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Environmental Management of Air Quality Issues in the Greater Yellowstone Area

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2441





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Environmental Management of Air Quality Issues in the Greater Yellowstone Area

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2441

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Abstract

The Greater Yellowstone Area (GYA) is a national treasure in the United States, containing sensitive resources of high value to the public such as scenic vistas, remote wilderness, intact fisheries, geothermal areas, and charismatic megafauna. The GYA also supplies ecosystem services including clean water, clean air, and recreation, as well as providing critical habitat for plant and animal species. However, air pollutants from local and regional sources are degrading key resources and pollutant emissions are expected to remain steady or increase in the next few decades. Four air quality issues in the GYA are identified along with associated effects on human health and ecosystem health from these pollutants: (1) smoke from wildfire; (2) atmospheric nitrogen deposition; (3) atmospheric mercury deposition; and (4) ozone. Key research to date is synthesized, important knowledge relevant to science-based land management and policy decisions is identified, and relevance for available air pollution emissions strategies and environmental management actions are highlighted. Because the GYA is comprised of many different jurisdictional boundaries spanning state and federal agencies, the environmental management of air quality and associated effects on human health and ecosystems in the area is complex. Understanding how the four issues affect human and ecosystem health, aids in development of a management strategy, which multi-agency groups can use to address air quality concerns and mitigation strategies in a cohesive manner. The insights and strategies provided here may be applied to other sensitive regions.

Keywords: Air Quality; Smoke; Nitrogen; Mercury; Ozone; Critical Loads

1.0 Introduction

The Greater Yellowstone Area (GYA), spanning approximately 22 million acres, is one of the largest intact temperate ecosystems left in the world. Millions of people are drawn to the GYA each year to experience renowned recreation opportunities, learn about the rich cultural history, and to view the abundant wildlife, flora, unique geothermal features, and pristine vistas. The GYA also contributes freshwater to three main river systems, the Columbia, the Colorado, and the Missouri, and provides a wide range of ecosystem services including carbon storage, biodiversity, wildlife habitat, forestry, grazing, energy and minerals, and tourism. Just as tourism and visitation to the GYA have increased in recent years, so has development around and within the boundaries of these ecosystems. Increases in use, population, and development have direct and indirect effects that threaten species, habitat, and public benefits within the GYA.

Four federal agencies manage land within the GYA including the National Park Service (NPS), United States Forest Service (FS), Bureau of Land Management (BLM), and Fish and Wildlife Service (FWS) (Figure 1). In 1964, NPS and FS created the Greater Yellowstone Coordinating Committee (GYCC) (http://www.fedgycc.org/), to facilitate cooperation and coordination in maintaining and enhancing the integrity of the GYA as an ecosystem, while striving to meet the differing agency management goals and directives. Since then, the BLM, FWS, and some State Agencies have also joined. The roles of the GYCC include serving the public while sustaining the GYA resources, coordinating monitoring and management practices across boundaries to maximize efficiency and consistency, identifying GYA priorities, and striving for resolution of ongoing and emerging issues. Ecosystem health, which includes air and water quality, is one of the GYCC top priority management issues and is addressed through different subcommittee groups. One subcommittee; the Clean Air Partnership (GYCC-CAP), started in 1997, communicates and coordinates on air quality issues in the GYA.

Monitoring and research of air quality and its impacts to ecosystem health in the GYA started in the mid-1980s and has expanded to measure ambient concentrations of gas phase and particulate species, wet and dry deposition of atmospheric pollutants, spatial patterns and temporal trends in lake chemistry and aquatic biota, and impacts of air pollution on sensitive vegetation. GYA monitoring sites for atmospheric deposition of pollutants and ecosystem effects are shown in Figures 1 and 2, respectively. After reviewing monitoring and research data and listening to public and management concerns, the GYCC-CAP identified the following four main air issues in the GYA to focus and synthesize existing data on and to provide management recommendations: (1) smoke from wildfire; (2) atmospheric nitrogen (N) deposition; (3) atmospheric mercury (Hg) deposition; and (4) ozone.

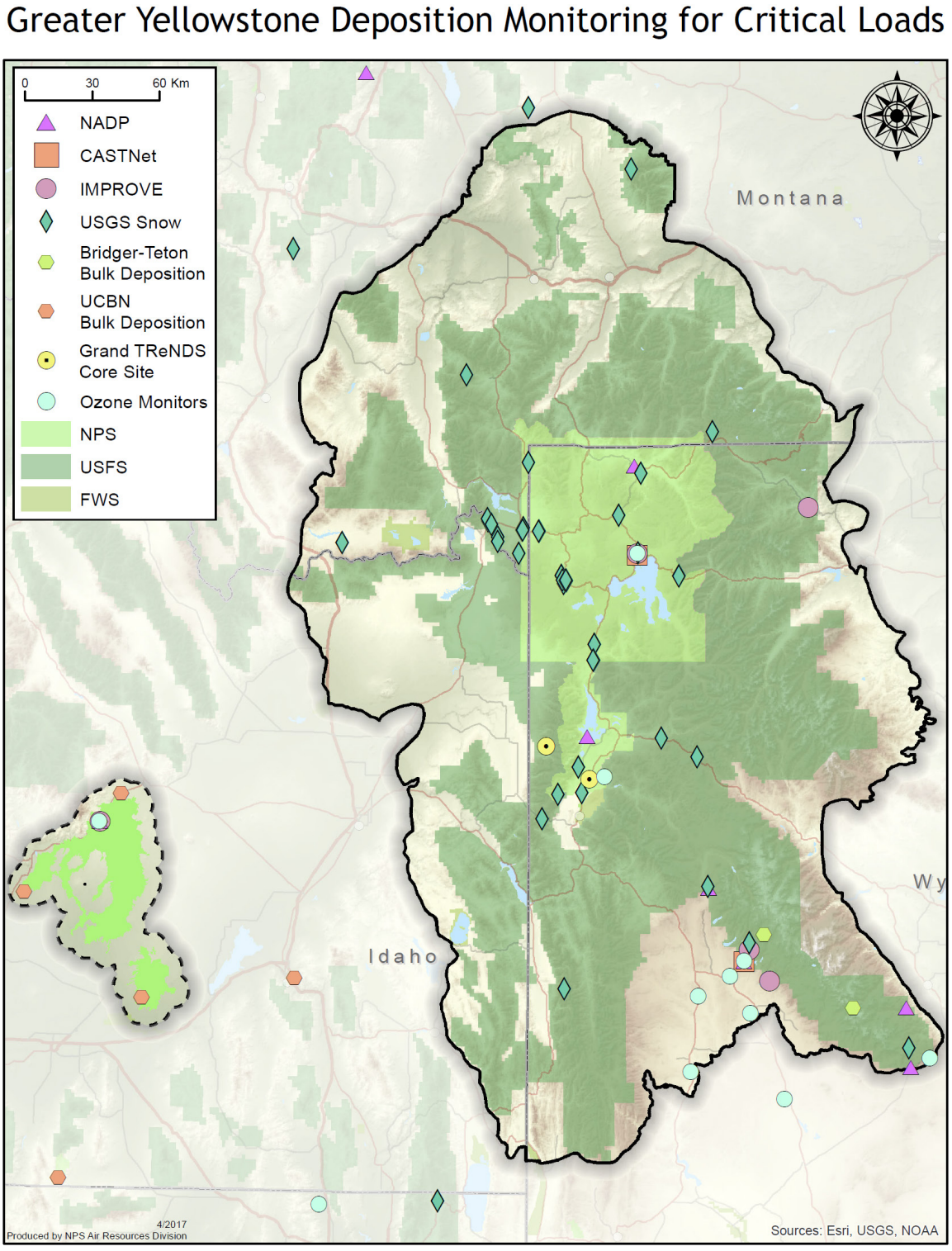


Figure 1. Federally managed land and air monitoring in the GYA. Nitrogen is measured at the NADP, CASTNET, IMPROVE, USGS snow, Upper Columbia River Basin (UCBN) Bulk Deposition, the Bridger Teton Bulk Deposition, and the GrandTrends sites. Ozone is measured at the CASTNET and Ozone sites. Mercury is measured at the USGS snow sites.

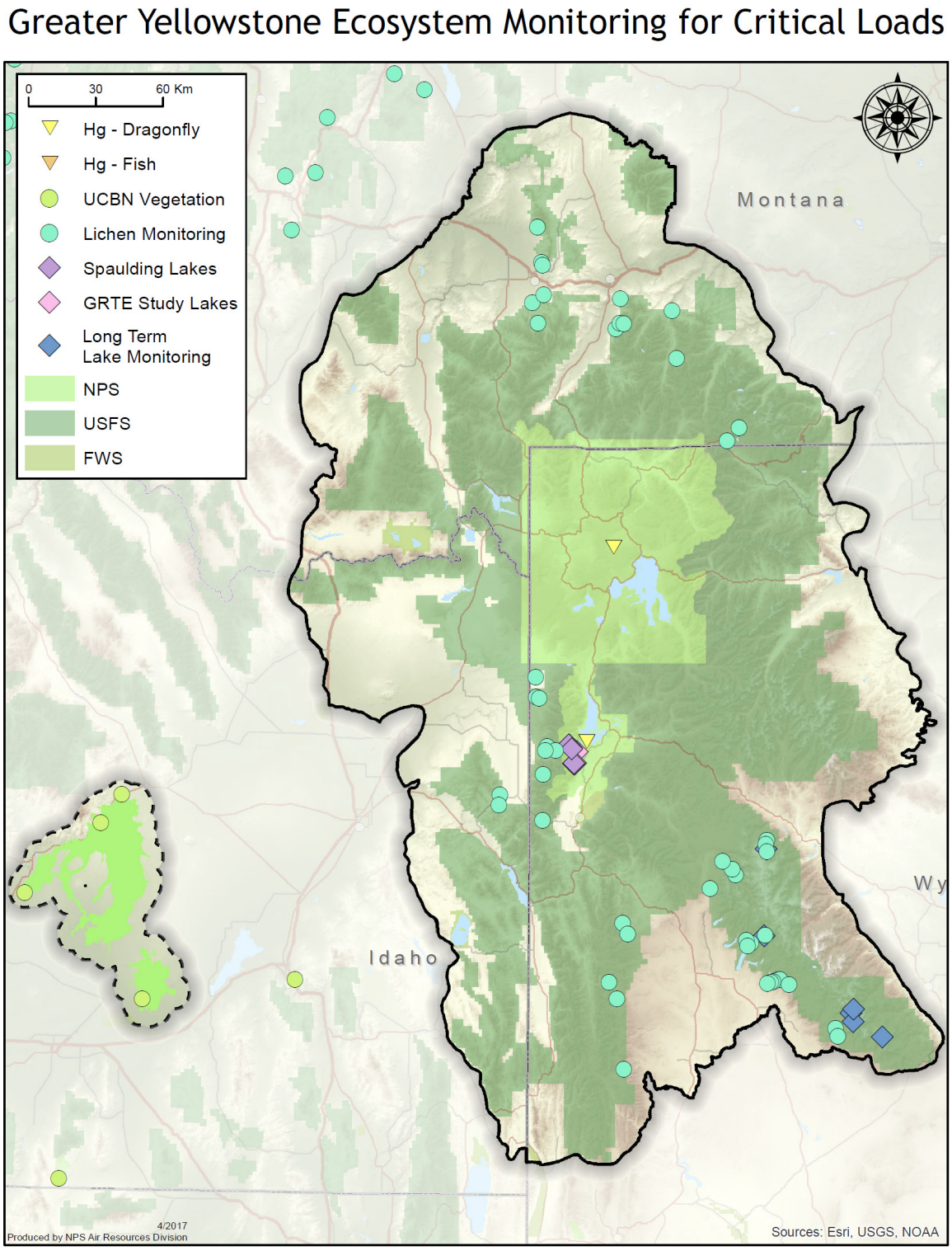


Figure 2. Greater Yellowstone Area ecosystem monitoring sites.

(1) Smoke from wildfire: Research and modeling predict an increase in intensity, duration, and frequency of smoke events from wildland fires through the mid-century, posing health, economic, and ecosystem impacts (Abatzoglou and Williams, 2016; Liu et al., 2016). Smoke releases N

compounds, ozone precursors, and mercury—among hundreds of other chemical constituents. Chemicals found in smoke can contribute to ozone formation and pollutant deposition.

(2) Atmospheric N deposition: Monitoring networks and modeling efforts broadly agree that atmospheric N deposition, specifically ammonia (NH_3), is increasing in the GYA while sulfur pollution is decreasing (Nanus et al., 2017).

(3) Atmospheric Hg deposition and methylmercury (MeHg) formation: Research and monitoring studies show that Hg deposition and MeHg formation may be increasing in the GYA (Weiss-Penzias et al., 2016).

(4) Ozone: Elevated ozone concentration near oil and gas operations have led to intensive monitoring and modeling which uncovered the formation of winter-time ozone in rural areas, an anomalous and emergent concern for affected regions of the western U.S. However, ozone levels and effects in wilderness areas and other remote high-elevation sites remain unknown within the GYA.

The objectives of this study are to identify and discuss important air quality issues as well as ecosystem effects and human health response to air pollution in the region, in order to develop a science-based management strategy to protect sensitive resources. This represents the first-time air quality issues and associated indicators within the GYA have been synthesized in a comprehensive review that will be useful for land managers, policy makers, scientists, the GYCC, conservation groups, and the public

1.1 Legal Basis for Air Quality Protections

Air quality and natural resources affected by air pollution in the GYA are protected by U.S. laws including the Organic Acts for each agency, the Wilderness Act (1964), and the Clean Air Act (CAA) and its Amendments (1970, 1977, and 1990). Legal authorities related to natural and visual resources in the GYA vary between the federal land management agencies and type of land designation, but all federal agencies have mandates to safeguard public lands from destruction or degradation, for the benefit of the American public and future generations. It is important to note that the land management agencies do not have regulatory authority over emissions, that responsibility resides with the federal and state air regulatory agencies.

Federal Class I areas are defined in the CAA as National Parks over 6,000 acres and Wilderness Areas and Memorial Parks over 5,000 acres, established as of 1977. Class I airsheds that are afforded special protection under the CAA within the GYA include: the Bridger, Fitzpatrick, North Absaroka, Teton, Washakie, Red Rock Lakes Wilderness Areas, Grand Teton NP and Yellowstone NP. Sensitive airsheds in the GYA protected by the Wilderness Act and Agency Organic Acts include Gros Ventre, Popo Agie, Jedediah Smith, Winegar Hole, Absaroka-Beartooth, and Lee Metcalf Wilderness Areas and the National Elk Refuge. Approximately 40% of the 15 million federally managed units in the GYA are managed as wilderness.

1.2 Visibility and Regional Haze

Haze impacts visibility when atmospheric particles absorb or scatter light, reducing visibility and impairing the ability to see distant views, a valued asset for recreational visitors to federal lands.

Under the CAA, Congress set forth a national goal that calls for "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I federal areas which impairment results from manmade air pollution" (42 U.S.C. 7491). The Regional Haze Rule implemented this mandate by requiring monitoring in locations representative of the 156 visibility-protected federal Class I areas (118 are located in the West). The Regional Haze Rule requires federal, tribal, and state government to work with air pollution emission sources to improve visibility in Class I areas on the most impaired visibility days and prevent degradation of visibility on the clearest days. The Interagency Monitoring of Protected Visual Environments (IMPROVE; http://vista.cira.colostate.edu/Improve/) program tracks visibility in Class I areas by collecting and analyzing ambient air samples with a network of 110 monitors sited in or near Class I areas nationwide. The resulting data are used to detect the extent of degradation or improvement in visibility at these sites and extrapolate and map the results at national scales.

1.3 Air Pollution Thresholds and Critical Loads

The National Ambient Air Quality Standards (NAAQS) were established under the CAA (40 CFR part 50). NAAQS identify 6 criteria pollutants and establish standards for each that must be met by state and federal agencies, tribal and local governments, and private industry. States must comply with NAAQS but have the authority to uphold stricter standards. Criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter ($PM_{2.5}$ and PM_{10}), and sulfur dioxide (SO_2). The NAAQS include primary and secondary standards: primary standards are designed to protect public health while secondary standards are intended to protect against damage to animals, crops, vegetation, buildings, and against decreased visibility. Some areas of the GYA have been in violation of the NAAQS. Sublette and portions of Lincoln and Sweetwater counties in Wyoming were categorized "marginal non-attainment" for ozone (2008 standard) in 2012.

Air Quality Related Values (AQRVs) are resources that may be adversely affected by air quality, including visibility and regional haze, cultural, physical, biological, ecological, or recreational resources. AQRVs may include diatoms, lichens, dilute water bodies, soils, visibility, etc. AQRVs are often used in conjunction with critical loads (described below), to characterize impacts to Class I areas under the CAA, and other sensitive areas. AQRV assessments are also used by federal agencies to understand how air pollutants may be altering wilderness character and to manage the preservation and protection of natural wilderness conditions (16 U.S.C. 1131-1136).

Critical loads (CLs) have been used to describe thresholds for atmospheric deposition loading (in kg-N ha^{-1} yr^{-1}), below which no harmful effect is expected to occur in a specified sensitive part of the ecosystem (Burns et al., 2008; Pardo et al., 2011). CLs help inform land managers, policy makers and the public about how much deposition from air pollution is in excess for an ecosystem. Hundreds of empirical CLs for N have been developed for natural areas across the U.S. at the Ecoregion Level I (Pardo et al., 2011). Land managers such as the NPS (https://www.nps.gov/subjects/air/critical-loads.htm), FS (https://www.srs.fs.usda.gov/airqualityportal/critical_loads/index.php) and multi-agency stakeholder groups (http://nadp.slh.wisc.edu/committees/clad/) are beginning to use these and other CLs to guide land management planning, assessment, and decision making (Burns et al., 2008).

Ecosystem damage occurs when deposition exceeds CLs (Baron et al., 2011; Pardo et al., 2011; Burns et al., 2008). For example, eutrophication can lead to stimulation of plant and algal growth and increased competition within biotic communities, often favoring invasive species and decreasing occurrence of sensitive species (Burns, 2011; Baron et al. 2011; Rhodes et al, 2017). The CL for N deposition varies among different species and ecosystem components (Table 1), based on their relative sensitivities (Pardo et al., 2011). Therefore, understanding various environmental thresholds and at what deposition level lichen species, lichen communities, lake eutrophication, soil chemistry, forest health, or other biological indicators begin to decline are important to the viability of different species. In addition, N deposition estimates developed at high spatial resolution in topographically complex terrain (Nanus et al., 2017) are useful to assess where deposition is exceeding CLs. N deposition CLs for acidification and eutrophication have been established for many types of sensitive biological resources in the GYA.

Table 1. Critical Loads of nitrogen relevant to the GYA. Nitrogen deposition estimates for the GYA (Nanus et al., 2017) range from 1.4 kg-N $ha^{-1}yr^{-1}$ to 7.5 kg-N $ha^{-1}yr^{-1}$, indicating that critical load exceedances are occurring in some areas, for some sensitive resources.

Critical Load (kg-N $ha^{-1}yr^{-1}$)	**Ecosystem Change above CL**	**Reliability of CL for GYA ***	**Reference**
1.9	Epiphytic forage lichen abundance	Reliable	Geiser et al., 2019
2.7	Phytoplankton shifts in alpine lakes - Beartooth wilderness	Reliable	Saros et al., 2003
3.0	Nutrient enrichment in Rocky Mountain lakes	Reliable	Baron et al., 2011
3.0	Increase in sedge growth in alpine vegetation	Fairly Reliable	Bowman et al., 2012
3.4	Decline in growth of Balsam Poplar trees	Reliable	Horn et al., 2018
3.5	Decrease in probability of survival of Douglas-fir trees (over 10 years)	Reliable	Horn et al., 2018
3.5	Epiphytic lichen species richness	Reliable	Geiser et al., 2019
4.0	Episodic acidification of high elevation lakes	Reliable	Baron et al., 2011
5.0	Decrease in probability of survival of Balsam Poplar trees (over 10 years)	Reliable	Horn et al., 2018

* Reliability description after Pardo et al, 2011: “reliable” indicates CL is based upon data from large number of sites and/or data collected from within the GYA; “fairly reliable” indicates CL is based upon data from within the same eco-region as the GYA, but not the GYA per-se.

Table 1 (continued). Critical Loads of nitrogen relevant to the GYA. Nitrogen deposition estimates for the GYA (Nanus et al., 2017) range from 1.4 kg-N ha−1yr−1 to 7.5 kg-N ha−1yr−1, indicating that critical load exceedances are occurring in some areas, for some sensitive resources.

Critical Load (kg-N $ha^{-1}yr^{-1}$)	Ecosystem Change above CL	Reliability of CL for GYA *	Reference
6.6	Decrease in probability of survival of Quaking Aspen trees (over 10 years)	Reliable	Horn et al., 2018
10.0	Community shifts in alpine plants	Fairly Reliable	Bowman et al., 2012
10.0	Nitrate leaching in alpine ecosystems	Fairly Reliable	Bowman et al., 2012
13.6	Decrease in decadal survival of Quaking Aspen trees	Reliable	Horn et al., 2019

* Reliability description after Pardo et al, 2011: “reliable” indicates CL is based upon data from large number of sites and/or data collected from within the GYA; “fairly reliable” indicates CL is based upon data from within the same eco-region as the GYA, but not the GYA per-se.

2.0 Air Quality Issues

2.1 Smoke from Wildland Fires

2.1.1 Background and Trends

In the GYA the length of the fire season by number of days is increasing (Liu et al., 2016). The GYA has also recorded increases in both minimum and maximum temperatures (Sepulveda et al., 2015). These changes combined with a history of fire suppression and other disturbances can influence wildland fire frequency, severity, intensity, size, and length of fire season (Abatzoglou and Williams, 2016; Barbero et al., 2015; Liu et al., 2014; Liu et al., 2016). Barbero et al. (2015) modeled changes in fire potential across the US and found the largest future increases are projected for the intermountain west, including the northern Rocky Mountains and the GYA. In the northern Rocky Mountains, the intensity, length, and frequency of smoke exposure are predicted to increase (Liu et al., 2014; Liu et al., 2016; Westerling et al., 2011), as wildland fire behavior effects smoke emissions and smoke exposure (Hallar et al., 2017; Liu et al., 2016).

Strong weather events caused by large wildland fires can force dust and smoke into the free troposphere (Baars et al., 2011; Colarco et al., 2004), making transport of smoke over thousands of kilometers possible within a few days (Creamean et al., 2016). Counties in the northern Rocky Mountains have experienced some of the longest and highest intensity smoke events in the western United States (U.S.), primarily because this area is impacted by smoke from local and regional fires and from long-range transport from fire prone regions (Liu et al., 2016). Southern MT is predicted to have one of the highest increases in wildfire smoke risk in the western U.S. and many counties in the GYA are predicted to increase fire seasons between 25–69 days by midcentury (Liu et al., 2016).

In the intermountain west, smoke emissions from wildland fires are associated with increases in particulate matter (PM). PM is typically monitored in two different size cuts (or fractions): <2.5 and <10 microns. A study of 561 western counties between 2004 through 2009 found that on days when the NAAQS for PM2.5 was exceeded, an average of 71.3% of the PM2.5 was linked to emissions from wildland fires, with many counties in the GYA above 90% (Liu et al., 2016). PM is not a single pollutant but a mixture of many different compounds, both solid and liquid. Some of the compounds found in smoke include carbon dioxide, carbon monoxide, methane, organic carbon, water vapor, N and sulfur compounds, mercury, volatile organic compounds (VOCs), organic aerosols, and trace minerals and metals (Baker et al., 2016; Benedict et al., 2017; Hallar et al., 2017; Jaffe and Wigder, 2012; Jaffe et al., 2008; Liu et al., 2016; Liu et al., 2017; Spracklen et al., 2009; US-EPA, 2016).

Carbonaceous aerosol in the GYA generally account for more than three quarters of the haze on the haziest days, the majority of which is from biomass burning (Schichtel et al., 2017). An air quality study in Grand Teton NP in 2011 found that high NH_3 concentrations occurred during periods of biomass burning in the area, indicating that smoke may contribute intermittently to N deposition in the GYA (Prenni et al., 2014). Organic aerosol concentrations in the West are predicted to increase significantly (up to 40%) by midcentury from increases in wildland fire smoke emissions with high-elevation and remote regions of the intermountain west being affected (Hallar et al., 2017; Spracklen

et al., 2009). The increase in intensity, duration, and frequency of smoke events affects public and ecosystem health and local economies (Liu et al. 2016).

2.1.2 Health Effects

Smoke exposure can pose significant health risks (US-EPA 2016) and will affect an increasing number of people as the population density in the wildland-urban interface increases (Theobald and Romme, 2007). PM is the most common pollutant measured during fires to inform the public of varying levels of smoke exposure. In addition to the chemicals mentioned previously, smoke contains harmful chemicals, such as isocyanic acid and known carcinogens including benzene, formaldehyde and some polycyclic aromatic hydrocarbons (PAHs).

PM2.5 is the main health concern for short-term exposure because PM2.5 particles are small enough to enter the bloodstream via the respiratory system and PM2.5 typically transports further than larger PM (US-EPA, 2016). High concentrations of PM2.5 pose a health threat to the public, especially sensitive groups. Symptoms of PM exposure include irritation of eyes, throat, and respiratory tract, bronchitis, and exacerbation of asthma and heart disease, potentially to the point of heart failure (US-EPA, 2016). Premature death of individuals in sensitive groups, has been linked to smoke exposure (Liu et al., 2015; US-EPA 2016). More studies are needed to evaluate effects of smoke intensity and duration on human health.

Smoke emissions from wildland fire also contain the precursors for ozone formation, as a result, measured ozone concentrations can temporarily increase near or downwind of wildland fire activity (Baker et al., 2016; Bytnerowicz et al., 2013; Lin et al., 2017). Ozone is one of the most important phytotoxic air pollutants to plants and is also known to affect human health (see ozone section).

2.1.3 Other Effects

Smoke from wildland fire can have negative short-term impacts on visibility at vistas, health effects in affected neighborhoods and cause safety concerns on roadways, and aviation corridors. Unimpeded visibility is valued by tourists and residents. Recreation and tourism are vital to the local economies in many small western towns and cities. Short-term impacts on visibility can have large impacts on local economies by decreasing tourism and recreation, especially when smoke emissions reach unhealthy and hazardous levels.

When large wildland fire events produce enough smoke emissions, regional events such as changes in surface temperature, humidity, wind, and percent fuel moisture can occur (Liu et al. 2014). Large quantities of smoke may also influence precipitation. In some instances, PM from smoke can suppress cloud formation and precipitation causing a feedback loop by enhancing drought conditions and thus increasing the risk of future fires (Liu et al., 2014).

2.2 Atmospheric Nitrogen Deposition

2.2.1 Background and Trends

While N deposition has declined in many parts of the country since CAA Regulations were enacted in the 1990s (Burns, 2011; Ellis et al., 2013; Sullivan et al., 2018), it has increased over the past two decades at numerous locales in the intermountain west, including portions of the GYA (Ellis et al.,

2013; Grenon et al., 2010; Ingersoll et al., 2016). The range in measured N deposition for different monitoring networks in the GYA is shown in Table 2.

Table 2. Range in measured Nitrogen (N) deposition for different monitoring networks in the GYA.

Network	N Dep Range (kg-N $ha^{-1}yr^{-1}$)	Type	Temporal scale	Number of Sites in the GYA *	Years	Reference
NADP	0.2–2.1	Wet	Annual	6	2013–2019	NADP/NTN
Bulk Deposition	2.0–4.3	Bulk	Annual	2	2004–2008	Grenon et al., 2010
IER	0.3–1.7	Bulk	Summer Season	15	2016	Hoffman et al., 2019
IER	0.8–4.1	Throughfall	Annual	9	2010	McMurray et al., 2013
CASTNET	1.6–1.8	Dry	Annual	2	2013–2019	CASTNET
Snowpack	0.5–1.8	Bulk	Snow Season	22	2018	USGS RMS

* This value represents the average number of sites for years when the network operated. Long term monitoring networks include the range in measured data for select years as indicated. Deposition type is indicated. Wet deposition represents dissolved inorganic N (DIN = nitrate (NO_3^-) + ammonium (NH_4^+)). Dry deposition represents dry HNO_3, dry NH_3, dry NH_4^+, and dry NO_3^-. Bulk deposition represents TN deposition (total reactive N). Ion exchange resin collectors (IER) measure throughfall and bulk deposition.

The National Atmospheric Deposition Program (NADP), measures weekly precipitation chemistry from rain and snow at sites across the country. In Yellowstone NP, the NADP monitor shows an increasing trend in N primarily from wet NH_4^+ deposition over a 38-year monitoring period (Figures 3 & 4) (https://nadp.slh.wisc.edu). NADP wet deposition sites at Pinedale and Sinks Canyon in the central and southern GYA have also shown increases in NH_4^+ deposition. Bulk deposition monitoring (wet + dry) at Hobbs and Black Joe lakes, high-elevation sites in the Wind River Range, WY (Figure 1) showed increasing trends in NH_4^+, and Total Nitrogen (TN, defined as total reactive N) from 1.6 and 2.1 kg-N $ha^{-1}yr^{-1}$ (1987–1991) to 2.0 and 4.3 kg-N $ha^{-1}yr^{-1}$ (2004–2008), respectively (Table 2) (Grenon et al., 2010). Yellowstone and Pinedale, WY, CASTNET (Figure 1) dry deposition values ranged from 1.6–1.8 (Table 2).

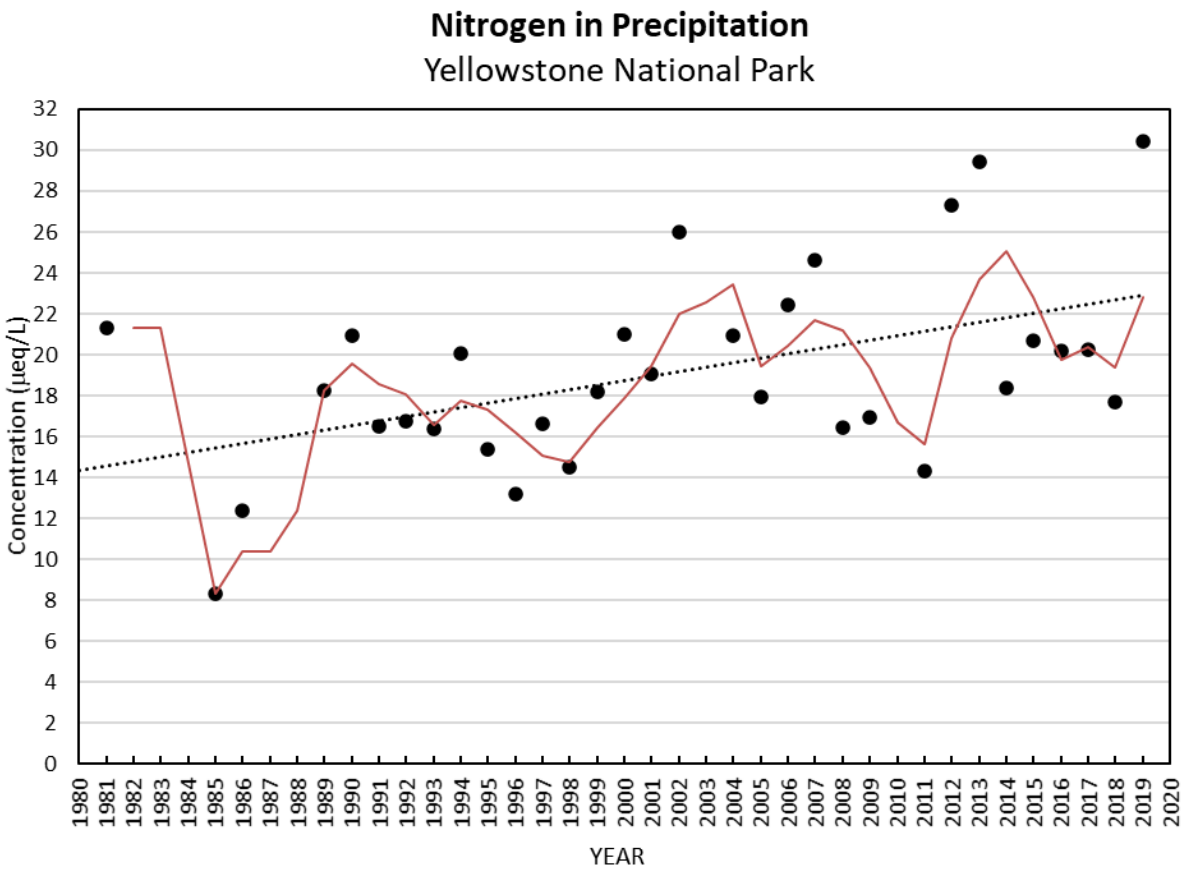


Figure 3. Trend in N in precipitation (NO_3^- + NH_4^+) for Yellowstone NP. NADP Monitor ID: WY08, WY. Significant linear trend (dashed black line) in N concentration increasing over time (p-value < 0.005; slope = 0.22 µeq/L) shown with a smoothed 3-year moving average (red line). Only data that met the NADP validation and completeness criteria were included.

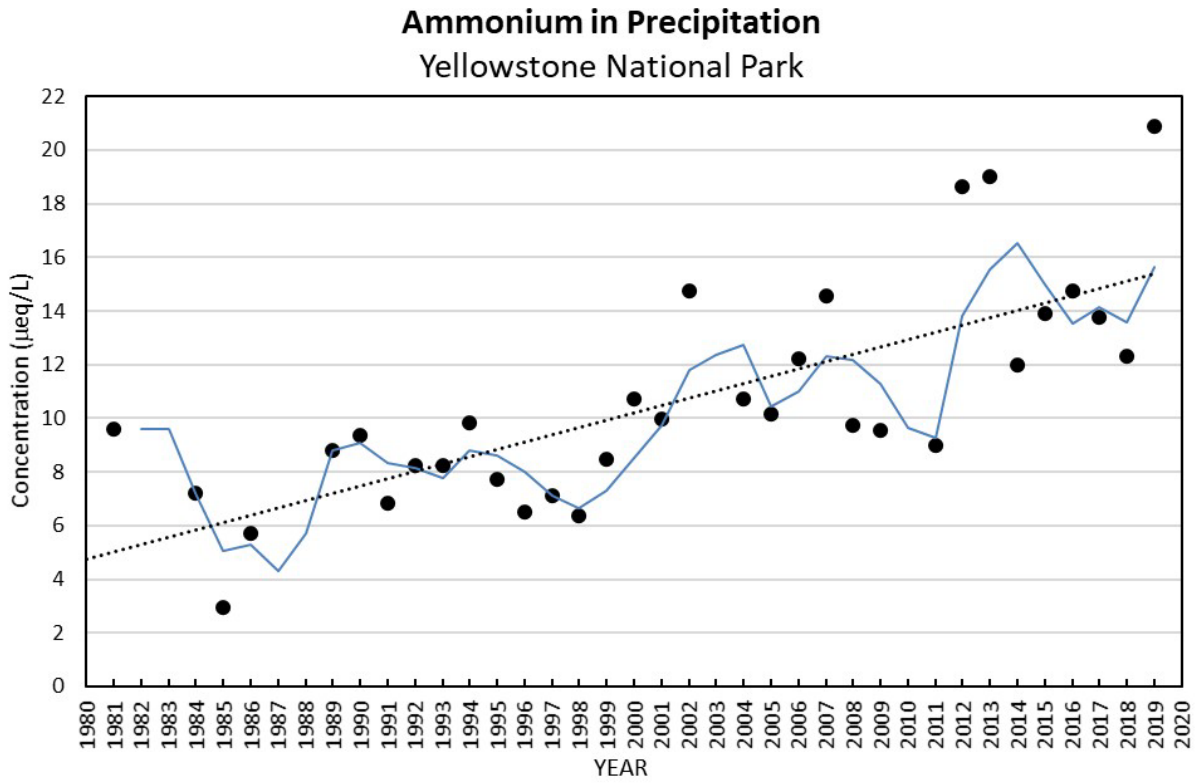


Figure 4. Trend in NH_4^+ in Precipitation for Yellowstone NP. NADP Monitor ID: WY08, WY. Significant linear trend (dashed black line) in NH_4^+ concentration increasing over time (p-value < 0.0001; slope = 0.27 µeq/L) shown with a smoothed 3-year moving average (blue line). Only data that met the NADP validation and completeness criteria were included.

The USGS Rocky Mountain Regional Snowpack Chemistry Monitoring Program (RMS) has been collecting and analyzing snowpack chemistry at over 150 sites along the Continental Divide in the Rocky Mountains since 1993 (Ingersoll et al., 2016; http://co.water.usgs.gov/projects/RM_snowpack/html/data.html). Snowpack sites showed significant increasing trends over 20 years in both NH_4^+ concentration and deposition, with mean NH_4^+ concentrations in snowpack higher in the GYA (Central Rockies Subregion) than for elsewhere in the Rocky Mountains. The highest NH_4^+ concentrations in snow were on the west side of the Continental Divide, adjacent to the Snake River Plain agricultural zone in Idaho (Ingersoll et al., 2016).

A study conducted on the west and east side of the Teton Mountains in the GYA (GrandTReNDS) in 2011 assessed composition, spatial variability, and potential sources of reactive N. NH_3 was found to be the most abundant N species during the summer with the highest measurements at the western most sites of the GYA, on the Caribou-Targhee National Forest (Benedict et al., 2013). At these sites NH_3 comprised 28–39% of quantified N deposition, and elevated nitric acid concentrations and deposition were measured at the high-elevation Grand Targhee ski area (2258–3006 m) (Prenni et al., 2014, Benedict et al., 2013). The elevated NH_3 concentrations were associated with transport patterns from the Snake River Plain and northern Utah (Benedict et al., 2013; Prenni et al., 2014). Organic N species are not routinely measured as part of these national monitoring networks because of the

difficulty and complexity involved; however, organic N may contribute an additional 30% to TN deposition estimates (wet + dry) (Lee et al., 2016).

Total N deposition estimates for the GYA vary across the landscape and are difficult to ascertain at fine scales because of high variability over elevational gradients, local and regional source contributions, limited on-site monitoring, and atmospheric models which do not perform optimally in complex terrain. However, such estimates are necessary in using CLs and exceedances to identify where sensitive resources may be at risk. Background (pre-industrial) N deposition in the northern Rockies forested ecosystems is estimated at $\leq$ 1.0 kg-N ha^{-1} yr^{-1} (Holland et al., 1999; Sverdrup et al., 2011). TN deposition estimates for modeled grid cells across the GYA have been developed at multiple scales ranging from local (GYA TN Dep) to national (TDEP) and are shown in Table 3 (Lee et al., 2016; Schwede and Lear, 2014; Nanus et al., 2017). The high end of each deposition range generally represents high-elevation sites within the GYA, which receive higher snowpack loading; or areas located closer to anthropogenic emissions sources.

Table 3. Range in annual Total Nitrogen (TN) deposition estimates for the GYA from different models and scales, and years included in the models.

Model	TN Dep Range (kg-N $ha^{-1}yr^{-1}$)	Scale	Years	Reference
GEOS-Chem	2.0–5.0	Regional	2010	Lee et al., 2016
TDEP	1.9–8.1	National	2016–2018	Schwede and Lear, 2014
GYA TN Dep	1.4–7.5	Local	1993–2014	Nanus et al., 2017

2.2.2 Sources of Atmospheric Nitrogen

While national regulatory efforts have focused on achieving emissions reductions from large sources such as coal-fired power plants, N emissions from other sources—agriculture, oil and gas activities, and wildland fire smoke—have been increasing in some areas of the western U.S. Atmospheric modeling found that mobile sources of NO_x from vehicles and NH_3 from commercial livestock operations are the two largest sources of N to the GYA, with estimates to total N at Grand Teton NP at around 65% (Lee et al., 2016). The third largest source (11%) was NH_3 from fertilizer (Lee et al., 2016). N emissions from wildland fire may also contribute over the short-term during fire events (Benedict et al., 2017). Half of the N deposition is estimated to come from within 400km of the GYA, with most inputs from the Snake River Plain and UT, but some NO_x may come from as far away as CA (Lee et al., 2016).

Other studies in the GYA found that high NH_3 emissions from agriculture in the Snake River Plain and northern Utah contribute to increases in NH_3 dry deposition (Benedict et al., 2013; Clarisse et al., 2009; Spaulding et al., 2015; Zhang et al., 2018) and increases in NH_4^+ wet deposition in parts of the GYA (Mast and Ingersoll, 2011). For example, deposition modeling in the GYA indicates that 74% of atmospheric N deposition attributed to agricultural activities originated in the Snake River Plain (Zhang et al., 2018). Using N isotope analysis, Hundey et al. (2016) found that at least 70% of NO_3^-

in remote high-elevation lakes in the Uinta Wilderness of northeastern Utah, south of the GYA, was transported through the atmosphere and originated from agricultural activities. The National Atmospheric Deposition Program includes a network that monitors ambient ammonia passively every two weeks (AMoN). The Grand Teton AMoN site shows NH_3 is highest in spring and summer (2012–2014), which is consistent with inputs from agricultural sources (Benedict et al., 2013). NO_x emissions are expected to decrease over the western U.S. in the next few decades which could limit the formation of ammonium nitrate, a key contributor to visibility impairment. However, NH_3 emissions, which are not federally regulated, are projected to increase and may increase TN deposition in the western U.S. (Ellis et al., 2013; Li et al., 2016).

2.2.3 Terrestrial Effects of Nitrogen

Epiphytic lichens are useful bio-indicators of air pollution because they obtain their nutrients from the atmosphere and many lichen species are sensitive to air pollution (Munzi et al., 2010; Geiser et al., 2019). Lichens also serve as habitat and food sources for many insects, birds and other animals, and community shifts in lichen species can serve as sentinels of forest health decline (Geiser et al., 2019). CLs of N deposition for lichens are increasingly being used to understand air pollution impacts to forest communities (Pardo et al., 2011; Geiser 2010; Geiser et al., 2019). Lichen communities in the GYA were surveyed in 2008, 2010, and 2011 to explore interactions between climate, air pollution, and lichen community composition, and to evaluate lichen community-based CLs for total N deposition (McMurray et al., 2013; McMurray et al., 2015). This work showed that N concentrations in lichens were well correlated with atmospheric deposition, and that N in both lichens and throughfall deposition decreased exponentially with increasing distance from natural gas activities. The highest deposition (4.1 kg-N ha^{-1} yr^{-1}) sites were nearest to gas production facilities, and coincided with degradation to lichen communities, resulting in a CL for lichens in the GYA of <4.1 kg-N ha^{-1} yr^{-1} (McMurray et al., 2013). Nationally, CLs for epiphytic lichen species richness and forage lichen abundance has been estimated around 3.5 kg-N ha^{-1} yr^{-1} and 1.9 kg-N ha^{-1} yr^{-1} respectively (Geiser et al., 2019). GYA lichen N isotope ($\delta^{15}N$) values range from −15.3 to −10 permil indicating agriculture is a primary emission source of N deposition outside more urban centers where vehicle emissions are prominent (Hoffman et al., 2019).

Excess N deposition can result in terrestrial eutrophication, which can affect plant biodiversity, and cause invasive or non-native species to outcompete native plants (Pardo et al., 2011). In a low elevation sagebrush steppe plant community study on the eastern edge of the GYA, invasive cheatgrass (Bromus tectorum) increased and native forbs and grasses decreased along an N deposition gradient between 3.0 and 11.2 kg-N ha^{-1} yr^{-1} (Apel et al., 2014).

High-elevation alpine environments are common across the GYA and may be particularly sensitive to excess N deposition. No GYA-specific research on the effects of N to alpine vegetation has been conducted, thus research in similar environments within the same Level III ecoregion in Rocky Mountain NP and Niwot Ridge, CO are used as proxies for potential effects and thresholds in the GYA (Pardo et al., 2011). N-addition experiments conducted in these alpine environments showed that the common sedge (Carex rupestris) began to increase at 3 kg-N ha^{-1} yr^{-1} Rocky Mountain NP, CO (Bowman et al., 2014). This indicates the CL to protect alpine ecosystems against terrestrial

eutrophication is around 3 kg-N ha^{-1} yr^{-1}. Whole-community responses to excess N deposition in alpine environments were estimated at 10 kg-N ha^{-1} yr^{-1} (Bowman et al., 2012).

Trees have species-specific responses to N for example an increase in N deposition may enhance growth in some species, and impair it in others (Thomas et al., 2010). A recent study examined tree-species growth rate and probability of survival over 10 years from 2000–2014 from thousands of Forest Inventory and Analysis (FIA) plots (USDA-FS, 2007) across N deposition gradients nationwide (Horn et al., 2018). The study identified 89 tree species for which sufficient national data were available to assess responses: only three of these species, Balsam Poplar, Douglas-fir, and Quaking Aspen are present in the GYA. Tree N CLs to protect against declines in growth rate and probability of survival were 3.4 kg-N ha^{-1} yr^{-1} and between 3.4–6.6 kg-N ha^{-1} yr^{-1} respectively (Horn et al, 2018, Table 1). N deposition in the GYA ranges between 1.4–7.5 kg-N ha^{-1} yr^{-1} (Nanus et al, 2017, Figure 5), indicating that many of the N CLs identified in the literature are near or exceeding CLs.

The majority of terrestrial responses to N deposition result from increased plant and microbial uptake of soil N. Once added N exceeds biological demand, excess N in soils can result in NO_3^- leaching which can lead to plant nutrient deficiencies, loss of soil buffering capacity, and eventually, mobilization of forms of aluminum toxic to plant roots, soil microbes and aquatic organisms. In Rocky Mountain alpine dry meadow environments, NO_3^- leaching has been shown to occur beginning at a CL of 10 kg-N ha^{-1} yr^{-1} (Bowman et al., 2014). Because this work was conducted in the same Level 1 Ecoregion (Northwestern Forested Mountains) as the GYA, the CL of 10 kg-N ha^{-1} yr^{-1} also applies to NO_3^- leaching in alpine environments within the GYA (Pardo et al., 2011; McClung et al., 2021).

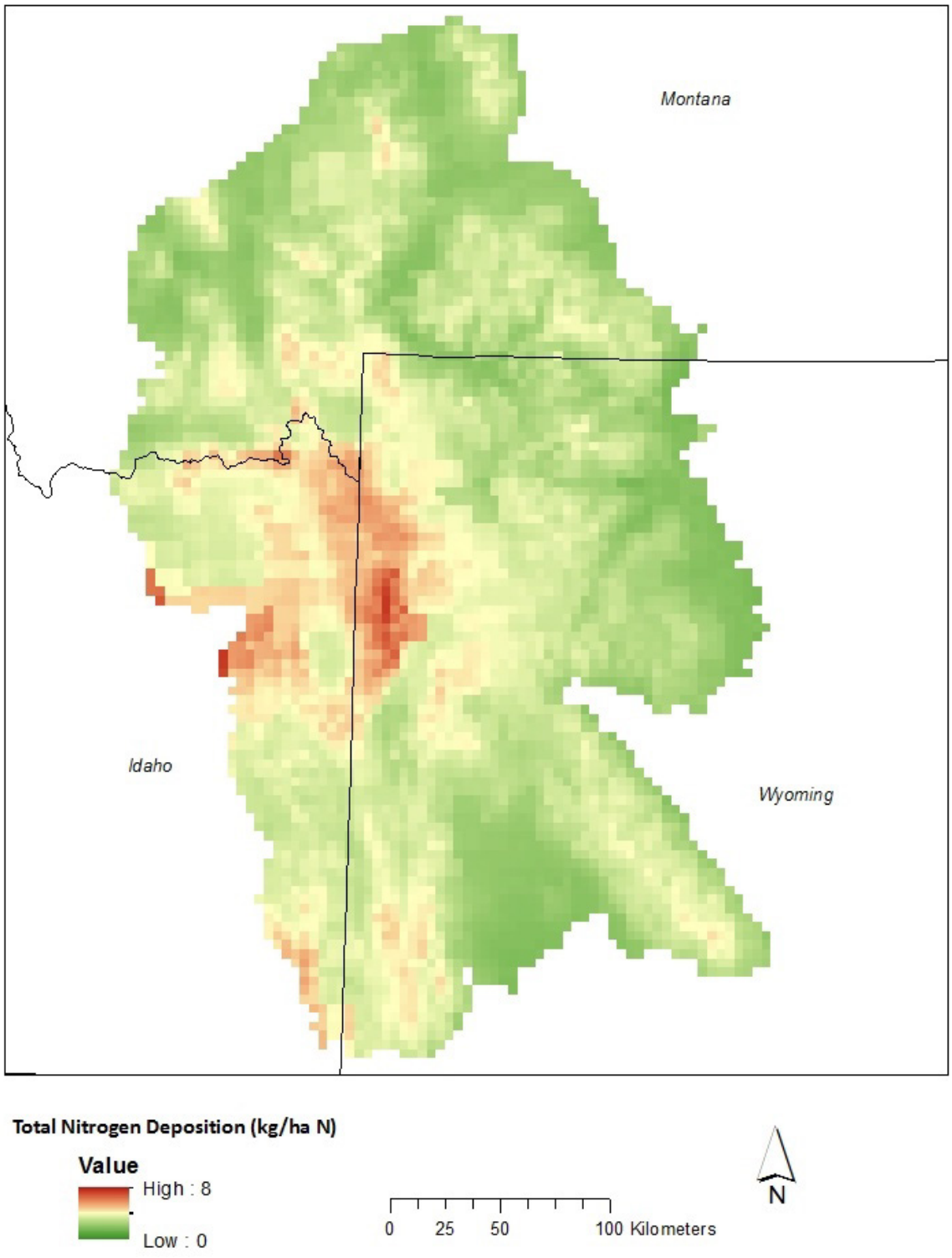


Figure 5. Average annual total nitrogen deposition (wet + dry) for the Greater Yellowstone Area (kg-N ha^{-1} yr^{-1}) (modified from Nanus et al., 2017).

2.2.4 Aquatic Effects of Nitrogen

Atmospheric N deposition can result in eutrophication or acidification of sensitive surface waters in the GYA. High-elevation lakes are particularly susceptible to these changes because they are naturally N-limited and occur in areas with poorly developed soils or vegetation to buffer incoming nutrients (Clow and Sueker, 2000). Excess N in lakes and streams can contribute to enhanced phytoplankton growth, which can result in algal or cyanobacteria blooms and decreased oxygen availability for fish and other biota (Baron et al, 2011; Rhodes et al, 2017) as well as reduced water clarity. Additionally, excess N can change phytoplankton species from oligotrophic (tolerant of only low N conditions) to eutrophic (thriving in high N conditions) species. These species shifts can disrupt aquatic food chains potentially leading to lower quality food sources for fish and other biota (Rhodes et al., 2017).

Lake chemistry samples collected at 125 lakes ranging in elevation from 2020 to 3662 m across the GYA had late-growing season NO_3^- concentrations that ranged from the detection limit to 32.9 µmol L^{-1} (Nanus et al., 2017). NO_3^- threshold concentrations of 0.5 or 1.6 µmol L^{-1} are generally used to indicate early-stage eutrophication in western high-elevation lakes, based on multiple lines of evidence that the diatom *Asterionella formosa*, used as an indicator of N enrichment, rapidly increases at this threshold level (Nanus et al., 2017; Baron et al, 2011; Mast and Ingersoll, 2011). Isotopic N signatures in sediment samples from five shallow high-elevation lakes in Grand Teton NP, showed that N deposition from anthropogenic emissions sources caused similar shifts in diatom species, beginning around 1960 (Spaulding et al., 2015).

Diatom cores from four lakes in the Beartooth Range in northern Wyoming showed shifts in taxonomic diatom flora starting around 1995 that are indicative of both increased N loading to these systems, as well as changes in thermal stratification patterns (Saros et al., 2003). The N deposition CL for changes in the lake phytoplankton species signaling the initiation of aquatic eutrophication was estimated at 1.5 kg-N ha^{-1} yr^{-1} wet deposition, which is approximately equivalent to 2.7 kg-N ha^{-1} yr^{-1} TN deposition. The CL for nutrient enrichment in high-elevation lakes of the western U.S. was estimated to range from 1.0 to 3.0 kg-N ha^{-1} yr^{-1} TN deposition (Baron et al., 2011).

N, together with sulfate, can also contribute to acidification of aquatic ecosystems, and episodic acidification may occur in some areas. High-elevation lakes in the GYA are susceptible to acidification because they are naturally dilute with low acid neutralizing capacity (ANC), and they are often located in areas with large snowpacks which provide a flush of meltwater diluting base cation buffering potential during the spring (Sullivan, 2016). The CL for episodic acidification in high-elevation lakes was determined to be 4.0 kg-N ha^{-1} yr^{-1}, at an inflection point of 3.7 µeq/L mean lake NO_3; based on water chemistry from 285 lakes in the Rocky Mountains (Baron et al., 2011). Therefore, given that N deposition may exceed the CL at times, it is possible that episodic acidification of some sensitive surface waters may be occurring in the GYA.

2.3 Mercury

2.3.1 Background and Trends

Mercury (Hg) is a persistent highly toxic pollutant with the potential to harm humans and other organisms. Mercury exists in many forms; elemental, inorganic and organic, reactive and unreactive,

but the form that most negatively affects ecosystem and human health is methylmercury—converted from other forms of Hg by microscopic bacteria. Methylmercury (MeHg) enters food webs and can be concentrated to levels that damage brain and kidney function, fetuses and reproductive success, and even alters behavior in humans and wildlife.

Recent studies of birds, fish, and dragonfly larvae suggest that Hg is a concern in Yellowstone NP and the GYA (Ackerman et al., 2016; Eagles-Smith et al., 2016a; Eagles-Smith et al., 2016b; Eagles-Smith, 2014; Yellowstone NP vital signs; Weiss-Penzias et al., 2016). The Mercury Deposition Network (MDN), part of NADP, is the only long-term monitoring network in the U.S. which measures total Hg concentration and deposition in weekly precipitation (https://nadp.slh.wisc.edu/networks/mercury-deposition-network/). There is one MDN site in the GYA—Tower Falls (WY08) in Yellowstone NP. Hg wet deposition at WY08 and other MDN sites in the Rocky Mountains increased between 2005 and 2013 (Weiss-Penzias et al., 2016). In the GYA and other parts of the intermountain west, Hg deposition typically increases with elevation (Wright et al., 2014: MDN; https://nadp.slh.wisc.edu/networks/mercury-deposition-network/) and is likely a mix of local, regional, and long-distance sources. GYA snowpack chemistry data for 2016 showed Hg deposition was highest on the western side of the Teton Mountain Range (http://co.water.usgs.gov/projects/RM_snowpack/index.html). An ice core from Fremont Glacier in the Wind River Range, WY found increased Hg deposition between 1930 and 1990, coinciding with industrialization (Chellman et al., 2017).

Mercury emissions can have a long atmospheric residence time, approximately 6 months to over a year (Biswas et al., 2007), allowing global travel before potentially depositing on the landscape. Despite the decrease in U.S. anthropogenic Hg emissions during the last decade, some studies indicate Hg deposition could increase in the U.S. due to increased Hg emissions transported to the U.S. from developing nations (Weiss-Penzias et al., 2016; Wright et al., 2014). In response to the concerns about global mercury emissions, The Minamata Convention on Mercury was created with the aim to help reduce global mercury pollution in the coming decades, the U.S signed on in 2013.

2.3.2 Sources of Mercury

Natural and anthropogenic processes release Hg into the atmosphere. Anthropogenic Hg emission sources are primarily from fossil-fuel combustion (largely coal), cement production, mining of gold, silver and Hg, manufacturing non-ferrous metals, water disposal, and caustic soda production (Eckley et al., 2016; Pirrone et al., 2010). Natural processes of Hg re-emission include volcanoes, biomass burning, soils and vegetation, and evasion in oceans, lakes, and wetlands (Pirrone et al., 2010). Climate change can influence Hg emissions (Lei et al., 2014). For example, rising temperatures have been correlated with an increased release of Hg emissions from reservoirs, oceans, and other waterbodies (Holloway, 2012; Lei et al., 2014).

Forested landscapes accumulate deposited Hg over time and have the potential to release large amounts of Hg from soil and fuels during wildland fires, especially during high severity fires (Mitchell et al., 2012; Webster et al., 2016). Because fire severity plays a major role in the release of Hg from soil, increasing wildfire severity in the western U.S. is predicted to increase Hg emissions (Webster et al., 2016). The Rocky Mountains including WY, ID, and MT are predicted to release

high amounts of Hg during burning, and other areas predicted to release large amounts of Hg, such as the coastal ranges, are upwind of the GYA (Webster et al., 2016).

Distinct chemical signatures from aerosol particles measured in Yellowstone NP in 2003, indicated that active wildfires were the main source of atmospheric Hg, whereas elemental mercury typically reflected global background concentrations with elevated levels only in areas of concentrated geothermal activity which are a unique and natural local source of mercury in the GYA (Hall et al., 2006; https://toxics.usgs.gov/highlights/yellowstone_mercury.html).

Estimated Hg released during fires in the U.S. accounted for 30% of the 2002 Environmental Protection Agency's (EPA) National Emission Inventory (NEI) for Hg emissions (44 metric tons of Hg per year from 2002–2005; Wiedinmyer and Friedli, 2007).

2.3.3 Terrestrial and Aquatic Effects of Mercury

In terrestrial ecosystems, Hg accumulation tends to be highest in forested landscapes followed by agriculture, herbaceous, shrubland, and landscapes containing barren soils with concentrations of Hg in forested ecosystems averaging 2.5 times higher than ecosystems with barren soils (Obrist et al., 2016). Forested ecosystems are often sinks for atmospheric Hg whereas sparsely vegetated regions tend to re-emit Hg back into the atmosphere or transport it into waterways and thus have low soil Hg concentrations (Eckley et al., 2016; Obrist et al., 2016). Re-emission of Hg can be particularly high after initial wetting of dry soils (Song and Van Heyst, 2005). In arid parts of the GYA Hg re-emission was lowest in the winter and highest in the summer due to snow cover (Eckley et al., 2016). Ecosystem characteristics such as soil moisture, solar radiation, precipitation, canopy cover/greenness, plant productivity, and snow cover all play a role in Hg cycling (Eckley et al., 2016; Obrist et al., 2016).

In aquatic and terrestrial ecosystems, bacteria can convert Hg to MeHg, which bioaccumulates in flora and fauna, compounding the toxic effects up the food chain. In aquatic ecosystems, MeHg is responsible for over 80% of fish consumption advisories in the U.S. (US-EPA 2011).

Watershed characteristics are key in identifying a landscape as a source or a sink of Hg (Domagalski et al. 2016). The rate of methylation potential varies among types of waterbodies and terrestrial surroundings, which means that the risk of Hg contamination in food webs may vary greatly within the GYA (Eagles-Smith et al., 2016a). High MeHg concentrations in fish and wildlife occur in more arid regions including parts of the Rocky Mountains and GYA (Eagles-Smith et al., 2014; Fleck et al., 2016), but wetlands also have high rates of methylation (Eagles-Smith et al., 2016a).

Birds are affected by Hg in the environment through MeHg accumulation up the food chain with piscivores having the highest Hg blood concentrations, but carnivores, insectivores, herbivores and granivores can also be negatively affected (Ackerman et al., 2016). In the GYA, birds were found to have elevated blood equivalent Hg concentrations (Ackerman et al., 2016). With high and extra high risk of Hg toxicity for bald eagles and osprey respectively, which was related to their dietary consumption of fish (Jackson et al., 2016). Six species of songbirds were sampled in Grand Teton NP, with the Dusky Flycatcher having the highest Hg blood concentration levels (Adams et al.,

2013). The Western Airborne Contaminant Assessment Project (WACAP) found that fish exceeded the EPA MeHg threshold for safe consumption by birds (30 ng/g) in all National Parks in the western U.S. (Landers et al., 2008).

Some watersheds in the GYA contain above average (for western U.S.) Hg concentrations in fish (Eagles-Smith et al., 2016a). Fish in Yellowstone NP have been found to have some of the highest Total Hg concentrations (119.9 ± 10.2 ng/g ww) from the 200 mm standard length size class measured from 21 western National Parks, whereas fish from Grand Teton NP had some of the lowest (Eagles-Smith et al., 2014). Dragonfly larvae in Yellowstone NP also had Total Hg levels in the highest top 5 compared with 34 National Parks (Eagles-Smith et al., 2016b). The national Dragonfly Mercury Project uses dragonflies to predict mercury risk within the related food chain (data for both parks available at https://wim.usgs.gov/geonarrative/dmpdatadashboard/).

MeHg occurs naturally in Yellowstone NP hot springs with highly variable concentrations (Ball et al. 2007; https://toxics.usgs.gov/highlights/yellowstone_mercury.html). Microbial mats that form in Yellowstone NP hot springs have been found to concentrate MeHg even when the water source had relatively low MeHg levels. Microbial mats offer a way for MeHg to enter the food chain via primary consumers. Soldier fly (*Stratiomyidae*) larvae that consumed microbial mats were found to have two to five times higher MeHg concentrations than in the microbial mat biomass (Boyd et al., 2009).

2.4 Ozone

2.4.1 Background and Trends

Ozone (O_3) is a highly reactive chemical compound that can damage human, animal, and plant cells and tissues upon contact. The formation of tropospheric, or ground-level, ozone occurs when the precursor emissions, nitrogen oxides (NO_x) and volatile organic carbon (VOCs) react in the presence of sunlight. Natural levels of ozone in much of the western U.S., are high and often increase with elevation even in remote areas of the Rocky Mountains (McDonald-Buler et al., 2011; Musselman and Korfmacher, 2014). The majority (80%) of NO_x emissions contributing to U.S. ozone pollution originates from within the U.S. (Lapina et al., 2014). Additional NOx emissions that contribute to ozone in western US have been linked to increasing emissions in Asia (Lin et al., 2017).

Yellowstone NP currently operates a Clean Air Status and Trends Network (CASTNET) station (1996 to the present https://www.epa.gov/castnet) which measure dry deposition of various analytes including forms of NO_y and NH_x, Grand Teton NP operates an ozone monitor (2011 to the present), and the FS operates a CASTNET station at Pinedale, Wyoming (1988 to the present), all of which provide ozone monitoring data (Figure 1). In addition, the state of WY operates ozone monitors at five Special Purpose Monitoring stations in the Upper Green River Basin.

The EPA National Ambient Air Quality Standards for ozone is currently 0.070 ppm or 70 ppb for the 4th highest 8-hour daily maximum. Annual ozone concentration in the GYA over the past two decades has hovered between 60–70 ppb. However, in a seasonal analysis of the data, models incorporating global ozone levels found that springtime ozone concentrations at the Yellowstone NP site have been increasing, due to an increase in contribution from Asian emissions (Lin et al., 2017).

Ozone data from the Yellowstone NP and Grand Teton NP sites display similar seasonal variability, with low (around 40 ppb) winter concentrations, and higher and more variable summer ozone values (fluctuating between around 20–60 ppb). Grand Teton NP ozone data show similar characteristics to urban-influenced sites, in that diurnal patterns show steep ozone declines in the nighttime, suggesting that there are sources of NO_x influencing the Grand Teton NP area. This pattern is likely related to the topography of the area and local emissions, from Jackson Hole including the airport and mobile emissions from tourism, commuters, and residents (NPS, 2013). Data from the Yellowstone NP ozone monitoring station show patterns more characteristic of a rural site. Ozone exceedances of the primary air quality standard in national parks are tracked and monitored monthly; Yellowstone NP and Grand Teton NP have rarely logged exceedances (https://www.nps.gov/subjects/air/ozone-exceed.html).

Climate change may create conditions in the GYA more favorable for ozone formation. Seasonal ozone concentrations are expected to increase as the climate warms, due to warmer temperatures, buildup of anthropogenic NOx, increase in VOCs released from plants and soils, and increases in wildfire precursor emissions (Lin et al., 2017).

2.4.2 Sources

Emissions sources primarily responsible for emitting ozone precursors include oil and gas operations, power plants, mobile sources, wildland fire and prescribed burns, agricultural production, natural vegetation, and transpacific emissions transport (most notably from Asia) (Lin et al., 2017). Within the GYA increases in ozone concentrations have been attributable to increases in alkanes from oil and natural gas production (McDuffie et al., 2016). Other emission sources that may influence ozone formation in the GYA include, industrial and electric generating plants in Idaho, and urban areas such as Salt Lake City, Utah (Sullivan, 2016).In 2005, the state of WY began detecting elevated ozone levels in the Upper Green River Basin (Sublette County and portions of Lincoln and Sweetwater Counties), which were sufficient to trigger a violation of the 2008 ozone standard, leading to a recommended designation of "ozone nonattainment" for that area in 2009. Significant oil and gas activity in the area, coupled with heavy snowpack and inversions during winter (January–March), were considered contributing factors to the elevated ozone levels. The state subsequently increased ozone monitoring, required detailed emissions inventories, enhanced stakeholder involvement, as well as developed voluntary and regulatory measures for an overall ozone reduction strategy. In addition, an ozone contingency plan program was created in and near the Upper Green River Basin, utilizing forecasting of potential weather conditions favorable for elevated ozone. The EPA categorized the area as "marginal nonattainment" in 2012; however air quality improvements in the area led the EPA to determine that the Upper Green River Basin attained the 2008 ozone standard of 75 ppb by 2015. After five winters without elevated ozone (2012–2016), in the winter of 2017, ozone levels in the Upper Green River Basin were again elevated, raising concerns about additional ozone exceedances in the area (https://deq.wyoming.gov/aqd/winter-ozone/).

2.4.3 Ozone Effects on Human Health and Vegetation

Ground level ozone is an air pollutant detrimental to human health and vegetation. Ozone can irritate the airways in the lungs of humans, making it difficult to breathe, particularly for children, the

elderly, and people with respiratory conditions such as asthma (http://www.epa.gov/ground-level-ozone-pollution).

Ozone is one of the most important phytotoxic air pollutants to plants, killing leaf tissues, damaging stomata, reducing plant growth, and weakening resistance to other stressors. Air quality standards set to address human health concerns are not low enough to prevent damage to some sensitive plant species (CASAC, 2014). Consequently, recommendations have been made to use a cumulative ozone exposure index, the W126 value (https://www.epa.gov/sites/production/files/2015-09/documents/w126_steps_to_calculate_revised_feb19.pdf). The W126 value is a 3-calendar-month rolling sum of the one-hour values. this threshold is used to describe the levels of ozone at which plant damage to sensitive species begins to occur (Sullivan, 2016). Current W126 thresholds adopted by the NPS are based on the EPA's 2014 *Policy Assessment for the Review of the Ozone National Ambient Air Quality Standards*, which suggested a threshold at 7 ppm-hrs to prevent tree seedling biomass loss of more than 2% per year, and a threshold at 13 ppm-hrs to prevent annual seedling biomass loss of 4–10% in sensitive species (https://www.nps.gov/articles/analysis-methods2020.htm#onthisPage-9). Ozone W126 annual values and temporal trends are available online for both Yellowstone and Grand Teton NP (https://www.nps.gov/subjects/air/index.htm).

Concerns for potential ozone damage to vegetation on natural and protected lands in the GYA are generally related to reductions in sensitive species and decreased biodiversity. Some ozone-sensitive plant species in the GYA include *Amelanchier alnifolia* (Saskatoon serviceberry), *Apocynum androsaemifolium* (Spreading dogbane), *Apocynum cannabinum* (Indian hemp), *Artemisia ludoviciana* (Silver wormwood), *Physocarpus malvaceus* (Pacific ninebark), *Pinus ponderosa* (Ponderosa pine), *Populus tremuloides* (Quaking aspen), *Rhus aromatica* (Skunkbush), *Rubus parviflorus* (Thimbleberry), *Rudbeckia laciniata* (Cutleaf coneflower), *Salix scouleriana* (Scouler's willow), *Sambucus racemose* (Red elderberry), *Symphoricarpos albus* (Common snowberry), and *Vaccinium membranaceum* (Huckleberry) (Sullivan, 2016).

3.0 Relevance for Policy and Management

3.1 Smoke

Prescribed and managed wildland fire can be useful tools in forest restoration projects, maintaining healthy ecosystems while potentially decreasing the likelihood of extreme wildland fires, through reductions in fuel loading, and thus reducing overall smoke emissions. However, prescribed fires produce smoke and result in short-term air quality deterioration which can place the goals of forest managers at odds with the goals of air quality regulators and public support. This challenge is likely to increase as the frequency and duration of smoke events from large wildland fires increases (Hyde et al., 2017). Air Resource Advisors (ARAs), effective communication, management practices, and online resources can all help reduce smoke impacts.

Resource managers should confirm that at least one ARA is available for large local fires to help reduce smoke exposure to fire personnel, to work with the health and regulatory agencies regarding smoke issues and exposure, and to communicate smoke risk. In addition, ARAs should work with fire managers to reduce smoke exposure to firefighters and other fire personnel. Examples of decisions which can reduce smoke exposure include the locations chosen for the main fire and spike (smaller camps often closer to the fire line) camps and the decision to move firefighters away from heavy smoke when they are on standby or if the duration of exposure can be reduced. In continuing fire education classes, communication of smoke risk to firefighter health and tactics to reduce smoke exposure on a fire should be emphasized.

The importance of measuring smoke impact and communicating to communities downwind cannot be underestimated (Hyde et al., 2017; Long et al., 2017). Communication and education with the public about smoke is essential to meet forest restoration goals that involve prescribed and managed wildland fire and reduce wildland urban interface fire hazard, both of which help reduce the risk of extreme smoke events by decreasing the likelihood of large-scale fires (Long et al., 2017). Communication and collaboration between management and regulatory agencies is vital to meet current and future management objectives along with regulatory guidance (Hyde et al., 2017), this is often achieved by following state and local Smoke Management Plans (SMPS). Management strategies should also continue to support the logistics and funding of projects which measure how smoke emissions and associated impacts are changing relative to baseline data.

Strategies to minimize smoke impact from prescribed burns should consider atmospheric conditions for emission dispersal, the amount of fuel burned, fuel moisture, and the intensity, duration and severity of the burn since these factors influence the amount, composition, and dispersal of smoke released (Long et al., 2017). For example, smoldering fuels release high amounts of PM and CO and high severity fires have the potential to release large pools of stored mercury (Wiedinmyer and Friedli, 2007).

Many state agencies report continuous PM levels to AirNow and on their state websites. During a smoke event, daily Air Quality Index (AQI) values, as calculated by EPA guidelines may be reported as well as the PM level. The AQI is a measure of how clean or polluted the air is and associates a calculated number with a level of concern and the associated range of health effects. The AQI and

PM levels help the public, especially sensitive groups, make informed decisions to minimize their risk to smoke exposure.

Additional resources available online include: AirNow's fire and smoke map (https://fire.airnow.gov/) shows current air quality $PM_{2.5}$ conditions, including modeled smoke plumes, and alerts in every state. NOAA offers a smoke forecast tool (https://airquality.weather.gov/ and a fire weather outlook tool (https://www.spc.noaa.gov/products/fire_wx/). NASA provides MODIS active fire mapping (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms), and Inciweb shows up to date information about fire activity (https://inciweb.nwcg.gov/).

3.2 Atmospheric Nitrogen Deposition

CLs provide managers information about deposition thresholds at which change, or damage may be occurring presently in the GYA. Local N deposition estimates (Schwede and Lear, 2014), can then be used by managers to evaluate whether the CLs are exceeded. The literature review above indicates many ecologically sensitive areas in the GYA are currently exceeding CLs for N deposition, meaning that ecosystem damage is likely occurring to some sensitive species and communities (Table 1).

Resources impacted by N in the GYA include high-elevation lakes, soils, aquatic food-chains, lichen species richness and abundance, biodiversity of forbs and grasses, alpine plants, and tree species growth and probability of survival over 10 years.

N deposition estimates and CL exceedances help determine if emissions reductions are needed to protect sensitive resources in the GYA. These reductions could be achieved through regulatory actions by states and EPA, and/or collaborative or voluntary efforts involving stakeholders. Understanding N CL exceedences, will help inform decision making processes and considerations for large and small projects both inside and outside the GYA that may contribute additional N emissions. Estimating N deposition to GYA landscapes will continue to be important to identify locations of N hotspots and improve understanding of where CLs of N are exceeded.

3.3 Mercury

Understanding the level and location of elevated Hg in the environment is essential to inform management decisions that reduce Hg exposure and help protect fish, wildlife, and human health. For example, the goal of fish consumption advisories in Yellowstone NP is to protect human health. Knowledge about current Hg and MeHg levels and trends can inform decisions to direct resources for ongoing and future studies.

There is one NADP/MDN site in the GYA that has met the data completeness criteria for NADP, all other Hg monitoring in the GYA has been project specific. It is important to improve understanding of baselines, current levels, and trends in Hg deposition on the landscape along with MeHg production and cycling within the GYA. One way to achieve this goal is to continue to support the logistics and funding of projects which measure how Hg levels are changing in species and resources that have baseline data. In addition, stable isotope Hg analysis would add to the understanding of sources of Hg in the environment.

When areas in the GYA with elevated Hg are identified, managers can minimize mobilization through a variety of environmental management strategies. Wildland fires, prescribed burns, and logging disturb surface sediments which has the potential to increase Hg mobilization through run-off during storms and spring snowmelt (Caldwell et al., 2000). Mobilized Hg that enters water bodies may be converted to MeHg, which can accumulate to toxic levels in biota. Location, timing (season and duration), project size, and minimizing surface sediment disturbance of a prescribed fire or logging operation are important management considerations related to Hg.

Because burn severity, frequency, duration, fuel moisture, and area affect the amount of Hg emissions released from a fire, prescribed burns have the potential to reduce Hg emissions in smoke and Hg mobilization in soils that might occur from a wildland fire.

Logging techniques and planning that minimize surface sediment disturbance help reduce risk of Hg mobilization. For example, clear cuts may cause the water table and soil moisture to increase, which in turn enhances mercury methylation potential (Kronberg et al., 2016).

3.4 Ozone

The state of WY continues to closely monitor ozone levels and use weather forecasting to issue "ozone action days" for the Upper Green River Basin, with the goal of reducing ozone precursor emissions during periods of weather conditions favorable for elevated ozone formation. Wyoming has also implemented additional strategies for industry to reduce ozone precursor emissions.

The NPS has continued interest in monitoring ozone sensitive plant species in the western U.S., particularly in riparian and wetland areas where plant stomata remain open longer in the season, rendering them at increased risk for ozone damage. Although sensitive plant species in the GYA are currently characterized at moderate risk for ozone damage based on W126 thresholds from existing monitoring stations, some sensitive species not currently monitored are potentially at higher risk and further investigation is warranted based on the seasonality of ozone events which coincide with periods of plant photosynthesis and growth.

3.5 Management Recommendations

Knowledge of the impacts of air pollution on resources and human health in the GYA is critical for informing resource management and facilitating science-based policy decisions. The bullets below highlight current available strategies that FLMs can take to reduce air pollution effects on sensitive resources, such as:

- Minimize emissions from projects under FLM jurisdiction to reduce impacts to resources already at risk.
- Utilize the role given to FLMs to comment on:
    - Prevention of Significant Deterioration (PSD) permits for new sources of emissions or major modification to existing equipment
    - State Implementation Plans (SIPs) to reduce ozone, regional haze, and other related pollutants

- National Environmental Protection Act (NEPA) projects to ensure agencies consider significant environmental consequences of their proposed actions

- Work with State and Federal regulatory agencies and other stakeholders to address air pollution concerns that affect the GYA, for example:
  - Members of the GYCC have participated in meetings with WY Department of Environmental Quality and others to find solutions to reduce ozone formation from oil and gas operations in Sublette County (the southern GYA).
  - GYCC Members and other stakeholders could engage with agricultural producers to identify practices and technologies which will reduce N emissions from agricultural land upwind of the GYA, similar to the Rocky Mountain National Park Initiative in Colorado.
- Continue support for long-term air monitoring networks within the GYA (e.g., IMPROVE, NADP, CASTNET, and USGS Snowpack) and ecosystem monitoring (e.g., lakes, lichen, soils, vegetation) that allow FLMs to assess conditions and trends of resources in the GYA
- Add monitoring sites in areas of high risk or concern with no current monitoring coverage, such as additional sites that:
  - Analyze lichen species composition and elemental content to identify hotspots of Hg, N, S, and other elements of concern and to monitor ecosystem health.
  - Sample lakes to assess changes in the diatom *Asterionella formosa* and measure other indicators (chlorophyll-a, total nitrogen, and total phosphorus) for eutrophication of aquatic resources.
  - Measure ozone at remote sites along elevational gradients in the GYA and estimate W126 values to determine whether sensitive plants or forest health is likely being impacted. Conduct plant surveys in areas where damage to flora in predicted.
  - Increase spatial resolution of Hg deposition and methyl mercury in biota measurements to assess ecosystem risk.
- Support research to advance our understanding of the sources, transport, deposition, cycling and effects of these pollutants on terrestrial and aquatic resources, such as:
  - Research to better characterize N, Hg, and other pollution emissions from wildland fire.
  - Synthesis of air quality monitoring data of multiple pollutants by the scientific community to understand and inform best management practices for the different pollutants.
- Encourage training for select employees at each land unit (park, forest, refuge, etc.) such as Air Resource Advisor (ARA) training and classes on Smoke Management Techniques (RX 410, wildlandfiresmoke.us). Encourage communication and continual education related to topics of smoke impacts on communities, and human and ecosystem health.
- Continue to educate and perform outreach to visitors and the public about air pollution and the issues that FLMS face in order to protect resources for current and future generations.

4.0 Conclusions

Coordination of environmental management and monitoring networks is critical. Federal Land Managers such as the NPS, FS, BLM, and FWS all maintain and protect resources in the GYA according to their individual mandates. The GYCC-CAP subcommittee, containing members of the four federal land management agencies, coordinates efforts between agencies to advance the science and understanding around air quality issues and to communicate air quality issues with partners and the public. Four important air quality issues in the GYA are smoke from wildland fires, atmospheric N deposition, atmospheric Hg deposition, and ozone.

Research and modeling predict an increase in intensity, duration, and frequency of smoke events from wildland fires through the mid-century, posing health, economic, and ecosystem impacts (Abatzoglou and Williams, 2016; Liu et al., 2016). Monitoring networks and modeling efforts broadly agree that atmospheric N deposition, specifically ammonia (NH_3), is increasing in the GYA while sulfur pollution is decreasing. Exceedances of N critical loads are occurring for multiple indicators in the GYA. Research and monitoring studies show that Hg deposition and MeHg formation may be increasing in the GYA (Weiss-Penzias et al., 2016). Elevated ozone concentration near oil and gas operations have led to intensive monitoring and modeling which uncovered the formation of winter-time ozone in rural areas, an anomalous and emergent concern for affected regions of the western U.S. However, ozone levels and effects in wilderness areas and other remote high-elevation sites remain unknown within the GYA.

The sections above highlight current available strategies that managers can take to influence air pollution effects on sensitive resources. Awareness of the impacts of air pollution on resources and human health in the GYA could be better incorporated into resource management and science-based policy decisions. In addition, forest plans, wilderness condition assessments, ecosystem health reports, and resource stewardship strategies being developed by agencies would benefit from inclusion of air quality (e.g. smoke, nitrogen, mercury, and ozone) as forcing factors that may alter the ability of ecosystems to recover from, or be resilient to, rapid changes, as well as used to consider the synergistic effects of air pollution with insect and disease, invasive plants, fire risk, land use changes, and climate change.

To continue to support the air, water, soils, wildlife, and biodiversity within this complex ecosystem; understanding and identifying risks and assessing multiple air quality indicators is critical to inform environmental management. Multi-agency groups such as the GYCC, and their partners can use this information to address key air quality concerns and mitigation strategies in a cohesive manner.

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