



Air Quality Related Values (AQRVs) for Arctic Network (ARCN) Parks

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

Natural Resource Report NPS/ARCN/NRR—2016/1155



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 Arctic Network (ARCN). AQRVs are those resources sensitive to air quality and include streams, lakes, soils, vegetation, fish and wildlife, and visibility. The ARCN parks that are included in the NPS Inventory and Monitoring (I&M) Program, and discussed in this report, are Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park & Preserve (GAAR), Kobuk Valley National Park (KOVA), and Noatak National Preserve (NOAT). Sullivan et al. (2011a, 2011b) and Kohut (2007a) conducted risk assessments for acidification, eutrophication and ozone (O_3) for the ARCN parks; their results are described in this report. This report also describes air pollutant emissions and air quality in the ARCN, 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 information 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 ARCN is remote from the influence of most human activities. There are no population centers of any significant magnitude ($> 25,000$ people) within the ARCN region, and only Fairbanks is within a 300-mile radius of the network boundary. The sparse available atmospheric deposition data for Alaska are consistent with the general understanding that atmospheric deposition of both N and S tends to be very low at most national park lands within Alaska. It can be assumed that S and N deposition across the ARCN would each be lower than about 1 or 2 kg/ha/yr, on average. There is, however, a lead and zinc mine located between CAKR and NOAT. It contributes heavy metal-laden fugitive dusts as well as sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions.

Data on potential effects of acidic deposition on aquatic and terrestrial resources in the ARCN are generally lacking. However, in view of the very low levels of emissions and deposition at most locations, effects are expected to be minimal. Acidification of soils and drainage waters does not appear to be an important threat in the ARCN. Resources might respond to nutrient inputs in the form of atmospheric N deposition. In the short term, most arctic and alpine plant communities would be expected to increase productivity in response to increased N supply. In the long term, however, added N might change the species composition, perhaps resulting in a community that is less resistant to stress.

Most of the parks in the ARCN were ranked in the middle quintile among parklands in a coarse screening analysis (Sullivan et al. 2011b) with respect to ecosystem sensitivity to nutrient N enrichment. It is possible, however, that the ecosystem sensitivity to nutrient N enrichment of parks in this network was underestimated by the methodology and data used for this analysis. Shrub and forest vegetation communities in high-latitude locations may indeed be highly sensitive to relatively low levels of N addition. Unfortunately, experimental data are generally lacking. Much of the land coverage in some of these parks is sparse vegetation or barren land, generally lacking vascular plants. Lichens and mosses in the ARCN may be very sensitive to N deposition. Lichens in the high arctic

areas of Greenland and elsewhere have been found to respond to very low additions of N, with changes in abundance and cover.

Various studies have identified organochlorine compounds in polar ecosystems. The accumulation of these compounds in remote northern locations has been attributed to long-range atmospheric transport. Compounds detected commonly include dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexane (HCH), hexachlorobenzene (HCB), and polychlorinated biphenyls (PCBs). Such compounds tend to concentrate in aquatic biota and their mammalian predators in response to biomagnification processes and have been associated with disruption of endocrine systems in some aquatic species. NOAT and GAAR were included in the Western Airborne Contaminants Assessment Project (WACAP) study of airborne toxics. Fish in these parks were found to have elevated mercury (Hg), as well as dieldrin and other semivolatile organic compounds (SOCs).

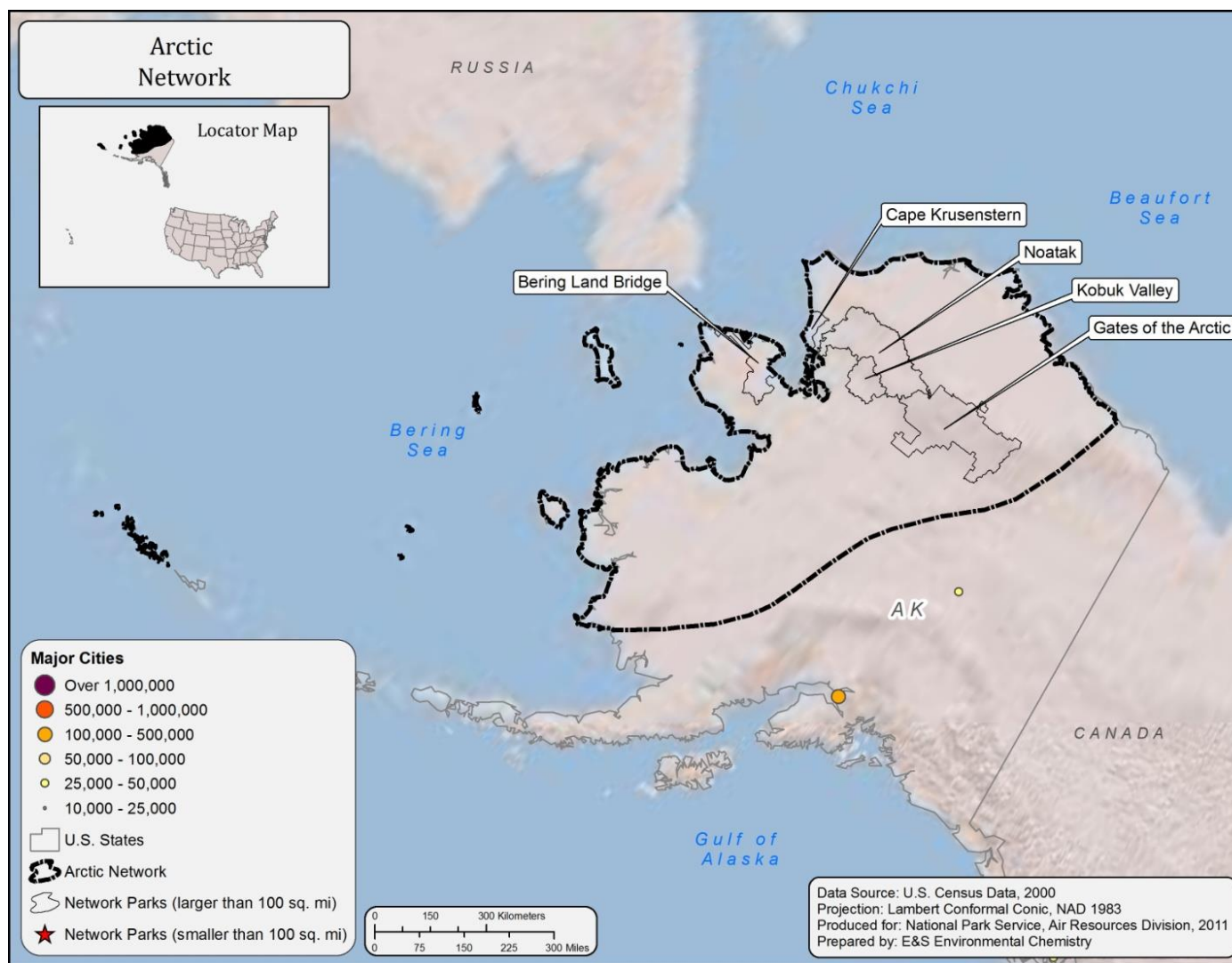
Background

There are five parks in the Arctic Network, ranging in size from about 900 to 12,000 square miles (mi^2): Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park & Preserve (GAAR), Kobuk Valley National Park (KOVA), and Noatak National Preserve (NOAT). Map 1 shows the network boundary along with locations of each park and population centers having more than 10,000 people around the network. There are no population centers of any significant magnitude ($> 25,000$ people) within the ARCN region, and only Fairbanks is within a 300-mile radius of the network boundary.

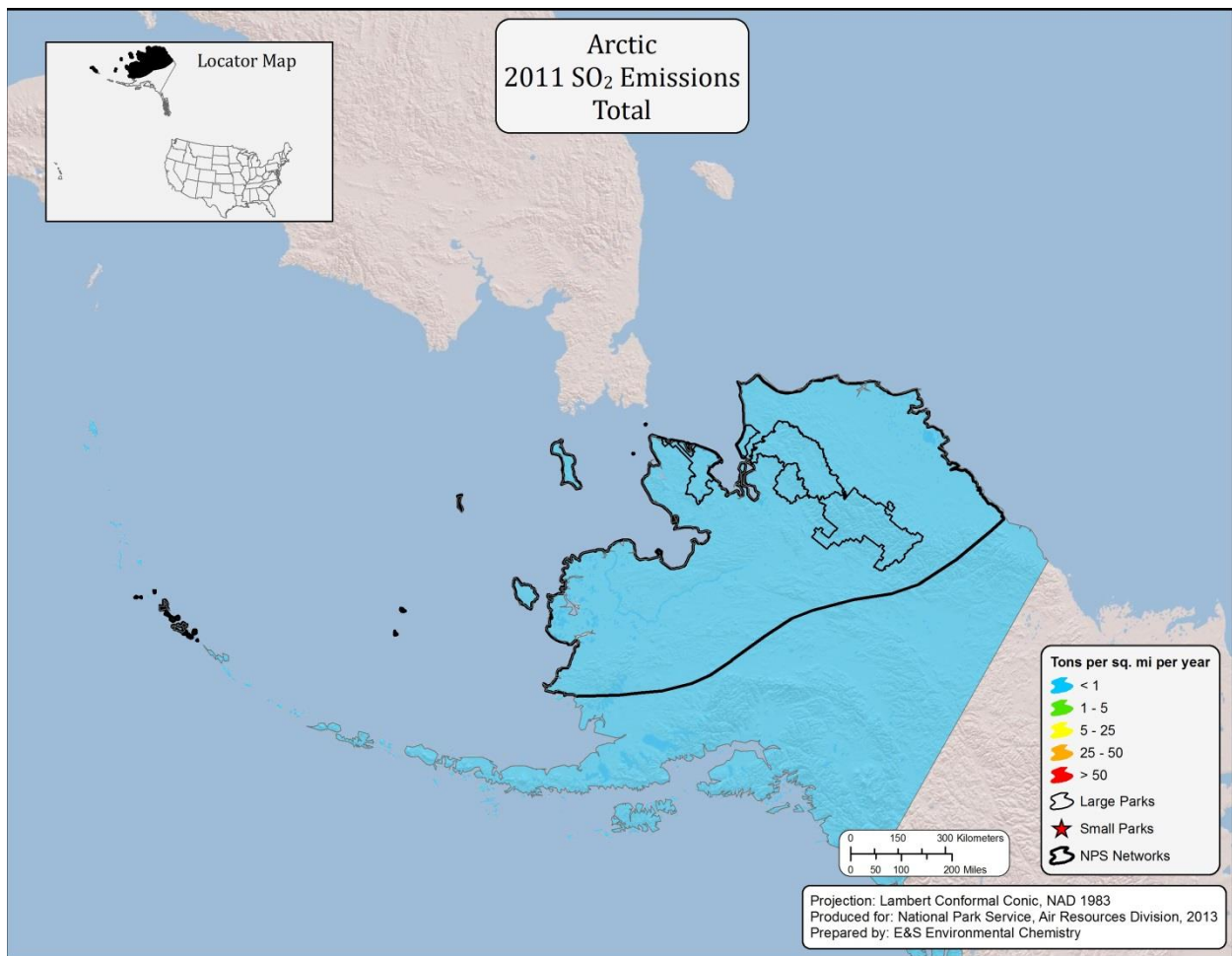
Much of land area of the ARCN parks lies within the tundra and taiga ecoregions in interior Alaska. Almost all of GAAR is mountainous, as are large portions of NOAT and the northern portion of KOVA. Bering Land Bridge NP and CAKR grade from high elevation to coastal plains. There is an abundance of organic deposits and substantial permafrost in the northern portions of the network. Lowlands are primarily covered with peatlands. Wetlands interspersed with shrublands grade into tundra at the northern extent of the taiga. Most plants in this ecoregion are adapted to low N supply (Geiser and Nadelhoffer 2011).

Atmospheric Emissions and Deposition

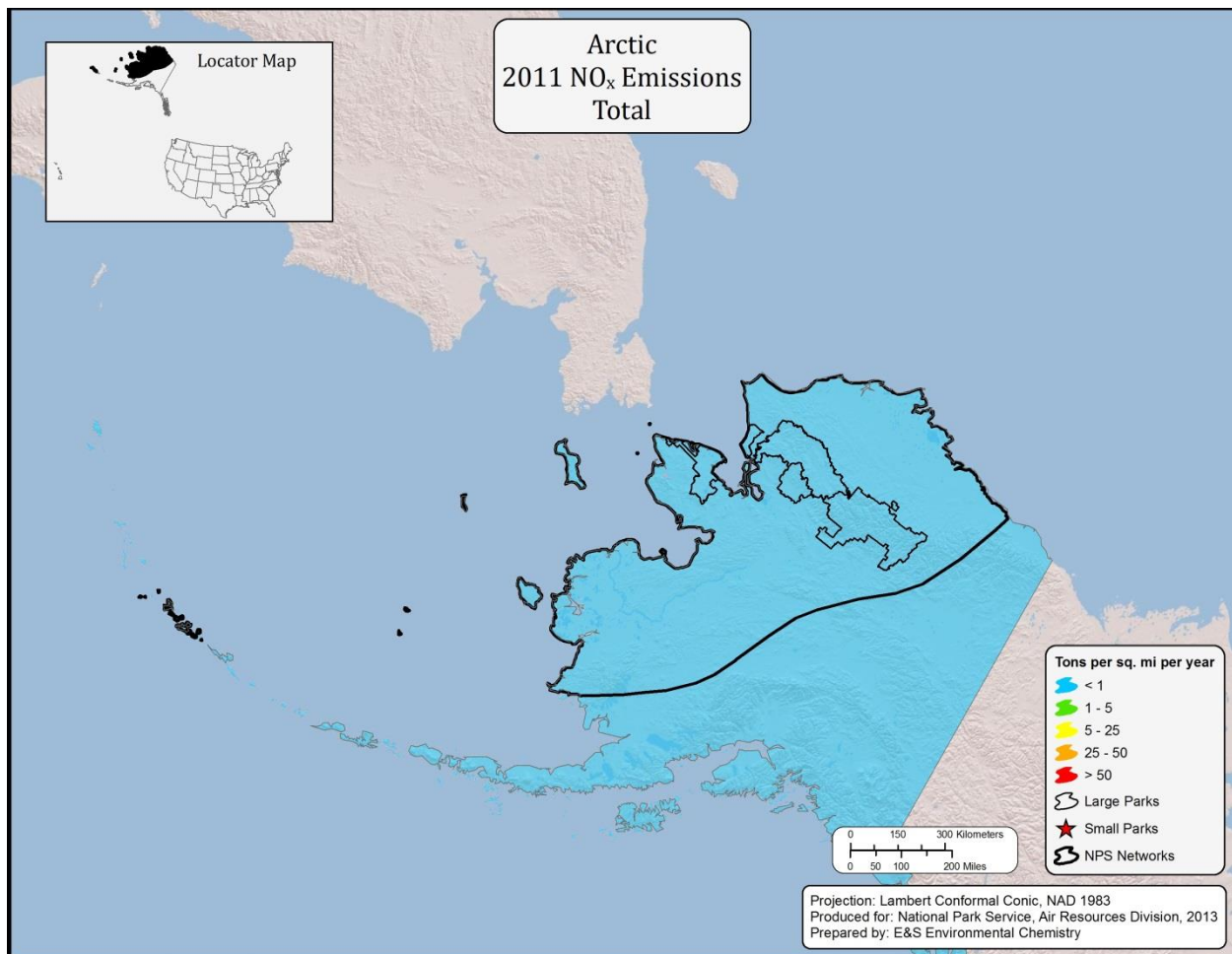
Sulfur dioxide (S) and nitrogen (N) emissions in recent years were both estimated to be less than 1 ton per square mile per year throughout the entire network region. Red Dog Mine, located between CAKR and NOAT, is a major point source of SO_2 , nitrogen oxide (NO_x), and heavy metal-laden fugitive dusts. There were few other S point sources around the network. Most point sources in the network region emitted SO_2 in the range of 1,000 to 5,000 tons per year or less (Sullivan et al. 2011b). Many of the point sources of NO_x were on the coast of the Beaufort Sea, in the easternmost portion of the network region. There were no substantial point sources of reduced N (NH_3 ; Sullivan et al. 2011b).



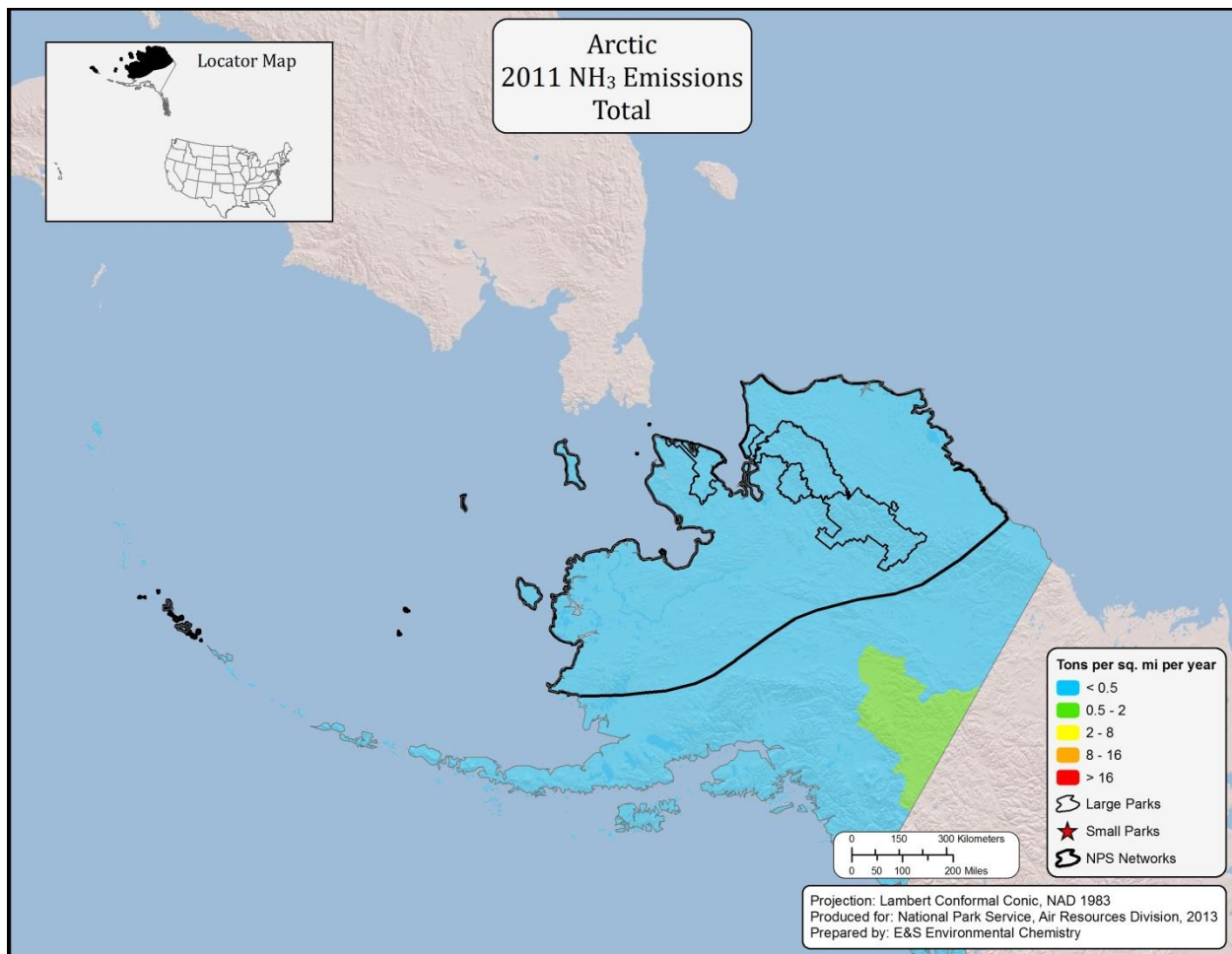
Map 1. Network boundary and locations of parks and population centers greater than 10,000 people near the ARC region.



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



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



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

Emissions near the ARCN, 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. All boroughs near ARCN parks had very low SO₂ and NO_x emissions (< 1 ton/mi²/yr; Maps 2 and 3). Emissions of NH₃ near ARCN parks were also low, mostly less than 0.5 tons/mi²/yr; one area south of the network parks showed slightly higher NH₃ emissions, between 0.5 and 2 tons/mi²/yr (Map 4).

Data regarding regional emissions of mercury (Hg) and semivolatile organic compounds (SOCs) near ARCN are generally not available. The lifetime of gaseous elemental Hg (GEM) in the atmosphere, which constitutes about 95% of atmospheric Hg, is generally about one year (Lin and Pehkonen 1999). However, during spring (March through June), the lifetime of GEM in the Arctic is much shorter, and atmospheric GEM can be depleted in less than one day during what are called atmospheric Hg depletion episodes (AMDE; Lindberg et al. 2002, Skov et al. 2004). During the AMDE, GEM is rapidly oxidized to reactive gaseous Hg that can be efficiently deposited to the ground surface (Skov et al. 2004).

The Western Airborne Contaminants Assessment Project (WACAP) studied airborne contaminants in a number of national parks of the western United States from Alaska to southern California, including NOAT and GAAR from 2002 to 2007. At these two parks, atmospheric concentrations of SOCs were generally low compared with other WACAP parks. As there are no regional air pollutant sources near the WACAP sampling sites in NOAT and GAAR, the presence of pesticides and metals in environmental compartments within the parks suggested atmospheric transport of pollutants from global anthropogenic sources. The primary SOC contaminants detected in the air at these parks were the historic use pesticides (HUP) hexachlorobenzene and hexachlorocyclohexane- α . There were highly variable SOC concentrations in snow across sites and time, but NOAT and GAAR had mid to high levels of endosulfans and hexachlorocyclohexane- α compared to other WACAP study sites. Many of the SOC levels were below detection limits in lake sediments. Spheroidal carbonaceous particles were not present, consistent with the scarcity of nearby coal combustion emissions sources.

The snowpack is efficient at scavenging both particulate and gas phase pesticides from the atmosphere. However, little was known prior to the WACAP study about the occurrence, distribution, or sources of SOCs in alpine, sub-arctic, and arctic ecosystems. Analysis of pesticides in snowpack samples from seven national parks in the western U.S. by Hageman et al. (2006) illustrated the deposition and fate of 47 pesticides and their degradation products. Correlation analysis with latitude, temperature, elevation, PM, and two indicators of regional pesticide use suggested that regional patterns in historical and current agricultural practices are largely responsible for the distribution of pesticides in most of the western national parks in the conterminous United States that were included in WACAP. In contrast, pesticide deposition to parks in Alaska was attributed to long-range atmospheric transport (Hageman et al. 2006).

It is believed that persistent organic pollutants (POPs) can be atmospherically transported across the globe because of their volatility and response to changes in temperature. This "global distillation theory" (Holmqvist et al. 2006, Wania and Mackay 1993) predicts that POPs in the northern hemisphere are generally transported towards the Arctic, and in the southern hemisphere they are

transported toward the Antarctic. In general, POP concentrations measured in the Arctic are higher than in the Antarctic.

Perfluorinated acids (PFAs) can exhibit substantial long range transport even though they have very low volatility. Some of the highest PFA concentrations in wildlife were reported for polar bears (Martin et al. 2004), and the contamination levels have been increasing since the 1990s (Clair et al. 2011, Dietz et al. 2008). Some of the PFAs in the Arctic may have derived from the degradation of chemical precursors that were transported atmospherically in the vapor phase (Ellis et al. 2004, Martin et al. 2006).

Organochlorine pesticide residues found in arctic regions are apparently attributable to long range atmospheric transport (Cotham and Bidleman 1991, Fellin et al. 1996, Gregor and Gummar 1989, Rice and Chernyak 1997). Chlorinated POPs can be transported through the atmosphere as particles from industrial and agricultural sources and deposited in remote regions. They have been detected at all levels of the arctic food web (Oehme et al. 1995).

A wet deposition sampler has been operating at Bettles AK, in GAAR since fall 2008, as part of the National Acid Deposition Program/National Trends Network (NADP/NTN). Limited data are available, but indicate that S and N deposition are both very low in the area around GAAR and likely throughout most of the ARCN. Both N and S wet deposition were less than 0.5 kg/ha/yr for the two years with valid data, 2010-2011. Other active NADP/NTN sites in Alaska include Poker Creek, Juneau, Denali National Park, and Katmai National Park. Data have been collected since 1980 at Denali and since 1993 at Poker Creek. The other three monitoring sites have been added within the last decade. There are also Clean Air Status and Trends Network (CASTNET) dry deposition measurements at Denali and Poker Flat. 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 estimates 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 Alaska are consistent with the general understanding that total (wet plus dry) atmospheric deposition of both N and S tends to be very low at national park lands within Alaska. It can be assumed that S and N deposition across the Alaskan networks would each be lower than about 1 or 2 kg/ha/yr, on average.

Acidification

The network rankings determined in a coarse screening analysis 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 ARCN that was in the middle of the distribution among all networks. The overall level of concern for S and N acidification effects on Inventory and Monitoring (I&M) parks within this network was judged by Sullivan et al. (2011b) to be Moderate. Concern may be greater in portions of CAKR and NOAT that are in proximity to SO_x and NO_x point source emissions.

The five parks in this network were all ranked by Sullivan et al. (2011b) in the lowest quintile in acid Pollutant Exposure. Sulfur and N emissions near most park lands in this network and expected deposition levels were both low. The parks varied with respect to Ecosystem Sensitivity to acidification, from Very High (GAAR) to Low (CAKR; Sullivan et al. 2011b). Ecosystem sensitivity to acidification rankings take into account elevation and land slope, which often influence the degree of acid neutralization provided by soils and bedrock within the watershed. Land slope across all parks within the ARCN is variable, but most park lands have relatively low relief. All of BELA has less than 10° slope. Slope is less than 20° across all park lands within the network except a few watersheds in GAAR that have a slope between 20° and 30°, where higher sensitivity of aquatic ecosystems to acidification might be expected. Data on potential effects of acidic deposition on aquatic and terrestrial resources in the ARCN are generally lacking. The WACAP study found that Burial Lake in NOAT and Matcharak Lake in GAAR were both very well buffered, with acid-neutralizing capacities (ANC) of about 280 and 2000 $\mu\text{eq/L}$, respectively. In view of the very low levels of emissions and deposition, acidification effects are expected to be minimal or nonexistent, even in lakes with lower ANC.

Forsius et al. (2010) reported critical loads (CL) of acidity (S+N) for terrestrial ecosystems north of 60° latitude using the simple Mass Balance (SMB) model and the critical chemical criteria $\text{Bc/Al} = 1$ and $\text{ANC} = 0 \mu\text{eq/L}$. Critical loads were exceeded in large areas of northern Europe and the Norilsk region of western Siberia during the 1990s, largely due to S emissions from metal smelters in northern Russia. There were no acidity exceedances in northern North America because S deposition was estimated to be uniformly low. Modeled N deposition at northern latitudes was less than 5 kg N/ha/yr throughout the entire study area, and empirical CL for eutrophication were not exceeded to any extent in Europe or North America. The minimum calculated CL for North America was three to four times higher than the maximum modeled S+N deposition (Forsius et al. 2010).

Nutrient Nitrogen Enrichment

Ecosystem Response to Nitrogen

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 types of plant communities (Chapin et al. 1980). Across a relatively small area of tundra, there may be 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 N (Schlesinger and Chabot 1977, Thomas and Grigal 1976).

Plant species distributions in arctic tundra are often N-limited (Shaver and Chapin 1980). Soluble N in tundra soil solution is dominated by organic N, including free amino acids, rather than NH_4^+ or 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.

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 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). Nonvascular plants tend to dominate where conditions are more hostile to 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.

The distribution of arctic plant communities is largely controlled by the presence of permafrost and moisture gradients. Where they are present, soils tend to be acidic and vegetation is largely restricted to tussock-shrub tundra and wetlands. 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). These differences modify responses to atmospheric N input.

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

Increased N could contribute to increased deciduous biomass at the expense of the diverse lichen flora. Lichens are the primary winter food source for the western Arctic caribou herd, the largest herd in North America, with numbers ranging from 250,000 to 500,000 animals. Herds like this are probably not possible in Alaskan areas with less continuous lichen cover.

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, however, changes in the abundance of one species will result in compensatory changes in other species, likely with little impact on ecosystem functioning (Chapin and Körner 1996).

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. The availability of N has major influence on plant communities that develop over permafrost 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). 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). Such an effect would have important implications for plant community dynamics in the ARCN.

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). Wet tundra sites are more likely to be P-limited, and dry tundra sites tend to be N-limited (Shaver et al. 1998). Therefore, changes in N deposition are more likely to affect dry tundra sites.

The coarse network screening rankings developed by Sullivan et al. (2011a) for nutrient N Pollutant Exposure, Ecosystem Sensitivity to nutrient N enrichment, and Park Protection yielded an overall network nutrient N enrichment Summary Risk ranking for the ARCN that was relatively low among all networks. All five parks in the ARCN were ranked by Sullivan et al. (2011a) in the lowest quintile in nutrient N Pollutant Exposure. Most of the parks in the ARCN were ranked in the middle quintile with respect to Ecosystem Sensitivity to nutrient N enrichment. The exception was CAKR, which was ranked in the highest quintile due to the presence of larger amounts of presumed nutrient N sensitive vegetation. It is possible, however, that the Ecosystem Sensitivity to nutrient N enrichment of parks in this network was underestimated by the methodology and data used for this coarse screening analysis. Shrub and forest vegetation communities in high-latitude locations may indeed be highly sensitive to relatively low levels of N addition. Unfortunately, experimental data are generally lacking. 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. In addition, much of the land coverage in some of these parks is snow and ice or barren land, with a scarcity of vascular plants. Lichens and mosses in barren areas may be highly sensitive to N addition. Holt and Neitlich (2010) inventoried lichens in ARCN parks. They identified more than 400 taxa. The strongest community gradient was associated with site moisture and elevation (alpine versus lowlands). The next strongest gradient was pH, which was partly driven by organic acidity associated with *Sphagnum* spp. and alkaline bedrock chemistry. There is concern that future increases in SO_x, and especially NO_x, emissions could affect the distribution and abundance of nonvascular plants in the ARCN.

There has been a paucity of studies on taiga and tundra responses to N addition in North America. However, changes in ground vegetation have been shown to occur in Swedish boreal forests at relatively low levels of atmospheric N deposition. For example, 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).

Some experimental work has been done in tundra ecosystems. In dry heath tundra in the northern Brooks range near Toolik Lake, Alaska, 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. 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 phosphorus (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 shrub dominance (Gough and Hobbie 2003). 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 Long Term Ecological Research (LTER) site (Weiss et al. 2005).

Samples of feather moss (*Hylocomium splendens*) are periodically collected and analyzed by NPS for S, N, and heavy metals as part of the ARCN terrestrial monitoring program. Moss samples can be used as passive monitors to evaluate pollutant deposition. Ultimately, it is hoped that such monitoring data can be combined with dose-response data in a CL context to guide future resource management in arctic Alaska (Linder et al. 2013).

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). 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).

Gordon et al. (2001) investigated the effects of N and P fertilization on arctic vegetation health, especially bryophytes which can account for up to 70% of the vegetative cover in some arctic communities (Richardson 1981). Added N reduced lichen cover, but did not affect the cover of other functional groups. The combination of added N and P changed species composition. Because N and P are often co-limiting, the CL of N would be expected to be lower where P availability is greater (Gordon et al. 2001).

Interactions with Climate Change

Effects of increased N supply interact with effects from other perturbations, especially climatic drivers. Loss of permafrost in response to climate change may have dramatic effects on the distribution of wetland vegetation in Alaska, especially along the southern edge of the zone of continuous permafrost. In KOVA, preliminary analysis of monitoring data indicated that lake surface area has decreased by about 14% in the Ahnewetut wetlands and by 20% in the Nigeruk Plain over the past two decades. Lake drainage in these areas is caused by permafrost melting, terrain subsidence, and subsequent channel incision (Larsen 2011). Any changes that occur in N deposition would be expected to interact with these climate-related changes to modify vegetation structure and function.

Future climate warming could have important effects on N cycling in arctic tundra ecosystems. In the past, organic materials have accumulated in tundra soils, largely because decomposition has been slower than plant growth in this harsh environment. Climate warming may increase the rate of 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 C and N cycling. For example, the dominant shrub species in the arctic tundra in Alaska is dwarf birch (*Betula nana*); it is expanding its distribution in tussock vegetation communities (Weintraub and Schimel 2005). Additionally, 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 easily accessible form may augment atmospherically deposited N, leading to greater eutrophication effects in the future under a warming climate.

Changes in competitive interactions among species can be just as important as growth stimulation effects caused by N inputs. 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).

Critical Load

Linder et al. (2013) reported results of preliminary analysis of existing data for characterizing CL values for N deposition for interior Alaska. They selected CL for N deposition in the range of 1-3 kg N/ha/yr to protect lichen and bryophyte cover in tundra and to protect community composition in taiga ecosystems.

Pardo et al. (2011) compiled data on empirical CL for protecting sensitive resources in Level I ecoregions across the conterminous United States against nutrient enrichment effects caused by atmospheric N deposition. As part of the Pardo et al. (2011) assessment, Nadelhoffer and Geiser (2011) recommended CL in the range of 1 to 3 kg N/ha/yr for both taiga and arctic tundra in Alaska to protect sensitive plant communities against effects of N enrichment. To protect shrub and grass community composition, the CL 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). Data compiled by Nadelhoffer and Geiser (2011) suggested that ambient N deposition may exceed the lower limit of the expected CL to protect against nutrient enrichment effects in each of the parks in ARCN. These potential exceedances were reported for the protection of lichens and herbaceous vegetation (Table ARCN 1).

Table 1. Empirical critical loads (CL) for nitrogen in the ARCN, by ecoregion and receptor from Pardo et al. (2011).

NPS Unit	Ecoregion	N Deposition (kg N/ha/yr)	Critical Load (kg N/ha/yr)				
			Mycorrhizal Fungi	Lichen	Herbaceous Plant	Forest	Nitrate Leaching
Bering Land Bridge NP	Tundra	NA	NA	1	1	NA	NA
Cape Krusenstern NM	Tundra	NA	NA	1	1	NA	NA
Gates of the Arctic NP & Pres	Northwestern Forested Mountains	NA	5	1.2	4	4	4
Gates of the Arctic NP & Pres	Taiga	NA	5	1	6	NA	NA
Gates of the Arctic NP & Pres	Tundra	NA	NA	1	1	NA	NA
Kobuk Valley NP	Taiga	NA	5	1	6	NA	NA
Kobuk Valley NP	Tundra	NA	NA	1	1	NA	NA
Noatak NP	Taiga	NA	5	1	6	NA	NA
Noatak NP	Tundra	NA	NA	1	1	NA	NA

Aquatic Ecosystem Response

Relatively little information is available regarding the effects of atmospheric N inputs on fresh waters in arctic settings. Nevertheless, lake diatom flora and nutrient balances have been shown to have been altered by N deposition in the Canadian Arctic (Wolfe et al. 2006). Similar responses have been observed in lakes at high elevation in Colorado and Wyoming. 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 plus 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 suggests secondary limitation by a micronutrient such as iron during the latter parts of the growing season.

Ozone Injury to Vegetation

The O_3 -sensitive vascular plant species that are known or thought to occur within the ARCN are listed in Table 2. Those considered to be bioindicators are designated by an asterisk. All but one of the parks (CAKR) within the network contained at least one O_3 -sensitive and bioindicator species (*Populus tremuloides*). GAAR also contained *Salix scouleriana*.

Table 2. Ozone-sensitive and bioindicator vascular plant species known or thought to occur in the I&M parks of the ARCN. (Data Source: E. Porter, National Park Service, pers. comm., August 30, 2012; lists are periodically updated and available at <https://irma.nps.gov/NPSpecies/Report>).

Species	Common Name	Park ¹				
		<i>BELA</i>	<i>CAKR</i>	<i>GAAR</i>	<i>KOVA</i>	<i>NOAT</i>
No Species Present			x			
<i>Populus tremuloides</i> *	Quaking aspen	x		x	x	x
<i>Salix scouleriana</i> *	Scouler's willow			x		

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

* Bioindicator species

The W126 and SUM06 O_3 exposure and Kohut's (2007a) O_3 risk rankings were not calculated for ARCN parks because O_3 data were not available for any of the parks in the ARCN at the time this assessment was prepared. The risk of O_3 injury to plant foliage in the ARCN cannot be evaluated at the time of this writing due to lack of data on O_3 exposure in the parks (Kohut 2007b). However, four of the five parks in this network contain quaking aspen (*Populus tremuloides*), an important O_3 -sensitive species.

Biomass burning in Eurasia is known to affect O_3 levels in western North America during spring and summer (Bertschi et al. 2004, Bertschi and Jaffe 2005). For example, during April 2008, a severe O_3 episode occurred at western park locations in response to particularly active and early wildfires 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 Denali National Park (DENA), an hourly average of 79 ppbv was recorded during the 8-hour period in which the average exceeded the 75 ppbv ambient air quality standard. Based on extensive trajectory calculations, biomass burning in Russia was identified as the likely source of the observed high O₃ concentration (Oltmans et al. 2010). Such events might become more frequent under a warming climate.

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, 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).

Based on limited data from Bettles, AK, average haze levels are moderate (6.8 dv) at GAAR, increasing by a factor of two on the 20% haziest days. Boundary layer transport of air pollutants from Europe to the Arctic region during winter and spring contribute to what is called “arctic haze” (Barrie 1986).

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,

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.

including agriculture, industry, and fires. Atmospheric sea salt concentrations are higher in coastal areas. Soil can enter the atmosphere through both natural processes and human disturbance.

Data indicating the composition of haze levels are available for only one year (2010) for one park (GAAR) in the ARCN. Based on these available data, SO_4^{2-} is by far the largest contributor to haze (56%) on the 20% clearest days. For the 20% haziest days and the annual average, however, organic material is the largest contributor to haze, followed by SO_4^{2-} (Figure 1).

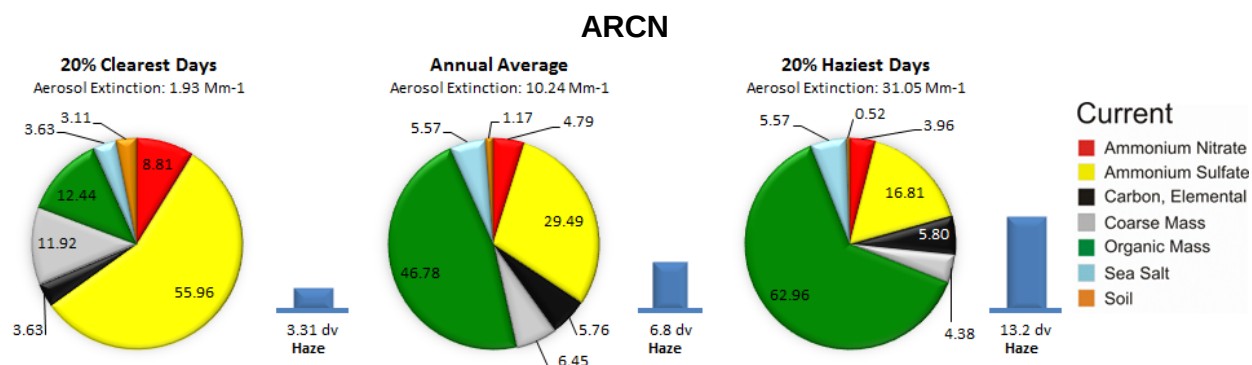


Figure 1. Estimated current levels of haze (blue columns) and its composition (pie charts) on the 20% clearest, annual average, and 20% haziest visibility days for GAAR. Note that data are only available for the year 2010. Data Source: NPS-ARD

Toxic Airborne Contaminants

Biogeochemical cycling of Hg in the Arctic has been investigated, in part because observed Hg concentrations in marine animals may pose health risks for local human populations. Because of the increased solar flux to the Arctic during spring and the seasonal melting of sea ice, there may be an increased efficiency of Hg bioaccumulation in arctic food webs than would be expected based on data collected at mid-latitudes (U. S. EPA 2009). Mercury concentrations measured in WACAP exceeded thresholds for fish consumption by both humans and wildlife.

Many POPs have been shown to concentrate to high levels in the Arctic, at great distance from source areas. Both long range atmospheric transport and animal migration can be involved in this transport process, in addition to biomagnification at the receptor location.

Historic use pesticide concentrations in fish in NOAT and GAAR were mid-range among WACAP study sites. Dieldrin concentrations in fish exceeded contaminant health thresholds for human subsistence fishers. Current use pesticide (CUP) concentrations in fish were low among WACAP study lakes.

Various studies have identified organochlorine compounds in remote polar ecosystems (cf., Blais 2005, Simonich and Hites 1995, Wania and Mackay 1993). The accumulation of these compounds at these locations has been at least partly attributed to long-range atmospheric transport. Compounds detected commonly include dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexane (HCH), hexachlorobenzene (HCB), and polychlorinated biphenyls (PCBs). Such compounds tend to

concentrate in aquatic biota in response to biomagnification processes and have been associated with disruption of endocrine systems in aquatic species.

Bioconcentration of organochlorines in the arctic food web has been shown in fish, seals, and polar bears (Oehme et al. 1995). Levels measured in polar bears have been especially high (AMAP 2004). The polar bear is the top predator in the Arctic and feeds preferentially on ringed seals and, to a lesser extent, on other seal species. The concentrations of DDT and HCH in polar bear tissue declined slowly between the 1960s and 2000s (Norstrom 2001). Other POPs, such as PCBs and chlordanes, did not show declining trends during that time period.

Long-range transport of atmospherically deposited contaminants can be augmented by biotransport. A good example of this phenomenon was documented by Ewald et al. (1998), who showed that biotransport by migrating sockeye salmon (*Oncorhynchus nerka*) in the Copper River watershed, Alaska, had a greater influence than atmospheric transport on bioaccumulation of PCBs and DDT in lake food webs. Organic pollutants accumulated by salmon during their ocean residence were effectively transferred 410 km inland to their spawning lake. Arctic grayling (*Thymallus arcticus*) in the salmon spawning lake were found to contain organic pollutants more than twice as high as arctic grayling in a near-by salmon-free lake. The pollutant composition of the grayling in the salmon spawning lake was similar to that of the migrating salmon (Ewald et al. 1998), suggesting that salmon migration contributed to bioaccumulation in other fish species of organic contaminants in the lake used for spawning by the salmon.

Pacific sockeye salmon have been shown to transport PCBs to salmon nursery lakes in Alaska (Krümmel et al. 2003). Salmon were shown to be a major source of PCBs to lakes that receive high densities of salmon spawners. Once transported to the lake location by the migrating fish, PCBs can move to various levels of the food web.

Hageman et al. (2010) reported results of pesticide analyses of snowpack at remote alpine, arctic, and subarctic sites in eight national parks, including NOAT/GAAR. Various CUPs (dacthal, chlorpyrifos, endosulfans, and γ -HCH) and HUPs (dieldrin, α -HCH, chlordanes, and HCB) 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.

Pesticide concentrations in snowpack in NOAT and GAAR, 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 Denali National Park (Hageman et al. 2010). The reason(s) for the observed high concentrations of pesticides at NOAT and GAAR, distant from regional cropland, is/are not known.

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 GAAR and NOAT in the ARCN. Contaminant loading was highest in fish from Alaskan and Sierra Nevada parks. The HUPs were highest in Alaskan parks, whereas the CUPs 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 roles played by anadromous fish and atmospheric contributions in defining that risk (Flanagan Pritz et al. 2014).

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