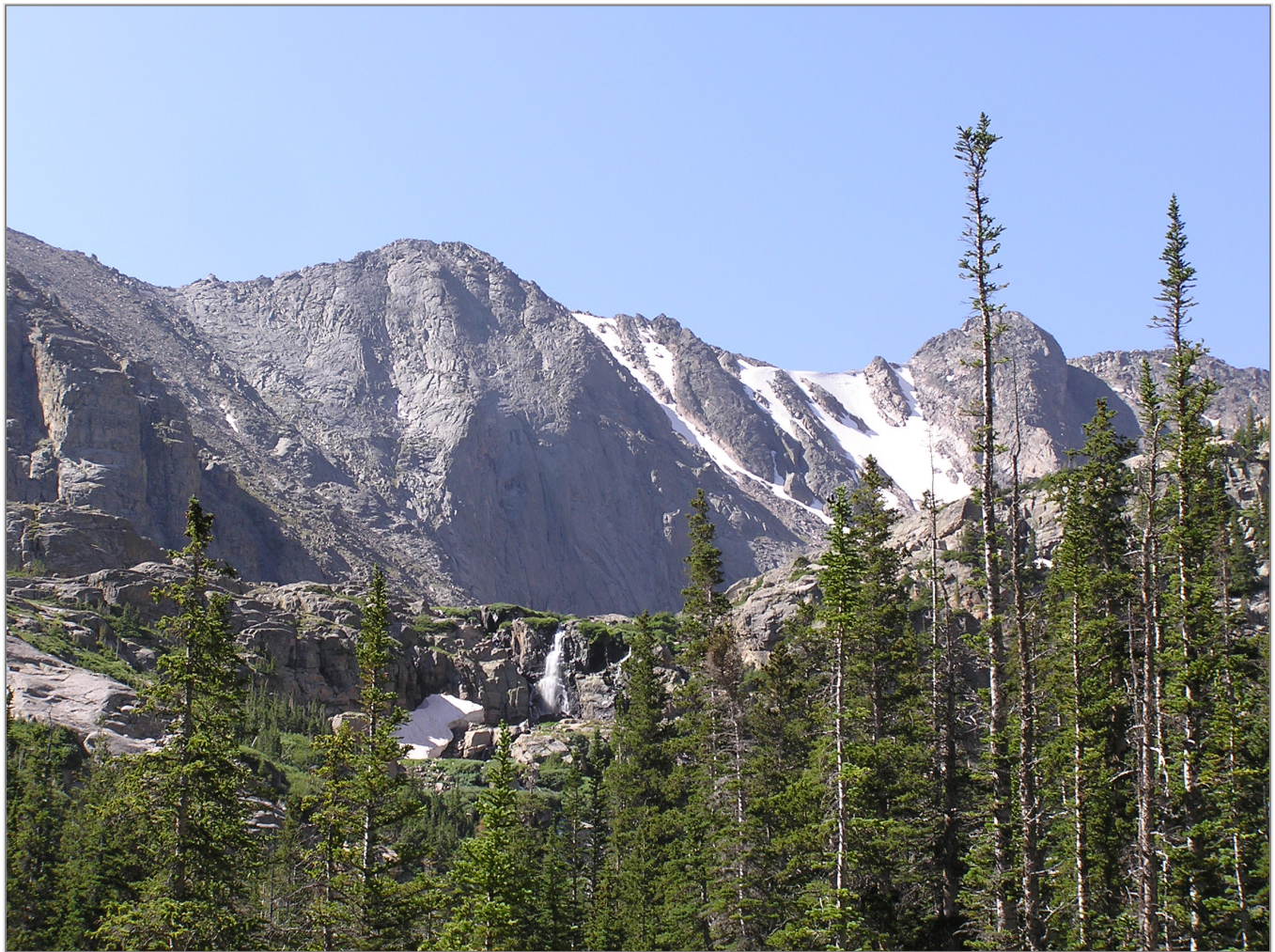




2022 Monitoring and Tracking Wet Nitrogen Deposition at Rocky Mountain National Park

May 2024



View of the waterfall from Loch Vale in Rocky Mountain National Park.

NPS / JIM CHEATHAM

2022 monitoring and tracking wet nitrogen deposition at Rocky Mountain National Park: May 2024

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Contents

	Page
Figures.....	iv
Tables	v
Appendices.....	v
Abstract.....	vi
Acknowledgments.....	vi
1.0 Background Information on the Nitrogen Deposition Reduction Plan	1
2.0 Purpose.....	3
3.0 Monitoring Wet Nitrogen Deposition	4
4.0 Monitoring Wet Nitrogen Deposition in Rocky Mountain National Park.....	5
5.0 Tracking Wet Nitrogen Deposition at Rocky Mountain National Park.....	7
6.0 Methods Updates	8
7.0 Assessment of Progress Along the Glidepath	9
8.0 Trend Analyses for Rocky Mountain National Park and Other Regional Sites	11
8.1 Long-term trends	21
8.2 Shorter-term trends.....	22
9.0. Summary of Glidepath Assessment and Trends Analysis.....	26
Literature Cited	27

Figures

	Page
Figure 1. Nitrogen Deposition Reduction Plan glidepath.	2
Figure 2. Wet nitrogen deposition and precipitation at Loch Vale in Rocky Mountain National Park compared to the Nitrogen Deposition Reduction Plan glidepath.....	10
Figure 3. Map of NADP/NTN sites in and near Rocky Mountain National Park used in trends analysis.....	12
Figure 4. Annual wet deposition, concentrations, and precipitation for RMNP – Loch Vale.	14
Figure 5. Annual wet deposition, concentrations, and precipitation for RMNP – Beaver Meadows.	15
Figure 6. Annual wet deposition, concentrations, and precipitation for RMNP – Kawwuneeche Meadow.	16
Figure 7. Annual wet deposition, concentrations, and precipitation for Niwot Saddle.....	17
Figure 8. Annual wet deposition, concentrations, and precipitation for Niwot Ridge - Southeast.	18
Figure 9. Annual wet deposition, concentrations, and precipitation for Sugarloaf.	19
Figure 10. Annual wet deposition, concentrations, and precipitation for Pawnee.	20
Figure 11. Ammonia concentrations at Rocky Mountain National Park and nearby sites.....	34
Figure 12. Ammonia concentrations at Rocky Mountain National Park sites.	35

Tables

	Page
Table 1. NADP/NTN sites in and near Rocky Mountain National Park used in trends analyses.	11
Table 2. Long-term trends in wet nitrogen deposition over the period of record (through 2022).	21
Table 3. Long-term trends in precipitation-weighted mean ammonium concentrations over the period of record (through 2022).	21
Table 4. Long-term trends in precipitation-weighted mean nitrate concentrations over the period of record (through 2022).	22
Table 5. Long-term trends of precipitation over the period of record (through 2022).	22
Table 6. Short-term trends of wet nitrogen deposition since 2006 (2006-2022) and 7-year (2016–2022) time periods.	23
Table 7. Short-term trends for precipitation-weighted mean ammonium concentrations since 2006 (2006-2022) and 7-year (2016–2022) time periods.	23
Table 8. Short-term trends for precipitation-weighted mean nitrate concentrations since 2006 (2006-2022) and 7-year (2016–2022) time periods.	24
Table 9. Short-term trends for precipitation since 2006 (2006-2022) and 7-year (2016–2022) time periods. S S	24
Table 11. Loch Vale NADP/NTN monitoring site history.	29
Table 12. Example: sample concentration and precipitation amount.	30

Appendices

	Page
Appendix A: History of the Loch Vale NADP/NTN Monitoring Site	29
Appendix B: Explanation of NADP/NTN terms and calculations	30
Appendix C: Methods of Testing Trends in NADP Precipitation Chemistry Data.....	32
Appendix D: NADP Ammonia Monitoring Network (AMoN) Data.....	34

Abstract

The Colorado Department of Public Health and Environment (CDPHE), the National Park Service (NPS), and the U.S. Environmental Protection Agency (EPA) issued the Nitrogen Deposition Reduction Plan (NDRP) in 2007 to address the impacts of nitrogen deposition at Rocky Mountain National Park (RMNP). The agencies chose a glidepath approach to reduce wet nitrogen deposition to a level of 1.5 kilograms of nitrogen per hectare per year (kg N/ha/yr), the resource management goal, by the year 2032 to protect sensitive ecosystems within RMNP. This report summarizes wet nitrogen deposition data collected in 2022 and places it in the context of measurements made since 1984. In 2022, wet nitrogen deposition (5-year average) at Loch Vale in RMNP was 2.8 ± 0.22 kg N/ha/yr, which is above the glidepath (2.2 kg N/ha/yr), but below the 2006 baseline of 3.3 kg N/ha/yr. Another goal of the NDRP is to “reverse the trend of increasing nitrogen deposition at the park” that occurred from 1984 to 2000. Trends in wet nitrogen deposition, ammonium and nitrate concentrations, and precipitation were analyzed at three sites in RMNP and four regional sites outside of the park. Wet nitrogen deposition has not decreased at any of the RMNP locations or other sites in the region over the long-term (>35 years). Moreover, wet nitrogen deposition and precipitation increased at the Beaver Meadows site in RMNP. Ammonium concentrations showed a statistically significant increase at three of four sites and nitrate concentrations showed a significant decrease at four sites over the period of record ($p\text{-value} \leq 0.05$). Since the NDRP was developed in 2006, wet nitrogen deposition showed no significant trend at sites in RMNP, but significantly decreased at one regional site, Pawnee. Concentrations of ammonium showed no trends and concentrations of nitrate significantly decreased from 2006-2022 at all four sites that met data completion criteria. Even though the trend in wet nitrogen deposition did not decrease significantly at Loch Vale since 2006, the current wet nitrogen deposition (2018-2022) of 2.8 kg/ha/yr is approximately 15% lower than the baseline average (2002-2006) of 3.3 kg/ha/yr. Wet nitrogen deposition at Loch Vale has decreased 0.5 ± 0.38 kg/ha/yr (0.13 to 0.88 kg/ha/yr) at the 95% confidence interval, suggesting some progress has been made.

Acknowledgments

The authors acknowledge Jill Baron (USGS, Colorado State University, Natural Resource Ecology Laboratory) and Jana Milford (Department of Mechanical Engineering and Environmental Engineering Program, University of Colorado, Boulder) for their careful review of the report. We also recognize the extensive research by Jill Baron in RMNP, without which, this Initiative to protect the park would not exist. Greg Wetherbee (USGS, Hydrologic Networks Branch, NADP External QA Project) has provided important counsel on equipment and collecting the highest quality data. We also thank Tim Wienmann (CDPHE, Natural Resource Ecology Laboratory), Derek Day (retired Cooperative Institute for Research on the Atmosphere), Lisa Foster Kostadinov (Renaissance Mountaineering, LLC), and many previous technicians and students for collecting samples from Loch Vale in RMNP every Tuesday through rain and snow.

1.0 Background Information on the Nitrogen Deposition Reduction Plan

In 2004, multiple agencies including the Colorado Department of Public Health and Environment (CDPHE), the National Park Service (NPS), and the U.S. Environmental Protection Agency (EPA) met to address the effects and trends of nitrogen deposition and related air quality issues at Rocky Mountain National Park (RMNP). These agencies signed a Memorandum of Understanding (MOU) to facilitate interagency coordination, calling the effort the “Rocky Mountain National Park Initiative.” After much collaboration, the MOU agencies (CDPHE, NPS, and EPA) issued the Nitrogen Deposition Reduction Plan (NDRP) in 2007, which was endorsed by the three agencies and the Colorado Air Quality Control Commission (AQCC). The NDRP and other related documents are available on the CDPHE website: <http://www.colorado.gov/cdphe/rmnpinitiative>.



High-elevation ecosystems at Rocky Mountain National Park are sensitive to atmospheric nitrogen deposition (NPS / ROCKY MOUNTAIN NATIONAL PARK).

As part of the NDRP, the MOU agencies endorsed a wet deposition level of 1.5 kilograms of nitrogen per hectare per year (kg N/ha/yr) as a science-based threshold above which adverse effects occur in sensitive ecosystems in RMNP. This threshold is based on decades of research and is the

estimated “critical load” (Baron 2006). To achieve this threshold or resource management goal, the MOU agencies have chosen a glidepath approach. This type of approach anticipates gradual improvement in conditions over time and has been used as a regulatory structure for long-term, goal-oriented air quality planning like the Regional Haze Rule (40 CFR 51.301).

The glidepath is shown in Figure 1 with the resource management goal for RMNP of 1.5 kg N/ha/yr being met over the course of 25 years in 2032. The baseline wet deposition at Loch Vale in RMNP was 3.3 kg N/ha/yr based on the 5-year average of annual data from 2002 to 2006. Milestones are assessed at 5-year intervals until the resource management goal is reached in 2032. The first interim milestone was based on a reduction of wet nitrogen deposition from baseline conditions to 2.9 kg N/ha/yr in 2012. The next interim milestone was 2.6 kg N/ha/yr for 2017. The current interim milestone is 2.2 kg N/ha/yr for 2022. The estimate for nitrogen deposition under natural pre-industrial conditions, 0.2 kg N/ha/yr is also shown on the graph (Galloway et al. 1995 and 1996; Dentener 2001).

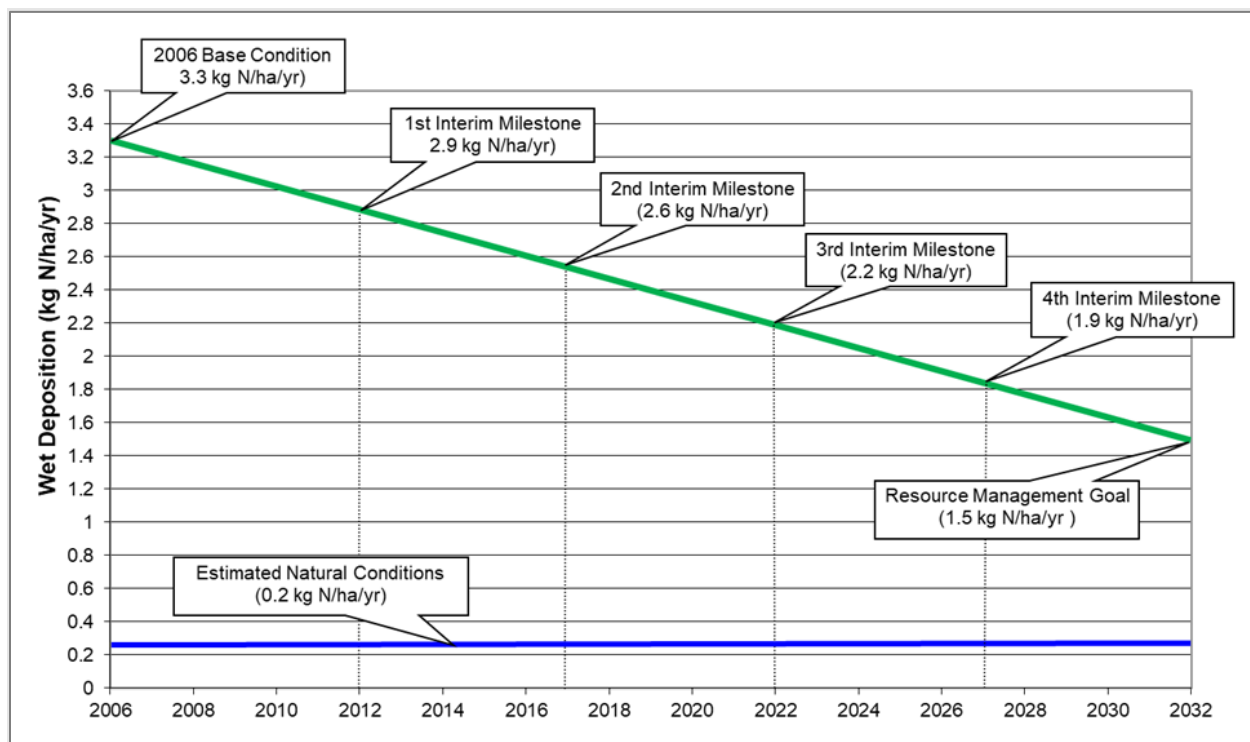


Figure 1. Nitrogen Deposition Reduction Plan glidepath.

The MOU agencies meet in the fall of each year to discuss the latest analyses. In the years following the interim milestones, the MOU agencies use a weight of evidence approach to evaluate whether current and planned emission reductions and management are sufficient to achieve project goals, and whether additional measures should be implemented. The 2022 Milestone Report is currently under development; when it is finished, it will also be available on the CDPHE website.

2.0 Purpose

The purpose of this report is to inform the MOU agencies, stakeholders, and the public about the status and trends of wet nitrogen deposition at RMNP through 2022. The MOU agencies will use the information provided in this report, in addition to other types of information as part of the “weight of evidence” to determine whether the 2022 interim milestone was achieved, and whether the Contingency Plan should be activated.

3.0 Monitoring Wet Nitrogen Deposition

The resource management goal and interim milestones identified in the NDRP are based on wet nitrogen¹ deposition from precipitation samples collected from the Loch Vale NADP site (CO98) in RMNP through the National Atmospheric Deposition Program/National Trends Network (NADP/NTN). The NADP/NTN is a nationwide precipitation chemistry monitoring network and a cooperative effort among many different groups, including the NPS, EPA, U.S. Geological Survey, U.S. Department of Agriculture-National Institute of Food and Agriculture, State Agricultural Experiment Stations, National Oceanic and Atmospheric Administration, U.S. Fish and Wildlife Service, Bureau of Land Management, universities, tribal agencies, and other governmental and private entities. The NADP/NTN began monitoring in 1978 with 22 sites and grew rapidly in the early 1980s. Much of the expansion occurred during the implementation of monitoring under the National Acid Precipitation Assessment Program. In 2022, the network had over 250 sites spanning the continental U.S., Alaska, Puerto Rico, and the U.S. Virgin Islands.

Site-specific results are highly useful for the sites and regions in which they are located, but the purpose of the network is to monitor spatial patterns for long-term trends in precipitation chemistry. Precipitation samples at each site are collected weekly and analyzed for pH and specific conductance, as well as sulfate, nitrate, ammonium, chloride, calcium, magnesium, potassium, and sodium concentrations by the NADP Analytical Laboratory located at the Wisconsin State Laboratory of Hygiene in Madison. Each monitoring site consists of a precipitation collector and a precipitation gage that records precipitation depth. Quality assurance programs (nadp.slh.wisc.edu/quality-assurance) prescribe stringent quality-control measures to monitor and enhance data accuracy and precision.

Annual data are available on the NADP website approximately 6 months after completion of the calendar year. More information on these programs and the monitoring data can be found on the NADP website at <http://nadp.slh.wisc.edu/>. NADP/NTN data are used widely in publications, including 191 peer-reviewed journal articles in 2023 (David Gay, NADP Coordinator, personal communication, 2024). These data are also used extensively by the EPA to (1) assess progress made by the Clean Air Act Acid Rain Program, which seeks to reduce the acidity of precipitation by reducing U.S. emissions of sulfur oxides (SO_x) and nitrogen oxides (NO_x) (EPA 2023); (2) assess progress under the Canada - U.S. Air Quality Agreement (ECCC 2023); and (3) assess and review the NO_x/SO_x/PM secondary standard that must be set at a level that affords protection to ecosystems from acid deposition (EPA 2020).

¹ The nitrogen measured by NADP/NTN is inorganic reactive nitrogen (from ammonium + nitrate), and all references to wet nitrogen deposition in this report refer to this portion of nitrogen deposition only.

4.0 Monitoring Wet Nitrogen Deposition in Rocky Mountain National Park

In 2022, there were three NADP/NTN sites in RMNP. The site in the Loch Vale watershed (CO98) (at an elevation of 3,159 meters) has been in operation since 1983 with the first full year of data starting in 1984. Data from Loch Vale are the primary focus of the NDRP because the resource management goal of 1.5 kg N/ha/yr wet deposition is based on NADP/NTN data from this site (<http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=CO98>). The RMNP resource management goal was set to protect the most sensitive resources in the park, which are located at the highest elevations. Routine monitoring in a remote, high-elevation area presents several challenges. The samples from Loch Vale are collected each week by a dedicated site operator who hikes or snowshoes 5 kilometers one way to the monitoring site year-round. Equipment malfunction and/or inadequate solar power supply during the harsh winter months sometimes result in missed samples. Many upgrades have been made to the site over the years to increase power production and storage and improve site communications. From 2009-2014, the MOU agencies funded a second site at Loch Vale (CO89) to evaluate overall variability in the NADP/NTN measurements. Appendix A provides a history of modifications made to the Loch Vale NADP monitoring site.



NADP Precipitation Collector at Loch Vale in RMNP (© LISA FOSTER KOSTADINOV).

The Beaver Meadows NADP/NTN site (CO19) is located at a lower elevation of 2,490 meters and has been in operation since 1980. In the summer of 2012, a third site was installed in RMNP on the west side of the Continental Divide at Kawuneeche Meadow (CO09) at an elevation of 2,633 meters. Each of these sites includes the same equipment as the Loch Vale site (as shown).

5.0 Tracking Wet Nitrogen Deposition at Rocky Mountain National Park

In addition to reaching the resource management goal in 2032, another goal stated in the NDRP is to “reverse the trend of increasing nitrogen deposition at the park” that occurred from 1984 to 2000.

Following a weight of evidence approach, several analyses are used to track wet nitrogen deposition at RMNP. These analyses may be expanded as additional information becomes available; they currently include the following:

- 1) Assessment of progress along the glidepath,
- 2) Trend analyses for RMNP and other regional sites for
- 3) the period of record (>35 years)
- 4) since the 2006 development of the NDRP, and
- 5) the most recent 7-years of data.

The glidepath assessment and trends analyses allow us to answer the following questions:

- 1) Is current wet nitrogen deposition in RMNP on or below the glidepath?
- 2) Has wet nitrogen deposition decreased at RMNP and other sites in the region over the long-term (period of record)?
- 3) Has wet nitrogen deposition decreased at RMNP and other sites in the region since the development of the NDRP in 2006?
- 4) Has wet nitrogen deposition decreased at RMNP and at other sites in the region in the past 7 years)?

6.0 Methods Updates

There were several changes made to the methods in 2018 that were first discussed in the [RMNP Initiative: 2017 Nitrogen Deposition Milestone Report](#), Schichtel et al. 2019, and Morris 2021 including:

- Missing and invalid concentration data are now replaced with modeled data that accounts for seasonal variations in nitrogen concentrations and the inverse relationship between concentration and precipitation. Previously, the standard NADP approach was used that substituted average concentrations for missing and invalid concentration data. This results in deposition estimates that were biased high since many large winter storms (typically with low concentrations) experience missing or invalid data. This model was developed for the Loch Vale site only.
- Missing and invalid precipitation data are now replaced with modeled data by the Parameter-elevation Regressions on Independent Slopes Model (PRISM). This model spatially interpolates measured precipitation data from hundreds of sites in conjunction with digital elevation models to account for the spatial variability of precipitation amount in mountainous terrain. Previously, the standard NADP approach was used that substituted sample volume for missing or invalid precipitation data which results in deposition estimates that are typically biased low. This is done for the Loch Vale site only.

Note: these two changes resulted in slight modifications to the base condition and interim milestones presented in Figure 1.

- Trends are reported for the period of record (long-term), since 2006, and the most recent 7-years of data. Previously they were reported for the period of record (long-term), the most recent 7-year, and the most recent 5-years of data.
- Trends are reported when $\geq 70\%$ of the data for the time period meet [NADP's data completeness criteria](#). Previous criteria were relaxed.

The methods for determining trends in the data are detailed in Appendix C.

7.0 Assessment of Progress Along the Glidepath

This assessment compares current wet nitrogen deposition (defined as the 5-year rolling average of the annual wet nitrogen deposition measured at the Loch Vale NADP/NTN site) to the interim milestones on the NDRP glidepath. The 2022 milestone is 2.2 kg N/ha/yr.

Annual wet nitrogen deposition is calculated by multiplying the annual precipitation-weighted mean nitrogen concentration by the annual amount of precipitation (see Appendix B for explanation of NADP/NTN terms and calculations). Therefore, annual deposition values are influenced by the amount of precipitation in any given year, with wet years often having greater nitrogen deposition and dry years often having lesser deposition. The rolling 5-year average of wet nitrogen deposition reduces the interannual variability caused by annual variations in precipitation. Data are obtained from the NADP/NTN website.

Figure 2 shows the annual (1984–2022) and 5-year (1988–2022) rolling average of wet nitrogen deposition at the Loch Vale NADP/NTN site as compared to the glidepath. The 5-year rolling average is bounded by 95% confidence intervals due to measurement error and the substitution for invalid concentrations. Annual precipitation and average precipitation (117 cm) over the 1984–2022 period are also shown. Precipitation at Loch Vale was above average in three of the last five years, including 2019, 2021 and 2022.

The 5-year rolling average of wet nitrogen deposition was above 3 kg N/ha/yr for most of the period of record, except for the early years (1988–1993), 2012, and the last 5 years (2018–2022). In 2012, the 5-year rolling average (2.9 kg N/ha/yr) was on the glidepath when annual precipitation in 2012 dropped to 90 cm, the second lowest on record.

In contrast, 2013 recorded the highest annual wet deposition recorded over the history of the site (4.1 kg N/ha/yr). 2021 was only slightly lower at 4.0 kg N/ha/yr. Back-trajectories showed that the data for these two years are characterized by higher-than-average transport from source areas in eastern Colorado ([2017 Milestone Report](#), [2022 Milestone Report \(in preparation\)](#)).

Annual wet nitrogen deposition was low in 1987 and 1988. Nitrogen concentrations were also lower during these two years. While there is no clear explanation, lower concentrations were also observed at other NADP sites in the region.

In 2022, the 5-year average (2018–2022) of wet nitrogen deposition was 2.8 ± 0.22 kg N/ha/yr, which is above the 2022 milestone of 2.2 kg N/ha/yr, but below the 2006 base year deposition of 3.3 kg N/ha/yr.

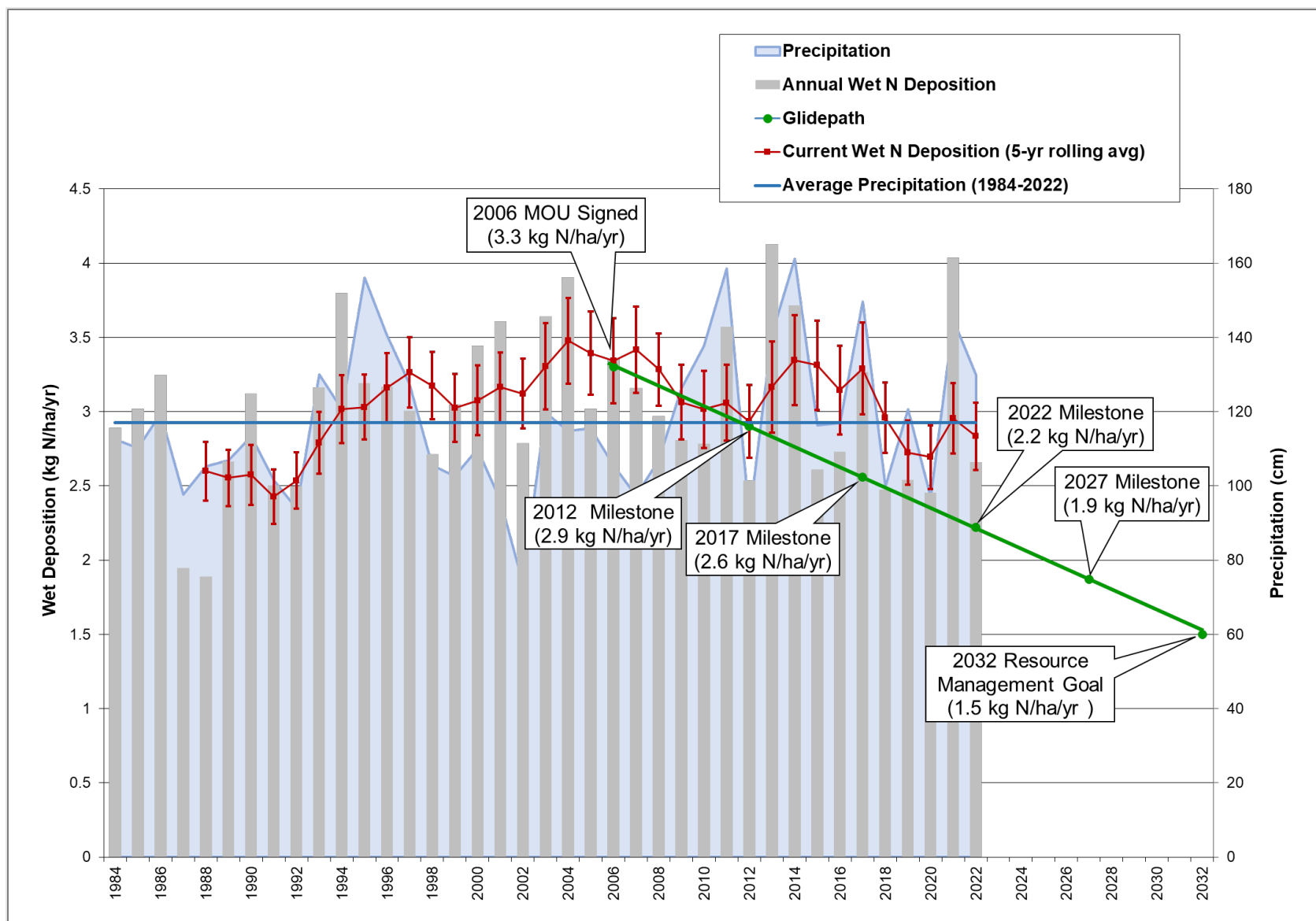


Figure 2. Wet nitrogen deposition and precipitation at Loch Vale in Rocky Mountain National Park compared to the Nitrogen Deposition Reduction Plan glidepath.

8.0 Trend Analyses for Rocky Mountain National Park and Other Regional Sites

Statistical trends for several different parameters were evaluated to determine how nitrogen has changed over time and whether nitrogen inputs to RMNP ecosystems and other regional sites have increased, decreased, or remained unchanged. The parameters include wet nitrogen deposition (kg N/ha/yr), precipitation-weighted mean nitrate and ammonium concentrations in milligrams N per liter (mg N/L), and precipitation depth (cm). Deposition data provide information on ecosystem inputs and are directly comparable to the resource management goal. Concentration data are more closely related to ambient air quality at individual sites and allow for comparison among sites. Precipitation data influence both concentration values and deposition estimates.

NADP/NTN data from Loch Vale are compared to the two lower elevation sites within RMNP, three sites along the Front Range (Niwot Saddle, Niwot Ridge - Southeast, and Sugarloaf), and a site east of the park in the plains (Pawnee). These sites provide regional context (Figure 3) with their period of record, elevation, and distance to Loch Vale given in Table 1.

Table 1. NADP/NTN sites in and near Rocky Mountain National Park used in trends analyses.

Site Name	NADP/NTN Site ID	Period of Record (years)	Elevation	Distance to Loch Vale
Loch Vale (RMNP)	CO98	39	3,159 m (10,364 ft)	–
Beaver Meadows (RMNP)	CO19	43	2,490 m (8,169 ft)	11 km (6.8 mi)
Kauwuneeche Meadows (RMNP)	CO09	10	2,633 m (8,638 ft)	14.5 km (9 mi)
Niwot Saddle	CO02	39	3,520 m (11,549 ft)	26.6 km (16.5 mi)
Niwot Ridge - Southeast	CO90	17	3015 m (9,889 ft)	29.7 km (18.4 mi)
Sugarloaf	CO94	36	2,524 m (8,281 ft)	36.2 km (22.5 mi)
Pawnee	CO22	44	1,641 m (5,384 ft)	96 km (59.7 mi)

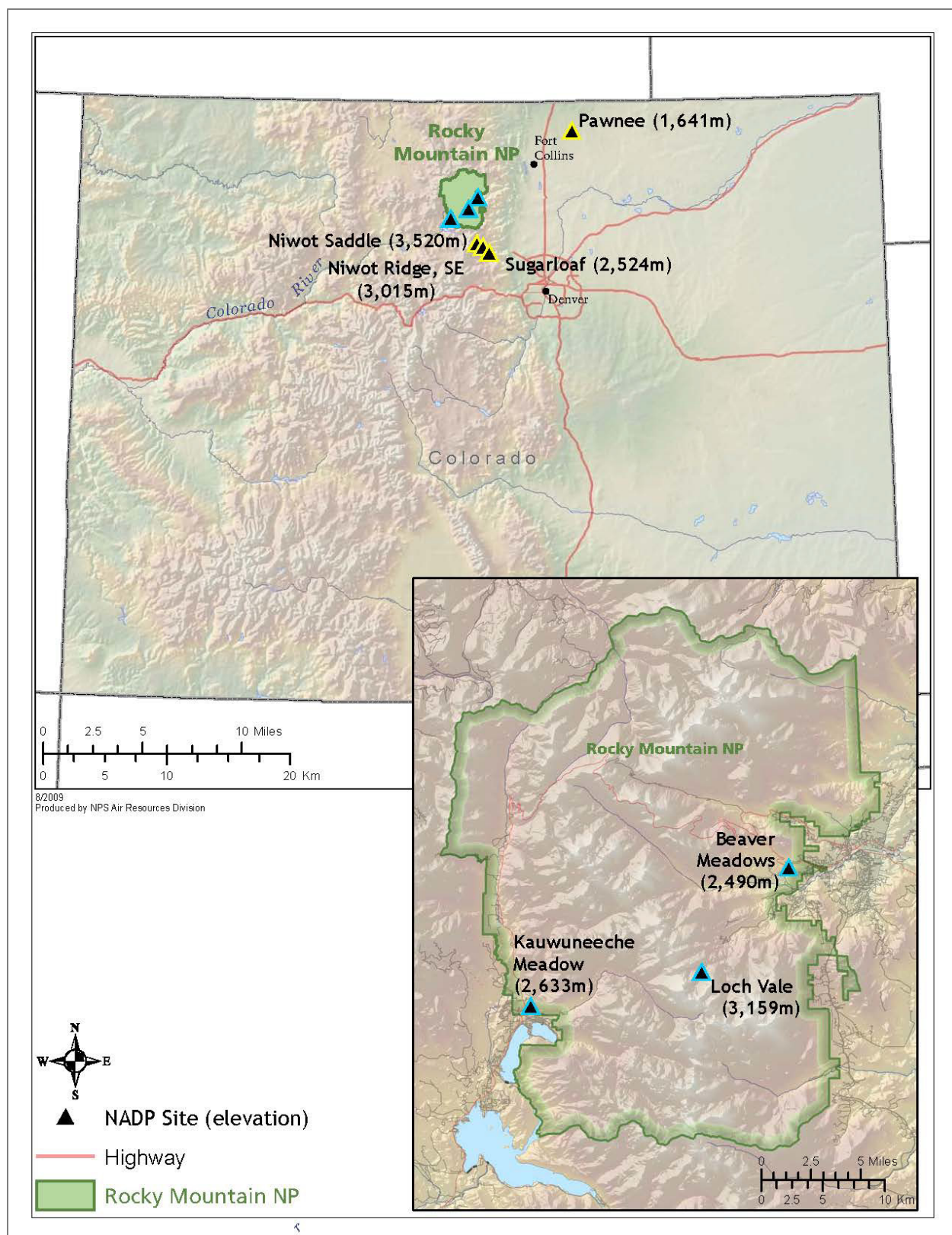


Figure 3. Map of NADP/NTN sites in and near Rocky Mountain National Park used in trends analysis. Elevation is shown in meters (m) in parentheses.

Figures 4-10 show annual data for the period of record at each of the seven sites for deposition, concentration, and precipitation. The Y-axes for each graph are different for each site to best show patterns over time. Precipitation amount varied substantially among these seven sites over the periods of record, which range from 10–44 years. The higher elevation sites receive much more precipitation than the lower elevation sites. Pawnee (at the lowest elevation) records the least amount of precipitation on average.

Wet nitrogen deposition generally ranged from 2.0 to 4.0 kg N/ha/yr at Loch Vale, Beaver Meadows, Niwot Ridge – Southeast, Sugarloaf, and Pawnee over the period of record. Wet nitrogen deposition at Kawwuneeche Meadow, on the western slope, was lower and ranged from 0.5 – 2.0 kg N/ha/yr, while wet nitrogen deposition at Niwot Saddle was often above 4.0 kg N/ha/yr. Niwot Saddle is the only site included in this analysis that is located above treeline with extreme winds and where blowing snow has caused an over-estimation of precipitation (Williams et al. 1998).

Nitrate deposition was higher than ammonium deposition at most sites until 2010. From 2010 to 2013, ammonium deposition began exceeding nitrate deposition. However, ammonium deposition has always been higher than nitrate deposition at the Pawnee site.

Concentrations were generally lower at the higher elevation sites, where precipitation amount was greater. Between 2008 and 2013, ammonium concentrations began exceeding nitrate concentrations at all sites except for Kawwuneeche Meadow, where the shift occurred in 2017. Concentrations of ammonium have always been higher than nitrate at the Pawnee site.

Kawwuneeche Meadow is located on western slope of RMNP and has little to no influence from sources along the Front Range. On the other hand, Beaver Meadows is on the eastern edge of RMNP and is regularly impacted by Front Range emissions. While complicated by varying precipitation patterns, the concentrations at Beaver Meadows are twice that of Kawwuneeche Meadow, suggesting the importance of N emissions from Front Range sources. Note, Loch Vale is in the middle and influenced by both western and eastern sources.

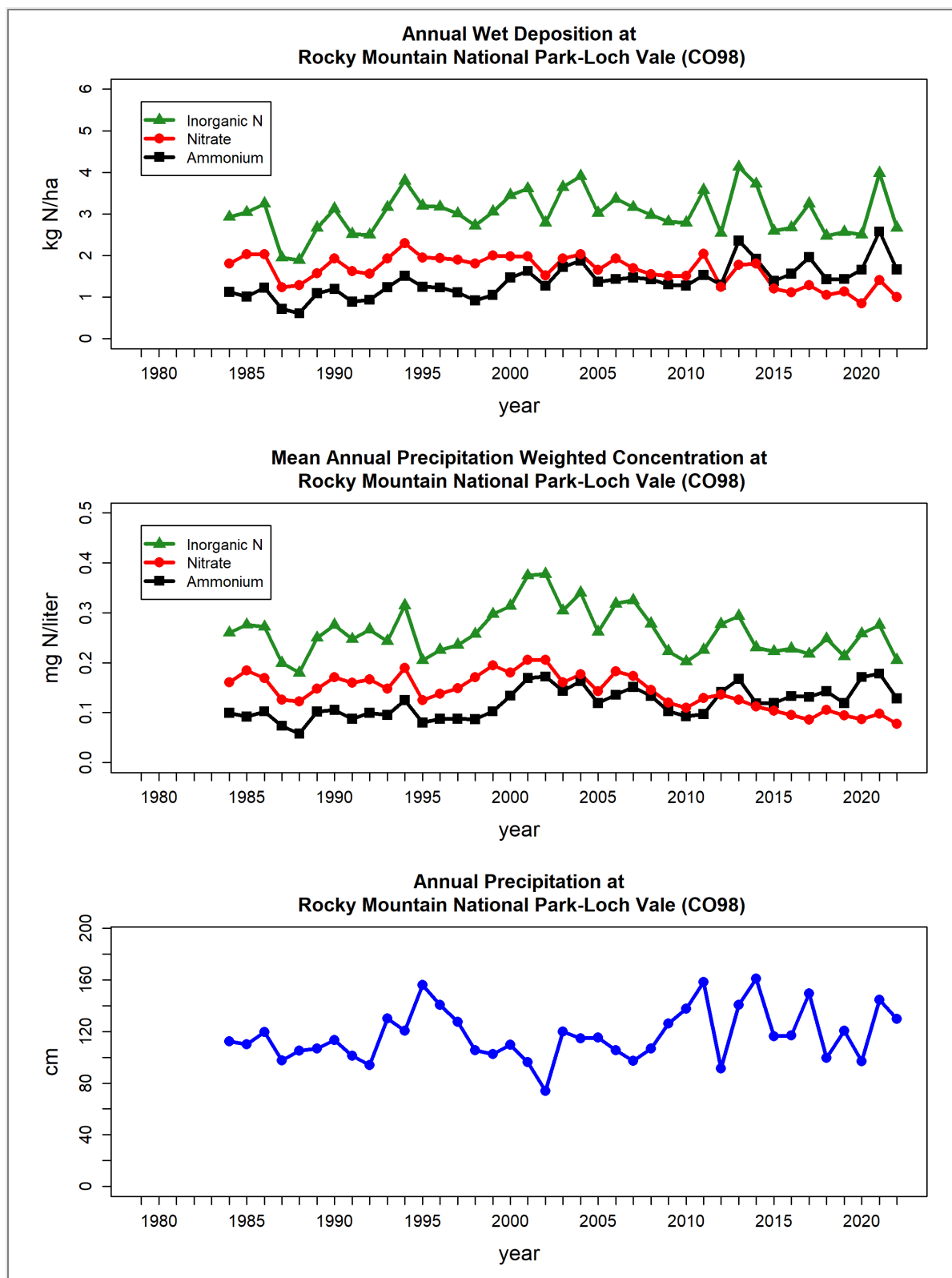


Figure 1. Annual wet deposition, concentrations, and precipitation for RMNP – Loch Vale. Missing/invalid sample concentration and precipitation amounts at Loch Vale were modeled using data substitution methods described in Morris 2021 and Schichtel et al. 2019.

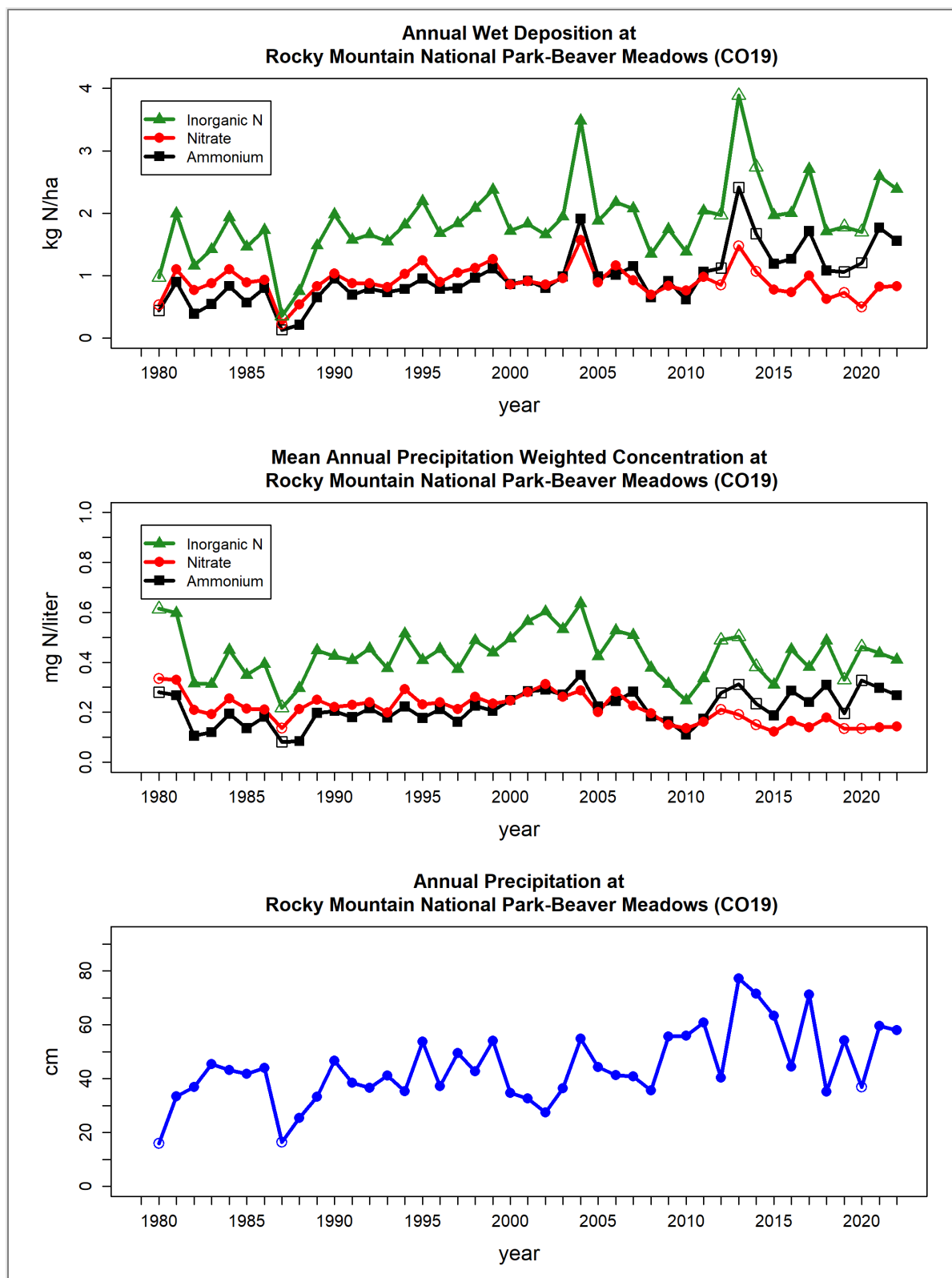


Figure 2. Annual wet deposition, concentrations, and precipitation for RMNP – Beaver Meadows. Open symbols demark years when NADP Data Completeness were not met.

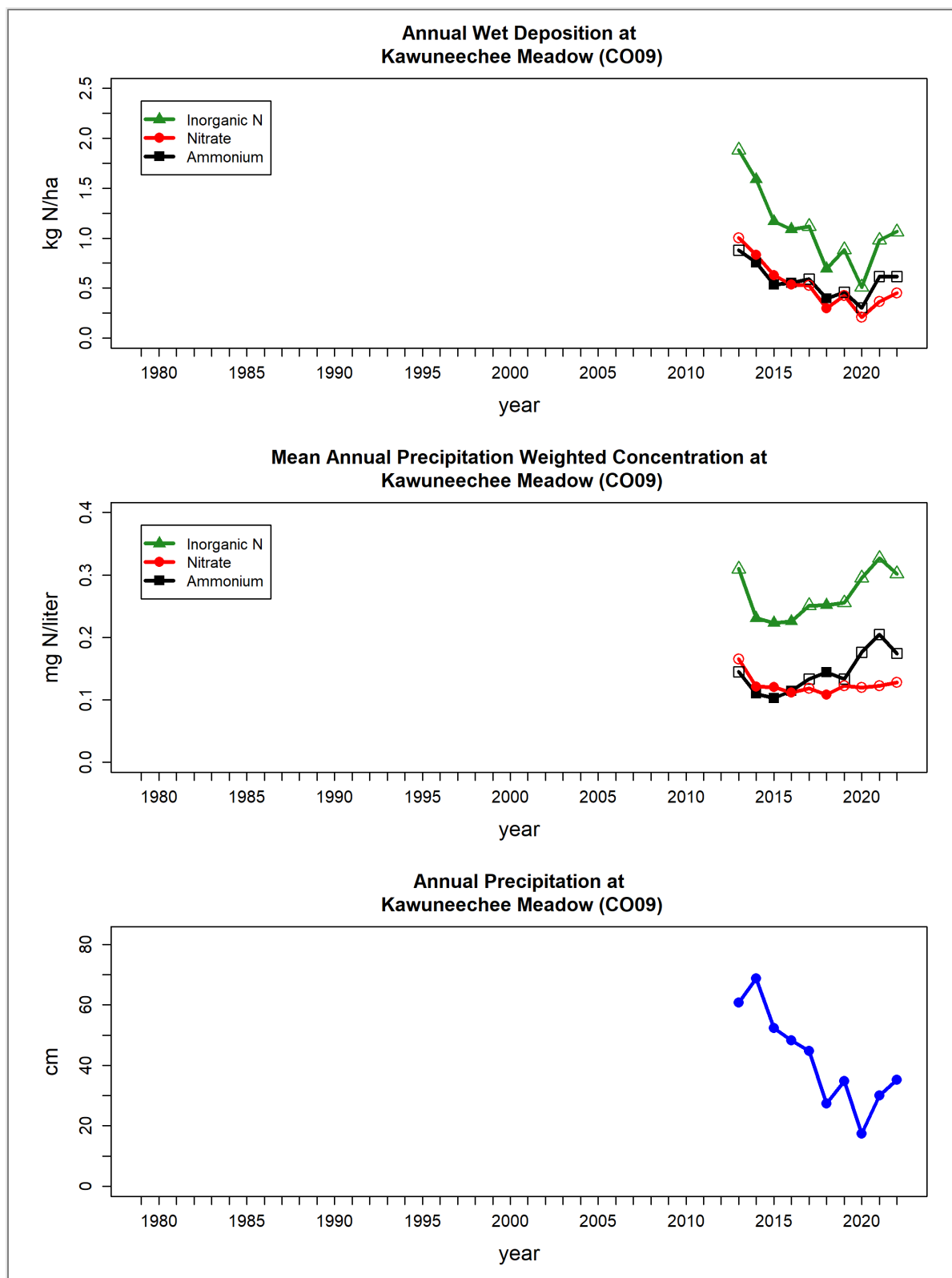


Figure 3. Annual wet deposition, concentrations, and precipitation for RMNP – Kawuneechee Meadow. Open symbols demark years when NADP Data Completeness were not met.

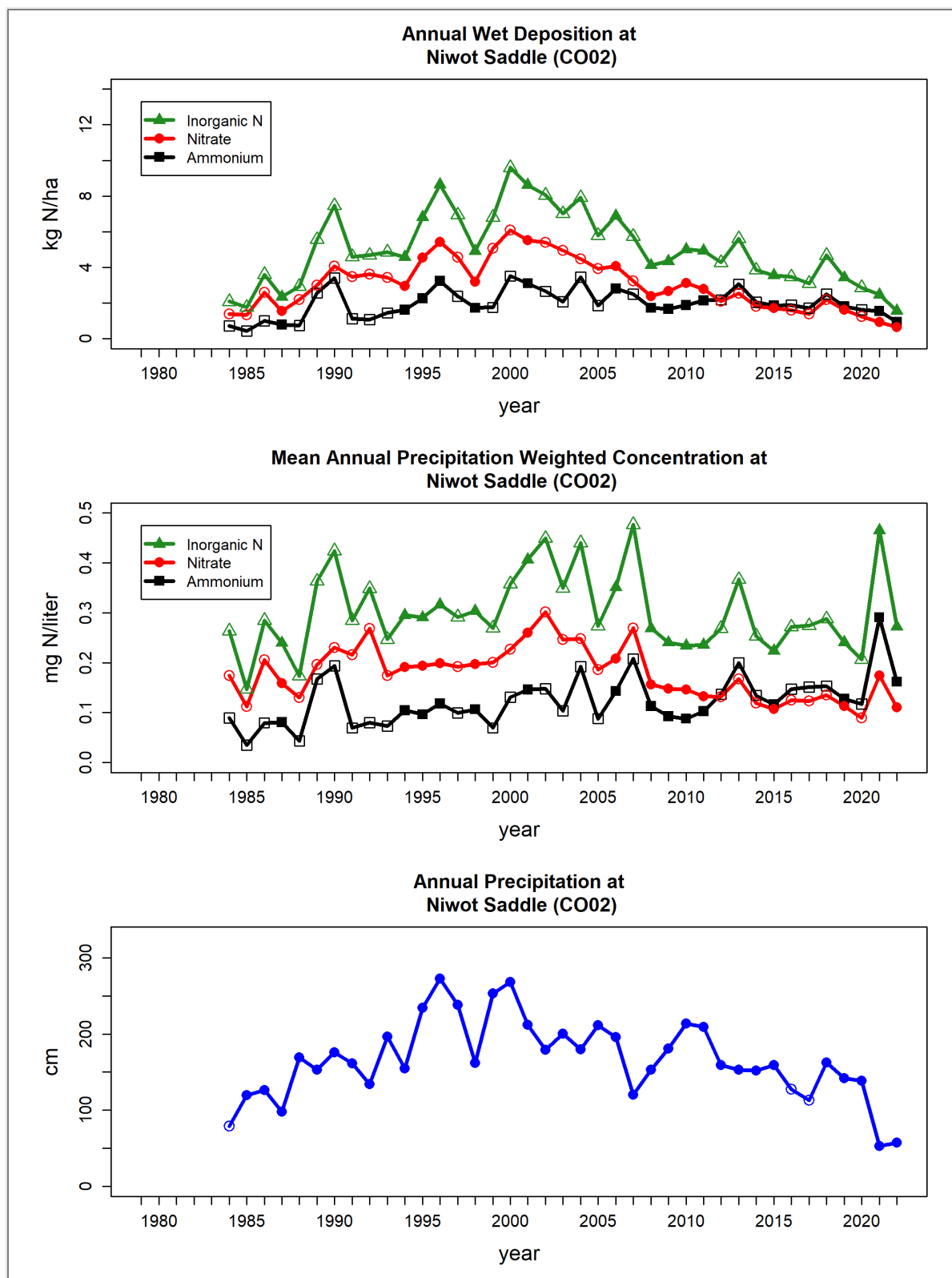


Figure 4. Annual wet deposition, concentrations, and precipitation for Niwot Saddle. Open symbols demark years when NADP Data Completeness were not met.

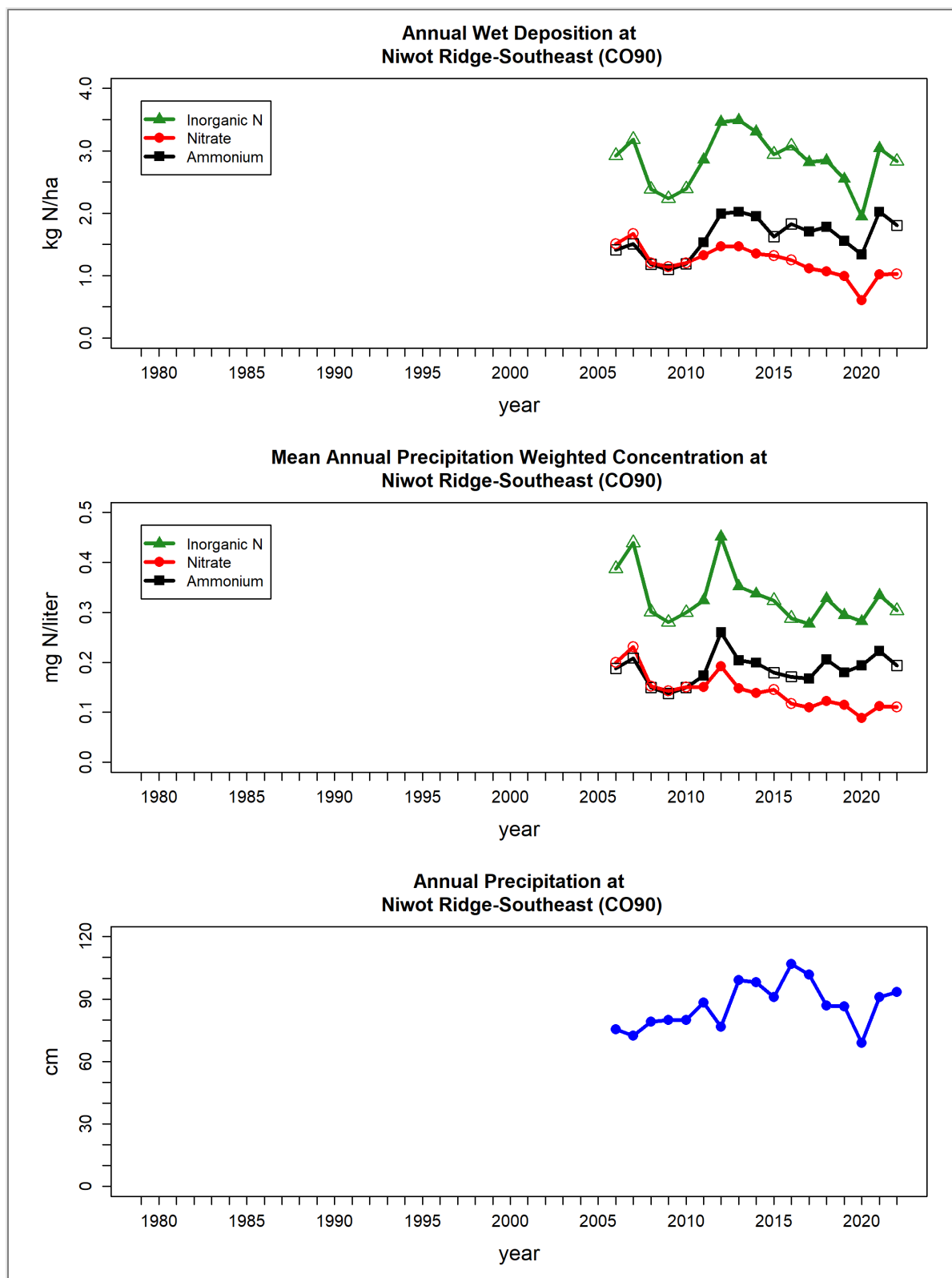


Figure 5. Annual wet deposition, concentrations, and precipitation for Niwot Ridge - Southeast. Open symbols demark years when NADP Data Completeness were not met.

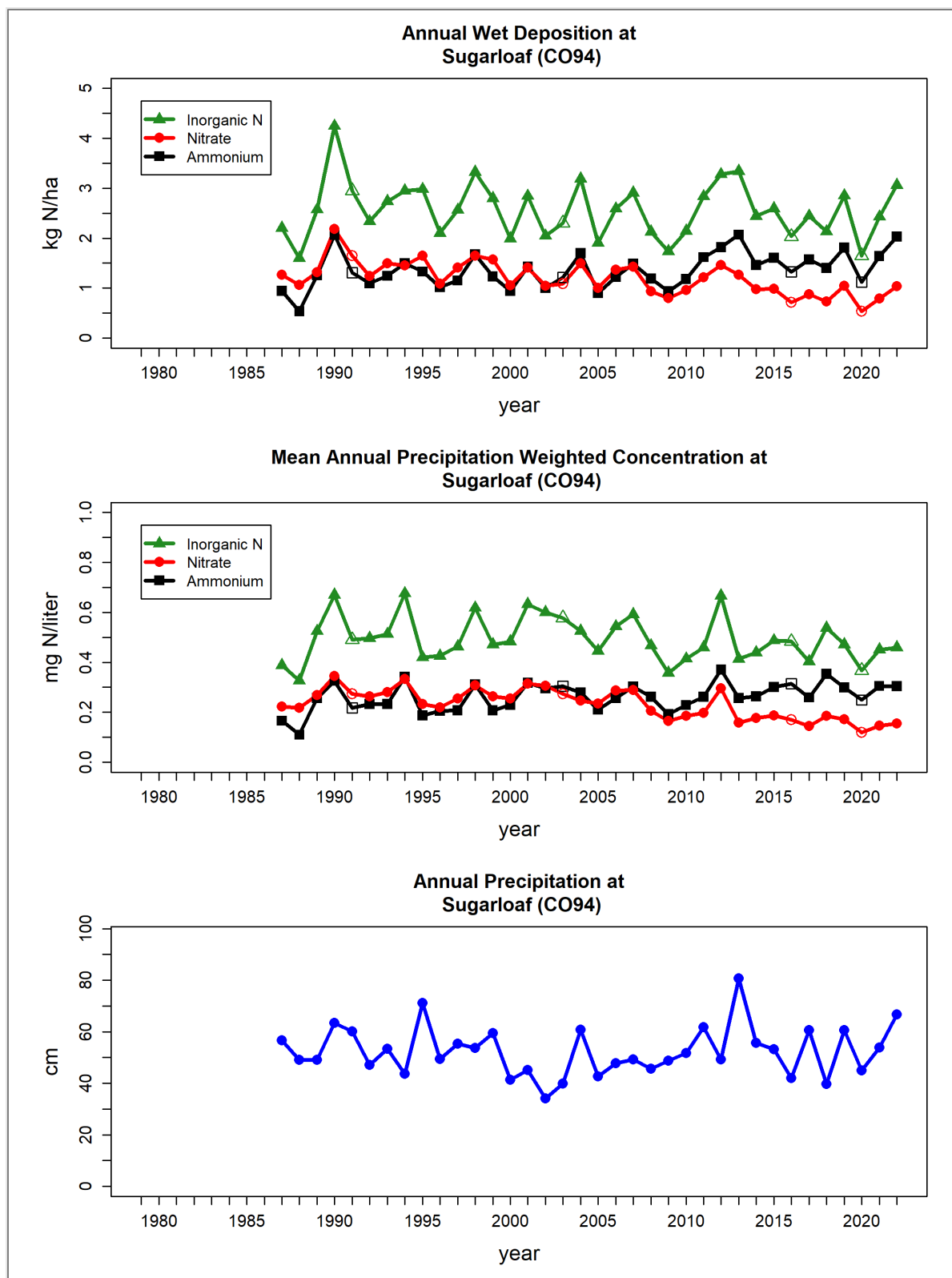


Figure 6. Annual wet deposition, concentrations, and precipitation for Sugarloaf. Open symbols demark years when NADP Data Completeness were not met.

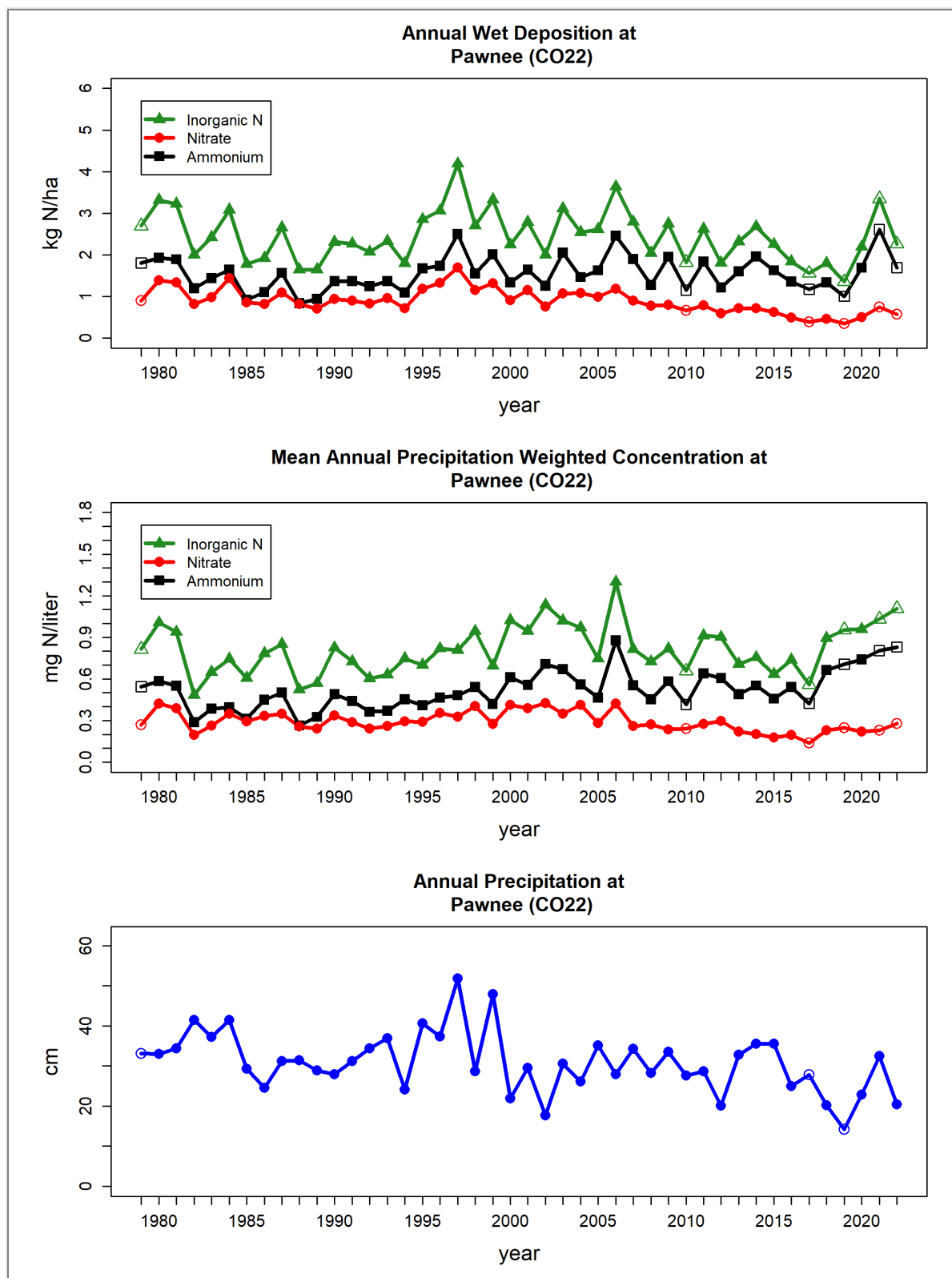


Figure 7. Annual wet deposition, concentrations, and precipitation for Pawnee. Open symbols demark years when NADP Data Completeness were not met.

8.1 Long-term trends

Tables 2-5 show results from the trend analyses through 2022 for the long-term sites (>35 years of data). Trends in annual deposition and precipitation were run using the Mann-Kendall Test and trends in precipitation-weighted mean concentrations were run on seasonal data using the Seasonal Mann-Kendall Test. Trends were evaluated for statistical significance at the 95 percent confidence level ($p\text{-value} \leq 0.05$). The Seasonal Mann-Kendall Test (SKT) is a non-parametric statistical test that is capable of detecting trends in data sets that have strong seasonality, missing data, and non-normal data distribution. The test has become one of the most frequently used to determine trends in environmental data. Examples of the use of the seasonal Kendall test to determine trends in atmospheric deposition data include Lehmann et al. (2005, 2011) and Ingersoll et al. (2008). The trends are not available (NA) when less than 70% of the years in the time period failed NADP completeness criteria.

Table 2. Long-term trends in **wet nitrogen deposition** over the period of record (through 2022). Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$).

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	1984	0.006	0.492	no trend
Beaver Meadows	1981	0.018	0.003	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	0.003	0.673	no trend
Pawnee	1980	-0.005	0.632	no trend

Table 3. Long-term trends in **precipitation-weighted mean ammonium concentrations** over the period of record (through 2022). Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$).

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	1984	0.125	<0.001	increasing
Beaver Meadows	1981	0.217	<0.001	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	0.061	0.061	no trend
Pawnee	1980	0.307	0.004	increasing

Table 4. Long-term trends in **precipitation-weighted mean nitrate concentrations** over the period of record (through 2022). Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05).

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	1984	-0.128	<0.001	decreasing
Beaver Meadows	1981	-0.167	0.001	decreasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	-0.252	<0.001	decreasing
Pawnee	1980	-0.219	0.005	decreasing

Table 5. Long-term trends of **precipitation** over the period of record (through 2022). Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05).

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	1984	0.544	0.0546	no trend
Beaver Meadows	1981	0.444	0.007	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	0.154	0.307	no trend
Pawnee	1980	-0.186	0.056	no trend

The long-term trend (1984-2022) of wet nitrogen deposition was stable at Loch Vale, consistent with trends reported since 2009. So, while the increasing trend (1984-2000; Burns, 2003) has not been reversed, moving from an increasing trend to a stable trend is a step in the right direction. Wet nitrogen deposition showed a statistically significant increasing trend at Beaver Meadows, over the period of record (Table 2, p-value=0.003). An increasing trend in precipitation amount was also significant at Beaver Meadows (Table 5, p-value =0.007).

Precipitation-weighted mean ammonium concentrations increased significantly over the period of record at Loch Vale, Beaver Meadows, and Pawnee (Table 4, p-values $\leq$ 0.004). Precipitation-weighted mean nitrate concentrations decreased significantly at Loch Vale, Beaver Meadows, Sugarloaf, and Pawnee over the period of record (Table 5, p-values $\leq$ 0.005).

Long-term trends at Loch Vale were generally consistent with trends at other Front Range sites, indicating that air quality at Loch Vale is regionally representative.

8.2 Shorter-term trends

While long-term trends are more robust, shorter-term trends in nitrogen deposition and concentrations over a recent period of time are more relevant to recent changes in emissions. Determining statistical significance of trends on shorter-time periods is more difficult because fewer data points are used in the analysis. Shorter-term trend analyses were conducted using two time

periods: since the 2006 development of the NDRP (2006-2022), and the last 7-years (2016–2022). Tables 6-9 show the results of the trend analysis for the individual sites, wherein statistically significant trends ($p\text{-value} \leq 0.05$) are identified. Trends are not available (NA) when less than 70% of the years in the time period failed NADP completeness criteria. Kauwuneeche Meadow started in 2012, so did not qualify for the 2006-2022 trend analysis.

Table 6. Short-term trends of **wet nitrogen deposition** since 2006 (2006-2022) and 7-year (2016–2022) time periods. Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$).

Site Name	Since 2006			7-year		
	Trend (kg N/ha/yr)	P-value	Significant Trend	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	-0.031	0.174	no trend	0.014	1.000	no trend
Beaver Meadows	0.037	0.373	no trend	0.017	1.000	no trend
Kauwuneeche Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge- Southeast	NA	NA	NA	-0.051	1.000	no trend
Sugarloaf	0.02	0.656	no trend	0.111	0.462	no trend
Pawnee	-0.08	0.016	decreasing	NA	NA	NA

Table 7. Short-term trends for **precipitation-weighted mean ammonium concentrations** since 2006 (2006-2022) and 7-year (2016–2022) time periods. Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$).

Site Name	Since 2006			7-year		
	Trend (kg N/ha/yr)	P-value	Significant Trend	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	0.164	0.051	no trend	-0.051	0.822	no trend
Beaver Meadows	0.270	0.093	no trend	-0.222	0.764	no trend
Kauwuneeche Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge- Southeast	NA	NA	NA	0.610	.055	no trend
Sugarloaf	0.111	0.277	no trend	0.480	0.377	no trend
Pawnee	-0.043	0.941	–	NA	NA	NA

Table 8. Short-term trends for **precipitation-weighted mean nitrate concentrations** since 2006 (2006–2022) and 7-year (2016–2022) time periods. Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05).

Site Name	Since 2006			7-year		
	Trend (kg N/ha/yr)	P-value	Significant Trend	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	-0.325	<0.001	decreasing	-0.190	0.115	no trend
Beaver Meadows	0.270	0.033	decreasing	-0.097	0.764	no trend
Kauwuneeche Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	0.032	1.000	no trend
Sugarloaf	-0.480	0.011	decreasing	0.134	0.899	no trend
Pawnee	-0.826	0.008	decreasing	NA	NA	NA

Table 9. Short-term trends for **precipitation** since 2006 (2006–2022) and 7-year (2016–2022) time periods. Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05).

Site Name	Since 2006			7-year		
	Trend (kg N/ha/yr)	P-value	Significant Trend	Trend (kg N/ha/yr)	P-value	Significant Trend
Loch Vale	1.107	0.434	no trend	1.196	1.000	no trend
Beaver Meadows	1.128	0.193	no trend	0.417	1.000	no trend
Kauwuneeche Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	-5.170	0.462	no trend
Sugarloaf	0.960	0.048	increasing	1.632	0.807	no trend
Pawnee	-0.369	0.631	no trend	NA	NA	NA

Since the 2006 development of the NDRP, wet nitrogen deposition significantly decreased at Pawnee (Table 7, p-value = 0.016) and precipitation significantly increased at Sugarloaf (Table 10, p-value = 0.048). Precipitation-weighted ammonium concentrations increased at both Loch Vale and Beaver Meadows, however not at the specified 0.05 significance level (p-values = 0.51 and 0.93, respectively). In addition, precipitation-weighted mean nitrate concentrations decreased at four sites including Loch Vale, Beaver Meadows, Sugarloaf and Pawnee (Table 9, p-values $\leq$ 0.033).

At Loch Vale, wet nitrogen deposition has not significantly decreased since 2006, however, current wet nitrogen deposition (2018-2022) of 2.8 kg/ha/yr is approximately 15% lower than the baseline average (2002-2006) of 3.3 kg/ha/yr. The difference between these averages is 0.5 and the Root

Mean Square Error (RMSE) is 0.38, so wet nitrogen deposition at Loch Vale decreased 0.5 ± 0.38 kg/ha/yr (0.13 to 0.88 kg/ha/yr) at the 95% confidence interval, suggesting some progress has been made.

There were no significant trends in deposition, concentration, or precipitation in the most recent 7 years.

9.0. Summary of Glidepath Assessment and Trends Analysis

In summary, the glidepath assessment and trends analyses allow us to answer the following questions:

- 1) Is current wet nitrogen deposition in RMNP on or below the NDRP glidepath?
 - a) Current wet nitrogen deposition (5-year average 2018-2022) in 2022 at Loch Vale in RMNP was 2.8 kg N/ha/yr which is 0.6 kg N/ha/yr above the 2022 milestone of 2.2 kg/ha/yr and outside the 95% confidence interval.
- 2) Has wet nitrogen deposition decreased at RMNP and other sites in the region over the long-term (period of record)?

Wet nitrogen deposition has not decreased at RMNP or other sites in the region over the long-term. The long-term trend (1984-2022) of wet nitrogen deposition was stable at Loch Vale, consistent with trends reported since 2009. So, while the increasing trend (1984-2000) has not been reversed, moving from an increasing trend to a stable trend is a step in the right direction. Statistical analyses show a significant increase in long-term wet nitrogen deposition and precipitation at Beaver Meadows in RMNP. Ammonium concentration increased significantly at both sites in RMNP and Pawnee. Nitrate concentration data decreased significantly at all four sites that met data completion criteria (Loch Vale, Beaver Meadows, Sugarloaf and Pawnee) over the long-term.

1. Has wet nitrogen deposition decreased at RMNP and other sites in the region since the development of the NDRP in 2006?

Wet nitrogen deposition has not decreased significantly at Loch Vale, Beaver Meadows or Sugarloaf but did decrease at Pawnee from 2006-2022. Trends reported for 2006-2020 showed a significant decrease in wet nitrogen deposition at Loch Vale, however this changed to no trend with the addition of 2021 and 2022 data. Concentrations of ammonium showed no significant trends at all sites and concentrations of nitrate decreased significantly at all four sites that met data completion criteria (Loch Vale, Beaver Meadows, Sugarloaf, and Pawnee). Precipitation significantly increased at Sugarloaf.

Even though the trend in wet nitrogen deposition did not decrease significantly at Loch Vale since 2006, the current wet nitrogen deposition (2018-2022) of 2.8 kg/ha/yr is approximately 15% lower than the baseline average (2002-2006) of 3.3 kg/ha/yr. Wet nitrogen deposition at Loch Vale has decreased 0.5 ± 0.38 kg/ha/yr (0.13 to 0.88 kg/ha/yr) at the 95% confidence interval, suggesting some progress.

1. Has wet nitrogen deposition decreased at RMNP and at other sites in the region in the past 7 years?

Wet nitrogen deposition has not decreased significantly at RMNP or other sites in the region in the past 7 years. There were no significant trends in concentrations of ammonium and nitrate, or precipitation from 2016-2022.

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Appendix A: History of the Loch Vale NADP/NTN Monitoring Site

The Loch Vale NADP/NTN site (CO98) was established in the summer of 1983, when an Aerochem Metrics Model 301 precipitation collector and mechanical Belfort rain gage were installed (Table 11). During the summer of 2007, a newly approved electronic rain gage (ETI NOAH IV) was installed. The original Belfort and the new NOAH IV rain gages operated side-by-side for two years (2008 and 2009). Differences in recorded precipitation (approximately 5 percent) were negligible (National Park Service, Air Resources Division 2011; Richer and Baron 2011).

Table 11. Loch Vale NADP/NTN monitoring site history.

Date	Event
Summer 1983	Site installed with precipitation collector and original Belfort rain gage (NADP/NTN site CO98).
Summer 2007	NOAH IV rain gage added (replaced Belfort rain gage once differences were documented).
Fall 2009	Co-located site (NADP/NTN site CO89) and telemetry installed, solar power and storage increased.
Summer 2010	Belfort rain gage removed.
Summer 2011	Passive ammonia samplers installed NADP/AMoN (site CO98 and site CO88)
Fall 2011	Solar panels replaced and relocated.
Fall 2014	Co-located precipitation collector removed. (Co-located rain gage remains.)

A second and temporary co-located NADP/NTN site (CO89) was installed at Loch Vale in the fall of 2009 for quality assurance assessments. The co-located sites CO98 and CO89 operated side-by-side for five complete water years (2009-2014). During these years, this site consisted of two independent precipitation collectors and two NOAH IV rain gages with satellite telemetry. The co-located rain gage remains in place as a back-up gage, in the case the original rain gage is not operating.

The original Belfort rain gage was removed during the summer of 2010 and the co-located precipitation collector was removed during the fall of 2014 in an effort to keep the monitoring site footprint to a minimum in accordance with the park's wilderness policy. In fall 2011, the four solar panels were replaced with two higher efficiency, less-reflective panels and moved to a location of less snow accumulation.

Two ammonia passive samplers were installed in the park in the summer of 2011 as part of the NADP Ammonia Monitoring Network (AMoN); one at the Loch Vale CO98 NADP monitoring site (AMoN CO98) and one at the base of Long's Peak (AMoN CO88) at an elevation of 2,743 meters. Data from these two sites are available at <http://nadp.slh.wisc.edu/amon/>. While the ammonia data are not included in the body of this report, they are shown in Appendix D due to the importance of ammonia gas to dry deposition and in order to show spatial patterns along the Front Range and within the park.

Appendix B: Explanation of NADP/NTN terms and calculations

The NADP/NTN collects weekly precipitation samples and records daily precipitation depths. Concentrations of sulfate, nitrate, ammonium, chloride, and base cations are determined laboratory analyses, and reported in units of milligrams per liter (mg/L). Hydrogen ion is reported as pH. Valid weekly precipitation samples are aggregated into precipitation-weighted mean concentrations for monthly, seasonal, and annual time periods by using Equation (1).

$$\bar{C}_{ppt.wt} = \frac{\sum_{i=1}^n (C_{w,i} \times P_{w,i})}{\sum_{i=1}^n P_{w,i}} \quad (\text{Eq. 1})$$

where:

$\bar{C}_{ppt.wt}$ = precipitation-weighted mean concentration, mg/L

$C_{w,i}$ = precipitation concentration for weekly sample, mg/L

$P_{w,i}$ = precipitation depth for weekly sample, cm

n = number of events

Precipitation-weighted mean concentrations are used to simulate having one composite sample over the time period of interest. For example, a precipitation-weighted mean concentration for one year (or month or season) is equivalent to adding all of the weekly samples together into one sample and then determining the concentrations of ions in that sample (Table 12).

Table 12. Example: sample concentration and precipitation amount.

Sample	Concentration	Precipitation Amount
1	15 mg/L	1 cm
2	5 mg/L	6 cm

A precipitation-weighted mean concentration is more representative of the average concentration of the majority of the precipitation. In the above example, the precipitation-weighted mean concentration is 6.43 mg/L $[(15 \times 1 + 5 \times 6)/(1+6)]$ and is more heavily influenced by the larger precipitation event, whereas an arithmetic mean is 10 mg/L.

Wet deposition is calculated by multiplying the precipitation-weighted mean concentration for a period of time by the total amount of precipitation during that time (Equation 2).

$$D_w = \bar{C}_{ppt.wt} \times P_{TOT} \times 10^{-1} \quad (\text{Eq. 2})$$

where:

D_w = wet deposition, kg/ha

$\bar{C}_{ppt.wt}$ = precipitation-weighted mean concentration, mg/L

P_{TOT} = total precipitation depth measured by the rain gage for period, cm

Note: 1 mm of precipitation depth over 1 square meter = 1 liter.

Nitrogen deposition is calculated by summing the nitrogen (N) from nitrate (NO_3^-) deposition and ammonium (NH_4^+) deposition as shown in Equation 3. The conversion factors in the equation represent the molecular weight ratios of N to NH_4 and NO_3 , respectively.

$$D_{IN} = \left(D_{\text{NH}_4^+} \times \frac{14.01}{18.01} \right) + \left(D_{\text{NO}_3^-} \times \frac{14.01}{62.01} \right) \quad (\text{Eq. 3})$$

where:

D_{IN} = wet deposition of N, kg/ha

$D_{\text{NH}_4^+}$ = wet deposition of NH_4 , kg/ha

$D_{\text{NO}_3^-}$ = wet deposition of NO_3 , kg/ha

Appendix C: Methods of Testing Trends in NADP Precipitation Chemistry Data

The trends in precipitation chemistry in this report are run for the parameters and sites listed below using the Seasonal Kendall Test (SKT) and the Mann Kendall Test (MKT). The SKT performs a MKT for individual seasons of the year, and then combines the results into one overall test. Increasing the number of samples by a factor of 4 seasons strengthens the statistical results. The Seasonal Kendall Test (SKT) was used to evaluate trends in ammonium and nitrate concentrations in precipitation, which is consistent with other publications on trends in precipitation chemistry (Lehmann 2005 and 2011). The MKT was used for trends in nitrogen (N) deposition and precipitation amount because seasonality is incorporated within the annual value. The SKT and MKT produce identical results for data sets with one season or annual data.

The SKT and MKT tests can be run using a computer code available from the USGS (Helsel et al. 2006). An executable version of the computer code (Kendall.exe) and example files can be downloaded at <http://pubs.usgs.gov/sir/2005/5275/downloads/>. A report describing the trend program is available at <http://pubs.usgs.gov/sir/2005/5275/pdf/sir2005-5275.pdf>.

Trends are only presented in this report when $\geq 70\%$ of the data for the time period meet [NADP's data completeness criteria](#).

NADP sites

CO98 - Loch Vale

CO19 - Beaver Meadows

CO09 – Kawwuneeche Meadow

CO02 - Niwot Saddle

CO90 – Niwot Ridge - Southeast

CO94 - Sugarloaf

CO22 - Pawnee

Parameters

Annual wet nitrogen deposition in kg N/ha/yr

Seasonal precipitation-weighted mean NH_4^+ concentrations in mg/L (winter, spring, summer, fall)

Seasonal precipitation-weighted mean NO_3^- concentrations in mg/L (winter, spring, summer, fall)

Annual precipitation amount in cm

Time Frame

Period of Record (POR)

Since 2006

Most recent 7 years

Trend Tests

Seasonal Kendall Test (SKT) for seasonal concentrations (NH₄ and NO₃)

Mann Kendall Test (MKT) for annual inorganic nitrogen deposition and precipitation amount

Procedure

1. Retrieve Data

Annual and seasonal precipitation chemistry data are retrieved from the National Atmospheric Deposition Program (NADP) web site at <https://nadp.slh.wisc.edu/networks/national-trends-network/>.

Available annual deposition data and seasonal concentration data are downloaded for all sites by calendar year by querying under the “Data Export” section. The data are downloaded using the “calendar year” option under “Period” and incomplete data are included. The files downloaded from these queries are titled NTN-ALL-a-i-dep.csv and NTN-ALL-s-i-mgl.csv. These files provide the data used to run trends for the NADP sites CO98, CO19, CO02, CO94, CO22, CO90, and CO09.

Methods were updated in 2018 to include modeled data substitutions for missing and invalid concentration and precipitation data at CO98 (Schichtel et al. 2019, Morris 2021). Trends for the substituted data are reported under the site name CO98s in these files. CO98s trends are presented in this report, not CO98.

A program written in the R programming language by the USGS is used to compute the trends. The program excludes data collected during time periods that do not meet completeness criteria and removes any -9s indicating missing data from the files downloaded from NADP. The seasonal and annual averages are computed by NADP using only valid samples. The winter seasonal data include the months of December, January, and February. Spring includes March, April, and May. Summer includes June, July, and August. Fall includes September, October, and November.

The R program calls a USGS-developed function to run the Seasonal Kendall test (SKT) and Mann-Kendall test (MKT). These tests are available as part of an R package called smwrStats. This package can be downloaded from USGS (<https://code.usgs.gov/water/analysis-tools/smwrQW>). The program uses the “seaken” function, which is part of the smwrStats package, to calculate the individual annual and seasonal trends. The seaken function performs the same trend calculation as the stand-alone executable Kendall.exe program. The program loops through the three different time periods for all eight sites to calculate the trends and outputs the results in two comma-separated files.

Appendix D: NADP Ammonia Monitoring Network (AMoN) Data

Ammonia monitors were installed at two locations in RMNP in the summer of 2011 as part of the NADP Ammonia Monitoring Network (AMoN); one at the Loch Vale NADP monitoring site (AMoN CO98) at 3,159 meters (10,364 feet) and one near the base of Longs Peak (AMoN CO88) at a lower elevation of 2,743 meters (8,999 feet). Data are available at nadp.slh.wisc.edu/networks/ammonia-monitoring-network/.

Figure 11 compares ammonia concentrations at the RMNP sites with the AMoN site in Fort Collins (AMoN CO13) at 1,570 meters (5,150 feet) and two more sites that were installed at the end of 2020/beginning of 2021 near agricultural areas in Greeley (AMoN CO81) and Fort Morgan (CO82), Colorado. Another site near agricultural areas in Akron (AMoN CO80) was added late in 2022. Concentrations of ammonia at the RMNP sites were mostly below 2.0 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) with Loch Vale having slightly lower concentrations than the Long's Peak site. Concentrations at the Fort Collins site ranged mostly from 2-7 $\mu\text{g}/\text{m}^3$, while the sites near agricultural areas mostly ranged from 5-18 $\mu\text{g}/\text{m}^3$ with a spike at Fort Morgan on 12/17/21 of 32 $\mu\text{g}/\text{m}^3$.

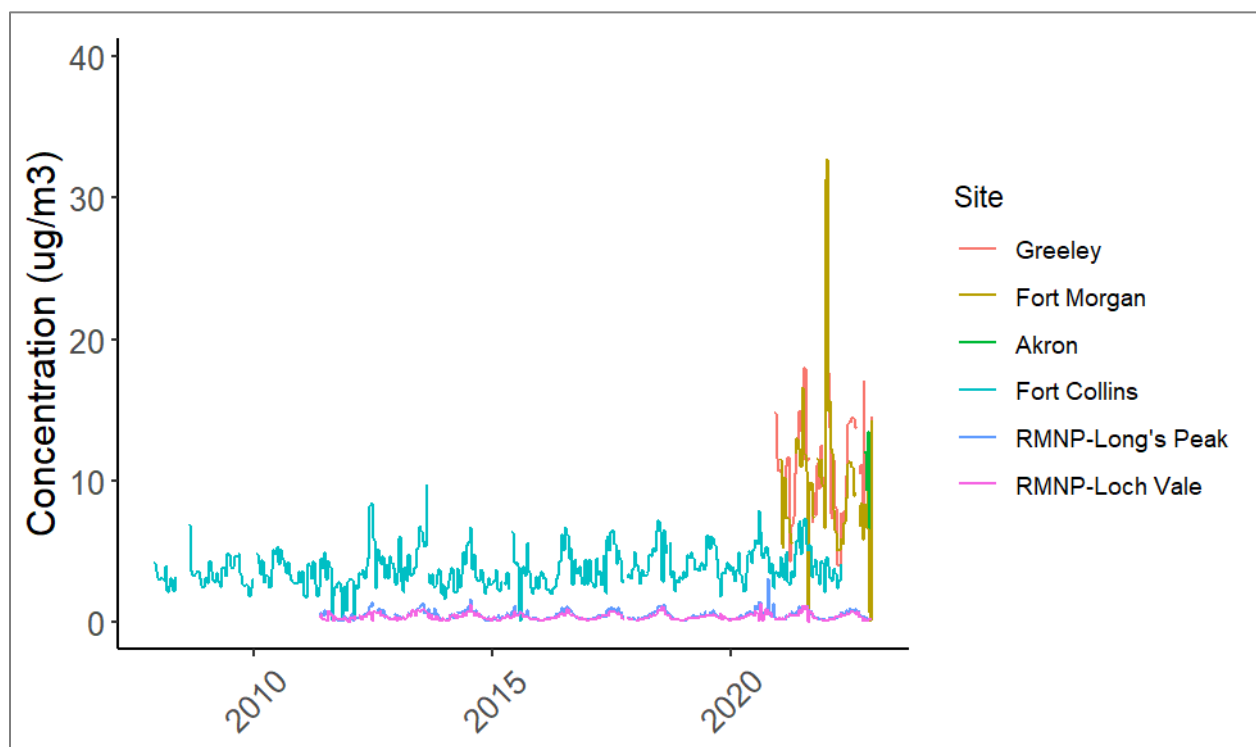


Figure 11. Ammonia concentrations at Rocky Mountain National Park and nearby sites.

Figure 12 shows a spike in ammonia concentration of 3.1 $\mu\text{g}/\text{m}^3$ at Long's Peak on 10/7/2020. Two of the largest wildfires in Colorado State history, the Cameron Peak fire and the East Troublesome fire, were burning around and in the park in October 2020.

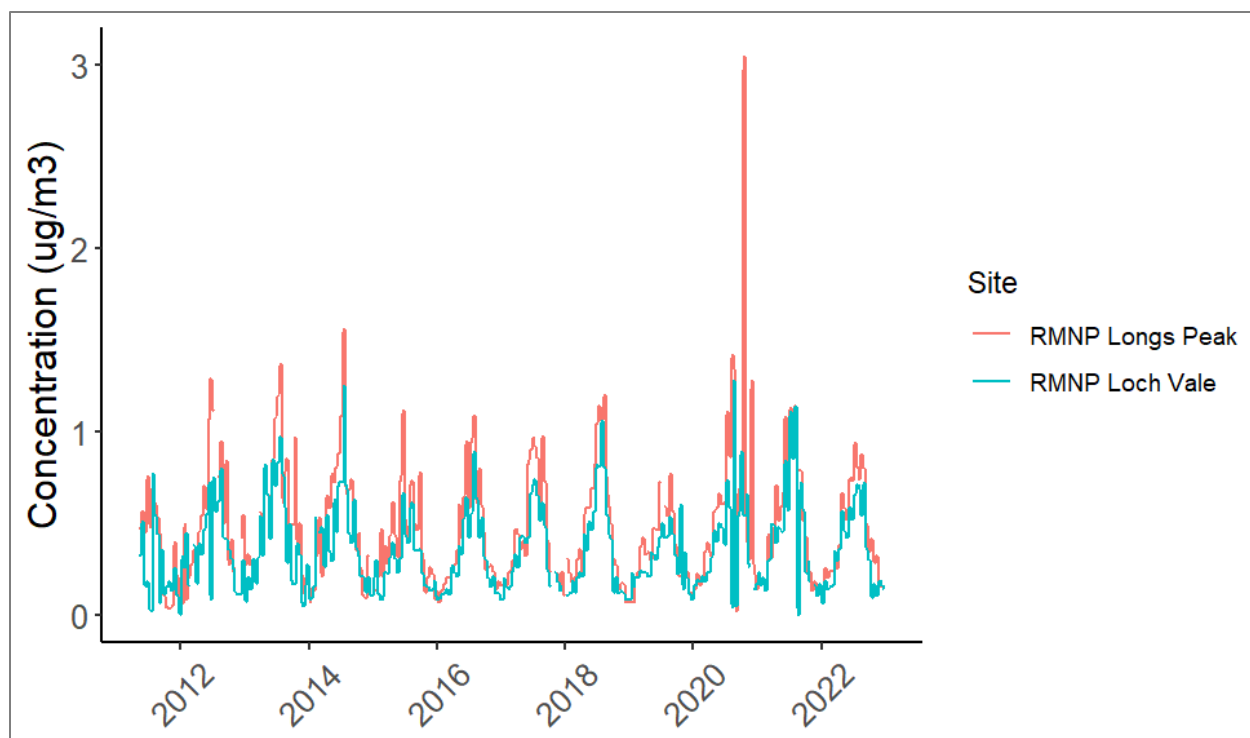


Figure 12. Ammonia concentrations at Rocky Mountain National Park sites.

Ammonia data from AMoN are useful in identifying spatial and temporal patterns in and near the park and can be used to validate atmospheric models. EPA and other stake holders continue to develop a process to estimate deposition from ammonia concentrations.

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