



Air Quality Related Values (AQRVs) for Central Alaska Network (CAKN) Parks

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

Natural Resource Report NPS/CAKN/NRR—2016/1156



ON THE COVER

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

Photographs courtesy of the National Park Service

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Summary

This report describes the Air Quality Related Values (AQRVs) of the Central Alaska Network (CAKN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The CAKN parks that are included in the NPS Inventory and Monitoring (I&M) Program, and discussed in this report, are Denali National Park (DENA), Wrangell-St. Elias National Park and Preserve (WRST), and Yukon-Charley Rivers National Preserve (YUCH). DENA is designated as Class I, giving it 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 the CAKN parks; their results are described in this report. This report also describes air pollutant emissions and air quality in CAKN, and their effects on AQRVs. The primary pollutants likely to affect AQRVs include nitrogen (N) and sulfur (S) compounds (nitrate [NO_3^-], ammonium [NH_4^+], and sulfate [SO_4^{2-}]); ground-level O_3 ; haze-causing particles; and airborne toxics. Background for this section can be found in “Air Quality Related Values (AQRVs) in National Parks. Effects from Ozone; Visibility Reducing Particles; and Atmospheric Deposition of Acids, Nutrients and Toxics” (Sullivan 2016).

The parks in the CAKN are relatively isolated from human activities and air pollutant emissions, in comparison to parks in the contiguous 48 states. However, DENA is located 6.1 km from the Healy Power Plant, perhaps the closest proximity of a coal-fired power plant to a Class I national park. Total S and N deposition near this network are both expected to be low due to the scarcity of point sources and urban areas and the low calculated emissions levels from the various boroughs that comprise the network region. The sparse available atmospheric deposition data are consistent with the general understanding that atmospheric deposition of both N and S tends to be very low at national park lands within Alaska and more specifically within the CAKN. In agreement with measured values at DENA, it can be assumed that S and N deposition across this network would each be lower than about 1 kilogram per hectare per year (kg/ha/yr), on average.

Sulfur and N pollutants can cause acidification of streams, lakes, and soils. Despite the presumed acid sensitivity of some resources in parks in the CAKN, aquatic and terrestrial acidification have not been documented in this network and are considered unlikely in view of the very low levels of S and N deposition. Acid-sensitive resources constitute potentially important AQRVs, but are at little risk of damage under any reasonable future deposition scenario.

Nitrogen pollutants can also cause undesirable enrichment of natural ecosystems, leading to changes in plant species diversity and soil nutrient cycling. Shrub and forest vegetation communities in high-latitude ecosystems, such as are commonly found within the parks in the CAKN, may be highly sensitive to relatively low levels of N addition. However, both arctic and alpine plant communities dominated by lichens, graminoids, and herbaceous plants are likely to be especially sensitive. Less information is available for evaluating the relative sensitivity of woody plants at high-latitude locations. Lichens and mosses in barren areas may be highly sensitive to N addition, responding at relatively low levels of N deposition with changes in species composition. Lichens vary from those

adapted to very low N levels to lichens more tolerant of pollution and disturbance. Geiser and Nadelhoffer (2011) summarized effects on lichens and bryophytes in ecosystems of the Taiga Ecoregion, which suggested that N deposition levels of 1-3 kg/ha/yr were sufficient to cause changes in lichen species composition and cover.

In the short term, most arctic and alpine plant communities are expected to increase productivity in response to increased N supply. In the long term, however, added N is expected to change the species composition, typically resulting in a community that is less resistant to stress. If the arctic climate continues to warm, widespread melting of permafrost may contribute additional N to soil waters and surface waters. This conversion of stored N to a more highly available form may augment atmospherically-deposited N, leading to greater eutrophication effects in the future under a warming climate.

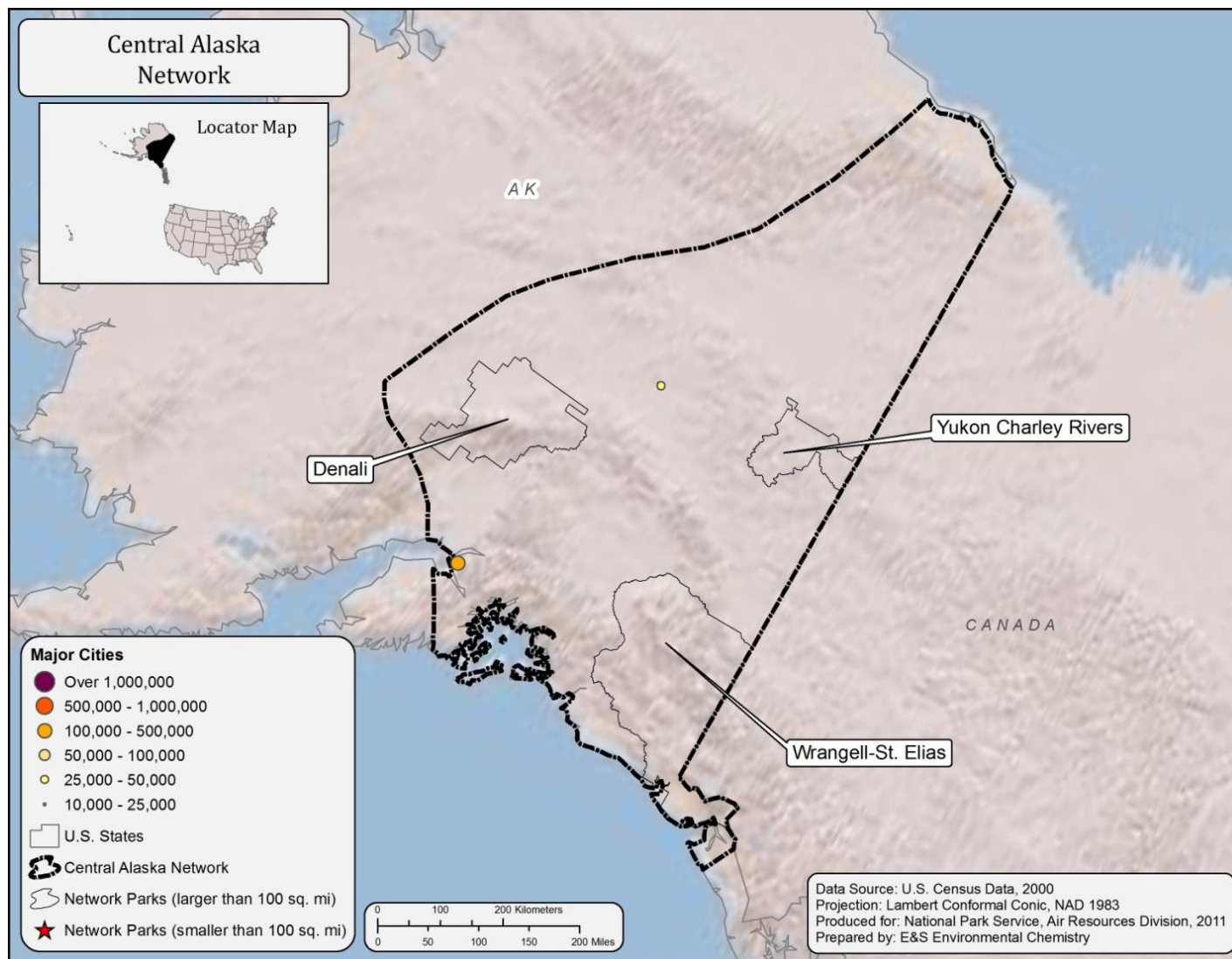
Ozone pollution can harm human health, reduce plant growth, and cause visible injury to foliage. Measured O₃ levels at DENA, which are probably typical of the other CAKN parks, are relatively low, and often well below the human health standard. An assessment to evaluate the risk to vegetation from O₃ concluded that the risk was Low at DENA. There is no information to suggest that O₃ levels at the other CAKN parks are sufficient to harm plants. Ozone exposure is not considered to be an important threat to vegetation in the CAKN.

Particulate pollution can cause haze, reducing visibility. Visibility is monitored at DENA. Measured ambient haze values for the period 2004 through 2008 were slightly higher than the estimated natural haze condition that would exist in the absence of human-caused pollution. Measured ambient haze within DENA was classified as Very Low on clear, hazy, and average days compared with other I&M parks elsewhere in the United States.

Airborne contaminants, including mercury (Hg), can accumulate in food webs, reaching toxic levels in top predators. Concentrations of semivolatile organic compounds (SOCs – e.g., pesticides, industrial contaminants), nutrients, and toxic metals in vegetation were measured at two parks in the CAKN as part of the Western Airborne Contaminant Assessment Project (WACAP). Concentrations of these substances at DENA and WRST were mostly lower than in parks in the lower 48 states. Nevertheless, fish in both WACAP study lakes in DENA had dieldrin pesticide concentrations that exceeded EPA contaminant health thresholds for people who consume at least 19 servings of fish per month. Wonder Lake had Hg concentrations that exceeded health thresholds for mammals (river otter [*Lutra canadensis*] and mink [*Mustela vison*]), and both study lakes exceeded Hg thresholds for piscivorous birds. In Wonder Lake, concentrations of Hg and lead in sediments showed increasing trends since the 1920s, likely a result of global Hg emissions.

Background

The Central Alaska Network (CAKN) contains three park units: Denali National Park (DENA), Wrangell-St. Elias National Park and Preserve (WRST), and Yukon-Charley Rivers National Preserve (YUCH). All are larger than 100 square miles. Only two urban centers, Anchorage and Fairbanks, are located near the CAKN. Map 1 shows the network boundary along with locations of each park and population centers with more than 10,000 people. Emissions from urban centers in Alaska are not expected to be particularly important to the parks in the CAKN, although wildfires and international pollution from urban, industrial, and agricultural sources can affect air quality related values (AQRVs), including visibility, in these parks.



Map 1. Network boundary and locations of parks and population centers greater than 10,000 people near the CAKN.

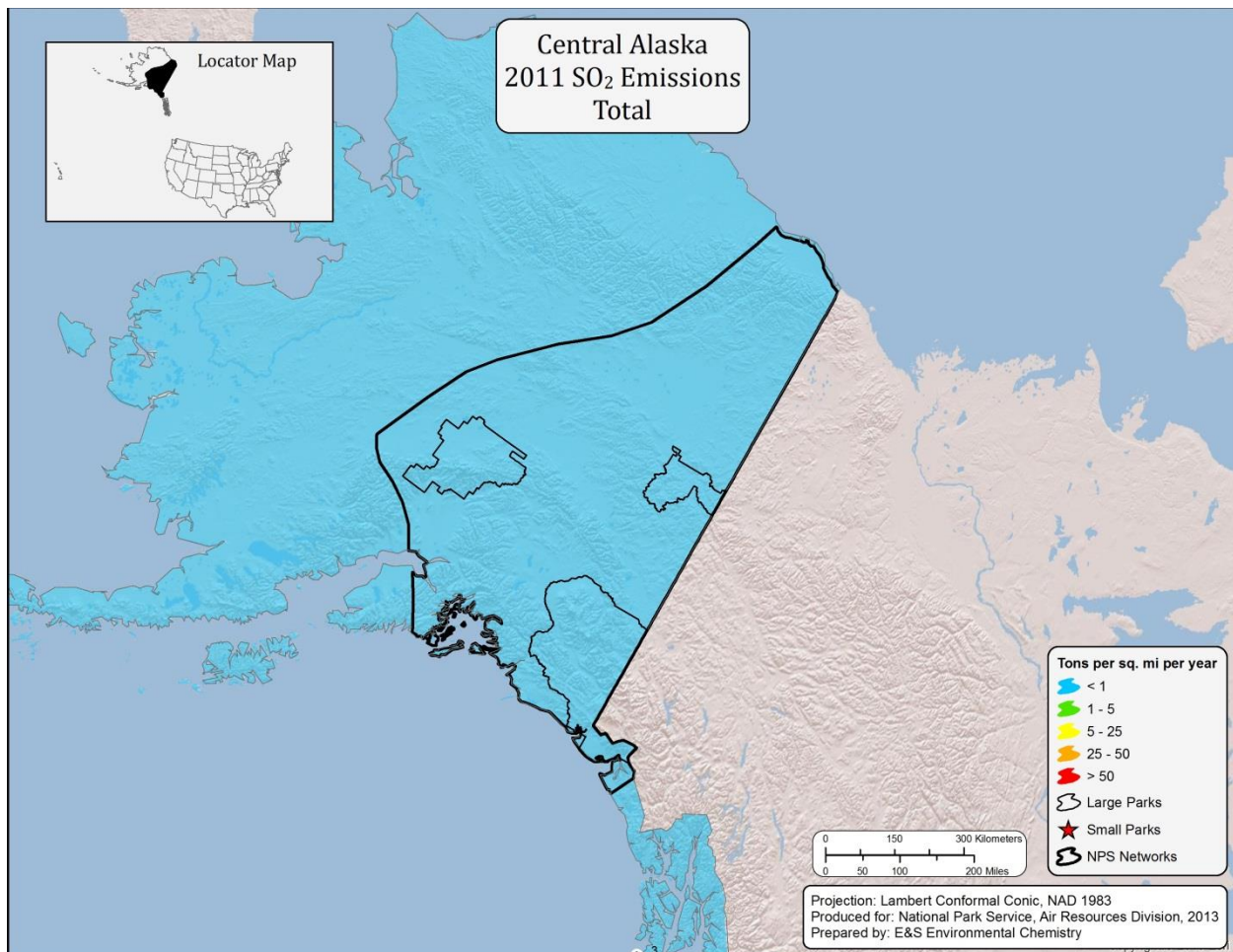
Atmospheric Emissions and Deposition

Emissions near CAKN, based on data from the EPA's National Emissions Inventory (NEI) during a recent time period (2011), are depicted in Maps 2 through 4 for sulfur dioxide (SO₂), oxidized N (NO_x), and reduced N (NH₃), respectively. All boroughs near CAKN parks had very low SO₂ emissions (< 1 ton/mi²/yr; Map 2). Emissions of NO_x and NO₃ were also low in most boroughs near network parks (Maps 3 and 4); there was one small area that had higher NO_x emissions, between 5 and 25 tons/mi²/yr (Map 3).

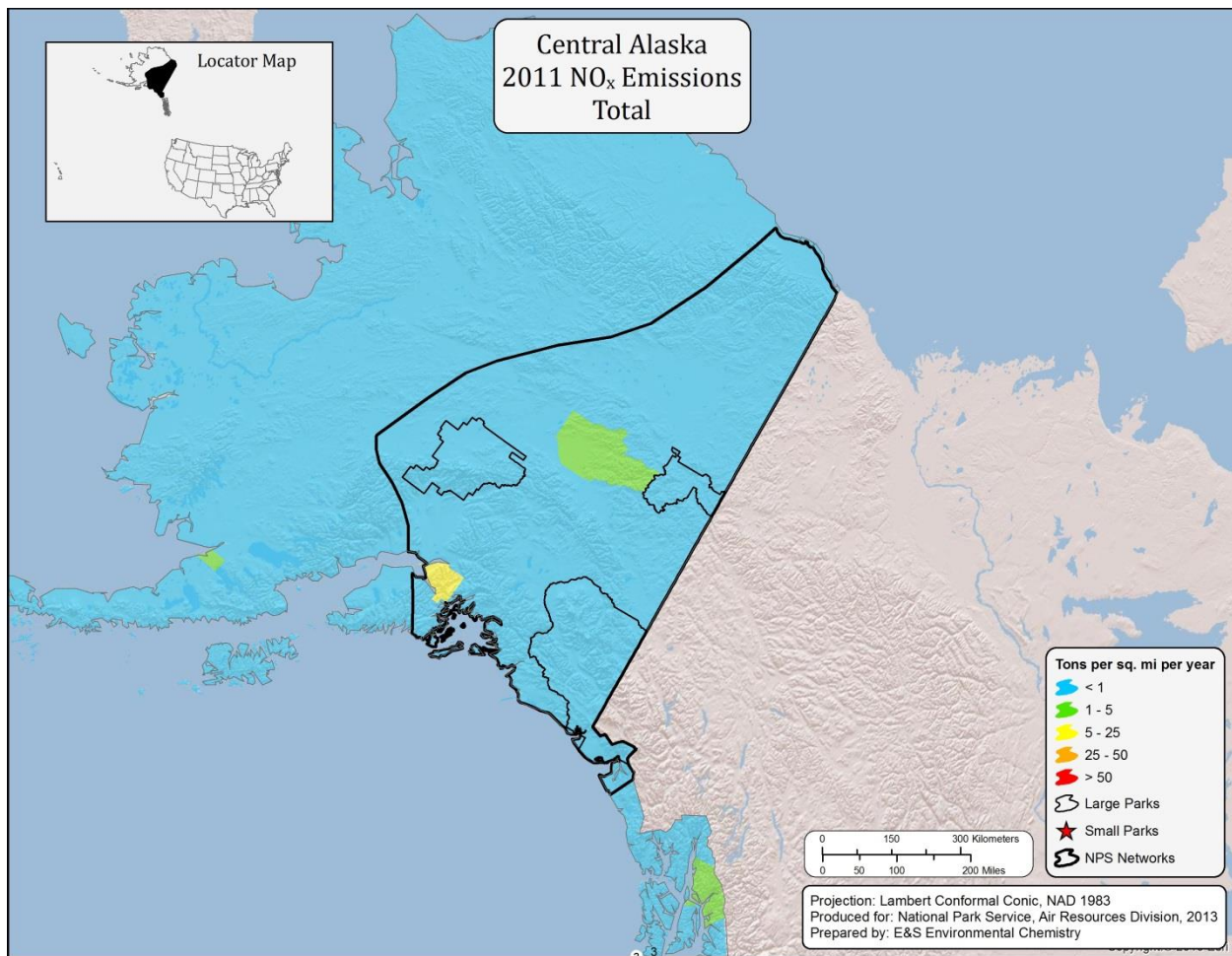
Regionally estimated deposition data are not available for Alaska because of the scarcity of monitors. Total sulfur (S) and nitrogen (N) deposition within the CAKN are both expected to be low because there are few point sources and urban areas and because estimated emissions levels from the various boroughs that comprise the network are low (Sullivan et al. 2011b). There are five active National Atmospheric Deposition Program/National Trends Network (NADP/NTN) wet deposition monitoring sites in Alaska: Poker Creek, Juneau, DENA, Gates of the Arctic National Park (GAAR), and Katmai National Park. Data have been collected since 1980 at DENA and since 1993 at Poker Creek. The other three monitoring sites have been added within the last decade. There have also been Clean Air Status and Trends Network (CASTNET) dry deposition measurements at DENA and Poker Flat. The latter operated through January, 2004. At all monitored sites in Alaska, wet N deposition has consistently been less than 1 kg N/ha/yr, and it has been less than 0.5 kg N/ha/yr at all monitored sites except Juneau. Wet S deposition has been slightly higher than 1 kg S/ha/yr at Juneau, but less than that at the other monitoring sites. The CASTNET dry deposition measurements have also been low, below about 0.25 kg N/ha/yr for each site and year measured. Thus, the sparse available atmospheric deposition data for DENA and for Alaska in general are consistent with the general understanding that atmospheric deposition of both N and S tends to be very low. It can be assumed that both S and N deposition across the CAKN would be lower than about 1 kg/ha/yr, on average.

The Western Airborne Contaminant Assessment Project (WACAP) studied airborne contaminants in a number of national parks of the western United States, including two parks in the CAKN (DENA and WRST) from 2002 to 2007. The primary semivolatile organic compounds (SOC) contaminants detected in the air at DENA were hexachlorobenzene and hexachlorocyclohexane- α , both historic use pesticides (HUPs). This finding is consistent with contaminant composition found in the air by WACAP elsewhere in Alaska, at Noatak (NOAT) and GAAR. Research conducted as part of WACAP measured snowpack SOC concentrations at DENA that were among the lowest of all WACAP parks. This finding indicates that atmospheric deposition of SOC in DENA is low compared with other WACAP parks. Air sampled in WRST contained the fewest identified SOC contaminants of any WACAP park. The only SOC detected were low levels of polycyclic aromatic hydrocarbon (PAH), and hexachlorocyclohexane- γ . Furthermore, lichen data collected by WACAP showed no evidence of elevated N deposition in this park. Smoke from wildfires is common in CAKN parks and the fire frequency and area burned may be increasing in response to climate change. Smoke can contribute to visibility degradation. International air pollution sources also

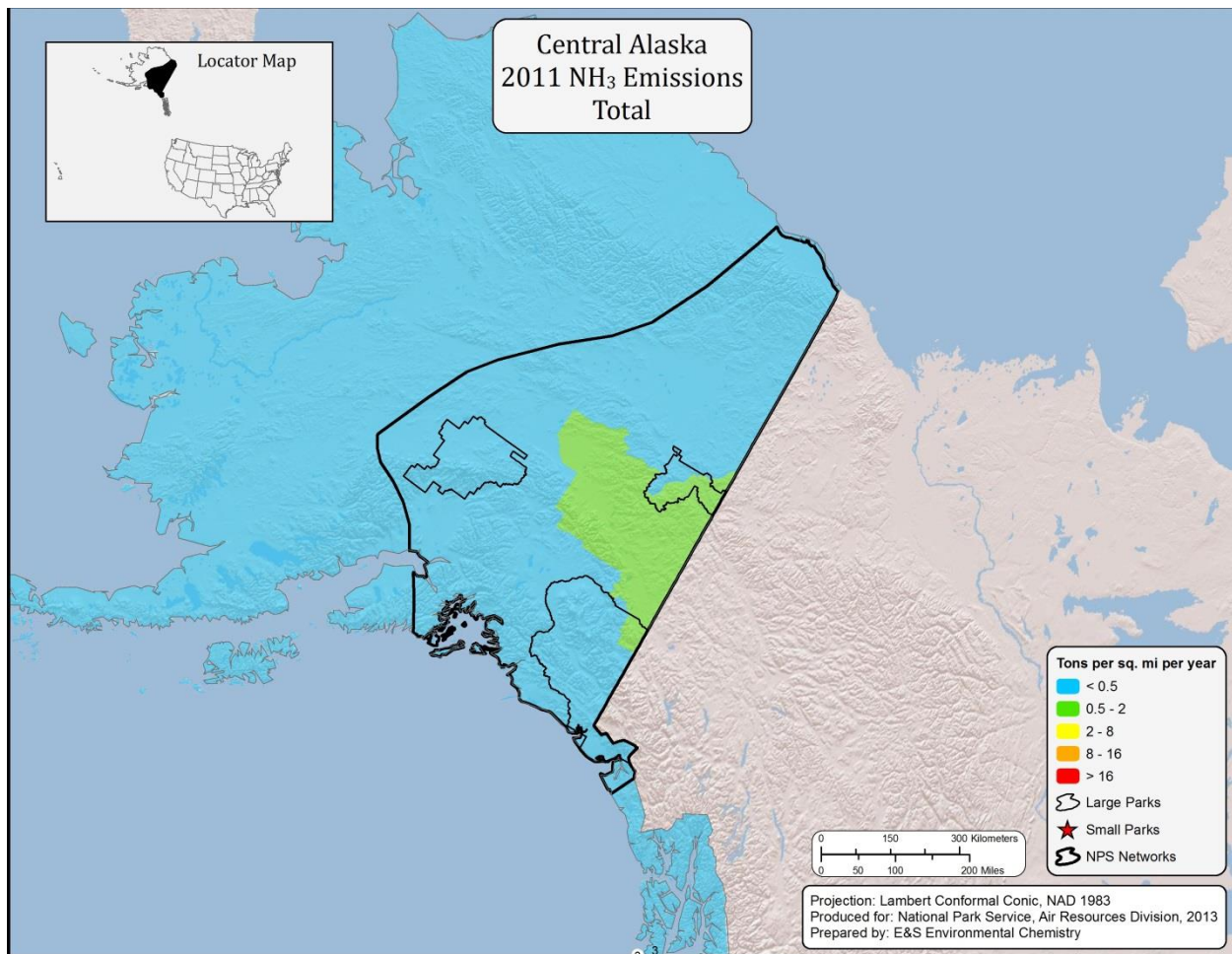
contribute air contaminants to CAKN parks. Direct pollutant transport across the Pacific Ocean and development of arctic haze contribute to decreased air quality.



Map 2. Total SO₂ emissions near CAKN for the year 2011. Data from EPA's National Emissions Inventory.



Map 3. Total NO_x emissions near CAKN for the year 2011. Data from EPA's National Emissions Inventory.



Map 4. Total NH₃ emissions near CAKN for the year 2011. Data from EPA's National Emissions Inventory.

Acidification

All three I&M parks in this network were ranked in the lowest quintile for acid Pollutant Exposure in a coarse screening assessment by Sullivan et al. (2011b). However, they were ranked Very High (DENA, WRST) to High (YUCH) in Ecosystem Sensitivity to acidification (Table 1). Low weathering rates attributable to cold temperatures, some relatively impervious rock types, and thin poorly developed soils contribute to acid sensitivity in this network. Despite the presumed acid sensitivity of parks in the CAKN, however, aquatic and terrestrial acidification have not been documented in this network and are considered unlikely in view of the very low levels of S and N deposition. There are no surface water chemistry data to demonstrate low-acid neutralizing capacity (ANC) lakes or streams in the parks in CAKN.

Table 1. 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
Denali	DENA	Very Low	Very High
Wrangell-St. Elias	WRST	Very Low	Very High
Yukon-Charley Rivers	YUCH	Very Low	High

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

Nutrient Enrichment

The network rankings for nutrient N Pollutant Exposure, Ecosystem Sensitivity to nutrient N enrichment, and Park Protection developed by Sullivan et al. (2011a) in a coarse screening assessment of I&M parks yielded an overall network Summary Risk ranking for nutrient N enrichment that was low compared with other networks. Lichens and mosses are known to be highly sensitive to N addition, but cannot be used for inter-park and inter-network comparisons because data on distribution and abundance of these species are not available for enough locations at the present time. Other vegetation types thought to be highly sensitive to nutrient enrichment from atmospheric N deposition within the parks found in the CAKN are wetland and herbaceous vegetation. It is likely, however, that the ecosystem sensitivity of parks in this network was underestimated by the methodology and data used for the analysis of Sullivan et al. (2011a). Shrub and forest vegetation communities in high-latitude ecosystems, such as are commonly found within the I&M parks in the CAKN, may indeed be highly sensitive to relatively low levels of N addition. Unfortunately, experimental data at relevant rates of nutrient addition are inadequate. It is expected that both arctic and alpine plant communities dominated by graminoids and herbaceous plants are likely to be especially sensitive, but there is not an adequate basis for evaluating the relative sensitivity of woody plants at high-latitude locations.

The availability of N has major influence on plant communities in arctic tundra ecosystems. Plant species community composition, plant growth, and a variety of ecosystem processes are partially

controlled by N supply (Mack et al. 2004, Shaver et al. 1992). Bryophytes and lichens have major influence on water and energy balances in arctic tundra vegetation communities. High inputs of N can reduce their growth, while increasing the growth of competing grass and sometimes also shrub species (Berendse et al. 2001, Bubier et al. 2007, van der Wal et al. 2005).

Competitive interactions among plants can be just as important as growth stimulation effects in response to N addition. For example, competition by erect vascular plants can decrease moss cover despite the N-limitation of the mosses (Klanderud 2008). Such competitive effects are more likely to occur in low- and mid-arctic regions than in high-arctic regions where growth is more strongly limited by harsh climatic conditions (Cornelissen et al. 2001, Madan et al. 2007, van Wijk et al. 2004).

Tundra lichens that live near the southern extent of arctic tundra vegetation and in alpine areas may be more susceptible to effects of climate warming because higher temperatures may increase availability of N and phosphorous (P) and this favors vascular plants more than bryophytes and lichens (Cornelissen et al. 2001). Some experimental data are available with which to evaluate potential effects on plant communities due to increased N loading. In dry heath tundra near Toolik Lake in the northern Brooks Range, primary productivity increased in response to very high (100 kg N/ha/yr) N fertilization (Gough et al. 2002). Dwarf birch became dominant, while species of grass, other shrubs, forbs, bryophytes, and lichens decreased in coverage. Wet tundra sites are more likely to be P-limited, and dry tundra sites tend to be N-limited (Shaver et al. 1998). Lichens were completely eliminated subsequent to over 10 years of experimental N addition at a rate of 100 kg N/ha/yr at the Toolik Lake Tundra LTER site (Weiss et al. 2005).

Van Wijk et al. (2004) conducted a meta-analysis in mid-Arctic regions of Alaska and Sweden to examine ecosystem response to experimental N addition. They found that growth of vascular plants, primary productivity, and total biomass all increased substantially subsequent to addition of N alone and also addition of N plus P and other nutrients. Growth of shrubs and graminoids increased, while growth of forbs, bryophytes, and lichens decreased. Shrub response appeared to vary with soil condition. At locations having base-rich soils, N addition did not necessarily contribute to increasing shrub dominance (Gough and Hobbie 2003).

Plant species in arctic tundra are often N-limited (Shaver and Chapin 1980). Soluble N in tundra soil solution is often dominated by organic N, including free amino acids, rather than ammonium (NH_4^+) or nitrate (NO_3^- ; Kielland 1995). Tundra plants appear to exhibit a range of interspecific differences that allow coexistence under conditions that reflect a single limiting element. Species differ in rooting depth, phenology, and uptake preferences for organic and inorganic forms of N (Chapin et al. 1993, Kielland 1994, McKane et al. 2002, Shaver and Billings 1975). McKane et al. (2002) demonstrated, based on ^{15}N field experiments, that arctic tundra plant species were differentiated in timing, depth, and chemical form of N utilization. Furthermore, the species that exhibited greatest productivity were those that efficiently used the most abundant N forms.

Arctic ecosystems appear to respond to increased N supply at levels less than 5 kg N/ha/yr by changing the level of primary productivity and the structure of the plant community (Arens et al.

2008). There has been a paucity of studies on Taiga responses to N addition in North America. However, changes in ground vegetation occurred in Swedish boreal forests at relatively low levels of atmospheric N deposition. Whortleberry (*Vaccinium myrtillus*) cover decreased at N deposition ≥ 6 kg N/ha/yr (Nordin et al. 2005, Strengbom et al. 2003); the growth of wavy hairgrass (*Deschampsia flexuosa*) increased at ≥ 5 kg N/ha/yr (Kellner and Redbo-Torstensson 1995, Nordin et al. 2005).

Geiser and Nadelhoffer (2011) recommended a critical load of atmospheric N deposition to protect lichen and mosses of the Taiga ecoregion in North America less than 1 to 3 kg N/ha/yr (Table 2). To protect shrub and grass community composition, the critical load would likely be higher, in the range of about 6 kg N/ha/yr (Geiser and Nadelhoffer 2011, Nordin et al. 2005, Strengbom et al. 2003).

Table 2. Empirical critical loads for nitrogen in the CAKN, by ecoregion and receptor from Pardo et al. (2011).

NPS Unit	Ecoregion	Critical Load (kg N/ha/yr)				
		Mycorrhizal Fungi	Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Denali NP & Pres	Marine West Coast Forests	5	2.7	NA	5	NA
Denali NP & Pres	Northwestern Forested Mountains	5	1.2	4	4	4
Denali NP & Pres	Taiga	5	1	6	NA	NA
Wrangell-St. Elias NP & Pres	Marine West Coast Forests	5	2.7	NA	5	NA
Wrangell-St. Elias NP & Pres	Northwestern Forested Mountains	5	1.2	4	4	4
Yukon-Charley Rivers NP	Northwestern Forested Mountains	5	1.2	4	4	4
Yukon-Charley Rivers NP	Taiga	5	1	6	NA	NA

Much of interior Alaska lies within the Taiga ecoregion, which is underlain by sandstone, limestone, and shale, creating a generally flat rolling plain. There is an abundance of organic deposits and substantial permafrost in the north. Lowlands are primarily covered with peatlands. Wetlands interspersed with shrublands grade into tundra at the northern extent of the Taiga (Geiser and Nadelhoffer 2011). Most plants in this ecoregion are adapted to low N supply.

Increased N deposition to Taiga plant communities, provided the increase is sufficiently large, is expected to increase plant growth in the short term, followed by the likelihood of a longer-term change in species composition and richness (Geiser and Nadelhoffer 2011, Gough et al. 2000). Any change from the natural state in species composition or richness in a Class I area may be viewed as adverse. In peatland bogs, species richness commonly decreases in response to N addition (Allen 2004), perhaps in part because the low pH and high water table inhibit nitrophyte invasion (Geiser and Nadelhoffer 2011). In contrast, forested areas may exhibit increases in nitrophilic (nitrogen-loving) plant species and decreases in species that evolved under low N supply, with little change in

richness (Bobbink 2004, Geiser and Nadelhoffer 2011). Increased N supply, especially in combination with a warming climate, might cause an advance of the location of treeline to the north or to higher elevation (Chapin and Körner 1996, Sverdrup et al. 2012).

Emissions of N from an industrial complex on the Kenai Peninsula caused downwind damage to white spruce (*Picea glauca*) trees, including crown thinning and needle chlorosis. Changes were also observed in the forest understory plant composition; ectomycorrhizal fungal diversity decreased (Lilleskov et al. 2002, Whytemare et al. 1997). Effects were acute adjacent to the industrial complex, but were not geographically extensive.

Classification of arctic plants into functional types or growth forms provides a useful framework for evaluating the effects of added N and climate change on plant community composition, functioning, and ecosystem processes (Chapin et al. 1996). Functional plant types such as deciduous and evergreen shrubs, forbs, graminoids, mosses, and lichens have been used extensively in arctic environments to describe plant responses to changes in nutrient supply (Chapin et al. 1996, Walker et al. 1989). Typically, woody plants can achieve greater canopy height than non-woody plants. Large stature, provided by woodiness, allows individual plants to capture a disproportionate amount of available light (Tilman 1988). Non-vascular plants tend to dominate where conditions limit plant growth: too wet, too dry, too nutrient-poor. Vascular plants dominate under more favorable growth conditions (Chapin et al. 1996). Deciduous woody plants have a shorter season of photosynthetic activity and require proportionately more nutrient resources than do evergreen vascular plants. As a consequence, deciduous shrubs tend to dominate fertile nutrient-rich upland sites; evergreen shrubs are more common on dry and infertile sites (Shaver and Chapin 1991). Grasses dominate steep south-facing slopes (Walker et al. 1991); forbs generally prefer moist, nutrient-rich sites (Chapin et al. 1996). Ecological sorting results in species of greater stature and higher rates of resource acquisition dominating nutrient-rich sites. Species having low rates of resource capture and relatively low nutrient turnover dominate infertile sites and sites subjected to frequent disturbance (Chapin and Körner 1996).

In the short term, most arctic and alpine plant communities increase productivity in response to increased N supply. In the long term, however, added N is expected to change the species composition, typically resulting in a community that is less resistant to stress (Chapin and Körner 1996, Körner 1989, Shaver and Chapin 1986).

Plant species diversity provides insurance against dramatic changes in ecosystem processes or nutrient cycles. If there are multiple species present within a given functional group, severe disturbance is less likely to have serious ecosystem consequences (Chapin and Körner 1996). Thus, species richness, on its own, can be important for maintaining ecosystem structure and function, mainly in the case of a dramatic change in a key ecosystem forcing function.

Most commonly, changes in the abundance of one species will result in compensatory changes in other species, with little impact on ecosystem functioning (Chapin and Körner 1996). Dramatic changes in the relative abundance of entire functional groups of species, however, would be more likely to have impacts at the ecosystem level.

Most major ecosystem types, including temperate forest, grassland, and tropical forest, tend to be dominated by a single physiognomic type of vegetation. In contrast, arctic and alpine tundra tend to be dominated by multiple plant communities (Chapin et al. 1980). Across a relatively small area of tundra, there may be a wide variety of plant community types in which graminoids, forbs, mosses, lichens, deciduous shrubs, or evergreen shrubs dominate (Bliss et al. 1973). There can be important differences among these plant growth forms in their use of, and response to, addition of nutrients (Schlesinger and Chabot 1977, Thomas and Grigal 1976).

Future climate warming could have important effects on N cycling in arctic tundra ecosystems in the CAKN. In the past, organic materials have accumulated in tundra soils, largely because decomposition has been slower than plant growth. Climate warming may increase the decomposition of soil organic matter, thereby increasing the availability of stored N (Weintraub and Schimel 2005). The distributions of woody plant species are also increasing in response to warming, with likely feedbacks on carbon (C) and N cycling. For example, a dominant shrub birch species (*Betula nana*) in the arctic tundra in Alaska is expanding its distribution in tussock vegetation communities (Weintraub and Schimel 2005).

Arctic tundra is characterized by the presence of continuous permafrost, which limits root penetration into deeper soil layers, and maintains high water content in the overlying soil during summer. This modifies the response of the tundra environment to deposition of contaminants, especially N. If the arctic climate continues to warm, widespread melting of permafrost may contribute N to surface waters. This conversion of stored N to a more highly available form may augment atmospherically-deposited N, leading to greater eutrophication effects in the future under a warming climate. Loss of permafrost in response to climate warming may have dramatic effects on the distribution of wetland vegetation in Alaska, especially along the southern edge of the zone of continuous permafrost. For example, in Kobuk Valley National Park in the Arctic Network, preliminary analysis of monitoring data indicated that lake surface area has decreased by about 14% in the Ahnewetut wetlands and by 20% in the Nigruk Plain over the past two decades. Lake drainage in these areas is caused by permafrost melting, terrain subsidence, and subsequent stream channel incision (Larsen 2011). Such changes may alter the distribution and abundance of plant communities that are sensitive to air quality.

Hobbs et al. (2010) synthesized diatom records from lakes in western North America and west Greenland, finding that both temperature and N deposition drove species composition changes in diatoms, with temperature driving changes in the Arctic and N deposition driving changes in mid-latitude alpine lakes. The authors concluded that remote lakes will continue to experience diatom species shifts, particularly in regions where increasing temperatures intersect with increasing N deposition.

Relatively little information is available regarding the effects of atmospheric N inputs on fresh waters in arctic settings. However, Levine and Whalen (2001) reported results of nutrient enrichment bioassays in 39 lakes and ponds in the Arctic Foothills region of Alaska. Significant ^{14}C uptake responses were observed subsequent to experimental addition of N + P, N alone, and P alone in 83%, 35%, and 22% of the bioassays, respectively. Overall, the data suggested that N was somewhat more

important than P in regulating phytoplankton production in lakes and ponds in this Arctic region. As the summer progressed, the strength of the response to nutrient addition decreased, but this decrease was not related to irradiance or water temperature. This suggested secondary limitation by a micronutrient such as iron during the latter parts of the growing season (Levine and Whalen 2001).

Arctic lake diatom flora and nutrient balances have been shown to have been altered by N deposition in the Canadian arctic (Wolfe et al. 2006). Anadromous salmonid fish constitute an important source of N to nutrient-poor streams and lakes in the Pacific Northwest and major parts of Alaska. These fish accumulate nutrients, including N, during adult life in the ocean, and then return to spawn and die in fresh waters that can be considerable distances inland. Thus, anadromous salmonids transport to inland fresh waters the N and other nutrients that they accumulate while in the ocean, thereby potentially altering responses to N input and nutrient cycling.

Ozone Injury to Vegetation

The O₃-sensitive plant species that are known or thought to occur within the I&M parks found in the CAKN are listed in Table 3. Those considered to be bioindicators exhibit distinctive symptoms when injured by O₃ (e.g., dark stipple). They are designated in the table by an asterisk. Each park within the network contains four or more O₃ sensitive and/or bioindicator species.

Table 3. Ozone-sensitive and bioindicator plant species known or thought to occur in the I&M parks of the CAKN. (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		
		DENA	WRST	YUCH
<i>Alnus rubra</i> *	Red alder		X	
<i>Amelanchier alnifolia</i>	Saskatoon serviceberry	X	X	X
<i>Apocynum androsaemifolium</i> *	Spreading dogbane			X
<i>Populus tremuloides</i> *	Quaking aspen	X	X	X
<i>Salix scouleriana</i> *	Scouler's willow	X	X	X
<i>Sambucus racemosa</i> *	Red elderberry	X	X	

* Bioindicator species

An assessment to evaluate risk to vegetation from O₃ exposure found that levels at DENA, expressed as cumulative exposures using the SUM06 (a measure of cumulative exposure that includes only hourly concentrations over 60 ppb [parts per billion] O₃) and W126 (a measure of cumulative O₃ exposure that preferentially weights higher concentrations) metrics, were below levels known to induce foliar injury; no O₃ monitoring data were available for WRST or YUCH (Kohut 2007b). All three CAKN parks contain several O₃-sensitive species, including quaking aspen (*Populus tremuloides*), Saskatoon serviceberry (*Amelanchier alnifolia*), and Scouler's willow (*Salix scouleriana*). Soil moisture data were not available for evaluation of potential drought constraints on foliar O₃ uptake (Kohut 2007b).

Studies have documented the influence of wildfire in Eurasia on O₃ levels in western North America during spring and summer (Bertschi et al. 2004, Bertschi and Jaffe 2005). During April 2008, a severe O₃ episode occurred at western park locations in response to particularly active and early wildfires that were burning in Russia, coupled with favorable transport meteorology (Fuelberg et al. 2010, Oltmans et al. 2010). Unprecedented high O₃ concentrations were recorded from northern Alaska to northern California. The highest O₃ concentrations recorded in 37 years of monitoring were recorded for Barrow, Alaska, in the northernmost portion of the United States (hourly average O₃ concentration > 55 ppbv). At DENA, an hourly average of 79 ppbv was recorded during the 8-hour

period in which the average was over 75 ppbv, exceeding the ambient air quality standard. Based on extensive trajectory calculations, wildfire smoke from Russia was identified as the likely source of the observed high O₃ concentration (Oltmans et al. 2010).

Although O₃ levels in DENA are generally low, there is evidence that they may be increasing. NPS (2010) reported long-term trends in annual fourth highest 8-hour daily maximum O₃ concentration for 31 monitoring sites in 27 national parks having more than 10 years of data through 2008. Statistically significant increases were reported for only four parks, including DENA. From 1990 to 2008, O₃ increased about 0.33 ppb/yr, or about 6 ppb over 19 years. More recently, O₃ concentrations showed no trend from 2000-2009.

Kohut's (2007a) O₃ risk ranking, ranging from possible Low to High values (three classes) was available for DENA, which received a Low ranking. WRST and YUCH did not receive a risk ranking by Kohut due to the absence of monitored or kriged data representative of these parks.

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 visibility¹ 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 (IMPROVE) Network and typically reported using the haze index deciview² (dv).

DENA is the only park in the CAKN that has an IMPROVE monitoring site. 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 IMPROVE monitors were used in generating the visibility ranking. DENA experienced relatively low natural haze levels for the 20% clearest days, the 20% haziest days, and for the average of all natural haze conditions (Table 4).

Measured ambient haze values for the period 2004 through 2008 were only slightly higher than the estimated natural haze condition (Table 4). Measured ambient haze within DENA was classified as Very Low for each category compared with other I&M parks.

IMPROVE data allow estimation of visual range (VR). Data from DENA indicate that air pollution has reduced average VR in the park from 160 to 130 miles (257 to 209 km). On the haziest days, VR has been reduced from 110 to 80 miles (177 to 129 km). Severe haze episodes occasionally reduce visibility to 10 miles or less.

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.

Table 4. Estimated natural haze and measured ambient haze in I&M parks averaged over the period 2004 through 2008¹.

Park Name	Park Code	Site ID	Estimated Natural Haze					
			20% Clearest Days	20% Haziest Days	Annual Average			
			dv	dv	dv			
Denali	DENA	DENA1	1.77	7.31	3.79			
Wrangell-St. Elias	WRST	No Site						
Yukon-Charley Rivers	YUCH	No Site						
Park Name	Park Code	Site ID	Measured Ambient Haze (For Years 2004 through 2008)					
			20% Clearest Days		20% Haziest Days		Annual Average	
			dv	Ranking	dv	Ranking	dv	Ranking
Denali	DENA	DENA1	2.41	Very Low	9.55	Very Low	5.34	Very Low
Wrangell-St. Elias	WRST	No Site						
Yukon-Charley Rivers	YUCH	No Site						

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

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 plants, smelters, and other industrial facilities. Nitrates form in the atmosphere from NO_x emissions from combustion sources including vehicles, power plants, industry, and fires. Organic compounds are emitted from a variety of both natural (biogenic) and anthropogenic sources, including agriculture, industry, and fires. Atmospheric seasalt concentrations are higher in coastal areas. Soil can enter the atmosphere through both natural processes and human disturbance.

Extinction charts are shown for DENA in Figure 1. The majority of total particulate light extinction (b_{ext}) in DENA was contributed by sulfate (SO₄²⁻) and organics, followed by coarse mass and light-absorbing carbon (C). On an annual average basis, 42.3% of b_{ext} was attributable to SO₄²⁻, and 32.5% to organics. On the 20% haziest days, SO₄²⁻ contributed 36.4% of b_{ext} and organics contributed 43.6%. On the clearest 20% visibility days, SO₄²⁻ contributed 49.2% of b_{ext} , organics 18.4%, and coarse mass 15.7%.

Trends in Visibility

Available monitoring data from DENA suggest trends in visibility over the period of record, although haze was relatively high on the 20% haziest and average days during one recent year (2009; Figure 2). There is indication that haze levels may be decreasing slightly on the 20% clearest, average and 20% haziest days.

Development of State Implementation Plans

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

natural background levels 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). Other than the one relatively high haze year in 2009, ambient measured values are generally following the glideslope to attain zero human-caused haze (7.31 dv) by the year 2064 (Figure 3).

Toxic Airborne Contaminants

Within the CAKN, the effects of atmospheric deposition of toxic materials have been investigated in DENA as part of the WACAP study. Vegetation concentrations of SOCs, nutrients, and toxic metals measured at DENA were lower than at any other WACAP park except the other two WACAP sites in Alaska (NOAT and GAAR). Contaminant concentrations in vegetation were also low in WRST, compared with other WACAP parks, and mostly included PAHs, hexachlorobenzene, and hexachlorocyclohexane- γ . Howe et al. (2004) found that concentrations of PAHs and hexachlorobenzene (HCB) in spruce (*Picea* spp.) needles at 36 sites in eastern Alaska varied by an order of magnitude. Samples collected near the city of Fairbanks generally had higher concentrations than samples collected from rural areas.

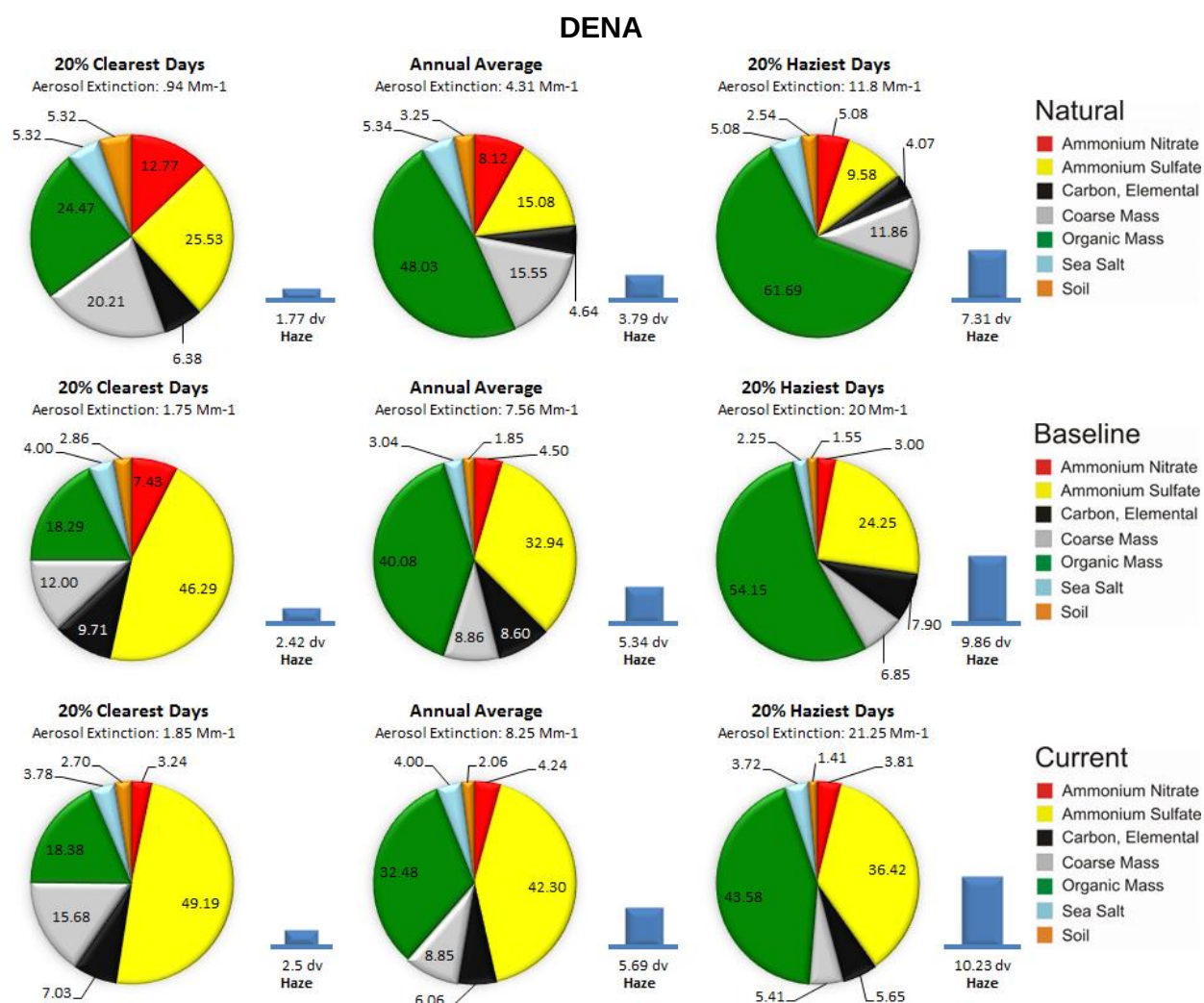


Figure 1. Estimated natural (pre-industrial), baseline (2000-2004), and current (2006-2010) levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for DENA. Data Source: NPS-ARD

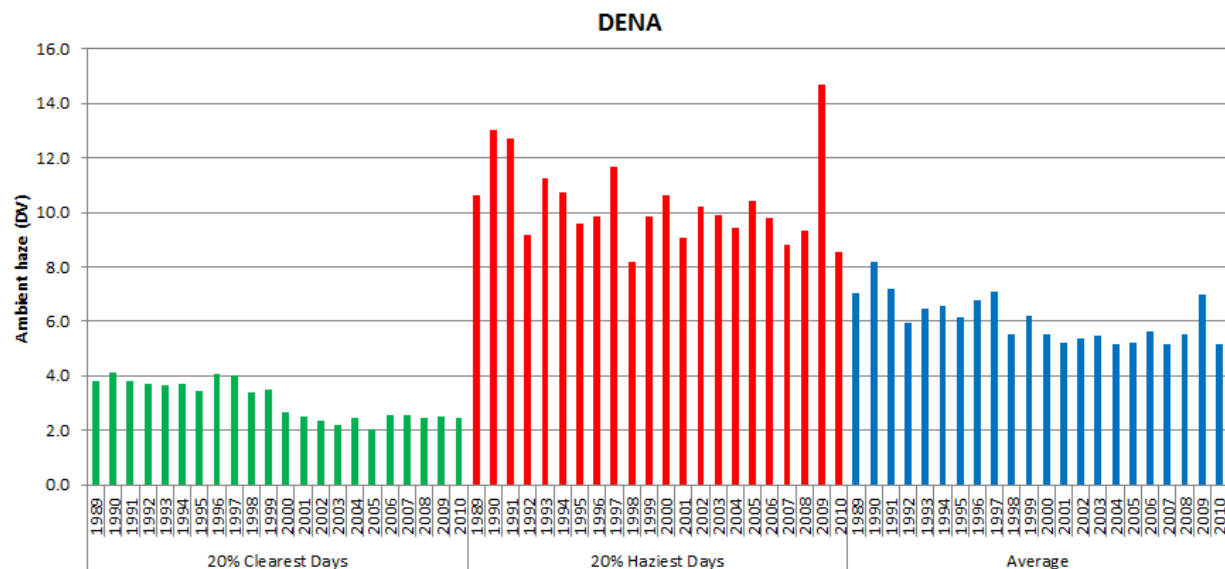


Figure 2. Trends in ambient haze levels at DENA, based on IMPROVE measurements on the 20% clearest, 20% haziest, and annual average visibility days over the monitoring period of record. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

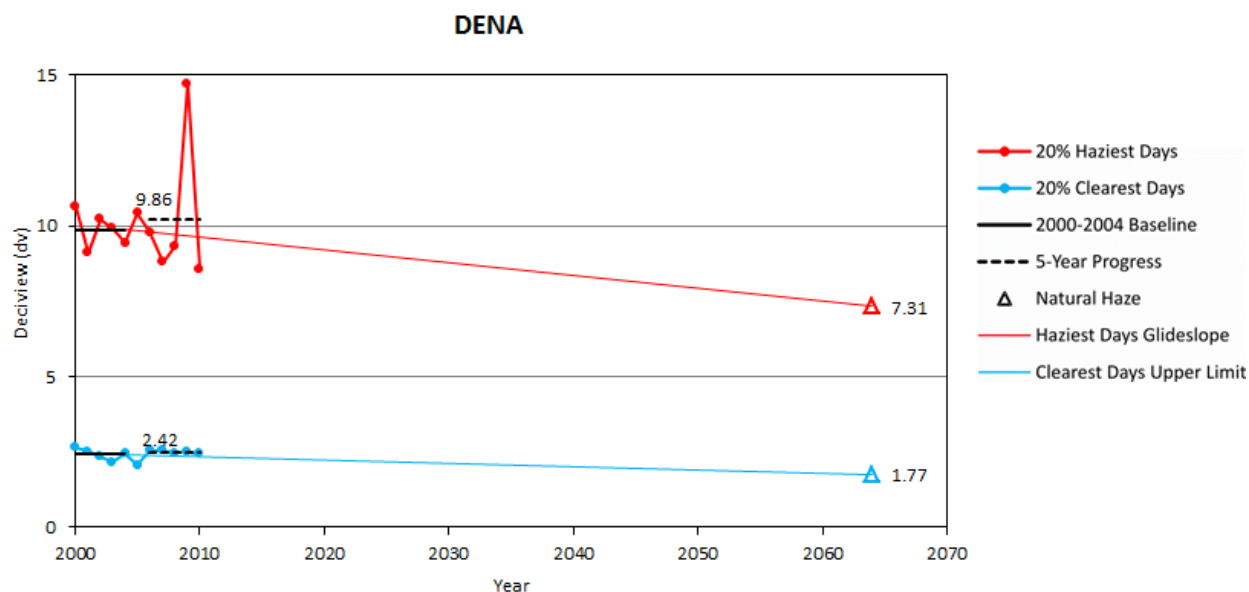


Figure 3. Glideslopes to achieving natural visibility conditions in 2064 for the 20% haziest (red line) and the 20% clearest (blue line) days in DENA. Data Source: http://vista.cira.colostate.edu/improve/Data/IMPROVE/summary_data.htm

Fish in both WACAP study lakes in DENA had dieldrin concentrations that exceeded health thresholds for mammals (river otter [*Lutra canadensis*] and mink [*Mustela vison*]), and both lakes exceeded mercury (Hg) thresholds for piscivorous birds. In Wonder Lake, concentrations of Hg and lead in sediments showed increasing trends since the 1920s, likely a result of changes in global emissions (Landers et al. 2008).

Flanagan Pritz et al. (2014) analyzed SOC data for fish collected from 14 national parks in Alaska and the western United States. The study included data for fish sampled in WRST and DENA in the CAKN. Contaminant loading was highest in fish from Alaskan and Sierra Nevada parks. Historic use compounds were highest in Alaskan parks, whereas current-use pesticides were higher in Rocky Mountain and Sierra Nevada parks. Concentrations of the HUPs dieldrin, p,p'-DDE, and/or chlordanes in fish exceeded U.S. EPA guidelines for wildlife (kingfisher) and for human subsistence fish consumers health thresholds at 13 of 14 parks. Additional research is needed to determine how best to manage the risk of toxic substances in these parks and to judge the role played by anadromous fish in defining that risk (Flanagan Pritz et al. 2014).

Hageman et al. (2010) reported results of pesticide analyses of snowpack at remote alpine, arctic, and subarctic sites in eight national parks, including DENA. Various current use pesticides (CUPs; dacthal, chlorpyrifos, endosulfans, and γ -hexachlorocyclohexane [HCH]) and historic-use pesticides (dieldrin, α -HCH, chlordanes, and hexachlorobenzene) were commonly measured at all sites and years (2003-2005). The pesticide concentration profiles were unique for individual parks, suggesting the importance of regional sources.

The distributions of CUPs among the parks were explained, using mass back trajectory analysis, based on the mass of individual CUPs used in regions located one-day upwind of the parks. For most pesticides and parks, more than 75% of the snowpack pesticide burden was attributed to regional transport. The authors concluded that the majority of pesticide contamination in U.S. national parks is due to regional pesticide applications.

Pesticide concentrations in snowpack in DENA, where regional cropland does not occur, were in some cases as high as those found for parks located in the lower 48 states. In most cases (dacthal and chlorpyrifos being exceptions), pesticide concentrations at NOAT/GAAR were more than six times higher than at DENA (Hageman et al. 2010). The reason(s) for the observed relatively high concentrations of pesticides at NOAT/GAAR, distant from regional cropland, is/are not known.

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. Lake-specific average fish Hg content from fish collected from three lakes in WRST varied nearly 8-fold, from rainbow trout (*Oncorhynchus mykiss*) collected in Summit Lake (53 ng/g ww) to lake trout (*Salvelinus namaycush*) collected in Tanada Lake (417 ng/g ww). The latter fish had the highest Hg concentration of any fish included in the study. The average size-adjusted Hg concentration in 400 mm fish from Copper Lake (242 ng/g ww) and Tanada Lake (321 ng/g ww) approached or exceeded the EPA fish tissue criterion, the avian reproductive impairment benchmark, and the tissue-based criterion for fish toxicity (Eagles-Smith et al. 2014). The cause(s) of these high concentration of Hg in fish from WRST is/are not known. Northern pike (*Esox lucius*) were sampled from one lake in DENA. The concentrations of Hg in fish from that lake were among the lowest recorded in the study. Similar results were found previously by Landers et al. (2008) for burbot (*Lota lota*) and whitefish (*Coregonus clupeaformis*) in DENA.

Organochlorine chemicals can be estrogenic (Garcia-Reyero et al. 2007), contributing to the occurrence of intersex fish, and can accumulate in the aquatic food chains of remote mountain ecosystems (Blais et al. 1998). Biomarkers of exposure to estrogenic chemicals suggest the likelihood of reproductive dysfunction (Harries et al. 1997). Organochlorines are likely transported as atmospheric contaminants to high-elevation sites (Hageman et al. 2006). Work by Schreck and Kent (2013) followed up on some of the work performed in the WACAP Study. They expanded the range of coverage to additional western parks, including WRST within CAKN. Two of 20 male kokanee salmon sampled in WRST were intersex. The low observed frequency of intersex fish in these study parks and water bodies may be a natural phenomenon (Schwindt et al. 2009). The extent to which human-caused contaminants contribute to an increased frequency is difficult to determine (Schreck and Kent 2013).

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.
- Allen, E. 2004. Effects of nitrogen deposition on forests and peatlands: A literature review and discussion of the potential impacts of nitrogen deposition in the Alberta Oil Sands region. Report to the Wood Buffalo Association, Fort McMurray, AB, Canada.
http://wbea.org/index2.php?option=com_docman&task=doc_view&gid=299&Itemid=104.
- Arens, S.J.T., P.F. Sullivan, and J.M. Welker. 2008. Nonlinear responses to nitrogen and strong interactions with nitrogen and phosphorus additions drastically alter the structure and function of a high arctic ecosystem. *J. Geophys. Res.* 113:G03509.
- Berendse, F., N. van Breemen, H. Rydin, A. Buttler, M. Heijmans, M.R. Hoosbeek, J.A. Lee, A. Mitchell, T. Saarinen, H. Vassander, and B. Wallen. 2001. Raised atmospheric CO₂ levels and increased N deposition cause shifts in plant species composition and production in Sphagnum bogs. *Glob. Change Biol.* 7(5):591-598.
- Bertschi, I.T., D.A. Jaffe, L. Jaegle, H.U. Price, and J.B. Dennison. 2004. PHOBEA/ITCT 2002 airborne observations of transpacific transport of ozone, CO, volatile organic compounds, and aerosols to the northeast Pacific: impacts of Asian anthropogenic and Siberian boreal fire emissions. *J. Geophys. Res.* 109 (D23S12).
- Bertschi, I.T. and D.A. Jaffe. 2005. Long-range transport of ozone, carbon monoxide, and aerosols to the NE Pacific troposphere during the summer of 2003: observations of smoke plumes from Asian boreal fires. *J. Geophys. Res.* 110 (D05303).
- 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.
- Bliss, L.C., G.M. Courtin, D.L. Pattie, R.R. Riewe, D.W.A. Whitfield, and P. Widden. 1973. Arctic tundra ecosystems. *Ann. Rev. Ecol. Syst.* 4:359-399.
- Bobbink, R. 2004. Plant species richness and the exceedance of empirical nitrogen critical loads: an inventory. *Landscape Ecology*, Utrecht University, Utrecht, The Netherlands.
- Bubier, J.L., T.R. Moore, and L.A. Bldezki. 2007. Effects of nutrient addition on vegetation and carbon cycling in an ombrotrophic bog. *Glob. Change Biol.* 13:1168-1186.
- Chapin, F.S., III, D.A. Johnson, and J.D. McKendrick. 1980. Seasonal movement of nutrients in plants of differing growth form in an Alaskan tundra ecosystem: Implications for Herbivory. *J. Ecol.* 68:189-209.

- Chapin, F.S., III, M.S. Bret-Harte, S.E. Hobbie, and H. Zhong. 1996. Plant functional types as predictors of transient responses of arctic vegetation to global change. *J. Veg. Sci.* 7:347-358.
- Chapin, F.S., III and C. Körner. 1996. Arctic and alpine biodiversity: Its patterns, causes and ecosystem consequences. *In* H.A. Mooney, J.H. Cushman, E. Medina, O.E. Sala and E.-D. Schulze (Eds.). *Functional Roles of Biodiversity: A Global Perspective*. John Wiley & Sons Ltd., Chichester. pp. 7-32.
- Chapin, F.S.I., L. Moilanen, and K. Kielland. 1993. Preferential use of organic nitrogen for growth by a non-mycorrhizal arctic sedge. *Nature* 361:150-153.
- Cornelissen, J.H.C., T.V. Callaghan, J.M. Alatalo, A. Michelsen, E. Graglia, A.E. Hartley, D.S. Hik, S.E. Hobbie, M.C. Press, C.H. Robinson, G.H.R. Henry, G.R. Shaver, G.K. Phoenix, D.G. Jones, S. Jonasson, F.S. Chapin, U. Molau, C. Neill, J.A. Lee, J.M. Melillo, B. Sveinbjornsson, and R. Aerts. 2001. Global change and arctic ecosystems: is lichen decline a function of increases in vascular plant biomass? *J. Ecol.* 89:984-994.
- 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>.
- Flanagan Pritz, C.M., J.E. Schrlau, S.L. Massey Simonich, and T.F. Blett. 2014. Contaminants of emerging concern in fish from western U.S. and Alaskan National Parks — spatial distribution and health thresholds. *J. Am. Water Resour. Assoc.* 50(2):309-323. 10.1111/jawr.12168.
- Fuelberg, H.E., D.L. Harrigan, and W. Sessions. 2010. A meteorological overview of the ARCTAS 2008 mission. *Atmos. Chem. Phys.* 10:817-842.
- Garcia-Reyero, N., J.O. Grimalt, I. Vives, P. Fernandez, and B. Piña. 2007. Estrogenic activity associated with organochlorine compounds in fish extracts from European mountain lakes. *Environ. Pollut.* 145(3):745-752. <http://dx.doi.org/10.1016/j.envpol.2006.05.021>.
- Geiser, L.H. and K. Nadelhoffer. 2011. Taiga. *In* L.H. Pardo, M.J. Robin-Abbott and C.T. Driscoll (Eds.). *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. pp. 49-60.
- Gough, L., C.W. Osenberg, K.L. Gross, and S.L. Collins. 2000. Fertilization effects on species density and primary productivity in herbaceous plant communities. *Oikos* 89:428-439.
- Gough, L., P.A. Wookey, and G.R. Shaver. 2002. Dry heath arctic tundra responses to long-term nutrient and light manipulation. *Arct. Anarct. Alp. Res.* 34:211-218.
- Gough, L. and S.E. Hobbie. 2003. Responses of moist non-acidic arctic tundra to altered environment: productivity, biomass, and species richness. *Oikos* 103:204-216.

- Hageman, K.J., S.L. Simonich, D.H. Campbell, G.R. Wilson, and D.H. Landers. 2006. Atmospheric deposition of current-use and historic-use pesticides in snow at national parks in the western United States. *Environ. Sci. Technol.* 40(10):3174-3180.
- Hageman, K.J., W.D. Hafner, D.H. Campbell, D.A. Jaffe, D.H. Landers, and S.L.M. Simonich. 2010. Variability in pesticide deposition and source contributions to snowpack in western U.S. national parks. *Environ. Sci. Technol.* 44(12):4452-4458. 10.1021/es100290q.
- Harries, J.E., D.A. Sheahan, S. Jobling, P. Matthiessen, P. Neall, J.P. Sumpter, T. Tylor, and N. Zaman. 1997. Estrogenic activity in five United Kingdom rivers detected by measurement of vitellogenesis in caged male trout. *Environ. Toxicol. Chem.* 16(3):534-542. 10.1002/etc.5620160320.
- Hobbs, W.O., R.J. Telford, H.J.B. Birks, J.E. Saros, R.R.O. Hazewinke, B.B. Perren, É. Saulnier-Talbo, and A.P. Wolfe. 2010. Quantifying recent ecological changes in remote lakes of North America and Greenland using sediment diatom assemblages. *PLoS ONE* 5(4)e10026. doi:10.1371/journal.pone.0010026.
- Howe, T.S., S. Billings, and R.J. Stolzberg. 2004. Sources of polycyclic aromatic hydrocarbons and hexachlorobenzene in spruce needles of eastern Alaska. *Environ. Sci. Technol.* 38(12):3294-3298.
- Kellner, P.S. and P. Redbo-Torstensson. 1995. Effects of elevated nitrogen deposition on the field-layer vegetation in coniferous forests. *Ecol. Bull.* 44:227-237.
- Kielland, K. 1994. Amino acid absorption by arctic plants: implications for plant nutrition and nitrogen cycling. *Ecology* 75:2373-2383.
- Kielland, K. 1995. Landscape patterns of free amino acids in arctic tundra soils. *Biogeochemistry* 31:85-98.
- Klanderud, K. 2008. Species-specific responses of an alpine plant community under simulated environmental change. *J. Veg. Sci.* 19:363-372.
- 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>.
- Körner, C. 1989. The nutritional status of plants from high altitudes. A worldwide comparison. *Oecologia* 81:379-391.

- 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/>.
- Larsen, A. 2011. Impacts of permafrost degradation on shallow lakes and wetlands in Kobuk Valley National Park. Abstract. George Wright Society Conference on Parks, Protected Areas, & Cultural Sites. New Orleans, LA, March 14-18, 2011.
- Levine, M.A. and S.C. Whalen. 2001. Nutrient limitation of phytoplankton production in Alaskan arctic foothill lakes. *Hydrobiologia* 455:189-201.
- Lilleskov, E.A., T.J. Fahey, T.R. Horton, and G.M. Lovett. 2002. Belowground ectomycorrhizal fungal community change over a nitrogen deposition gradient in Alaska. *Ecology* 83(1):104-115.
- Mack, M.C., E.A.G. Schuur, M.S. Bret-Harte, G.R. Shaver, and F.S. Chapin. 2004. Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. *Nature* 431:440-443.
- Madan, N.J., L.J. Deacon, and C.H. Robinson. 2007. Greater nitrogen and/or phosphorus availability increase plant species' cover and diversity at a High Arctic polar semidesert. *Polar Biology* 30:559-570.
- McKane, R.B., L.C. Johnson, G.R. Shaver, K.J. Nadelhoffer, E.B. Rastetter, B. Fry, A.E. Giblin, K. Kielland, B.L. Kwiatkowski, J.A. Laundre, and G. Murray. 2002. Resource-based niches provide a basis for plant species diversity and dominance in arctic tundra. *Nature* 415:68-72.
- 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.
- Nordin, A., J. Strengbom, J. Witzell, T. Nasholm, and L. Ericson. 2005. Nitrogen deposition and the biodiversity of boreal forests: Implication for nitrogen critical loads. *Ambio* 34:20-24.
- Oltmans, S.J., A.S. Lefohn, J.M. Harris, D.W. Tarasick, A.M. Thompson, H. Wernli, B.J. Johnson, P.C. Novelli, S.A. Montzka, J.D. Ray, L.C. Patrick, C. Sweeney, A. Jefferson, T. Dann, J. Davies, M. Shapiro, and B.N. Holben. 2010. Enhanced ozone over western North America from biomass burning in Eurasia during April 2008 as seen in surface and profile observations. *Atmos. Environ.* 44:4497-4509.
- Pardo, L.H., M.J. Robin-Abbott, and C.T. Driscoll (Eds.). 2011. 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.

- Schlesinger, W.H. and B.F. Chabot. 1977. The use of water and minerals by evergreen and deciduous shrubs in Okefenokee Swamp. *Bot. Gaz.* 138:490-497.
- Schreck, C.B. and M. Kent. 2013. Extent of Endocrine Disruption in Fish of Western and Alaskan National Parks. Final Report, NPS-OSU Task Agreement J8W07080024.
- Schwindt, A.R., M.L. Kent, L.K. Ackerman, S.L.M. Simonich, D.H. Landers, T. Blett, and C.B. Schreck. 2009. Reproductive abnormalities in trout from western U.S. national parks. *Trans. Am. Fish. Soc.* 138(3):522-531. 10.1577/T08-006.1.
- Shaver, G.R. and W.D. Billings. 1975. Root production and root turnover in a wet tundra ecosystem, Barrow, Alaska. *Ecology* 56:401-410.
- Shaver, G.R. and F.S. Chapin. 1980. Response to fertilization by various plant growth forms in an Alaskan tundra: nutrient accumulation and growth. *Ecology* 61:662-675.
- Shaver, G.R. and F.S. Chapin, III. 1986. Effect of fertilizer on production and biomass of tussock tundra, Alaska, U.S.A. *Arct. Alp. Res.* 18:261-268.
- Shaver, G.R. and F.S. Chapin, III. 1991. Production:biomass relationships and element cycling in contrasting arctic vegetation types. *Ecol. Monogr.* 61:1-31.
- Shaver, G.R., W.D. Billings, F.S. Chapin, A.E. Giblin, K.J. Nadelhoffer, W.C. Oechel, and E.B. Rastetter. 1992. Global change and the carbon balance of arctic ecosystems. *BioScience* 42:433-441.
- Shaver, G.R., L.C. Johnson, D.H. Cades, G. Murray, J.A. Laundre, E.B. Rastetter, K.J. Nadelhoffer, and A.E. Giblin. 1998. Biomass and CO₂ flux in wet sedge tundras: Responses to nutrients, temperature, and light. *Ecol. Monogr.* 68:75-97.
- Strengbom, J., M. Walheim, T. Näsholm, and L. Ericson. 2003. Regional differences in the occurrence of understory species reflect nitrogen deposition in Swedish forests. *Ambio* 32:91-97.
- 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.
- Sverdrup, H., T.C. McDonnell, T.J. Sullivan, B. Nihlgård, S. Belyazid, B. Rihm, E. Porter, W.D. Bowman, and L. Geiser. 2012. Testing the feasibility of using the ForSAFE-VEG model to map the critical load of nitrogen to protect plant biodiversity in the Rocky Mountains region, USA. *Water Air Soil Pollut.* 23:371–387. DOI 10.1007/s11270-011-0865-y.
- Thomas, B. and D.F. Grigal. 1976. Phosphorus conservation by evergreenness of mountain laurel. *Oikos* 27:19-26.
- Tilman, D. 1988. *Plant Strategies and the Dynamics and Function of Plant Communities*. Princeton University Press, Princeton, NJ.
- van der Wal, R., I.S.K. Pearce, and R.W. Brooker. 2005. Mosses and the struggle for light in a nitrogen-polluted world. *Ecophysiology* 142:159-168.
- van Wijk, M.T., K.E. Clemmensen, G.R. Shaver, M. Williams, T.V. Callaghan, F.S. Chapin, J.H.C. Cornelissen, L. Gough, S.E. Hobbie, S. Jonasson, J.A. Lee, A. Michelsen, M.C. Press, S.J. Richardson, and H. Rueth. 2004. Long-term ecosystem level experiments at Toolik Lake, Alaska, and at Abisko, Northern Sweden: generalizations and differences in ecosystem and plant type responses to global change. *Glob. Change Biol.* 10:105-123.
- Walker, D.A., E. Binnian, B.M. Evans, N.D. Lederer, E. Nordstrand, and P.J. Webber. 1989. Terrain, vegetation, and landscape evolution of the R4D research site, Brooks Range foothills, Alaska. *Holarct. Ecol.* 12:238-261.
- Walker, M.D., D.A. Walker, K.R. Everett, and S.K. Short. 1991. Steppe vegetation on south-facing slopes of pingos, central Arctic Coastal Plain, Alaska, U.S.A. *Arct. Alp. Res.* 23:170-188.
- Weintraub, M.N. and J.P. Schimel. 2005. Nitrogen cycling and the spread of shrubs control changes in the carbon balance of the arctic tundra ecosystems. *BioScience* 55(5):408-415.
- Weiss, M., S.E. Hobbie, and G.M. Gettel. 2005. Contrasting responses of nitrogen-fixation in arctic lichens to experimental and ambient nitrogen and phosphorus availability. *Arct. Anarct. Alp. Res.* 37:396-401.
- Whytemare, A.B., R.L. Edmonds, J.D. Aber, and K. Lajtha. 1997. Influence of excess nitrogen deposition on a white spruce (*Picea glauca*) stand in southern Alaska. *Biogeochemistry* 38:173-187.
- Wolfe, A.P., C.A. Cooke, and W.O. Hobbs. 2006. Are current rates of atmospheric nitrogen deposition influencing lakes in the eastern Canadian Arctic? *Arct. Anarct. Alp. Res.* 38(3):465-476.

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