



2018/2019 Data Summary of Wet Nitrogen Deposition at Rocky Mountain National Park

Natural Resource Report NPS/NRSS/ARD/NRR—2021/2339



ON THE COVER

Photograph of the wet deposition collector at Loch Vale in Rocky Mountain National Park
Photograph courtesy of Kristi Morris

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Abstract

The National Park Service is working with the Colorado Department of Public Health and Environment and the Environmental Protection Agency Region 8 (referred to as the Memorandum of Understanding agencies) to reduce atmospheric nitrogen deposition at Rocky Mountain National Park due to its detrimental effects on park ecosystems. The data summarized in this report informs these agencies, stakeholders, and the public about the current status and trends of nitrogen deposition in accordance with the RMNP Nitrogen Deposition Reduction Plan (NDRP). Analyses include assessment of progress along the glidepath and trend analyses for RMNP and other regional sites for the following time periods: long-term/period of record (>31 years), since 2006 when the NDRP was initiated, and short-term (the most recent 7 years). Wet N deposition in 2019 at Loch Vale in RMNP was not below glidepath. Long-term trends showed that N deposition levels are stable, with ammonium concentrations increasing and nitrate concentrations decreasing at most of the sites. Trends from 2006–2019 and 2013–2019 indicated that wet N deposition and ammonium concentrations were mostly stable, but nitrate concentrations decreased at some sites. There were several changes made to the methods in 2018, including a new approach for data substitution when sample concentrations and precipitation amounts were invalid or missing, and more strict criteria for reporting significant trends over time.

Introduction

The purpose of this data summary is to inform the Memorandum of Understanding (MOU) agencies, stakeholders, and the public about the current status and trends of wet nitrogen (N) deposition in accordance with the [Nitrogen Deposition Reduction Plan](#) (NDRP) for Rocky Mountain National Park (RMNP). Full reports on Monitoring and Tracking Wet Nitrogen Deposition at RMNP were peer-reviewed and published annually from 2009 to 2013. In 2014, however, it was decided that a summary of the data would be compiled and distributed annually between milestone years. This data summary is reviewed by the MOU agencies including the National Park Service, the Environmental Protection Agency Region 8 and the Colorado Department of Public Health and Environment. During milestone years (2022, 2027, and 2032), a full report will be published and undergo external review.

The analyses presented here to track wet nitrogen deposition at RMNP, include:

1. assessment of progress along the glidepath, and
2. trend analyses for RMNP and other regional sites for the following time periods:
 - long-term/period of record (>31 years),
 - since 2006, and
 - short-term (the most recent 7 years).

Methods and Results

Background information and a complete description of the monitoring is provided in the last full report, [2017 Monitoring and Tracking Wet Nitrogen Deposition at Rocky Mountain National Park](#) (Morris et al. 2019). There were several changes made to the methods in 2018, including a new approach for data substitution when data (sample concentrations and precipitation amounts) were invalid or missing, and more strict criteria for reporting significant trends over time.

The challenges of collecting weekly data from remote high elevation monitoring sites like Loch Vale in RMNP has sometimes resulted in missing or invalid data, particularly during large snow events in winter and spring. NADP employs a rigorous quality assurance program to ensure accurate data that includes criteria on instrument operation, sample longevity in the field, and sample contamination. When equipment fails, samples are contaminated or fail other quality assurance checks, or operators are prevented from getting to the site within the allotted time frame, data are invalidated by the NADP. This can result in large fractions of the annual precipitation having invalid concentrations that are not used to calculate annual wet deposition. The failure of the rain gage can also result in large fractions of missing precipitation data.

Data Substitution

To account for *missing/invalid sample concentrations*, the standard NADP protocol is to substitute with the average precipitation-weighted concentration from valid samples during the year. While this protocol is appropriate for the majority of NADP sites across the US, it is problematic for high elevation sites in Colorado, where the majority of missing/invalid samples occurs during the winter. At these sites, winter concentrations are generally lower than summer concentrations by a factor of 2 to 4 times, and the substitution of an average concentration can produce an annual deposition rate that is biased high.

To address this bias, an alternate method for data substitution was developed that accounts for seasonal variations in N concentrations and the inverse relationship between concentration and precipitation. This model was then used to estimate concentrations for all samples with missing/invalid concentrations. More details on this method and a comparison of it to the NADP protocol were presented in Section 4.2 of the [RMNP Initiative: 2017 Milestone Report](#) and published in Schichtel et al. (2019).

It was shown that the modeled data substitution method produced annual deposition rates with smaller errors and biases than the standard NADP protocol. It also tended to reduce the 5-year average of wet N deposition. Error bars were estimated using a Monte Carlo methodology and were added to the 5-year average and removed from the glidepath, as previously presented. The bars are the 95th confidence intervals due to measurement error and the substitution for invalid concentrations.

The reduction of the 5-year average of wet N deposition along with the error bars, however, did not alter deposition levels enough to meet the 2017 Milestone. The modeled data substitution method provides a more accurate approach for substituting missing/invalid data, and therefore a less biased estimate of wet N deposition at Loch Vale.

To account for *missing/invalid precipitation amounts*, the standard NADP protocol substitutes with weekly measured sample volume. On average 92% of wet weekly samples had valid rain gage data at Loch Vale. The 8% of weeks with missing rain gage data were estimated to account for only 4% of the annual precipitation totals. However, in some years more than 20% of the weekly rain gage data were invalid, and up to 15% of the reported annual precipitation was estimated from sample volumes.

Using sample volume at Loch Vale underestimated the weekly precipitation totals by 48% on average. This also led to an underestimation of annual wet nitrogen deposition. The sample collector underestimates the precipitation totals due to a delay in collection while the sensor is triggered and the lid opens after precipitation begins, and high winds that blow snow out of the collector.

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) provides an alternative estimate of weekly precipitation rates. The PRISM 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 topographically complex and mountainous terrain. Daily PRISM precipitation estimates are available on a 4km grid over the conterminous US from 1981 to present. These data have been shown to produce relatively accurate annual precipitation totals in complex terrain (Daly et al., 2008; 2017) and at Loch vale (Schichtel et al., 2019). The NADP also uses PRISM data to spatially interpolate measured wet deposition across the US for their annual map products.

To minimize errors in the annual wet deposition at Loch Vale, weekly samples with missing rain gage data were replaced with estimates from PRISM as opposed to using sample volume estimates. This increased the annual deposition in years with large fractions of missing rain gage data, compensating for the overestimation resulting from the standard NADP protocol for handling missing concentration data. Consequently, the new procedures for substituting for missing concentration and precipitation data did not appreciably change the Loch Vale annual wet N deposition values.

The similarity of the wet N deposition values using the new data substitution methods compared to the standard NADP protocols suggests that the resource management goal of 1.5 kg/ha/yr derived from the hindcasting analysis remains suitable. This value is also supported in the literature for many other sites in the Rocky Mountains (Baron et al. 2011, Saros et al. 2011). However, the 2002–2006 baseline deposition value estimated by using PRISM was about 10% higher than using sample volume, therefore the baseline deposition rate in 2006 was adjusted from 3.1 to 3.3 kg N/ha/yr. This increase resulted in relatively small adjustments to the Milestones (Table 1).

Table 1. Adjustments to Baseline (2002–2006) Wet N Deposition and Milestones (kg N/ha/yr).

Year	Original Milestones	Milestones with New Baseline
Baseline	3.1	3.3
2012	2.7	2.9
2017	2.4	2.6
2022	2.1	2.2
2027	1.8	1.9
2032	1.5	1.5

At this time, the data substitution methods for invalid/missing sample concentrations and precipitation amounts are only available for Loch Vale because the models are site specific. There is potential of developing models for other regional monitoring sites included in this report at a later time. A publication on the precipitation substitution with PRISM method is being pursued.

Trends

NADP utilizes three data completeness criteria for sites to be included in their interpolated annual maps. The criteria include:

Criterion 1 – Percentage of time during the year for which valid samples are available (75%)

Criterion 2 – Percentage of time during the year for which valid precipitation amounts are available (90%)

Criterion 3 – Percentage of the total measured precipitation associated with valid samples for the year (75%)

In previous reports, trends were presented for the period of record (POR) and the most recent 7 and 5 years of data when sites met NADP Data Completeness Criteria 2. Trends will now be presented for the period of record (POR), since 2006 (when the NDRP went into effect), and the most recent 7 years of data. Annual data are shown with a solid symbol when NADP Data Completeness Criteria 1–3 are met. The symbol is open when the Criteria are not met. Trends are only presented if the Criteria are met for >70% of the years in the time period (i.e. 10 years of the 14-year 2006–2019 period or 5 years of the 7-year 2013–2019 period). Due to the minimum number of years required, the 7-year trend could be a 5-year trend, so a separate 5-year trend is not presented. Trends will always be presented for Loch Vale because the data were completed with the data substitution methods described above. The Niwot Ridge-Southeast NADP site (elevation 3015 m) was added to the regional trends analysis this year. The site is near Niwot Saddle (3520 m), has more complete data and started collecting data in 2006.

In a comparison of the “old” trend methods to the “new,” there were 7 changes in trends reported. In general, the requirement to meet more data completeness criteria made it less likely to report a significant trend. The data substitution method for Loch Vale changed the 7 year wet N deposition trend from decreasing to no trend and the 7 year nitrate concentration from no trend to decreasing.

Table 2. Changes in trends reported under new method. (NA, trend not available due to failure to meet data completeness criteria.).

Site	Constituent	Time period	Old Method	New Method
Sugar Loaf	Ammonium concentration	POR	increasing	no trend
Niwot Saddle	Ammonium concentration	POR	increasing	NA
Niwot Saddle	Nitrate concentration	POR	decreasing	NA
Loch Vale	Wet N deposition	7 year	decreasing	no trend
Kawuneechee Meadow	Wet N deposition	7 year	decreasing	NA
Loch Vale	Nitrate concentration	7 year	no trend	decreasing
Kawuneechee Meadow	Precipitation	7 year	decreasing	NA

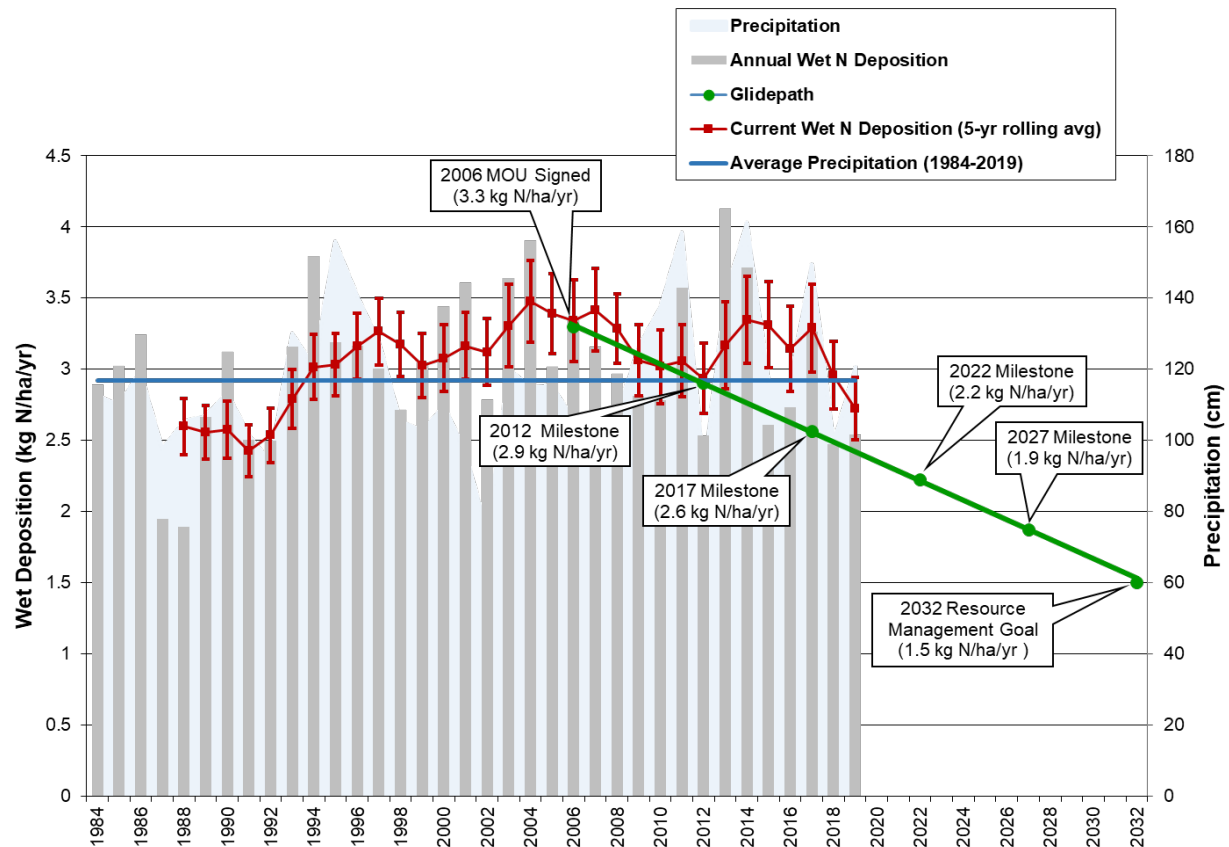


Figure 1. The glidepath compared to annual and 5-year average of wet N deposition. Annual wet N deposition in 2018 and 2019 was around 2.5 kg N/ha/yr, decreasing from 3.2 in 2017. The 5-year rolling average (2.7 ± 0.22 kg N/ha/yr) remains above the glidepath (~ 2.4 kg N/ha/yr). Error bars are based on a Monte Carlo simulation.

Wet N deposition data through 2019 are presented in Figures 2–9 and Tables 3–10 and are available on the [National Atmospheric Deposition Program \(NADP\) website](#).

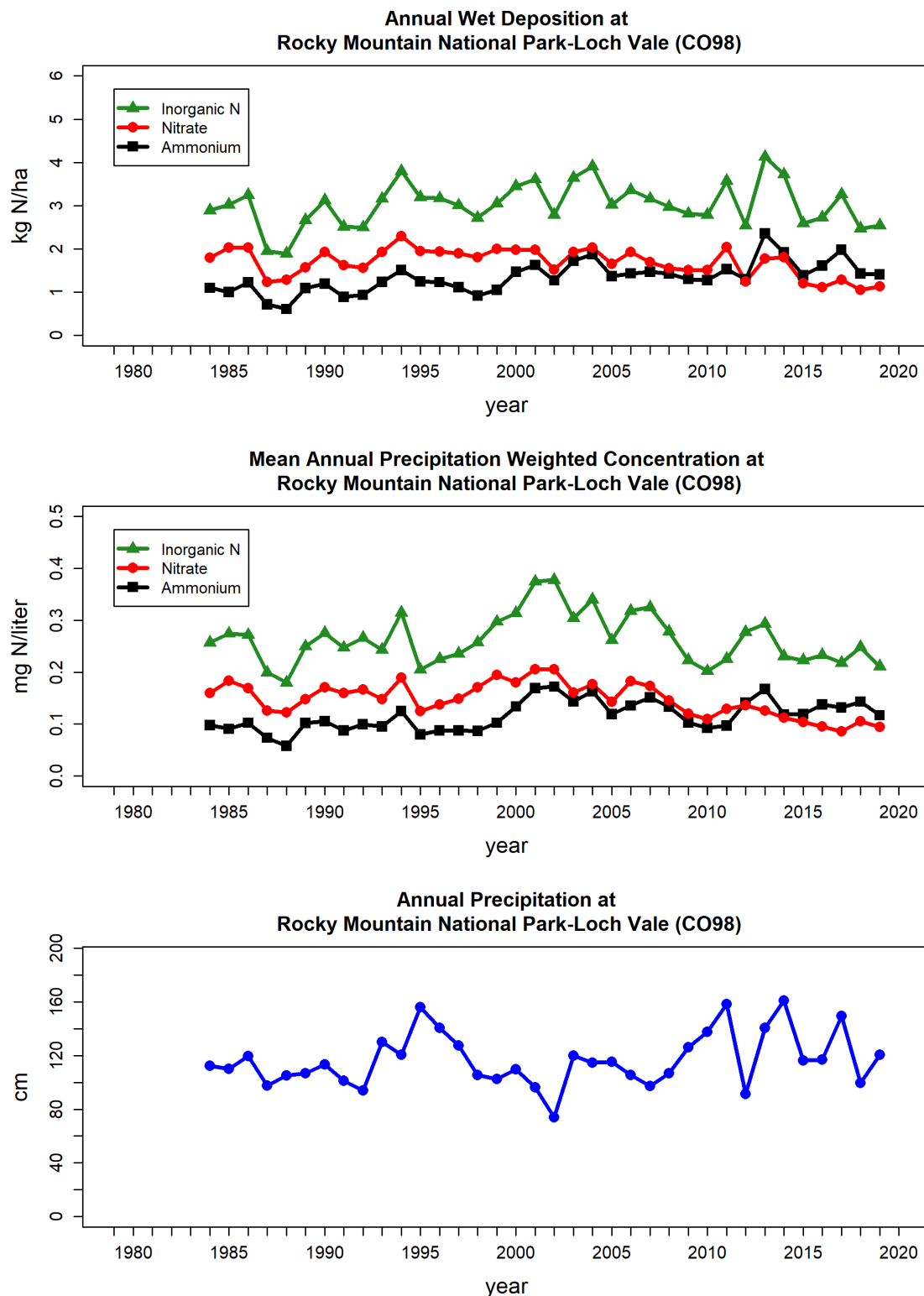


Figure 2. Data at Loch Vale, RMNP using the data substitution methods for missing/invalid sample concentration and precipitation amount. Precipitation in 2018 and 2019 was slightly below and just above average at Loch Vale, RMNP, respectively. Concentrations of nitrate and ammonium were slightly lower in 2019. Wet nitrogen deposition was around 2.5 kg N/ha/yr in both 2018 and 2019.

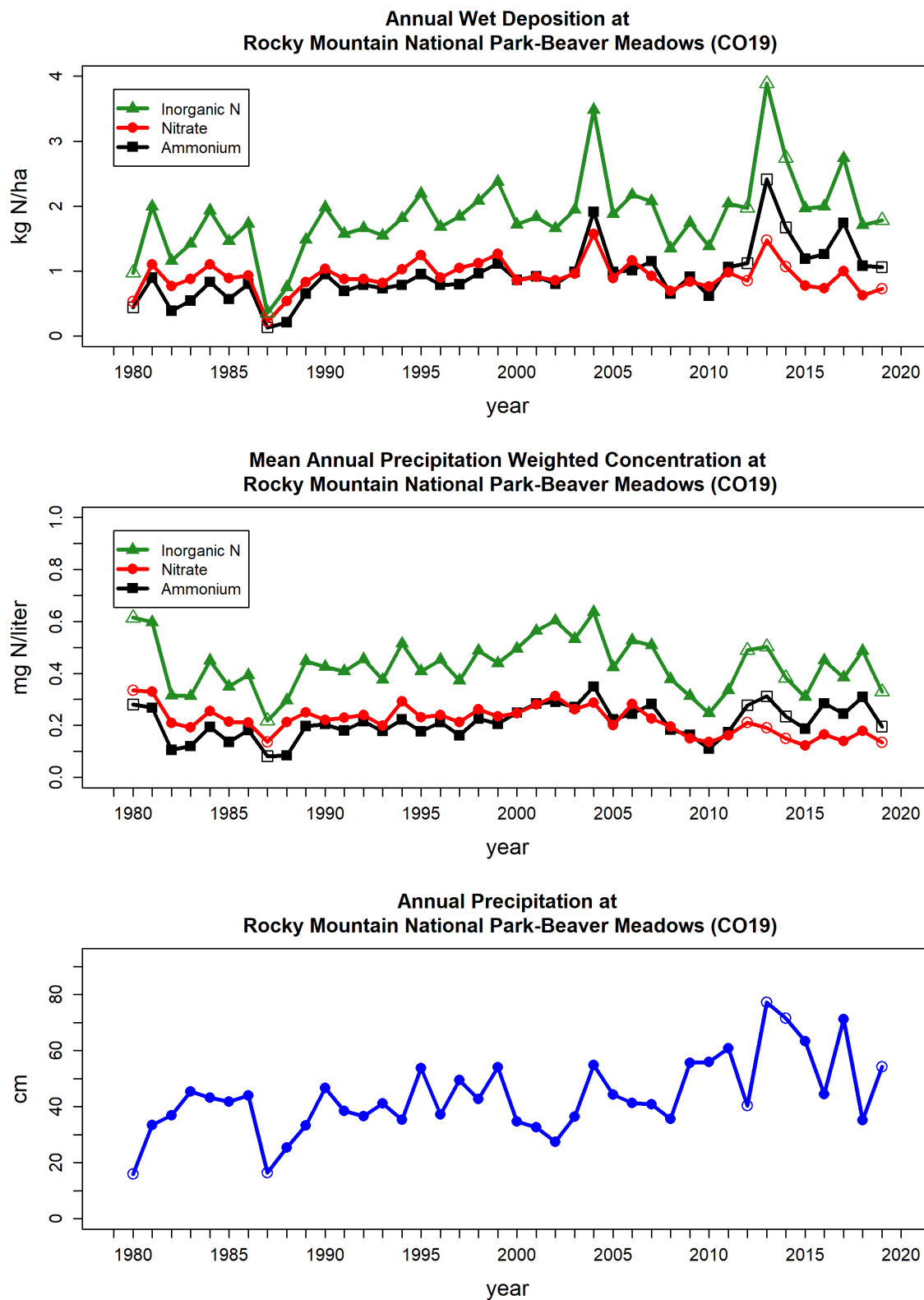


Figure 3. Precipitation increased in 2019, while concentrations of ammonium and nitrate decreased, resulting in similar wet N deposition in 2018 and 2019 at Beaver Meadows, RMNP. Open symbols demark years when NADP Data Completeness were not met.

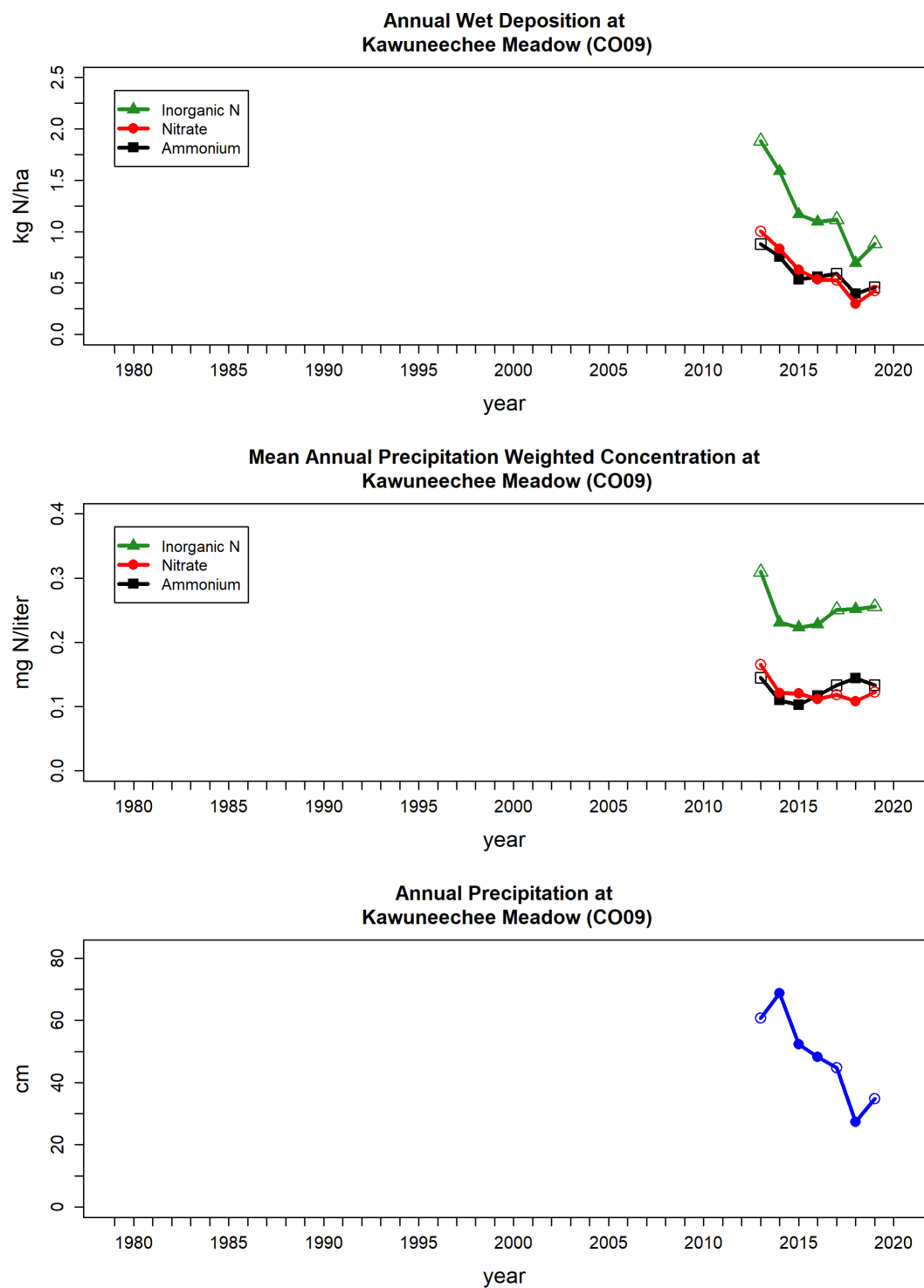


Figure 4. Precipitation increased slightly in 2019, while concentrations of nitrate and ammonium were about equal, resulting in a slight increase wet N deposition in 2019 at Kawuneechee Meadow, RMNP. Open symbols demark years when NADP Data Completeness were not met.

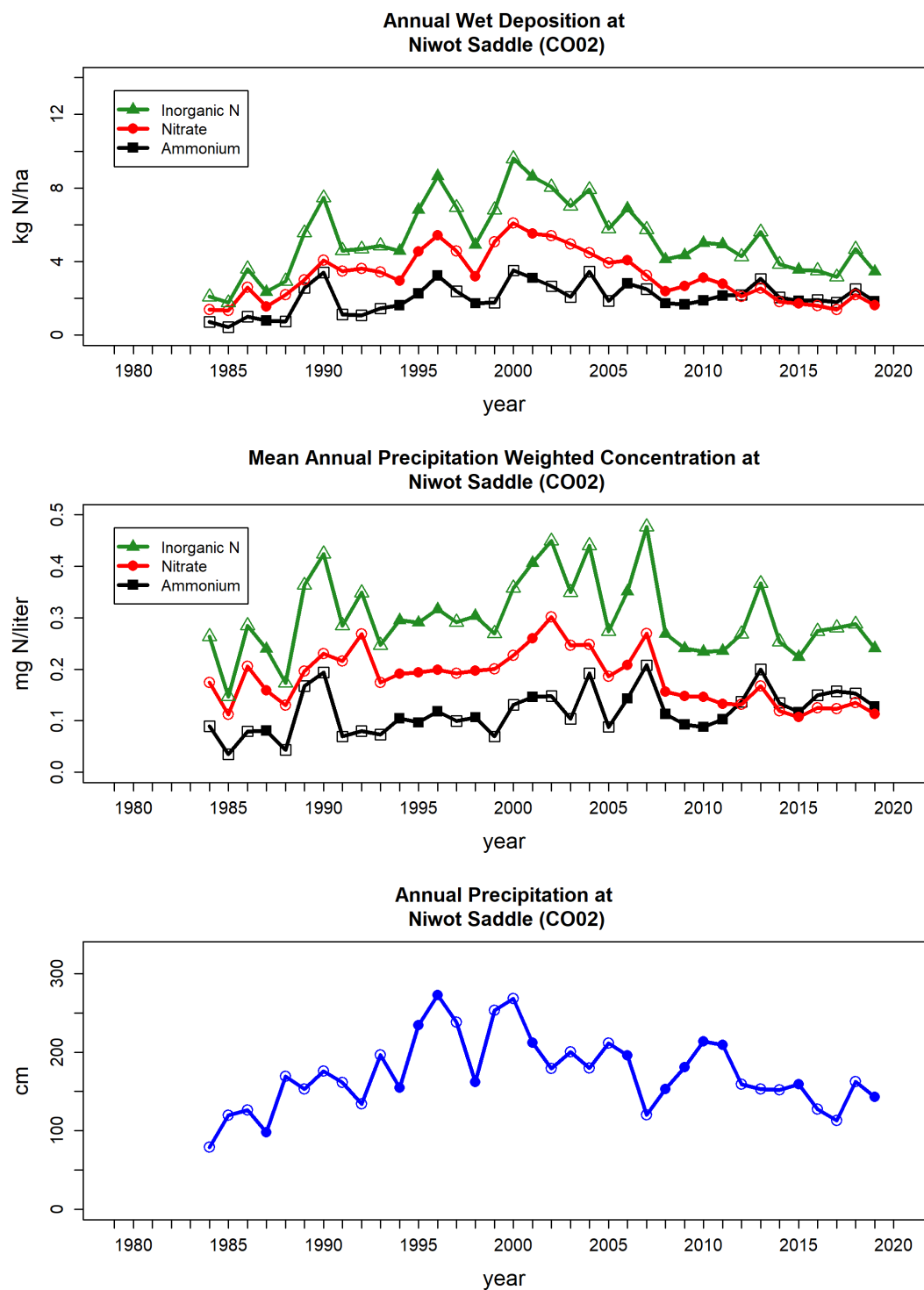


Figure 5. Precipitation decreased slightly in 2019 while concentrations also decreased slightly, resulting in decreased wet N deposition in 2019 at Niwot Saddle. Open symbols demark years when NADP Data Completeness were not met.

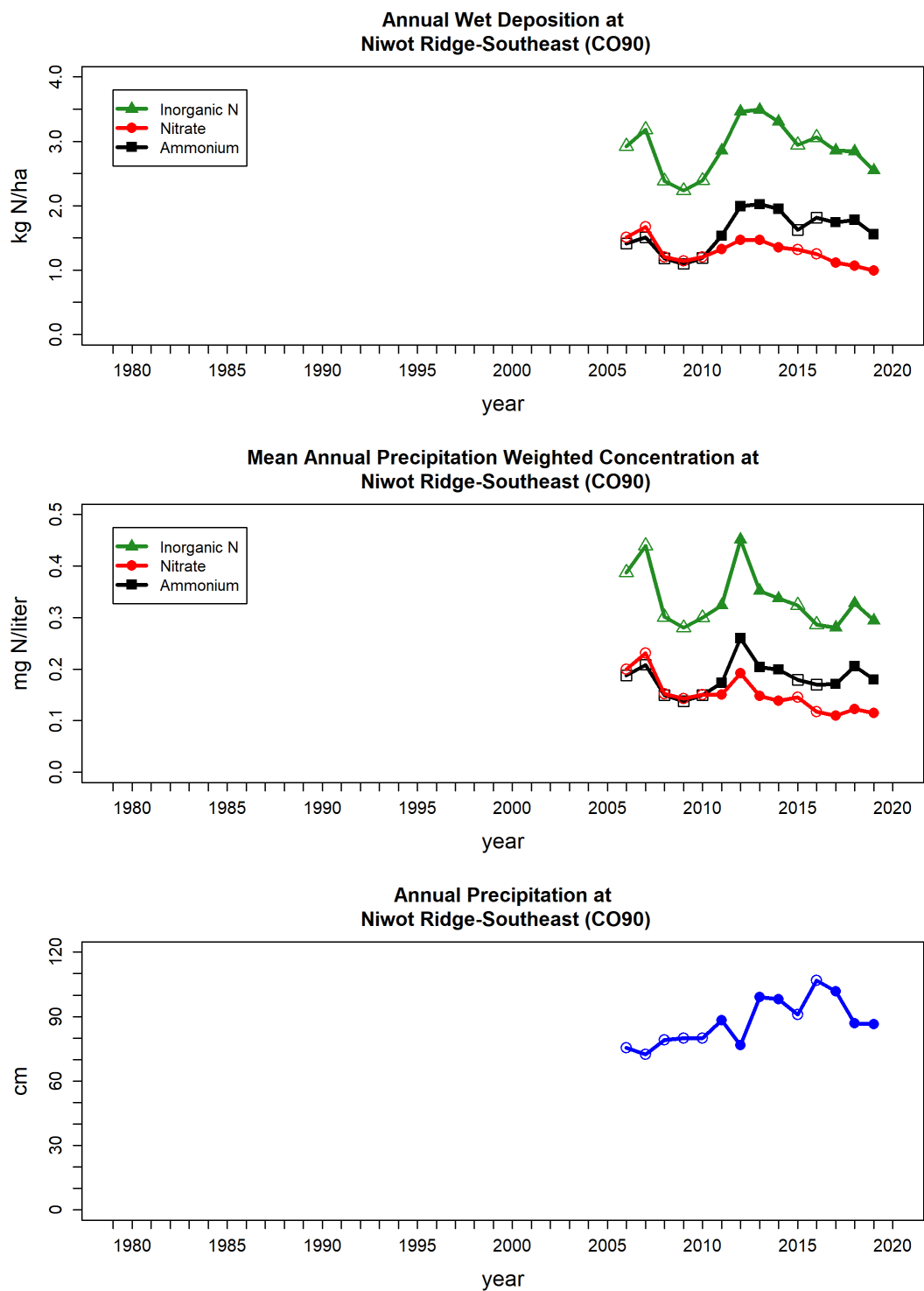


Figure 6. Precipitation was constant between 2018 and 2019 while concentrations decreased slightly, resulting in a slight decrease in wet N deposition in 2019 at Niwot Ridge-Southeast. Open symbols demark years when NADP Data Completeness were not met.

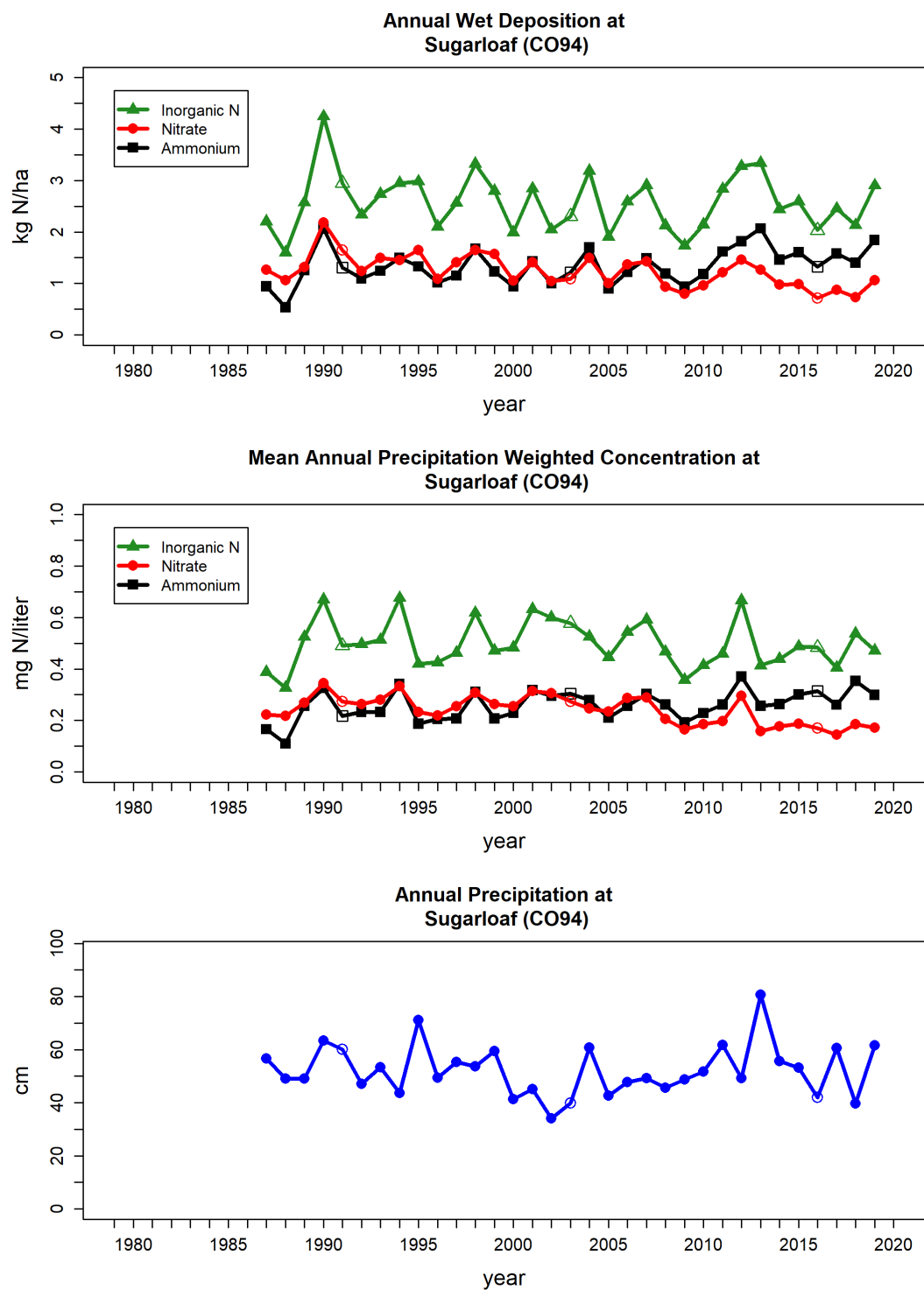


Figure 7. Precipitation increased in 2019 while concentrations of ammonium and nitrate decreased slightly, resulting in an increase in wet N deposition at Sugarloaf. Open symbols demark years when NADP Data Completeness were not met.

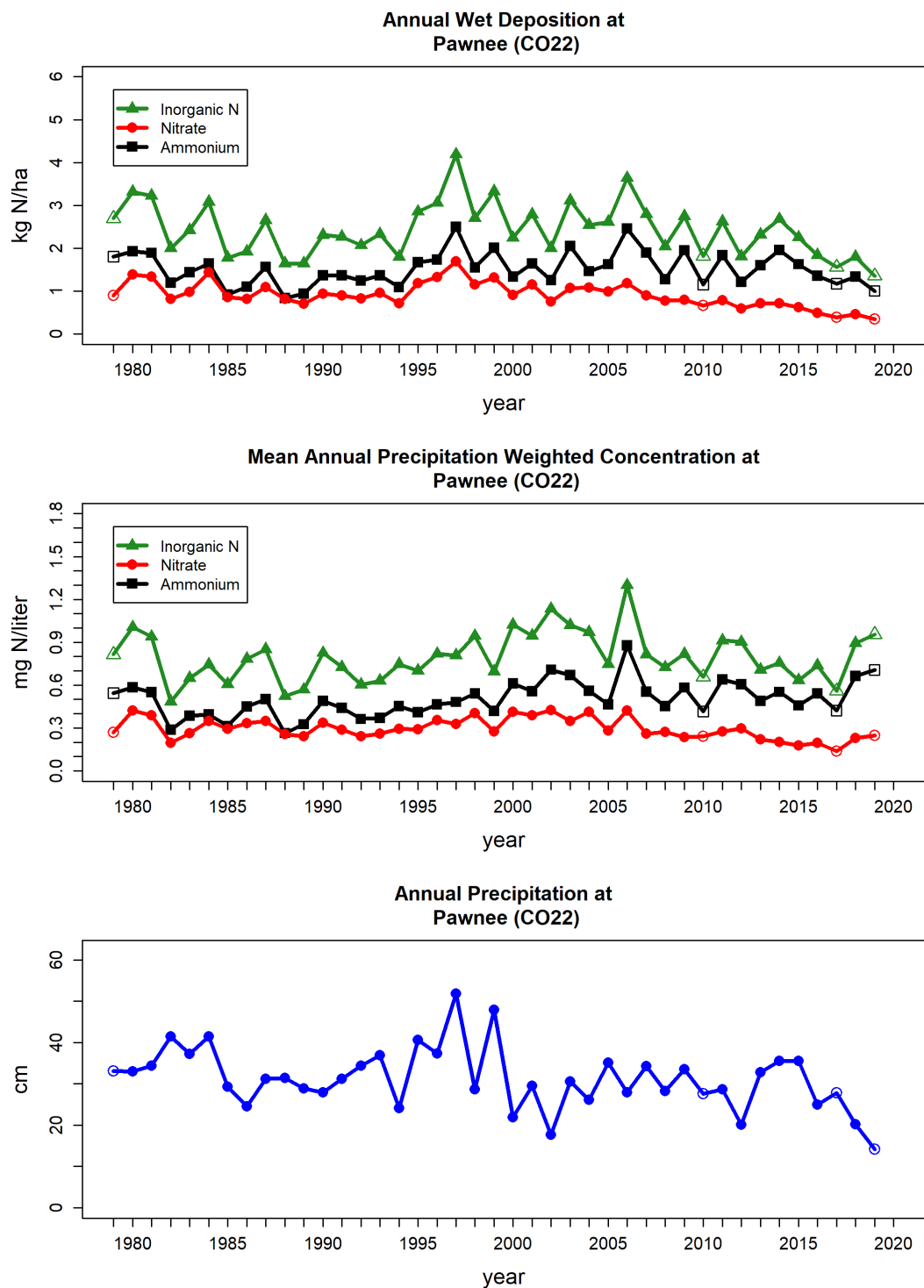


Figure 8. Precipitation decreased in 2019. Concentrations of nitrate and ammonium increased slightly, resulting in a slight decrease in wet N deposition at Pawnee. Open symbols demark years when NADP Data Completeness were not met.

Table 3. Long-term trends in **wet nitrogen deposition** over the period of record (through 2019). Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05). [NA, trend not available due to failure to meet data completeness criteria].

Site Name	Start Year	Trend (kg N/ha/yr)	P-value	Significant Trends
Loch Vale	1984	0.005	0.634	no trend
Beaver Meadows	1981	0.014	0.021	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	-0.002	0.803	no trend
Pawnee	1980	-0.003	0.744	no trend

Table 4. Long-term trends in **precipitation-weighted mean ammonium concentrations** over the period of record (through 2019). Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05). [NA, trend not available due to failure to meet data completeness criteria].

Site Name	Start Year	Trend (μ eq/L/yr)	P-value	Significant Trends
Loch Vale	1984	0.111	<0.001	increasing
Beaver Meadows	1981	0.204	<0.001	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	0.137	0.089	no trend
Pawnee	1980	0.300	0.007	increasing

Table 5. Long-term trends in **precipitation-weighted mean nitrate concentrations** over the period of record (through 2019). Significant trends were determined at the 95 percent confidence level (p-value $\leq$ 0.05). [NA, trend not available due to failure to meet data completeness criteria].

Site Name	Start Year	Trend (μ eq/L/yr)	P-value	Significant Trends
Loch Vale	1984	-0.113	0.002	decreasing
Beaver Meadows	1981	-0.144	0.013	decreasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	-0.245	<0.001	decreasing
Pawnee	1980	-0.209	0.009	decreasing

Table 6. Long-term trends of **precipitation** over the period of record (through 2019). Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, trend not available due to failure to meet data completeness criteria].

Site Name	Start Year	Trend (cm/yr)	P-value	Significant Trends
Loch Vale	1984	4.111	0.153	no trend
Beaver Meadows	1981	0.408	0.035	increasing
Niwot Saddle	1986	NA	NA	NA
Sugarloaf	1987	0.099	0.617	no trend
Pawnee	1980	-0.170	0.108	no trend

Table 7. Trends of **wet nitrogen deposition** since 2006 (2006–2019) and 7 year (2013–2019) time periods. Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, trend not available due to failure to meet data completeness criteria]. Kawuneechee Meadow began monitoring in 2013.

Site Name	Since 2006 NDRP Inception			7 year		
	Trend (kg N/ha/yr)	P-value	Significant Trends	Trend (kg N/ha/yr)	P-value	Significant Trends
Loch Vale	-0.044	0.125	no trend	-0.235	0.072	no trend
Beaver Meadows	-0.004	1.000	no trend	NA	NA	NA
Kawuneechee Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	-0.153	0.0275	decreasing
Sugarloaf	0.005	0.760	no trend	-0.079	0.707	no trend
Pawnee	-0.101	0.013	decreasing	-0.155	0.086	no trend

Table 8. Trends for **precipitation-weighted mean ammonium concentrations** since 2006 (2006–2019) and 7 year (2013–2019) time periods. Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$). [NA, trend not available due to failure to meet data completeness criteria]. Kawuneechee Meadow began monitoring in 2013.

Site Name	Since 2006 NDRP Inception			7 year		
	Trend ($\mu\text{eq/L/yr}$)	P-value	Significant Trends	Trend ($\mu\text{eq/L/yr}$)	P-value	Significant Trends
Loch Vale	0.111	0.329	no trend	-0.166	0.707	no trend
Beaver Meadows	0.166	0.432	no trend	NA	NA	NA
Kawuneechee Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	-0.450	0.115	no trend
Sugarloaf	0.151	0.304	no trend	0.157	0.726	no trend
Pawnee	-0.294	0.697	no trend	0.055	1.000	no trend

Table 9. Trends for **precipitation-weighted mean nitrate concentrations** since 2006 (2006–2019) and 7 year (2013–2019) time periods. Significant trends were determined at the 95 percent confidence level ($p\text{-value} \leq 0.05$). [NA, trend not available due to failure to meet data completeness criteria]. Kawuneechee Meadow began monitoring in 2013.

Site Name	Since 2006 NDRP Inception			7 year		
	Trend ($\mu\text{eq/L/yr}$)	P-value	Significant Trends	Trend ($\mu\text{eq/L/yr}$)	P-value	Significant Trends
Loch Vale	-0.403	0.001	decreasing	-0.322	0.013	decreasing
Beaver Meadows	0.403	0.055	no trend	NA	NA	NA
Kawuneechee Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	-0.473	0.032	decreasing
Sugarloaf	-0.507	0.037	decreasing	-0.012	1.000	no trend
Pawnee	-0.886	0.005	decreasing	-1.127	0.407	no trend

Table 10. Trends for **precipitation** since 2006 (2006–2019) and 7 year (2013–2019) time periods. Significant trends were determined at the 95 percent confidence level (p-value ≤ 0.05). [NA, trend not available due to failure to meet data completeness criteria]. Kawuneechee Meadow began monitoring in 2013.

Site Name	Since 2006 NDRP Inception			7 year		
	Trend (cm/yr)	P-value	Significant Trends	Trend (cm/yr)	P-value	Significant Trends
Loch Vale	11.969	0.324	no trend	-55.367	0.548	no trend
Beaver Meadows	1.488	0.283	no trend	NA	NA	NA
Kawuneechee Meadow	–	–	–	NA	NA	NA
Niwot Saddle	NA	NA	NA	NA	NA	NA
Niwot Ridge-Southeast	NA	NA	NA	-2.22	0.221	no trend
Sugarloaf	0.970	0.127	no trend	-3.372	0.452	no trend
Pawnee	-0.188	1.000	no trend	-2.566	0.462	no trend

Summary

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

Current wet N deposition (5-year rolling average) in 2019 at Loch Vale in RMNP was 2.7 ± 0.22 kg/ha/yr which is 0.3 kg/ha/yr above the glidepath (2.4 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?

Wet N deposition has not decreased at RMNP or other sites in the region over the long-term. An increasing trend was reported by Burns 2003 for the period 1984–2000. Trend analyses since then (for 1984–2008 and beyond) for all sites except Beaver Meadows in RMNP show no trend. Data from Beaver Meadows indicate an increase in wet N deposition and precipitation for the period of record. Ammonium concentration data show an increase at both sites in RMNP and Pawnee but not at Sugarloaf over the long-term. Nitrate concentration data show a decreasing trend at all sites that met criteria over the long-term.

3. Has wet nitrogen deposition decreased at RMNP and other sites in the region since the NDRP was initiated in 2006?

Wet N deposition has not decreased at RMNP or other sites in the region since 2006, except at Pawnee. Concentrations of ammonium showed no trends at any sites and concentrations of nitrate decreased at three sites (Loch Vale, Sugarloaf, and Pawnee).

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

Wet N deposition has not recently decreased at RMNP or other sites in the region, except at Niwot Ridge-Southeast. Concentrations of ammonium showed no trends at any sites and concentrations of nitrate decreased at two sites (Loch Vale and Niwot Ridge-Southeast).

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