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2017 Monitoring and Tracking Wet Nitrogen Deposition at Rocky Mountain National Park

February 2019

Natural Resource Report NPS/NRSS/ARD/NRR—2019/1905

ON THIS PAGE
Aspen trees in Rocky Mountain National Park.
Credit: National Park Service photo.

ON THE COVER
View of the Colorado River from Holzwarth Historic Site on the west side of Rocky Mountain National Park. Credit: National Park Service photo by Emi Buck

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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 effects and trends 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) by the year 2032 to protect sensitive ecosystems within RMNP from adverse effects. Another goal of the NDRP is to "reverse the trend of increasing nitrogen deposition at the park." Trends in wet deposition data were analyzed at three sites in RMNP and three regional sites outside of the park. Wet nitrogen deposition (5-year rolling average) at Loch Vale in RMNP was 3.3 kg N/ha/yr, which is above the glidepath (2.4 kg N/ha/yr) in 2017. Wet nitrogen deposition has not decreased at RMNP or other sites in the region over the long-term. Ammonium concentrations showed a statistically significant increasing trend at all sites and nitrate concentrations showed a significant decreasing trend at four of the five sites over the period of record. In more recent years (2011-2017), wet nitrogen deposition showed no significant trend at monitoring sites in RMNP. Ammonium concentrations also showed no significant trend over the short-term, however nitrate concentrations did significantly decrease at two of the six sites.

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1. 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.

As part of the NDRP, the NPS adopted and 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 for identifying adverse ecosystem effects in RMNP. This threshold is based on decades of research and is the estimated "critical load" of wet nitrogen that can be utilized by sensitive ecosystems within RMNP before detrimental changes occur (Baron 2006). To achieve this threshold, referred to as the resource management goal, the MOU agencies have chosen a glidepath approach. This type of approach anticipates gradual improvement over time and is a commonly used regulatory structure for long-term, goal-oriented air quality planning.

High elevation ecosystems at Rocky Mountain National Park are sensitive to atmospheric nitrogen deposition. Credit: National Park Service photo by Schonlau.

The glidepath is shown in Figure 1 and establishes the resource management goal for RMNP to be met over the course of 25 years. The baseline wet deposition at Loch Vale in RMNP was 3.1 kg N/ha/yr based on the 5-year rolling average of annual data from 2002 to 2006. Milestones are

assessed at 5-year intervals and also based on the 5-year rolling average until the resource management goal of 1.5 kg N/ha/yr is achieved in the year 2032. The first interim milestone was based on a reduction of wet nitrogen deposition from baseline conditions to 2.7 kg N/ha/yr in 2012. The current interim milestone is 2.4 kg N/ha/yr for 2017. The estimate for nitrogen deposition under natural pre-industrial conditions, 0.2 kg N/ha/yr also is shown (Galloway et al. 1995 and 1996; Dentener 2001).

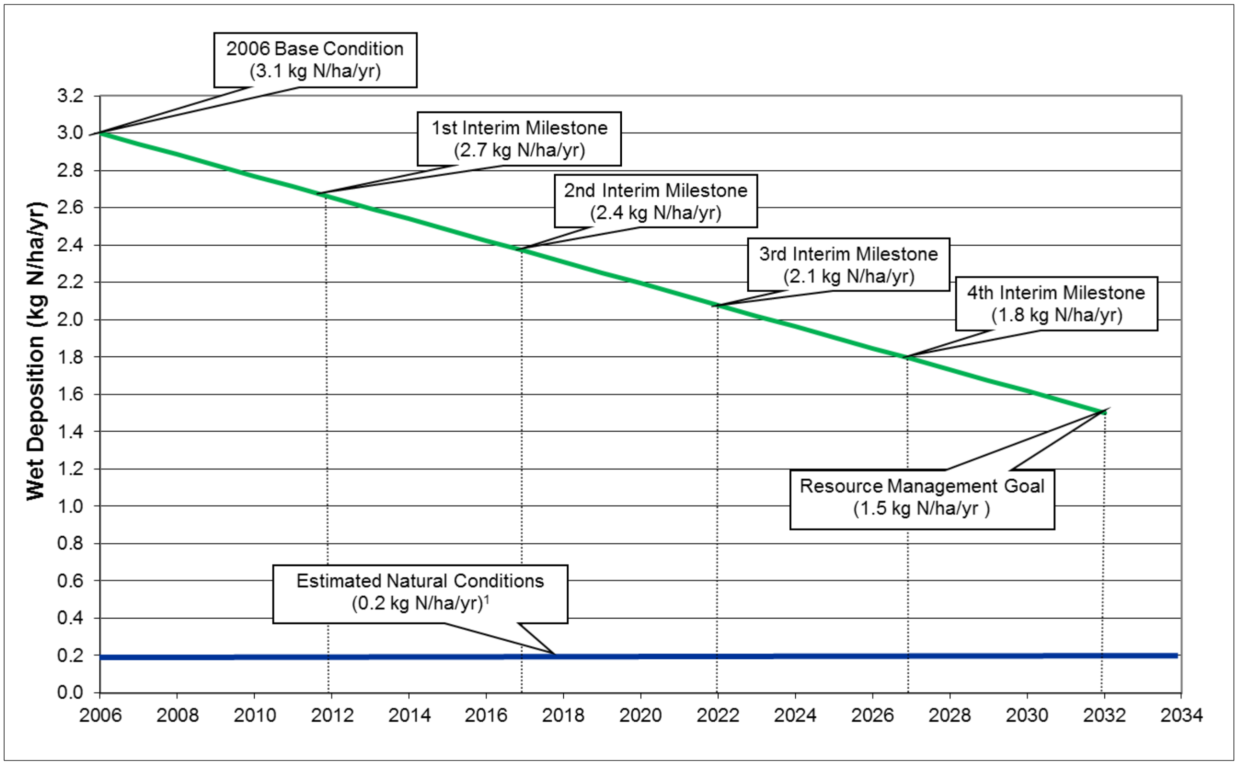

Figure 1. Nitrogen Deposition Reduction Plan glidepath. [1]Galloway et al. 1995 and 1996; Dentener 2001.

The Nitrogen Deposition Reduction Contingency Plan was developed in 2010 to put corrective measures in place should the interim milestones not be achieved. A Nitrogen Deposition Data Tracking Plan was originally included as Appendix B of the Contingency Plan (https://www.colorado.gov/pacific/cdphe/nitrogen- reduction-contingency-plan). As part of the Tracking Plan, the MOU agencies agreed to produce this annual report on the status of wet deposition at RMNP; for Milestone years, it is a publication that meets USGS peer-review standards, in off years it is a data summary that undergoes MOU agency and internal NPS review.

The MOU agencies meet in the fall of each year to discuss the latest analyses and determine if the Contingency Plan should be revised based on new information. In the years following the interim milestones (and within 180 days of issuance of the deposition data), the MOU agencies evaluate how nitrogen deposition has changed at RMNP and determine whether or not an interim milestone was achieved, and whether the Contingency Plan will be triggered, using the weight of evidence approach. The 2012 milestone of 2.7 kg N/ha/yr was not met when wet deposition that year was

recorded at 2.9 kg N/ha/yr. However, the MOU agencies agreed to not trigger the Contingency Plan due to the weight of evidence suggesting that wet nitrogen deposition at RMNP was no longer increasing and the anticipation of future emission and deposition reductions from regulations and strategies with agriculture. The RMNP Initiative 2012 Milestone Report is available on the CDPHE website (http://www.colorado.gov/cdphe/rmnpinitiative). The 2017 Milestone Report is currently under development; when it is finished, it will also be available on the CDPHE website.

2. 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 2017. 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 2017 interim milestone was achieved, and whether the Contingency Plan will be triggered

NADP site at Loch Vale in RMNP (the original site in the foreground and the co-located site).

This report addresses the following questions:

1. Is current wet nitrogen deposition in RMNP on or below the glidepath?
2. Has nitrogen deposition decreased at RMNP and other sites in the region?
3. Has nitrogen deposition *recently* decreased at RMNP and at other sites in the region?

3. Monitoring Wet Nitrogen Deposition

The resource management goal and interim milestones identified in the NDRP are based on wet nitrogen[1] deposition from nitrate and ammonium measurements at the Loch Vale site in RMNP. Monitoring data are collected 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 U.S. Geological Survey, EPA, NPS, 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 2018, the network has over 250 sites spanning the continental U.S., Alaska, Puerto Rico, and the U.S. Virgin Islands.

The purpose of the network is to monitor geographical 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 Central 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 in centimeters (cm). Quality assurance programs 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 213 peer-reviewed journal articles in 2017 (David Gay, NADP Program Office, personal communication, 2018). Data also are 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 dioxide (SO_2) and nitrogen oxides (NO_X) (EPA 2017); (2) assess progress under the Canada – U.S. Air Quality Agreement (ECCC 2017); 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 2018).

[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. Monitoring Wet Nitrogen Deposition in Rocky Mountain National Park

In 2017, there were three NADP/NTN sites in RMNP. The site in the Loch Vale watershed (CO98) (at an elevation of 3,159 meters - 10,364 feet) 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 (approximately 3 miles) 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.

The Beaver Meadows NADP/NTN site (CO19) is located at a lower elevation of 2,490 meters (8,169 feet) and has been in operation since 1980. In the summer of 2012, a site was installed in RMNP on the west side of the Continental Divide at Kawuneeche Meadow (CO09) at an elevation of 2,633 meters (8,638 feet).

5. Tracking Wet Nitrogen Deposition at Rocky Mountain National Park

The interim milestones in the NDRP are based on a 5-year rolling average of the annual wet nitrogen deposition data from the Loch Vale NADP/NTN site in RMNP. As mentioned previously, the first interim milestone of the NDRP that called for the 5-year rolling average of wet nitrogen deposition at RMNP to be reduced from the baseline loading of 3.1 kg N/ha/yr in 2006 to 2.7 kg N/ha/yr in 2012 was not met. The 2017 milestone is 2.4 kg N/ha/yr.

Another goal of the NDRP is to "reverse the trend of increasing nitrogen deposition at the park." Because determination of success or failure of the NDRP is made using a weight of evidence approach, several analyses are used to track 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) long-term (>30 years) trend analyses for RMNP and other regional sites, and (3) short-term (5 and 7 years) trend analyses for RMNP and other regional sites. Each section below describes the data analyses for results obtained through 2017.

5.1 Assessment of progress along the glidepath

This assessment compares current (through 2017) wet nitrogen deposition at the Loch Vale NADP/NTN site to the interim milestones on the NDRP glidepath. 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 and screened for data completeness (Morris et al. 2012).

Figure 2 shows the annual (1984–2017) and 5-year (1988–2017) rolling average of wet nitrogen deposition at the Loch Vale NADP/NTN site as compared to the glidepath. The glidepath is bounded by 90% confidence intervals (green dashed line) that were determined by the co-located study (Wetherbee 2016). Annual precipitation and average precipitation over the 1984–2017 period are also shown.

The 5-year rolling average of wet nitrogen deposition increased in the early 1990s. Annual nitrogen deposition was particularly low in 1987 and 1988, which is in part due to precipitation amounts that were well below average; 1988 had the second lowest precipitation on record for Loch Vale. However, nitrogen concentrations were also lower during these 2 years, and while there is no clear explanation, lower concentrations were also observed at other NADP sites in the region.

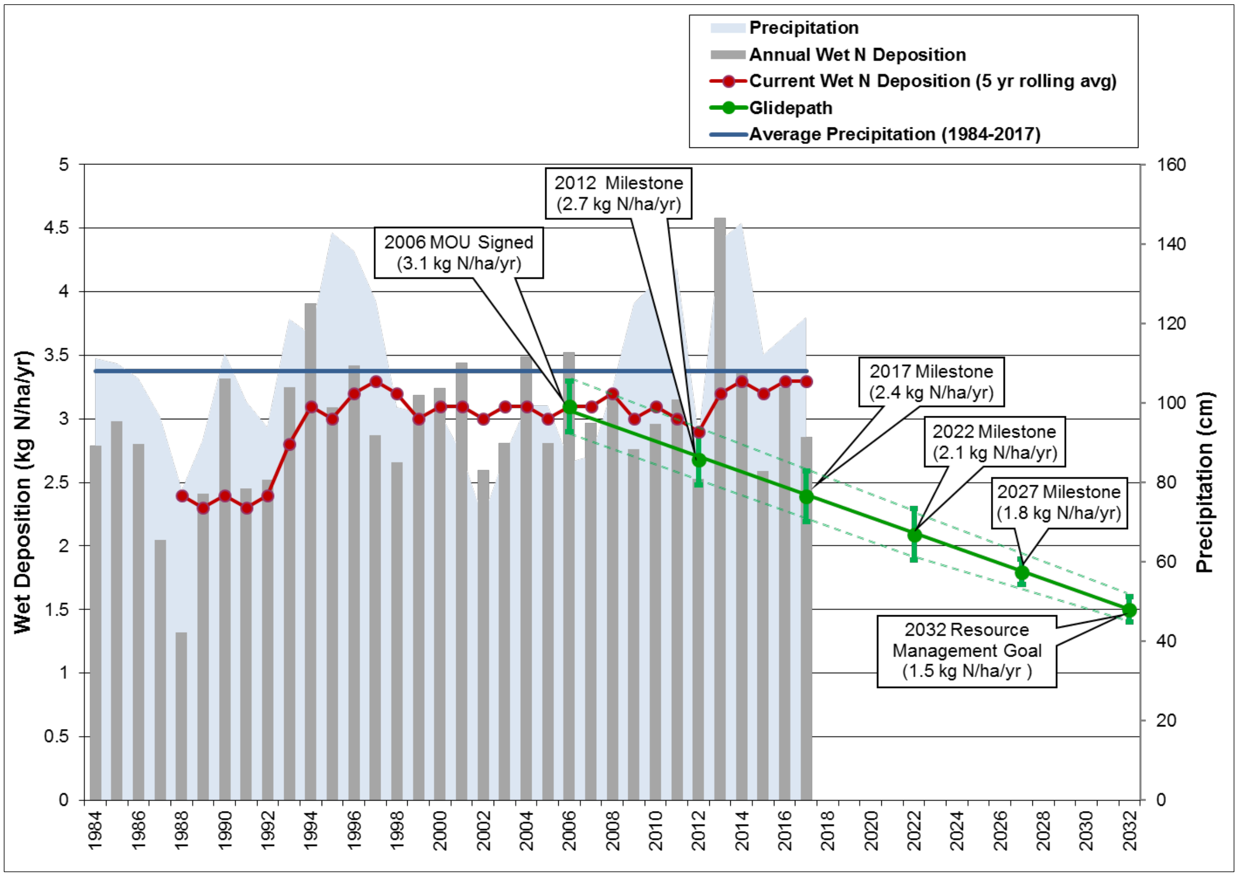

Figure 2. Wet nitrogen deposition and precipitation at Loch Vale in Rocky Mountain National Park compared to the Nitrogen Deposition Reduction Plan glidepath. Dashed green lines are drawn for illustrative purposes only.

Since 1994, the 5-year rolling average of nitrogen deposition has been relatively stable even as Loch Vale experienced an extended period of below average precipitation from 1998–2008 and above average precipitation from 2009 to 2011 (Figure 2). In 2012, the 5-year rolling average equaled the upper limit of the 90% confidence interval, however data from the following years were all above the upper limit. Annual precipitation in 2012 dropped to 90 cm (35.4 inches), which contributed to the lowest annual deposition recorded in two decades (2.5 kg N/ha/yr). In contrast, 2013 recorded the highest precipitation in the history of the site at 141 cm (55.5 inches). This contributed to the highest annual deposition recorded over the history of the site (4.6 kg N/ha/yr). Nitrogen concentrations were also high in 2013 (Figure 4a).

The glidepath model provides the foundation for the weight of evidence approach, and addresses the question: **Is current wet nitrogen deposition in RMNP on or below the glidepath?** In 2017, the calculated 5-year average (2013–2017) of wet nitrogen deposition was 3.3 kg N/ha/yr, which is above the 2017 milestone of 2.4 kg N/ha/yr. Therefore, wet nitrogen deposition was not on or below the glidepath in 2017.

5.2 Long-term trend analyses for Rocky Mountain National Park and other regional sites

Changes in nitrogen in precipitation were evaluated over the 34-year period of record at the Loch Vale site, which collected the first full year of data starting in 1984. Statistical trends for several different parameters provide information on how nitrogen has changed over time and whether nitrogen inputs to RMNP ecosystems have increased, decreased, or remained unchanged. The parameters include wet nitrogen deposition (kg N/ha/yr), precipitation-weighted mean nitrate and ammonium concentrations in microequivalents per liter (μeq/L), and precipitation depth in centimeters (cm). Trend analyses on deposition data provide ecological relevance to the resource management goal for RMNP. Additionally, trend analyses on concentrations, which removes variability due to precipitation amount, provides information more closely coupled to air quality at individual sites and allow for comparison between sites.

NADP/NTN data from Loch Vale are compared to sites within RMNP at lower elevations. Beaver Meadows is located at 2,490 m (8,169 ft) and Kawuneechee Meadow, which has now collected data for 5 years, is located at 2,633 m (8,638 ft). The data are also compared to three sites outside of the park including Niwot Saddle at 3,520 m (11,549 ft) and Sugarloaf at 2,524 m (8,281 ft) that are located in the mountains 26.6 km (16.5 mi) and 36.2 km (22.5 mi) southeast of Loch Vale, respectively. The sites complement each other as paired monitoring sites with elevation differences similar to Loch Vale and Beaver Meadows. The NADP/NTN site at Pawnee is at a much lower elevation (1,641 m; 5,384 ft), located 96 km (59.7 mi) east of Loch Vale on the plains of eastern Colorado, near agricultural sources. These additional sites provide regional context and are listed in Table 1 and shown in Figure 3. All of the sites are located on the eastern slope of the Continental Divide and are exposed to similar Front Range emission sources, except for Kawuneechee Meadow which is located on the western slope.

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	34	3,159 m (10,364 ft)	–
Beaver Meadows (RMNP)	CO19	37	2,490 m (8,169 ft)	11 km (6.8 mi)
Kawuneechee Meadows (RMNP)	CO09	5	2,633 m (8,638 ft)	14.5 km (9 mi)
Niwot Saddle	CO02	32	3,520 m (11,549 ft)	26.6 km (16.5 mi)
Sugarloaf	CO94	31	2,524 m (8,281 ft)	36.2 km (22.5 mi)
Pawnee	CO22	38	1,641 m (5,384 ft)	96 km (59.7 mi)

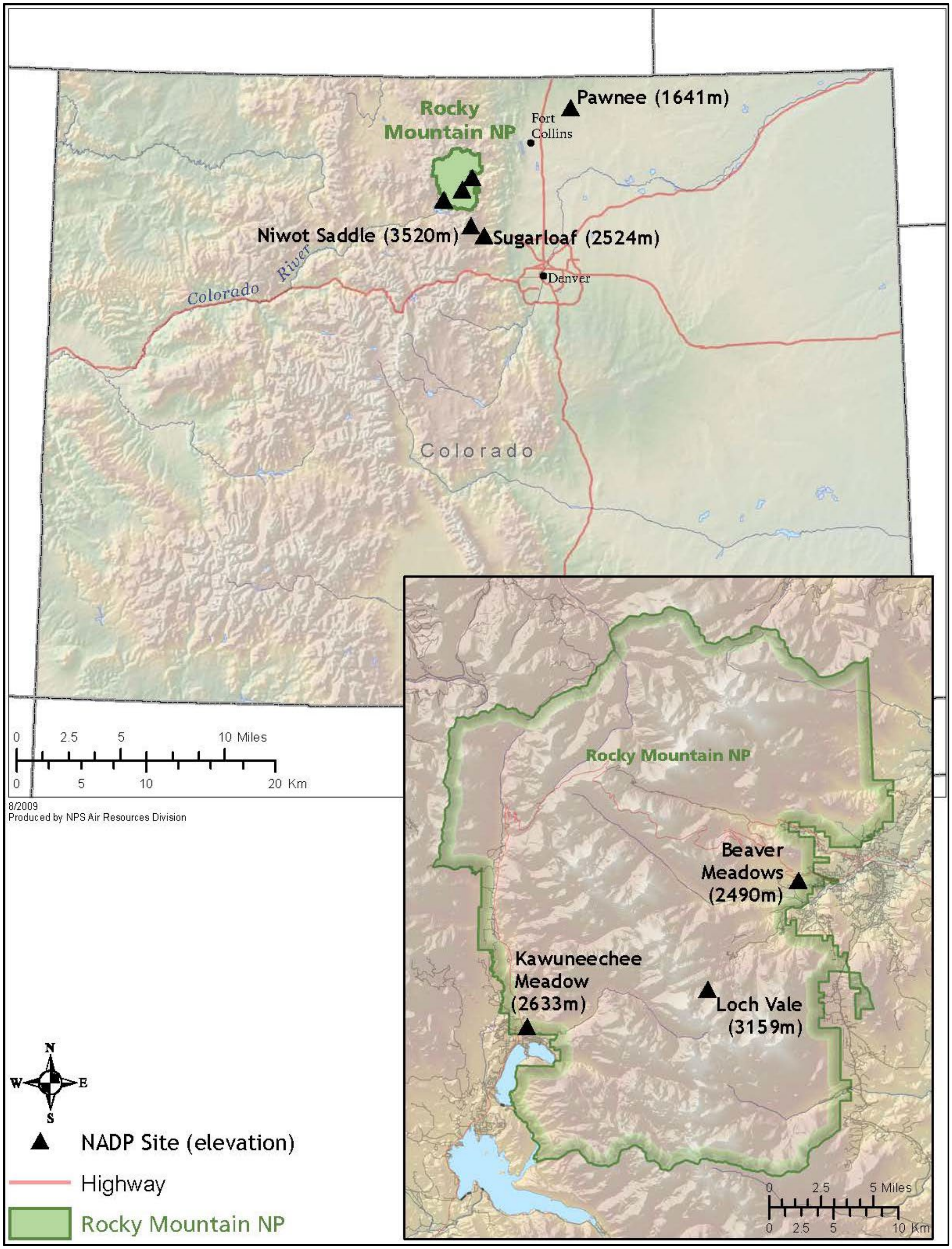

Figure 3. Map of NADP/NTN sites in and near Rocky Mountain National Park used in trends analysis. Elevation is shown in meters (m) in parentheses.

Figures 4a–f show annual data for the period of record at each of the six sites for deposition, concentration, and precipitation. The Y-axes for each graph are different for each site in order to best show patterns over time. Precipitation amount varied substantially among these six sites over the periods of record, which range from 5–38 years. The higher elevation sites record much more precipitation than the lower elevation sites. Pawnee (at the lowest elevation) records the least amount of precipitation on average. Precipitation at Loch Vale was above average in 2017 but varied widely at the other sites. In 2017, precipitation was high at Beaver Meadows compared to previous years, low at Kawuneechee Meadow and Niwot Saddle, and average at Sugarloaf and Pawnee.

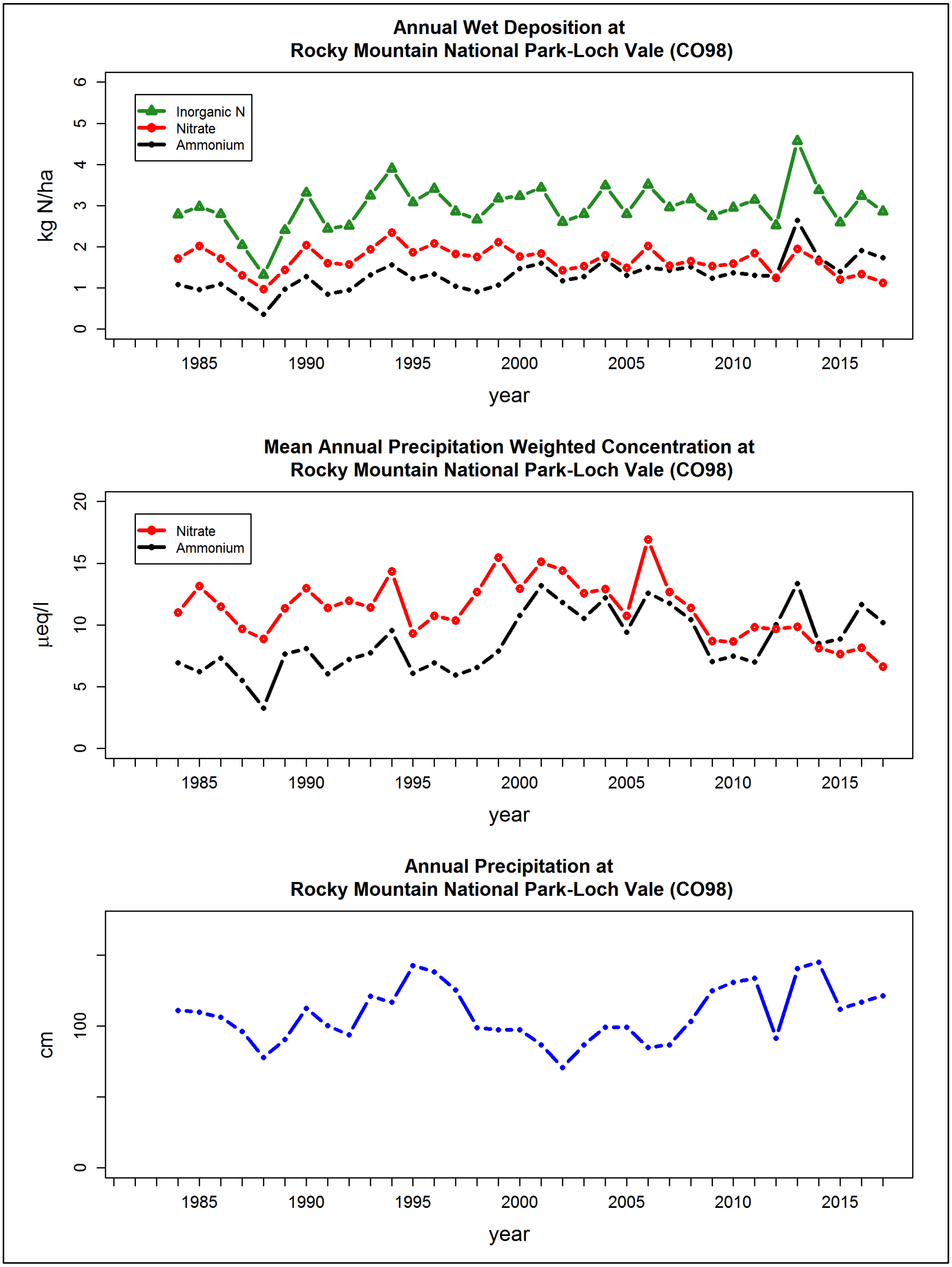

Figure 4a. Annual wet deposition, concentrations, and precipitation for RMNP – Loch Vale.

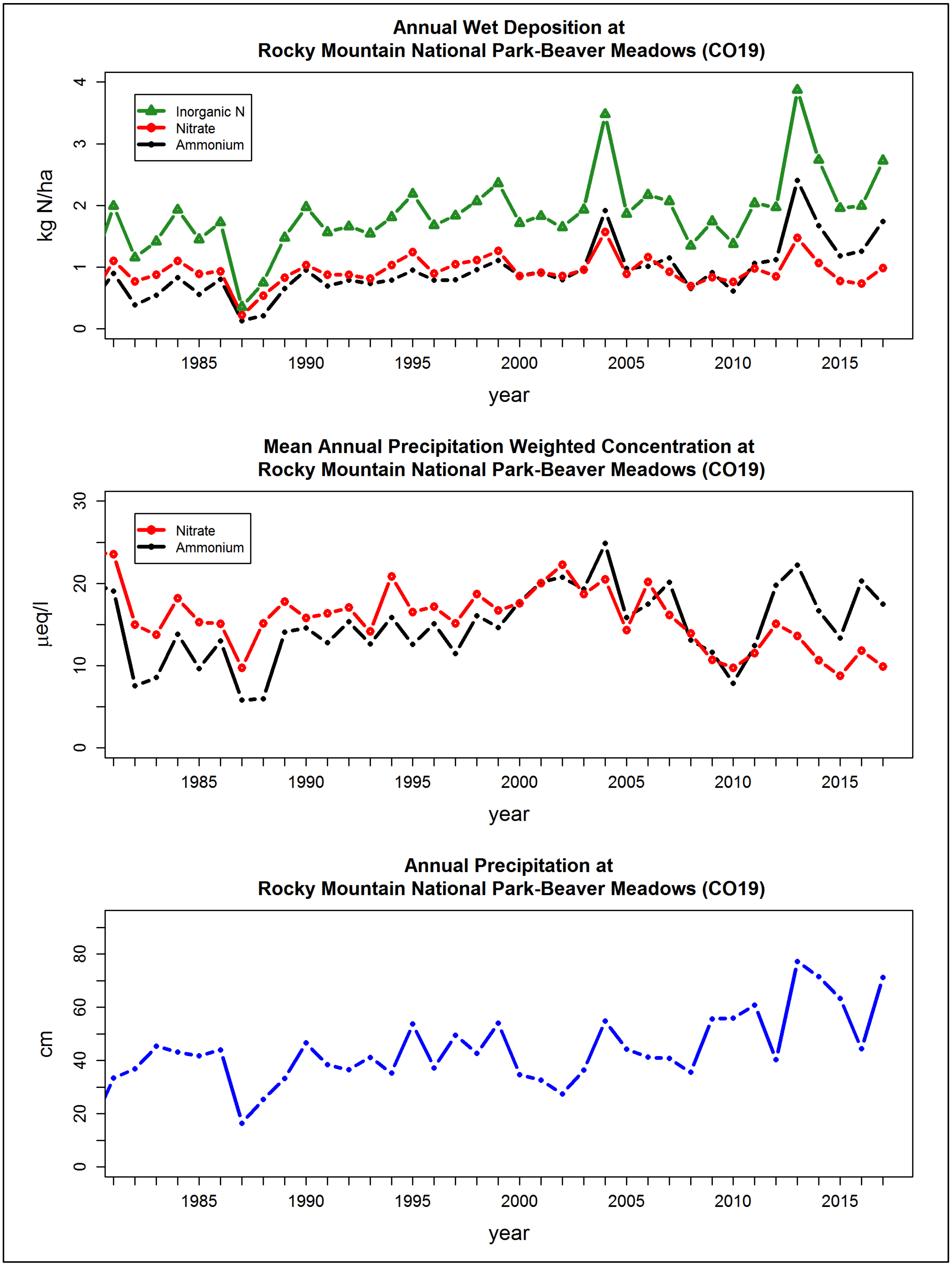

Figure 4b. Annual wet deposition, concentrations, and precipitation for RMNP – Beaver Meadows.

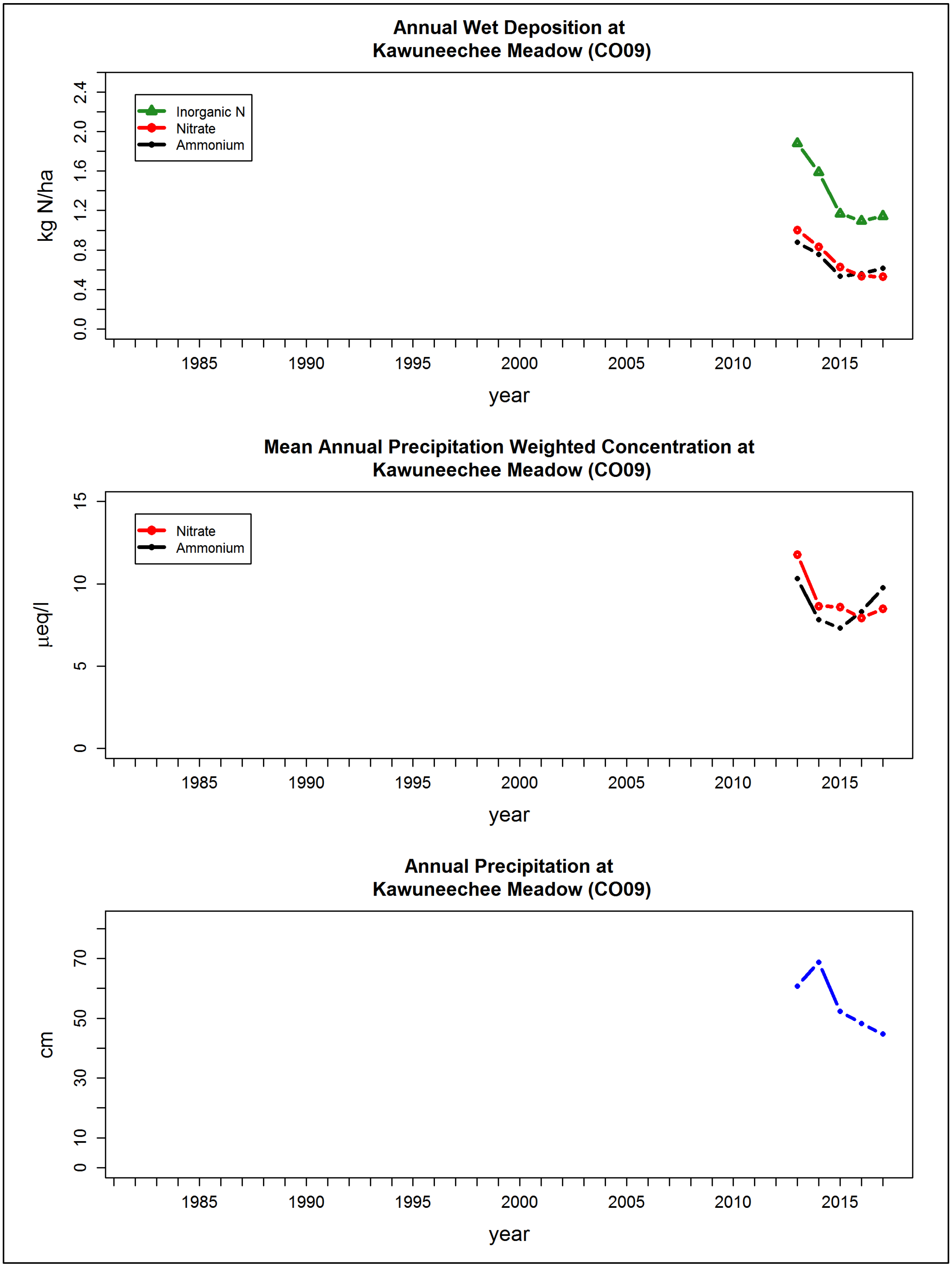

Figure 4c. Annual wet deposition, concentrations, and precipitation for RMNP – Kawuneechee Meadow.

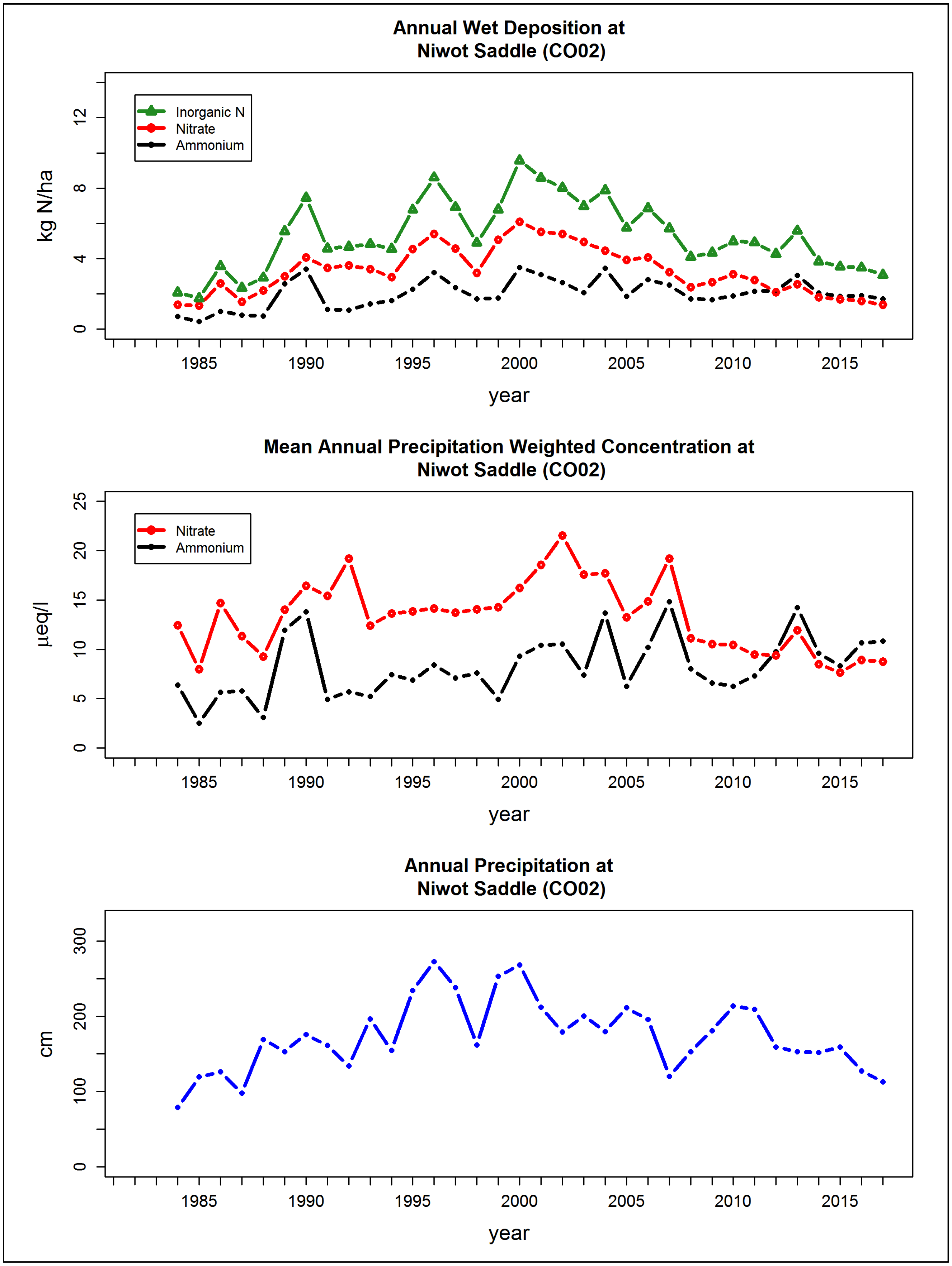

Figure 4d. Annual wet deposition, concentrations, and precipitation for Niwot Saddle.

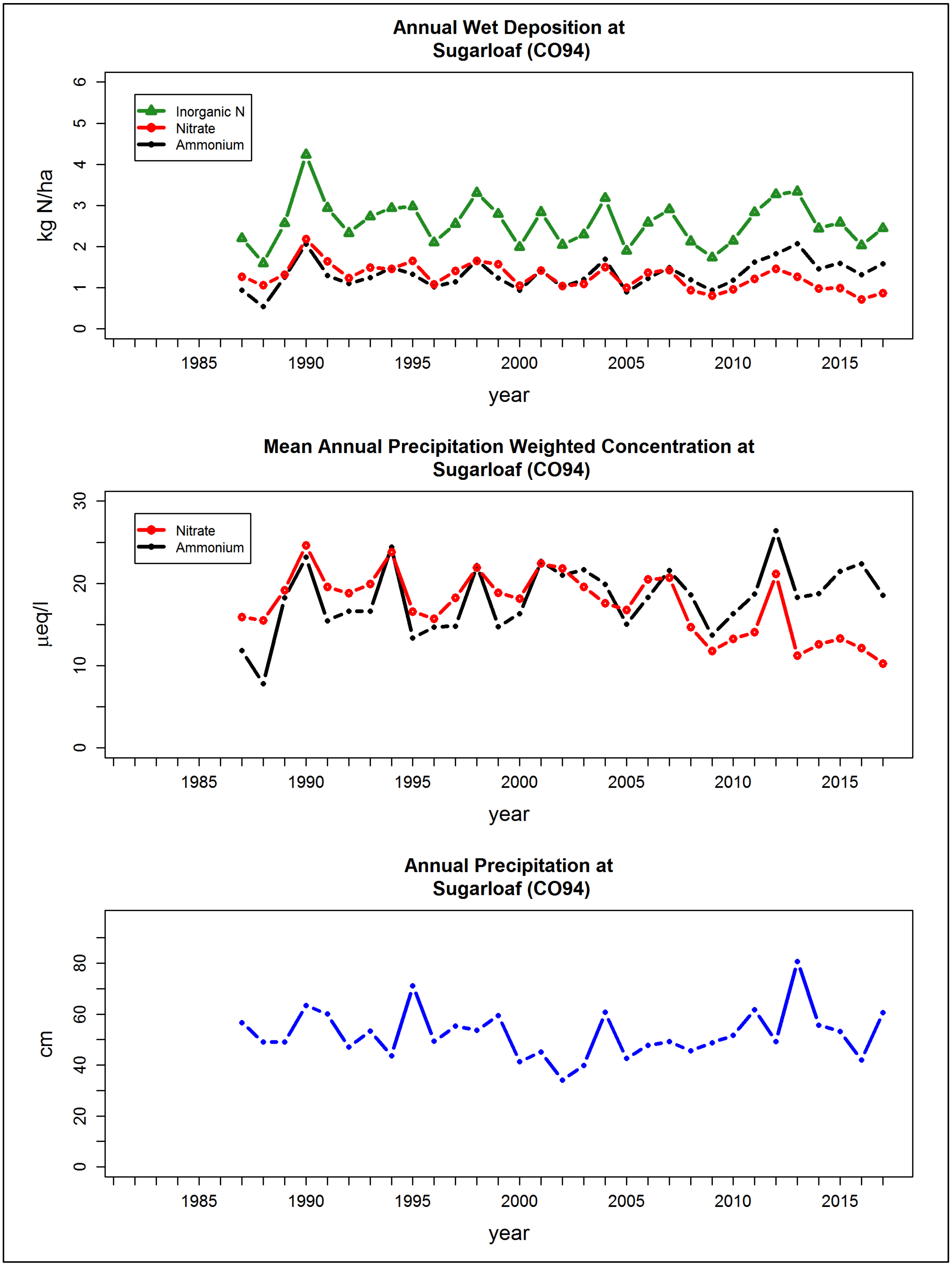

Figure 4e. Annual wet deposition, concentrations, and precipitation for Sugarloaf.

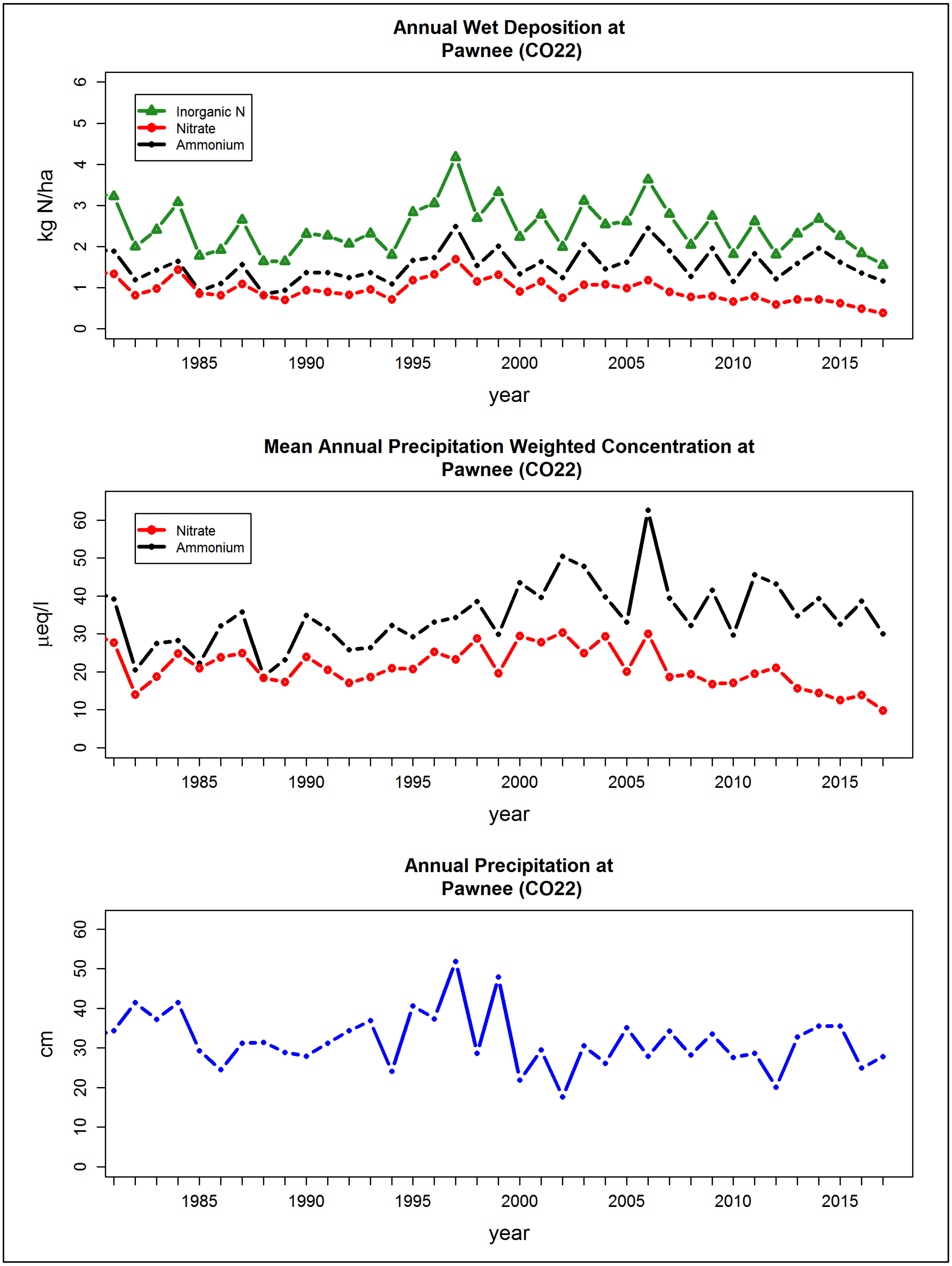

Figure 4f. Annual wet deposition, concentrations, and precipitation for Pawnee.

Wet nitrogen deposition generally ranged from 1.0 to 3.0 kg N/ha/yr at all six sites in 2017. This is the general range over the period of record as well, with the exception of Niwot Saddle, where deposition has often been above 4.0 kg N/ha/yr. Niwot Saddle is the only site included in this analysis that is located above treeline, where blowing snow has caused an over-estimation of precipitation (Williams et al. 1998). Nitrate deposition was higher than ammonium deposition at Loch Vale until 2000 when contributions of ammonium and nitrate to nitrogen deposition became approximately equal. In 2013, ammonium deposition began exceeding nitrate deposition at Loch Vale, and at other sites in a similar timeframe. By comparison, 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. Through 2012, nitrate concentrations generally exceeded ammonium concentrations at all sites except Pawnee. In 2013, ammonium concentrations exceeded nitrate concentrations at all sites for the first time in the period of record, except for Kawuneechee Meadow, which is on the western slope. At Kawuneechee Meadow, ammonium and nitrate concentrations were approximately equal in 2016, and then ammonium concentrations exceeded nitrate concentrations in 2017.

Monthly data from 2013 and 2016 at Loch Vale showed high precipitation amounts in April, coupled with high ammonium concentrations that resulted in a large amount of nitrogen deposition occurring in April (Morris 2015, Morris et al. 2018). By contrast, precipitation in 2017 was highest in February, April, and September, and very low in June (Figure 5). Concentrations of nitrate and ammonium were highest during the summer months, not during April as in previous years. Nitrogen deposition in 2017 was more evenly distributed over the year with highest rates occurring in February, April, July, August, and September.

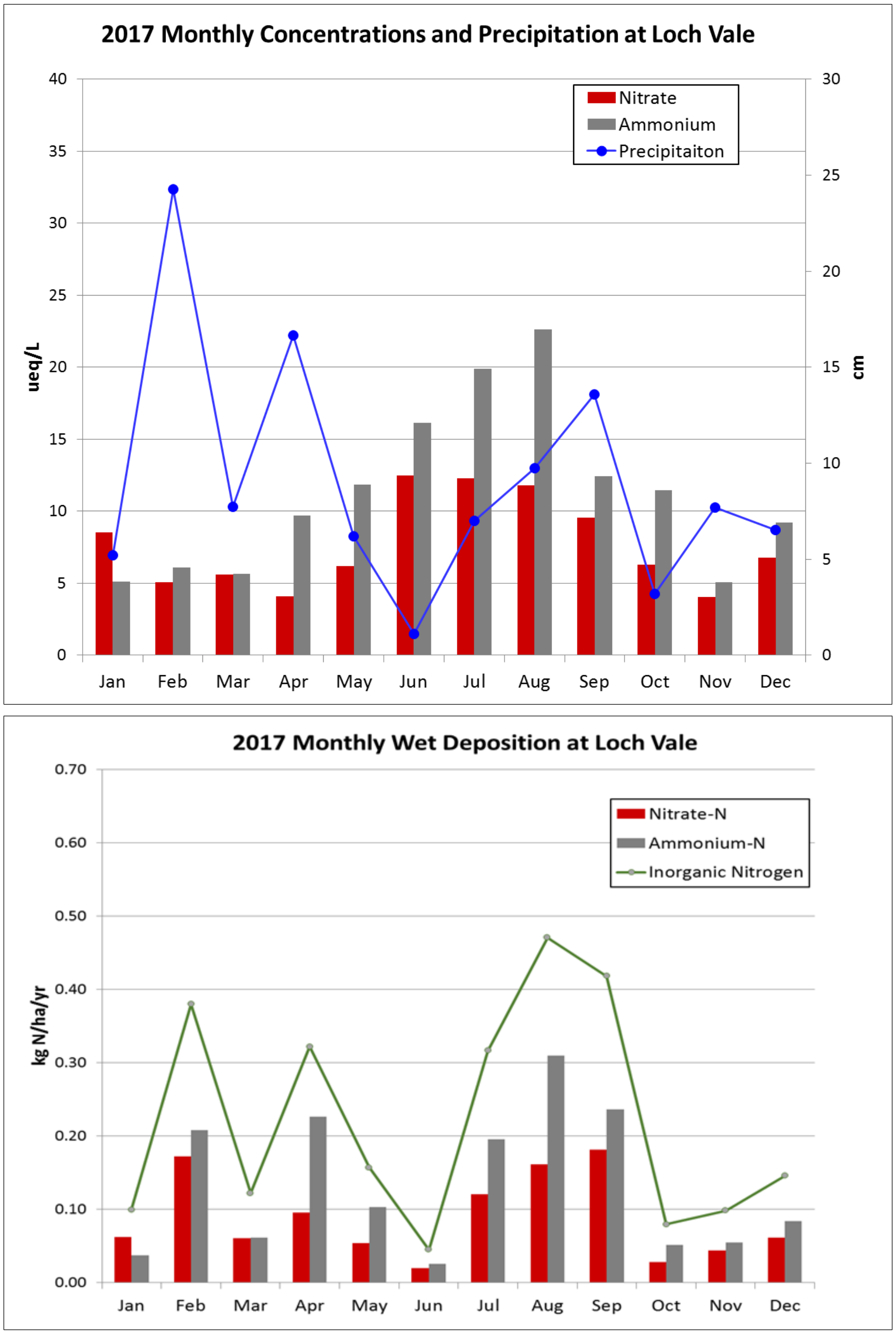

Figure 5. 2017 monthly data for Loch Vale; nitrate and ammonium concentrations and precipitation amount (top), nitrate-nitrogen, ammonium-nitrogen and inorganic nitrogen deposition (bottom).

Tables 2-5 show results from the trend analyses for different periods of record through 2017 for the long-term sites. Trends were computed using a computer code for the Kendall family of trend tests (Helsel and Frans 2006, Helsel et al. 2006). Trends in annual deposition and precipitation were run

on annual data using the Mann-Kendall test. Trends in precipitation-weighted mean concentrations were run on seasonal (quarterly) data using the seasonal Kendall test. Trends were evaluated for statistical significance at the 95 percent confidence level (p-value ≤ 0.05). The seasonal Kendall test 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 (Helsel et al. 2006). 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). Appendix C contains a detailed description of the methods used for trends analysis in this report.

Table 2. Long-term trends in **wet nitrogen deposition** over the period of record (through 2017). Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05).

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trends
Loch Vale	1984	0.015	0.127	no trend
Beaver Meadows	1981	0.020	0.002	increasing
Niwot Saddle	1986	-0.014	0.887	no trend
Sugarloaf	1987	-0.003	0.812	no trend
Pawnee	1980	-0.002	0.865	no trend

Table 3. Long-term trends in **precipitation-weighted mean ammonium concentrations** over the period of record (through 2017). Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05).

Site Name	Start Year	Trend (μeq/L/yr)	P-value	Significant Trends
Loch Vale	1984	0.137	<0.001	increasing
Beaver Meadows	1981	0.203	<0.001	increasing
Niwot Saddle	1986	0.139	0.003	increasing
Sugarloaf	1987	0.182	0.018	increasing
Pawnee	1980	0.303	0.005	increasing

Table 4. Long-term trends in **precipitation-weighted mean nitrate concentrations** over the period of record (through 2017). Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05).

Site Name	Start Year	Trend (μeq/L/yr)	P-value	Significant Trends
Loch Vale	1984	-0.074	0.048	decreasing
Beaver Meadows	1981	-0.133	0.007	decreasing
Niwot Saddle	1986	-0.111	0.099	no trend
Sugarloaf	1987	-0.230	0.002	decreasing
Pawnee	1980	-0.208	0.013	decreasing

Table 5. Long-term trends of **precipitation** over the period of record (through 2017). Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05).

Site Name	Start Year	Trend (cm/yr)	P-value	Significant Trends
Loch Vale	1984	0.492	0.236	no trend
Beaver Meadows	1981	0.577	0.003	increasing
Niwot Saddle	1986	0.256	0.775	no trend
Sugarloaf	1987	0.007	0.973	no trend
Pawnee	1980	-0.148	0.154	no trend

Wet nitrogen deposition showed a statistically significant increasing trend at only one site, Beaver Meadows, over the period of record (Table 2, p-value=0.002). An increasing trend in precipitation amount was also significant at Beaver Meadows (Table 5, p-value =0.003). Precipitation-weighted mean ammonium concentrations increased significantly over the period of record at all sites (Table 3, p-values ≤ 0.018). Precipitation-weighted mean nitrate concentrations decreased significantly at four of the five sites, including Loch Vale, Beaver Meadows, Sugarloaf, and Pawnee over the period of record (Table 4, p-value ≤ 0.048).

The analysis of long-term trends answers the question: **Has nitrogen deposition decreased at RMNP and other sites in the region?** A significant increasing trend in wet nitrogen deposition at Loch Vale in RMNP was reported for 1984–2000 (p-value < 0.05) (Burns 2003). The data indicate that the trend in wet nitrogen deposition at Loch Vale is no longer increasing, suggesting progress toward NDRP goals. However, a significant increase in wet nitrogen deposition at Beaver Meadows in RMNP was reported for 1981–2017 (p-value=0.002).

Long-term trends at Loch Vale were generally consistent with trends at other Front Range sites, indicating that data from Loch Vale are not unique. Therefore, the answer to the question is: nitrogen

deposition has not decreased at Loch Vale in RMNP or other sites in the region over the long-term with the exception of Beaver Meadows in RMNP, where nitrogen deposition was increasing.

5.3 Short-term trend analyses for Rocky Mountain National Park and other regional sites

While long-term trends are more robust, trends in nitrogen deposition and concentrations over a more 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 are used in the analysis. Due to this, trend analyses were evaluated using two time periods covering the last 5 (2013–2017) and 7 (2011–2017) years. Tables 6-9 show the results of the trend analysis for the individual sites, wherein statistically significant trends (p-value ≤ 0.05) are identified.

Table 6. Short-term trends of **wet nitrogen deposition** for 5 year (2013–2017) and 7 year (2011–2017) time periods. No significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

Site Name	5 year			7 year		
	Trend (kg N/ha/yr)	P-value	Significant Trends	Trend (kg N/ha/yr)	P-value	Significant Trends
Loch Vale	-0.386	0.221	no trend	-0.043	1.000	no trend
Beaver Meadows	-0.331	0.462	no trend	-0.003	1.000	no trend
Kawuneechee Meadow	-0.218	0.086	no trend	NA	NA	NA
Niwot Saddle	-1.03	0.296	no trend	-0.322	0.221	no trend
Sugarloaf	-0.214	0.462	no trend	-0.160	0.230	no trend
Pawnee	-0.285	0.308	no trend	-0.092	0.707	no trend

Table 7. Short-term trends for **precipitation-weighted mean ammonium concentrations** for 5 year (2013–2017) and 7 year (2011–2017) time periods. No significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

Site Name	5 year			7 year		
	Trend (µeq/L/yr)	P-value	Significant Trends	Trend (µeq/L/yr)	P-value	Significant Trends
Loch Vale	0.496	0.254	no trend	0.442	0.175	no trend
Beaver Meadows	-0.329	0.769	no trend	0.310	0.794	no trend
Kawuneechee Meadow	0.139	0.834	no trend	NA	NA	NA

Table 7 (continued). Short-term trends for **precipitation-weighted mean ammonium concentrations** for 5 year (2013–2017) and 7 year (2011–2017) time periods. No significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

Site Name	**5 year**			**7 year**		
Niwot Saddle	-0.556	0.857	no trend	0.225	0.708	no trend
Sugarloaf	0.013	0.862	no trend	0.477	0.091	no trend
Pawnee	-0.945	0.477	no trend	-2.13	0.073	no trend

Table 8. Short-term trends for **precipitation-weighted mean nitrate concentrations** for 5 year (2013–2017) and 7 year (2011–2017) time periods. Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

	5 year			**7 year**		
Site Name	**Trend (µeq/L/yr))**	**P-value**	**Significant Trends**	**Trend (µeq/L/yr)**	**P-value**	**Significant Trends**
Loch Vale	-0.296	0.120	no trend	-0.459	0.021	decreasing
Beaver Meadows	-0.686	0.281	no trend	-0.403	0.143	no trend
Kawuneechee Meadow	-0.282	0.35	no trend	NA	NA	NA
Niwot Saddle	0.177	0.880	no trend	-0.060	0.773	no trend
Sugarloaf	-0.486	0.487	no trend	-0.324	0.264	no trend
Pawnee	-1.236	0.041	decreasing	-1.61	0.013	decreasing

Table 9. Short-term trends for **precipitation** for 5 year (2013–2017) and 7 year (2011–2017) time periods. No significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

	5 year			**7 year**		
Site Name	**Trend (cm/yr)**	**P-value**	**Significant Trends**	**Trend (cm/yr)**	**P-value**	**Significant Trends**
Loch Vale	-6.37	0.806	no trend	3.47	1.000	no trend
Beaver Meadows	-6.36	0.221	no trend	0.641	1.000	no trend
Kawuneechee Meadow	-4.165	0.086	no trend	NA	NA	NA
Niwot Saddle	3.09	1.000	no trend	-5.02	0.221	no trend

Table 9 (continued). Short-term trends for **precipitation** for 5 year (2013–2017) and 7 year (2011–2017) time periods. No significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, 7 years of data not available].

Site Name	5 year			7 year		
	Trend (cm/yr)	P-value	Significant Trends	Trend (cm/yr)	P-value	Significant Trends
Sugarloaf	-5.94	0.462	no trend	-2.01	0.548	no trend
Pawnee	-1.28	1.000	no trend	1.40	0.452	no trend

There were no significant trends in wet nitrogen deposition or precipitation amount at any sites over the past 5 or 7-years (Tables 6 and 9). There were also no significant trends in precipitation-weighted mean ammonium concentrations over the short-term (Table 7). Precipitation-weighted mean nitrate concentrations decreased at Loch Vale (7-yr) and Pawnee (5- and 7-yr period) (Table 8, p-values ≤ 0.041). The analysis of short-term trends answers the question: **Has nitrogen deposition recently decreased at RMNP and at other sites in the region?** Results indicate that nitrogen deposition has not decreased or increased at RMNP in the last 5 to 7 years.

6. Summary

Achievement of the goals of the NDRP will be determined by the weight of evidence. Results from the three analyses provided in this report are summarized below:

1. Is current wet nitrogen deposition in RMNP on or below the NDRP glidepath?

   Wet nitrogen deposition (5-year rolling average) at Loch Vale in RMNP in 2017 was 3.3 kg N/ha/yr, which is above the glidepath (2.4 kg N/ha/yr).

2. Has wet nitrogen deposition decreased at RMNP and other sites in the region?

   Wet nitrogen deposition has not decreased at RMNP or other sites in the region over the long-term. Over the entire period of record, wet nitrogen deposition showed no significant trend at Loch Vale in RMNP (1984-2017). Previously, a significant increase in wet nitrogen deposition at Loch Vale in RMNP was reported for 1984–2000 (Burns 2003); however, the trend for 1984–2017 is not significant, indicating some progress toward NDRP goals. Data from Beaver Meadows in RMNP, however, indicate an increase in wet nitrogen deposition and precipitation for the period of record (1981-2017). Over the long term, ammonium concentrations showed a statistically significant increasing trend at all sites and nitrate concentrations showed a significant decreasing trend at four of the five sites.

3. Has wet nitrogen deposition recently decreased at RMNP and at other sites in the region?

   In more recent years (2011-2017), wet nitrogen deposition showed no significant trend at monitoring sites in RMNP. Ammonium concentrations also showed no significant trend over the short-term, however nitrate concentrations did significantly decrease at two of the six sites (Loch Vale and Pawnee).

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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 the Aerochem Metrics Model 301 precipitation collector[1] and mechanical Belfort rain gage were installed. 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).

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 operated side-by-side for five complete water years (2009-2014). During these years, this site consisted of two independent precipitation collectors and NOAH IV rain gages with satellite telemetry. The co-located gage was left in place in order to serve as a back-up, 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 NADP monitoring site (AMoN CO98) and one near the Long's Peak Ranger Station at the Clean Air Status and Trends Network (CASTNET) and Interagency Monitoring of Protected Visual Environments (IMPROVE) sites (AMoN CO88) at an elevation of 2,743 meters (8,999 feet). 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.

[1]Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Table A-1. 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.)

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, chloride, ammonium, and base cations are determined by laboratory analysis 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).

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

where:

$\overline{C}_{ppt.wt}$ = 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 in order 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 B-1. 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 x 1 + 5 x 6)/(1+6)] and is more heavily influenced by the larger precipitation event, whereas an arithmetic mean is 10 mg/L.

Precipitation concentrations can also be presented in terms of microequivalents per liter (µeq/L). An equivalent is defined as a mass of an element that can combine with 1 gram of hydrogen in a

chemical reaction. It is a way of normalizing for ionic charge. Nitrate ion has one negative charge [NO_3^-] and ammonium has one positive charge [NH_4^+], once converted to µeq/L the ion concentrations can be compared to each other. Concentrations in mg/L are converted to µeq/L by using the factors listed in the following table.

Table B-2. Conversion factors for ion concentrations, mg/L to µeq/L.

Ion	Conversion Factor
Ammonium	1 mg/L = 55.4371 µeq/L
Nitrate	1 mg/L = 16.12776 µeq/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).

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

where:

D_w = wet deposition, kg/ha

$\overline{C}_{ppt.wt}$ = 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.

$$D_{IN} = \left(D_{NH_4^+} \times \frac{14.01}{18.01} \right) + \left(D_{NO_3^-} \times \frac{14.01}{62.01} \right) \qquad \text{(Eq. 3)}$$

where:

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

$D_{NH_4^+}$ = wet deposition of NH_4, kg/ha

$D_{NO_3^-}$ = wet deposition of NO_3, kg/ha

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

By M. Alisa Mast, U.S. Geological Survey

The trends in precipitation chemistry for this report are for the parameters and sites listed below using the trend methods described in this document. 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 SKT performs a Mann-Kendall Test (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. However, the MKT was used for trends in nitrogen (N) deposition and precipitation amount, because seasonality is incorporated within the annual value (i.e. 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). 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.

NADP sites

- CO98 - Loch Vale
- CO19 - Beaver Meadows
- CO09 – Kawuneechee Meadow
- CO02 - Niwot Saddle
- CO94 - Sugarloaf
- CO22 - Pawnee

Parameters

- Seasonal precipitation-weighted mean NH_4^+ concentrations in µeq/L/yr (winter, spring, summer, fall)
- Seasonal precipitation-weighted mean NO_3^- concentrations in µeq/L/yr (winter, spring, summer, fall)
- Annual inorganic nitrogen deposition in kg N/ha/yr
- Annual precipitation amount in cm

Time frame

- Period of Record (POR)

- 5 year
- 7 year

Trend Tests

- Seasonal Kendall Test (SKT) for seasonal concentrations (NH_4 and NO_3)
- Mann Kendall Test (MKT) for annual inorganic nitrogen deposition and precipitation amount

Procedure

1. Retrieve Data

Annual and seasonal precipitation chemistry data can be retrieved from the National Atmospheric Deposition Program (NADP) web site at http://nadp.slh.wisc.edu/data/NTN/. Use "Select data from a single site using a site list ", and select one of the stations from the list. Next, select the Data tab, and then "Annual Averages, Calendar Year". Repeat this for all sites (CO98, CO19, CO09, CO02, CO94, and CO22).

Retrieve seasonal data (winter, spring, summer, fall) for precipitation-weighted mean concentrations (in µeq/L) and annual data for deposition (in kg/ha/yr) and precipitation amount (in cm) based on calendar years (January to December) by selecting "Seasonal Averages" under the Data tab. 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.

Pull data for the entire period of record in tab or comma delimited format and import into Excel or Access for further file formatting. In order to run the program you must remove all -9s from the file and replace with empty cells. Remove the first year of data from each station if it is incomplete (most stations began operation in the summer or fall months so the first year represents a partial year of data). Include all seasons and years when the NADP completeness criterion 2 is $\geq$ 90 percent (Morris et al. 2012).

2. Trend Calculations

This section describes how to set up input files and run the Seasonal Kendall test (SKT) and Mann-Kendall test (MKT) using the NADP data. Annual data (one season per year) tested with the SKT yields the same result as a MKT. Therefore both seasonal and annual results can be tested using the method outlined below.

The first line of each input file should follow this format:

```
2 0   NH4 Concentrations Station CO22
```

It is important to have "2" in column 1 of line 1 and "0" in column 3 of line 1. A description can be added starting in column 9. The next lines of the file contain the data with Year in the first column, Season (winter = 1, spring = 2, summer = 3, fall = 4) in the second column and the Value (e.g. concentration) in the third column. The final files will be space delimited and should look something

like the examples below. For annual deposition and precipitation data, set the season equal to 1 for all years. Delete any lines with missing values.

Example input file for seasonal data from station CO22:

```
2 0  NH4 Concentrations Station CO22
1980 1 3.71
1980 2 7.37
1980 3 16.85
1980 4 17.02
1981 1 4.21
1981 2 19.84
1981 3 26.22
1981 4 9.48
1982 1 5.76
1982 2 13.80
1982 3 14.85
1982 4 6.59
1983 1 3.27
1983 2 10.25
1983 3 8.87
1983 4 6.59
-----continued-----
```

To compute a trend, copy the "Kendall.exe" file into the directory that contains the input file. Double click on the Kendall.exe icon to start the program. Enter the input file name (e.g. NH4CO22.txt) and provide a name for the output file to which the results are written (e.g. NH4CO22out.txt).

An example of an output file is shown below. In this example, the trend was 0.3930 µeq/L/yr with a p-value of 0.0089. Because the period of record was longer than 10 years the adjusted p-value should be reported. This adjustment corrects for serial correlation in the data set.

Example output file:

```
Seasonal Kendall Test for Trend US Geological Survey, 2005
Data set:  NH4 Station CO22
The record is 31 complete calendar years with 4 seasons per
year beginning in year 1980.
The tau correlation coefficient is 0.219
S = 407.
z = 3.450
p = 0.0006
p = 0.0089 adjusted for correlation among seasons (such as
serial dependence)
```

The adjusted p-value should be used only for data with more than 10 annual values per season. The estimated trend may be described by the equation:

$$Y = 22.48 + 0.3930 * Time$$

where Time = Year (as a decimal) - 1979.75 (beginning of first water year)

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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 Longs Peak Ranger Station (AMoN CO88) at a lower elevation of 2,743 meters (8,999 feet). Data are available at http://nadp.slh.wisc.edu/amon/ and are presented here for 2013–2017.

Figure D-1 compares ammonia concentrations at the RMNP sites versus the AMoN site in Fort Collins (AMoN CO13) at 1,570 meters (5,150 feet). Concentrations of ammonia are much higher at the Fort Collins site ranging mostly from 2-7 micrograms per cubic meter (μg/m^3), while the RMNP sites recorded ammonia concentrations that were less than 1.6 μg/m^3 throughout recent years.

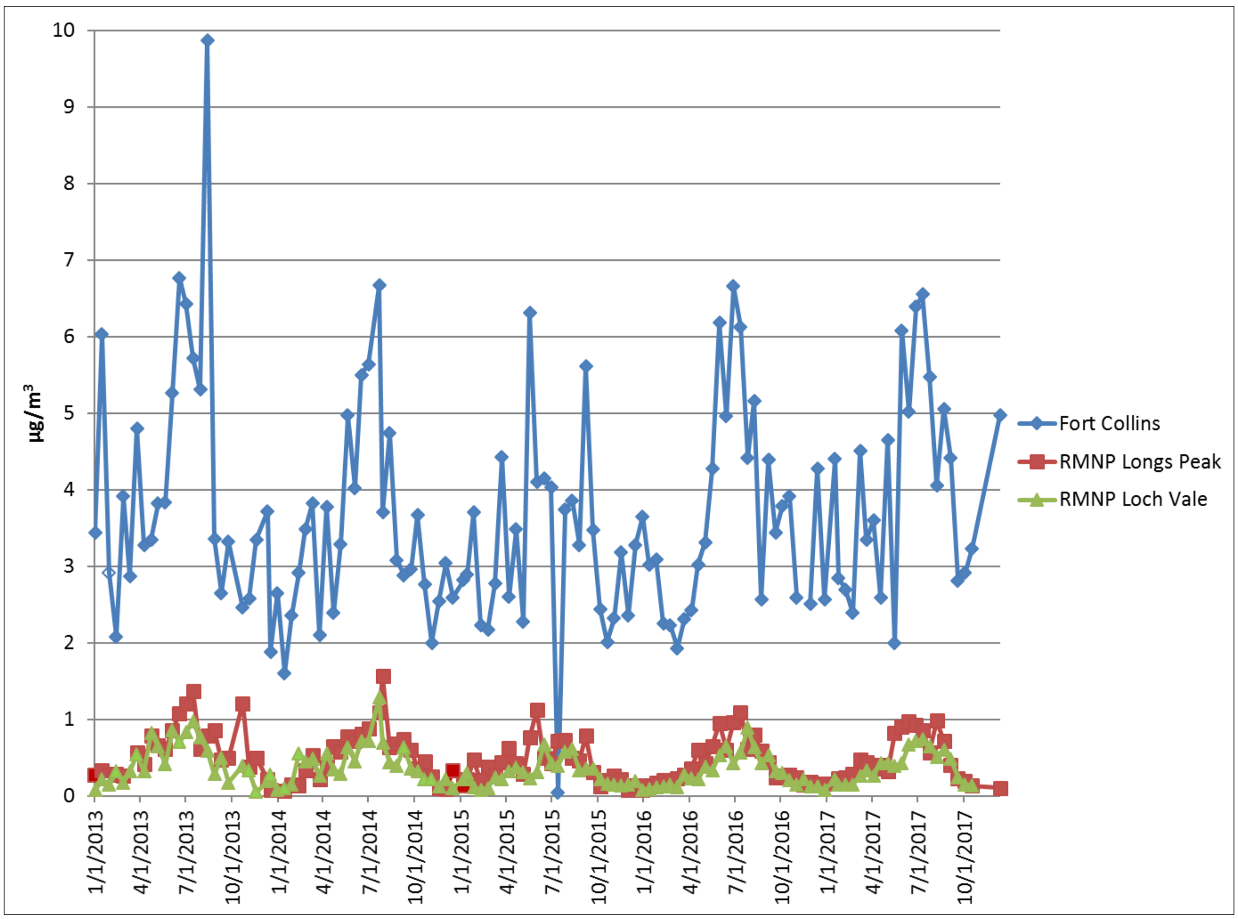

Figure D-1. Ammonia concentrations at Rocky Mountain National Park and Fort Collins, 2013–2017.

Figure D-2 takes a closer look at the data from the two sites in RMNP. Ammonia concentrations tended to be higher at the lower elevation Longs Peak site.

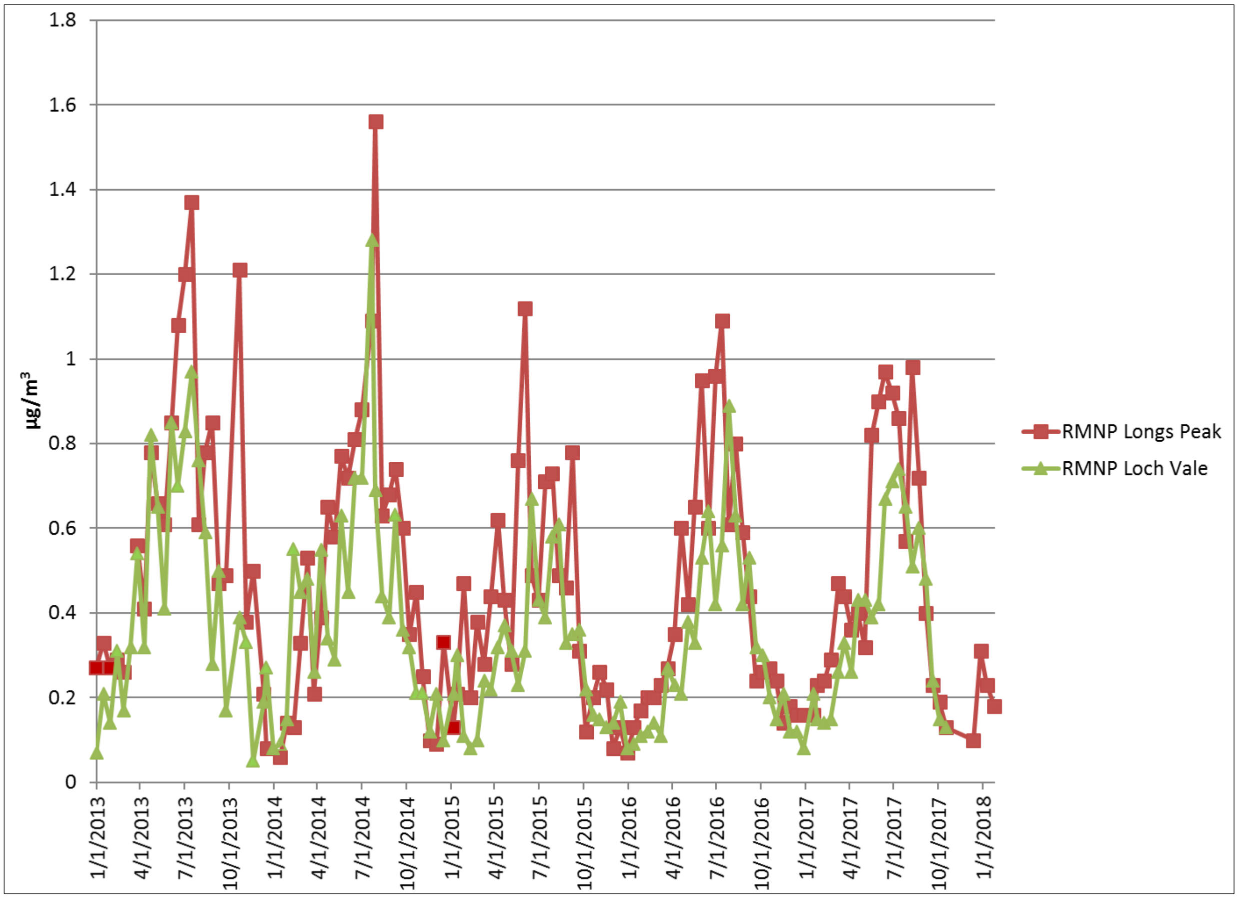

Figure D-2. Ammonia concentrations at Rocky Mountain National Park sites, 2013–2017.

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. An algorithm is under development in partnership with the EPA and other stakeholders to estimate deposition from ammonia concentrations.

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