



State of the Alpine Report for Rocky Mountain National Park

2010 Summary Report

Natural Resource Data Series NPS/ROMN/NRDS—2013/535



ON THE COVER

A GLORIA sentinel site (PIK) with the Never Summer Mountains in the background, July 2010, Rocky Mountain National Park. Photograph by: Brittany Thompson

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data. Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Introduction

Rocky Mountain National Park (ROMO), established by an Act of Congress in 1915, "is dedicated and set apart as a public park for the benefit and enjoyment of the people of the United States." The purpose of ROMO is to preserve the park's natural conditions and scenic beauties, its natural and historic objects and wild life, and to provide the freest recreational uses consistent with this purpose. The National Park Service's mission at ROMO is to care for, protect, manage, improve, understand and interpret park resources and to provide for a high-quality visitor experience.

Rocky Mountain National Park provides exceptional accessibility to a wild landscape with dramatic scenery, opportunities for solitude and tranquility, wildlife viewing and a variety of recreational opportunities. The fragile alpine tundra encompasses one-third of the park and is one of the main scenic and scientific features for which the park was established. This is one of the largest examples of alpine tundra ecosystems preserved in the National Park System in the lower 48 states. The park, which straddles the Continental Divide, preserves some of the finest examples of physiographic, biologic, and scenic features of the Southern Rocky Mountains. The park contains the headwaters of the South Platte and the Colorado Rivers. Geologic processes, including glaciation, have resulted in a varied and dramatic landscape. Elevations span from 7,630 feet to 14,259 feet atop Longs Peak, a landmark feature. The park's varied elevations encompass diverse ecosystems where wilderness qualities dominate. Varied plant and animal communities and a variety of ecological processes prevail.

Alpine ecosystems are important ecosystems and monitoring targets for the Rocky Mountain Inventory and Monitoring Network (ROMN) and ROMO for a number of reasons, including their value to park visitors, wildlife, and water resources in the West and because the alpine is particularly vulnerable to climate change. In a warmer climate, alpine wildlife may show population declines and there will be changes in the structure and function of vegetation (Ashton et al. 2010; Figure 1).

This report describes the current status and trends in a number of vital signs relevant to alpine regions of ROMO (Table 1). These indicators include not only many of the vital signs developed and monitored by ROMN (Britten et al. 2007), but also include data from other research programs in the park. The vital signs chosen by ROMN were selected based on park interest and feasibility of setting up long-term monitoring. These include alpine vegetation, climate, and snow chemistry. The park and outside researchers have measured indicators such as wildlife, stream chemistry, and soil temperature. In many cases, we are left to infer the status and trend in alpine based on data from lower elevations or studies from outside the park. For each indicator, we provide some background information on predicted effects of climate change, what is known about regional trends, status and trends within the park, and key uncertainties of the metrics we have chosen to describe the resource. There are numerous potential indicators that were not included in this report because of space considerations, lack of complete data, or to avoid duplication. These potential metrics are listed in Appendix 1.



Figure 1. A conceptual figure of potential effects of climate change on alpine and subalpine ecosystems. Predicted biological responses to climate change include alterations in treeline, an increase in number of invasive plants, changes in plant community structure, and a loss of alpine-obligate species. (Robert, Bennetts, NPS)

Summary of Conditions Table

The summary of conditions table (Table 1) presents data from indicators that are relevant to the alpine of Rocky Mountain National Park. This report is similar to the Natural Resource Condition Assessments and park-specific superintendent's reports. However, our intent is to identify specific metrics (e.g. August stream temperature from Andrews Creek) that can be used to represent condition and to provide more information to the natural resource manager about the quality and confidence of the data sources. Our hope is that future reports on condition can repeat and build from this initial effort. The table also includes reference values that current conditions and trends can be compared against. In order to understand the data presented in Table 1, definitions and explanations of each column are given as follows:

Vital Sign & Measure Class: These are based on the Vital Signs Framework (<http://science.nature.nps.gov/im/monitor/VitalSigns.cfm>)

Indicator: Measure of structure, composition, or function and based on the Vital Signs Framework

Current Average Value: Estimated mean value (plus standard error) from most recent data. The data source is referenced in the footnotes above. Units follow all values. In this report, the current value is most often based on 2010 data. The year is noted when the recent data are not from 2010.

Assessment Point/Reference Value: The numeric value used in comparison to current monitoring data. It may be an ecological or management threshold or a baseline derived from a period of record or single year.

Type of Reference: The type of comparison value against which current values and conditions are measured, interpreted, and reported. This includes ecological threshold; management threshold, baseline (initial year of data), normal (defined by 30 year period used for climate data), period of record (mean of the dataset for a given time), regulatory criterion, critical load. Where applicable, this is followed by the period of record or years of data in parentheses.

Current Status: Estimate of amount (as % or in resource units) that is above/below the comparison value. Must be interpreted at the indicated scale of inference (i.e., park or site(s) - see Scale and Type of Assessment field). For example, if the data are from a survey, the inference is to all of the resources in the park. If the data are from a sentinel site(s) the inference is to just these locations. Where there are multiple years of data, the percentile of the current year is given (e.g. 99th percentile corresponds to one of the highest values on record).

Magnitude and direction of change or trend: Estimated change (as a percent from comparison value) or trend (if data are sufficient to estimate). Rate of change is given when known. TBD is used when there are fewer than 5 years of data or the quality of the data is not appropriate for trend analyses.

Scale and Type of Assessment (Scale; Sample size; Method, Site Locations): Spatial scale of inference for current value. If park, estimated using a survey design and inference is to an

extensive target population. Region refers to data that are representative of an area larger than the park. Site level data are the most common. In these cases, the number and location of sites is given. Care should be taken that the estimates given within the table are interpreted only at the given scale.

Confidence: Confidence in the data is estimated by three aspects of data quality- how well data represent the resource, quality of methods, and the length of the record. A score of 5 is of high confidence, 3 is moderate confidence, and 1 is low confidence. Confidence was calculated by averaging the scores for each of the three categories and rounding to the nearest whole number. The categories were scored as follows:

Relevance to the Park Unit

5= Data are from multiple locations within the park that are representative of the resource.

The best examples are studies with statistical inference to the entire resource or a survey of the entire park resource.

4= Data are from several locations within the park or a regional study with multiple locations in and around the park. Alternatively, one to two sites that represent a greater area (e.g. sampling that captures an entire airshed or watershed)

3= Data are from one to two locations within the park resource; a regional study with multiple sites near the park; data from multiple locations for the same resource type (e.g. a global survey of tundra sites)

2= Data are from one nearby location (<100mi); a regional study with no sites near (<100mi) the park

1= Data are from a global or US scale study that is not specific to the resource (e.g. global temperature trends)

Data Quality

5= Data derived from published and peer-reviewed protocols with results appearing in peer-reviewed publications. Data and metadata are available.

4= Data derived from established peer-reviewed protocols. Gray literature or thesis work exists but not many peer-reviewed publications have been derived from the data.

3= Data derived from established protocols with known inconsistencies (e.g. SNOTEL temperature data) or few publications.

2= Data with concerns regarding consistency or quality (e.g. many citizen science projects) with or without formal protocols established.

1= Unknown methods used to acquire data. There are significant concerns regarding consistency or quality of data.

Temporal Scale (scale 1-5)

5=Long-term data (e.g. >15 years)

4=Data exist for 6-15 years

3=Data from 3-5 years

2=Data from 2-3 years

1=Data from 1 year

Table 1. Summary of Conditions relevant to the alpine of Rocky Mountain National Park. This table presents alpine indicators and a draft of possible thresholds, the form of the threshold, estimated mean values and variance, any available status and/or trend information, general summaries of the condition of each vital sign, when meaningful and possible, and the quality of the monitoring data. Current average values are based on 2010 data, unless otherwise noted. See also Data Sources below.

Vital Sign	Measure Class	Indicator	Current Average Value (+/- SE or SD) (period)	Assessment Point/ Reference Value	Type of Reference	Current Status (% above/ below assessment point or percentile relative to period of record)	Magnitude and direction of change or trends	Scale and Type of Assessment (Sample size; Sites)	Confidence (scale from 1-5, low to high)
Climate	Temperature	Mean Minimum Temperature	-5.5°C ^a	-6.1°C	Normal (1971-2000)	75 th percentile	TBD*	Site (1;Grand Lake)	4
		Average Annual Temperature	-	-	Normal (1971-2000)	-	Increase of 1.6°F in 30 yr ^b	Region (79; North Central CO Mountains)	5
		Frost Free Days	96 ¹	99.9 ± 11.85	Normal (1971-2000) ²	-	TBD*	Site (1;Grand Lake)	-
	Snowpack	Snow Water Equivalent	72 ± 6.7 cm ^c (2009)	78 ± 3.6 cm ^c	Period of Record (1993-2009)	30 th percentile	TBD*	Site (3; Lake Irene, Loch Vale forest & meadow)	4
		April 1 Snow Water Equivalent	-	-	Period of Record (1993-2009)	-	Decrease 1.2-2.7 cm per decade ^d	Region (9; SNOTEL sites)	4
	Soil temperature	Average surface winter temperature	-9.6 ± 0.44°C ^d	-8.2 ± 0.47°C ^d	Baseline (2009)	-	TBD*	Site (30; Trail Ridge)	3
		Average deep winter temperature	-7.5 ± 0.38°C ^e	-6.3 ± 0.47°C ^e	Baseline (2009)	-	TBD*	Site (30; Trail Ridge)	3
Air quality	Wet Deposition	Inorganic nitrogen	2.96 kg/ha ^f	1.5 kg/ha ^g	Management Threshold	197% above target	Increase	Site (1; Loch Vale)	4
	Snow Chemistry	Sulfate	5.3 ± 0.54 µeq/L (2009) ^c	6.8 ± 0.30 µeq/L ^c	Period of Record (1993-2009)	15 th percentile	No important change	Site (3; Lake Irene, Loch Vale forest & meadow)	4
		Mercury	3.2 ± 0.5 ng/L (2009) ^c	2.9 ± 0.3 ng/L ^c	Period of Record (2001-2009)	75 th percentile	No important change	Site (3; Lake Irene, Loch Vale forest & meadow)	4
		Calcium	17.5 ± 1.6 µeq/L (2009) ^c	8.9 ± 0.79 µeq/L ^c	Period of Record (1993-2009)	99 th percentile	Increase	Site (3; Lake Irene, Loch Vale forest & meadow)	4
Water Quality	Discharge	Average June discharge	9.4 ± 0.55 cfs ^h	6.6 ± 0.12 cfs ^h	Period of Record (1992-2010)	99 th percentile	No important change	Site (1; Andrews Creek)	4
		Average August discharge	3.5 ± 0.37 cfs ^h	3.8 ± 0.20 cfs ^h	Period of Record (1992-2010)	45 th percentile	No important change	Site (1; Andrews Creek)	4
	Water Temperature	Average August water temperature	11.5 ± 0.32°C ^h	11.6 ± 0.22°C ^h	Period of Record (2008-2010)	-	TBD*	Site (1;Loch Vale Outlet)	4

¹ December temperature data are missing in 2010.

² Estimated based on the 20 years between 1971-2000 that have complete temperature records for National Weather Service Coop. climate station Grand Lake 1 NW

Vital Sign	Measure Class	Indicator	Current Average Value (+/- SE or SD) (period)	Assessment Point/ Reference Value	Type of Reference	Current Status (% above/ below assessment point or percentile relative to period of record)	Magnitude and direction of change or trends	Scale and Type of Assessment (Sample size; Sites)	Confidence (scale from 1-5, low to high)
Wildlife-Focal Species	Pika	Percent of Habitat with Pika Present	0.7 ⁱ	0.7 ⁱ	Baseline (2010)	-	TBD*	Park (58; survey)	3
	Ptarmigan	Ptarmigan Density	6.9 ^j	4.5-13 ^j	Period of Record (1966-1994)	-	TBD*	Site (3; near Trail Ridge)	4
	Butterflies	Average number of species per transect	0.8 ^k	1.1 ± 0.14 ^k	Period of Record (1997-2010)	30 th percentile	No important change	Site (1; Lava Cliffs)	3
Wetland Community	Multimetric Index	MMI	4.8 ± 0.47 ^l (2007-2009)	>4.77 ^l	Threshold	-	TBD*	Site (12; throughout park above 3350 m)	3
	Conservatism score	Mean C score of native species	7.2 ± 0.10 ^l (2007-2009)	7.2 ± 0.10 ^l (2010)	Baseline	-	TBD*	Site (12; throughout park above 3350 m)	3
	Ground water chemistry	pH	4.84 ± 0.06 ^l (2007-2009)	5-6.5 ^m	Reference Condition	-	TBD*	Site (12; throughout park above 3350 m)	3
Vegetation and soils	Vegetation Cover	Percent Plant Cover	51 ± 1.8 ⁿ (2009-2010)	<15% ^o	Management Threshold	-	TBD*	Site (4; GLORIA - Jackstraw, Mt Ida Ridge)	3
	Woody vegetation	Mean shrub/tree richness	3 ± 0.8 ⁿ (2009-2010)	3 ± 0.8 ⁿ	Baseline (2009-2010)	-	TBD*	Site (4; GLORIA - Jackstraw, Mt Ida Ridge)	3
	Invasive/Exotic Plants	Number of Exotic Species	0.02 ± 0.01 ⁿ (2009-2010)	0 ^p	Reference Condition	-	TBD*	Site (4; GLORIA - Jackstraw, Mt Ida Ridge)	3
	Conservatism score	Mean C score of native species	7.1 ± 0.19 ⁿ (2009-2010)	7.1 ± 0.19 ⁿ	Baseline (2009-2010)	-	TBD*	Site (4; GLORIA - Jackstraw, Mt Ida Ridge)	3
	Soil Chemistry	C:N	10.9 ± 0.26 ⁿ (2009)	10.9 ± 0.26 ⁿ (2009)	Baseline (2009)	-	TBD*	Site (4; GLORIA - Jackstraw, Mt Ida Ridge)	3
Visitor Experience	Visitors to Rocky Mountain NP	Annual number of visitors	3,128,446 ^q	2,933,582 ± 52,619 ^q	Period of Record (1981-2010)	71 st percentile	No important change	Site (1; Rocky Mountain NP)	4
	Alpine Backcountry Permits	Annual number of user nights at Little Rock Lake	137 ^r	123 ± 7.5 ^r	Period of Record (1998-2010)	70 th percentile	No important change	Site (1; Little Rock Lake)	3

*Insufficient data at time of publication to determine trend. Continued monitoring will be used to determine trends.

Data Sources

a. Data are from COOP climate station at Grand Lake 1NW where minimum temperature is measured daily. Data was acquired from Colorado Climate Center. Reference value is based on National Climatic Data Center Normal for the period of 1971-2000. Percentile is calculated based on entire length of record 1940-2010. Confidence is based on moderate relevance, good quality, and a long period of record.

b. Ray, A. J., J. J. Barsugli, and K. B. Averyt. 2008. Climate change in Colorado: a synthesis to support water resources management and adaptation. A report by the Western Water Assessment for the Colorado Water Conservation Boards. CU-NOAA Western Water Assessment, Boulder, CO. Page 10. Rocky Mountain NP is within the North Central Mountains region which includes 79 stations (based on a count from the figure). Confidence is based on good relevance, high quality, and a long period of record.

c. Based on data from average of 3 snow pack monitoring sites. Ingersoll http://co.water.usgs.gov/projects/RM_snowpack/html/data.html. Chemistry data are not converted to loadings because SWE values are not available for all years. Current data are from 2009. Confidence is based on good relevance, high quality, and a long period of record.

d. Based on data from Clow, D. W. 2010. Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate* **23**:2293–2306. Confidence is based on good relevance, high quality, and a long period of record.

e. Data from Jason Janke 30 Hobo temperature loggers along Trail Ridge Road. Surface depth refers to 10cm below surface and deep temperatures are from sensors at 30-85 cm deep. Confidence is based on high relevance, moderate quality, and short period of record.

f. Data from NADP network <http://nadp.sws.uiuc.edu/sites/siteinfo.asp?id=CO98&net=NTN>; annual estimate from 2010. Confidence is based on good relevance, high quality, and long period of record.

g. Management Threshold based on 2032 target from NPS, EPA, and CDPHE. 2010. Rocky Mountain National Park initiative nitrogen deposition reduction contingency plan. <http://www.cdphe.state.co.us/ap/rmnp/RMNPContingencyPlanFinal.pdf>. Colorado Air Quality Control Commission.

h. Data from USGS stations at Loch Vale and Andrews Creek available through <http://waterdata.usgs.gov/nwis/si>. Confidence is based on moderate relevance, high quality, and long period of record.

i. Based on data provided in the Jeffress et al. 2010. *Pikas in Peril: Multi-Regional Vulnerability Assessment of a Climate-Sensitive Sentinel Species Project Accomplishment Report 2010*. Confidence is based on high relevance, good quality, and short period of record.

j. Data from Gregory Wann (at Colorado State University) and Cameron Aldridge (USGS), average density across 3 sites. The reference value is based on annual surveys from the Colorado Division of Wildlife. Confidence is based on moderate relevance, good quality, and long period of record.

k. Data from Richard Bray and colleagues for the butterfly transect at Lava Cliffs, surveyed during the summer. Confidence is based on moderate relevance, moderate quality, and long period of record. Trained observers walk the length of the transect and record individual butterflies within a band that is 5 m wide.

l. Data from Rocky Mountain I&M wetland ecological integrity survey. A subset of all wet meadow sites above 3350 ft in elevation. Reference values based on distribution derived from park-wide survey. Confidence is based on high relevance, moderate quality, and short period of record.

m. Reference value based on best professional judgment of David Cooper, CSU and values typical of other wetlands in the area.

- n. Average value of 56 1m² plots at the four GLORIA sentinel sites from 2009-2010. Conservatism score is based on Rocchio (2007) where high scores are plants that are of high conservation value that show low tolerance to disturbance. Confidence is based on good relevance, good quality, and short period of record.
- o. Data from survey of impaired alpine sites after Trail Ridge Road construction from Greller, A. M. 1974. Vegetation of roadcut slopes in the tundra of Rocky Mountain National Park, Colorado. *Biological Conservation* 6:84-93. Where there is less than <15% vegetation cover, the alpine is considered degraded and management actions, such as fencing or planting, should be taken to restore conditions.
- p. Reference value based on best professional judgment of Isabel Ashton, NPS and general theory presented in Pauchard, et al. 2009. Ain't no mountain high enough: plant invasions reaching new elevations. *Frontiers in Ecology and the Environment* 7:479-486.
- q. Data from Rocky Mountain National Park statistics at: <http://www.nps.gov/romo/parkmgmt/statistics.htm>. Records exist from 1915 to the present, for this analysis included only 30 years (1981-2010). Confidence is based on high relevance, moderate quality, and long period of record.
- r. Data from backcountry office at NPS ROMO. Confidence is based on good relevance, low quality, and long period of record.

Climate

Climate changes in the western United States have been particularly noticeable in the last century. There has been an average rise of 0.5°C to 2.0°C in mean annual air temperatures, depending on location and elevation (Diaz and Eischeid 2007, Pederson et al. 2010). Warmer winters and springs have resulted in more precipitation falling as rain instead of snow, reduced snowpack, earlier snowmelt, earlier streamflow from snowmelt, an 8 to 10 day advance in the onset of spring on average across the West, more frequent large fires, and possibly an increase in insect outbreaks and plant mortality (Cayan et al. 2001, Breshears et al. 2005, Mote et al. 2005, Knowles et al. 2006, Westerling et al. 2006, Raffa et al. 2008). The preponderance of evidence suggests that the magnitude of these changes has been influenced by human activity (Barnett et al. 2008). Future projections suggest that temperatures will warm 1–5°C for much of the West by 2100 (McWethy et al. 2010). There is substantial variability in precipitation and changes in the amount and spatial distribution of precipitation are still poorly understood. As a result, there is much lower confidence in projections of future precipitation patterns (Solomon et al. 2007).

Temperature trends in Colorado have been consistent with the changes across the western United States and have increased about 1.1°C (2°F) in the past 30 years and average minimum temperatures are warming faster than maximum temperatures (Ray et al. 2008). Average temperatures in the Northern Central Mountains and Northern Front Range of Colorado, have increased 0.9°C (1.6°F) and 1.4°C (2.5°F), respectively from 1977-2006 (Ray et al. 2008; Table 1, Figure 2). While the general pattern is consistent, there are variations in the magnitude of warming across areas of the state (Figure 2). In Colorado, changes in the proportion of precipitation falling as rain rather than snow and reductions in snow water equivalent (SWE) are smaller and not as significant as elsewhere in the West (Knowles et al. 2006). Most of the reduction in snowpack in the West has occurred below about 8200 feet, but most of Colorado's snowpack is above this elevation, where winter temperatures remain well below freezing (Ray et al. 2008). A recent paper examining trends in SWE has found that since the late 1970's there has been a decline in April 1 SWE of 1.2- 2.7 cm per decade as measured at SNOTEL stations in and nearby ROMO (Clow 2010; Table 1).

Paleoenvironmental records reveal that concurrent with changes in precipitation and temperature, there have been large shifts from tundra to forest and forest to shrubland since the local glaciers retreated 17,000-12,000 before the present (McWethy et al. 2010). As climate changes continue into the future, it is highly likely that over time there will be shifts in communities and ecosystems within ROMO.

Status and Trends in Rocky Mountain National Park

It is difficult to document climate trends in high elevation sites of ROMO because of the lack of climate data at the appropriate scale. There are numerous climate stations in and around ROMO (Figure 3) but they are not at high elevations and few have recorded data for more than 25 years (Davey et al. 2007). Grand Lake 1NW is one of the stations with the longest and most consistent climate record in Colorado (Colorado Climate Center 2011). While current data is usually reliable, trends are difficult to detect due to the number of missing months and data gaps in the historic record. SNOTEL stations which are in the interior of the park tend to be at higher elevations, but the highest stations, Lake Irene and Willow Park are only at 10,699 feet (below treeline) and the record is relatively short for determining trends (30 years).

In 2010, annual mean minimum temperature at Grand Lake was -5.5°C (21.1°F ; Table 1). This is very close to normal minimum temperature of -6.1°C (21.0°F) based on the period from 1971-2000. Thus, 2010 is not within the 10% hottest or coolest years on record (Figure 4). Annual average maximum temperature was 11.7°C (53°F) which is the same as normal. While 2010 was relatively normal, the hottest years on record have been clustered in the recent past (Figure 4). The total accumulated precipitation at the Grand Lake 1NW climate station was 45.5 cm (17.9 in) in 2010, or 86% of normal conditions based on a period from 1971-2001. At higher elevations, precipitation and SWE were also slightly below average for 2010 (Table 1, Figure 5).

Key Uncertainties and Science Strategies

The Grand Lake 1NW station provides the longest and most complete climate record for ROMO. Therefore, data from Grand Lake 1NW are noted in Table 1. We focus on minimum temperature because historic data have shown it to be changing faster than maximum temperatures. There is a good amount of confidence given to the 2010 condition because of the long-length of the record and quality controls associated with data acquisition. However, the station represents just one location in the park, so it has only moderate spatial relevance. Prior to deriving a long-term trend in temperature using these data, the record needs to be put through rigorous quality control measures to account for gaps. Higher confidence can be placed in trend estimates based on published reports and multiple stations in and around ROMO, such as the trend based on the 79 sites in the North Central Colorado Mountains is included in Table 1 (e.g. Ray et al. 2008).

ROMO is a large park that varies considerably in terms of topography and unique microclimates and thus SNOTEL stations provide valuable records of recent climate trends and should be maintained because they are well distributed through the park and are at relatively high elevations. However, to understand climate changes in the alpine, it is critical to support and maintain stations, such as the USGS Sharkstooth station that are truly alpine (http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=401638105402601). Confidence in measuring alpine climate change could be improved in the future by investing in alpine stations that have spatial relevance. The park might also invest in comparing Sharkstooth station records with Niwot Ridge, Grand Lake, and/or patterns from the North Central Mountains as a whole to see how well Sharkstooth correlates with sites at comparable (Niwot) or lower elevations.

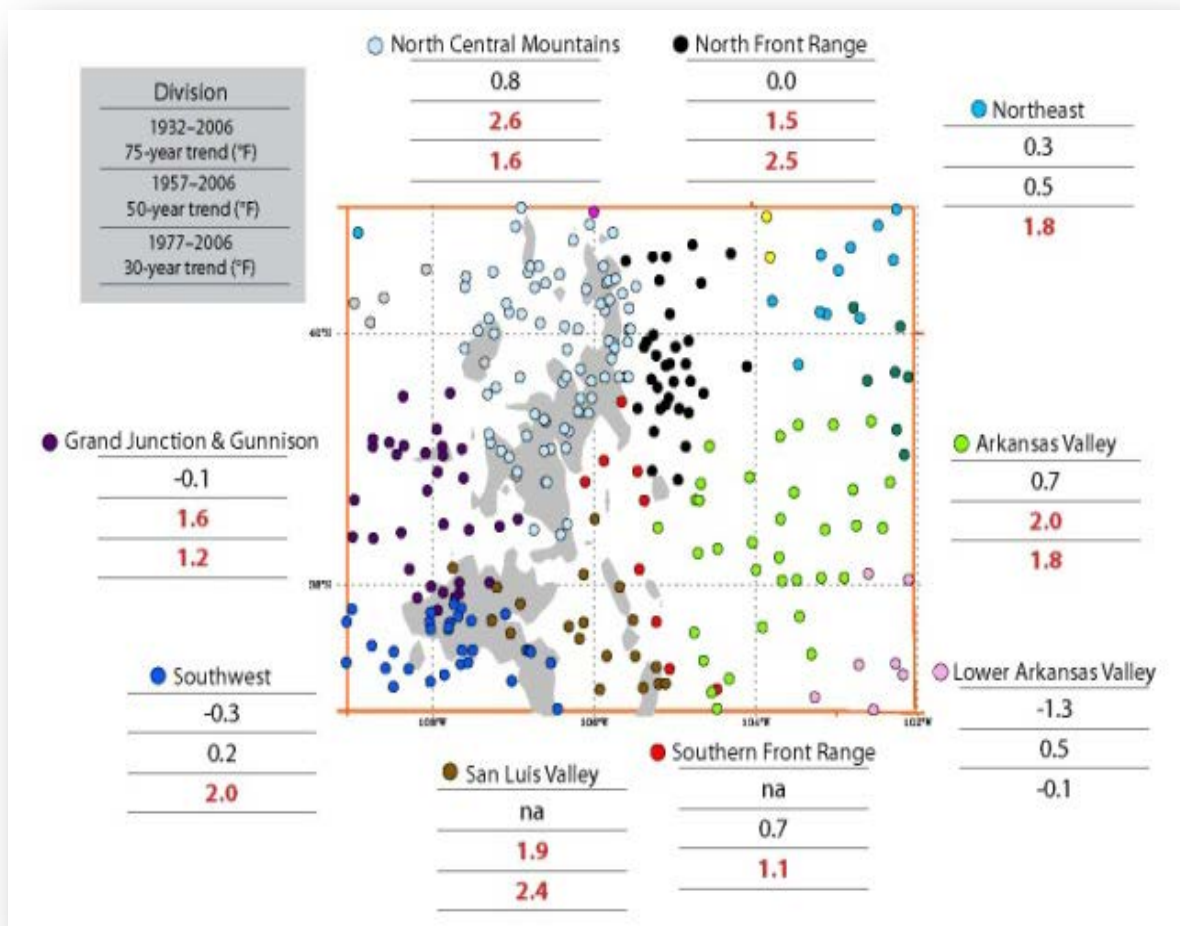


Figure 2. Regional trends in annual average temperature (°F) for experimental climate divisions in Colorado. Groups of stations with similar climates comprise the divisions indicated by colored circles; there are no delineated geographic boundaries. Gray shading indicates terrain at an elevation higher than 9850 feet (3000 m). The tables show temperature changes for the 30-, 50-, and 75-year periods ending in 2006, as determined from linear trend analysis. Statistically significant trends (>95%) are shown in red (warming) and blue (cooling). Trends were computed by averaging observations from a subset of locations within each division (between three and seven stations, depending on the division) that met quality control requirements. Although some divisions extend beyond the state's borders, only stations within Colorado were used to determine trends. Insufficient data were available to calculate 75-year trends for the San Luis Valley and the Southern Front Range divisions. Significant warming is evident in most divisions in the past 30 and 50 years. Figure from Ray et al. 2008. Rocky Mountain National Park falls within the North Central Mountain region.

Climate Stations

Inventory & Monitoring Program

National Park Service
U.S. Department of the Interior

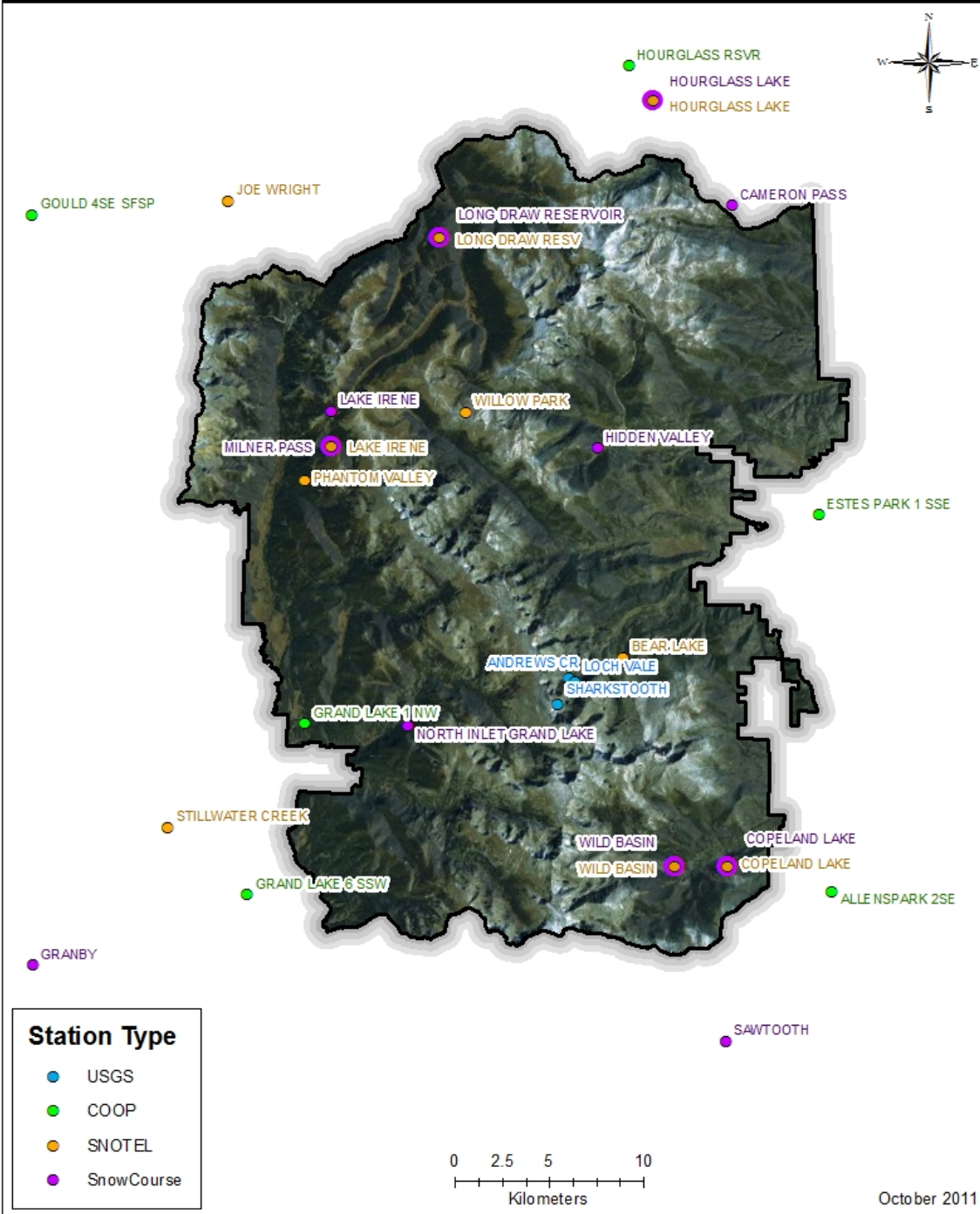


Figure 3. Climate stations currently operating in and around Rocky Mountain National Park. COOP stations (green) maintain the longest and most consistent climate records.

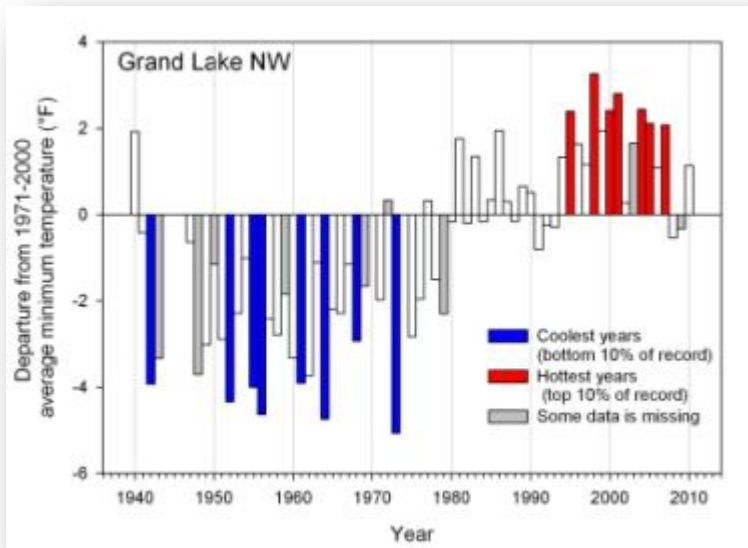


Figure 4. Grand Lake annual departure from the mean minimum temperature for the period of 1971-2001. Positive numbers indicate years warmer than average and negative numbers are cooler. Many of the hottest years since 1939 were in the last decade. Data are from the Colorado Climate Center (<http://ccc.atmos.colostate.edu/dataaccess.php>)

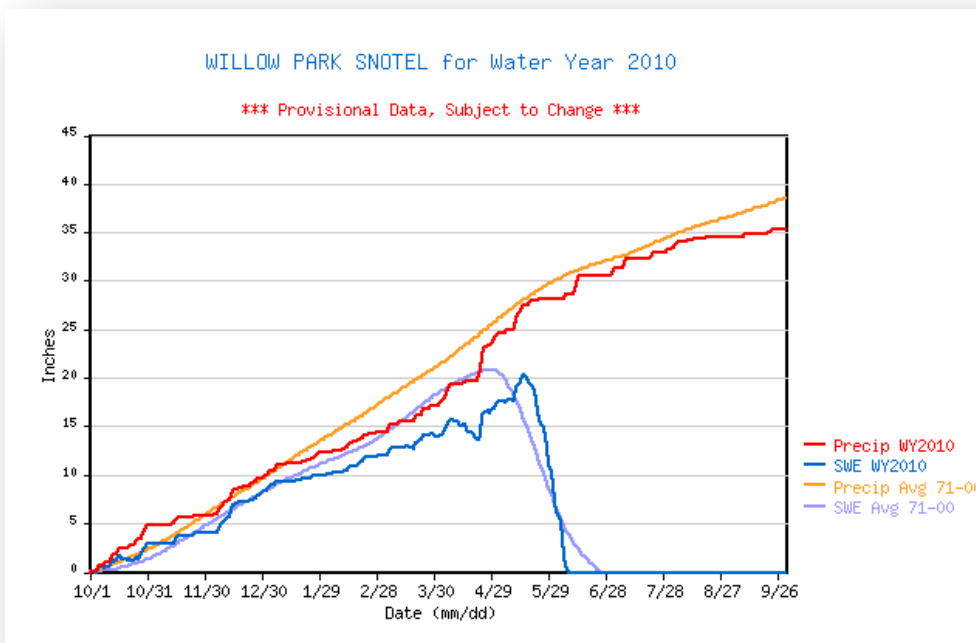


Figure 5. Precipitation and snow water equivalent for the 2010 water year from Willow Park (10,700 ft) SNOTEL site. Precipitation and snow water equivalent in 2010 were below the 30-yr normal. Graph and data are available from <http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=870&state=co>

Wildlife

While a number of factors contribute to stress on wildlife populations in the West (e.g. hunting, development, habitat fragmentation), rapid changes in climate have begun to act as a new pressure on animal populations at global scales (Root and Schneider 2002, Parmesan and Yohe 2003). There is evidence that warmer temperatures and changes in precipitation have caused habitat and range shifts, changes in population size, altered plant phenology, increased disease prevalence, and altered migration patterns (Walther et al. 2002, Root et al. 2003). Moreover, climate change has indirectly affected animal populations through its effects on disturbance regimes, such as fire, and the abundance and distribution of exotic species (Logan et al. 2003). An analysis of potential climate change impacts on U.S. national parks indicates that on average about 8% of current mammalian species diversity may be lost due to large scale shifts in vegetation and while species diversity may be balanced by influxes of new species moving northward, species composition will likely differ (Burns et al. 2003).

Some of the best documented effects of climate change on wildlife are from its effects on range size, population growth, and phenology. Range shifts have been well documented in a variety of species, including birds (see references in Parmesan 2006), butterflies (Parmesan 1996, Forister et al. 2010), and small mammals (Moritz et al. 2008). Several of these species have moved their range upward in elevation as a result of warmer temperatures (Parmesan 1996, Parmesan and Yohe 2003). Concurrently, high elevations species such as pika (*Ochotona princeps*) have seen substantial range contractions (Moritz et al. 2008). Reduced precipitation, especially less snow, has created more favorable conditions for elk (*Cervus canadensis*) population growth in Montana (Creel and Creel 2009) and is predicted to improve conditions for elk in Colorado (Wang et al. 2002). Changes in phenology and migration may cause asynchronies between wildlife populations and food sources, resulting in population declines (Both et al. 2006). Asynchronies have developed for marmots (*Marmota flaviventris*) and their food plants in the Rocky Mountains (Inouye et al. 2000), but there is evidence that longer growing seasons have led to increases in population size (Ozgul et al. 2010).

Although wildlife responses are expected to be complex and species-specific, several patterns can be projected based on life-history characteristics. First, highly mobile species with large geographic ranges, wide physiological tolerances, faster generation times, and generalist diets are more likely to adapt to a changing climate, while endemic specialists are projected to decline. For example, global change is generally predicted to increase the spread of invasive species (Dukes and Mooney 1999). Species that are currently limited by temperature or precipitation are likely to respond more quickly to climate change than are other species. Snow-dependent species such as lynx (*Lynx canadensis*) and snowshoe hare (*Lepus americanus*) are considered particularly vulnerable to climate change. For example, modeling of potential future climate and subsequent changes in vegetation and snow cover indicates that potential lynx habitat may decrease significantly by 2100 (Gonzalez et al. 2007).

Status and Trends in Rocky Mountain National Park

To understand the effects of climate change on wildlife, it is essential to have high-quality monitoring data on historic and current populations. In ROMO, three monitoring datasets exist that can provide some indication of the current conditions of wildlife in the alpine and in the future may be used to elucidate trends. These datasets include a park-scale survey of pika

completed in 2010; butterfly counts along transects at Lava Cliffs repeated annually since 1998; and density estimates of white-tailed ptarmigan (*Lagopus leucura*) from 1966-1994 and repeated in 2010.

American pika

The American pika, a charismatic and conspicuous inhabitant of many western mountain landscapes, is considered a sentinel species for detecting ecological effects of climate change. The pika is a suitable model for projecting the potential nature of climate-mediated range-shifts because both temperature and precipitation—the major determinants of range in most species—appear to control recent range shifts in the species. In 2010, a total of 58 sites were surveyed for evidence of pika activity (17 of the 75 site surveys attempted were abandoned due to lack of target habitat or difficulties with access) (Jeffress et al. 2010). Thirty-nine of the sites surveyed were considered occupied, seven sites contained only old sign, and 12 sites lacked any evidence of pika activity within the plot. Therefore, the proportion of sites surveyed and considered occupied in ROMO was 0.672 (Figure 6; Table 1). This value is similar to occupancy seen in other National Parks in 2010, including YELL (0.55), GRSA (0.71), and GRTE (0.45). Since 2010 was the first comprehensive survey of pika in the park this occupancy rate can provide a baseline for subsequent monitoring efforts.

White-Tailed Ptarmigan

A mark-recapture study was done in June 2010 to examine the current status of white-tailed ptarmigan along Trail Ridge Road in ROMO in three areas (Braun et al. 2010). Surveys were conducted during 1-7 June, before any captures and bandings began, in an effort to estimate population densities. The Toll Memorial and Fall River areas had the highest densities, followed by the Tombstone Ridge-Sundance area (12.8, 11.1, and 3.7 birds/km², respectively). The density estimate was 6.9 birds/km² for the entire area surveyed (Table 1). This number was within the range of densities observed from 1966 to 1994: 4.5 to 13.5 birds/km² (Braun et al. 2010).

The white-tailed ptarmigan study is impressive for consistency of methods and record of surveys dating back to 1966. However, the study is limited to the Trail Ridge Road corridor and an unknown number of elk inhabit that area year-round. The impact of elk on alpine willow has not been quantified and may have varied over time.

Butterflies

Butterflies have been monitored in ROMO for 16 years with a goal of creating indices of abundance and community associations for major species (Bray et al. 2010). One transect is in the alpine at Lava Cliffs at 12,233 feet elevation. Since 1997, 28 species have been observed at Lava Cliffs. Rocky Mountain Parnassian (*Parnassius smintheus*), Melissa Arctic (*Oeneis melissa*), Painted Lady (*Vanessa cardui*), and Mead's Sulphur (*Colias meadii*) are the most common species at this site. These species tend to display cyclical patterns of increasing and decreasing numbers (Figure 7). The average number of butterflies of all species seen per transect was low in 2010 (6 individuals) compared to the period of record (14 individuals). The average number of species seen per transect (0.8; Table 1) is also lower than the long-term average (1.1). It is not clear whether this decline is within the range of natural variation or if climate change or other factors have contributed to this pattern.

Key Uncertainties and Science Strategies

It is clear that climate change may play a role in the current and future population dynamics of alpine wildlife. Unfortunately, the inherent variability in animal populations and the difficulty in accurately surveying wildlife make it necessary to have long and consistent monitoring records prior to finding a causal link between climate change and population size. To understand changes in alpine condition and wildlife response, it will be necessary to support continued monitoring of focal species.

For ROMO, the best records for wildlife in the alpine are from pika, ptarmigan, and butterflies. The 2010 data for pika are comprehensive, provide excellent spatial coverage of the park and the study design is high quality; however because this is a recent study with just one year of data available we have only moderate confidence in the results. Future pika surveys and additional years of data will greatly improve the confidence in these occupancy estimates. Ptarmigan and butterfly studies in ROMO have been conducted since 1966 and 1997, respectively and provide a good degree of confidence in status estimates and reference conditions. In both cases, however, the studies are limited to one area of the park. Studies across a broader area of the park or a spatially-balanced sampling design would provide greater confidence in future estimates of abundance and density.

All three of the studies described above need funding and plans to maintain them for the long-term. The pika survey protocol could be adapted for a more limited but annual effort to monitor accessible sites. Glacier NP staff have tested and implemented a limited pika monitoring project using citizen scientists; this approach and the tools they have developed (e.g. training materials, field forms, etc.) could be implemented at ROMO. Still, an investment in understanding annual fluctuations of pika occupancy, especially at the lowest elevation sites, is needed to distinguish short-term from long-term change. The white-tailed ptarmigan work has no long-term funding.

The Principal Investigator for the butterfly project, Richard Bray, retired after summer 2011. Ideally, a new PI might be recruited to continue the project while Bray is available to train him or her. Thought should be given to whether the emphasis should be placed on an elevational range of transects or whether surveying more sites in one elevational band (e.g. alpine) is more desirable. Data from a past Flattop Mountain transect is also available but that transect was abandoned due to time constraints. The butterfly project has been a volunteer run effort and developing a new cohort of citizen science butterfly observers is likely worthwhile. Because so few species are seen on the alpine, maintaining just alpine transects requires much less training than maintaining a suite of park-wide transects.

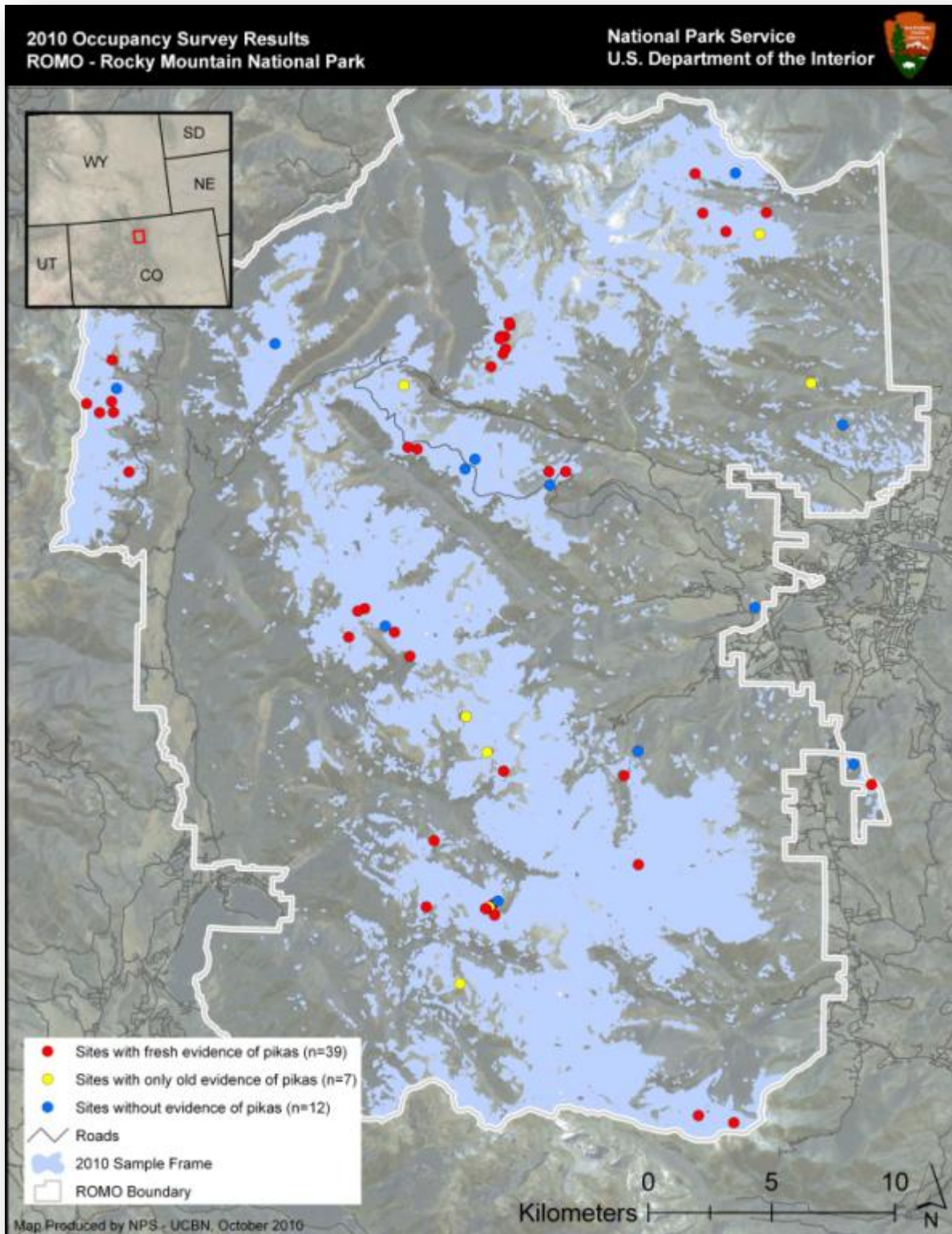


Figure 6. Map of pika survey results from 2010 in Rocky Mountain National Park (Jeffress et al. 2010). Of 58 sites surveyed, fresh evidence of pikas was found at 39 sites.

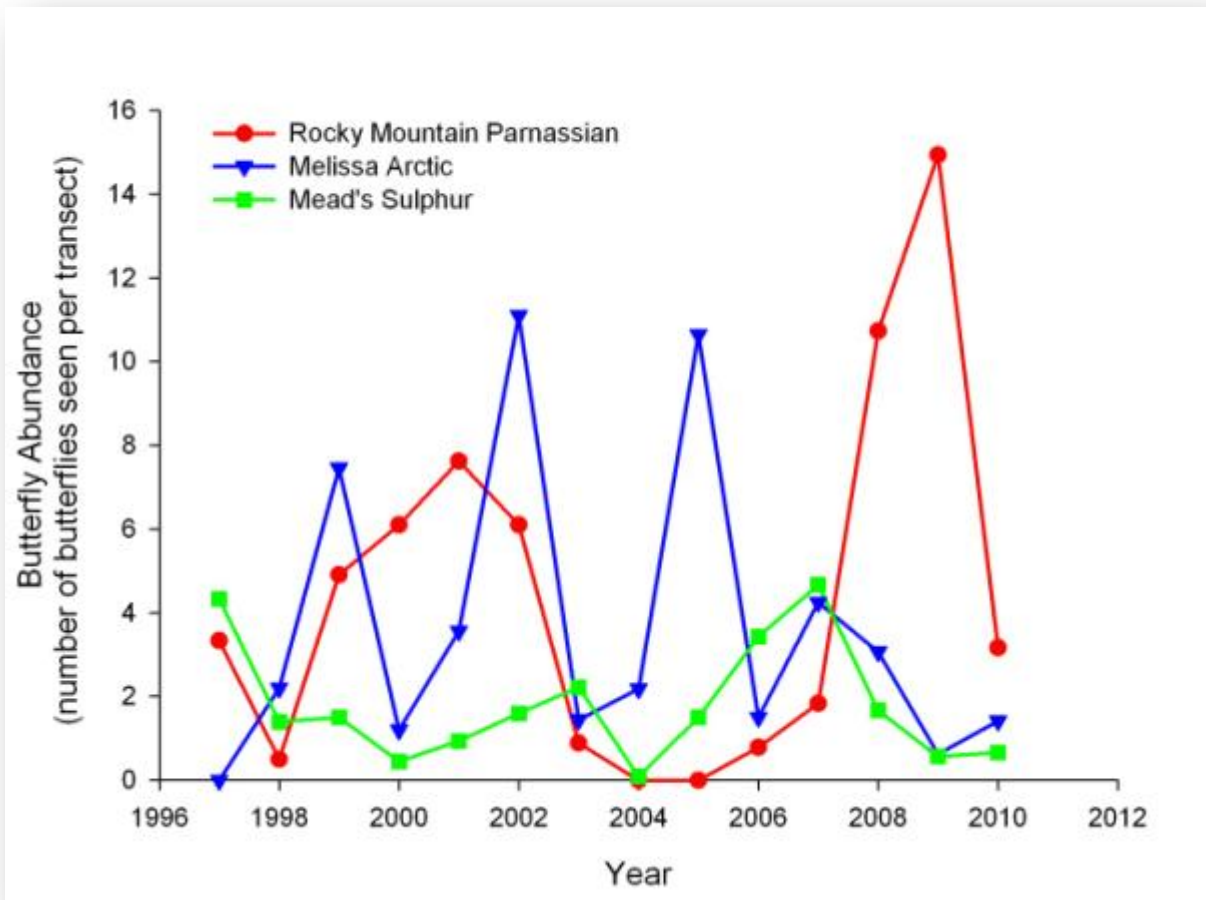


Figure 7. The abundance of three common butterfly species seen at Lava Cliffs from 1998-2010 in Rocky Mountain National Park (Bray et al. 2010).

Alpine Vegetation Communities

Plant species that persist in alpine areas have adapted to the extreme environment, but growth and reproduction are strongly limited by environmental conditions and nutrient availability. As a result, warming temperatures and changes in precipitation may strongly influence the persistence of alpine communities. Tree line may shift upward and encroach on alpine tundra in the Rockies as temperatures continue to rise, but it may not be a clear and dramatic change due to variations in local geomorphology, plant response, and human disturbance (Malanson et al. 2007). Global surveys suggest that another consequence of warming temperatures in the mountains may be an increase in the abundance and distribution of exotic plants (Pauchard et al. 2009).

Warming experiments at numerous tundra sites, including one in the Rockies, suggest that a temperature increase of 1–2°C can increase the height and cover of deciduous shrubs and graminoids, decrease the cover of mosses and lichens, and decrease species diversity and evenness (Walker et al. 2006). For instance, warming led to an increase in shrubs and a decrease in forbs in a subalpine meadow in the southern Rockies (Harte and Shaw 1995). Invariably, long-term changes in snowfall and wind deposited snow will result in changes in the area of wet meadows, fell-field, and dry meadow communities. Finally, changes in climate may interact and exacerbate other stressors such as increasing deposition of atmospheric N, ultraviolet radiation, increased human influence, and dust storms.

All wetlands are considered extremely vulnerable to climate change, but alpine wet meadows are thought to be at extreme risk. Warming temperatures and changes in precipitation are projected to diminish their number and extent and cause a decline in associated flora and fauna (Field et al. 2007). Warmer temperatures will affect the growth and reproduction of wetland species by increasing decomposition rates and evaporation from wetlands and their water supplies, reducing peat accumulation, thawing upper layers of permafrost in alpine wetlands, and changing nutrient dynamics (OTA 1993, Burkett and Kusler 2000). Reduced ground water flow due to lower snowpack, earlier melt dates, or reduced summer precipitation could result in lower water tables in wetlands dependent on ground water inputs (Poff et al. 2002). Wet meadows are particularly sensitive to hydrological changes because a reduction in the water table of a few inches could convert wetlands to upland habitats (Kusler 2006).

Status and Trends in Rocky Mountain National Park

The ROMN has begun two monitoring efforts in alpine vegetation: GLORIA and a survey of wetland ecological integrity.

Global Observation Research Initiative in Alpine Environments

Rocky Mountain National Park is part of the Global Observation Research Initiative in Alpine Environments (GLORIA), an international monitoring network established in 2001 to assess and predict biodiversity changes in alpine communities in response to broad drivers such as climate (Pauli et al. 2004). The methodology is extended by cooperators, such as the ROMN and ROMO, to create a long-term monitoring network at the global scale. The GLORIA sampling design is a sentinel site approach, where vegetation is monitored on four summits in a region, or park, that vary in elevation from treeline to the limits of vascular plants. This method is also being used in ROMO's sister park Tatra National Park in Slovakia to assess alpine vegetation

change. The GLORIA peaks at ROMO are much higher in elevation than the Tatra sites, but they share many of the same genera and species (Table 2).

Table 2. A comparison of GLORIA sites in Rocky Mountain and Tatra National Park.

	ROMO	TATRA	Number in Common
<i>Elevation of highest peak</i>	3862m	2375m	-
<i>Number of Vascular Plant Families</i>	28	27	20
<i>Number of Genera</i>	74	54	27
<i>Number of Species</i>	113	76	7

The alpine vegetation in the four sentinel GLORIA sites at ROMO is characterized by alpine dry meadow communities on the north and east exposures and fellfield communities on the south and west exposures. The plots established on the peaks were typically well vegetated (51%; Table 1) and contained an average of 17 vascular plant species. Data from 2009-2010 will be used as a baseline to evaluate trends in alpine vegetation in the future. However, in the case of vascular plant cover, there is some historic data to suggest a management threshold of 15% (Table 1). This low vascular plant cover was documented in sites impacted by the creation of Trail Ridge Road and resulted in reduced diversity and functioning (Greller and NPS 1974). While bedrock and scree may result in some pristine areas with little plant cover, the condition across many sites should be above this threshold. If areas are found that are below this threshold of 15% cover, the park should consider taking management action such as fencing off the area or plantings. In 2009-2010, no woody plants were present on the higher summits (PIK, GLA) and very few on the lower summits (VQS, JSM; Table 1). Exotic plants were absent on all peaks except the lowest which had a few individual common dandelion plants. Across all plots there was an average of only 0.02 exotic species, just slightly above the reference condition of 0 exotic species (Table 1; Pauchard et al. 2009).

Wetland Ecological Integrity

From 2007-2010, ROMN conducted a park-wide survey of wetland ecological integrity. Of the numerous sites visited, 16 sites were at or above treeline (greater than 3350 m) and 12 of the 16 were alpine wet meadows. The survey was used to develop a multimetric index (MMI) of biological integrity. The alpine wet meadows were within the reference condition where the mean MMI of 4.8 was just slightly above the statistically derived reference condition of 4.77 (Table 1). There are many species of high conservation value found in wetlands, particularly at high elevations. This conservation value was measured by assigning all the plants in Colorado with a C score that ranges from 0 to 10 (Rocchio 2007). Plants of high conservation value are species that are not able to adapt to human induced alterations and are typically the first plants to disappear from a habitat impacted by human activities (Wilhelm 1996, Lopez and Fennessy 2002). For example, many native sedges and orchids are assigned high conservation values of 10. Non-conservative species (i.e., generalist and highly adaptable species w/low conservatism scores indicating they are not restricted to a specific habitat or set of environmental conditions)

tend to dominate habitats that have been exposed to prolonged and/or severe human impacts, resulting in a loss of ecological complexity. For example, invasive plants and weedy species are assigned conservation values of zero. The Alpine Sentinel complex, and alpine wetlands in general, contain species of higher conservation value than wetlands at lower elevations (Figure 9). The mean C score in 2010 can be used as a baseline to compare future monitoring efforts (Table 1). In addition to vegetation measures, numerous measures of groundwater dynamics, water chemistry, and soil quality were measured at all sites. Typically, groundwater in wet meadows has a pH that ranges from 5-6.5 (Table 1). Alpine wet meadows had a lower pH than reference (Table 1). This may be explained by differences in soil type or increased acidic deposition at these high elevations.

In addition to the survey, an alpine wetland sentinel site was established along Trail Ridge Road that will be used to assess future trends in ecological integrity. Vegetation in the Alpine Sentinel complex is fairly typical of alpine snow-melt basin wetlands in ROMO and supports a mix of wetland and upland species (Driver 2010). The saturated areas are dominated by common sub-alpine and alpine wetland species such as *Carex scopulorum* and *C. aquatilis* while in the drier margins *Deschampsia cespitosa* is mixed with species also found on upland tundra. To date 67 taxa have been recorded at the four sites within the alpine sentinel site (12 bryophytes and 55 vascular species) and there are no exotic species present. There are three high value conservation taxa (Rocchio 2007) found at the site: *Carex nova* (black sedge), *Juncus triglumis* (threehulled rush) and *Podagrostis humilis* (alpine bentgrass).

Key Uncertainties and Science Strategies

The direction of precipitation changes in the alpine and the vegetation response is one of the key uncertainties in describing the alpine response to climate change. To date, direct human disturbance has not played a major role in shaping alpine vegetation in ROMO (with the exception of the construction of Trail Ridge Road and nitrogen deposition). However, if there is an increase in visitation, it will have the potential to increase trampling effects and increase the spread of invasive species. The loss of vegetation due to human trampling in the alpine of ROMO has been well documented (Willard and Marr 1970, Willard et al. 2007). Another major driver of vegetation change in the alpine is ungulate population size and browsing pressure. If climate change causes a shift in elk or bighorn sheep populations this may affect vegetation, particularly alpine willow communities.

Past studies have examined the composition of alpine vegetation communities near Trail Ridge Road (Willard 1979). The best current datasets to describe the status of alpine vegetation both come from the ROMN Inventory & Monitoring program. Because this is a new program, little historic data exist but there are published protocols and there is a high probability that monitoring will continue into the future. Inference to the park is limited because the subset of wetlands and the GLORIA sites represent just a few locations in the park, rather than a comprehensive survey. Future efforts to survey alpine vegetation in conjunction with repeated visits to sentinel sites would decrease the uncertainty in status and trend estimates. Currently, the ROMN monitors soil temperatures continuously (hourly) using data loggers. Given high annual variation in temperatures, precipitation, and timing of snow cover accumulation and melt off, consideration should be given to more frequent vegetation monitoring at the GLORIA sites.

Since available moisture has been proposed as a key factor in changing vegetation communities with climate change, some consideration should be given to monitoring soil moisture at a network of alpine sites on an annual basis. Instruments for doing so are unobtrusive and relatively inexpensive.

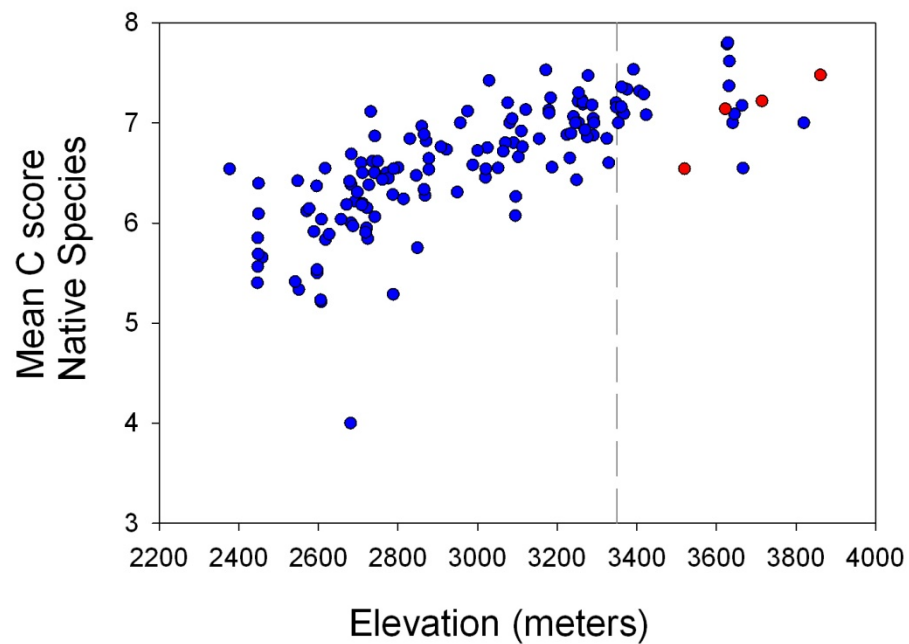


Figure 8. The mean conservation value of plants in wetlands (blue) and alpine GLORIA sites (red) across different elevations in Rocky Mountain National Park. The dashed line indicates the elevation typically associated with treeline in this region. Plants of high conservation value are species that are not able to adapt to human induced alterations and are typically the first plants to disappear from a habitat impacted by human activities. Data from the Rocky Mountain Inventory & Monitoring Network.

Air and Water Quality in the Alpine

Since 1990, air pollution across the United States has improved significantly for six major pollutants including ground-level ozone, sulfur dioxide, and nitrogen dioxide (USEPA 2010). However, a warmer climate will make it more difficult to meet U.S. air quality standards, particularly for ozone (Field et al. 2007, Karl et al. 2009). Changes in climate affect air quality by changing wind patterns, precipitation, dry deposition, chemical production and loss rates, natural emissions, and background concentrations (Jacob and Winner 2009). For instance, higher temperatures increase the oxidation of sulfur and nitrogen (N) oxides, and precipitation changes will influence the distribution of acids deposited across the landscape (Bernard et al. 2001).

Compared to the rest of the United States, N deposition in the Intermountain West is fairly low, but the ecological consequences, particularly in alpine areas, are great (e.g. Baron et al. 2000, Bowman et al. 2002). Alpine ecosystems are poorly suited to assimilating N because of their short growing season, low vegetative cover, low ambient soil nutrients, and high rates of snowmelt flushing (Williams and Tonnessen 2000). Nitrogen causes changes in alpine ecosystem structure and function and can contribute to acidification of alpine streams, lakes, and soils (Fenn et al. 2003). The deposition of dust from storms originating in the arid Colorado Plateau has increased in the southern Rockies over the past two centuries due to expansion and increased human activity (Neff et al. 2008). The dust covers the snow, which changes the albedo and accelerates the timing of snowmelt, which in turn alters alpine phenology and community dynamics (Steltzer et al. 2009). Dust events are also significant inputs of other elements such as calcium and phosphorus. These inputs have the potential to alter water chemistry and alpine community structure.

Status and Trends in Rocky Mountain National Park

Wet deposition has been measured continuously in ROMO at Loch Vale as part of the National Atmospheric Deposition Network (NADP; Figure 9). Precipitation is collected in a bucket and analyzed weekly for various acid and nutrient constituents. Critical loads can provide a meaningful management or ecological threshold for national parks (Porter et al. 2005). The critical load for Rocky Mountain National Park is estimated to be 1.5 kg/ha/yr based upon changes in diatom communities in the subalpine (Baron 2006). This critical load is a long-term target for management (NPS et al. 2010). In 2009, the amount of N deposition measured at Loch Vale (2.96 kg/ha/yr) was above this critical load and just slightly above the interim goals of 2.7 kg/ha/yr for 2012 (NPS et al. 2010).

From 1993–2004, deposition and snowpack records show a marked decrease in sulfate deposition in the northern, central, and southern Rockies (Ingersoll et al. 2008). However, ammonium (from ammonia) and nitrate (from N oxides) concentrations in snow increased during that period in the southern and central Rockies (Ingersoll et al. 2008). Snow chemistry has been measured at three sites in ROMO in the spring of each year from 1993–2011 (Figure 9). Sulfate concentrations in snow were lower in 2009 in ROMO (5.3 ± 0.54 ueq/L³) than the average for the period of record (Table 1). However, there has not been a significant decreasing trend across these 3 sites (Table 1). Increasing calcium concentrations may indicate increased dust events (because the dust is rich in calcium). In 2009, the calcium concentration in snow was 17.5 ± 1.61 ueq/L³, almost twice that of the period of record (Table 1; Figure 9). Mercury is a persistent, toxic, and volatile heavy metal that is globally distributed via the atmosphere and it has been

measured in the snowpack of ROMO since 2001. The average mercury concentration in 2009 at three sites in ROMO was slightly higher than the average across the period of record (Figure 10; Table 1).

Key Uncertainties and Science Strategies

Despite uncertainties, air pollution is expected to increase in a warmer climate. Tracking changes in air and water quality in the alpine of ROMO using deposition data from existing NADP and snow chemistry monitoring sites is very limited spatially, especially in the alpine. These efforts should be continued and if possible, expanded to provide a better understanding of spatial patterns. Recent initiatives such as high elevation ozone studies, N and phosphorus passive ion-exchange resin (IER) studies, and the water blitz are providing some spatial coverage. Alpine air and water quality monitoring sites are expensive to install and operate and current deposition rates in the alpine must be inferred from lower elevations. Moreover, installing monitoring structures in alpine areas has the potential to impact wilderness experience.

The ROMN is planning a stream ecological integrity survey of ROMO in 2014-2017 or 2018. The survey will include water quality, stream biota and physical habitat measures throughout the park, including in alpine streams. After the survey is complete, the ROMN will likely monitor stream water quality and ecological integrity annually at several (likely four) long-term sentinel monitoring sites. One or two of these should be in predominately alpine watersheds.

Recent work, not yet published at the time of this publication, used passive IER collectors to examine deposition at some alpine sites. Future work to compare IER data to models that interpolate between NADP sites would be useful. Site-level studies in the alpine that measure acids and nutrients in soils or water would be useful for interpreting monitoring deposition data and also for distinguishing between factors contributing to low pH.

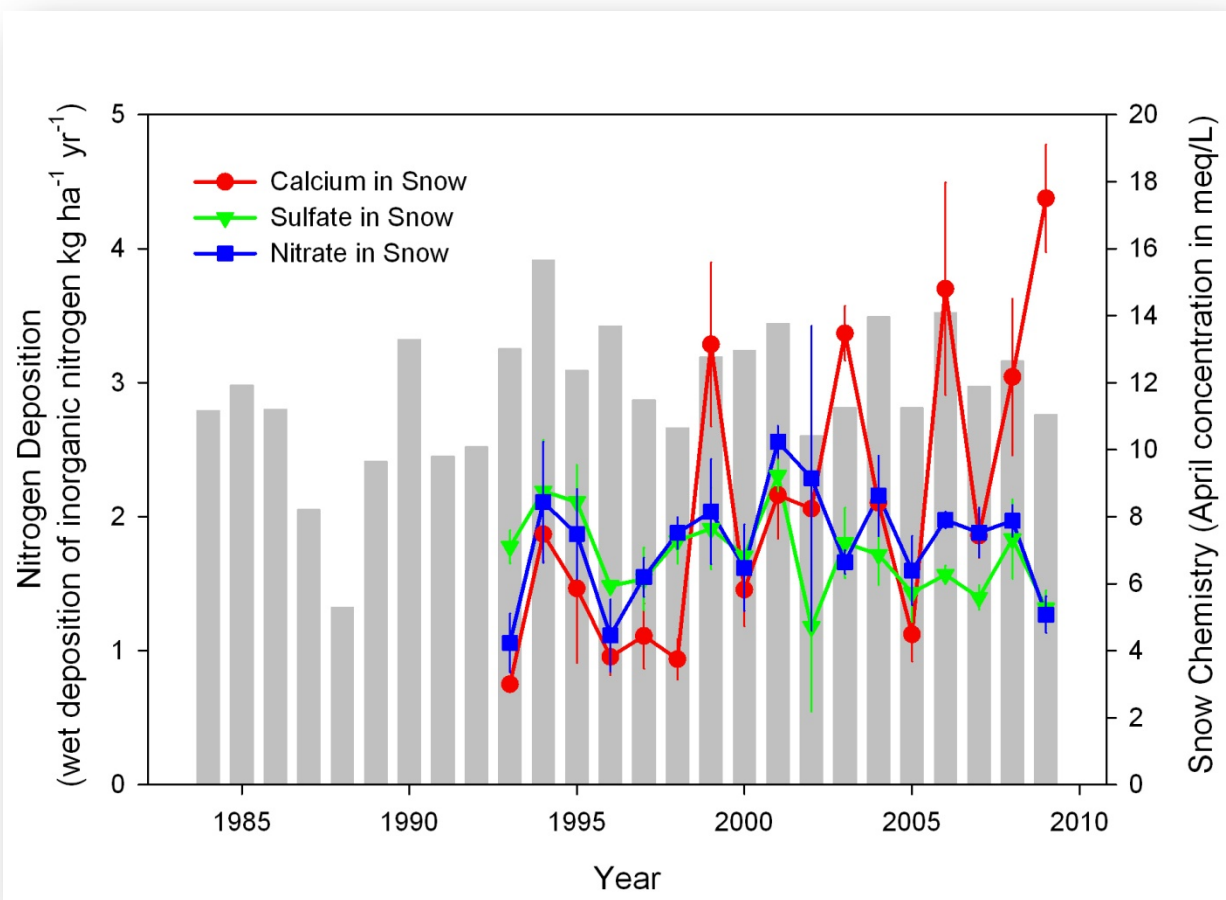


Figure 9. Wet deposition of nitrogen at Loch Vale (gray bars) and the average concentration of calcium, sulfate, and nitrate in snowpack from three sites in Rocky Mountain National Park 1984-2009.

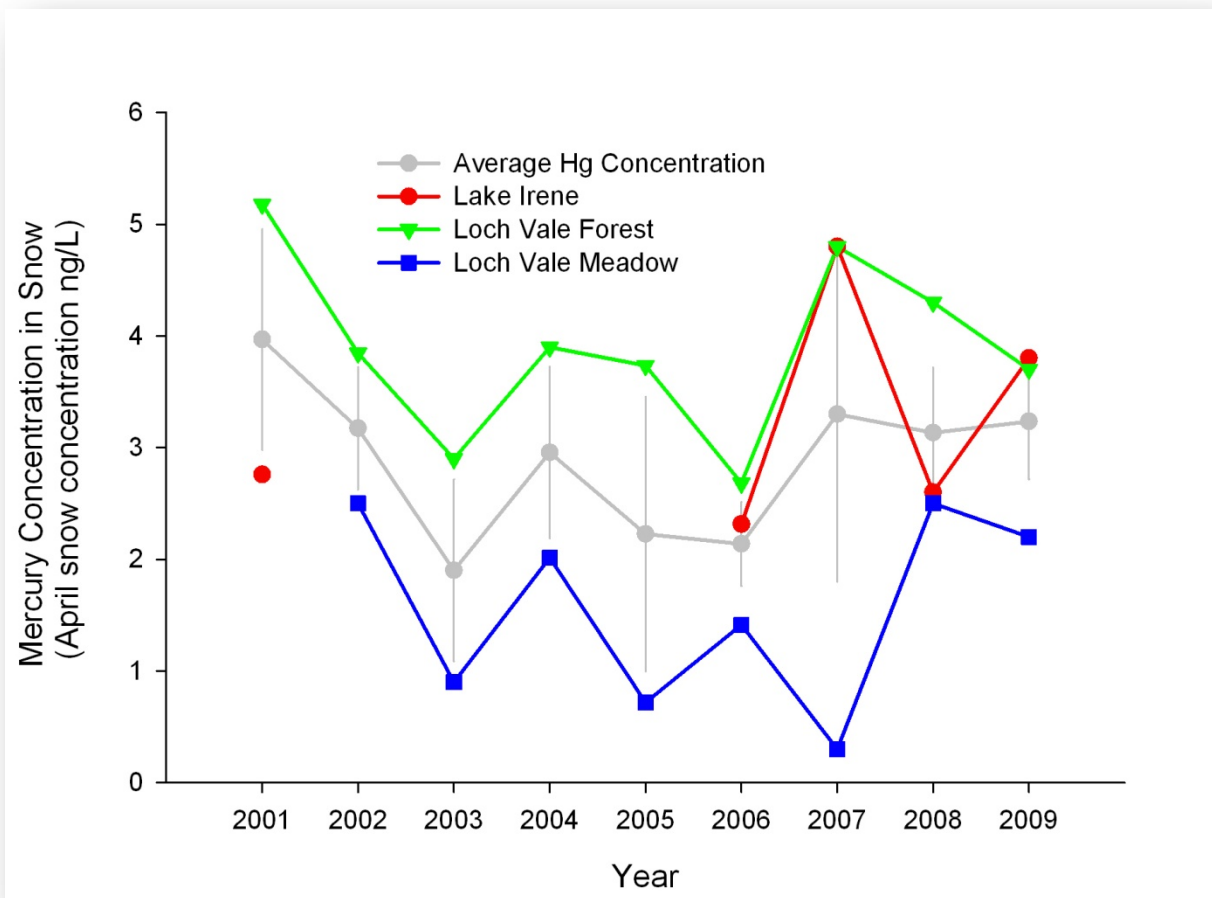


Figure 10. Average mercury concentrations seen in snowpack from three sites in Rocky Mountain National Park for the period of 2001-2009.

Soils in the Alpine

Snow, glaciers, and permafrost in mountain systems are particularly vulnerable to climate change because they are already close to melt conditions (Haeberli and Beniston 1998). The loss of glaciers and changing snowfall and melt has been well documented in the Rocky Mountains (Hall and Fagre 2003, Clow 2010), but even less is known about soils in the region and climate change. Permafrost, defined as ground that is frozen continuously for at least 2 years, is particularly sensitive to air temperatures and the loss of permafrost has been documented in boreal regions and the alpine regions of Europe and Asia (Harris et al. 2003, Li et al. 2008). Thawing of permafrost can cause subsidence and a release of carbon from the soil pool which has large implications for the global carbon balance (Schuur et al. 2008). Permafrost was documented in the Front Range in the 1970s (Ives and Fahey 1971) and models show that it likely occurs throughout the region (Janke 2005).

Changes in soil temperature, even in areas without permafrost, has large implications for vegetation and nutrient dynamics in the alpine. Through its effects on plant mortality, frost heave and thrusting is a large factor driving the pattern and distribution of plants in tundra communities (Inouye 2000). Snow is an important insulator of soils, and in the alpine, increased snow depth and duration is associated with warmer soil temperatures (Williams et al. 1998). Microbial activity in snow-covered soils may play a key role in alpine N cycling before plants become active (Brooks et al. 1996). In windswept areas of the alpine, there is little snow cover and warmer air temperatures will likely result in warmer soil temperatures. Dynamics of snow-covered alpine tundra will be more difficult to predict. If warmer air temperatures result in shorter period of snowpack, climate change may result in soils freezing more (Groffman et al. 2001). In New England, experiments have shown that the loss of snow can result in increased freeze events which in turn influences root and microbial mortality, nutrient cycling, and the chemistry of drainage waters (increased nitrate loss) (Groffman et al. 2001). Where lower winter soil temperatures cause root damage and turnover, roots may increase their carbohydrate demand, decrease nutrient uptake, and ultimately cause a reduction of plant growth during the following summer (Weih and Karlsson 2002) and possibly onward. Conversely, warmer soil temperatures in the alpine could favor plant growth and increase productivity when and where water is not limiting (Walker et al. 2006), initially uptaking more atmospheric CO₂, but in the long term, with more biomass decomposing, additional CO₂ could be added to the atmosphere.

Status and Trends in Rocky Mountain National Park

Models suggested that there was likely permafrost throughout the alpine regions in ROMO and particularly around Longs Peak (Janke 2005). In 2008, thirty HOBO © temperature data loggers with internal and external sensors were installed along Trail Ridge Road and an additional 16 were installed at the four GLORIA sites at depths ranging from 10-85 cm depth. In 2010, 6m boreholes were constructed along Trail Ridge Road and temperature loggers were placed at 1m increments within these. These sensors collectively allowed a ground truthing of the models and permafrost is now believed to be very limited or non-existent along Trail Ridge Road (Janke et al. 2012).

Soil temperatures in 2010 along Trail Ridge Road were generally cooler than in 2009 (Table 1). Annually, soils along Trail Ridge Road cooled by about 0.5° C from mid-July 2008 to mid-July 2010. This pattern is consistent with the soil temperatures recorded at the GLORIA sites (Ashton

2011; Figure 12). Lower snow pack (Figure 5) may have increased soil exposure to cold temperatures in winter months during 2010. There is less variability of soil temperature with depth; the range between the minimums and maximums is reduced. Surface soils typically freeze by late-October and thaw by late June (Table 3). At a greater depth, the freeze and thaw are delayed by about 1 to 3 weeks. The short lag time during the winter of 2009 indicates an abrupt, pronounced cooling that caused quicker cooling of deeper soils compared to the previous year.

Table 3. Thaw and freeze dates of soil at GLORIA summits and along Trail Ridge Road as defined by average minimum temperatures below or above 0°C.

	GLORIA sites				Trail Ridge Road		Lag-time (days) between the surface and deeper probes
	JSM	VQS	PIK	GLA	Surface	Deeper	
2008 freeze	Nov-4	Nov-3	Oct-14	Oct-13	Oct- 22	Nov-5	14
2009 thaw	May-16	May-18	May-22	May-22	Jun-21	Jul- 10	19
2009 freeze	Oct- 25	Oct-1	Oct-1	Oct-1	Oct-20	Oct-27	7
2010 thaw	May-27	May-27	May-31	Jun-1	19-Jun	2-Jul	14

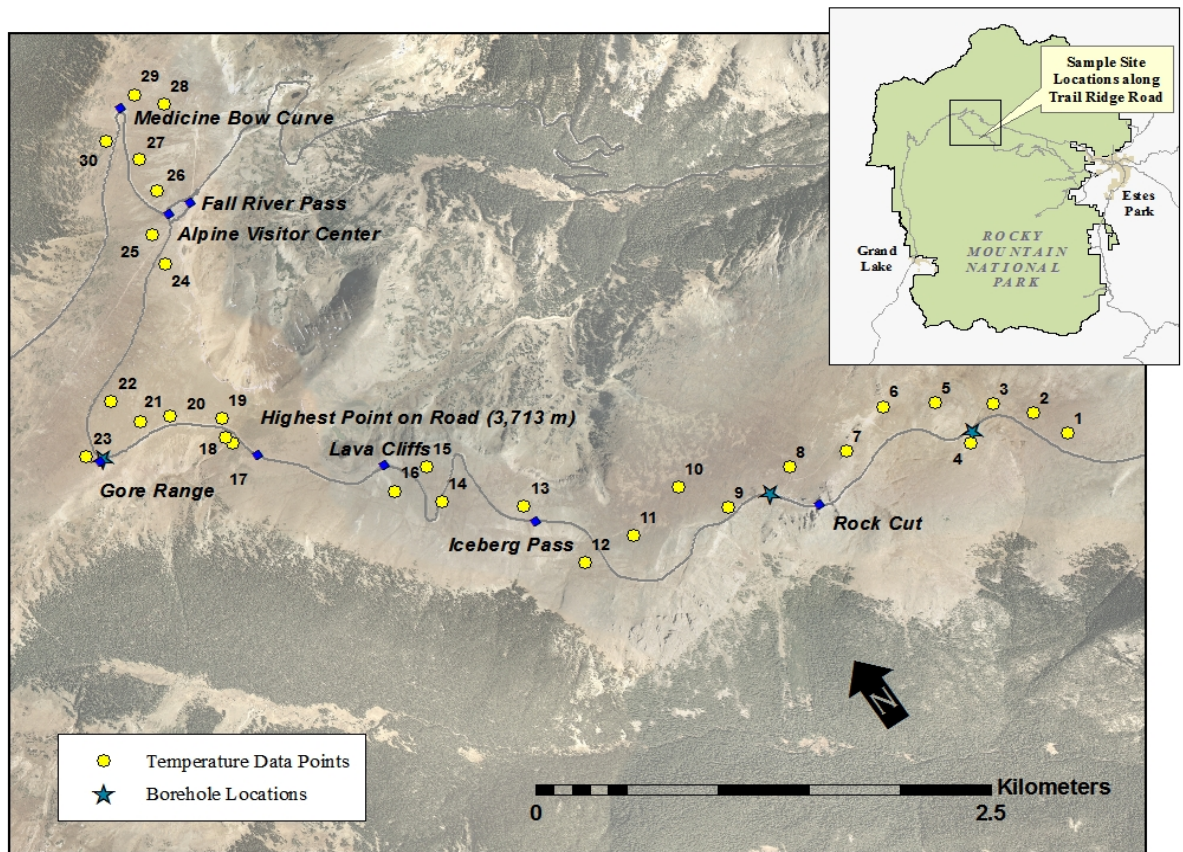


Figure 11. Soil temperature data points and borehole locations along Trail Ridge Road in Rocky Mountain National Park (Janke 2010). Data from this study will be used to examine soil temperature and permafrost dynamics.

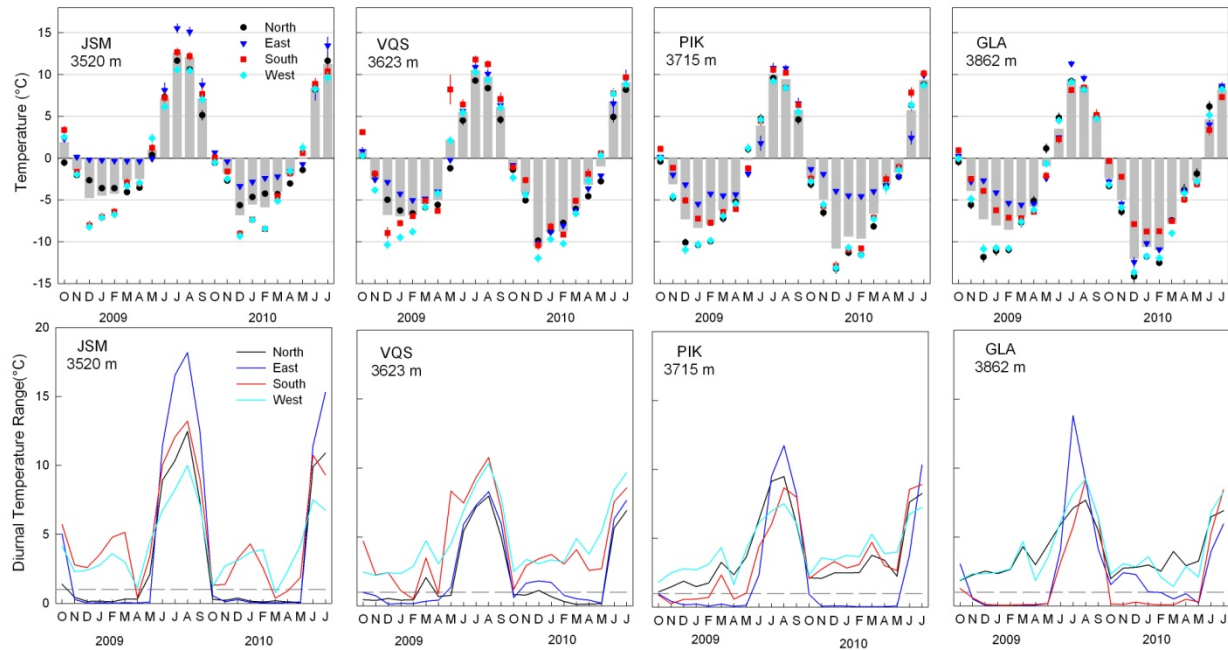


Figure 12. Mean monthly soil temperature on the GLORIA peaks at Rocky Mountain National Park from October 2008- July 2010 (top panel, gray bars) and mean monthly soil temperature on the east, south, and west sides of each peak (top panel, colored symbols). Bottom panel shows the diurnal temperature range on all peaks and all aspects from October 2008- July 2010.

Key Uncertainties and Science Strategies

While soil temperatures are slower to change than air temperature, soil temperatures and permafrost will respond to a changing climate. The insulating effect of snow and the uncertainty in projections of future snow pack makes it difficult to predict whether soils will cool or warm. The soil temperature data records from the park are relatively short in duration (~ 3 years) but over time these may provide a valuable record of climate change. Now that permafrost models have been refined, further ground-truthing of permafrost extent could be performed using electrical conductivity or ground penetrating radar. Changes in the timing, depth, and duration of snow or permafrost may have a greater impact on warming soils than changing air temperatures, but inaccessibility during the winter months makes it difficult to determine a relationship. Changes in soil temperature may also impact other factors such as CO₂ production, N production, or tundra species diversity. Future work could focus on adding soil moisture monitoring in the alpine and on the relationship of ground temperatures and soil moisture to microbial activity as well as understanding the relationships between soil temperature regimes and moisture levels and plant species.

Visitors in the Alpine

Climate change can alter the quality, timing and magnitude of visitation to the national parks. In alpine wilderness areas, longer summer seasons and a shorter time with snow on the ground will likely increase the opportunity for visitation. For instance, in the national parks in the Canadian Rockies, 64% of visits occur during the warmer months (May-Sept); longer warm-weather seasons are expected to increase visitation (Scott et al. 2007). A statistical model of monthly visitation and anticipated climate change at Waterton Lakes National Park projected that annual visitation would increase between 6% and 10% in the 2020s and between 10% and 36% in the 2050s as the result of an increase in the length and quality of warm-weather tourism seasons. However, warmer temperatures may drive a decline in visitor experience. Increased fire and drought, and decreased wildlife and glacial extent may reduce visitation to mountain parks (Scott et al. 2007). Moreover, changes in the frequency, intensity and severity of storms and floods may pose threats to park infrastructure and roads and cause a decline in the quality of visitor experience and reduce access (Loehman and Anderson 2009).

Increased visitation may bring an economic benefit to the park and surrounding communities, but there is an environmental cost. There will be increasing strain on fragile environments with increased visitation. Increased trampling and litter could cause changes in alpine vegetation and wildlife. It will be important to monitor visitation to understand how and if it changes with climate change.

Status and Trends in Rocky Mountain National Park

In a visitor survey at ROMO, more than 70% of respondents indicated that current opportunities for viewing conifer forests and wildflowers were important reasons for visitation to the park (Richardson and Loomis 2004). Therefore, any reduction in the quality of the wildflowers wrought by climate change may reduce visitation. However, they also found that temperature and precipitation were important factors in determining visitors' net willingness to pay for recreation, where an increase of 1°F was associated with a willingness to pay an additional \$4.37 (Richardson and Loomis 2005).

A little over three million visitors came to ROMO in 2010 and 80% of the visitation occurred between the months of June and October. In the past five years there has been between 2.9 and 3.3 million visitors to ROMO (Figure 11). The level of visitation in 2010 was slightly higher than number of visitors during the last 6 years (Table 1). It is difficult to monitor how many people are using the backcountry alpine areas of ROMO. The number of permitted user-nights at Forest Canyon has declined since the late 1990s, but there does not appear to be a change in the use of Little Rock Lake (Figure 11; Table 1). While these permit data are limited to only one area of the park, they can provide a valuable index to better understand annual trends and patterns in visitor use in the alpine. Visitation data are highly variable (Figure 11) but despite this, there seems to be a good correlation between annual visitation and the number of user-nights in Forest Canyon and Little Rock Lake.

Key Uncertainties and Science Strategies

Understanding how climate change will affect visitation is difficult to anticipate. Past survey data can be used to estimate people's potential response to increases in temperature, but there are numerous other factors to consider when predicting realized visitation. Gas prices, the economy,

changes in the quality of the experience, construction projects, and population growth are just a few of the many factors that affect the number of visitors to ROMO. Monitoring or modeling off-trail visitor use in alpine areas, along with vegetation impacts could assist in determining thresholds of degradation. Impacts are likely linked to soil moisture (i.e., wet soils are more easily damaged) and monitoring should take this into account.

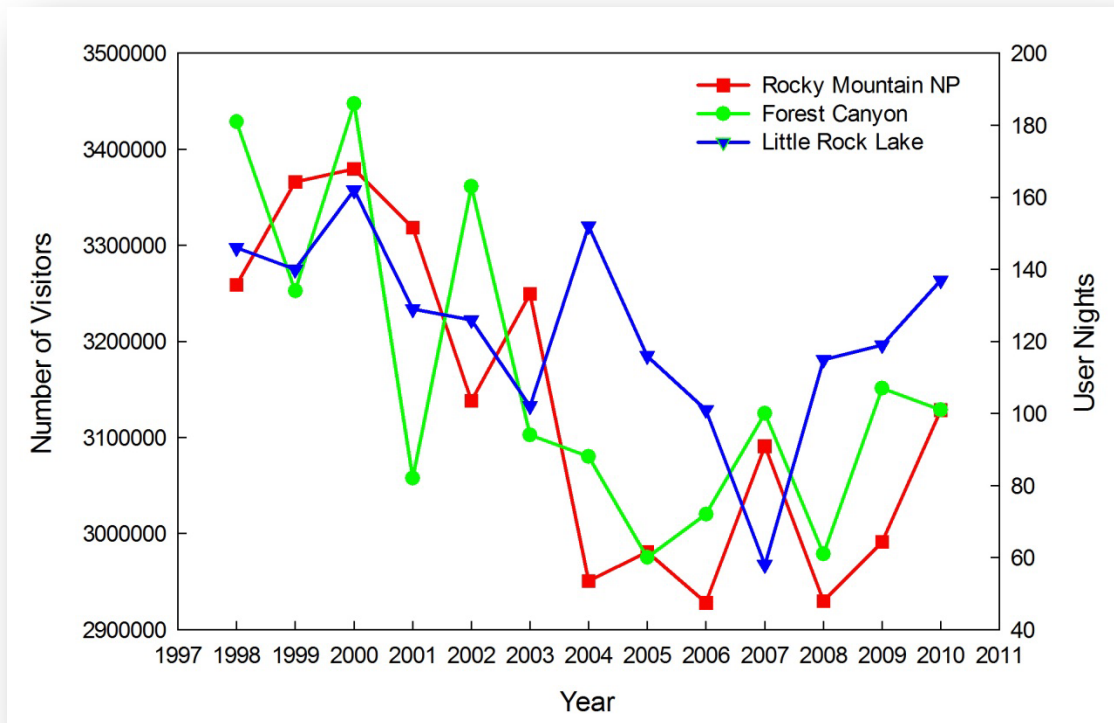


Figure 13. The annual number of visitors to Rocky Mountain National Park and the number of backcountry user nights at Forest Canyon and Little Rock Lake.

Conclusions

The fragile alpine tundra encompasses one-third of ROMO and is one of the main scenic and scientific features for which the park was established. This is one of the largest examples of alpine tundra ecosystems preserved in the National Park System in the lower 48 states. Given the central location of ROMO, the proximity to the Denver Metropolitan area and easy access via Trail Ridge Road, ROMO provides access to alpine communities to millions of visitors annually. The alpine is particularly vulnerable to climate change and understanding its current condition and the potential for future changes will be critical for park management in the coming century. With this report, we have compiled, analyzed, and interpreted scientific data from the alpine relating to climate, air quality, wildlife, vegetation, soils, and visitation. This is one of the first steps in incorporating sound science into park management.

In conclusion, we found that alpine condition in ROMO is good, but warming trends are a cause for concern. In many cases, the 2010 condition was within the range of natural variability or similar to the period of record. For instance, alpine butterfly populations, stream discharge, visitation, and some pollutants have not changed significantly. In other cases, conditions have deteriorated. For example, temperatures have been increasing over the past century. In a warmer climate, alpine wildlife populations may decline and there will be changes in the structure and function of vegetation. Unfortunately for the majority of indicators, we lack sufficient data to analyze long-term trends or see a change in condition. This highlights the need to continue monitoring efforts and where possible, expand them in the alpine. Resources are limited, but providing support to the researchers and programs that are collecting the long-term datasets included in this report should be prioritized and if possible, efforts should be expanded.

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Appendix 1: Potential Metrics

Below we list some of the other possible metrics that relate to alpine environments in Rocky Mountain National Park.

Table 1. Vital sign reference condition table of potential indicators, source, and contact information for Rocky Mountain National Park.

Vital Sign	Indicators	Source	Contact/Reference
Climate	Temperature, windspeed, Precipitation	Loch Vale	USGS, Clow
	Temperature, windspeed, Precipitation, Snowpack	SNOTEL stations (6)	SNOTEL, ROMN
	Temperature, Precipitation	Grand Lake, Estes Park	COOP, ROMN
	Snowpack	Rocky Mountain Snow Survey	USGS, Ingersoll
	Snowpack	Snow course stations	SNOTEL, ROMN
	Soil temperature	GLORIA sites	ROMN
	Soil temperature/Permafrost studies	Trail ridge Rd	Jason Janke
	Temperature, precipitation	RAWS	RAWS
Air Quality	Wet deposition acids, nutrients, base cations	NADP- Loch Vale, Beaver meadows	NADP
	Dry deposition, Ozone	CASTNET- Beaver Meadows	CASTNET/EPA
	Ozone	Long's Peak	NPS ARD
	Deposition of acids, nutrients, base cations and mercury in snow	Rocky Mountain Snow Survey	USGS, Ingersoll
Water quality	Discharge, temperature, chemistry	Loch Vale, Colorado River, Grand Lake Inlet, Big Thompson	USGS
	Water Bio Blitz	Throughout Park	ROMO
	Stream Ecological Integrity	ROMN- Colorado River Headwaters	ROMN
Wildlife	Pika	NPS Pikas in Peril	ROMN/Chris Ray
	Butterflies	Bray transects	Richard Bray
	Ptarmigan	2010 surveys	Gregory Wan
	Birds	RMBO	RMBO
	Bees	NPS- Pollination Project	NPS Ann Rodman
	Elk	NPS	NPS
Vegetation & Soils	Wetland Ecological Integrity (vegetation, soil, ground water dynamics)	Fens, Riparian, and Wet Meadows throughout the park- ROMN	ROMN
	Alpine vegetation, soil chemistry	Four GLORIA sites- ROMN	ROMN
	Limber Pine	NPS/USFS	NPS
	Soil chemistry	Trail Ridge w/ permafrost studies	Jason Janke
	Phenology	Alpine Visitor Center	NPS- Leanne Benton