



Air Quality Related Values (AQRVs) for Cumberland Piedmont Network (CUPN) Parks

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

Natural Resource Report NPS/CUPN/NRR—2016/1164



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 Cumberland Piedmont Network (CUPN) Parks

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

Natural Resource Report NPS/CUPN/NRR—2016/1164

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

March 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 Cumberland Piedmont Network (CUPN) parks: Effects from ozone; visibility reducing particles; and atmospheric deposition of acids, nutrients and toxics. Natural Resource Report NPS/CUPN/NRR—2016/1164. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures.....	iv
Tables.....	iv
Maps.....	v
Summary.....	vi
Background.....	1
Atmospheric Emissions and Deposition	3
Acidification	10
Acidification of Terrestrial Ecosystems	15
Acidification of Aquatic Ecosystems	15
Nutrient Nitrogen Enrichment	16
Ozone Injury to Vegetation	19
Ozone Exposure Indices and Concentrations	20
Ozone Formation.....	21
Visibility Degradation.....	23
Natural Background and Ambient Visibility Conditions	23
Trends in Visibility.....	27
Development of State Implementation Plans	27
Toxic Airborne Contaminants.....	29
References.....	31

Figures

	Page
Figure 1a. Estimated natural, baseline, and current levels of haze and its composition on the 20% clearest, annual average, and 20% haziest visibility days for ABLI and MACA.....	26
Figure 1b. Estimated natural, baseline and current levels of haze and its composition on the 20% clearest, annual average, and 20% haziest visibility days for FODO.	27
Figure 2. Trends in ambient haze levels at ABLI, FODO, and MACA, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record.....	29
Figure 3. Glideslopes to achieving natural visibility conditions in 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in ABLI, FODO, and MACA.....	30

Tables

	Page
Table 1. Changes in SO ₂ emissions during the 1990s near the CUPN parks	Error! Bookmark not defined.
Table 2. Average changes in S and N deposition between 2001 and 2011 across park grid cells at CUPN parks	7
Table 3. Estimated I&M park rankings ¹ according to risk of acidification impacts on sensitive receptors	15
Table 4. Distribution of steady-state critical loads of sulfur (in kg/ha/yr) to protect stream ANC = 50 µeq/L for parks modeled in the EMDS project within the CUPN).	16
Table 5. Estimated park rankings ¹ according to risk of nutrient enrichment impacts on sensitive receptors	17
Table 6. Empirical critical loads for nitrogen in the CUPN, by ecoregion and receptor from Pardo et al. (2011b).....	18
Table 7. Ozone-sensitive and bioindicator plant species known or thought to occur in the I&M parks of the CUPN	19
Table 8. Ozone assessment results for I&M parks in the CUPN based on estimated average 3-month W126 and SUM06 ozone exposure indices for the period 2005-2009 and Kohut's (2007) ozone risk ranking for the period 1995-19991.....	20
Table 9. Estimated natural haze and measured ambient haze in I&M parks averaged over the period 2004 through 2008 ¹	24

Maps

	Page
Map 1. Network boundary and locations of parks and population centers having more than 10,000 people near the CUPN.....	2
Map 2. Total SO ₂ emissions, by county, near the CUPN for the year 2011	4
Map 3. Total NO _x emissions, by county, near the CUPN for the year 2011.....	5
Map 4. Total NH ₃ emissions, by county, near the CUPN for the year 2011.....	6
Map 5. Total S deposition for the three-year period centered on 2011 in and around the CUPN	11
Map 6. Total oxidized inorganic N deposition for the three-year period centered on 2011 in and around the CUPN	12
Map 7. Reduced inorganic N deposition for the three-year period centered on 2011 in and around the CUPN	13
Map 8. Total N deposition for the three-year period centered on 2011 in and around the CUPN	14

Summary

This report describes the Air Quality Related Values (AQRVs) of the Cumberland Piedmont Network (CUPN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The CUPN parks that are included in the NPS Inventory and Monitoring (I&M) Program, and discussed in this report, are Abraham Lincoln Birthplace National Historical Park (ABLI), Carl Sandburg Home National Historic Site (CARL), Chickamauga and Chattanooga National Military Park (CHCH), Cowpens National Battlefield (COWP), Cumberland Gap National Historical Park (CUGA), Fort Donelson National Battlefield (FODO), Guilford Courthouse National Military Park (GUCO), Kings Mountain National Military Park (KIMO), Little River Canyon National Preserve (LIRI), Mammoth Cave National Park (MACA), Ninety Six National Historic Site (NISI), Russell Cave National Monument (RUCA), Shiloh National Military Park (SHIL), and Stones River National Battlefield (STRI).

Sullivan et al. (2011a, 2011b) and Kohut (2007) conducted risk assessments for acidification, eutrophication, and ozone (O_3) for all of the CUPN 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 National Parks. Effects from Ozone; Visibility Reducing Particles; and Atmospheric Deposition of Acids, Nutrients and Toxics” (Sullivan 2016).

Emissions from large power plants and urban, industrial, and agricultural sources affect air quality in CUPN parks. There are several large population centers near the network area, including Nashville, TN; Chattanooga, TN; Charlotte, NC; Memphis, TN; and Atlanta, GA.

Atmospheric S and N pollutants can cause acidification of streams, lakes, and soils, and levels of atmospheric S and N deposition are high across the CUPN parks. Many streams in these parks have low pH and acid-neutralizing capacity (ANC), suggesting acid sensitivity and/or human-caused acidification. Some of the acidification sensitivity may be attributable to the fact that underlying rocks are low in buffering capacity. Given the relatively high levels of acidic deposition over the last half century in this region, however, it is likely that S and N deposition have also caused some depletion of ANC and pH in some streams. This acidification may have already affected acid-sensitive fish and aquatic invertebrates. Terrestrial species may also be affected by soil acidification. Sugar maple (*Acer saccharum*), a species known to be sensitive to soil acidification, occurs in several of the CUPN parks. Acidification of soils has been linked to sugar maple decline in northeastern forests, but to date not in the CUPN parks (Jernigan et al. 2012).

In addition to contributing to acidification, N deposition can also cause undesirable nutrient enrichment of natural ecosystems, leading to changes in plant species diversity and soil nutrient cycling. Although eastern forests generally have the capacity to assimilate some level of increased N from deposition, sensitive species may be affected at current levels of N deposition in the region.

Ozone pollution can harm human health, reduce plant growth, and cause visible injury to foliage. Ozone concentrations and seasonal exposures are high in the CUPN region, and visible injury to a number of plant species has been documented in CUPN parks (Jernigan et al. 2012).

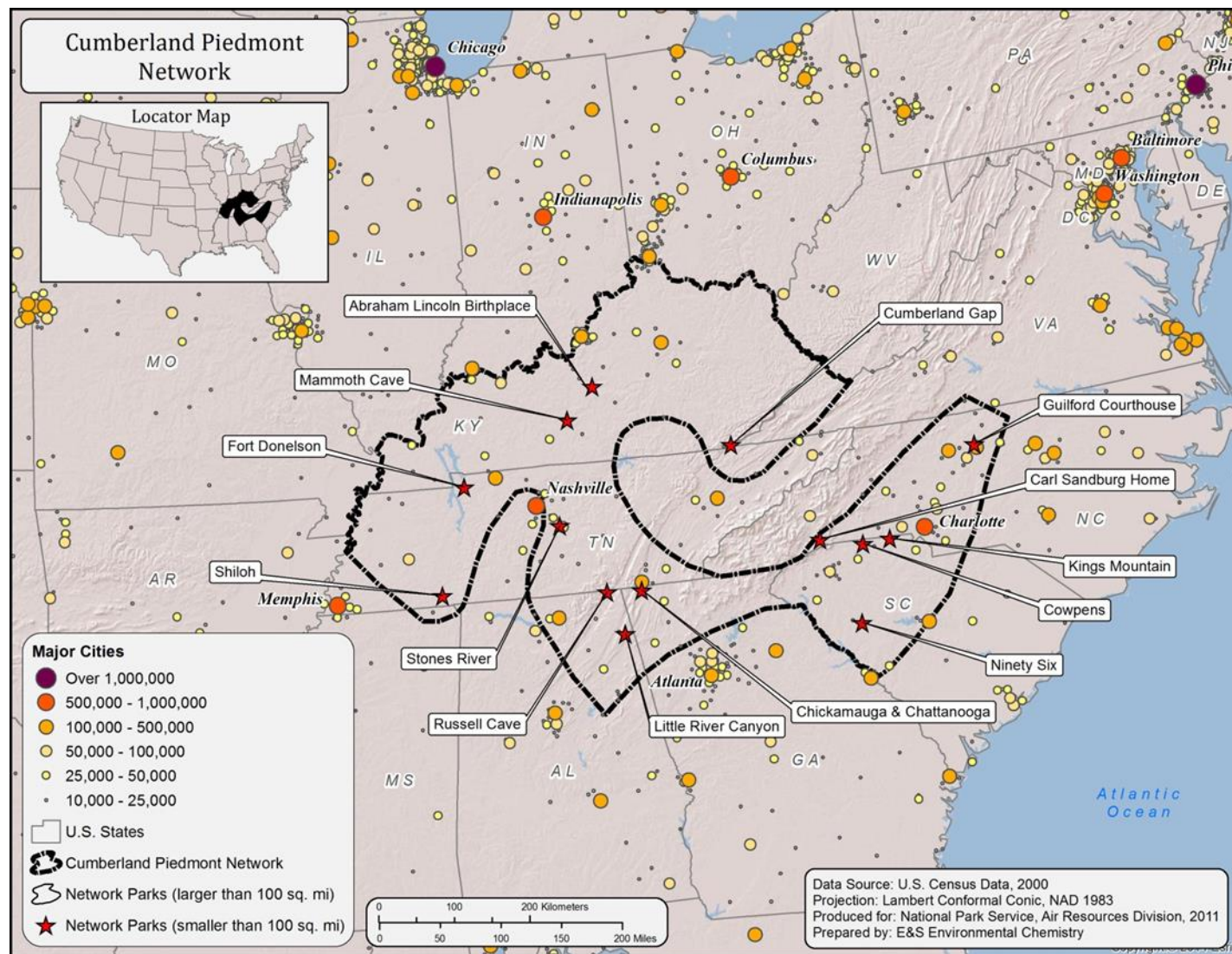
Particulate pollution can cause haze, reducing visibility. Haze levels are high in the CUPN region, primarily as the result of sulfates forming in the atmosphere from sulfur dioxide emitted by coal-burning power plants. Nitrates and organic aerosols also contribute to haze in this network.

Airborne contaminants, including mercury (Hg) and other heavy metals, can accumulate in food webs, reaching toxic levels in top predators. The National Park Service (NPS; 2010) reported long-term trends in concentrations of Hg in wet deposition during the period beginning in 1996 to 2003, and running through 2008 for nine national parks. Mammoth Cave National Park had among the highest wet Hg deposition. Mercury has also been detected in dragonfly larvae and other biota in CUPN parks.

Background

The Cumberland Piedmont Network (CUPN) contains 14 parks: Abraham Lincoln Birthplace National Historical Park (ABLI), Carl Sandburg Home National Historic Site (CARL), Chickamauga and Chattanooga National Military Park (CHCH), Cowpens National Battlefield (COWP), Cumberland Gap National Historical Park (CUGA), Fort Donelson National Battlefield (FODO), Guilford Courthouse National Military Park (GUCO), Kings Mountain National Military Park (KIMO), Little River Canyon National Preserve (LIRI), Mammoth Cave National Park (MACA), Ninety Six National Historic Site (NISI), Russell Cave National Monument (RUCA), Shiloh National Military Park (SHIL), and Stones River National Battlefield (STRI). There are many large population centers (more than 500,000 people) near the network, including Atlanta, Charlotte, Nashville, and Memphis. Map 1 shows the network boundary along with locations of each park and population centers with more than 10,000 people. Land cover in and around the CUPN is variable. The predominant cover types within this network region are generally pasture/hay, forest, and row crop, based on the National Land Cover Dataset. The agricultural and urban land uses may be important source areas for atmospheric nitrogen (N) emissions.

The southeastern United States is geologically diverse and was not glaciated during the most recent period of glaciation. As a consequence, a large number of aquatic animal species have evolved and colonized this region. Streams in the Tennessee-Cumberland aquatic region are among the most biologically diverse in the world (Smith et al. 2002). This region contains the highest diversity of freshwater mussel and crayfish species and the highest levels of aquatic species endemism in North America (Abell et al. 2000, Smith et al. 2002). The region contains 231 species of fish (67 endemic), 125 species of mussels (20 endemic), and 65 species of crayfish (40 endemic). More than 57 species of fish and 47 species of mussels are considered at risk (Abell et al. 2000, Master et al. 1998). Therefore, potential effects of acidic deposition on acid-sensitive streams in this region are of great concern. In nearby Shenandoah National Park (SHEN), for example, it has been estimated that park streams on siliciclastic rock have generally lost one or two species, and some streams may have lost up to four species of fish in response to acidic deposition (Sullivan et al. 2003).



Map 1. Network boundary and locations of parks and population centers having more than 10,000 people near the CUPN.

Atmospheric Emissions and Deposition

County-level sulfur (S) emissions within the CUPN region in 2002 generally ranged from less than 1 ton of sulfur dioxide (SO₂) per square mile per year (ton/mi²/yr) to between 50 and 100 tons/mi²/yr. Most counties in the network region emitted less than 1 ton/mi²/yr year of SO₂, though a few emitted more than 100 tons mi²/yr (Sullivan et al. 2011b). There were several S point sources of substantial magnitude within the network, with some emitting more than 40,000 tons/mi²/yr. There were also many S point sources of considerable magnitude located in close proximity to the network, mostly to the north and south (Sullivan et al. 2011b).

Malm et al. (2002) analyzed spatial patterns in atmospheric sulfate (SO₄²⁻) concentrations throughout the United States from 1988 to 1999 and also atmospheric SO₂ emissions from 1990 to 1999. The 90th percentile summer season atmospheric SO₄²⁻ concentrations were highest along the Ohio River Valley and in central Tennessee, where the density of SO₂ emissions was largest. The atmospheric concentrations of SO₄²⁻ in this region during the 1990s were twice as high as concentrations in the northeastern and coastal southeastern United States. Emissions of SO₂ decreased during the 1990s in some states and increased in others (Table 1).

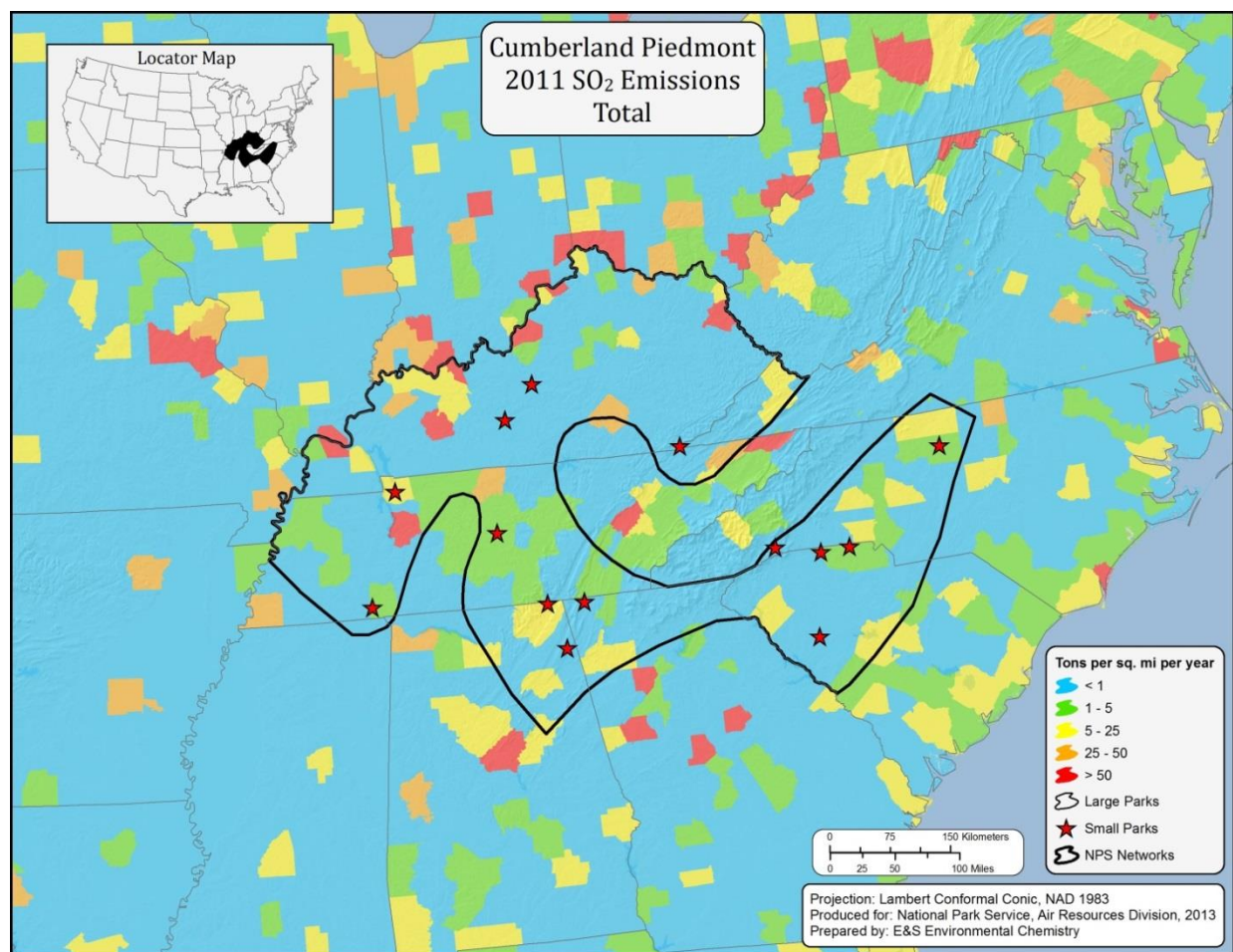
Table 1. Changes in SO₂ emissions during the 1990s near the CUPN parks (Malm et al. 2002).

State	Change in SO ₂ Emissions (%)
Ohio	-35
Indiana	-44
Tennessee	-35
Georgia	-42
Arkansas	+87
Louisiana	+48
North Carolina	+37

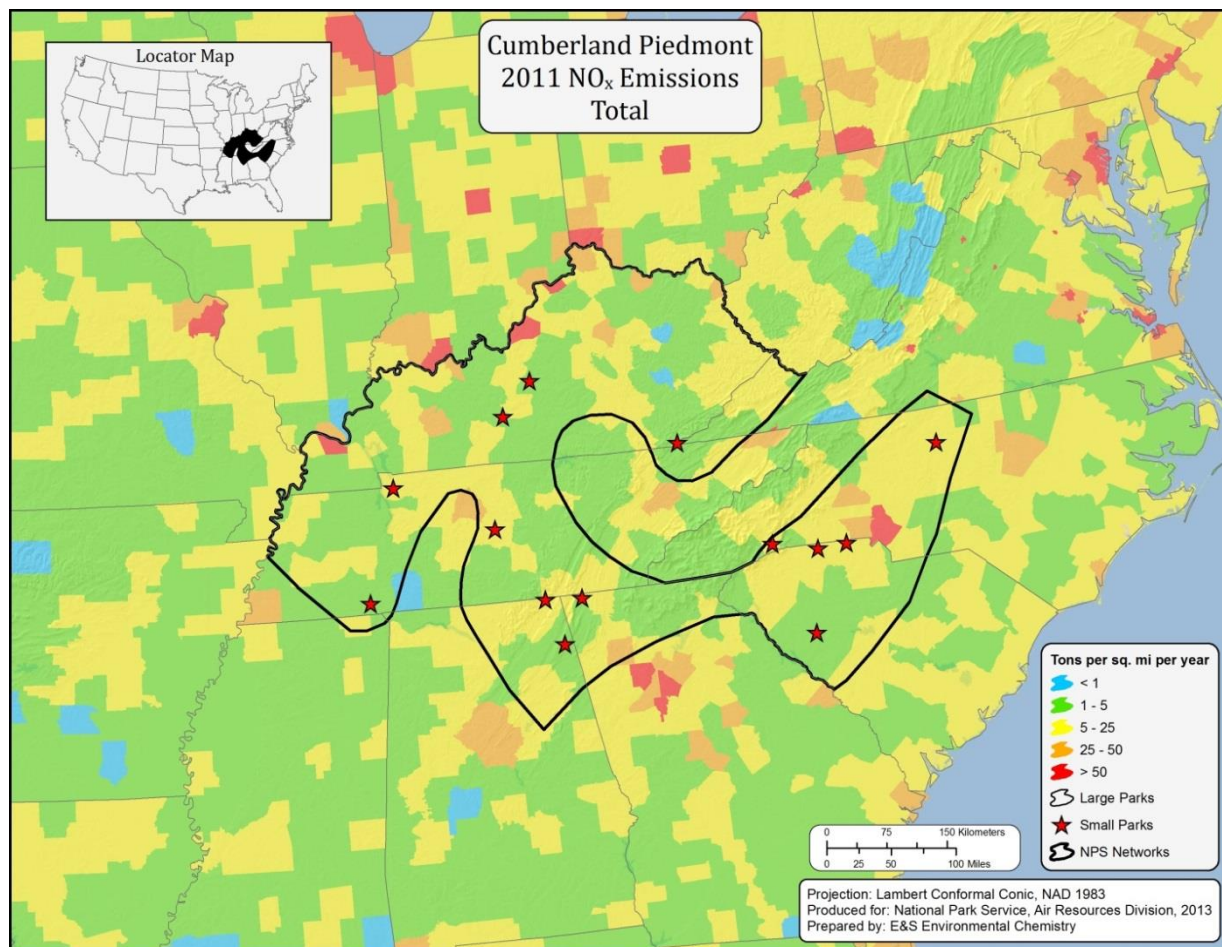
Annual county-level nitrogen (N) emissions within the CUPN region ranged from less than 1 ton/mi²/yr year to between 50 and 100 tons/mi²/yr year. In general, county emissions of N were between 1 and 20 ton/mi²/yr year throughout most of the network region. There were many relatively large (greater than 5,000 tons) point sources of oxidized N (NO_x) emissions located in close proximity to the network (Sullivan et al. 2011b).

County-level emissions near the CUPN, based on data from the EPA's National Emissions Inventory (NEI) during a recent time period (2011), are depicted in Maps 2 through 4 for SO₂, oxidized N (NO_x), and reduced N (NH₃), respectively. Many counties to the north and west of CUPN parks had relatively high SO₂ emissions (> 50 tons/mi²/yr; Map 2). Spatial patterns in NO_x emissions were generally similar, with highest values to the northwest of CUPN parks (Map 3). Emissions of NH₃ near CUPN parks were somewhat lower, with most counties showing emissions levels below 8 tons/mi²/yr (Map 4).

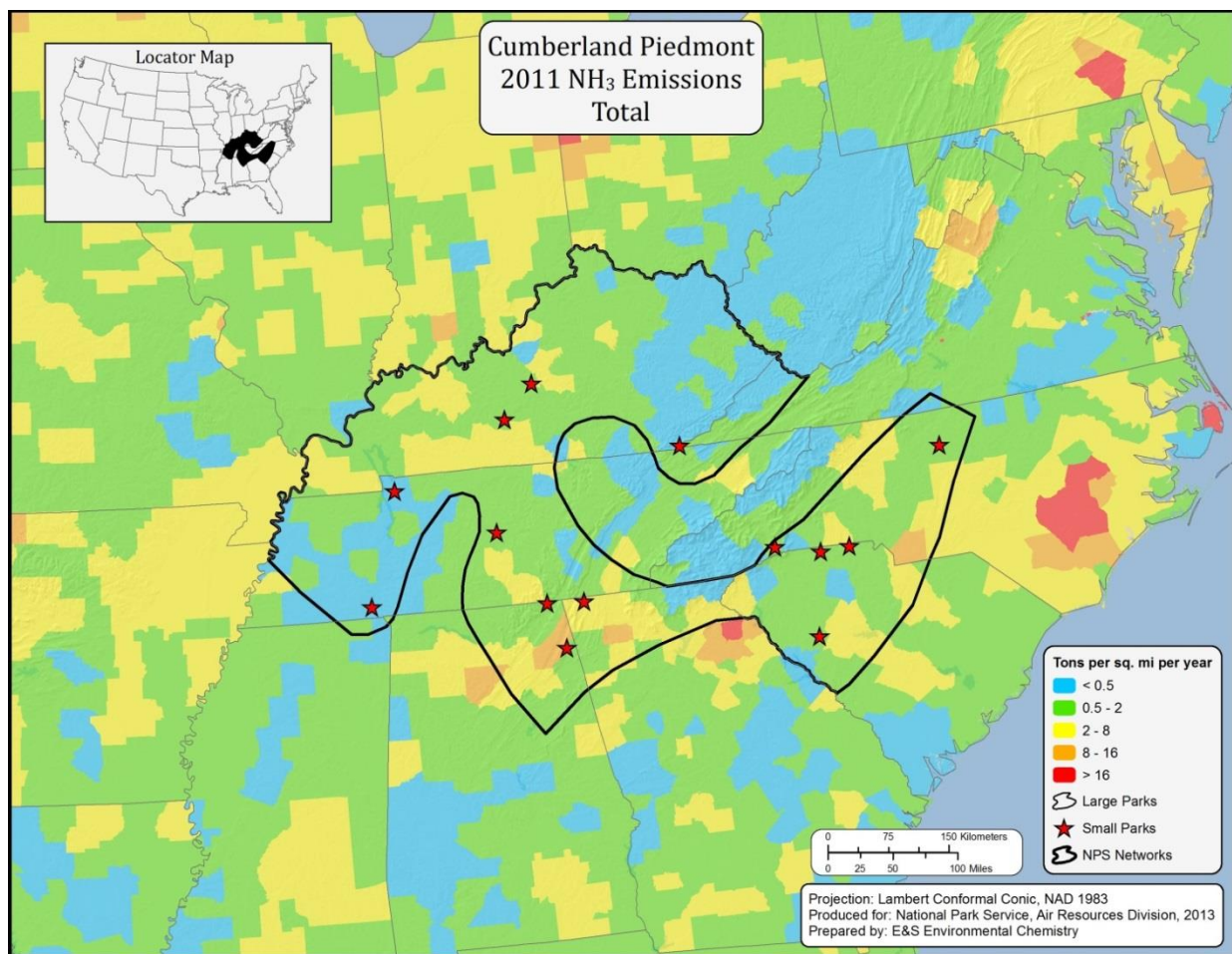
Total S deposition throughout most of the CUPN region generally ranged from about 10 to 15 kg S/ha/yr in 2002, based on Community Multiscale Air Quality (CMAQ) model estimates (Sullivan et al. 2011b). Some areas of the network, predominately in the northern part, were estimated to receive as much as 20 to 30 kg S/ha/yr. Total N deposition within the network ranged from as low as 5 to 10 kg N/ha/yr to as high as 15 to 20 kg N/ha/yr. Throughout most of the network region, total N deposition was relatively high compared to other networks, in the range of 10 to 15 kg N/ha/yr (Sullivan et al. 2011b).



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



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



Map 4. Total NH_3 emissions, by county, near the CUPN for the year 2011. Data from EPA's National Emissions Inventory.

Recently, Schwede and Lear (2014) documented a hybrid approach developed by the National Atmospheric Deposition Program (NADP) Total Deposition (TDEP) Science Committee for estimating total N and S deposition. This approach combined monitoring and modeling data. Modeling was accomplished using the CMAQ model (Byun and Schere 2006). Priority was given to measured data near the locations of the monitors and to modeled data where monitoring data were not available. In addition, CMAQ data were used for N species that are not routinely measured in the monitoring programs: peroxyacetyl nitrate (PAN), 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.

Atmospheric S and NO_x deposition levels have declined at CUPN parks since 2001, based on TDEP estimates (Table 2). Decreases in total S deposition over the previous decade for the parks in this

Table 2. Average changes in S and N deposition between 2001 and 2011 across park grid cells at CUPN 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)
ABLI	Abraham Lincoln Birthplace	Total S	17.03	9.32	-7.71	-45.3%	9.14	9.40	0.26
		Total N	14.16	11.26	-2.90	-20.5%	11.19	11.40	0.21
		Oxidized N	9.34	5.44	-3.89	-41.7%	5.43	5.46	0.03
		Reduced N	4.82	5.81	0.99	20.5%	5.75	5.94	0.19
CARL	Carl Sandburg Home	Total S	8.20	4.48	-3.71	-45.3%	4.48	4.48	0.00
		Total N	8.73	7.72	-1.01	-11.6%	7.72	7.72	0.00
		Oxidized N	6.40	4.50	-1.90	-29.7%	4.50	4.50	0.00
		Reduced N	2.33	3.22	0.89	38.1%	3.22	3.22	0.00
CHCH	Chickamauga and Chattanooga	Total S	11.77	6.15	-5.61	-47.7%	5.93	7.55	1.62
		Total N	13.19	11.32	-1.88	-14.3%	9.28	12.05	2.77
		Oxidized N	9.19	5.61	-3.59	-39.1%	5.03	6.02	0.99
		Reduced N	4.00	5.71	1.71	42.8%	4.24	6.09	1.85
COWP	Cowpens	Total S	8.15	4.21	-3.93	-48.3%	4.21	4.21	0.00
		Total N	9.38	7.60	-1.78	-19.0%	7.60	7.60	0.00
		Oxidized N	6.59	3.97	-2.62	-39.7%	3.97	3.97	0.00
		Reduced N	2.79	3.62	0.83	29.9%	3.62	3.62	0.00
CUGA	Cumberland Gap	Total S	15.64	6.33	-9.29	-59.4%	5.75	7.38	1.63
		Total N	11.13	8.35	-2.76	-24.8%	7.85	9.20	1.35
		Oxidized N	7.85	4.84	-3.00	-38.2%	4.47	5.44	0.97
		Reduced N	3.27	3.52	0.24	7.5%	3.38	3.84	0.47
FODO	Fort Donelson	Total S	13.38	9.66	-3.72	-27.8%	9.66	9.66	0.00
		Total N	11.10	12.80	1.70	15.3%	12.80	12.80	0.00
		Oxidized N	7.87	6.02	-1.85	-23.5%	6.02	6.02	0.00
		Reduced N	3.23	6.78	3.55	109.7%	6.78	6.78	0.00

Table 2 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at CUPN 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)
GUCO	Guilford Courthouse	Total S	10.94	6.15	-4.79	-43.8%	6.15	6.15	0.00
		Total N	12.16	10.47	-1.69	-13.9%	10.47	10.47	0.00
		Oxidized N	8.82	5.45	-3.38	-38.3%	5.45	5.45	0.00
		Reduced N	3.33	5.02	1.69	50.7%	5.02	5.02	0.00
KIMO	Kings Mountain	Total S	9.75	4.94	-4.81	-49.3%	4.88	4.97	0.09
		Total N	11.44	9.71	-1.73	-15.1%	9.35	9.84	0.49
		Oxidized N	8.16	4.97	-3.19	-39.1%	4.80	5.03	0.23
		Reduced N	3.27	4.74	1.47	44.8%	4.55	4.82	0.26
LIRI	Little River Canyon	Total S	12.74	7.38	-5.33	-41.8%	6.30	7.78	1.48
		Total N	14.94	15.31	0.47	3.1%	12.28	16.25	3.98
		Oxidized N	8.47	5.46	-2.99	-35.3%	4.78	5.72	0.94
		Reduced N	6.47	9.86	3.47	54.2%	7.35	10.53	3.18
MACA	Mammoth Cave	Total S	14.78	10.38	-4.40	-29.8%	10.06	10.97	0.91
		Total N	12.73	12.67	-0.06	-0.4%	12.23	13.21	0.98
		Oxidized N	8.48	6.34	-2.14	-25.2%	6.20	6.53	0.34
		Reduced N	4.25	6.33	2.08	49.1%	5.79	6.82	1.03
NISI	Ninety Six	Total S	7.03	3.93	-3.11	-44.2%	3.90	3.94	0.03
		Total N	9.31	6.98	-2.34	-25.1%	6.95	6.99	0.04
		Oxidized N	6.05	3.72	-2.33	-38.5%	3.71	3.73	0.02
		Reduced N	3.27	3.26	-0.01	-0.3%	3.24	3.26	0.02
RUCA	Russell Cave	Total S	14.02	7.38	-6.64	-47.4%	7.23	7.38	0.15
		Total N	13.94	11.38	-2.55	-18.3%	11.11	11.39	0.29

Table 2 (continued). Average changes in S and N deposition between 2001 and 2011 across park grid cells at CUPN 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)
SHIL	Shiloh	Oxidized N	9.44	5.37	-4.07	-43.1%	5.22	5.38	0.16
		Reduced N	4.50	6.01	1.52	33.8%	5.89	6.02	0.13
		Total S	9.21	6.43	-2.78	-30.2%	6.31	7.37	1.06
		Total N	10.51	8.05	-2.47	-23.5%	7.91	8.29	0.38
		Oxidized N	7.35	4.71	-2.64	-35.9%	4.57	4.91	0.33
		Reduced N	3.16	3.34	0.17	5.5%	3.33	3.38	0.05
STRI	Stones River	Total S	11.93	6.49	-5.44	-45.6%	6.48	6.50	0.02
		Total N	12.16	9.89	-2.27	-18.6%	9.71	10.16	0.45
		Oxidized N	8.13	4.99	-3.14	-38.6%	4.92	5.10	0.17
		Reduced N	4.03	4.90	0.87	22.0%	4.79	5.07	0.28

network ranged from 27.8% at FODO to 59.4% at CUGA. Estimated total N deposition ranged from an increase of 15.3% at FODO to a relatively large decrease (-24.8%) at CUGA. Reduced N deposition (NH_4^+ , NH_3) increased at all parks in the CUPN except NISI, which showed a very small decrease; it more than doubled at FODO.

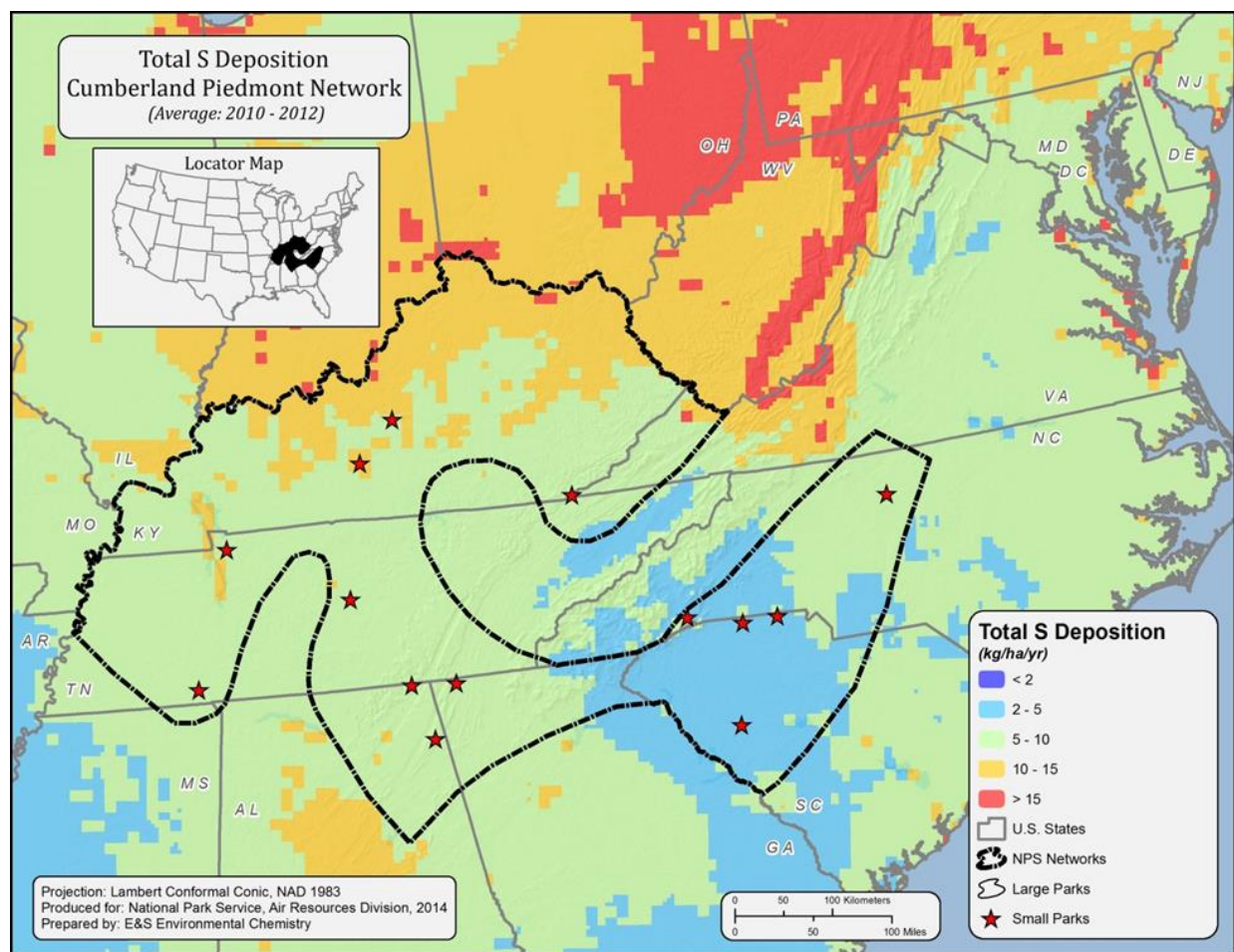
Total S deposition in and around the CUPN for the period 2010-2012 was generally highest (> 10 kg S/ha/yr) to the north and lowest (< 5 kg S/ha/yr) in the southeast portion of the network area (Map 5). Oxidized inorganic N deposition for the period 2010-2012 was less than 10 kg N/ha/yr throughout the park lands within the CUPN (Map 6). Some areas received less than 5 kg N/ha/yr. Reduced inorganic N deposition during this same period was in the range of 5-10 kg N/ha/yr at many park locations (Map 7). Total N deposition was in the range of 10-15 kg N/ha/yr at most park locations (Map 8).

NPS (2010) reported long-term trends in concentrations of mercury (Hg) in wet deposition during the period beginning in 1996 to 2003, and running through 2008, for nine national parks located throughout the conterminous United States. Most of the parks, including MACA in the CUPN, did not show statistically significant ($p \leq 0.05$) changes in wet Hg deposition. Three-year means of annual Hg concentration in wet deposition were reported by NPS (2010) for 13 parks that had at least two years of valid data during the period 2006-2008. MACA had among the highest levels of wet Hg deposition, as did Great Smoky Mountains (GRSM) and SHEN national parks and Indiana Dunes National Lakeshore (INDU) in nearby networks. These results suggest the possibility of higher Hg concentrations in biota of CUPN parks.

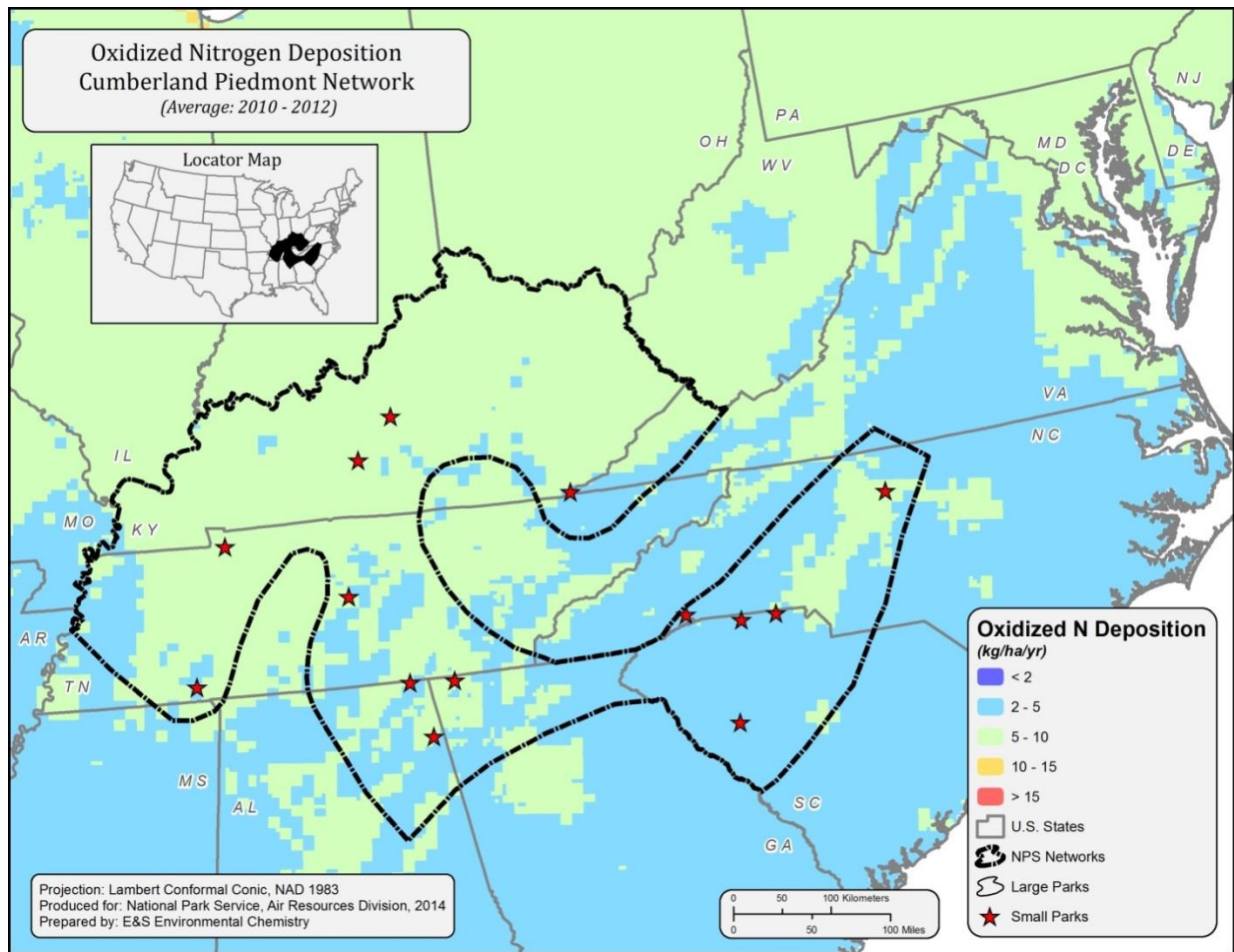
Acidification

The network rankings determined in a coarse screening assessment by Sullivan et al. (2011b) for Acid Pollutant Exposure, Ecosystem Sensitivity to Acidification, and Park Protection yielded an overall network acidification Summary Risk ranking for the CUPN that was relatively high among networks. The overall level of concern for acidification effects on I&M parks within this network was considered by Sullivan et al. (2011b) to be High.

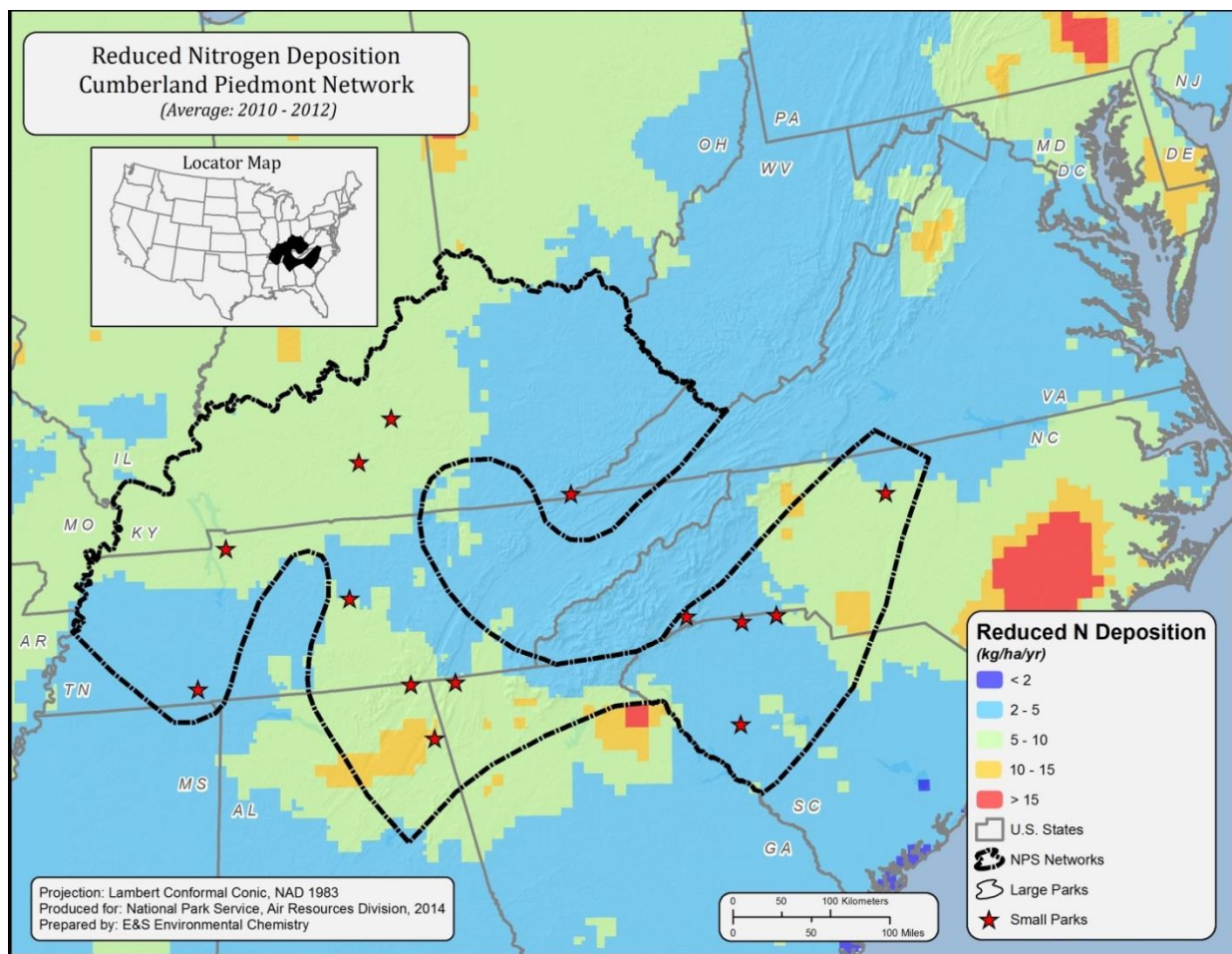
All parks in the CUPN were ranked High or Very High in Acid Pollutant Exposure by Sullivan et al. (2011b; Table 3). Emissions upwind of this network and estimated atmospheric S and N deposition within the network were relatively high among all NPS networks. Estimated Ecosystem Sensitivity to Acidification for the parks in this network varied considerably, ranging from Very Low to Very High (Table 3). Some of the parks in this network contain acid-sensitive vegetation as well as areas known to have acid-sensitive surface waters and/or geology. Ecosystem sensitivity to acidification takes into account elevation and land slope, which often influence the degree of acid neutralization provided by soils and bedrock within the watershed. Most of the parks in the CUPN tend to have relatively low relief, less than 20° in average slope. Two parks, CUGA and RUCA, exhibit slopes in the range of 30° to 40° , suggesting increased potential for acid sensitivity of aquatic ecosystems. While rankings are an indication of risk, park-specific data, particularly data on ecosystem sensitivity, are needed to fully evaluate risk from acidification.



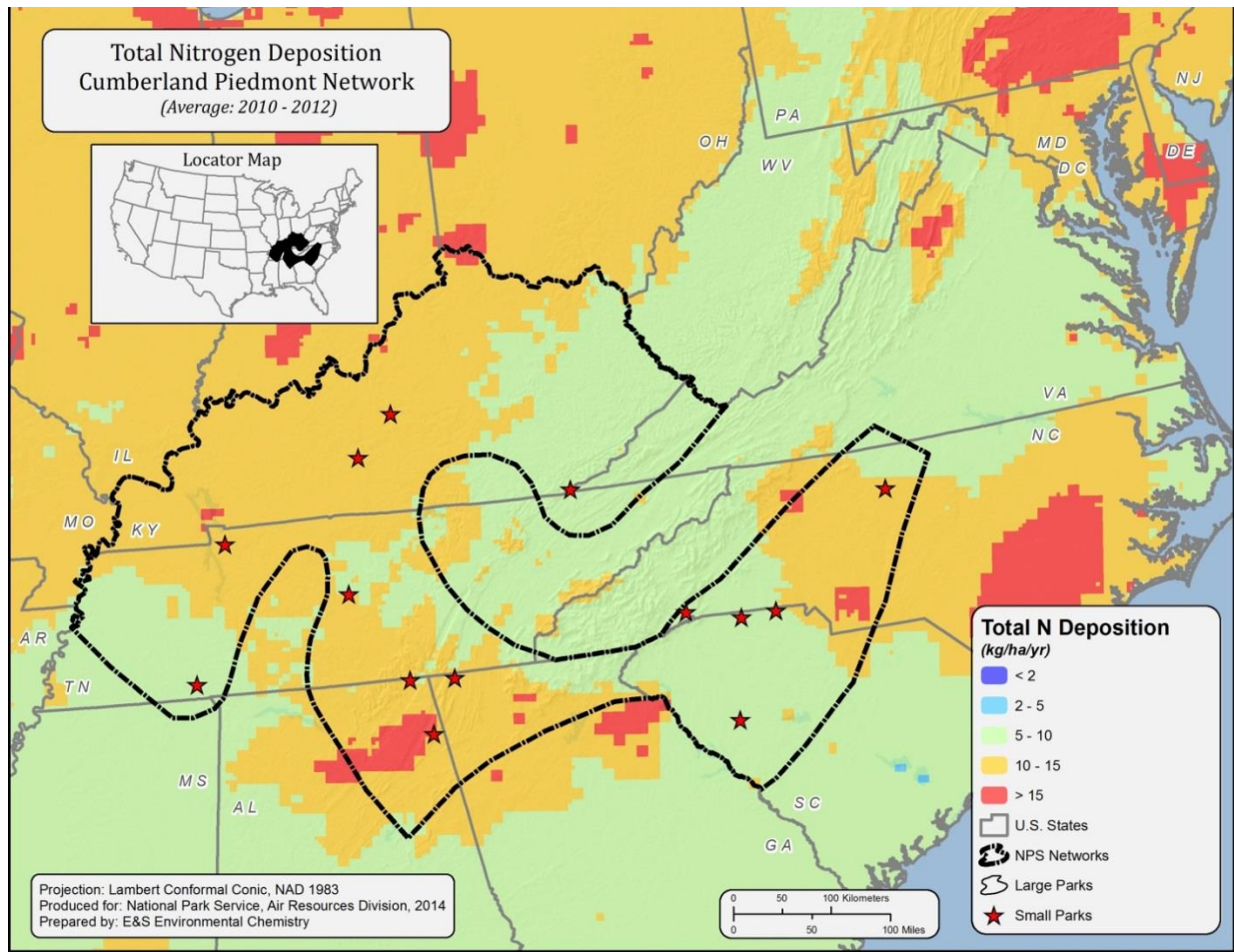
Map 5. Total S deposition for the three-year period centered on 2011 in and around the CUPN. (Source: Schwede and Lear 2014)



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



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



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

Table 3. Estimated I&M park rankings¹ according to risk of acidification impacts on sensitive receptors (Source: Sullivan et al. 2011b)

Park Name	Park Code	Estimated Acid Pollutant Exposure	Estimated Ecosystem Sensitivity to Acidification
Abraham Lincoln Birthplace	ABLI	Very High	Moderate
Carl Sandburg Home	CARL	High	Very High
Chickamauga and Chattanooga	CHCH	Very High	Very High
Cowpens	COWP	High	Very Low
Cumberland Gap	CUGA	High	Very High
Fort Donelson	FODO	Very High	Moderate
Guilford Courthouse	GUCO	Very High	Very Low
Kings Mountain	KIMO	High	Low
Little River Canyon	LIRI	Very High	Very High
Mammoth Cave	MACA	Very High	High
Ninety Six	NISI	High	Very Low
Russell Cave	RUCA	Very High	High
Shiloh	SHIL	High	Low
Stones River	STRI	High	Very Low

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

Acidification of Terrestrial Ecosystems

Data are not available regarding the effects of acidic deposition on terrestrial resources within CUPN parks. However, sugar maple, a species known to be sensitive to acidification, occurs in several of the CUPN parks. Acidification of soils has been linked to sugar maple decline in eastern forests (Long et al. 2009, Sullivan et al. 2013). Given the relatively high levels of acidic deposition in the CUPN, it is likely that some soil acidification has occurred, with potential effects on acid-sensitive plant species such as sugar maple.

Acidification of Aquatic Ecosystems

The CUPN has an ongoing water quality sampling program at the network parks. Monitoring results suggest that many park streams have naturally low pH and acid neutralizing capacity (ANC) because they are located on bedrock types (especially sandstones) that provide limited acid-buffering and base cation supply. These streams are likely sensitive to atmospheric acid inputs. Given the high levels of acidic deposition that the region has experienced for over 40 years, it is likely that pH and ANC have been depressed by human-caused pollution. Streams in SHEN on similar bedrock, for example, have lost significant amounts of ANC since pre-industrial times because of acidic deposition (Sullivan et al. 2003). Of a group of five streams on siliciclastic bedrock in SHEN, all had pre-industrial ANC levels above 50 µeq/L; by 1990, their ANCs had been depleted to between 0 and 26 µeq/L (Sullivan et al. 2003). Eight parks in the CUPN (CARL, CHCH, COWP, CUGA, GUCO, KIMO, LIRI, and SHIL) contain streams that have naturally low pH and ANC (Meiman 2005, 2007a, b, c, d, e, 2009a, b) that have likely been further depressed by acidic deposition.

Table 4. Distribution of steady-state critical loads of sulfur (in kg/ha/yr) to protect stream ANC = 50 µeq/L for parks modeled in the EMDS project within the CUPN (McDonnell et al. 2014, Reynolds et al. 2012).

Park Name	Park Code	# of CLs ¹	Minimum	25th Percentile	Median	25th Percentile	Maximum
Carl Sandburg Home	CARL	7	5	6	6	7	8
Cumberland Gap	CUGA	146	0	6	High	High	High

¹ Number of small watersheds (generally approximately 1 km²), for which CL were calculated by Reynolds et al.(2012), that are wholly or partly within the park

0 signifies that the target ANC cannot be attained, even if S deposition is reduced to zero; "High" signifies that the CL is significantly higher than ambient deposition

CLs of S in units of kg/ha/yr can be converted to meq/m²/yr by multiplying by 6.25

Reynolds et al. (2012) and McDonnell et al. (2014) reported S critical load (CL) estimates generated within the Ecosystem Management Decision Support (EMDS) aquatic acidification assessment for the southern Appalachian Mountains (Table 4). Steady-state model CL estimates were given for two parks in the CUPN: CARL and CUGA. The estimated CL values for seven streams in CARL were fairly low. In CUGA, 146 streams were modeled; the median stream had a high CL, but 25% of the streams had CL ≤ 6 kg S/ha/yr. The most acid-sensitive stream in CUGA had a modeled CL = 0 kg S/ha/yr, suggesting that even if S deposition was reduced to zero, the stream would still not recover to ANC above 50 µeq/L.

Nutrient Nitrogen Enrichment

The network rankings developed in a coarse screening assessment 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 CUPN that was in the of the middle quintile among all networks. This middle quintile ranking was derived, in part, by the absence of high-elevation lakes and limited coverage within this network of vegetation types that are among those expected to be especially sensitive to nutrient enrichment effects from N deposition (grassland, wetland, alpine, arctic herbaceous, arid, and semi-arid). Thus, the high level of N pollutant exposure indicated in Table 5 appears to be countered to some degree by a relatively low level of inherent ecosystem sensitivity to nutrient N enrichment. 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 Moderate compared with all networks.

Rankings for nutrient N enrichment impacts on sensitive receptors in CUPN parks are shown in Table 5. All parks in the network were ranked High or Very High in nutrient N Pollutant Exposure. Emissions upwind of this network and estimated atmospheric N deposition within the network were both relatively high compared with other networks. Ecosystem Sensitivity to nutrient N enrichment for the various parks was ranked Low (for 3 parks) to Very Low (for 10 parks, including MACA). Carl Sandburg Home NHS was ranked Moderate for Ecosystem Sensitivity to nutrient N enrichment. 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.

Table 5. Estimated park rankings¹ according to risk of nutrient enrichment impacts on sensitive receptors (Source: Sullivan et al. 2011a)

Park Name	Park Code	Estimated Nutrient N Pollutant Exposure	Estimated Ecosystem Sensitivity to Nutrient N Enrichment
Abraham Lincoln Birthplace	ABLI	Very High	Low
Carl Sandburg Home	CARL	High	Moderate
Chickamauga and Chattanooga	CHCH	Very High	Very Low
Cowpens	COWP	High	Very Low
Cumberland Gap	CUGA	High	Very Low
Fort Donelson	FODO	High	Very Low
Guilford Courthouse	GUCO	Very High	Very Low
Kings Mountain	KIMO	High	Very Low
Little River Canyon	LIRI	Very High	Very Low
Mammoth Cave	MACA	Very High	Very Low
Ninety Six	NISI	High	Low
Russell Cave	RUCA	High	Very Low
Shiloh	SHIL	High	Low
Stones River	STRI	High	Very Low

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

It appears that some impacts on terrestrial ecosystems have occurred in the CUPN region in response to N deposition to date. For example, McCune et al. (1997) found N-tolerant epiphytic lichen species to be present, along with relatively low epiphytic lichen species richness in urban and industrial areas within Georgia, North Carolina, South Carolina, Tennessee, and Virginia. In contrast, sensitive species were more common, and richness was higher, in rural areas. Brookshire et al. (2007) documented increased stream NO_3^- concentrations across North Carolina and West Virginia with increasing N deposition ranging from 5 to 32 kg N/ha/yr. This finding suggests that watersheds in this region may be experiencing some level of N saturation.

Pardo et al. (2011b) compiled data on empirical CL for protecting sensitive resources in Level I ecoregions across the conterminous United States against nutrient enrichment (eutrophication) effects caused by atmospheric N deposition. Estimated atmospheric N deposition to each of the parks in the CUPN was higher than the Pardo et al. (2011b) suggested ranges (Table 6). These likely CL exceedances pertained to protection of mycorrhizal fungi, lichens, and forests and for prevention of NO_3^- leaching in drainage water. Based on these data, CL exceedances for protection of sensitive terrestrial resources in the CUPN appear to be widespread in park lands throughout the network.

Ellis et al. (2013) estimated the CL for nutrient-N deposition to protect the most sensitive ecosystem receptors in 45 national parks. The lowest terrestrial CL of N is generally estimated for protection of lichens (Geiser et al. 2010). Changes to lichen communities may signal the beginning of other changes to the ecosystem that might affect structure and function (Pardo et al. 2011a). Ellis et al. (2013) estimated the N CL for MACA in the range of 3-8 kg N/ha/yr for protection of hardwood forests.

Table 6. Empirical critical loads for nitrogen in the CUPN, 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
Abraham Lincoln Birthplace NHP	Eastern Temperate Forests	13.6	5 - 12	4 - 8	17.5	3 - 8	8
Carl Sandburg Home NHS	Eastern Temperate Forests	11.2	5 - 12	4 - 8	17.5	3 - 8	8
Chickamauga and Chattanooga NMP	Eastern Temperate Forests	13.1	5 - 12	4 - 8	17.5	3 - 8	8
Cowpens NB	Eastern Temperate Forests	11.1	5 - 12	4 - 8	17.5	3 - 8	8
Cumberland Gap NHP	Eastern Temperate Forests	11.3	5 - 12	4 - 8	17.5	3 - 8	8
Fort Donelson NB	Eastern Temperate Forests	11.9	5 - 12	4 - 8	17.5	3 - 8	8
Guilford Courthouse NMP	Eastern Temperate Forests	12.6	5 - 12	4 - 8	17.5	3 - 8	8
Kings Mtn. NMP	Eastern Temperate Forests	11.9	5 - 12	4 - 8	17.5	3 - 8	8
Little River Canyon NPres	Eastern Temperate Forests	14.0	5 - 12	4 - 8	17.5	3 - 8	8
Mammoth Cave NP	Eastern Temperate Forests	13.5	5 - 12	4 - 8	17.5	3 - 8	8
Ninety Six NHS	Eastern Temperate Forests	10.2	5 - 12	4 - 8	17.5	3 - 8	8
Russell Cave NM	Eastern Temperate Forests	13.1	5 - 12	4 - 8	17.5	3 - 8	8
Shiloh NMP	Eastern Temperate Forests	10.7	5 - 12	4 - 8	17.5	3 - 8	8
Stones River NB	Eastern Temperate Forests	12.7	5 - 12	4 - 8	17.5	3 - 8	8

Table 7. Ozone-sensitive and bioindicator plant species known or thought to occur in the I&M parks of the CUPN. (Data Source: E. Porter, National Park Service, pers. comm., August 30, 2012); lists are periodically updated at <https://irma.nps.gov/NPSpecies/Report>).

		Park													
		ABLI	CARL	CHCH	COWP	CUGA	FODO	GUCC	KIMO	LIRI	MACA	NISI	RUCA	SHIL	STRI
Ozone-Sensitive Species															
<i>Ageratina altissima</i> var. <i>altissima</i> *	White snakeroot						x			x				x	
<i>Ailanthus altissima</i> *	Tree-of-heaven		x	x	x	x		x	x	x	x		x		x
<i>Apios americana</i> *	Groundnut		x		x	x		x	x	x	x	x		x	
<i>Apocynum androsaemifolium</i> *	Spreading dogbane		x												
<i>Apocynum cannabinum</i>	Dogbane, Indian hemp	x	x	x	x	x	x	x	x	x	x	x			x
<i>Artemisia ludoviciana</i> spp. <i>Ludoviciana</i> *	Silver wormwood										x				
<i>Asclepias exaltata</i> *	Tall milkweed					x					x				x
<i>Asclepias incarnata</i>	Swamp milkweed					x	x				x				
<i>Asclepias syriaca</i> *	Common milkweed		x	x		x	x	x			x		x		x
<i>Cercis canadensis</i> var. <i>canadensis</i> *	Redbud	x		x	x	x	x	x	x	x	x	x	x	x	x
<i>Clematis virginiana</i>	Virgin's bower	x	x	x		x	x	x		x	x		x	x	x
<i>Corylus americana</i> *	American hazelnut	x	x			x	x	x	x	x	x			x	x
<i>Eurybia macrophylla</i> *	Big-leaf aster		x		x						x				
<i>Fraxinus americana</i> *	White ash	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Fraxinus pennsylvanica</i>	Green ash	x		x		x	x		x	x	x	x		x	x
<i>Gaylussacia baccata</i> *	Black huckleberry		x		x	x		x	x		x				
<i>Liquidambar styraciflua</i>	Sweetgum	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Liriodendron tulipifera</i> *	Yellow-poplar	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Lyonia ligustrina</i> *	Maleberry		x			x			x	x					
<i>Oclemena acuminata</i> *	Whorled aster					x				x					
<i>Parthenocissus quinquefolia</i>	Virginia creeper	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Philadelphus coronarius</i>	Sweet mock orange				x										
<i>Pinus rigida</i>	Pitch pine		x			x		x							
<i>Pinus taeda</i>	Loblolly pine			x	x		x	x		x	x	x	x	x	
<i>Pinus virginiana</i>	Virginia pine	x	x	x	x	x	x	x	x	x	x		x	x	
<i>Platanus occidentalis</i> *	American sycamore	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Prunus serotina</i> var. <i>serotina</i> *	Black cherry	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Prunus virginiana</i>	Choke cherry			x							x				
<i>Rhus copallinum</i>	Winged sumac				x			x	x			x			
<i>Rhus copallinum</i> var. <i>latifolia</i>	Winged sumac										x				
<i>Robinia pseudoacacia</i>	Black locust	x	x	x		x	x	x	x	x	x		x	x	x
<i>Rubus allegheniensis</i> *	Allegheny blackberry			x		x					x				
<i>Rubus canadensis</i> *	Thornless blackberry					x									
<i>Rubus cuneifolius</i>	Sand blackberry					x		x							
<i>Rudbeckia laciniata</i> *	Cutleaf coneflower			x		x			x	x	x				
<i>Sambucus nigra</i> spp. <i>canadensis</i> *	American elder		x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Sassafras albidum</i>	Sassafras	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Solidago canadensis</i> var. <i>scabra</i>	Goldenrod		x		x	x	x		x		x				x
<i>Verbesina occidentalis</i> *	Crownbeard			x	x	x	x		x	x	x	x			
<i>Vitis labrusca</i> *	Northern fox grape	x		x	x	x			x		x				x

* Bioindicator species

Ozone Injury to Vegetation

The ozone (O₃)-sensitive plant species that are known or thought to occur within the I&M parks found in the CUPN are listed in Table 7. 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 a number of O₃-sensitive and bioindicator species.

Ozone Exposure Indices and Concentrations

The W126 (a measure of cumulative O₃ exposure that preferentially weights higher concentrations) and SUM06 (a measure of cumulative exposure that includes only hourly concentrations over 60 ppb O₃) exposure indices calculated by NPS staff for parks in the CUPN during the period 2005-2009 are given in Table 8, along with Kohut's (2007) O₃ risk ranking. The NPS and Kohut ranking

Table 8. Ozone assessment results for I&M parks in the CUPN based on estimated average 3-month W126 and SUM06 ozone exposure indices for the period 2005-2009 and Kohut's (2007) ozone risk ranking for the period 1995-19991.

Park Name	Park Code	W126		SUM06		Kohut O ₃ Risk Ranking
		Value (ppm-hr)	Ranking	Value (ppm-hr)	Ranking	
Abraham Lincoln Birthplace	ABLI	12.60	Moderate	17.32	High	Moderate
Carl Sandburg Home	CARL	11.88	Moderate	15.99	High	Moderate
Chickamauga and Chattanooga	CHCH	14.09	High	19.06	High	High
Cowpens	COWP	13.45	High	18.40	High	High
Cumberland Gap	CUGA	12.70	Moderate	16.44	High	High
Fort Donelson	FODO	13.59	High	17.41	High	High
Guilford Courthouse	GUCO	14.01	High	18.95	High	High
Kings Mountain	KIMO	14.41	High	19.66	High	High
Little River Canyon	LIRI	13.10	High	18.08	High	High
Mammoth Cave	MACA	12.77	Moderate	17.60	High	High
Ninety Six	NISI	12.44	Moderate	17.38	High	Low
Russell Cave	RUCA	13.75	High	18.77	High	Moderate
Shiloh	SHIL	12.33	Moderate	16.49	High	High
Stones River	STRI	13.20	High	17.79	High	High

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

systems differ. The NPS (2010) ranking system is a quick assessment of O₃ condition that ranks O₃ exposure levels according to injury thresholds from the literature (Heck and Cowling 1997), using a 5-year average of either the W126 or SUM06 index. 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).

Kohut's approach constitutes a more rigorous assessment of potential risk to plants. It considers both O₃ exposure and environmental conditions (soil moisture). Kohut also used injury thresholds from the literature, but evaluated a different O₃ metric (after Lefohn et al. 1997), the W126 over a 5-month period in conjunction with the N100 (number of hours over 100 ppb O₃). The rationale for the N100

statistic is that higher O₃ concentrations are most likely to cause plant injury. Kohut examined five individual years of O₃ exposure and soil moisture data and considered the effects of low soil moisture on O₃ uptake each year when assigning risk. Soil moisture is important because dry conditions induce stomatal closure in plants, which has the effect of limiting O₃ uptake and injury even when exposures are relatively high.

The results of both ranking systems should be considered when evaluating the potential for O₃ injury to park vegetation. The Kohut approach considered environmental conditions that significantly affect plant response to O₃, but exposures to plants in the field have likely changed since the time of the assessment (1995-1999). The NPS approach considers more recent O₃ conditions (2005-2009), but not environmental conditions.

Ozone condition, as rated by NPS, was Moderate or High in the CUPN parks. Kohut's evaluation of risk to plants was Moderate or High for all parks except NISI. In the five years analyzed, drought conditions at NISI were judged likely to constrain O₃ uptake by plants in the park.

The CUPN has an ongoing monitoring program to evaluate O₃ injury to plants. Ozone injury has been documented at CUGA (Jernigan et al. 2009); COWP, MACA, and SHIL (Jernigan et al. 2010); CHCH (Jernigan et al. 2011); LIRI and RUCA (Jernigan et al. 2012); and GUCO (Howie Neufeld, NPS, personal communication, July, 2014). Carl Sandburg Home NHS and FODO also had confirmed O₃ injury (Johnathan Jernigan, NPS, personal communication, July, 2014).

Ozone Formation

There are recognized differences in the potential to form atmospheric O₃ among the prominent southeastern national parks, including MACA in the CUPN (Kang et al. 2003). In areas like MACA, where O₃ is mainly produced locally, reducing NO_x and/or VOC emissions locally may reduce the capacity for O₃ production. Tong et al. (2005) quantified the relative importance of point and nonpoint-mobile emissions sources of NO_x, identified the origin of air masses associated with high concentrations of NO_x, and calculated NO_x production and removal budgets for MACA. Air pollution influence areas were identified using cluster analysis (Dorling et al. 1992) of model output generated using the Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) model (Draxler 1997) and also emission source identification based on EPA's national emissions inventory (U.S. EPA 2001). Clusters were labeled according to general direction of movement of the air mass towards the parks.

MACA experienced a larger contribution of NO_x from point sources, with the maximum occurring during midday and the minimum just before sunrise. This pattern was attributed by Tong et al. (2005) to formation of a stable nighttime boundary layer over MACA that prevents air masses having high pollutant concentrations from reaching the surface at night. This process is coupled with enhanced nighttime removal of pollutants by dry deposition due to the lower boundary layer and higher relative humidity at night (Finkelstein et al. 2000). Breakup of the nighttime boundary layer at MACA is triggered by sunrise, allowing air masses containing high concentrations of transported S and N to mix downward towards the surface during the day.

At MACA, the proportion of NO_x emissions derived from point sources was generally higher during winter and spring, and lower during summer and fall. In midsummer, point sources sometimes constituted an estimated 70% of total NO_x at MACA during episodes of high air pollutant levels; more commonly, summer point source contributions at MACA were much lower than mobile sources. On average, a minimum of one-fourth of reactive NO_x at MACA is estimated to have been emitted by point sources (Tong et al. 2005). Point sources tend to be episodic at MACA and occur mainly during daytime hours. However, MACA exhibits high concentrations of atmospheric O₃, in excess of the 0.08 ppm 8-hr standard, several times each year (Kang et al. 2001, Kang et al. 2003, Ryerson et al. 2001). It is generally assumed that NO_x is the main limiting factor for photochemical O₃ production in remote areas of the southeastern United States, including at MACA (Kang et al. 2003, Tong et al. 2005).

MACA also has strong biogenic volatile organic compound (VOC) sources. The most abundant VOC compound measured in the air during summer in MACA and nearby parks during the period 1995-1997 was isoprene, a natural biogenic compound produced by vegetation (Kang et al. 2001). Upon conversion of all VOCs into propylene-equivalent concentration units (to assess relative potential contribution of VOCs to O₃ formation), biogenic components accounted for 69-95% of the total atmospheric VOC concentration during all three years investigated. About 80% of the biogenic VOC was comprised of isoprene; other common VOCs included α -pinene, β -pinene, and limonene. The major anthropogenic VOCs during summer were isopentane, toluene, and propane. These are derived from automobile exhaust (isopentane), solvents (toluene), and natural gas (propane; Kang et al. 2001).

Kang et al. (2003) applied the Multiscale Air Quality Simulation Platform (MAQSIP) model to predict atmospheric O₃ concentration with an overall uncertainty less than 30% in three eastern parks, including MACA. The largest O₃ production due to local chemistry was simulated for the low elevation (219 m) site at MACA, nearly twice as high as for two nearby high-elevation sites. Modeling results suggested that VOCs were chemically saturated at all three locations, potentially causing decreased O₃ production in response to further increases in VOC emissions. More than half of the O₃ at the high-elevation sites was simulated to be transported from other areas, as compared with only 20% at MACA (Kang et al. 2003).

Visibility Degradation

According to the Regional Haze Rule (RHR), states and tribes must establish and meet reasonable progress goals for each federal Class I area to improve visibility on the 20% haziest days and to prevent visibility degradation on the 20% clearest days. The national goal is to return visibility in Class I areas to natural background levels 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).

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 visibility¹ in mandatory Class I federal areas which impairment results from manmade air pollution” (42 U.S.C. 7491). In 1999, EPA passed the 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 deciview² (dv).

Within the CUPN, haze has been estimated by the IMPROVE program for the monitoring site (MACA1) located in MACA for the 20% clearest visibility days, the 20% haziest visibility days, and average days. Data are also available that are considered to be representative of visibility conditions in two Class II areas (ABLI and FODO), based on measured values taken from nearby IMPROVE sites (MACA1 and CADI1, respectively; CADI1 is in Cadiz, KY). IMPROVE considers alternate sites to be representative if they are located within 60 mi (100 km) and 425 ft (130 m) elevation of an area.

Ambient visibility estimates reflect the pollution level 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 9 gives the relative park haze rankings on the 20% clearest, 20% haziest, and average days. Measured haze values in all of the parks studied for the period 2004 through 2008 were considerably higher than the estimated natural conditions; the haze rankings for all three groups were

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.

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.

Very High. These parks probably exhibit some of the highest visibility degradation from air pollutants among all I&M parks.

Annual mean dv levels on the haziest days at 47 monitored park locations during the period 2006-2008 ranged from 1.5 to 21 dv higher than the estimated natural condition (NPS 2010). The average difference between measured dv and estimated natural condition was 8.3 dv. Several eastern parks had annual mean dv on the haziest days that were substantially higher (more than about 10 dv) than estimated natural conditions; these included MACA and two parks close to the CUPN boundary: GRSM and SHEN. Monitoring sites showing the largest differences during the period 2006-2008 between measured visibility on the clearest days and estimated natural conditions included MACA (NPS 2010).

IMPROVE data allow estimation of visual range (VR). Data indicate that at the MACA1 monitoring site (in MACA and representative of ABLI), pollution has reduced average VR from 110 to 20 miles (177 to 32 km). On the haziest days, VR has been reduced from 80 to 10 miles (129 to 16 km). Severe haze episodes occasionally reduce visibility to 4 miles (6 km). At the CADI1 monitor, representative of FODO, pollution has reduced average VR from 110 to 25 miles (177 to 40 km). On the haziest days, VR has been reduced from 80 to 10 miles (129 to 16 km). Severe haze episodes occasionally reduce visibility to 5 miles (8 km).

Figure 1 shows estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze and its composition for ABLI, FODO, and MACA. Data for ABLI and FODO are from nearby sites. The majority of total particulate light extinction (b_{ext}) in MACA is attributable to SO_4^{2-} extinction (Figure 1). On average, SO_4^{2-} contributed 67.9% of annual b_{ext} , NO_3^- 12.7%, and organics 11.4%. For the other two parks, SO_4^{2-} was also the largest contributor to ambient haze. Thus, SO_4^{2-} has a disproportionately large impact on b_{ext} in this network, especially on the 20% haziest days. Nitrate is also important. Even on the 20% clearest visibility days, ($SO_4^{2-} + NO_3^-$) contributes almost three-fourths of the total b_{ext} .

Zhao and Hopke (2006) analyzed data from the IMPROVE monitoring program in order to distinguish the chemical composition and sources of fine aerosols at MACA and ultimately inform pollution control strategies. The data resolved nine sources of ambient aerosols at this park, and determined the average contribution of each source to total particulate matter mass, as follows: gasoline emission (6.7%), diesel emission (3.1%), summer secondary SO_4^{2-} (49.0%), winter secondary SO_4^{2-} (0.6%), organic C-rich secondary SO_4^{2-} (16.2%), secondary NO_3^- (2.8%), intercontinental dust plus soil (4.9%), wood smoke (13.6%) and aged sea salt (3.2%; Zhao and Hopke 2006). The researchers suggested that the intercontinental dust plus soil source may be primarily composed of Saharan dust from summer sandstorms in Africa (Zhao and Hopke 2006).

Table 9. Estimated natural haze and measured ambient haze in I&M parks averaged over the period 2004 through 2008¹. MACA1 is in MACA; CADI1 is in Cadiz, KY.

Park Name	Park	Site ID	Estimated Natural Haze (dv)
-----------	------	---------	-----------------------------

	Code		20% Clearest Days	20% Haziest Days	Average Days
Abraham Lincoln Birthplace ²	ABLI	MACA1	4.99	11.08	7.77
Carl Sandburg Home	CARL	No Site			
Chickamauga and Chattanooga	CHCH	No Site			
Cowpens	COWP	No Site			
Cumberland Gap	CUGA	No Site			
Fort Donelson ²	FODO	CADI1	5.17	10.84	7.77
Guilford Courthouse	GUCO	No Site			
Kings Mountain	KIMO	No Site			
Little River Canyon	LIRI	No Site			
Mammoth Cave	MACA	MACA1	4.99	11.08	7.77
Ninety Six	NISI	No Site			
Russell Cave	RUCA	No Site			
Shiloh	SHIL	No Site			
Stones River	STRI	No Site			

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
Abraham Lincoln Birthplace ²	ABLI	MACA1	16.19	Very High	31.38	Very High	23.20	Very High
Carl Sandburg Home	CARL	No Site						
Chickamauga and Chattanooga	CHCH	No Site						
Cowpens	COWP	No Site						
Cumberland Gap	CUGA	No Site						
Fort Donelson ²	FODO	CADI1	15.11	Very High	29.86	Very High	22.04	Very High
Guilford Courthouse	GUCO	No Site						
Kings Mountain	KIMO	No Site						
Little River Canyon	LIRI	No Site						
Mammoth Cave	MACA	MACA1	16.19	Very High	31.38	Very High	23.20	Very High
Ninety Six	NISI	No Site						
Russell Cave	RUCA	No Site						
Shiloh	SHIL	No Site						
Stones River	STRI	No Site						

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

² 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

MACA (also representing ABLI)

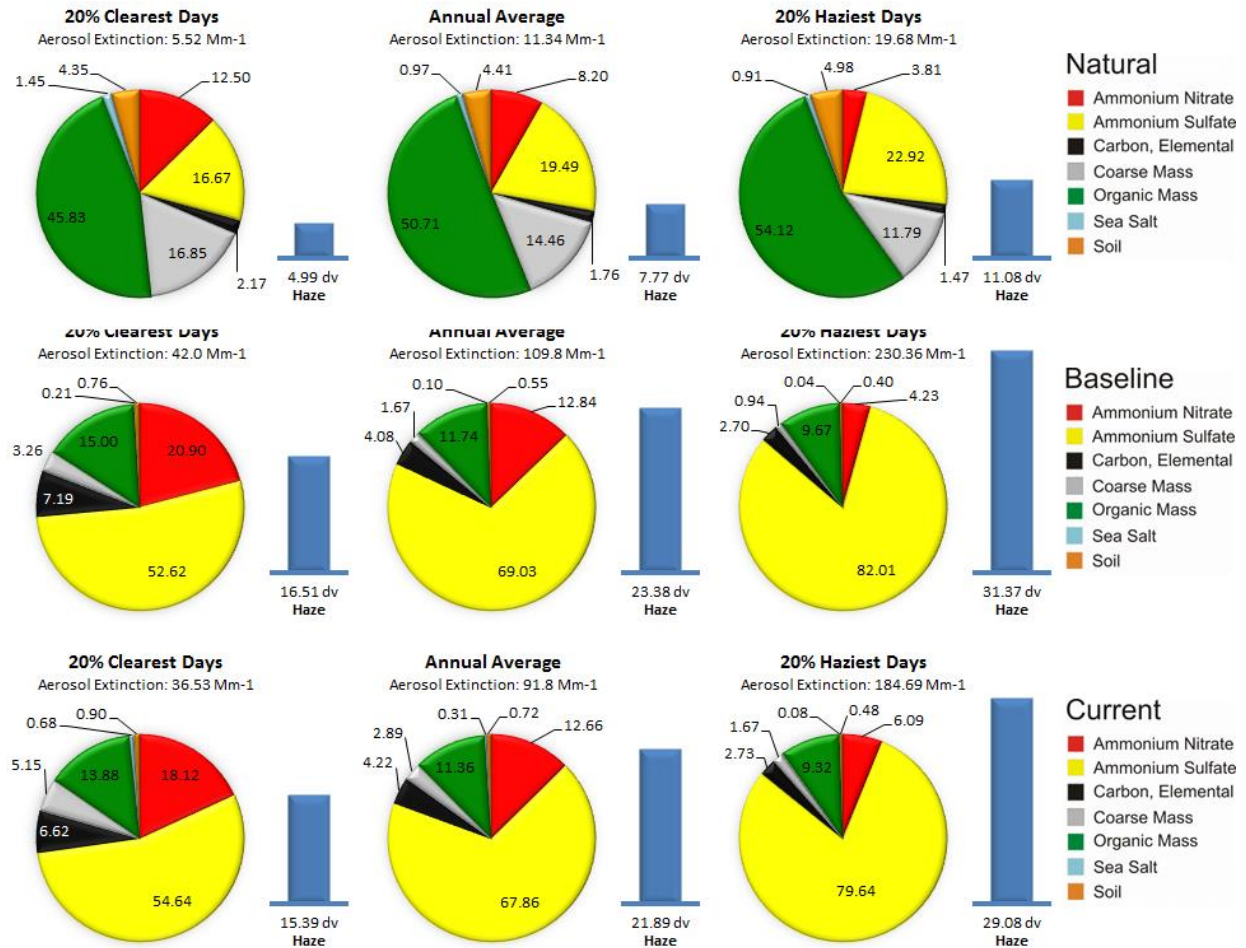


Figure 1a. Estimated natural (pre-industrial), baseline (2000-2004; FODO has no data for the years 2000 and 2001), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% hazeiest visibility days for ABLI and MACA. Data for ABLI and FODO were taken from nearby sites (MACA1 and CADI1, respectively). Data Source: NPS-ARD.

CADI1 (representing FODO)

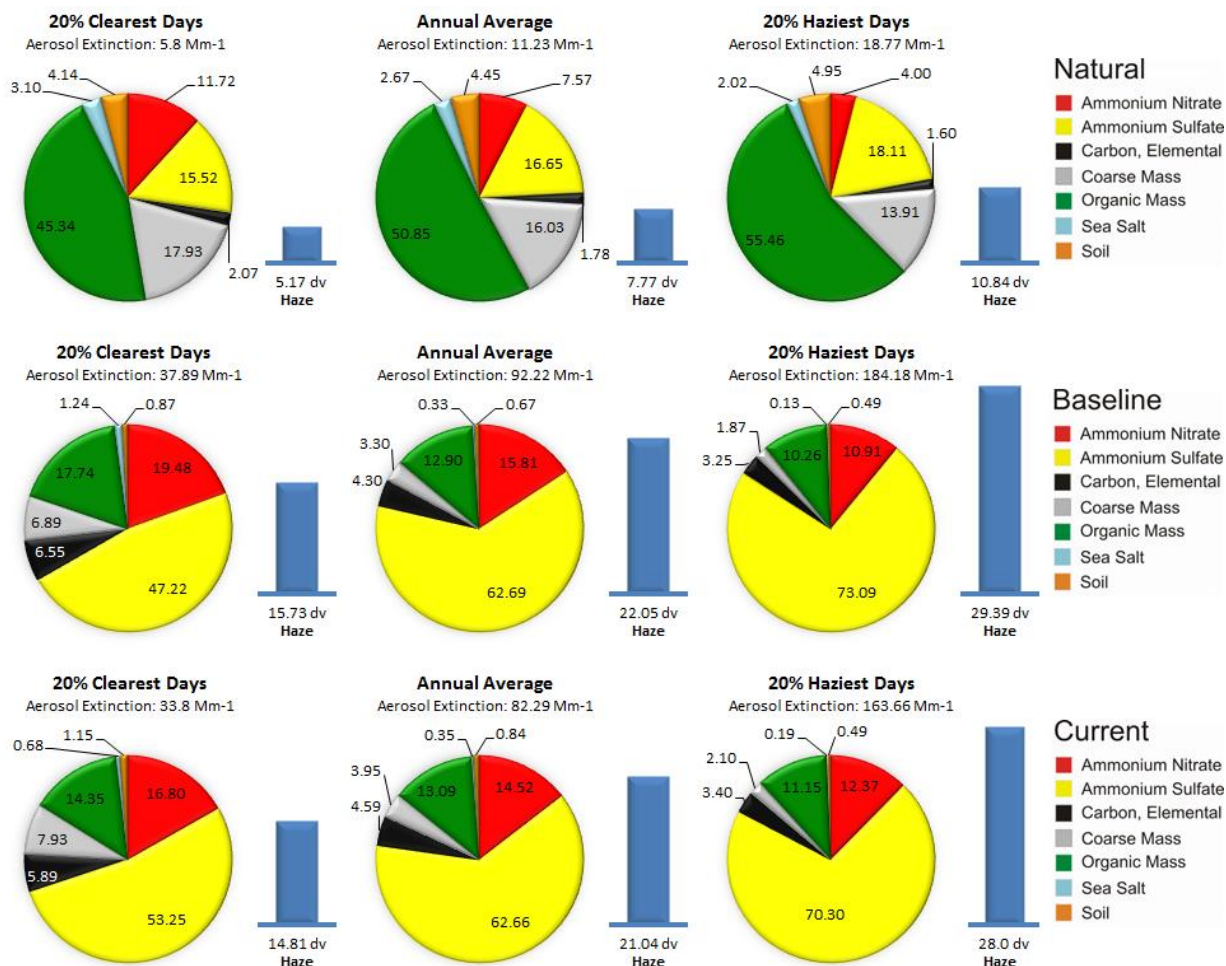


Figure 1b. Estimated natural (pre-industrial), baseline (2000-2004; FODO has no data for the years 2000 and 2001), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for FODO. Data for ABLI and FODO were taken from nearby sites (MACA1 and CADI1, respectively). Data Source: NPS-ARD.

Trends in Visibility

Large changes in haze levels are not apparent in the available monitoring data collected in MACA or in the IMPROVE site located near FODO (Figure 2). No trend in dv was observed on the clearest or haziest 20% of days for the visibility monitoring site in MACA during the period 1992-2008 (NPS 2010). There is some indication in the data graphed in Figure 2, however, that haze levels have decreased over the last approximately six years of monitoring data.

Development of State Implementation Plans

The Visibility Improvement State and Tribal Association of the Southeast (VISTAS) is a collaborative effort among state governments, tribal governments, and federal agencies involved in management of visibility and regional haze in the Southeast. The VISTAS region includes the

southeastern United States from Virginia and West Virginia in the north, south to Florida, and west to Kentucky, Tennessee, and Mississippi, including parts of the CUPN. Analyses conducted on behalf of VISTAS have included determination of baseline visibility conditions, calculation of the glide slope from the baseline necessary to achieve background conditions in 2064, and determination of air pollutant source areas. The apparent recent improvement in visibility in the monitored parks in the CUPN is evident in the glideslope analysis shown in Figure 3. Recent measured haze values on the 20% haziest days are decreasing roughly in accordance with the glideslope needed to attain natural visibility by 2064.

Toxic Airborne Contaminants

Mercury emissions and deposition have been high in the eastern United States because of the prevalence of coal-burning power plants. Biota have been evaluated for Hg contamination in some of the parks. The NPS has used dragonfly larvae to evaluate Hg in parks throughout the United States (http://www.nature.nps.gov/air/Studies/air_toxics/dragonfly/index.cfm). Three sites were sampled at MACA, two of which had total Hg concentrations in dragonfly larvae higher than the median across all 22 study parks (112 ppb dry weight). The potential impacts of these Hg concentrations are not known.

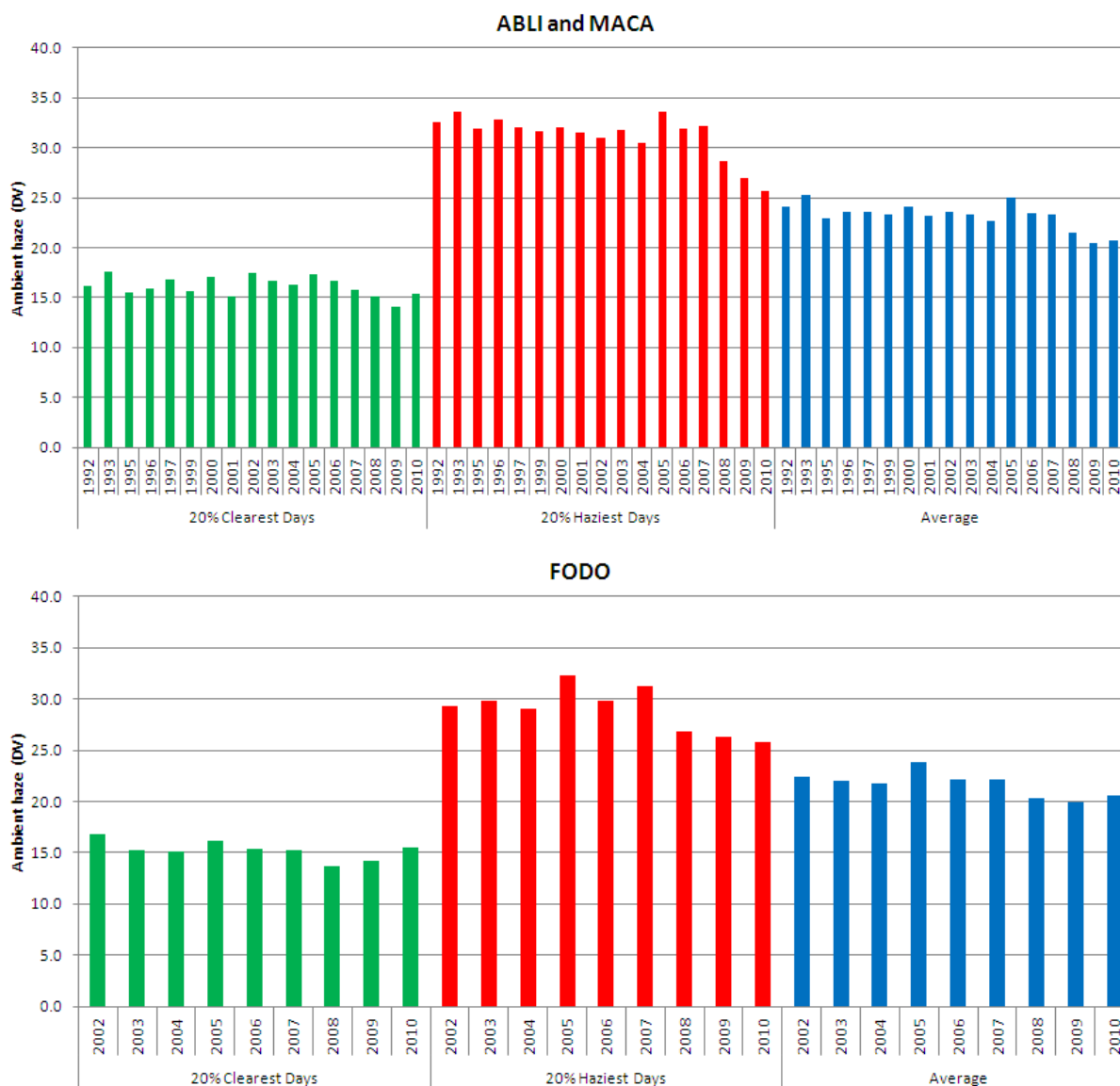


Figure 2. Trends in ambient haze levels at ABLI, FODO, and MACA, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data for ABLI and FODO were taken from nearby sites (MACA1 and CADI1, respectively). Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

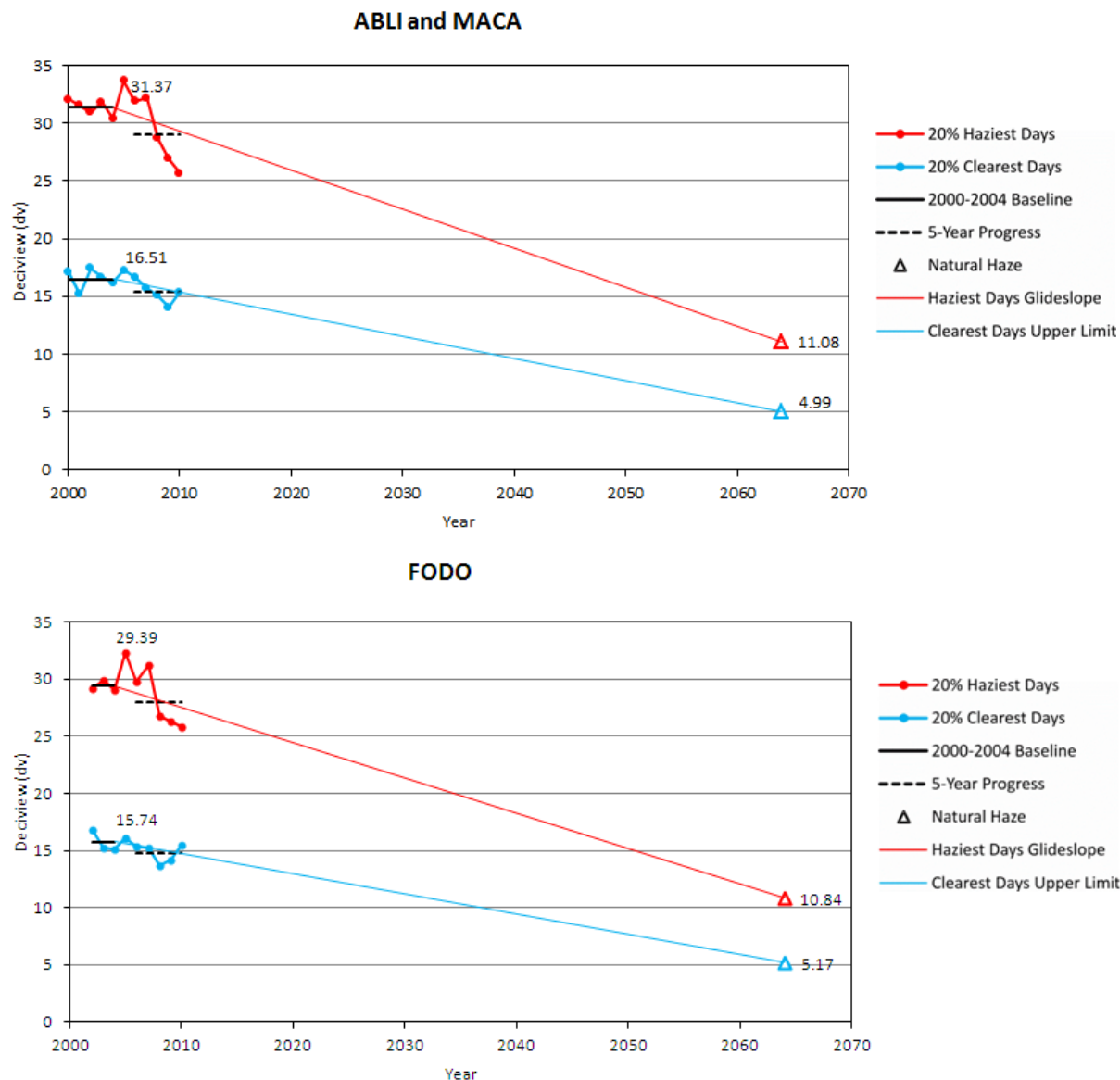


Figure 3. Glideslopes to achieving natural visibility conditions in 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in ABLI, FODO, and MACA. In the regional haze rule, the clearest days do not have a uniform rate of progress glideslope; the rule only requires that the clearest days do not get any worse than the baseline period. Also shown are measured values during the period 2000 to 2010. Data for ABLI and FODO were taken from nearby sites (MACA1 and CADI1, respectively). Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

References

- Abell, R., D.M. Olson, E. Dinerstein, P. Hurley, J.T. Diggs, W. Eichbaum, S. Walters, W. Wettengel, T. Allnutt, C. Loucks, and P. Hedao. 2000. Freshwater Ecoregions of North America: A Conservation Assessment. Island Press, Washington, DC.
- Air Resource Specialists. 2007. VISTAS Conceptual Description Support Document. Report prepared for Visibility Improvement State and Tribal Association of the Southeast. Fort Collins, CO.
- Brookshire, E.N.J., H.M. Valett, S.A. Thomas, and J.R. Webster. 2007. Atmospheric N deposition increases organic N loss from temperate forests. *Ecosystems* 10:252-262.
- 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.
- Dorling, S.T., T.D. David, and C.E. Pierce. 1992. Cluster analysis: a technique for estimating the synoptic meteorological controls on air and precipitation chemistry—method and applications. *Atmos. Environ.* 26A:2575-2581.
- Draxler, R.R. 1997. Description of the HYSPLIT_4 modeling system. Technical Memorandum ERL ARL-224. National Oceanic and Atmospheric Administration, Air Resources Laboratory, Silver Spring, MD.
- 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.
- Finkelstein, P.L., T.G. Ellestad, J.F. Clarke, T.P. Meyers, D.B. Schwede, E.O. Hebert, and J.A. Neal. 2000. Ozone and sulfur dioxide dry deposition to forests: observations and model evaluation. *J. Geophys. Res.* 105:15,365-315,377.
- 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.
- 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.
- Jernigan, J.W., B. Carson, and T. Leibfreid. 2009. Ozone and foliar injury report for Cumberland Piedmont Network parks: Annual report 2008. Natural Resource Data Series NPS/CUPN/NRDS—2009/012. National Park Service, Fort Collins, CO.

- Jernigan, J.W., B. Carson, and T. Leibfreid. 2010. Ozone and foliar injury report for the Cumberland Piedmont Network Parks consisting of Cowpens NB, Fort Donelson NB, Mammoth Cave NP and Shiloh NMP: Annual report 2009. Natural Resource Data Series NPS/CUPN/NRDS—2010/110. National Park Service, Fort Collins, CO.
- Jernigan, J.W., B. Carson, and T. Leibfreid. 2011. Cumberland Piedmont Network ozone and foliar injury report – Chickamauga and Chattanooga NMP, Mammoth Cave NP and Stones River NB: Annual report 2010. Natural Resource Data Series NPS/CUPN/NRDS—2011/219. National Park Service, Fort Collins, CO.
- Jernigan, J.W., B. Carson, and T. Leibfreid. 2012. Cumberland Piedmont Network Ozone and Foliar Injury Report – Little River Canyon National Preserve, Mammoth Cave NP and Russell Cave NM: Annual Report 2011. Natural Resource Data Series NPS/CUPN/NRDS—2012/xxx. National Park Service, Fort Collins, CO.
- Kang, D., V.P. Aneja, R.G. Zika, C. Farmer, and J.D. Ray. 2001. Nonmethane hydrocarbons in the rural southeast United States national parks. *J. Geophys. Res.* 106(D3):3133-3155.
- Kang, D., V.P. Aneja, R. Mathur, and J.D. Ray. 2003. Nonmethane hydrocarbons and ozone in three rural southeast United States national parks: A model sensitivity analysis and comparison to measurements. *Journal of Geophysical Research - Atmospheres* 108, D19, 4604 doi:10.1029/2002JD003054:17.
- Kohut, R. 2007. 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.
- 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.
- Long, R.P., S.B. Horsley, R.A. Hallett, and S.W. Bailey. 2009. Sugar maple growth in relation to nutrition and stress in the northeastern United States. *Ecol. Appl.* 19(6):1454-1466.
- 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).
- Master, L.L., S.R. Flack, and B.A. Stein (Eds.). 1998. *Rivers of Life: Critical Watersheds for Protecting Freshwater Biodiversity*. The Nature Conservancy, Arlington, VA.
- McCune, B., J. Dey, J. Peck, K. Heiman, and S. Will-Wolf. 1997. Regional gradients in lichen communities of the southeast United States. *Bryologist* 100(2):145-158.
- McDonnell, T.C., T.J. Sullivan, P.F. Hessburg, K.M. Reynolds, N.A. Povak, B.J. Cosby, W. Jackson, and R.B. Salter. 2014. Steady-state sulfur critical loads and exceedances for protection of aquatic ecosystems in the U.S. southern Appalachian Mountains. *J. Environ. Manage.* 146:407-419.

<http://dx.doi.org/10.1016/j.jenvman.2014.07.019>.

- Meiman, J. 2005. Cumberland Piedmont Water Quality Report: Chickamagua and Chattanooga National Military Park. National Park Service, Atlanta, GA.
- Meiman, J. 2007a. Cumberland Piedmont Network Water Quality Report: Guilford Courthouse National Military Park. National Park Service, Atlanta, GA.
- Meiman, J. 2007b. Cumberland Piedmont Water Quality Report: Carl Sandburg Home National Historic Site. National Park Service, Atlanta, GA.
- Meiman, J. 2007c. Cumberland Piedmont Network Water Quality Report: Cowpens National Battlefield. National Park Service, Atlanta, GA.
- Meiman, J. 2007d. Cumberland Piedmont Water Quality Report: Kings Mountain National Military Park. National Park Service, Atlanta, GA.
- Meiman, J. 2007e. Cumberland Piedmont Network Water Quality Report: Shiloh National Military Park. National Park Service, Atlanta, GA.
- Meiman, J. 2009a. Cumberland Piedmont Network Water Quality Report: Cowpens National Battlefield. National Park Service, Atlanta, GA.
- Meiman, J. 2009b. Cumberland Piedmont Network Water Quality Report: Little River Canyon National Preserve. National Park Service, Atlanta, GA.
- 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.
- Reynolds, K.M., P.F. Hessburg, T. Sullivan, N. Povak, T. McDonnell, B. Cosby, and W. Jackson. 2012. Spatial decision support for assessing impacts of atmospheric sulfur deposition on aquatic ecosystems in the Southern Appalachian Region. *Proc. of the 45th Hawaiian International Conference on System Sciences*, 4-7 January 2012. Maui, Hawaii

- Ryerson, T.B., M. Trainer, J.S. Holloway, D.D. Parrish, L.G. Huey, D.T. Sueper, G.J. Frost, S.G. Donnelly, S. Schauffler, E.L. Atlas, W.C. Kuster, P.D. Goldan, G. Hubler, J.F. Meagher, and F.C. Fehsenfeld. 2001. Observation of ozone formation in power plant plumes and implications of ozone control strategies. *Science* 292(5517):719-723.
- 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>.
- Smith, R.K., P.L. Freeman, J.V. Higgins, K.S. Wheaton, T.W. FitzHugh, A.A. Das, and K.J. Ernstrom. 2002. Priority Areas for Freshwater Conservation Action: A Biodiversity Assessment of the Southeastern United States. The Nature Conservancy.
- Sullivan, T.J., B.J. Cosby, J.A. Laurence, R.L. Dennis, K. Savig, J.R. Webb, A.J. Bulger, M. Scruggs, C. Gordon, J. Ray, H. Lee, W.E. Hogsett, H. Wayne, D. Miller, and J.S. Kern. 2003. Assessment of Air Quality and Related Values in Shenandoah National Park. NPS/NERCHAL/NRTR-03/090. U.S. Department of the Interior, National Park Service, Northeast Region. http://www.nps.gov/nero/science/FINAL/shen_air_quality/shen_airquality.html.
- 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., G.B. Lawrence, S.W. Bailey, T.C. McDonnell, C.M. Beier, K.C. Weathers, G.T. McPherson, and D.A. Bishop. 2013. Effects of acidic deposition and soil acidification on sugar maple in the Adirondack Mountains, New York. *Environ. Sci. Technol.* 47:12687-12694. 10.1021/es401864w.
- 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.
- Tong, D.Q., D. Kang, V.P. Aneja, and J.D. Ray. 2005. Reactive nitrogen oxides in the southeast United States national Parks: source identification, origin, and process budget. *Atmos. Environ.* 39:315-327.
- U.S. Environmental Protection Agency. 2001. National Air Quality and Emissions Trends Report,

1999. EPA-454/R-01-004. Office of Air Quality Planning and Standards, Emissions Monitoring and Analysis Division, Air Quality Trends Analysis Group, Research Triangle Park, NC.

Zhao, W. and P.K. Hopke. 2006. Source identification for fine aerosols in Mammoth Cave National Park. *Atmospheric Research* 80:309-322.

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 910/131998, 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

National Park Service.
CENTENNIAL

EXPERIENCE YOUR AMERICA™