CLEAN AIR STATUS AND TRENDS NETWORK (CASTNET)

PROGRAM OVERVIEW

CASTNET is a long-term atmospheric monitoring program with 99 sites located throughout the United States and Canada. CASTNET is managed and operated by the U.S. Environmental Protection Agency (EPA) Office of Atmospheric Programs in cooperation with the National Park Service (NPS) Air Resources Division; Bureau of Land Management, Wyoming State Office (BLM); and other federal, state, and local partners including seven Native American tribes. The network was established in response to the 1990 Clean Air Act Amendments to **assess the effectiveness of emission reduction programs** by reporting trends in pollutant concentrations and acidic deposition. Data from CASTNET also **support the assessment of the primary and secondary National Ambient Air Quality Standards (NAAQS)** for ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and fine particulate matter ($PM_{2.5}$). Additionally, CASTNET data are used for **assessing air pollution impacts to sensitive ecosystems and applications related to environmental assessments and permitting.**

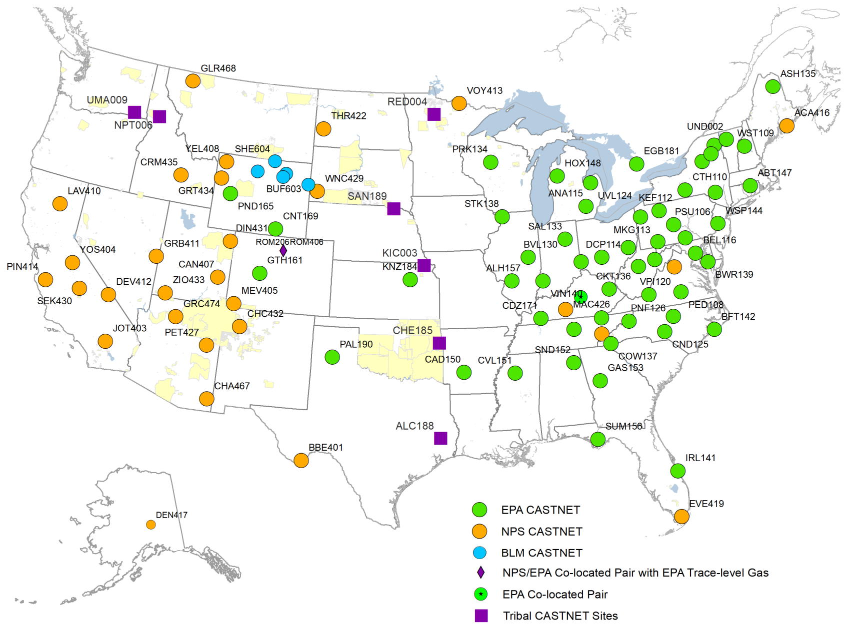

Figure 1 Current CASTNET site locations (December 2020). Co-located sites are operated by EPA and NPS at Rocky Mountain National Park, CO to evaluate network precision across the federal partners. Additionally, EPA operates a co-located site in Mackville, KY to assess overall network precision of the ozone and filter pack measurements. Tribal boundaries are shown on the map in yellow.

MEASUREMENTS

CASTNET sites measure weekly ambient concentrations of sulfur and nitrogen species as well as hourly O_3 concentrations (Table 1). Long-term measurements from CASTNET are an important tool for assessing trends in air quality in response to regulatory actions (e.g., Acid Rain Program, Cross-State Air Pollution Rule) and climate change.

Ozone can reduce lung function and increase respiratory symptoms leading to increased infections, hospital visits, and death. CASTNET O_3 data are reported to AirNow in near-real time, allowing the public to easily make decisions about risks associated with performing outdoor activities during periods of poor air quality. CASTNET monitors continuous O_3 concentrations with a UV monitor designated as a federal equivalency monitor. Data are used to support regulatory NAAQS assessments, modeling related to background levels, and regional transport. Ground-level O_3 data provided by CASTNET fill in spatial gaps in the State, Local, Tribal monitoring network (SLAMS). CASTNET data uniquely provide air quality information for rural and tribal communities, Class I areas, and National Parks. States utilize available monitoring data to determine if an area is in attainment (below or at the level of the NAAQS) or out of attainment (exceeds the NAAQS). CASTNET data validation, quality assurance (QA), and reporting procedures meet or exceed the requirements found in 40 CFR Parts 50 and 58.

Recognizing the increasing importance of reduced nitrogen species (ammonia [NH_3] + ammonium [NH_4]) on fine particle (PM) formation and nitrogen deposition, CASTNET also participates in the NADP's Ammonia Monitoring Network (NADP/AMoN). AMoN, established in 2007, is the only U.S. long-term monitoring network measuring ambient NH_3. CASTNET is co-located with AMoN at 70 sites, providing a more complete nitrogen budget. Results from the Community Multi-Scale Air Quality (CMAQ) model estimated that the addition of NH_3 at CASTNET sites improved the total nitrogen budget by 10 to 40 percent (Butler et al., 2016).

CASTNET is the only network in the United States that provides a consistent, long-term data record of acidic dry deposition. The National Atmospheric Deposition Program (NADP) was established in 1978 to measure acidic compounds in precipitation (acid rain). Most CASTNET sites are co-located with NADP's wet deposition network (NTN).

Weekly ambient concentrations of gases and particles are collected with an open-face 3-stage filter pack. Fine particle precursors (nitric acid [HNO_3] and SO_2) as well as coarse and fine PM are measured. The ambient concentrations are also used to report dry deposition fluxes. Deposition of sulfur and nitrogen to terrestrial and aquatic ecosystems can lead to acidification and eutrophication, causing a loss of species biodiversity and/or reduction in ecosystem health.

Dry deposition *is the fraction of atmospheric pollution that is deposited to the earth's surface by settling, impaction, or adsorption. Dry deposition is estimated using measured atmospheric concentrations from CASTNET with modeled deposition velocity (i.e., the rate at which the gases and particles are deposited to the surface).*

Wet deposition *is the fraction of atmospheric pollution deposited to the earth's surface by precipitation, predominantly as rain, snow, or cloud droplets. Wet deposition is measured by the NADP National Trends Network (NADP/NTN; Table 1). Measured pollutant concentrations in precipitation are combined with precipitation amounts.*

Total Deposition *is the sum of wet and dry deposition. Total deposition represents the amount of pollutants being deposited to the earth's surface.*

Network	Measurement Method	Pollutant(s)/Analyte(s)	Number of Sites	Length of Record (years)
CASTNET	Weekly filter pack	Particles (SO_4^{2-}, NH_4^+, NO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-); Gases (SO_2, HNO_3)	94	34
	Continuous UV analyzer	O_3	86	34*
	Continuous pulse florescence analyzer	SO_2	3	varies
	Continuous chemiluminescence analyzer	NO/NO_y	8	varies
	Continuous chemiluminescence analyzer	NO/NO_x	1	2
	Continuous gas filter correlation analyzer	CO	3	varies
NADP/NTN	Weekly precipitation collector + rain gage	SO_4^{2-}, NH_4^+, NO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, pH, precipitation amount	258	43
NADP/AMoN	Bi-weekly passive sampler	NH_3	101	14

Table 1 Summary of ambient concentration and deposition measurements. In 2011, all EPA-sponsored CASTNET sites upgraded the ozone systems to become regulatory compliant.

BUILDING TRIBAL MONITORING CAPACITY

In 2002, EPA worked with the Cherokee Nation to establish the first CASTNET tribal site at their Stilwell, OK monitoring station. Over the past 19 years, EPA has partnered with seven Native American tribes to establish monitoring sites on tribal lands. The CASTNET program installs the site, calibrates the equipment, and trains the operator – establishing a unique relationship with the tribe. Each tribal partner independently operates their site while utilizing the CASTNET equipment and established QA procedures. Most recently, CASTNET tribal sites have been small-footprint sites without a temperature-controlled shelter, making them more cost-effective and easier to maintain (Table 2).

The tribal sites operated by the Nez Perce Tribe and the Confederated Tribes of the Umatilla Indian Reservation provide spatial coverage for the network in the Pacific Northwest region, while the five additional tribal sites provide spatial coverage in the central United States.

Tribal Partner	Year Established	Site ID	Site Type
Cherokee Nation	2002	CHE185	F
Santee Sioux Nation, Nebraska	2006	SAN189	F
Alabama-Coushatta Tribe of Texas	2004	ALC188	F
Red Lake Band of Chippewa Indians, Minnesota	2014	RED004	S
Kickapoo Tribe of Indians of the Kickapoo Reservation in Kansas	2014	KIC003	S
Nez Perce Tribe	2015	NPT006	SO
Confederated Tribes of the Umatilla Indian Reservation	2020	UMA009	SO

Table 2 CASTNET tribal partners. Site type – F = full CASTNET site with temperature-controlled shelter, filter pack, and ozone; S = small footprint site with filter pack; SO = small footprint site with small enclosure for ozone analyzers.

ATMOSPHERIC CONCENTRATIONS

Ground-level O_3 concentrations are measured at 86 CASTNET sites. Ozone can cause negative health impacts, impaired visibility, and damage to vegetation. The 2015 O_3 NAAQS was set at 0.070 ppm (or 70 ppb) using the 3-year average of the fourth highest daily maximum 8-hour rolling average. Ozone is not directly emitted from sources but is formed in the atmosphere by oxides of nitrogen (NO_X) and volatile organic compounds (VOCs) in the presence of sunlight. Regulations to control NO_X emissions from the power sector and mobile sources have resulted in significant reductions in O_3 concentrations in the eastern United States (Figure 2, left). Smaller reductions in O_3 concentrations have been realized in the West (Figure 2, right) due to topography, international transport, and natural (i.e., wildfires) and anthropogenic emissions.

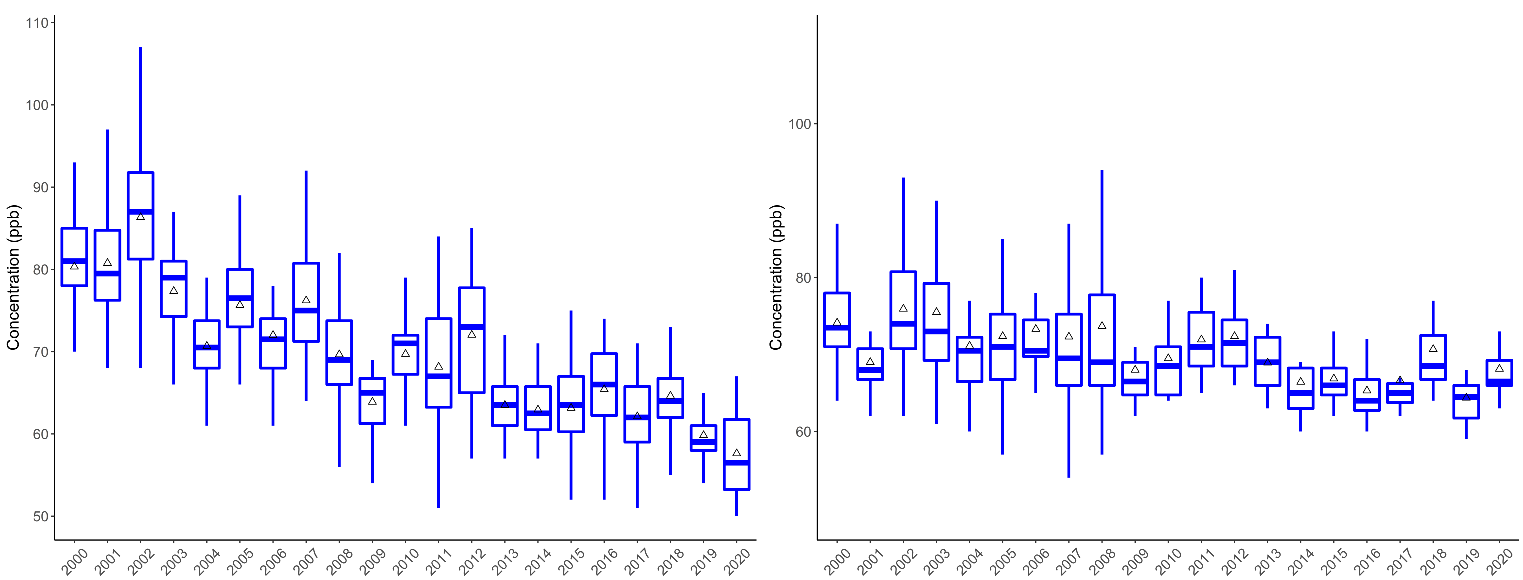

Figure 2 Trend in fourth highest daily maximum 8-hour ozone concentrations from eastern (left) and western (right) CASTNET reference sites. Boxes extend from the 25th to 75th percentiles with median line. The whiskers extend to 1.5 interquartile range and the mean is represented by a triangle.

Six CASTNET sites exceeded the 2015 O_3 NAAQS in 2020 (Table 3). For comparison, in 2000 48 sites reported concentrations greater than the 2015 NAAQS. In addition to providing data to support the NAAQS attainment designations, CASTNET data are used to identify stratospheric intrusions, background ozone, wildfire impacts, and regional transport.

Sulfur dioxide emissions from electric generating units (EGUs) have declined by 94 percent between 1990 and 2019. The trend in ambient concentrations measured by CASTNET showed similar decreases. In the East between 1990 and 2019, median SO_2 concentrations decreased 93 percent (data not shown) and median sulfate concentrations decreased 80 percent (Figure 3, left).

Site Name	State	Site ID	4th Highest 8-Hour Daily Maximum Concentration (ppb)
Sequoia & Kings Canyon National Park	CA	SEK430	91
Joshua Tree National Park	CA	JOT403	84
Yosemite National Park	CA	YOS404	84
Rocky Mountain National Park	CO	ROM406	73
Rocky Mountain National Park – co-located	CO	ROM206	73
Death Valley National Park	CA	DEV412	72

Table 3 CASTNET sites that exceeded the 2015 ozone NAAQS in 2020 (fourth highest 8-hour daily maximum concentration greater than 70 ppb)

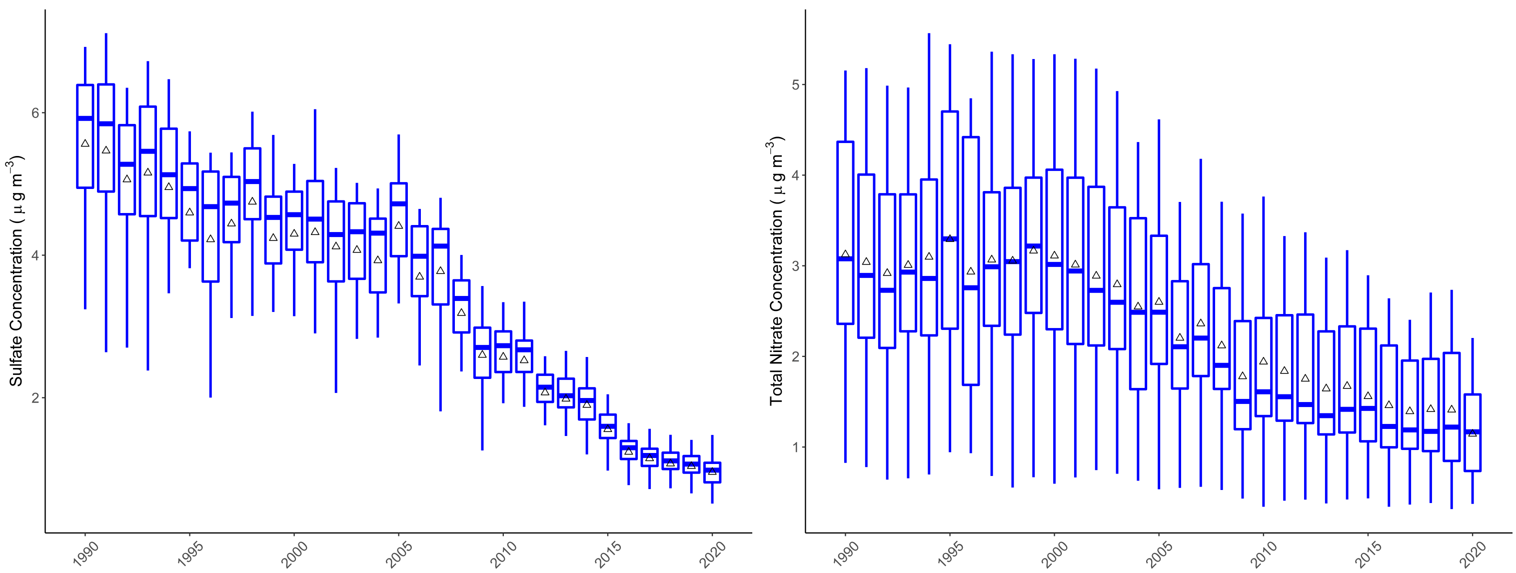

*Figure 3 Trends in ambient sulfate (left) and total nitrate (particulate nitrate + nitric acid) as measured by eastern CASTNET sites from 1990 – 2019. The boxes represent the 25th and 75th percentiles with the median line within the box. The whiskers extend to 1.5*quartile range. Triangles represent the mean concentration.*

NO_x emissions from EGUs have decreased 86 percent between 1990 and 2019. While trends in concentrations of oxidized and reduced nitrogen have declined with emissions, the atmospheric chemistry and diversity of emissions sources makes the relationship between emissions and ambient concentrations more complex. In the eastern U.S. between 1990 and 2019, total nitrate (particulate nitrate + nitric acid) decreased 57 percent (Figure 3, right) and particulate ammonium decreased 72 percent (data not shown). Unlike the downward trends in oxidized nitrogen species, AMoN data have shown a 33 percent increase in NH_3 concentrations between 2009-2011 and 2017-2019.

ATMOSPHERIC DEPOSITION

Air concentration data from CASTNET are combined with wet deposition fluxes and modeled estimates from the CMAQ chemical transport model to calculate fluxes of dry and total deposition. The measurement-model fusion process used to create the dry and total deposition fluxes are described in Schwede and Lear (2014), and gridded data and maps can be found on the NADP/TDep website. Similar to the significant reductions in air pollutant concentrations, reductions in oxidized sulfur and nitrogen deposition fluxes have been realized throughout the United States. Figure 4 shows the changes in oxidized nitrogen deposition between 2000-2002 and 2017-2019. Large reductions in stationary source emissions have resulted in significant decreases; however mobile sources continue to be a significant contributor to NO_x emissions in urban areas.

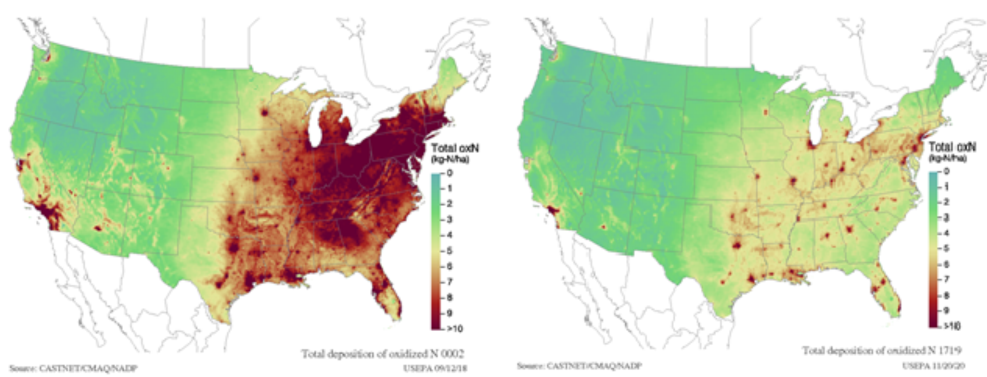

Figure 4 Total deposition of oxidized nitrogen (kg-N ha^{-1}) from 2000-2002 (left) and 2017-2019 (right)

CRITICAL LOADS

A critical load is a quantitative estimate of exposure to one or more pollutants below which significant harmful effects of specified sensitive elements of the environment do not occur according to present knowledge (Nilsson, 1988; CLRTAP, 2004). Excess nitrogen and sulfur deposition can negatively impact the biota in terrestrial and aquatic ecosystems and the services they provide. For example, excess nitrogen and sulfur deposition to a forest ecosystem can lead to decreased tree growth, increased mortality of trees, decreased survival of seedlings, and loss of biodiversity. However, the impacts vary by species and location, so critical loads are established for specific species within ecosystem boundaries (e.g., National Parks). Total deposition fluxes (Figure 4) are compared to the critical load criterion to determine exceedances (Figure 5), or areas where deposition is greater than the critical load and adverse ecological impacts are assumed to have occurred.

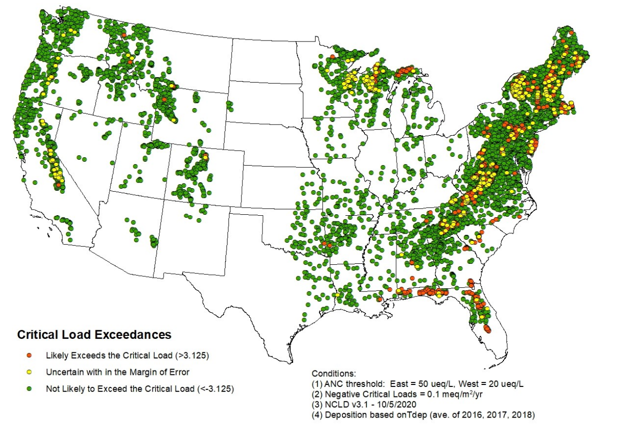

Figure 5 Map showing critical load exceedances for surface waters assuming an acid neutralizing capacity (ANC) threshold of 50 μeg L^{-1} in the eastern U.S. and 20 μeg L^{-1} in the West.

ADAPTING TO CURRENT AND FUTURE MONITORING NEEDS

While CASTNET data are primarily used to assess changes in air quality and deposition in response to emission reductions, the program also provides a platform for addressing new, policy-relevant research questions. For example, in 2020, CASTNET data were used to assess changes in O_3 concentrations resulting from dramatic NO_X emission reductions during COVID-19 stay-at-home orders. Archer et al. (2020) noted that U.S. NO_2 concentrations decreased by 24-27 percent in 2020 versus 2015-2019. CASTNET measured significant reductions in O_3 concentrations in the Northeast where the duration of stay-at-home orders were generally longer than other regions, but as noted in the literature, the relationship between NO_X and O_3 is not linear (Kroll et al., 2020). At present, wildfires in the West and lower than normal temperatures throughout most of the U.S. in the spring during the initial stay-at-home orders made it difficult to attribute widespread reductions in O_3 to COVID-19 travel restrictions. CASTNET will continue to evaluate air quality impacts from the pandemic into 2021.

CASTNET is well positioned to continue assessing air quality and deposition impacts from the power sector, and oil and gas development. Data from CASTNET are already used for model evaluations supporting emission control strategies (Rodriguez et al., 2012) and environmental impact assessments in the Intermountain West.

The network will continue to provide ambient concentrations and deposition fluxes, which can be impacted by climate change. Ozone contributes to radiative forcing and causes damage to vegetation (including forests and crops), which help remove CO_2 from the atmosphere. As climate change continues to impact air quality and managed and natural systems, reporting on the health impacts and amount of damage to these important systems will be critical for modeling current and future climate scenarios (USGCRP, 2018). CASTNET sites are in rural areas, often near agricultural activities which can be major sources of NH_3 and nitrous oxide (N_2O). Oxides of nitrogen can increase O_3 formation or increase the removal of methane, causing a warming or cooling effect, respectively (Hauglustaine et al., 2014). Further, NH_3 and NO_x play an important role in particle formation leading to a cooling effect by creating light-scattering aerosols. Air-surface exchange processes that drive deposition fluxes will continue to change with warming and extreme events. Long-term deposition measurements will be critical for understanding how modeling will need to adapt to new conditions.

The network infrastructure also allows the program to efficiently evaluate measurement technologies and provide information on emerging pollutants. To further enhance the assessment of emerging pollutants, extreme events, and changes to the energy sector, the CASTNET program is well situated to add new measurements or strategically place small-footprint monitoring sites to capture the changing environment. Assessing air impacts from pollutants such as ethylene oxide (EtO) or per- and polyfluoroalkyl substances (PFAS) at CASTNET sites could provide information on transport and background concentrations. CASTNET is already working with the EPA Office of Research and Development (ORD) to evaluate wet deposition of PFAS compounds in NADP/NTN samples at six locations. In 2020, CASTNET measured low concentrations of O_3 near the California wildfires due to poor ozone forming conditions (heavy smoke), but CASTNET does not currently measure $PM_{2.5}$. In areas heavily impacted by wildfires, additional $PM_{2.5}$ sensors would provide enhanced air quality information during the increasing number and size of wildfires. Finally, deploying measurement systems to capture VOCs and NH_3 would be beneficial to understand changes in air quality due to oil and gas development and the impacts on O_3 and PM concentrations, including the role of NH_3 on $PM_{2.5}$ formation in rural areas.

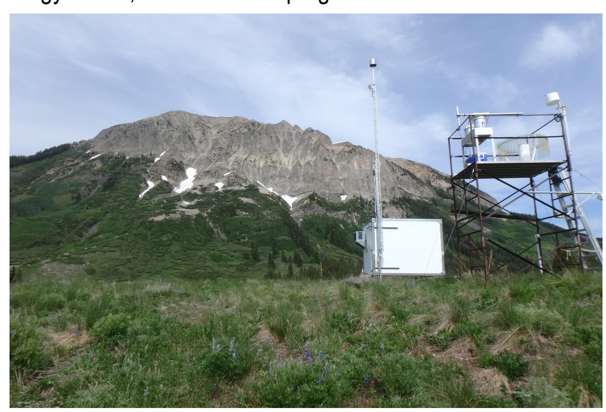

Figure 6 Monitoring site near Gothic, CO (GTH161). Photo includes the CASTNET shelter and 10m tower. On the platform there is equipment to support the NADP/ NTN site including a precipitation gage with a windshield and an NCON collector, and the NADP/AMoN shelter.

DATA AVAILABILITY

CASTNET Data: www.epa.gov/castnet
NADP Data: http://nadp.slh.wisc.edu
TDep Measurement Model Fusion: http://nadp.slh.wisc.edu/committees/tdep/
Critical Loads Mapper: https://clmapper.epa.gov
AirNow: airnow.gov

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