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ASSISTANCE FOR VISIBILITY DATA ANALYSIS AND IMAGE DISPLAY TECHNIQUES

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Abstract

The protection of national park resources from poor air quality is a central component of the National Park Service (NPS) Air Resources Division's (ARD) mission. One of these resources is visibility, the ability of visitors to see scenic vistas unimpaired by human-caused haze. To accomplish this broad goal, ARD, along with its collaborators and partners, monitors air quality at long-term sites and as part of short-term intensive studies. The data are analyzed and often integrated with air quality models to determine the composition and levels of air pollutants in and around park units to identify potential threats; track temporal trends in the air pollutant levels to gauge the effectiveness of air resource management strategies, including responses to changing emissions, and to identify emerging threats; understand the causal mechanisms of elevated pollutant levels in park units, including pollutant sources and transport; and inform air quality regulators, stakeholders, scientists, and the general public as to potential issues, causes, and solutions of air quality issues in national parks. The information obtained through these activities is critical to effectively communicate air quality issues to federal and state regulators and stakeholders, develop air quality policy positions within the NPS, and aid state and federal agencies in developing informed regulatory and voluntary strategies to mitigate air quality issues. As such, the information must be scientifically credible and defensible to withstand detailed scrutiny by others. The primary purpose of this agreement is to conduct research into long-term and pressing air quality issues that impact park units, including visibility, nitrogen deposition, and ozone problems. The tasks in the cooperative agreement focus on quantifying the levels and composition of the pollutants impacting parks and identifying their sources and other causal mechanisms. This work involves the development of the science and infrastructure needed to address current and future air quality issues, such as improving or developing measurement and modeling methodologies to better understand and quantify the chemical, physical, and optical properties of pollutants and their behavior in the atmosphere.

1. Objectives and Purpose for the Cooperative Agreement between the National Park Service and the Cooperative Institute for Research in the Atmosphere

The protection of national park resources from poor air quality is a central component of the National Park Service (NPS) Air Resources Division's (ARD) mission. One of these resources is visibility, the ability of visitors to see scenic vistas unimpaired by human-caused haze.

To accomplish this broad goal, ARD, along with its collaborators and partners, monitors air quality at long-term sites and as part of short-term intensive studies. The data are analyzed and often integrated with air quality models to

1. determine the composition and level of air pollutants in and around park units to identify potential threats;
2. track temporal trends in the air pollutant levels to gauge the effectiveness of air resource management strategies, including responses to changing emissions, and to identify emerging threats;
3. understand the causal mechanisms of elevated pollutant levels in park units, including pollutant sources and transport;
4. inform air quality regulators, stakeholders, scientists, and the general public as to potential problems, causes, and solutions of air quality issues in national parks.

The information obtained through these activities is critical to effectively communicate air quality issues to federal and state regulators and stakeholders, develop air quality policy positions within the NPS, and aid state and federal agencies in developing informed regulatory and voluntary strategies to mitigate air quality issues. As such, the information must be scientifically credible and defensible to withstand detailed scrutiny by others.

To aid in these activities, ARD collaborates with scientists at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University (CSU) under the cooperative agreement "Assistance for Visibility Data Analysis and Image Display Techniques". The primary purpose of this agreement is to conduct research into long-term and pressing air quality issues that impact park units, including visibility, nitrogen deposition, and ozone problems. The tasks in the cooperative agreement focus on quantifying the levels and composition of the pollutants impacting parks and identifying their sources and other causal mechanisms. This work involves the development of the science and infrastructure needed to address current and future air quality issues, such as improving or developing measurement and modeling methodologies to better understand and quantify the chemical, physical, and optical properties of pollutants and their behavior in the atmosphere.

In addition to the applied research that contributes to the protection of air quality in national parks, CIRA scientists also support specific ARD goals. CIRA scientists are involved in the support of ARD monitoring networks though data quality assurance activities, analysis and reporting of data, and participating in the guidance of the monitoring network's evolution due to changing needs. They perform regional air quality modeling analyses to understand and predict source impacts on air quality in specific park units. CIRA scientists are also available to provide expertise and support to ARD personnel to accomplish specific ARD tasks or to respond to requests made by park units to ARD.

The work conducted as part of the annual cooperative agreement is guided by a scope of work (see Appendix A). However, when necessary these defined activities are modified based on emerging needs and requests for additional assistance by ARD and others. The specific tasks fall within five main categories: aerosol research, nitrogen deposition, oil and gas development, web-based database development, and collaborative research with the U.S. Forest Service (USFS). The following section highlights results from these activities; detailed task lists are available in Appendix B. Deliverables from these activities (i.e., publications and presentations) are provided in Appendix C. Included at the end of Appendix C is a list of national organizations and science committees in which CIRA and NPS staff participate or have leading roles.

2. Highlights of Research Results from Major Activities

2.1 Aerosol Research

This activity supports applied scientific research into understanding the role of aerosols in visibility degradation (haze), as well as the reporting of the status, trends, and causes of visibility degradation in national parks. This information is necessary to meet the goals in the Clean Air Act of returning visibility in class I areas (CIAs) to natural conditions.

Visibility, often characterized by light extinction coefficients (b_{ext}), depends strongly on aerosol composition. Aerosol composition, which depends on source type, atmospheric processes, and transport, can exhibit significant spatial and temporal variability. Consequently, understanding spatial and temporal variability is critical to identifying the regions, seasons, and species associated with haze and its sources.

Aerosol composition in CIAs and other remote and rural areas is measured as part of the Interagency Monitoring of Protected Visual Environments (IMPROVE) program, which is operated by a consortium of federal land managers, including the NPS, the Environmental Protection Agency (EPA), and state organizations. The EPA's Chemical Speciation Network (CSN) is a similar monitoring network that measures aerosol composition at urban and suburban sites. The CSN is designed to support human health air quality regulations. However, the CSN data also characterize the urban haze that is transported to outlying rural areas, including national parks. Many of the projects completed as part of the cooperative agreement incorporated data from both the CSN and IMPROVE networks. Highlights from four studies under the Aerosol Research topic are discussed below. The first describes a spatial and seasonal study of the apportionment of carbonaceous aerosols to specific source categories in rural regions across the United States. The second describes the use of web cameras for monitoring visibility impairment. The third describes progress with the IMPROVE quality assurance activities. Finally, the fourth describes collaborative research with the USFS on the Regional Haze Rule revised visibility metrics.

2.1.1 Carbon Source Apportionment in Rural Areas

Carbonaceous aerosols are composed of organic (OC) and elemental carbon (EC), which together are known as total carbon (TC = OC + EC). OC can be emitted directly from combustion activities or produced from secondary reactions in the atmosphere, and EC is emitted directly from combustion sources. TC is ubiquitous in the atmosphere and contributes significantly to fine particulate matter and haze in national parks and wilderness areas. There are hundreds of carbonaceous compounds in the atmosphere, which makes determining their composition, sources, and fate a challenge. Identifying and apportioning carbon to various source categories, such as anthropogenic and natural sources, is especially important for characterizing anthropogenic visibility impairment with the EPA’s Regional Haze Rule (RHR), which has set the goal of returning visibility in CIAs on the most anthropogenically impaired days to natural conditions by 2064.

In an effort to identify source categories of carbonaceous aerosols, a chemical transport model was used to simulate the 2006−2008 contributions from various source types to measured TC in CIAs and other rural lands [Schichtel et al., 2017]. Source categories included wild fires, agricultural fires, area (e.g., residential and industrial wood combustion), vegetation, point, mobile, oil and gas, and other sources (e.g., offshore emissions, road, fugitive, and windblown dust). Natural TC was defined as the sum of fires, vegetation, and other natural sources. TC was apportioned to these sources both temporally (monthly) and spatially. These sources were aggregated into natural and anthropogenic sources, regardless of atmospheric chemical pathways.

Maps of the seasonal mean ratio of average anthropogenic TC to average total TC are shown in Figure 1(a-d) for winter (DJF), spring (MAM), summer (JJA), and fall (SON), respectively. Distinct seasonal and spatial patterns are clear. The lowest anthropogenic fractions (10–20%) occurred in the summer and fall in the West (Figure 1c and 1d, respectively), seasons associated with wildfire and vegetation-derived secondary organic carbon emissions. The highest fractions (>90%) occurred in winter when area and mobile contributions were highest, especially at sites in northern regions, such as New England and Washington State, likely associated with residential wood combustion. Spring and fall were transition seasons.

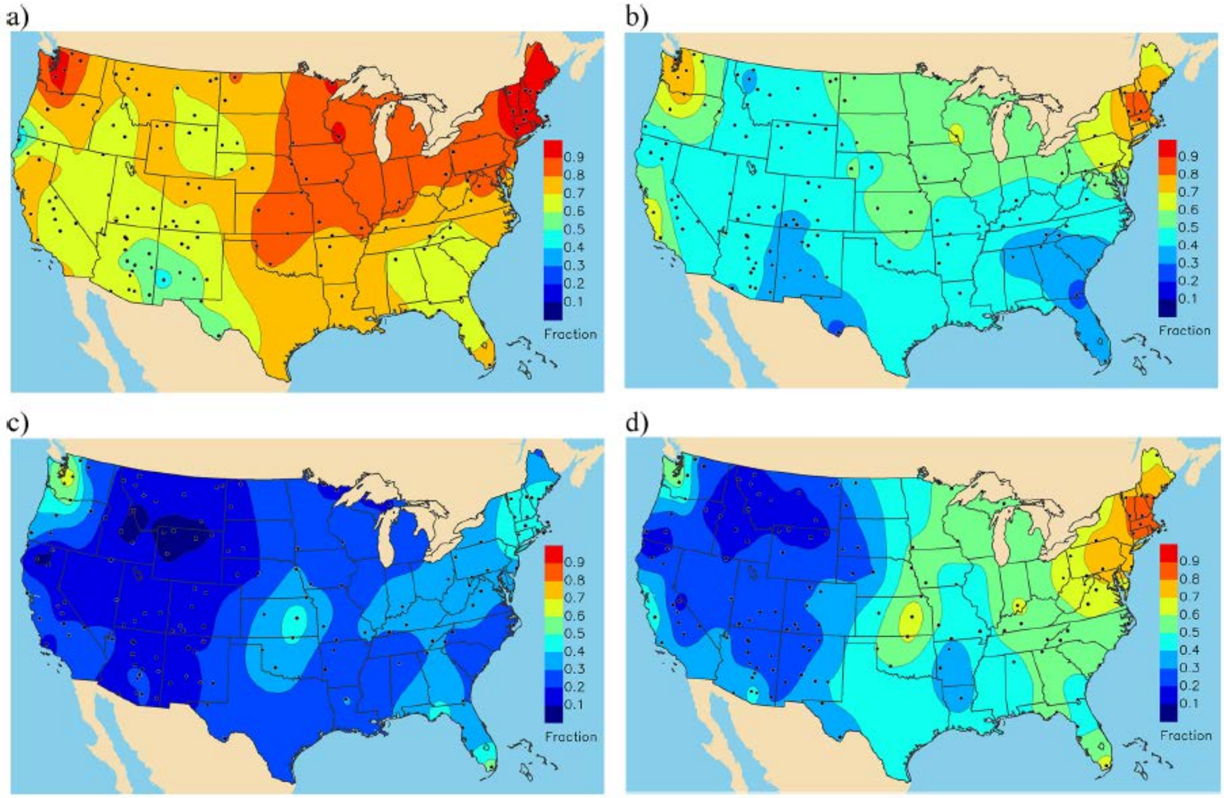


Figure 1. IMPROVE 2006–2008 (a) winter (b) spring (c) summer and (d) fall mean fraction of total carbonaceous aerosols from anthropogenic sources. IMPROVE sites are shown as dots on the maps [Schichtel et al., 2017].

Implications

With the reductions of pollutant precursor emissions and secondary anthropogenic aerosols (e.g., sulfate), carbonaceous aerosols are now an even greater contributor to particulate matter and visibility impairment across the United States. This study suggests anthropogenic sources (e.g., residential wood combustion and transportation) can have large contributions to TC that vary significantly both spatially and seasonally. Achieving the RHR goal of returning anthropogenically impaired visibility days to natural conditions requires a better understanding of the contributions of natural and anthropogenic sources to the TC. Based on these results, reductions of anthropogenic TC could reduce haze in northern regions where anthropogenic contributions were over 50%. However, reduction of anthropogenic TC will have little influence on the haziest conditions in the West because of the dominance of TC from natural sources including wildfires and vegetation-derived secondary organic aerosols. The EPA’s newly revised RHR anthropogenic visibility impairment metric recently was developed to account for the role of natural sources of TC, especially in the West.

2.1.2 Use of Cameras for Monitoring Visibility Impairment

The NPS and many other federal, state, and local agencies operate webcams on a routine basis. NPS images are collected every 15 minutes, 24 hours a day, 365 days a year. NPS visibility webcam images are available at http://www.nature.nps.gov/air/webcams/, U.S. Forest Service at http://www.fsvisimages.com/descriptions.aspx, and U.S. Fish and Wildlife at http://www.fws.gov/refuges/airquality/monitoring.html. Other visibility webcam sites can be found at http://www.hazecam.net/, which covers much of the northeastern United States, and http://airnow.gov/index.cfm?action=airnow.webcams, which includes some monitoring sites not available at the above web addresses.

It would be advantageous to extract useful quantitative information concerning the optical characteristics of atmospheric haze, such as light extinction, from the images. Light extinction (b_{ext}) is due to both scattering (b_{sp}) and absorption (b_{ap}) by particles in the atmosphere. Previous studies have demonstrated that in hazy atmospheres where the visual range is on the order of a few kilometers ($b_{ext} > 100$ Mm^{-1}), image processing techniques can extract information (i.e., image index) that is highly correlated with b_{ext}. Under high levels of haze (low visual range), landscape features are not significantly affected by atmospheric conditions such as cloud-cover characteristics and the shadows they create. Furthermore, images of these low visual range conditions in urban areas were for the most part devoid of color, as opposed to many national parks and wilderness areas that have highly colored landscapes. Furthermore, while urban visibility is on the order of a few kilometers, the visual range in the more-pristine national parks can be hundreds of kilometers. Under these clear conditions, lighting associated with sun angle, cloud cover, and other atmospheric conditions has a significant effect on the appearance of landscape features, independent of haze levels, and can potentially confound the relationship of image index with b_{ext}.

Webcams collect 2-dimensional arrays, referred to as pixels, of digitized voltages, in three color channels, that are proportional to the image radiance field. These image radiance values can be processed to derive indexes that can be related to estimates of b_{ext}. To test the relationship between image index and b_{ext} in pristine environments, images from two national parks, Grand Canyon and Great Smoky Mountains, taken over time periods of 2004–2014 and 1998–2014, respectively, were analyzed [Malm et al., 2017b]. Images represented all times of days and all types of lighting conditions resulting from varied cloud and other atmospheric conditions. Several different image indexes were explored, including gradient and contrast indexes. Gradient indexes were less sensitive to varying light conditions such as cloud cover or sun angle, unlike contrast indexes. However, gradient indexes were very sensitive to image resolution whereas contrast indexes were not, which has implications for calculating trends of indexes for images from camera systems that have been upgraded to higher pixel density over time.

A comparison of an image-derived contrast index (–ln(CRG)) and light scattering coefficients (b_{sp}) measured with nephelometery are shown for Great Smoky Mountains National Park in Figure 2. Averaging over a month reduced contrast index variability associated with clouds and meteorological conditions, and averages during afternoon yielded the highest correlation ($r^2 = 0.55$) between the index and b_{sp}. However, for images taken at the Grand Canyon, the best linear correlation between b_{sp} and the contrast index ($r^2 = 0.59$) occurred during morning hours.

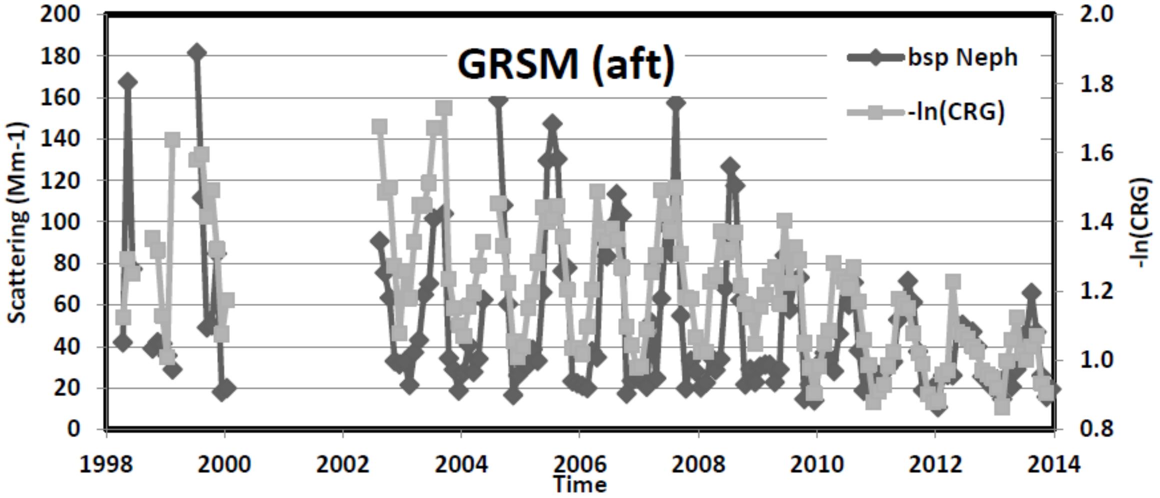


Figure 2. Timeline of light scattering coefficient (b_{sp}, Mm^{-1}) from the nephelometer and contrast image index (-ln(CRG) scaled to b_{sp} from the afternoon monthly average at Great Smoky Mountains National Park.

In rural environments, b_{ext} is primarily due to b_{sp}, and these results suggest that haze indexes derived from webcam images reliably track measured haze. Based on these results, quantitative relationships between b_{sp} and webcam contrast indexes were developed for other national parks. In addition, relationships such as these are now being explored for use with the real-time NPS-ARD webcam imagery, thereby extending the usefulness of webcam images to quantitative estimates of visibility impairment.

Implications

Webcam imagery is widely collected by different federal agencies. Developing and applying techniques to convert digital information in the images to a quantifiable estimate of visibility impairment extends the usefulness of these images and provides additional temporal and spatial information on trends in visibility impairment. In addition, extending this methodology to real-time webcam images has the potential to inform and educate the public about haze and provide a better appreciation of the quality of the views during park visits.

2.1.3 IMPROVE Quality Assurance Activities

Technical system audits (TSAs) of IMPROVE field operations are conducted to assess whether the IMPROVE sampling sites are in compliance with the IMPROVE Quality Assurance Project Plan and relevant standard operating procedures (http://vista.cira.colostate.edu/Improve/technical-system-audits/). The field audit quality assurance (QA) activities for the IMPROVE network have recently moved to CIRA. TSAs focus primarily on evaluating the sampling sites and the particle samplers in the field (Figure 3). This activity involves performing field audits at all IMPROVE sites within 10 years (about 15 sites per year) to ensure proper operation of samplers. Requirements for this activity include audit training, coordinating field QA audits with site operators, auditing data assessments, preparing summary reports, and presenting the results to the IMPROVE steering committee. Several trainings workshops were held at locations around the country to train auditors to conduct field audits. Materials for these trainings were developed as part of this activity. Thirty-five sites have been visited (Figure 4) and the 2016 report can be downloaded at http://vista.cira.colostate.edu/improve/wp-content/uploads/2017/02/2016-TSA-Report.pdf.

Figure 3. IMPROVE site at Tonto National Monument, Arizona, during a field audit visit in May 2017.

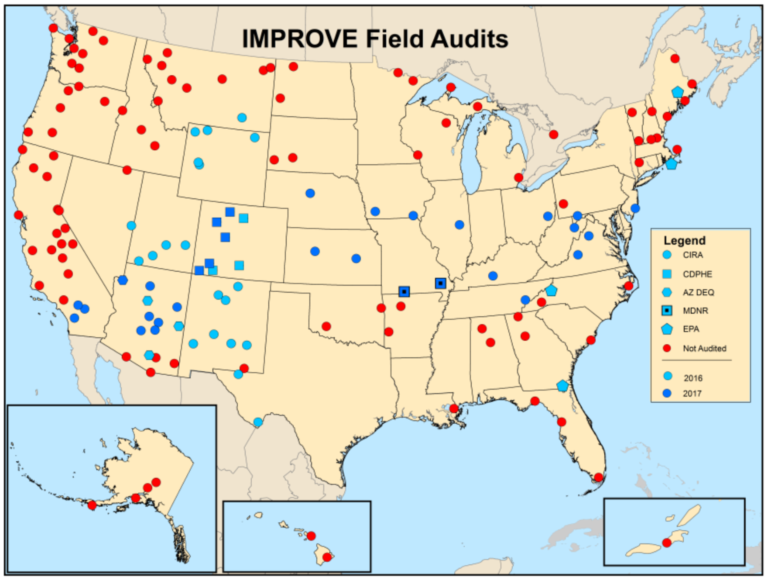


Figure 4. IMPROVE field audit summary. Symbols represent the agencies that conducted the site audit, and the colors represent the field audit status (completed or not yet audited).

Implications

The NPS is the key operational agency for the IMPROVE program. Managing the IMPROVE field audit QA activities at CIRA leverages the existing IMPROVE activities at CIRA, such as database management; IMPROVE website development and maintenance; and data analysis.

This leads to more efficient communication within the network in order to quickly identify and resolve any issues revealed during the audits.

2.1.4 Collaboration with and Support of the United States Forest Service

The NPS-ARD and USFS have several similar goals with respect to assessing air quality issues in remote and rural areas. In particular, activities related to the IMPROVE network, which has many sites that are located on USFS lands, and to IMPROVE and USFS database management meet the needs of tracking air quality by both agencies. As such, collaborative projects are a natural outcome of these similar goals. One CIRA staff member, funded by USFS, works closely with CIRA, NPS-ARD, and other federal agency personnel on air quality issues that impact both the NPS and the USFS. Of particular importance are the efforts related to the IMPROVE network, which include chairing the IMPROVE steering committee, coordinating with the technical leads, and overseeing the network, including budget issues, analytical procedures, operations, data reporting, special studies, staffing changes, Quality Assurance Project Plan (QAPP) development, and laboratory equipment purchases. In addition, activities include producing the RHR dataset, along with RHR metrics and summary information, ozone metrics for EPA Air Quality System (AQS) ozone monitors, and reporting these data to the database development software engineers at CIRA for serving on the Federal Land Manager Environmental Database (FED) website. Close collaboration with the USFS Air Program helps to develop strategies for the program’s involvement in the ongoing RHR revision process, including reviewing State Implementation Plans and providing technical assistance.

Development of revised RHR impairment metrics was a significant collaboration during this project. Participation with the EPA on new algorithms to characterize anthropogenic haze resulted in a draft guidance document outlining the procedure to separate natural from anthropogenic haze and reduce the impacts of episodic natural events, such as wildfire and dust emissions, on the RHR tracking metric [EPA, 2016]. Maps of pie charts showing the speciated aerosol contributions to haziest conditions at IMPROVE sites across the United States in 2016 are shown in Figure 5. Figure 5a shows results using the current RHR metric (mean of the 20% haziest days), and Figure 5b shows the mean of the 20% most anthropogenically impaired days. Most noticeable is the difference in composition and magnitude between the haziest days and most-impaired days at western sites. Carbonaceous aerosols dominated the composition on the haziest days, but when using the most-impaired days, the dominant contributor switched from carbon to other species, such as nitrate. Most days with significant carbonaceous aerosol contributions to haze are designated as natural when using the revised metric, and therefore the magnitude of haze on the most anthropogenically impaired days has decreased, relative to the haziest days.

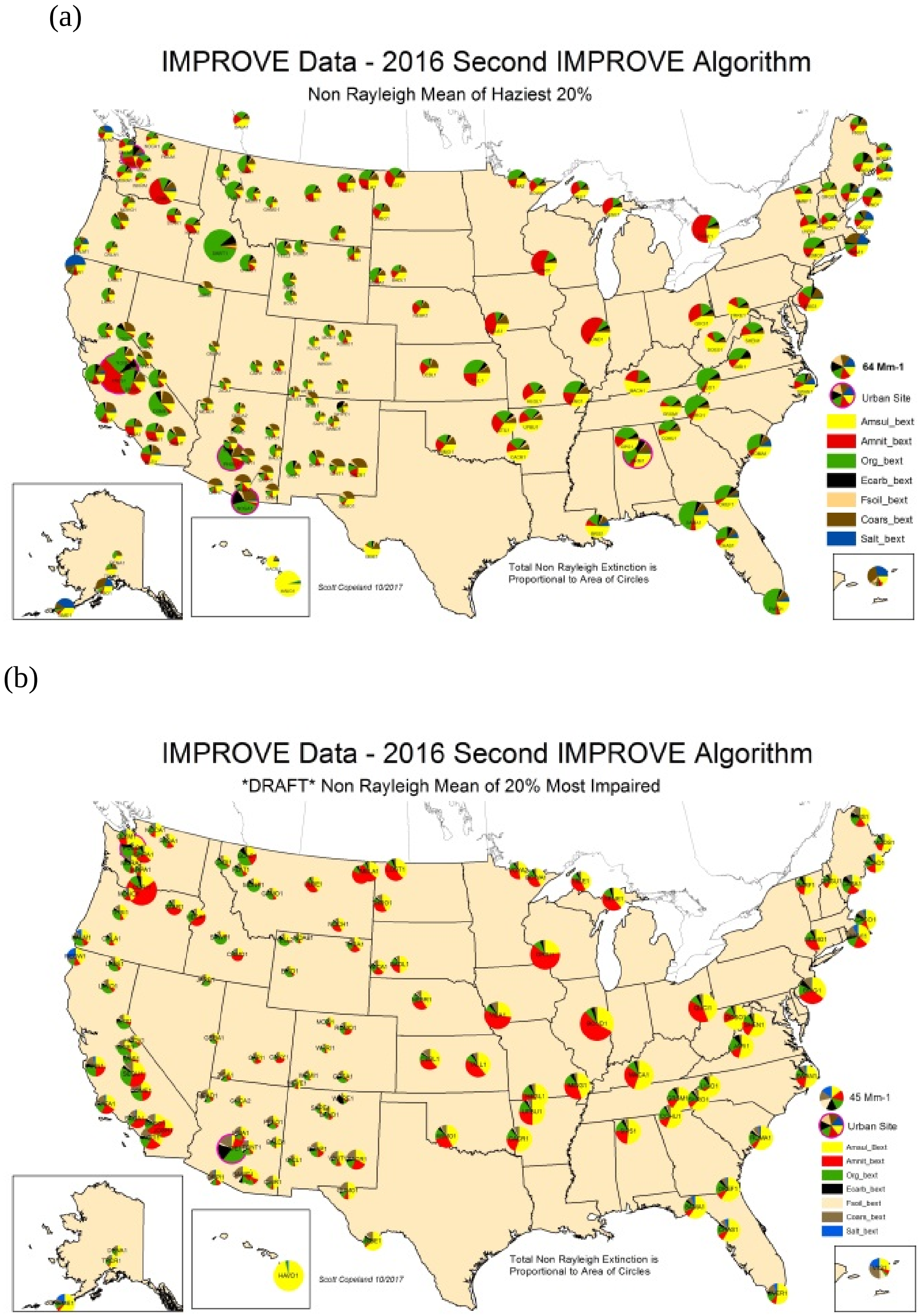


Figure 5. IMPROVE 2016 pie charts of the speciated aerosol contribution to extinction (b_{ext}, Mm^{-1}, circle size) for (a) the mean of the 20% haziest days and (b) mean of the 20% most anthropogenically impaired days.

Implications

The revised RHR tracking metric, proposed by the EPA, shifts the burden of the contribution from the haziest days to only the most anthropogenically impaired days. By categorizing most contributions from carbonaceous and dust aerosols as natural, the EPA no longer confounds uncontrollable, natural events with anthropogenic impairment. The largest impacts occurred in the western United States where carbon and dust contribute significantly to the haziest days. The role of carbon on the most anthropogenically impaired days decreased in the East, although to a lesser degree relative to the West. The seasonality of haziest days was also affected, especially at sites where nitrate became a larger fraction of the haziest days. Both the shift in composition and seasonality on the haziest days have important implications for control measures included as part of State Implementation Plans.

2.1.5 Relevance of Aerosol Research Results to ARD

Results from these examples, and other tasks listed in Appendix B, specifically address the four purposes listed in Section 1 by characterizing the current status of particulate matter and haze at monitoring sites in park units and other remote sites across the United States, quantifying the rate of change in speciated aerosol mass and haze over time, indicating species responsible for haze trends, reporting these results in peer-reviewed literature and conferences, and informing air quality regulators and stakeholders as to issues related to air quality in protected visual environments. These purposes also align with and directly support the needs of the RHR program. The collective results from the activities highlighted here and listed in Appendix B serve the development of meaningful national air quality regulations that have the potential to reduce pollution and haze throughout the country, including national parks.

2.2 Nitrogen Deposition

Healthy ecosystems are critical to the long-term sustainability of national parks, as well as the quality of the visitor experience. However, excess deposition of nitrogen and sulfur species can put these sensitive ecosystems at risk. For example, nitrogen deposition in some high alpine regions of the Rocky Mountains of the western United States have passed critical thresholds and are now causing adverse effects to these ecosystems. While ecosystem changes due to excess nitrogen deposition have been documented, the origins, chemical composition, and temporal changes in the deposition are not as well understood. Monitoring and regional air quality modeling studies are critical to understanding these changes and for charting a course for needed regulatory and policy actions to reduce nitrogen loadings. Such actions require an understanding of the major sources that impact sensitive ecosystems, such as the Greater Yellowstone Area (GYA). A modeling study was performed to investigate source contributions to nitrogen deposition during the 2011 Grand Teton Reactive Nitrogen Deposition Study (GrandTReNDS) air quality study in the GYA. Model evaluations require evaluation against data from GrandTReNDS, as well as from existing monitoring networks such as the National Atmospheric Deposition Program (NADP), Clean Air Status and Trends Network (CASTNET), and IMPROVE.

Understanding the levels and composition of the reactive nitrogen (N_r) deposited in sensitive ecosystems is a critical issue for identify threats and potential mitigation strategies. While monitoring programs measure a significant fraction of the N_r deposition, there are still a number of important information gaps in our ability to estimate these fluxes. These include incomplete understanding of physical processes, such as ammonia deposition; organic nitrogen levels and deposition rates; and continuous monitoring of N_r species. To fill the information gaps, the EPA is leading the development of a white paper, “Science needs for continued development of total nitrogen deposition budgets in the United States”. This project has brought together a consortium of scientists from across the country, including a number of NPS-CIRA personnel. Results from studies at CIRA, such as sources of excess N_r in the GYA, will help to fill some of these information gaps.

2.2.1 Source Contributions to Excess Reactive Nitrogen Deposition in the Greater Yellowstone Area

Excess reactive nitrogen (N_r) deposition in sensitive ecosystems of the GYA has passed critical thresholds and is potentially adversely affecting this vulnerable ecosystem. To better understand the sources causing excess N_r deposition, the Comprehensive Air quality Model with Extensions (CAMx) chemical transport model using Western Air Quality Study (WAQS) emission and meteorology inputs was used to simulate N_r deposition in the GYA during 2011 when extensive measurements were made as part of GrandTReNDS. CAMx’s particle source apportionment technology (PSAT) was used to estimate the contributions from agriculture, oil and gas, fires, and other source types (e.g., anthropogenic, biogenic, and lightning) from 27 source regions to the simulated N_r [Zhang et al., 2017].

The spatial pattern of total N_r deposition (kg of nitrogen per hectare, kg N/ha) over the GYA is shown in the left column of Figure 6. Other columns show the percent contributions from four emission sectors (agriculture, oil and gas emissions, fire, and other) and from boundary conditions in the farthest right column. Each row corresponds to the seasonal mean contribution (winter, DJF, spring, MAM, summer, JJA, and fall, SON) and the annual average. The source apportionment results for agricultural contributions suggest that the Snake River valley, with intensive agriculture activities, was the largest contributor to N_r deposition, accounting for more than half of the N_r deposition on the west side of the GYA, especially during the growing season. Oil and gas activity had little impact on the region except in the southern Wind River Mountain Range in winter. When wildfires occurred within the GYA, they were the dominant contributor to the local N_r deposition budget.

In terms of source origin, emissions from the Snake River valley, Northern Utah, western Wyoming, California, and boundary conditions were the top 5 contributors to N_r deposition throughout the GYA. A summary of seasonal source attribution results is shown in Figure 7. Overall, emissions from Idaho contributed almost 40% of the total budget. The following other top contributors were boundary conditions (21%), Wyoming (12%), Utah (8%), and California (7%). These contributions varied seasonally.

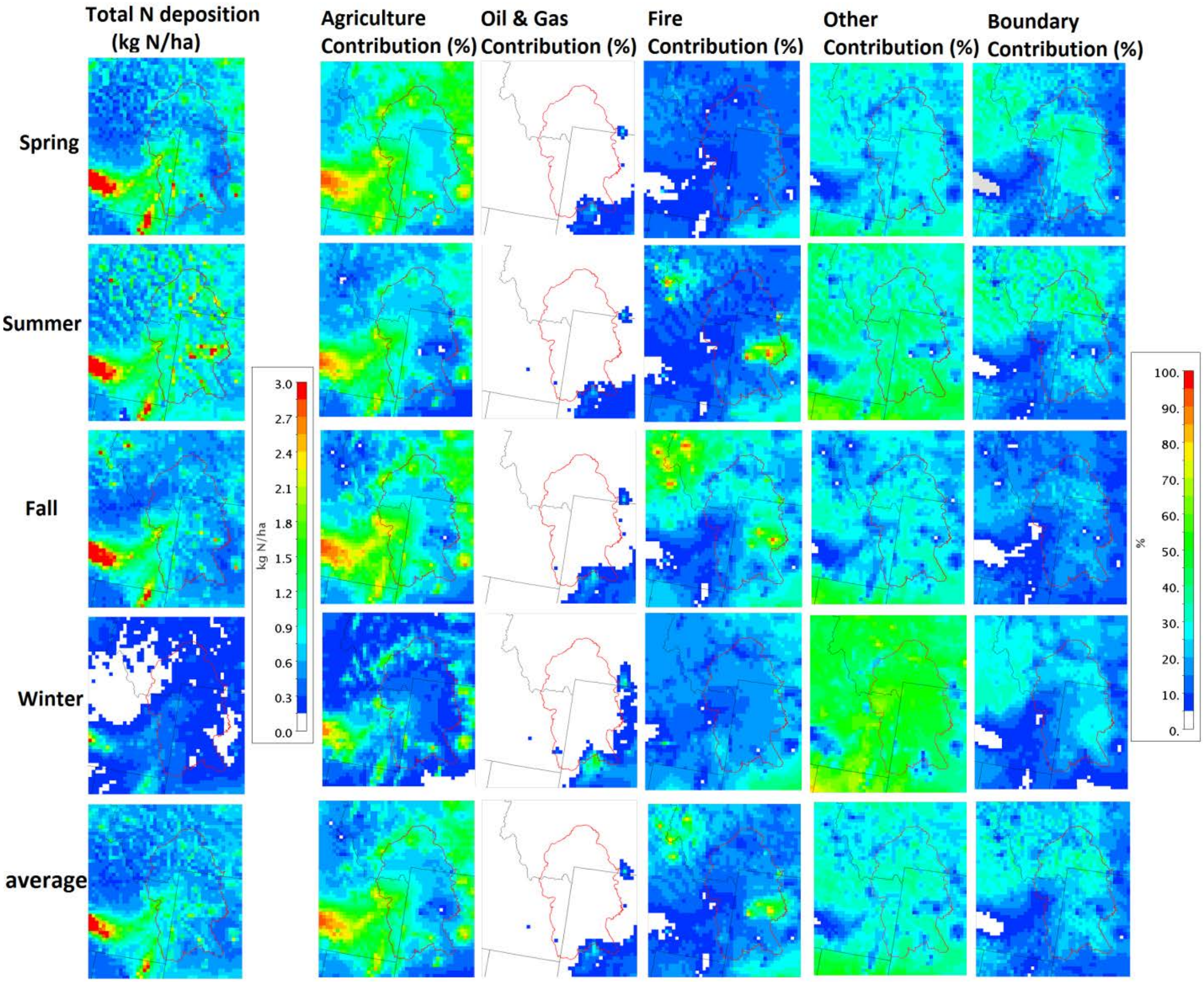


Figure 6. 2011 seasonal patterns of total reactive nitrogen deposition (kg N/ha) in the GYA in the left column, followed by percent contribution from different source sectors (agriculture, oil & gas activities, fires, others—e.g., anthropogenic, biogenic, and lighting—and boundary conditions) contributing to total nitrogen deposition. Seasonal and annual mean contributions are provided in rows [Zhang et al., 2017].

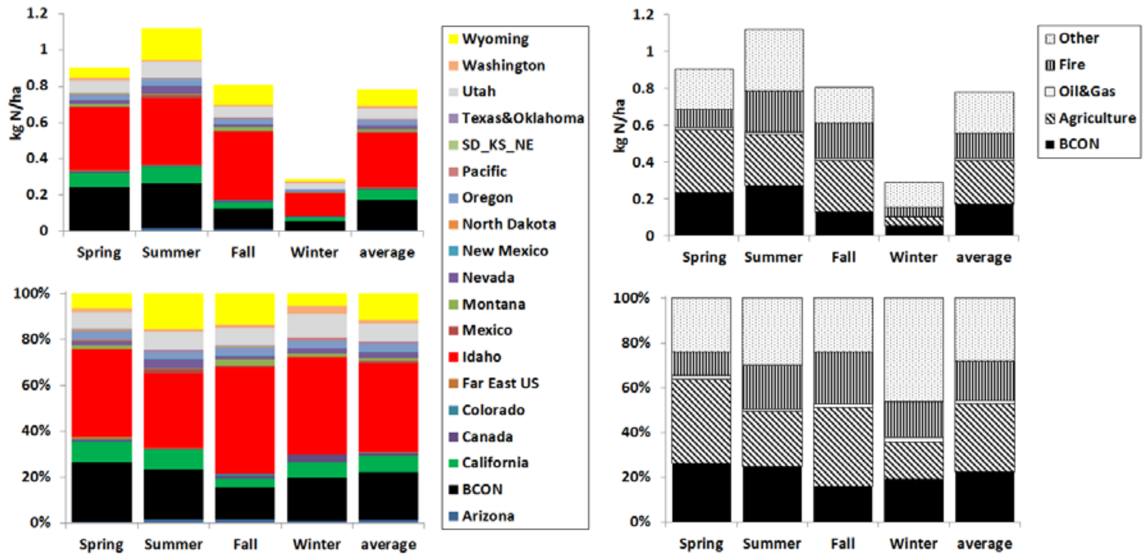


Figure 7. Contributions of different source regions (left) and source types (right) to the mean total reactive nitrogen deposition over the GYA at different seasons in 2011. BCON refers to boundary conditions [Zhang et al., 2017].

Implications

Detailed source apportionment studies provide scientific guidance to federal land managers to identify mitigation strategies for sources and regions contributing to excessive nitrogen deposition. In the GYA, agricultural emissions contributed significantly to deposition in the region. Fire emissions and other sources were also important during certain seasons. Oil and gas emissions had only a minor influence. The significant contribution from distant source regions and boundary conditions to N_r deposition illustrates the regional nature of the impacts and the need to further understand international contributions and to refine possible model biases.

2.2.2 Relevance of Results to ARD

Results from these examples, and other tasks listed in Appendix B, specifically address objectives 1, 2, and 3 in Section 1: identifying and quantifying the levels of nitrogen deposition, tracking trends in nitrogen deposition, and understanding the sources of the nitrogen deposition.

2.3 Oil and Gas Development

Increasing oil and gas development has potential negative impacts on air quality in NPS units throughout the United States due to its contributions to ozone, haze, and air toxics. The NPS-CIRA group and partners have conducted field and modeling studies to better understand these impacts, including the 2013–2014 field study in the oil- and gas-rich Bakken formation in North Dakota, where multiple class I areas (CIAs) are located, including Theodore Roosevelt NP. In addition to particulate matter and visibility degradation, oil and gas development can contribute to ozone precursors through the emission of volatile organic carbon (VOC) compounds. A preliminary study to investigate the levels of VOCs in parks near oil and gas activity was conducted over a five-month period, followed by a short, intensive study at parks in New Mexico and Texas. The majority of this work was done in collaboration with Dr. Jeff Collett of Colorado State University, through a separate agreement.

2.3.1 Oil and Gas Impacts in the Bakken Region of North Dakota

The potential impacts of oil and gas extraction activities on particulate matter and visibility degradation in CIAs in and around the Bakken oil and gas region of North Dakota was examined using back-trajectory, receptor-based techniques. Oil and gas activities began increasing rapidly around 2008 due to new extraction methods. Spatial and temporal patterns in speciated aerosol mass concentrations at IMPROVE sites in the region were compared before and after 2008 to examine the influence of the rapid increase in activity. Data from fourteen sites were analyzed for temporal trends and paired with back trajectories to examine potential source regions contributing to major constituents of fine mass. Back trajectory residence time analysis was performed to examine air mass transport pathways and identify the upwind areas that potentially contribute to high particulate matter and visibility degradation. The analysis focused on two time periods, before and after the 2008 expansion (2002–2007 versus 2008–2015) [Gebhart et al., 2017].

Back trajectory residence times were compared for days with high (90th percentiles) and low (10th percentile) concentrations for the early and late periods. The difference between the late and early period is shown in Figure 7 for the high concentrations of elemental carbon (EC), fine dust, and coarse mass (CM = PM_{10} - $PM_{2.5}$). Areas in yellow and red were more likely to have been in the transport pathway during later years relative to earlier years, while areas in dark green and blue were less likely. For days with the highest EC concentrations, air masses were more likely to arrive from the Bakken region in the later years than the earlier years. Similar results were observed for other primary aerosols like CM and fine dust. Impacts to EC, fine dust, and CM likely resulted from increased truck traffic in the region, which can result in fugitive dust emissions, particularly as many of the well areas are accessed from dirt roads. High OC concentrations were more likely to originate from the Bakken region in the later years, although the signal was weaker compared to primary EC, fine dust, and CM. OC is derived from biomass burning emissions or from secondary reactions from VOC precursor emissions, which have increased substantially in North Dakota. In contrast to the primary aerosols, impact from the Bakken region was less likely on days with high sulfate and nitrate during the later period relative to the earlier period. This was likely due to the low sulfur content of the oil and gas in the Bakken region and the decrease in emissions of precursors of these species from coal-fired electric stations in the region.

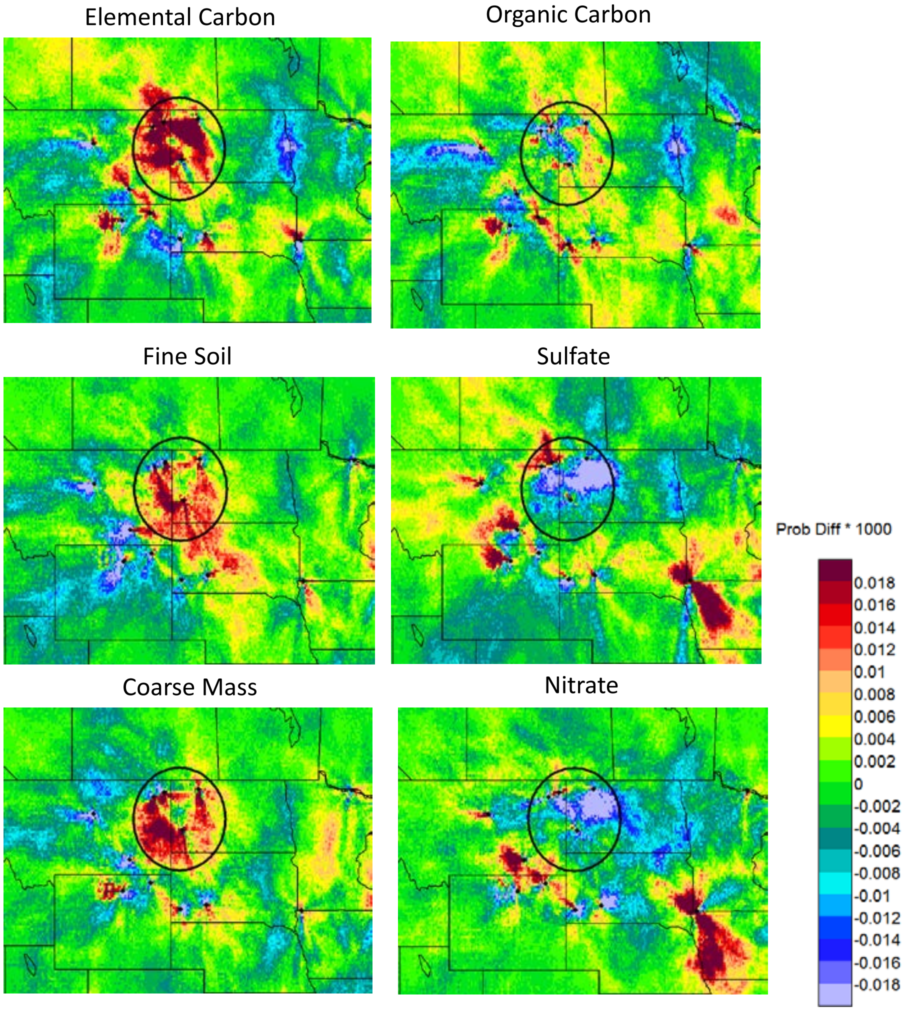


Figure 7. Difference between high (90th percentile) concentration residence times for 2008–2015 versus 2002–2007 for primary aerosol species in the left column and secondary aerosol species in the right column. Warm colors indicate more transport from the Bakken region in the later time period. Black circles highlight the Bakken region [Gebhart et al., 2017].

Implications

Recent oil and gas development in the Bakken region has led to an increase in regional EC, fine dust, and CM concentrations. Together these species accounted for approximately 13–27% of the particulate visibility impairment on average from 2002 to 2015. The largest impact occurred at sites in northwestern North Dakota and northeastern Montana, regions with the highest increase in recent fracking activity. The most likely sources of EC, fine dust, and CM were flaring, disturbed soils, trucking, and population growth related to oil and gas development. Gaseous pollutants such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_x) emissions in the region have declined during the same time period, mostly due to reductions in emissions from coal-fired power plants. This concurrent reduction obscures the impact of oil and gas on secondary species such as sulfate and nitrate. However, spatial patterns of temporal trends of sulfate and nitrate in the region indicate that concentrations at sites closest to the Bakken area did not decrease at the same rate relative to other sites in the region, suggesting potential impacts from oil and gas emissions.

2.3.2 Pilot Study Examining Volatile Organic Compounds in National Parks

VOC emissions are associated with oil and gas operations, motor vehicles, chemical manufacturing facilities, refineries, and natural (biogenic) sources. Investigating VOC composition is an important step in understanding ozone formation chemistry, and VOC composition can be used to characterize major emissions sources impacting park air quality. A collaborative monitoring study between CSU, the NPS-ARD, and park resource managers measured VOCs at parks near oil and gas development (Carlsbad Caverns National Park, New Mexico; Great Basin National Park, Nevada; Grand Canyon National Park, Arizona; Joshua Tree National Park, California; and Rocky Mountain National Park, Colorado). The majority of this work was performed under a separate agreement with Dr. Jeff Collett of CSU. Samples were collected from April 15, 2017 to September 15, 2017. At the end of this 5-month study period, a short, intensive field study was conducted in and around Carlsbad Caverns and Guadalupe Mountains National Parks. In addition to VOCs, related air quality measurements (NO_x, ozone, EC, and b_{sp}) were conducted using the CSU mobile laboratory. Samples from these studies are currently being analyzed, and study results are expected in 2018. Results from this study will be used to understand impacts on air quality in the parks and to inform future mitigation strategies.

2.3.3 Relevance of Results to ARD

National parks in the Bakken region have not experienced the same rate of reduction in haze as other parts of the country, even though emissions from a number of large point sources have been steeply reduced to comply with the RHR and other regulations. Results from these studies suggest that emissions associated with oil and gas development and population growth in the Bakken region have countered other emission reductions. In addition, results from the VOC study are anticipated to provide important information on the contributions of multiple sources, including transportation and oil and gas activities, to ozone levels in the monitored parks. These combined efforts address the four goals listed in Section 1, specifically to determine composition and levels of air pollutants in and around parks to identify potential threats, track temporal trends to gauge management strategies, understand the causal mechanisms of elevated pollutants in park units, and inform air quality regulators, scientists, and stakeholders as to the potential issues regarding air quality in national parks.

2.4 Web-based Database Development

The NPS and USFS use a number of disparate air quality and other datasets to assess air quality issues affecting NPS and USFS resources. These data are used to generate standard graphical and tabular products that represent the state of air quality in NPS and USFS lands and to track progress toward reaching air quality improvement goals. These products are used to communicate this information to other NPS and USFS personnel, federal and state regulators, scientists, researchers, and the general public. The air quality research community also uses these data to conduct research projects to better assess and understand the causes of poor air quality.

The primary activities include acquiring, importing/updating, and managing complete data inventories, processing the data, and displaying the data for government, academic, and public use. The sharing of these resources is done through a publicly-available website called the Federal Land Manager Environmental Database (FED) (http://views.cira.colostate.edu/fed/). The integrated environmental database and data delivery, aggregation, and visualization tools support and facilitate data analysis and data-driven decision making. The system provides tools to obtain and visualize air and water quality data and directly supports the NPS website, including air quality summary data products, USFS water chemistry data/metadata delivery, NPS–USFS RHR data summary needs, and IMPROVE data/metadata delivery.

2.4.1 USFS Water Chemistry Data

In response to a request from the USFS, CIRA developed a new series of chart products for the USFS water chemistry data, a dataset actively updated and maintained in the FED system. The new charts display historical time series of water chemistry parameters analyzed from discrete water samples taken within the boundaries of USFS lands, such that temporally coincident samples (including regular, blank, duplicate, experimental, and replicate samples) can be represented and compared on the same chart and the corresponding data be viewed and downloaded. Two examples of these new charts are shown in Figure 8(a-b) for Tabor Lake, CO. Figure 8a shows dissolved potassium ion from 2000 through 2010 and Figure 8b shows the acid neutralizing capacity as calcium carbonate ($CaCO_3$) over the same time period.

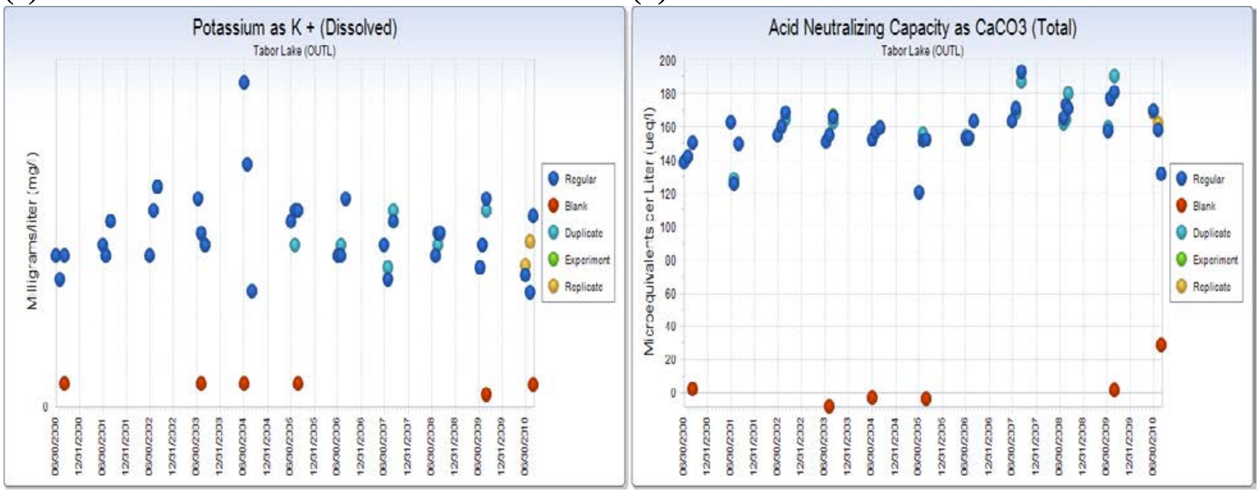
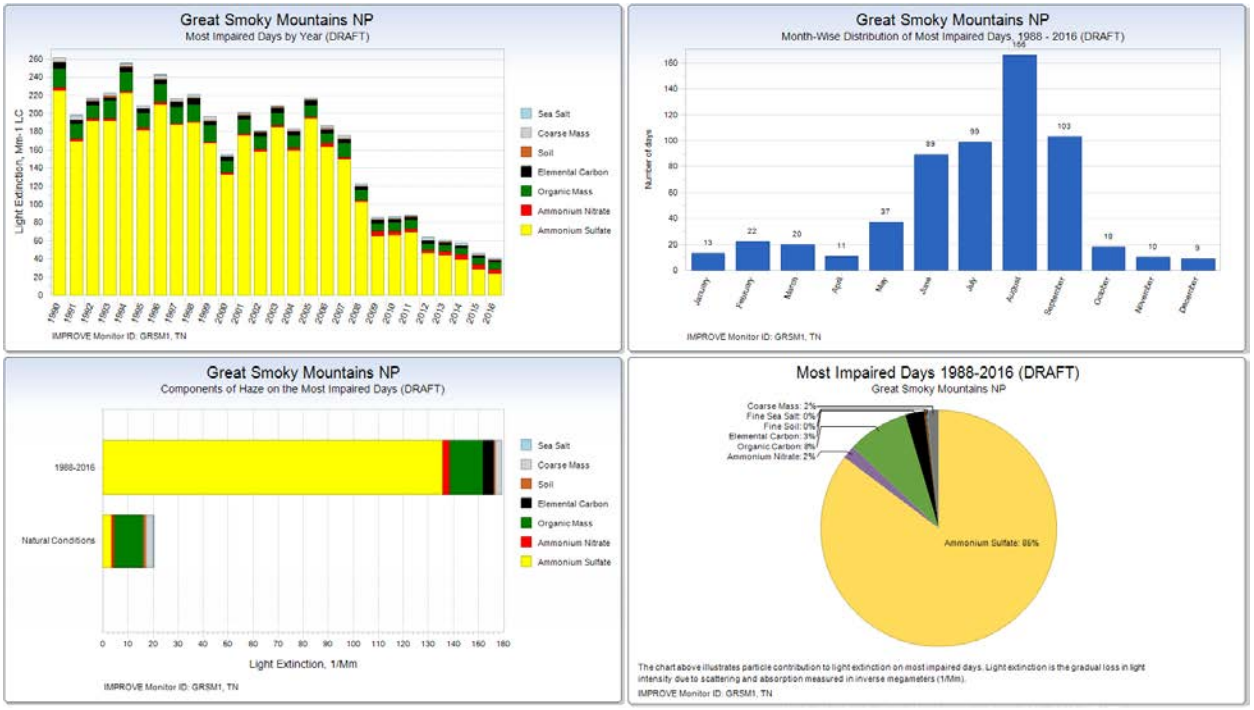

(a)
(b)

Figure 8. USFS water chemistry data at Tabor Lake, CO, for (a) dissolved potassium (mg/l) and (b) acid neutralizing capacity (μeq/l) as calcium carbonate ($CaCO_3$) (http://views.cira.colostate.edu/fed/FSWQ/SiteBrowser.aspx?appkey=SBCFSWQ_Default).

2.4.2 RHR Visibility Impairment Metrics

In July 2016, the EPA released new draft guidance regarding the second RHR implementation period (2018–2028). This guidance included changes to the calculation of the visibility impairment metrics used to support the RHR [EPA, 2016], and a subsequent outcome was the generation of a new set of historical impairment metrics based upon the data from the IMPROVE monitoring network. CIRA collaborated with NPS and USFS scientists to create the appropriate metadata for these metrics and to import the metrics into the integrated FED database so that the data could be made available through existing FED tools.

In addition, the existing Visibility AQRV Summary tools on the FED website were adapted to display the impairment metrics with the same suite of graphical products used for presenting the “RHR II” data used for the first implementation period (2001–2018). A mosaic of these new charts is shown in Figure 9 for Great Smoky Mountains National Park:


Great Smoky Mountains NP
Most Impaired Days by Year (DRAFT)

Great Smoky Mountains NP
Month-Wise Distribution of Most Impaired Days, 1988 - 2016 (DRAFT)

Great Smoky Mountains NP
Components of Haze on the Most Impaired Days (DRAFT)

Most Impaired Days 1988-2016 (DRAFT)
Great Smoky Mountains NP

The chart above illustrates particle contribution to light extinction on most impaired days. Light extinction is the gradual loss in light intensity due to scattering and absorption measured in inverse megameters (1/Mm).

Figure 9. Examples of graphical products to display the new RHR impairment metrics from the FED Visibility AQRV Summary tool (http://views.cira.colostate.edu/fed/SiteBrowser/Default.aspx?appkey=SBCF_VisSum).

2.4.3 Data Management

The EPA’s Chemical Speciation Network (CSN) discontinued its $PM_{2.5}$ gravimetric mass measurement in October 2014 with the intent to use an existing collocated Federal Reference Method(FRM) $PM_{2.5}$ mass measurement instead. NPS scientists determined that it would be useful to continue to report the FRM gravimetric $PM_{2.5}$ data with CSN dataset maintained by the FED system. CIRA created an “integrated $PM_{2.5}$ mass” parameter by first using the EPA Air Quality System (AQS) non-FRM $PM_{2.5}$ mass (88502) parameter and then the AQS FRM $PM_{2.5}$ mass (88101) parameter when and if an 88502 data point was not available. This new “integrated $PM_{2.5}$ mass” parameter provides a representative $PM_{2.5}$ mass measurement for the CSN dataset that could credibly be used for long-term trends beyond October 2014 and for comparisons between reconstructed and gravimetric $PM_{2.5}$ mass.

2.4.4 Relevance of Results to ARD

The FED database directly addresses objectives 1 and 2 through providing a website where researchers can download data to determine current levels of air pollution, as well as trends in pollutants over time. Objective 4 is also met through the distribution of graphics and summary reports generated from the website to individual park units and through the NPS website. Finally, this activity indirectly addresses objective 3 by providing data that is incorporated in source apportionment and modeling studies.

3. Assistance to ARD Staff and National Park Units

CIRA scientists often provide expertise and support to ARD personnel. These activities are typically not included in the original statement of work (Appendix A) because they arise in response to requests from ARD. During this past agreement period, several collaborations were undertaken. Back trajectory analyses were provided for special studies and site locations such as Rocky Mountain National Park (NP), Great Smoky Mountains NP, Guadalupe NP, and Carlsbad Caverns NP. Technical assistance requests were met for Dinosaur National Monument (visibility monitoring strategy), Valles Caldera (park monitoring strategy), and Bryce Canyon NP (webcam/photo summary). CIRA and NPS-ARD personnel hosted and participated with other NRSS park staff at CIRA to discuss climate change. Support was also provided for the NPS-ARD web products.

4. References

EPA Technical Support Document (TSD) Revised Recommendations for Visibility Progress Tracking Metrics for the Regional Haze Program; U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, available at https://www.epa.gov/sites/production/files/2016-07/documents/technical_support_document_for_draft_guidance_on_regional_haze.pdf

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Zhang, R., Barna, M. G., Thompson, T., and Schichtel, B. A. (2017), Source Regions Contributing to Excess Reactive Nitrogen Deposition in the Greater Yellowstone Area, *In Preparation.*

Appendix A. Statement of Work for Cooperative Agreement: September 15, 2016, to September 30, 2017.

INTRODUCTION

The public visits national parks and wilderness areas to enjoy nature in an unimpaired state. Air pollutants can adversely affect that visitor experience by degrading the vistas, affecting the natural ecosystems of these areas, and in some extreme cases, adversely affecting visitor health. The National Park Service (NPS) and Colorado State University (CSU) scientists are working together to better understand the scientific basis of these issues, providing that information to regulatory agencies at both the federal and state levels, and interpreting it for the public.

The scattering and absorption of light by particles in the atmosphere affect the clarity of scenic views associated with national parks and wilderness areas. The Interagency Monitoring of Protected Visual Environments (IMPROVE) program routinely collects samples of particles that are analyzed for their chemical composition and optical properties in order to assess their visibility impacts and source origin. Results of these analyses will be shared with regulatory agencies, published in the scientific literature, presented at scientific meetings, and provided with the data through the web to collaborating scientists at other institutions.

Some of the most effective ways to present the impacts of pollutants on scenic vistas is by photographic imaging techniques that accurately depict how the scene will appear under various pollutant and meteorological conditions. An image-based depiction of visibility is dependent on a firm understanding of the optical characteristics of pollutants, on state-of-the-art measuring techniques, on the ability to simulate accumulated effects, and on professional-quality image techniques.

In addition to unimpeded visibility, healthy ecosystems are critical to the long-term sustainability of national parks and the quality of the visitor experience. Ecosystem changes due to atmospheric deposition of nitrogen compounds have been documented at many locations in the Rocky Mountains. The origins, chemical composition, and temporal changes in the deposition are not well understood. Field measurements are critical to understanding these changes and for charting a course for needed regulatory and policy actions to reduce nitrogen loadings. During the spring and summer of 2011, the NPS monitored nitrogen deposition at Grand Teton National Park (NP), in collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA). Regional air quality modeling will be performed to assess atmospheric nitrogen deposition at class I areas in the Greater Yellowstone Area.

Oil and gas development negatively impacts air quality and visibility in pristine environments across the western United States. One region of particular interest is the Williston Basin in the northern Great Plains. During the winter of 2012–2013 and winter-spring of 2013–2014, monitoring studies were performed at Theodore Roosevelt NP and other nearby sites in the Bakken Shale region of North Dakota. Aerosol composition, visibility, ozone, and deposition data obtained during these studies will be analyzed in the context of prevailing wind patterns to understand impacts of the rapid development.

Investigating the causal mechanisms for elevated pollutant levels is a critical component of the activities described here. Eulerian, Lagrangian, and receptor models are used and integrated with measured data for source apportionment studies and to evaluate the role of meteorology and other physical and chemical processes on measured and modeled concentrations. The results assist in the development of air quality policy positions within the NPS and inform state and federal agencies in the development of strategies to mitigate air quality issues. These modeling tools will be used to estimate source contributions to nitrogen deposition and other pollutants at national parks and other sensitive regions in the Greater Yellowstone Area. In addition, these tools will be used to investigate impacts from oil and gas development to air quality and visibility at western class I and II areas and throughout the country.

The NPS and United States Forest Service (USFS) use a number of disparate air quality and other datasets to assess air quality issues affecting NPS and USFS resources. These data are used to generate standard graphical and tabular products that represent the state of the air quality in NPS and USFS lands and to track progress toward reaching air quality improvement goals. These products are used to communicate this information to other NPS and USFS personnel, federal and state regulators, and the general public. The air quality research community also uses these data to conduct research projects to better assess and understand the causes of poor air quality. Web-based database support includes activities such as providing these air quality data inventories, processing the data for trends and conditions for park units, and displaying the data for government, academic, and public use. The sharing of these resources will be done through an unrestricted website.

The specifics identified below describe a cooperative effort between the NPS and CIRA at CSU to analyze, interpret, and make available air quality, deposition, and visibility data, and analyses of these data. These data, interpretations, and analyses will be available to the scientific community, regulatory agencies, and the public.

Our effort for the period August 1, 2016, through January 31, 2018, will include

I. Aerosol Research

This activity supports policy-relevant research into understanding the role of aerosols in visibility degradation, as well as the reporting of the status, trends, and causes of visibility conditions in the parks. This information is necessary to meet the goals of the clean air act amendments and Regional Haze Rule, i.e., returning visibility in class I areas to natural conditions.

Visibility, often characterized by light extinction coefficients (b_{ext}), depends strongly on aerosol composition (among other properties). Therefore, understanding the spatial and temporal trends of major aerosol species is critical to characterizing visibility in the parks. Spatial and seasonal analyses of IMPROVE data aid in identifying regions, seasons, and the species associated with significant visibility degradation. In turn, this information helps to identify the causes of elevated haze in parks, including the types of sources causing the haze.

Integrating the Environmental Protection Agency’s (EPA) urban Chemical Speciation Network (CSN) and IMPROVE data extends the spatial analysis and provides for an examination of urban impacts on remote and rural regions across the country, thereby informing as to sources and source regions of haze in the parks. In addition, characterizing visibility and air quality trends at urban parks requires measurements from urban monitoring sites. These analyses are directly applicable to the NPS conditions and trends reports and online summary graphics.

Trend analyses quantify changes in major aerosol species and haze over long time periods and support studies designed to examine the impacts of emission mitigation strategies. Trend analyses have revealed significant widespread improvements in air quality at many national parks, especially in the East, but they also have revealed that visibility is unimproved, or even worsening, at specific parks during certain seasons (e.g., several sites in the western United States). The use of visual perception software to simulate images corresponding to measured visibility conditions in national parks provides a view of early and current conditions and is a powerful method for communicating improvements in visibility to the public. Trends in the Regional Haze Rule (RHR) haze metrics and aerosol components contributing to haze are necessary for evaluating progress with the RHR. This trend information is necessary for developing State Implementation Plans.

The impacts of meteorology and climate change on air quality in the parks can be significant. Understanding these connections requires additional tools, such as back trajectory analyses and regional and global modeling. Many publications have resulted from the incorporation of IMPROVE data in model evaluations and aerosol transport studies, with several that specifically focused on issues related to natural background concentrations and the impacts of intercontinental transport to remote and rural areas in the United States, in the context of the RHR. In addition, providing IMPROVE data for aerosol studies increases our understanding of changes in the optical properties of remote aerosols as well as expands the usefulness of IMPROVE data to the wider scientific community. For example, modeling and measurement studies that focus on climate change increasingly incorporate IMPROVE data because of its long data record. Peer-reviewed publications, conference presentations, and IMPROVE and NPS Air Resources Division (ARD) websites are the main avenues for disseminating the data and results of this work to the wider scientific and public communities.

The specific tasks related to The Aerosol Research activity are:

1. Complete derivation and analysis of visibility metrics and air quality indices from webcam images and publish a manuscript. Dr. William Malm will lead this effort.
2. Examine the use of visibility preference studies to establish alternate urban/suburban visibility metrics and goals. Dr. Bret Schichtel and Dr. William Malm will lead this effort.
3. Update annual, seasonal, and monthly mean statistics, trends, and spatial maps of major aerosols species from the most recent IMPROVE data (2015). Current standard analyses are important for investigating issues that arise at various parks throughout the year. Dr. Jenny Hand will lead this effort.
4. Update RHR trends and spatial maps using the most recent IMPROVE RHR data (2015). Included in this analysis is the update of WinHaze visualization software image to convey the visibility at about 50 national parks and wilderness areas. Dr. Jenny Hand will lead this effort, in collaboration with Mr. Scott Copeland.
5. Compute extinction estimates at urban parks using CSN data, FRM $PM_{2.5}$ data, and PM_{10}

data to estimate coarse mass contributions. These results will be incorporated into the NPS-ARD online air quality summary products. Dr. Jenny Hand will lead this effort, in collaboration Dr. Bret Schichtel and other ARD staff.

6. Continue investigations into IMPROVE speciated aerosol trends, including the difference between measured (FM) and reconstructed (RCFM) mass. Preliminary work suggests RCFM has decreased at a faster rate than FM, suggesting possible missing species contributions to RCFM or changing biases in FM measurements. This work has direct implications for visibility estimates derived from the IMPROVE algorithm. Dr. Jenny Hand will lead this effort in collaboration with Dr. Tony Prenni, Dr. Bret Schichtel, and Dr. William Malm.
7. Investigate differences in measured and reconstructed scattering using nephelometer data from 12 current sites. Initial work suggests this difference has grown over time and is likely associated with the difference in fine mass described above. However, the role of relative humidity and characterization of hygroscopic species will be examined. This work has direct implications for the accuracy of the current IMPROVE algorithm to estimate visibility. Dr. Tony Prenni will lead this effort in collaboration with Dr. Jenny Hand, Dr. Bret Schichtel, and Dr. William Malm.
8. Continue to provide formatted and relative-humidity-adjusted light scattering coefficients (b_{sp}) from nephelometers at IMPROVE sites to the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) database. The GAW database includes measured b_{sp} from around the world. Nephelometer data must be adjusted to specific sampling conditions in order to be compared with other measurements and included in trend studies of remote aerosol properties. Mr. Derek Day will perform these adjustments and submit the data. The incorporation of these data into the GAW database has increased the exposure of IMPROVE data and their use by the scientific community, including studies that investigate the effects of aerosols on climate change.
9. Continue to collaborate with scientists outside of NPS/CIRA who use the IMPROVE and CSN data for model evaluation and trends analyses that support climate change studies, as well as special studies such as recent field projects in the Southeast. To do this, the most current IMPROVE and CSN data will be converted to a model-friendly format (netCDF). Dr. Jenny Hand will lead this effort.
10. Perform all qualitative assessment (QA) duties for IMPROVE network monitors as described in the IMPROVE quality assessment plan, and assist data quality assurance activities by staff at University of California, Davis. Mr. Derek Day will lead this effort, in collaboration with Dr. Bret Schichtel, Mr. Scott Copeland, Dr. Tony Prenni, and Dr. Jenny Hand.
11. Begin analysis for the next IMPROVE report. This report is produced every four to five years and summarizes the current status of particulate mass and extinction using IMPROVE data for all sites across the United States. It also includes trends in speciated mass and extinction, as well as results from special studies. This is an extensive and collaborative effort between staff at CIRA, University of California, Davis, NPS, and EPA. Dr. Jenny Hand will lead the effort along with Dr. Bret Schichtel and Dr. Tony Prenni.

12. Examine the relationship in long term trends in carbonaceous aerosols and ammoniated sulfate. The focus of this study is to better understand the role that anthropogenic sulfate plays in the enhancement of the formation of secondary organic aerosols from volatile organic carbon emitted from vegetation. The implication is that a portion of the biogenic aerosol is due to anthropogenic sources. Dr. William Malm will lead this effort in collaboration with Dr. Bret Schichtel and Dr. Jenny Hand.

Collaboration with the USFS

13. Continue as the Chair of the IMPROVE steering committee. Mr. Scott Copeland coordinates with the technical lead and contract administrator to oversee the network. He oversees the IMPROVE budget, analytical procedures, operations, data reporting, special studies, staffing changes, Quality Assurance Project Plan (QAPP) development, and laboratory equipment purchases. He plans and coordinates conference calls. He also plans and facilitates the annual steering committee meeting.
14. Produce the Regional Haze Rule IMPROVE dataset, along with RHR metrics and summary information. In addition, generate needed ozone metrics for all EPA Air Quality System (AQS) ozone monitors. Mr. Scott Copeland leads this effort.
15. Participate with the EPA to develop new algorithms proposed for the RHR impairment metrics. Participate in the comment review period. Mr. Scott Copeland and Dr. Bret Schichtel will lead this effort.
16. Collaborate closely with the USFS Air Program to develop strategies for the program’s involvement in the ongoing Regional Haze Rule revision process, including reviewing State Implantation Plans and providing technical assistance when needed. Mr. Scott Copeland is responsible for this effort.
17. Provide visibility and air quality data analysis and expertise for the USFS. Mr. Scott Copeland leads this effort.
18. Provide wilderness character assessment values to the USFS based on IMPROVE data. Mr. Scott Copeland leads this effort.

II. Investigations into Nitrogen Deposition

Atmospheric nitrogen and sulfur species can cause a number of deleterious effects in the environment, including visibility impairment and changes in ecosystem function. Increased nitrogen deposition in high alpine regions of the Rocky Mountains of the western United States is adversely influencing ecosystems in those areas. Input of nitrogen to these sensitive ecosystems perhaps has already reached critical levels.

To investigate the sources of nitrogen in the atmosphere, measurements of nitrogen composition and deposition were performed during the 2011 GrandTReNDS study in an effort to understand nitrogen deposition in the Greater Yellowstone Area. Results from this study suggested that reactive oxidized nitrogen was the most abundant class of ambient gas-phase reactive nitrogen compounds, and ammonia was determined to be the most abundant individual nitrogen species. Results from this study have contributed to the development of methods for measuring nitrogen compounds in a routine monitoring program.

While monitoring studies are necessary for understanding the nitrogen deposition budget, observational data alone are unable to directly identify the contribution of a source or source region due to the complexities of the physicochemical processes and the meteorological patterns that govern the fate of nitrogen species. Air quality models are capable of simulating the atmospheric physicochemical processes and are used to understand source contributions. Performing regional air quality modeling requires meteorological fields, emission inventories, and boundary conditions. In addition to modeling, statistical inference techniques based on physical principles are used. Both are used as a part of this activity to identify the likely source regions that contribute significantly to deposition at national parks and class I areas in the Rocky Mountains. The tasks defined as a part of this activity aid the NPS in understanding nitrogen sources and their relative impacts on air quality and will assist in identifying needed regulatory and policy actions specifically related to deposition.

Greater Yellowstone Area and the Grand Tetons Reactive Nitrogen Deposition Study (GrandTRenNDS):

1. Continue to perform regional air quality modeling for the Greater Yellowstone Area. This work will provide a means of comparing modeled visibility and deposition impacts with measured impacts and attribute these to specific sources and source categories. Source apportionment studies will be performed to examine contributions from sources including agricultural emissions from the Snake River valley and nearby regions, oil and gas extraction and power plants in Wyoming and beyond, and wild and prescribed fires. This task will help identify sources of visibility impairment and assess the deposition of nitrogen compounds in class I areas in the Greater Yellowstone Area. Dr. Tammy Thompson will lead the air quality modeling activity in collaboration with Dr. Mike Barna, Ms. Kristi Gebhart, Dr. Bret Schichtel, and Ms. Tamara Blett. Appendix A provides a more detailed scope of work for this activity.

    Specific topics to be investigated as part of this project include:

    i. Based on previous work in Rocky Mountain NP, it was found that a significant fraction of the measured ammonia was from sources at distances of 1000 km or more. This regional signature of ammonia is contrary to conventional thoughts that ammonia is deposited near the source. The regional transport of ammonia to Grand Teton NP and the surrounding area will be evaluated.

    ii. The deposition of ammonia and its incorporation into the ecosystem is not well understood. Assuming a one-way deposition flux, reduced nitrogen is the primary form of deposited nitrogen into Grand Teton NP and many other ecosystems. However, the deposited ammonia may be reemitted (i.e., a bidirectional flux), which could result in significantly less reduced nitrogen being incorporated into the ecosystems. Consequently, the importance of ammonia in the net total reactive nitrogen deposition budget is still not well understood and needs to be resolved in order to develop meaningful mitigation strategies. Previous model evaluations using output from the CAMx unidirectional flux and the CMAQ bidirectional flux models suggest that bidirectional flux improves the model performance with respect to ammonia predictions. The CMAQ model will be used to test the sensitivity of bidirectional flux on model performance.

iii. Source apportionment will be performed using the CAMx model to determine the contributions from agriculture, oil and gas development and other sources from different sources regions. The emission inventory will be updated to include agricultural emissions. Dr. Tammy Thompson will lead this effort, in collaboration with Dr. Mike Barna and Dr. Bret Schichtel.

III. Impacts of Oil and Gas Development

The significant oil and gas development in the western United States, such as the Bakken Shale region in the northern Great Plains, is a significant new source of air pollutants that may negatively impact air quality and visibility at parks in the region. In order to fully understand the scope of the problem, intensive monitoring studies were performed during the winter of 2012–2013 and winter and spring of 2013–2014. Analyses of these data (e.g., aerosol composition, visibility, ozone, and deposition, meteorology) will continue, along with back trajectory analysis during the study period. Results from this work can help inform the development of meaningful policy and regulations to minimize the negative impacts of the oil and gas development. Specific activities include:

1. Evaluate the transport patterns associated with poor visibility and high concentrations of pollutants in the region. Understand differences in source regions and impacts to the region during the study period and historically. Publish results. Ms. Kristi Gebhart will lead this effort in collaboration with Mr. Derek Day, Dr. Tony Prenni, Dr. Jenny Hand and Dr. Bret Schichtel.
2. A monitoring study lead by Dr. Jeff Collett at CSU will measure volatile organic compounds (VOC) at 3 to 10 national parks. VOC data can be used to estimate the contributions of various source types including oil and gas, mobile and biomass burning to pollutants including particulate matter and ozone. NPS and CIRA personnel will assist with field work and analysis of collected data.

IV. Data, Dissemination, and Analysis Tools

This activity includes the development and maintenance of the infrastructure needed to perform regional air quality simulations and analyze, display, and disseminate large datasets and analyses.

1. Maintain three 12-core servers and two 20-core servers running 64-bit Linux, one 40TB, one 30TB, and four 10TB NAS's (network-attached storage), three local Linux machines, one 32 bit Linux X-server, and Windows machines for group members. CIRA IT support

in the budget covers this task.

2. Continue development of common applications and tools for accessing, integrating, filtering, aggregating, and visualizing model and data analyses. Dr. Tammy Thompson, Dr. Jenny Hand, Dr. William Malm, and Mr. Derek Day will create new scripts using the coding language R, IDL, or Gauss, in collaboration with Dr. Mike Barna, Ms. Kristi Gebhart, and Dr. Bret Schichtel.
3. Maintain and improve access to resources, including the IMPROVE website, for dissemination of data, summary reports, and network information and operations for the general public. Complete the update and reorganization of the IMPROVE website. This project will be headed up by Dr. Tony Prenni with support from Ms. Loretta Wilson. Specific additions will include:
    a. Development of an online reference database of peer-reviewed and gray articles using IMPROVE data.
    b. Development of a listing of proposed and executed ancillary projects that leverage the IMPROVE monitoring program and infrastructure.
4. Continue to develop the Federal Land Manager Environmental Database (FED) at CIRA to provide IMPROVE Regional Haze Rule and ozone datasets, metrics, and summary information. Collaboration will occur with ARD and USFS. Mr. Scott Copeland is responsible for ensuring the completion of the datasets. To facilitate the distribution and use of the IMPROVE data, new data visualization and exploration tools will be designed to be incorporated into the FED data system. This activity will involve mostly CIRA and NPS personnel.

V. Web-based Database Development

1. Respond to comments for the NPS/ARD Air Quality Summary report from reviewers and ARD staff. This activity includes managing, refining, and administering the Conditions and Trends tools, addressing user issues, refining graphical products, and updating datasets. Mr. Shawn McClure is responsible for this activity, in collaboration with Ms. Ksienya Pugacheva and Ms. Melanie Peters.
2. Extend the Conditions and Trends tools to include data summaries of particulate matter and mercury. Mr. Shawn McClure is responsible for this activity, in collaboration with Ms. Ksienya Pugacheva and Ms. Melanie Peters.
3. Support the IMPROVE monitoring program through the update of the IMPROVE datasets to the FED database, including RHR, calculated variables, and data resubmissions. Finalize a robust and long-term process for generating RHR and ozone metrics. Develop a system for better facilitating metadata management with NPS, UC Davis, and others. Interface with user groups such as scientists, land managers, and the public for use of the database. Mr. Shawn McClure is responsible for this activity, along with Dr. Bret Schichtel, Dr. Jenny Hand, and Mr. Scott Copeland.
4. Address refinements to the FED website, including improving functionality, online data tools, spatial visualization tools, gridded model data query and visualization tools. Mr. Shawn McClure is responsible for this activity, along with Dr. Bret Schichtel, Dr. Jenny Hand, and Mr. Scott Copeland.

5. Update and manage relevant datasets on an ongoing basis. Datasets include particulate (PM_{10}, $PM_{2.5}$, speciated) and gaseous monitoring data (O_3, NO_2, SO_2, CO) from IMPROVE, the EPA, CASTNET and the NPS, deposition data from the NADP and CASTNET, and nephelometer data from the NPS. Mr. Shawn McClure is responsible for updating datasets.

Collaboration with the USFS

1. Continue to develop aerosol and visibility exploration tools, including Composition and Trends tools for USFS sites.
2. Add USFS Resource units to the resource oriented data summaries in the Air Quality Summary Tool. Include “substituted” IMPROVE datasets where available. Add substituted dataset access to other tools, such as trends and composition tools.
3. Update water quality data from the USFS.

VI. Research Coordination

1. Coordinate day-to-day activities, such as answer phones, send and receive faxes, schedule meetings and conference rooms, interface with CIRA administrative staff, maintain group printers, etc. Ms. Loretta Wilson will be responsible for these activities.
2. Prepare and submit proposals. Continue to interface with CSU’s Office of Sponsored Programs and shepherd proposals through the system. Ms. Loretta Wilson will be responsible for these activities.
3. Maintain reference database. Enter and organize reference database for all publications and presentations from group members. Ms. Loretta Wilson will be responsible for these activities.
4. Support IMPROVE documentation by organizing and maintaining a reference database for all peer- and non-peer-reviewed publications that incorporate and leverage IMPROVE data in analyses. Ms. Loretta Wilson will be responsible for this activity.
5. Continue to act as a liaison between the NPS and CSU employees regarding University rules and regulations. Interact with CIRA administrative staff and keep abreast of all CIRA regulations. Ms. Loretta Wilson will be responsible for these activities.
6. Continue to act as technical editor for all publications, reports, conference proceedings, and abstracts in support of all the above research and outreach tasks. Ms. Helene Bennett will take the lead for this activity.

VII. Principal Investigator Duties

1. Prepare cooperative agreement with the NPS.
2. Oversee the annual budget.

3. Supervise seven CIRA employees, including the development and management of work plans and goals, and annual evaluation meetings. Organize and manage staff meetings.
4. Ensure that relevant research conducted by CIRA is published in the peer-reviewed literature and presented at national conferences.
5. Prepare monthly progress updates for NPS/ARD.
6. Prepare final annual reports for NPS and CIRA.
7. Serve on CIRA committees.

ESTIMATED PERFORMANCE PERIOD

All tasks under this agreement will be completed in a time frame from August 1, 2016, to January 31, 2018.

Appendix B. Detailed Activities Completed by CIRA/NPS

The specifics identified below describe a cooperative effort between the NPS and CIRA at CSU to analyze, interpret, and make available air quality, deposition, and visibility data and analyses of these data. These data, interpretations, and analyses are available to the scientific community, regulatory agencies, and the public. See Appendix C for Deliverables.

1. Aerosol Research

Accomplishments for this task period include the following. Many presentations and publications were derived from this work (see Appendix C):

1. Completed derivation and analysis of visibility metrics and air quality indices from webcam images and submitted a manuscript [Malm et al., 2017a, under review]
2. Published manuscript on trends in sulfate and biogenic carbon aerosols at IMPROVE sites [Malm et al., 2017b]
3. Published a manuscript on the overview of mineral dust and coarse mass concentrations across the remote and rural United States [Hand et al., 2017].
4. Published a manuscript on the carbon stuff [Schichtel et al., 2017]
5. Updated annual, seasonal, and monthly mean site and regional statistics, trends, and spatial maps of major aerosols species from the most recent IMPROVE mass and reconstructed extinction data (2015).
6. Updated annual, seasonal, and monthly mean site and regional statistics, trends, and spatial maps for major aerosol species for the SEARCH network and major aerosol species and reconstructed extinction for the CSN network.
7. Updated gaseous pollutant spatial and temporal trends using EPA's National Emission Inventory (NEI) data through 2016.
8. Updated Regional Haze Rule (RHR) trends and spatial maps using the most recent IMPROVE RHR data (2015).
9. Updated WinHaze visualization imagery to convey the visibility at about 50 national parks and wilderness areas.
10. Continued investigations into the difference between measured (FM) and reconstructed (RCFM) mass at IMPROVE, CSN, and SEARCH network sites.
11. Continued investigations into the difference between measured and reconstructed light scattering at 12 IMPROVE sites with operating nephelometer.
12. Ingested nephelometer light scattering coefficient data to World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) database.
13. Collaborated with scientists outside of NPS/CIRA who use the IMPROVE and CSN data for model evaluation and trends analyses that support climate change studies, as well as special studies such as recent field projects in the Southeast.
14. Calculated air mass back trajectories for all IMPROVE sites to support various studies

(e.g., cloud water trends, dust trends in the Southwest, nitrogen deposition in the Rocky Mountains, FRAPPE air quality study in northern Colorado, and volatile organic carbon monitoring study in the Southwest).

15. Performed all qualitative assessment (QA) duties for IMPROVE network monitors as described in the IMPROVE quality assessment plan. Visit and audit 36 sites. Update Technical System Audit (TSA) training materials.
16. Updated and supported the IMPROVE website (http://vista.cira.colostate.edu/improve/).

Collaboration with the United States Forest Service (USFS)

1. Continued as the Chair of the IMPROVE steering committee. Coordinated with the technical lead and contract administrator to oversee the network. Oversaw the IMPROVE budget, analytical procedures, operations, data reporting, special studies, staffing changes, Quality Assurance Project Plan (QAPP) development, and laboratory equipment purchases. Planned and facilitated the annual steering committee meeting.
2. Produced the Regional Haze Rule IMPROVE dataset, along with RHR metrics and summary information. In addition, generated needed ozone metrics for all EPA Air Quality System (AQS) ozone monitors.
3. Participated with the EPA to develop new algorithms proposed for the RHR impairment metrics. Participated in the comment review period.
4. Collaborated closely with the USFS Air Program to develop strategies for the program's involvement in the ongoing Regional Haze Rule revision process, including reviewing State Implantation Plans and providing technical assistance when needed.
5. Provided visibility and air quality data analysis and expertise for the USFS.
6. Provided wilderness character assessment values to the USFS based on IMPROVE data.

2. Investigations into Nitrogen Deposition

2.1 GrandTReNDS

1. Updated a CAMx modeling study of nitrogen deposition in the Greater Yellowstone Area (GYA). Analyzed model performance with comparisons to measured data from the IMPROVE, CASTNET and NADP networks.
2. Performed a source apportionment modeling study for 27 source regions for 2011.
3. Compared 2011 GYA source apportionment to a 2009 source apportionment study.
4. Evaluated sensitivity to boundary conditions from two different global models to source apportionment results (GEOSCHEM and MOZART).
5. Reran the CAMx model for slower ammonia dry deposition velocities to investigate the impacts on ambient concentrations and nitrogen deposition GYA.
6. Tracked fire emission impacts explicitly as part of the source apportionment study in GYA.

2.2 Extended Activities

1. Investigated and authored a chapter on recommendations for missing data in NADP

annual wet deposition trends.
2. Examined the impact of CAFOs to excess nitrogen deposition in Rocky Mountain National Park.
3. Contributed on chapter related to source apportionment of deposition in Rocky Mountain National Park.
4. Summarized the nitrogen deposition results the Rocky Mountain National Park study (RoMANS) and presented it to the Colorado Agricultural Subcommittee.

3. Impacts of Oil and Gas Development

1. Submitted manuscripts on the impacts of oil and gas development on particulate matter and visibility in the Bakken region [Gebhart et al. 2017; Evanoski-Cole et al., 2017].
2. Organized and participated in pilot study to examine volatile organic carbon (VOC) at Carlsbad Caverns National Park, NM, Great Basin National Park, NV, Grand Canyon National Park, AZ, Joshua Tree National Park, CA, and Rocky Mountain National Park, CO. Samples were collected from April 15, 2017 – September 15, 2017. A short, intensive field study was also conducted in and around Carlsbad Caverns and Guadalupe Mountains National Parks.
3. Reviewed NEPA oil and gas modeling studies for Colorado, Utah, Wyoming, and Montana/Dakotas BLM state offices (Colorado: CARMMS 2.0; Utah: Crescent Point; Wyoming: Greater Crossbow)

4. Data, Dissemination, and Analysis Tools

This activity includes the development and maintenance of the infrastructure needed to perform regional air quality simulations and analyze, display, and disseminate large datasets and analyses.

1. Refined online tools and web services for the Federal Land Manager Environmental Database (FED) database.
2. Mainted and updated the IMPROVE website. This includes updating appropriate quality assurance information, a displaying current IMPROVE graphics, up to date information about the visibility regulations, and a growing bibliographic reference site for visibility and IMPROVE scientific information (http://vista.cira.colostate.edu/improve).
3. Imported and updated databases of FED (IMPROVE, CASTNET, GPMP (Gasesous Pollutant Monitoring Program) hourly ozone, nephelometer, NADP wet deposition, and EPA annual summary).
4. Continued to work closely with the developers of FED at CIRA to provide IMPROVE Regional Haze Rule metrics, both the current (RHR2) and new revised impairment metric (RHR3) and summary information. Collaboration occurred with the ARD and USFS.
5. Implemented the regional air quality model CAMx 6.4 in parallel mode with NPS cluster, along with MPI. Performed optimization tests on computer run time using these modes.
6. Completed an online version of the WinHaze tool on the IMPROVE website (http://vista.cira.colostate.edu/Improve/winhaze/).

5. Web-based Database Development

1. Updated and managed relevant datasets on an ongoing basis. Datasets included particulate and gaseous monitoring data from IMPROVE, the EPA, CASTNET, and the NPS, deposition data from the NADP and CASTNET, nephelometer data from the NPS, and water quality data from the FS.
2. Released the 2015 Conditions and Trends and continued to implement changes to tools on the conditions page on NPS.gov (http://www.nature.nps.gov/air/data/products/parks/index.cfm).
3. Calculated ozone metrics (4th highest 8-hr ozone, W126, SUM60) and continued to develop tools for quality assuring ozone metrics using charting tools.
4. Developed the code framework for bulk-generating Theil trend statistics for ozone, visibility, deposition, and mercury data.
5. Provided additional data and metadata via web services.
6. Maintained, updated, and refined the Overall Air Quality Summary table and supporting graphical products for the Air Quality Summary Tool available from the NPS-ARD website, in collaboration with ARD staff.
7. Refined graphical tools for exploration of air quality data in the FED database.
8. Updated algorithms for calculated IMPROVE variables to be downloaded from the FED database.
9. Developed algorithms to provide "integrated $PM_{2.5}$" gravimetric fine mass data for CSN after 2015 using collocated FRM data.

6. Public Outreach

A graphics artist was utilized to provide illustration, animation, and presentation graphics for research, peer-reviewed manuscripts, and reports.

Appendix C. Project Deliverables

Deliverables for this project include publications, conference presentations, reports, a text book, and service.

1. Publications:

1.1 Aerosol Research

1 Brewer, P., **Schichtel, B. A.**, Shepherd, D., and Johnson, S. (2017), Looking Forward to 2028: Regional Haze Planning in the Western United States, *EM Magazine*, 13-19.

2 DeMott, P. J., Hill, T. C. J., Petters, M. D., Bertram, A. K., Tobo, Y., Mason, R. H., Suski, K. J., McCluskey, C. S., Levin, E. J. T., Schill, G. P., Boose, Y., Rauker, A. M., Miller, A. J., Zaragoza, J., Rocci, K., Rothfuss, N. E., Taylor, H. P., Hader, J. D., Chou, C., Huffman, J. A., Poschl, U., **Prenni, A. J.**, and Kreidenweis, S. M. (2017), Comparative Measurements of Ambient Atmospheric Concentrations of Ice Nucleating Particles using Multiple Immersion Freezing Methods and a Continuous Flow Diffusion Chamber, *Atmospheric Chemistry and Physics*, *17*(18), 11227-11245, 10.5194/acp-17-11227-2017.

3 Hallar, A. G., Molotch, N. P., **Hand, J. L.**, Livneh, B., McCubbin, I. B., Petersen, R. L., Michalsky, J., and Lowenthal, D. (2017), Impacts of Increasing Aridity and Wildfires on Aerosol Loading in the Intermountain Western U.S., *Environmental Research Letters*, *12*(1), 1748-9318, 10.1088/1748-9326/aa510a.

4 **Hand, J. L.**, Gill, T. E., and **Schichtel, B. A.** (2017), Spatial and Seasonal Variability in Fine Mineral Dust and Coarse Aerosol Mass at Remote Sites Across the United States, *Journal of Geophysical Research-Atmospheres*, *122*(5), 3080-3097, 10.1002/2016jd026290.

5 **Malm, W. C.,** Cismoski, S., **Prenni, A.,** and Peters, M. (2017a), Use of Cameras for Monitoring Visibility Impairment, *Under Review, Atmospheric Environment*.

6 **Malm, W. C., Schichtel, B. A., Hand, J. L.,** and Collett Jr., J. L. (2017b), Concurrent Temporal and Spatial Trends in Sulfate and Organic Mass Concentrations Measured in the IMPROVE Monitoring Program, *Journal of Geophyical Research*, 10.1002/2017JD026865.

7 Mouteva, G., Randerson, J., Fahrni, S., Bush, S., Ehleringer, J., Xu, X., Santos, G., Kuprov, R., **Schichtel, B. A.**, and Czimczik, C. (2017), Using radiocarbon to constrain black and organic carbon aerosol sources in Salt Lake City, *accepted by Journal of Geophysical Research-Atmospheres*.

8 Reid, J. S., Kuehen, R. E., Holz, R. E., Eloranta, E. W., Kaku, K. C., Newchurch, M. J., Thompson, A. M., Trepte, C. R., Zhang, J., Atwood, S. A., **Hand, J. L.**, Holben, B. N., Minnis, P., and Posselt, D. J. (2017), Ground-based High Resolution Lidar Observations of Aerosol Vertical Distribution in the Summertime Southeast United States, *Journal of Geophysical Research Atmospheres*, *122*(5), 2970-3004, doi: 10.1002/2016JD025798.

9 **Schichtel, B. A., Hand, J. L., Barna, M. G., Gebhart, K. A., Copeland, S.**, Vimont, J., and **Malm, W. C.** (2017), Origin of Fine Particulate Carbon in the Rural United States, *Environmental Science & Technology*, *51*(17), 9846–9855, 10.1021/acs.est.7b00645.

10 Webb, N. P., Van Zee, J. W., Karl, J. W., Herrick, J. E., Courtright, E. M., Billings, B. J., Boyd, R., Chappell, A., Duniway, M. C., Derner, J. D., **Hand, J. L.**, Kachergis, E., McCord, S. E., Newingham, B. A., Pierson, F. B., Steiner, J. L., Tatarko, J., Tedela, N. H., Toledo, D., and Van Pelt, R. S. (2017), Enhancing Wind Erosion Monitoring and Assessment for U.S. Rangelands, *Rangelands*, *39*(3-4), 85-96, 10.1016/j.rala.2017.04.001.

1.2 Nitrogen Deposition

1 Benedict, K. B., **Prenni, A. J.**, Carrico, C. M., Sullivan, A. P., **Schichtel, B. A.**, and Collett, J. L. (2017), Enhanced Concentrations of Reactive Nitrogen Species in Wildfire Smoke, *Atmospheric Environment*, *148*, 8-15, 10.1016/j.atmosenv.2016.10.030.

2 Isil, S., Lavery, T. F., **Gebhart, K. A.**, Rogers, C. F., and Wanta, C. (2017), Magnitude and Trends of High-elevation Cloud Water Pollutant Concentrations and Modeled Deposition Fluxes, *Journal of Environmental Sciences and Engineering*, *B6*, 127-143, 10.17265/2162-5263/2017.03.003.

3 Li, Y., **Thompson, T. M.**, Van Damme, M., Chen, X., Benedict, K. B., Shao, Y. X., Day, D., Boris, A., Sullivan, A. P., Ham, J., Whitburn, S., Clarisse, L., Coheur, P. F., and Collett, J. L. (2017), Temporal and Spatial Variability of Ammonia in Urban and Agricultural Regions of Northern Colorado, United States, *Atmospheric Chemistry and Physics*, *17*(10), 6197-6213, 10.5194/acp-17-6197-2017.

1.3 Oil and Gas Development

1 Evanoski-Cole, A. R**., Gebhart, K. A.**, Sive, B. C., Zhou, Y., Capps, S. L., **Day, D. E**., Prenni, A. J., Schurman, M. I., Sullivan, A. P., Li, Y., **Hand, J. L.**, **Schichtel, B. A.**, and Collett, J. L., Jr. (2017), Composition and Sources of Winter Haze in the Bakken Oil and Gas Extraction Region, *Atmospheric Environment*, *156*, 77-87, 10.1016/j.atmosenv.2017.02.019.

2 **Gebhart, K. A.**, **Day, D. E.**, **Prenni, A. J.**, **Schichtel, B. A.**, **Hand, J. L.**, Evanoski-Cole, A. R. (2017), Visibility Impacts at Class I Areas near the Bakken Oil and Gas Development, *Under Review, Journal of the Air & Waste Management Association.*

3 **Thompson, T. M.**, Shepherd, D., Stacy, A., **Barna, M. G.**, and **Schichtel, B. A.** (2017), Modeling to Evaluate Contribution of Oil and Gas Emissions to Air Pollution, *Journal of the Air & Waste Management Association*, *67*(4), 445-461, 10.1080/10962247.2016.1251508.

1.4 Supported by the IMPROVE Monitoring Program: Provided comments and discussion

1 Spada, N. J., and Hyslop, N. (2017), Comparison of Elemental and Organic Carbon Measurements between IMPROVE and CSN Before and After Method Transitions, *submitted to Atmospheric Environment.*

2 Weakley, A. T., Takahama, S., Wexler, A. S., and Dillner, A. M. (2017), Ambient Aerosol Composition by Infrared Spectroscopy and Partial Least Squares in the Chemical Speciation

Network: Multilevel Modeling for Elemental Carbon, *submitted to Aerosol Science and Technology*.

3 Yatkin, S., Trzepla, K., White, W. H., and Hyslop, N. (2017), Generation of Multi-Elemental Reference Materials on PTFE Filters Mimicking Ambient Aerosol Characteristics, *submitted to Atmospheric Environment.*

1.5 Other: Provided support, comments, and discussion

1 Pourhashem, G., Rasool, Q. Z., **Zhang, R.**, Cohan, D. S., Medlock, K., and Masiello, C. (2017), Valuing the air quality effects of biochar reductions on soil NO emissions, *Environmental Science & Technology*, 10.1021/acs.est.7b00748.

2 **Thompson, T. M.**, Rausch, S., Saari, R. K., and Selin, N. E. (2016), Air Quality Co-Benefits of Subnational Carbon Policies, *Journal of the Air & Waste Management Association*, *66*(10), 988-1002, 10.1080/10962247.2016.1192071.

3 **Zhang, R.**, Cohan, A., Cohan, D. S., and Pour-Biazar, A. (2017), Source apportionment of biogenic contributions to ozone formation over the United States, *Atmospheric Environment*, 164, 8-19.

4 **Zhang, R.**, White., A., Biazar, A. P., McNider, R. T., and Cohan, D. S. (2017), Incorporating GOES Satellite Photosynthetically Active Radiation (PAR) Retrievals to Improve Biogenic Emission Estimates in Texas, *submitted to Journal of Geophysical Research-Atmosphere*.

2**. Presentations/Proceedings**

2.1 Aerosol Research

1 Cismoski, D. S., **Malm, W. C.**, and **Schichtel, B. A.** (2016), Using Dark Sky Images Captured with a Standard Digital Camera to Quantify Visual Air Quality and the Night Sky Viewing Experience at Bryce Canyon National Park, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, Wyoming, September 27-30.

2 **Copeland, S. A.**, Gantt, B., Frank, N., Beaver, M., **Schichtel, B. A.**, and Vimont, J. (2016), Comparison of Tracking Progress Metrics under the Regional Haze Rule using Default and Impairment Based Approach, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

3 **Day, D. E.** (2016), IMPROVE Network QA/QC Field Audits, presentation, IMPROVE Steering Committee Meeting, Santa Fe National Forest Headquarters, Santa Fe, NM, November 1-2.

4 **Gebhart, K. A., Hand, J. L.**, White, W. H., Hyslop, N. P., **Schichtel, B. A.**, and Gill, T. E. (2016), Back Trajectory and Meteorological Factors in Spring Dust Trends in the Southwestern U.S., presented at Air & Waste Management Association Conference:

Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

5 **Gebhart, K. A., Hand, J. L.**, White, W. H., Hyslop, N. P., **Schichtel, B. A.**, and Gill, T. E. (2016), Meteorological Factors in Spring Dust Trends in the Southwestern U.S., National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

6 **Hand, J. L., Prenni, A. J., Schichtel, B. A., Malm, W. C.**, White, W. H., Ridley, D. A., and Heald, C. L. (2016), Temporal Trends in the Difference Between Gravimetric and Reconstructed Fine Mass at Rural and Urban Sites across the United States, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

7 **Hand, J. L., Schichtel, B. A., Gebhart, K. A.**, White, W. H., Hyslop, N. P., and Gill, T. E. (2016), Springtime Trends in Fine Mineral Dust in the Western United States, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance. Panel on Evolving Issues in Air Quality Related to a Changing Climate, Jackson Hole, WY, September 27-30.

8 **Hand, J. L., Schichtel, B. A.**, White, W. H., and Hyslop, N. P. (2016), Spatial and Seasonal Patterns in Mineral Dust Concentrations at Remote Sites Across the United States, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

9 **Hand, J. L., Prenni, A. J., Schichtel, B. A., and Malm, W. C.** (2016), Reconstructed Fine Mass Trends, IMPROVE Steering Committee Meeting, Santa Fe, NM, November 1-2.

10 **Hand, J. L., Schichtel, B. A.,** White, W. H., Hyslop, N. P., and Gill, T. E. (2016), Early Onset of the Spring Fine Dust Season in the Southwestern United States, National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

11 **Hand, J. L.,** White, W. H., Hyslop, N. P., **Schichtel, B. A.,** and Gill, T. E. (2016), The Spatial and Seasonal Variability in Fine Mineral Dust and Coarse Mass Concentrations at Remote Sites Across the United States, American Geophysical Union Fall Meeting, San Francisco, CA, December 12-16.

12 **Hand, J. L.,** Farber, R., **Schichtel, B. A.,** Morris, R., Pella, T., and Wierman, S. (2017), Issues and Topics in Visibility Panel, Air & Waste Management Association Annual Meeting, Pittsburgh, PA, June 5-8.

13 **Malm, W. C.**, Cismoski, D. S., Ransmeier, M., and **Schichtel, B. A.** (2016), The Application of a Fast Fourier Transform Index to Webcam Images for Quantitative Characterization of Haze, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

14 **Malm, W. C., Hand, J. L., and Schichtel, B. A.** (2016), Estimating Temporal Trends in Biogenically Formed Secondary Organic Aerosols Resulting From Reduction in Atmospheric Aerosol Water Content Across the Continental United States, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

15 **Malm, W. C., and Schichtel, B. A.** (2016), A Review of Seven Visibility Preference Studies as They Relate to Various Visibility Metrics, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

16 **Malm, W. C., Schichtel, B. A., and Hand, J. L.** (2016), Estimating Temporal Trends in Biogenically Formed Secondary Organic Aerosols Resulting From Reduction in Atmospheric Aerosol Water Content Across the Continental United States, National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

17 **Prenni, A. J., Hand, J. L., Malm, W. C., and Schichtel, B. A.** (2016), An Examination of the Current IMPROVE Algorithm, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

18 **Prenni, A. J., Hand, J. L., Malm, W. C., and Schichtel, B. A.** (2016), An Examination of the Current IMPROVE Algorithm, IMPROVE Steering Committee Meeting, Santa Fe, NM, November 1-2.

19 **Schichtel, B. A., Copeland, S. A.**, Frank, N. H., **Gebhart, K. A., Malm, W. C.**, Moore, T., and Vimont, J. (2016), The Dependence of the Distribution in Natural Haze on Haze Levels and the Contributions from Anthropogenic Sources, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

20 **Schichtel, B. A., Malm, W. C., Schmidt, D., and Hand, J. L.** (2016), Reconciliation of Urban Visibility Preference Studies: Implications for an Urban Visibility Standard, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

21 **Schichtel, B. A.** (2016), IMPROVE Research/Reporting Priorities, IMPROVE Steering Committee Meeting, Santa Fe, NM, November 1-2.

22 **Schichtel, B. A.,** Vimont, J., and **Copeland, S.,** Tracking Progress towards Natural Visibility on the Most Anthropogenically Impaired Days, Air & Waste Management Association Annual Meeting, Pittsburgh, PA, June 5-8, 2017.

23 **Schichtel, B. A.,** Vimont, J., and **Copeland, S.,** Tracking progress towards natural conditions: Current haziest days vs proposed most anthropogenically impaired days, 4th Biannual Western Modeling Workshop, NCAR Center Green Conference Center, Boulder, CO, September 6-8, 2017.

24 **Schmidt, D.**, Schreiner, F., Molenar, J., Miner, W., Cismoski, S., Tigges, M., and Adloch, J. (2016), WinHaze Updates, IMPROVE Steering Committee Meeting, Santa Fe, NM, November 1-2.

25 White, W. H., Trzepla, K., Hyslop, N. P., **Hand, J. L., and Schichtel, B. A.** (2016), A Decade of Backscatter-Corrected Transmittance Measurements by the IMPROVE Network, presented at Air and Waste Management Association International Specialty Conference on Atmospheric Optics: Aerosols, Visibility and the Radiative Balance, Jackson Hole, WY, September 27-30.

2.2 Nitrogen Deposition

1 Benedict, K. B., Shao, Y., Sullivan, A. P., Li, Y., Bangs, E., **Schichtel, B. A.**, and Collett, J. L., Jr. (2016), Atmospheric Reactive Nitrogen in Northern Colorado, presented at National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

2 **Barna, M.G.,** Moore, C.T., **Zhang, R., Thompson, T.M.** (2017), Modeling Reactive Nitrogen in the Western US, presented at the Western Modeling Workshop, September 6-8, 2017, Boulder, CO.

3 **Gebhart, K. A.**, Cheatham, J., Morris, K., and Vimont, J. (2016), Twist on a Back Trajectory Technique to Examine Wet Deposition Events, presented at National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

4 **Gebhart, K. A.**, Cheatham, J., Morris, K., and Vimont, J. (2016), Back Trajectory Insights on Sources of Nitrogen at Rocky Mountain National Park, CO, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

5 **Prenni, A. J.**, Benedict, K. B., Carrico, C. M., Sullivan, A. P., Collett, J. L., Jr., and **Schichtel, B. A.** (2016), Enhanced Concentrations of Reactive Nitrogen Species During the Hewlett Gulch and High Park Fires in Colorado presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

6 **Schichtel, B. A.,** Benedict, K. B., **Prenni, A. J., Thompson, T. M., Zhang, R.,** and Collett, J. L. (2016), Recent Ammonia Research Activities and Results in the Rocky Mountais, National Atmospheric Deposition Program Annual Meeting and Scientific Symposium – Total Depositon Science Committee, Santa Fe, NM, October 31-November 4, 2016.

7 **Schichtel, B. A.,** Benedict, K. B., **Prenni, A.J., Thompson, T. M.,** and Collett, J. L. (2016), Origin of Reactive Nitrogen Deposition in Rocky Mountain NP, Presented at the RMNP Agriculture Subcommittee Quarterly Meeting, Denver, CO, November 18, 2016.

8 **Schichtel, B. A.,** Morris, K., Wetherbee, G., and Larson, B. (2017), Recent Ammonia Research Activities and Results in the Rocky Mountais, Exploration of Biases in Annual N Wet Dep. Estimates and If We Can Do Better. Presentation at the NADP Total Depositon Science Committee Meeting, Louisville, Kentucky, April 24, 2017.

9 **Schichtel, B. A., Zhang, R., Barna, M. G., Gebhart, K. A., and Thompson, T. M.,** Source Regions Contributing to Excess Reactive Nitrogen Deposition in the Greater Yellowstone Area, Air & Waste Management Association Annual Meeting, Pittsburgh, PA, June 5-8, 2017.

10 **Thompson, T. M., Barna, M. G.**, Moore, T., and **Schichtel, B. A.** (2016), Sensitivity of Modeled Source Apportionment of Agricultural Ammonia to Bi-Directional Flux, presented

at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

11 **Thompson, T.M., Barna, M. G.,** Moore, C.T., **Schichtel, B.A.** (2016), Modeled Source Apportionment of Reactive Nitrogen in the Greater Yellowstone Area, presented at the Community Modeling and Analysis (CMAS) Annual Conference, Oct. 24-26, 2016, Chapel Hill, NC.

12 **Zhang, R., Barna, M. G., Thompson, T. M., and Schichtel, B. A.** (2017), Source Apportionment of Reactive Nitrogen Deposition in the Greater Yellowstone Area using CAMx-PSAT, presented at Community Modeling and Analysis System (CMAS) 16th Annual Conference, Chapel Hill, NC, October 23-25.

2.3 Oil and Gas Development

1 **Barna, M. G.**, **Thompson, T. M.**, Moore, T., McDonnell, T. C., and Sullivan, T. (2016), Simulating the Contribution of Emissions from Oil and Gas Development to Regional Nitrogen Deposition at National Parks within the Intermountain West, presented at International Global Atmospheric Chemistry (IGAC) Science Conference, Breckenridge, CO, September 26-30.

2 **Barna, M. G.,** Moore, C. T., McDonnell, T. C., and Sullivan., T. J., and **Thompson, T. M.,** (2016), Source Apportionment modeling with CAMx to Evaulate Impacts from Oil and Gas Development, presented at Community Modeling and Analysis System (CMAS) 15th Annual Conference, Chapel Hill, NC, October 24.

3 **Barna, M.G**., Moore, C. T., McDonnell, T. C., Sullivan, T.J., and **Thompson, T.M.** (2017), Simulating the Contribution of Emissions from Oil and Gas Development to Regional Nitrogen Deposition at National Parks within the Intermountain West, presented at the AWMA-RMSS 2017 Air Quality Conference, April 13, 2017, Denver, CO.

4 **Evanoski-Cole, A. R.,** Schurman, M. I., **Day, D. E., Gebhart, K. A.**, Sive, B. C., Zhou, Y., Sullivan, A. P., **Prenni, A. J.**, Li, Y., **Hand, J. L., Schichtel, B. A.,** and Collett, J. L., Jr. (2017), Characteristics and Sources of Organic Aerosol Near Oil and Natural Gas Drilling Operations, 19th Conference on Atmospheric Chemisty, American Meteorological Society, Seattle, WA, January 22-26.

5 Evanoski-Cole, A., **Gebhart, K. A.,** Sive, B., Zhou, Y., Capps, S. L., Day, D. E., **Prenni, A. J.,** Schurman, M., Sullivan, A. P., Li, Y., **Hand, J. L., Schichtel, B. A.,** and Collett, J. L., Jr. (2017), Characteristics, Sources, and Formation of Atmospheric Aerosol in the Bakken Oil and Gas Extraction Region, presented at American Chemical Society National Meeting, San Francisco, CA, April 2-6.

6 **Gebhart, K. A., Prenni, A. J., Schichtel, B. A., Day, D. E., Hand, J. L., Malm, W. C.,** and Evanoski-Cole, A. R. (2017), Impacts of the Bakken Oil and Gas Fields on Regional Fine Particle Concentrations, Air & Waste Management Association Annual Meeting, Pittsburgh, PA, June 5-8.

7 **Prenni, A. J.**, Sive, B., **Gebhart, K. A.**, **Schichtel, B. A., Day, D. E.**, Evanoski-Cole, A., Hecobian, A., Zhou, Y., **Hand, J. L.**, Sullivan, A., Li, Y., Schurman, M., Desyaterik, Y., **Malm, W. C.**, and Collett, J. L., Jr. (2016), An Overview of the Bakken Air Quality Study, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

8 **Prenni, A. J., Day, D. E.,** Evanoski-Cole, A. R., Sive, B. C., Hecobian, A., Zhou, Y., **Gebhart, K. A., Hand, J. L.,** Sullivan, A. P., **Malm, W. C.,** Collett, J. L., Jr., **and Schichtel, B. A.** (2017), An Overview of the Bakken Air Quality Study, 19th Conference on Atmospheric Chemistry, American Meteorological Society, Seattle, WA, January 22-26.

9 Sive, B. C., Zhou, Y., Evanoski-Cole, A., Benedict, K. B**., Prenni, A. J., Thompson, T. M., Day, D. E.,** Fischer, E., Callahan, S., Cheatham, J., **Schichtel, B. A.,** Apel, E., Hornbrook, R., Sullivan, A., Vimont, J., and Collett, J. L., Jr. (2017), Impacts of Oil and Natural Gas Operations and Urban Emissions on Air Quality in Rocky Mountain National Park during FRAPPÉ, 2017 Research Conference Rocky Mountain National Park, Estes Park, Colorado, March 1-2.

10 **Thompson, T. M., Barna, M. G.**, Moore, T., and **Schichtel, B. A.** (2016), Modeled Representation of Visibility Impacts due to Emissions Associated with Oil and Gas, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.

2.4 Supported by the IMPROVE Monitoring Program: Provided comments and discussion

1. Bein, K. J., Spada, N. J., McDade, C. E., and White, W. H. (2016), Optical Characterization of Filtered Aerosols Using Broad-band Illumination: An Enhanced Measurement System for the IMPROVE Air Quality Network, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.
2. Collett, J. L., Jr., Wentworth, G. R., Murphy, J. G., Benedict, K. B., and Bangs, E. (2016), Deposition and Re-emission of Ammonia by Dew, presented at National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.
3. Dillner, A. M., Kamruzzaman, M., and Takahama, S. (2016), Organic Functional Group and OM/OC Measurements at Select IMPROVE Sites using Infrared Spectra: Organosulfates and Amines, presented at National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.
4. Dillner, A. M., Kamruzzaman, M., and Takahama, S. (2016), Organic Functional Group and OM/OC Measurements at Select IMPROVE Sites using Infrared Spectra: Organosulfates and Amines, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.
5. Dillner, A. M., Weakley, A. T., Ruggeri, G., Reggente, M., and Takahahi, S. (2016), A Non-Destructive, Inexpensive Method for Predicting TOR OC and EC in the IMPROVE and CSN

Networks using Infrared Spectra, presented at National Atmospheric Deposition Program Annual Meeting and Scientific Symposium, Santa Fe, NM, October 31-November 4.

6. Dillner, A. M., Weakley, A. T., Ruggeri, G., Reggente, M., and Takahama, S. (2016), A Non-Destructive, Inexpensive Method for Predicting TOR OC and EC in the IMPROVE and CSN Networks using Infrared Spectra, presented at Air & Waste Management Association Conference: Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance, Jackson Hole, WY, September 27-30.
7. Spada, N., Yatkin, S., Trzepla, K., Hyslop, N., and Czyzycki, M. (2017), Comparison of Synchrotron-Induced X-ray Fluorescence with ED-XRF on the Elemental Analysis of Air Pollution Samples, presented at Denver X-Ray Conference, Big Sky, MT, July 21-August 4.
8. Takahama, S., Reggente, M., Ruggeri, G., Kuzmiakova, A., and Dillner, A. M. (2016), Fourier Transform Infrared Spectroscopy (FT-IR) Applied to Analysis of Organic Functional Groups, presented at TECH-AIR 2016 - Application of Non-Conventional Analytical TECHniques to Atmospheric PartIculate MatteR, Lecce, Italy, November 7.
9. Takahama, S., Reggente, M., Ruggeri, G., Weakley, A. T., and Dillner, A. M. (2017), Quantitative Feature Extraction for Calibration of Aerosol FT-IR Spectra, presented at European Aerosol Conference, Zurich, Switzerland, August 27-September 1.
10. Weakley, A. T., Takahama, S., and Dillner, A. M. (2016), Organic and Elemental Carbon in the Chemical Speciation Network determined by Fourier-Transform Infrared Spectrometry: Importance of Spectra Pretreatment on Partial Least Squares Factor Interpretation, presented at Annual Conference of the American Association of Aerosol Research (AAAR), Portland, OR, October 16-21.
11. Yatkin, S., Trzepla, K., Celo, V., White, W., Hyslop, N., and Dabek-Zlotorzynska, E. (2017), Interlaboratory Comparison of Reference Materials and Air Sample Analyzed by XRF and ICP-MS, presented at Denver X-Ray Conference, Big Sky, MT, July 31-August 4.

3. Service (Science Committees, Editorial Boards, etc.)

1. Air and Waste Management Association (A&WMA) Publications Committee [Schichtel]
2. Technical Program Planning Committee, International Specialty Conference of the (A&WMA) " Atmospheric Optics: Aerosols, Visibility, and the Radiative Balance," Jackson Hole, WY, September 2016 [Schichtel, Hand, Malm]
3. A&WMA Visibility Technical Coordinating Committee [Schichtel, Hand, Gebhart, Malm]
4. A&WMA Visibility Technical Coordinating Committee, Chair [Hand]
5. Guest Editor for Journal of Air and Waste Management Association Visibility Specialty Conference Issue [Hand]
6. A&WMA Particulate Matter Technical Coordinating Committee [Schichtel, Hand, Gebhart, Malm]
7. National Atmospheric Deposition Program (NADP): Total Deposition Science Committee (TDEP) [Schichtel]
8. IMPROVE Steering Committee [Schichtel]
9. IMPROVE Steering Committee Chair [Copeland]
10. Affiliate Colorado State University faculty member [Schichtel]

11. Journal of A&WMA editorial review board and publication committee [Schichtel]
12. Aerosol and Air Quality Research editorial review board [Schichtel]
13. Scientific World Journal [Schichtel]
14. WRAP Regional Technical Operations Work Group Co-chair [Barna]
15. Organizing committee for the Western Modeling Workshop, September 6-8, 2017, Boulder, CO [Barna]
16. Intermountain West Data Warehouse-Western Air Quality (IWDW-WAQS) Technical Committee [Barna]
17. NADP-TDEP Committee [Schichtel?, Barna]
18. Air Quality Oil and Gas MOU Technical Team [Barna]