen emissions, deposition, and monitoring in the western United States. *BioScience* 53(4):391-403.
- Geiser, L.H., S.E. Jovan, D.A. Glavich, and M.K. Porter. 2010. Lichen-based critical loads for atmospheric nitrogen deposition in western Oregon and Washington forests, USA. *Environ. Pollut.* 158:2412-2421.
- Gibson, J.H., J.N. Galloway, C.L. Schofield, W. McFee, R. Johnson, S. McCorley, N. Dise, and D. Herzog. 1983. Rocky Mountain Acidification Study. FWS/OBS-80/40.17. U.S. Fish and Wildlife Service, Department of Biological Services Eastern Energy and Land Use Team, Washington D.C.
- Grenon, J. and M. Story. 2009. U.S. Forest Service Region 1. Lake Chemistry, NADP, and IMPROVE Air Quality Data Analysis. Gen. Tech. Rep. RMRS-GTR-230WWW. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Gulley, D.D. and M. Parker. 1985. A limnological survey of 70 small lakes and ponds in Grand Teton National Park. Dept. Zoology and Physiology, Univ. of Wyoming, Laramie.
- Heck, W.W. and E.B. Cowling. 1997. The need for a long term cumulative secondary ozone standard - an ecological perspective. *Ecological Manager*:22-33.
- Ingersoll, G.P. 1999. Effects of snowmobile use on snowpack chemistry in Yellowstone National Park, 1998. Water-Resources Investigations Report 99-4148. U.S. Geological Survey, in cooperation with the National Park Service, Denver, Colorado.
- Ingersoll, G.P., M.A. Mast, L. Nanus, D.J. Manthorne, H.H. Handran, D.M. Hulstrand, and J. Winterringer. 2005. Rocky Mountain snowpack chemistry at selected sites, 2003. Open-File Report 2005-1332. U.S. Department of the Interior, Reston, VA.
- Ingersoll, G.P., M.A. Mast, D.H. Campbell, D.W. Clow, L. Nanus, and J.T. Turk. 2008. Trends in Snowpack Chemistry and Comparison to National Atmospheric Deposition Program Results for the Rocky Mountains, US 1993-2004. *Atmos. Environ.* 42:6098-6113.
- Ingersoll, G.P., M.A. Mast, J.M. Swank, and C.D. Campbell. 2011. Rocky Mountain Snowpack Physical and Chemical Data for Selected Sites, 2010. U.S. Geological Survey Data Series 570.
- Interlandi, S.J. and S.S. Kilham. 1998. Assessing the effects of nitrogen deposition on mountain waters: a study of phytoplankton community dynamics. *Water Sci. Technol.* 38:139-146.
- Jaffe, D., D. Chand, W. Hafner, A. Westerling, and D. Spracklen. 2008. Influence of fires on O₃

- concentrations in the western U.S. *Environ. Sci. Technol.* 42:5885-5891.
- Kahl, J.S., S.A. Norton, T.A. Haines, E.A. Rochette, R.C. Heath, and S.C. Nodvin. 1992. Mechanisms of episodic acidification in low-order streams in Maine, USA. *Environ. Pollut.* 78:37-44.
- Kegley, S.E., B.R. Hill, O. S., and A.H. Choi. 2011. PAN Pesticide Database. Pesticide Action Network, North America., San Francisco, CA. Available at <http://www.pesticideinfo.org>.
- Keteles, K. 2011. Screening for Pesticides in High Elevation Lakes in Federal Lakes. U.S. EPA Region 8, Denver, CO.
http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCAQFjAA&url=http%3A%2F%2Fwww.nature.nps.gov%2Fair%2FPubs%2Fpdf%2Ftoxics%2FKeteles_pesticides_2011.pdf&ei=jz2OU_GKDoyAogSE7oKgCw&usg=AFQjCNEfs1NTyHc-x9rdCjqa8RBqC060w.
- Kohut, R. 2007a. Assessing the risk of foliar injury from ozone on vegetation in parks in the U.S. National Park Service's Vital Signs Network. *Environ. Pollut.* 149:348-357.
- Kohut, R.J. 2007b. Ozone Risk Assessment for Vital Signs Monitoring Networks, Appalachian National Scenic Trail, and Natchez Trace National Scenic Trail. Natural Resource Technical Report NPS/NRPC/ARD/NRTR—2007/001. National Park Service, Natural Resource Program Center, Fort Collins, CO.
<http://www.nature.nps.gov/air/pubs/pdf/03Risk/OzoneRiskAssessmentsCoverRev20070227.pdf>.
- Komp, M.R., A.J. Nadeau, E. Iverson, L. Danzinger, S. Amberg, K. Kilkus, J. Sopcak, C. Jean, M. Myers, and B. Draskowski. 2012. Bighorn Canyon National Recreation Area. Natural Resource Condition Assessment. Natural Resource Report NPS/BICA/NRR - 2012/554. U.S. Department of the Interior, National Park Service, Natural Resource Stewardship and Science, Fort Collins, CO.
- Krabbenhoft, D.P., M.L. Olson, J.F. DeWild, D.W. Clow, R.G. Striegl, M.M. Dornblaser, and P. VanMetre. 2002. Mercury loading and methylmercury production and cycling in high-altitude lakes from the western United States. *Water, Air, and Soil Pollution: Focus* 2:233-249.
- Landers, D.H., J.M. Eilers, D.F. Brakke, W.S. Overton, P.E. Kellar, W.E. Silverstein, R.D. Schonbrod, R.E. Crowe, R.A. Linthurst, J.M. Omernik, S.A. Teague, and E.P. Meier. 1987. Characteristics of lakes in the western United States - Volume I: population descriptions and physico-chemical relationships. EPA-600/3-86/054a. U.S. Environmental Protection Agency, Washington, D.C.
- Landers, D.H., S.L. Simonich, D.A. Jaffe, L.H. Geiser, D.H. Campbell, A.R. Schwindt, C.B. Schreck, M.L. Kent, W.D. Hafner, H.E. Taylor, K.J. Hageman, S. Usenko, L.K. Ackerman, J.E. Schrlau, N.L. Rose, T.F. Blett, and M.M. Erway. 2008. The Fate, Transport, and Ecological

- Impacts of Airborne Contaminants in Western National Parks (USA). EPA/600/R-07/138. U.S. Environmental Protection Agency, Office of Research and Development, NHEERL, Western Ecology Division, Corvallis, Oregon. <http://www.epa.gov/nheerl/wacap/>.
- Lawrence, G.B. 2002. Persistent episodic acidification of streams linked to acid rain effects on soil. *Atmos. Environ.* 36:1589-1598.
- Lefohn, A.S., W. Jackson, D.S. Shadwick, and H.P. Knudson. 1997. Effect of surface ozone exposures on vegetation grown in the Southern Appalachian Mountains: Identification of possible areas of concern. *Atmos. Environ.* 31(11):1695-1708.
- Lefohn, A.S. 2011. Comments on the Integrated Science Assessment for Ozone and Related Photochemical Oxidants: Chapter 9. Environmental Effects: Ozone Effects on Vegetation and Ecosystems. Draft Report to National Park Service. A.S.L. & Associates.
- Lehmann, C.M.B., V.C. Bowersox, and S.M. Larson. 2005. Spatial and temporal trends of precipitation chemistry in the United States, 1985-2002. *Environ. Pollut.* 135:347-361.
- Ley, R., M.W. Williams, and S.K. Schmidt. 2004. Microbial population dynamics in an extreme environment: controlling factors in talus soils at 3750 m in the Colorado Rocky Mountains. *Biogeochemistry* 68(3):297-311.
- Malm, W.C., B.A. Schichtel, R.B. Ames, and K.A. Gebhart. 2002. A 10-year spatial and temporal trend of sulfate across the United States. *J. Geophys. Res.* 107(D22, 4627).
- Marcus, M.D., B.R. Parkhurst, R.W. Brocksen, and F.E. Payne. 1983. An assessment of the relationship among acidifying deposition, surface water acidification, and fish populations in North America. Vol. 1. Electric Power Research Institute.
- McDonnell, T.C., S. Belyazid, T.J. Sullivan, H. Sverdrup, W.D. Bowman, and E.M. Porter. 2014. Modeled subalpine plant community response to climate change and atmospheric nitrogen deposition in Rocky Mountain National Park, USA. *Environ. Pollut.* 187:55-64.
- Melack, J.M., S.C. Cooper, T.M. Jenkins, L. Barmuta, Jr., S. Hamilton, K. Kratz, J. Sickman, and C. Soiseth. 1989. Chemical and biological characteristics of Emerald Lake and the streams in its watershed, and the response of the lake and streams to acidic deposition. Final Report to the California Air Resource Board, Contract A6-184-32, Sacramento, CA.
- Nanus, L., D.H. Campbell, and M.W. Williams. 2005. Sensitivity of alpine and subalpine lakes to acidification from atmospheric deposition in Grand Teton National Park and Yellowstone National Park, Wyoming. U.S. Department of Interior, U.S. Geological Survey.
- Nanus, L., M.W. Williams, D.H. Campbell, K.A. Tonnessen, T. Blett, and D.W. Clow. 2009. Assessment of lake sensitivity to acidic deposition in national parks of the Rocky Mountains. *Ecol. Appl.* 19(4):961-973.

- Nanus, L., D.W. Clow, J.E. Saros, V.C. Stephens, and D.H. Campbell. 2012. Mapping critical loads of nitrogen deposition for aquatic ecosystems in the Rocky Mountains, USA. *Environ. Pollut.* 166:125-135.
- National Acid Precipitation Assessment Program (NAPAP). 1991. Integrated Assessment Report. National Acid Precipitation Assessment Program, Washington, DC.
- National Park Service (NPS). 2010. Air quality in national parks: 2009 annual performance and progress report. Natural Resource Report NPS/NRPC/ARD/NRR-2010/266. National Park Service, Air Resources Division, Denver, CO.
- Pardo, L.H., M.E. Fenn, C.L. Goodale, L.H. Geiser, C.T. Driscoll, E.B. Allen, J.S. Baron, R. Bobbink, W.D. Bowman, C.M. Clark, B. Emmett, F.S. Gilliam, T.L. Greaver, S.J. Hall, E.A. Lilleskov, L. Liu, J.A. Lynch, K.J. Nadelhoffer, S.S. Perakis, M.J. Robin-Abbott, J.L. Stoddard, K.C. Weathers, and R.L. Dennis. 2011a. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. *Ecol. Appl.* 21(8):3049-3082.
- Pardo, L.H., M.J. Robin-Abbott, and C.T. Driscoll (Eds.). 2011b. Assessment of Nitrogen Deposition Effects and Empirical Critical Loads of Nitrogen for Ecoregions of the United States. General Technical Report NRS-80. U.S. Forest Service, Newtown Square, PA.
- Peterson, D.A. and G.K. Boughton. 2000. Organic compounds and trace elements in fish tissue and bed sediment from streams in the Yellowstone River Basin, Montana and Wyoming, 1998. U.S. Department of the Interior, U.S. Geological Survey, Cheyenne, Wyoming.
- Peterson, D.L., T.J. Sullivan, J.M. Eilers, S. Brace, D. Horner, K. Savig, and D. Morse. 1998. Assessment of air quality and air pollutant impacts in national parks of the Rocky Mountains and Northern Great Plains. NPS D-657. U.S. Department of the Interior, National Park Service, Air Resources Division.
- Ramsey, R.D., C.M. McGinty, E.I.L. McGinty, L.A.L. Stoner, B.A. Crabb, W.A. Adair, A. Hernandez, J.C. Schmidt, M. Majerova, B. Hudson, and A.K. Montrone. 2012. Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. Natural Resource Condition Assessment. Natural Resource Report NPS/GRYN/NRR - 2012/550. U.S. Department of the Interior, National Park Service. Natural Resource Stewardship and Science, Fort Collins, CO.
- Ray, J.D. 2012. Winter Air Quality in Yellowstone National Park: 2009–2011. Natural Resource Technical Report NPS/NRSS/ARD/NRTR—2012/551. National Park Service, Denver, CO.
- Reuss, J.O., F.A. Vertucci, R.C. Musselman, and R.A. Sommerfeld. 1995. Chemical fluxes and sensitivity to acidification of two high-elevation catchments in southern Wyoming. *J. Hydrol.* 173:165-189.
- Saros, J.E., D.W. Clow, T. Blett, and A.P. Wolfe. 2011. Critical nitrogen deposition loads in high-

- elevation lakes of the western US inferred from paleolimnological records. *Water Air Soil Pollut.* 216:193-202.
- Schoettle, A.W., K. Tonnessen, J. Turk, J. Vimont, and R. Amundson. 1999. An Assessment of the Effects of Human-Caused Air Pollution on Resources Within the Interior Columbia River Basin. PNW-GTR-447. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
- Schwede, D.B. and G.G. Lear. 2014. A novel hybrid approach for estimating total deposition in the United States. *Atmos. Environ.* 92:207-220. <http://dx.doi.org/10.1016/j.atmosenv.2014.04.008>.
- Stoddard, J., J.S. Kahl, F.A. Deviney, D.R. DeWalle, C.T. Driscoll, A.T. Herlihy, J.H. Kellogg, P.S. Murdoch, J.R. Webb, and K.E. Webster. 2003. Response of Surface Water Chemistry to the Clean Air Act Amendments of 1990. EPA 620/R-03/001. U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Research Triangle Park, NC.
- Story, M.T., J. Shea, T. Svalberg, M. Hektner, and G. Ingersoll. 2006. Greater Yellowstone Area Air Quality Assessment Update. *In* A.W. Biel (Ed.) Greater Yellowstone public lands: A century of discovery, hard lessons, and bright prospects: Proceedings of the 8th Biennial Scientific Conference on the Greater Yellowstone Ecosystem, October 17-19, 2005, Mammoth Hotsprings Hotel. Yellowstone Center for Resources, Yellowstone National Park, WY. pp. 159-169.
- Suarez-Murias, T., J. Glass, E. Kim, L. Melgoza, and T. Najita. 2009. California Regional Haze Plan. California Environmental Protection Agency, Air Resources Board.
- Sullivan, T.J. and J.M. Eilers. 1994. Assessment of deposition levels of sulfur and nitrogen required to protect aquatic resources in selected sensitive regions of North America. Final Report prepared for Technical Resources, Inc., Rockville, MD, under contract to U.S. Environmental Protection Agency, Environmental Research Laboratory-Corvallis. E&S Environmental Chemistry, Inc., Corvallis, OR.
- Sullivan, T.J. 2000. Aquatic Effects of Acidic Deposition. Lewis Publ./CRC Press, Boca Raton, FL.
- Sullivan, T.J., T.C. McDonnell, G.T. McPherson, S.D. Mackey, and D. Moore. 2011a. Evaluation of the Sensitivity of Inventory and Monitoring National Parks to Nutrient Enrichment Effects from Atmospheric Nitrogen Deposition. Natural Resource Report NPS/NRPC/ARD/NRR—2011/313. U.S. Department of the Interior, National Park Service, Denver. <http://www.nature.nps.gov/air/permits/aris/networks/n-sensitivity.cfm>.
- Sullivan, T.J., G.T. McPherson, T.C. McDonnell, S.D. Mackey, and D. Moore. 2011b. Evaluation of the Sensitivity of Inventory and Monitoring National Parks to Acidification Effects from Atmospheric Sulfur and Nitrogen Deposition. U.S. Department of the Interior, National Park Service, Denver. <http://nature.nps.gov/air/Permits/ARIS/networks/acidification-eval.cfm>.

- Sullivan, T. J. 2016. Air quality related values (AQRVs) in national parks: Effects from ozone; visibility reducing particles; and atmospheric deposition of acids, nutrients and toxics. Natural Resource Report NPS/NRSS/ARD/NRR—2016/1196. National Park Service, Fort Collins, CO.
- Turk, J.T. and N.E. Spahr. 1991. Rocky Mountains. *In* D.F. Charles (Ed.) *Acidic deposition and aquatic ecosystems: regional case studies*. Springer-Verlag, New York. pp. 471-501.
- U.S. Environmental Protection Agency. 1995. Acid Deposition Standard Feasibility Study Report to Congress. EPA 430-R-95-001a. U. S. EPA, Office of Air and Radiation, Acid Rain Division.
- Western Regional Climate Center. 2004. Available at: <http://www.wrcc.dri.edu>. (Accessed December, 2004).
- Wigington, P.J. 1999. Episodic acidification: causes, occurrence and significance to aquatic resources. *In* J.R. Drohan (Ed.) *The effects of acidic deposition on aquatic ecosystems in Pennsylvania*. 1998 PA acidic deposition conference. Environmental Resources Research Institute, University Park, PA. pp. 1-5.
- Wigington, P.J., Jr., D.R. DeWalle, P.S. Murdoch, W.A. Kretser, H.A. Simonin, J. Van Sickle, and J.P. Baker. 1996. Episodic acidification of small streams in the northeastern United States: ionic controls of episodes. *Ecol. Appl.* 6(2):389-407.
- Williams, M.W. and J.M. Melack. 1991. Precipitation chemistry in and ionic loading to an alpine basin, Sierra Nevada. *Water Resour. Res.* 27:1563-1574.
- Williams, M.W. and K.A. Tonnessen. 2000. Critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA. *Ecol. Appl.* 10:1648-1665.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 960/132061, March 2016

National Park Service
U.S. Department of the Interior



Natural Resource Stewardship and Science

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

2016

NationalParkService.
CENTENNIAL

EXPERIENCE YOUR AMERICA™