Rocky Mountain National Park Air Quality and Air Quality Related Values Research			
Park	**Title**	**Project Summary/Findings**	**Citation**
Atmospheric Deposition of N or S			
Rocky Mountain National Park (ROMO)	Atmospheric Deposition and Its Effects in the Intermountain West	This paper focuses on sensitive areas, National Parks and National Forest Wilderness areas. Many of these areas are Class 1 areas protected by the Clean Air Act Amendments from any degradation of air-quality-related values, including degradation that might be caused by atmospheric deposition. Most of the annual load of pollutants in atmospheric deposition is delivered to the areas by spring snowmelt. The report examines spatial and temporal trends in atmospheric deposition, ecosystem sensitivity and response to deposition, and concerns for future protection of these ecosystems. The primary source of sulfate and related acidity is coal combustion for electric power generation. Also, fossil-fuel combustion from motor vehicles contributes a large amount of nitrogen oxides. Fertilization effects to terrestrial and aquatic life from nitrogen deposition on high-elevation ecosystems are currently the greatest concern related to atmospheric deposition. Significant atmospheric mercury deposition to Rocky Mountain National Park is indicated from sediment cores collected at Mills Lake.	Campbell, D.H., 2003, Atmospheric deposition and its effects in the Intermountain West, in Acid Rain: Are the Problems Solved? Proceedings of the conference, May 2-3, 2001, Washington D.C., J. White ed., American Fisheries Society, Bethe
Rocky Mountain National Park (ROMO)	Atmospheric deposition maps for the Rocky Mountains	Variability in atmospheric deposition across the Rocky Mountains is influenced by elevation, slope, aspect, and precipitation amount and by regional and local sources of air pollution. To improve estimates of deposition in mountainous regions, maps of average annual atmospheric deposition loadings of nitrate, sulfate, and acidity were developed. Researchers obtained chemical data from the National Atmospheric Deposition Program/National Trends Network and from US Geological Survey and National Park Service annual snowpack surveys. Maps of average annual atmospheric deposition loadings of nitrate, sulfate, and acidity were produced by using spatial statistics, primarily to develop a spatial distribution of pollutant loading to high-elevation ecosystems. Maps indicate an increasing spatial trend in concentration and deposition of nitrate and sulfate, in particular, from north to south throughout the Rocky Mountains. The maps also identify hot-spots of atmospheric deposition that result from combined local and regional sources of air pollution.	Nanus, L., Campbell, D. H., Ingersoll, G. P., Clow, D. W. & Mast, M. A. (2003) Atmospheric deposition maps for the Rocky Mountains. Atmospheric Environment, 37, 4881-4892.
Rocky Mountain National Park (ROMO)	Atmospheric Deposition of Nutrients, Pesticides, and Mercury in Rocky Mountain National Park, Colorado, 2002	Researchers measured atmospheric deposition during summers in Rocky Mountain National Park in Colorado, at Bear Lake area and Loch Vale watershed. Annual bulk nitrogen deposition in 2002 was 2.28 kg N/ha at Bear Lake and 3.35 kg N/ha at Loch Vale. Dry deposition may account for as much as 28 percent of annual nitrogen deposition. Annual deposition rates for three pesticides were estimated as 45.8 mg/ha for atrazine, 14.2 mg/ha for dacthal, and 54.8 mg/ha for carbaryl, with 80-90 percent of the annual pesticide deposition occurring during summer. Concentrations of nutrients in summer precipitation at Bear Lake ranged from less than 0.007 to 1.29 mg N/L for ammonium and 0.17 to 4.59 mg N/L for nitrate, similar to Loch Vale National Atmospheric Deposition Network station. At Bear Lake, carbaryl was present (0.0079 to 0.0952 µg/L, followed by atrazine (less than 0.0070 to 0.0604 µg/L), and dacthal (0.0030 to 0.0093 µg/L). Mercury was detected from Loch Vale in concentrations ranging from 2.6 to 36.2 ng/L. Additionally, mercury deposition to Loch Vale was estimated at 7.1 µg/m2.	Mast, M.A., Campbell, D.H., Ingersoll, G.P., Foreman, W.T., and Krabbenhoft, D.P., 2002, Atmospheric Deposition of Nutrients, Pesticides, and Mercury in Rocky Mountain National Park, Colorado, USGS Water-Resources Investigations Report 0
Rocky Mountain National Park (ROMO)	Atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming - a review and new analysis of past study results	The Rocky Mountain region of Colorado and southern Wyoming receives 2–4 kg/ha/yr of atmospheric N in wet deposition according to the National Atmospheric Deposition Program, and rates as high as 5.5 kg kg/ha/yr have been reported for the Loch Vale watershed in Rocky Mountain National Park. The researchers measured high elevation (> 3000 m) sites east of the Continental Divide in the Front Range The four sites with the highest NH4+ concentrations in wet deposition were among the six easternmost NADP sites, which is also consistent with a source to the east of the Rockies. The analysis found an increase in N loads in wet deposition at Niwot Ridge of 0.013 kg/ha/yr, an order of magnitude less than previously reported for this site. According to the researchers, increases in population and energy use in Colorado and throughout the west suggest a need for continued monitoring of atmospheric deposition of N, and may reveal more widespread trends in N deposition in the future.	Burns, D. A. (2003) Atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming - a review and new analysis of past study results. Atmospheric Environment, 37, 921-932.
Rocky Mountain National Park (ROMO)	Comparison of precipitation chemistry in the Central Rocky Mountains, Colorado, USA	Volume-weighted mean concentrations of nitrate, ammonium, and sulfate in precipitation were compared at high-elevation sites in Colorado from 1992 to 1997 to evaluate emission source areas to the east and west of the Rocky Mountains. Precipitation chemistry was measured by two sampling methods, the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) and snowpack surveys at maximum accumulation. Concentrations of nitrate and sulfate in winter precipitation were greater on the western slope of the Rockies; while concentrations of nitrate and ammonium in summer precipitation were greater on the eastern slope. Summer concentrations were almost twice as high as winter concentrations. High-elevation ecosystems in Colorado are influenced by air pollution emission sources located on both sides of the Continental Divide. The researchers suggest that sources of nitrogen and sulfur located east of the Divide have a greater influence on precipitation chemistry in the Colorado Rockies.	Heuer, K., Tonnessen, K. A. & Ingersoll, G. P. (2000) Comparison of precipitation chemistry in the Central Rocky Mountains, Colorado, USA. Atmospheric Environment, 34, 1713-1722.
Rocky Mountain National Park (ROMO)	Comparison of snowpack and winter wet-deposition chemistry in the Rocky Mountains, USA: implications for winter dry deposition	Depth-integrated snowpack chemistry was measured just prior to maximum snowpack depth during the winters of 1992-1999 at 12 sites co-located with National Atmospheric Deposition Program/National Trend Network (NADP/NTN) sites in the central and southern Rocky Mountains, USA. Winter volume-weighted mean wet-deposition concentrations were calculated for the NADP/NTN sites, and the data were compared to snowpack concentrations using the paired t-test and the Wilcoxon signed-rank test. The good agreement between snowpack and winter NADP/NTN SO42- and NO3- concentrations indicates that for those solutes the two data sets can be combined to increase data density in high-elevation areas, where few NADP/NTN sites exist. This combination of data sets will allow for better estimates of atmospheric deposition of SO4 and NO3- across the Rocky Mountain region.	Clow, D. W., Ingersoll, G. P., Mast, M. A., Turk, J. T. & Campbell, D. H. (2002) Comparison of snowpack and winter wet-deposition chemistry in the Rocky Mountains, USA: implications for winter dry deposition. Atmospheric Environment, **36**, 2337-2348.

Rocky Mountain National Park (ROMO)	Isotopic study of sulfate sources and residence times in a subalpine watershed	Stable sulfur and oxygen isotope ratios and naturally occurring S-35 (SO4) activities were used by the researchers to examine sulfate sources; to address the role of sulfur dynamics; and to estimate residence times of atmospherically derived sulfate in Loch Vale Watershed, Colorado. In 1996, surface water samples from small streams flowing through talus, forest, and wetland areas had delta(34)S(SO4) values ranging from 1.8 to 3.7 parts per thousand. Values of delta(18)O(SO4) at the three sites ranged from -1.3 4 to 3.7 parts per thousand. Average delta(34)S(SO4) and delta(18)O(SO4) values in Loch Vale precipitation (1991-1999) are higher (5.2 and 13.6, respectively) than surface water values. The investigators indicate that some of the deposited sulfate is transformed and/or mixed with other sulfur sources in the watershed.	Kester, C. L., Baron, J. S. & Turk, J. T. (2003) Isotopic study of sulfate sources and residence times in a subalpine watershed. Environmental Geology, **43**, 606-613.
Rocky Mountain National Park (ROMO)	Nitrogen emissions along the Colorado Front Range: response to population growth, land and water use change, and agriculture	Nitrogen emissions increased significantly along the Colorado Front Range from 1980-2000 in response to land use change associated with increased urbanization. Increases from point and mobile sources were responsible for most nitrogen emissions increases; agriculture was the other important source of N emissions. Livestock emissions increased somewhat due to more cattle and hogs in feedlots. Ecosystem responses to N deposition are likely to be an indirect result of land use change.	Baron, J.S., S. Del Grosso, D.S. Ojima, D.M. Theobald, and W.J. Parton. 2004. Nitrogen emissions along the Colorado Front Range: response to population growth, land and water use change, and agriculture. In: DeFries, R.S., G.P. Asner, and R.A. Houghton, (eds.). Ecosystems and land use change (Geophysical monograph series 153). Washington, DC: American Geophysical Union. p. 117-127.
Rocky Mountain National Park (ROMO)	Rocky Mountain Snowpack Chemistry Network: History, Methods, and the Importance of Monitoring Mountain Ecosystems	Rregional-scale atmospheric deposition data in the Rocky Mountains are sparse; as a result, a program designed by the U.S. Geological Survey was developed to determine the quality of precipitation and to identify sources of atmospherically deposited pollution in a network of high-elevation sites. Depth-integrated samples of seasonal snowpacks at 52 sampling sites, from New Mexico to Montana, were collected and analyzed each year since 1993. Results of the first 5 years (1993–97) of the program are discussed in the report. Spatial patterns in regional data have emerged from the geographically distributed chemical concentrations of ammonium, nitrate, and sulfate that clearly indicate that concentrations of these acid precursors in less developed areas of the region are lower than concentrations in the heavily developed areas. Snowpacks in northern Colorado that lie adjacent to both the highly developed Denver metropolitan area to the east and coal-fired power plants to the west had the highest overall concentrations of nitrate and sulfate in the network.	Ingersoll, G.P., Turk, J.T., Mast, M.A., Clow, D.W., Campbell, D.H., and Bailey, Z.C., 2002, Rocky Mountain Snowpack Chemistry Network: History, Methods, and the Importance of monitoring mountain ecosystems, U.S. Geological Survey Open-F
Rocky Mountain National Park (ROMO)	THE INFLUENCE OF MOUNTAIN METEOROLOGY ON PRECIPITATION CHEMISTRY AT LOW AND HIGH ELEVATIONS OF THE COLORADO FRONT RANGE, USA	Researchers explored the seasonal characteristics in wet deposition chemistry for two sites located at different elevations along the east slope of the Colorado Front Range in Rocky Mountain National Park. Strong acid anions, acidity, ammonium, and high salt concentrations originate to the east of Rocky Mountain National Park, and are transported via up-valley funneling winds or convective instability, resulting from differential heating of the mountains and the plains to the east. The mountain effect influences the composition of precipitation at Beaver Meadows (low elevation site) throughout the year, and also at Loch Vale (high elevation site) primarily during the summer. During the winter, Loch Vale precipitation is very dilute, and occurs in conjunction with westerly winds from the southerly location of the jet stream.	Baron, J. & Denning, A. S. (1993) THE INFLUENCE OF MOUNTAIN METEOROLOGY ON PRECIPITATION CHEMISTRY AT LOW AND HIGH ELEVATIONS OF THE COLORADO FRONT RANGE, USA. Atmospheric Environment Part a-General Topics, 27, 2337-2349.
Rocky Mountain National Park (ROMO)	Use of O-17/O-16 [oxygen isotopes] to trace atmospherically-deposited sulfate in surface waters: a case study in alpine watersheds in the Rocky Mountains	This case-study determines whether the oxygen isotope, O-17 might provide a new tool for quantifying the impact of atmospheric deposition on surface-water sulfate loads. In Rocky Mountain alpine regions, excess O-17 was evident in stream sulfate in one of two high-elevation watersheds and found to be characteristic of atmospheric sulfate deposited in snow. Isotope mass balance calculations gave low atmospheric contributions to stream sulfate.	Johnson, C. A., Mast, M. A. & Kester, C. L. (2001) Use of O-17/O-16 [oxygen isotopes] to trace atmospherically-deposited sulfate in surface waters: a case study in alpine watersheds in the Rocky Mountains. Geophysical Research Letters, 28, 4483-4486.
Rocky Mountain National Park (ROMO)	Use of stable sulfur isotopes to identify sources of sulfate in Rocky Mountain snowpacks	Stable sulfur isotope ratios and major ions in bulk snowpack samples were monitored at a network of 52 high-elevation sites along and near the Continental Divide from 1993 to 1999. This information was collected to better define atmospheric deposition to remote areas of the Rocky Mountains and to help identify the major source regions of sulfate in winter deposition. Average annual delta S-34 values at individual sites ranged from + 4.0 to + 8.2 parts per thousand, and standard deviations ranged from 0.4 to 1.6 parts per thousand. The chemical composition of all samples was extremely dilute and slightly acidic; average sulfate concentrations ranged from 2.4 to 12.2 µequiv/L and pH ranged from 4.82 to 5.70. The range of delta S-34 values measured in this study indicated that snowpack sulfur in the Rocky Mountains is primarily derived from anthropogenic sources.	Mast, M. A., Turk, J. T., Ingersoll, G. P., Clow, D. W. & Kester, C. L. (2001) Use of stable sulfur isotopes to identify sources of sulfate in Rocky Mountain snowpacks. Atmospheric Environment, 35, 3303-3313.
Biogeochemistry of Pollutants in Ecosystems			
Rocky Mountain National Park (ROMO)	Analysis of long term sulfate and nitrate budgets in a Rocky Mountain basin	Biogeochemistry of Seasonally Snow-Covered Catchments; Edited by Kathy A. Tonnessen, Mark W. Williams & Martyn Tranter; Available reprints: IAHS Publ. 228 (July 1995) ISBN 0-947571-44-2; 466 + xiv pp.; price £10.00. This IAHS title is the pre-published proceedings of Symposium H3 held at the XXI General Assembly of the International Union of Geodesy and Geophysics, in Boulder, Colorado, July 1995. The 48 papers cover recent developments in modeling, field investigations, synthesis of the state-of-the-science of snow and glacier hydrology, chemistry and biological processes. Analysis of long term sulfate and nitrate budgets in a Rocky Mountain Basin is found in the first section: Snowpack transformation and atmospheric interactions.	Baron, J.S., E.J. Allstott, and B.K. Newkirk. 1995. Analysis of long term sulfate and nitrate budgets in a Rocky Mountain basin. pp. 255-262 in: K.A. Tonnesson, M.W. Williams, and M. Tranter, eds.
Rocky Mountain National Park (ROMO)	Application of a coupled ecosystem-chemical equilibrium model, DayCent-Chem, to stream and soil chemistry in a Rocky Mountain watershed	According to the researchers, atmospheric deposition of sulfur and nitrogen species have the potential to acidify terrestrial and aquatic ecosystems, but nitrate and ammonium are also critical nutrients for plant and microbial productivity. Both the ecological response and the hydrochemical response to atmospheric deposition are of interest to regulatory and land management agencies. The investigators developed a non-spatial biogeochemical model to simulate soil and surface water chemistry by linking the daily version of the CENTURY ecosystem model (DayCent) with a low temperature aqueous geochemical model, PHREEQC. The model was able to replicate the measured seasonal and annual stream chemistry for most solutes for Andrews Creek in Loch Vale watershed, Rocky Mountain National Park. This model is appropriate for accurately describing ecosystem and surface water chemical response to atmospheric deposition and climate change.	Hartman, M. D., Baron, J. S. & Ojima, D. S. (2007) Application of a coupled ecosystem-chemical equilibrium model, DayCent-Chem, to stream and soil chemistry in a Rocky Mountain watershed. Ecological Modeling, 200, 493-510.

Rocky Mountain National Park (ROMO)	Controls on nitrogen flux in alpine/subalpine watersheds of Colorado	Research was conducted at two alpine/subalpine sub basins of the Loch Vale watershed. Atmospheric deposition of NO3- plus NH4+ was 3.2-5.5 kg N ha(-1), and watershed export was 1.8-3.9 kg N ha(-1) for water years 1992-1997. Annual N export increased in years with greater input of N, but most of the additional N was retained in the watershed, indicating that parts of the ecosystem are nitrogen-limited. Tundra landscapes had moderately high DIN concentrations, whereas forest and wetland landscapes had low concentrations, indicating little export of nitrogen from these landscapes. Between the two sub basins the catchment of Icy Brook had greater retention of nitrogen than that of Andrews Creek because of landscape and hydrologic characteristics that favor greater N assimilation in both the terrestrial and aquatic ecosystems.	Campbell, D. H., Baron, J. S., Tonnessen, K. A., Brooks, P. D. & Schuster, P. F. (2000) Controls on nitrogen flux in alpine/subalpine watersheds of Colorado. Water Resources Research, 36, 37-47.
Rocky Mountain National Park (ROMO)	CONTROLS ON SOIL SOLUTION CHEMISTRY IN A SUB-ALPINE FOREST IN NORTH-CENTRAL COLORADO	The Loch Vale Watershed in Rocky Mountain National Park, Colorado, was evaluated for sensitivity to acid precipitation. Researchers conducted a long-term research project to identify the processes controlling surface water chemistry. Using lysimeters, researchers estimated the concentration and flux of major solutes in the Oie and B horizons in an old-grown Engelmann spruce (*Picea engelmannii*) and subalpine fir [*Abies lasiocarpa)* forest, and in an adjacent site disturbed by a snow avalanche. Findings indicate that although precipitation inputs and theoretical mineral weathering can explain the total annual solute flux from Loch Vale Watershed, the effects of forest soil solutes may be important during the initial stages of snowmelt and following large-scale disturbance.	Arthur, M. A. & Fahey, T. J. (1993) CONTROLS ON SOIL SOLUTION CHEMISTRY IN A SUB-ALPINE FOREST IN NORTH-CENTRAL COLORADO. Soil Science Society of America Journal, 57, 1122-1130.
Rocky Mountain National Park (ROMO)	HYDROLOGIC PATHWAYS AND CHEMICAL-COMPOSITION OF RUNOFF DURING SNOWMELT IN LOCH VALE WATERSHED, ROCKY-MOUNTAIN-NATIONAL-PARK, COLORADO, USA	Intensive sampling of a stream draining an alpine-subalpine basin revealed that depressions in pH and acid neutralizing capacity (ANC) of surface water at the beginning of the spring snowmelt in 1987 and 1988 were not accompanied by increases in strong acid anions, and that surface waters did not become acidic (ANC < 0). Samples of meltwater collected at the base of the snowpeak in 1987 were acidic and exhibited distinct 'pulses' of nitrate and sulfate. Solutions collected with lysimeters in forest soils adjacent to the stream revealed high levels of dissolved organic carbon (DOC) and total Aluminum (Al). Peaks in concentration of DOC, Al, and nutrient species in the stream samples indicate a flush of soil solution into the surface water at the beginning of the melt. Infiltration of meltwater into soils and spatial heterogeneity in the timing of melting across the basin prevented stream and lake waters from becoming acidic, according to the researchers.	Denning, A. S., Baron, J., Mast, M. A. & Arthur, M. (1991) HYDROLOGIC PATHWAYS AND CHEMICAL-COMPOSITION OF RUNOFF DURING SNOWMELT IN LOCH VALE WATERSHED, ROCKY-MOUNTAIN-NATIONAL-PARK, COLORADO, USA. Water Air and Soil Pollution, 59, 107-123.
Rocky Mountain National Park (ROMO)	Natural variability in N export from headwater catchments: snow cover controls on ecosystem N retention	The study evaluates controls on the size of the leachable soil N pool concurrent with the spring hydrologic flush, which is primarily responsible for the transport of N to surface water. Controls on the amount of inorganic N leached from soil during the snowmelt period were evaluated in the major landscape types in four catchments in Colorado. Measurements of leached N were inversely related to measurements of over-winter CO2 flux at all sites, indicating that N was immobilized in soil heterotrophic biomass. The researchers used a long-term record of winter precipitation, N deposition, and N export from Loch Vale in Rocky Mountain National Park. This data set identified a strong, linear relationship (r(2) = 0.68) between catchment scale N retention and winter snow cover. The results indicate that the winter snow pack is the major control both on hydrologic N export and on soil source/sink relationships for N concurrent with this transport mechanism.	Brooks, P. D., Campbell, D. H., Tonnessen, K. A. & Heuer, K. (1999) Natural variability in N export from headwater catchments: snow cover controls on ecosystem N retention. Hydrological Processes, 13, 2191-2201.
Rocky Mountain National Park (ROMO)	Nitrogen fluxes in a high elevation Colorado Rocky Mountain basin	The purpose of the study was to develop an annual nitrogen budget for Loch Vale Watershed (LVWS) in the Colorado Front Range. Results from a variety of published and original data are synthesized in order to develop a model of nitrogen flux in Loch Vale Watershed, and to explore the fate of atmospherically deposited nitrogen in alpine and subalpine terrestrial and aquatic ecosystems.	Baron, J. S. & Campbell, D. H. (1997) Nitrogen fluxes in a high elevation Colorado Rocky Mountain basin. Hydrological Processes, **11**, 783-799.
Rocky Mountain National Park (ROMO)	NO3 uptake in shallow, oligotrophic, mountain lakes: the influence of elevated NO3 concentrations	Investigators conducted nutrient enrichment experiments in 1.2-m deep enclosures in 2 shallow, oligotrophic, mountain lakes. N-15-NO3 isotope tracer was used to compare the importance of phytoplankton and benthic compartments for NO3 uptake under high and low NO3 conditions. NO3 uptake approached saturation in the high-N lake, but not in the low-N lake. Phytoplankton productivity responded strongly to addition of limiting nutrients, and NO3 uptake was related to phytoplankton biomass and photosynthesis. The results suggest that phytoplankton are most sensitive to nutrient additions, but benthic processes are important for NO3 uptake in shallow, oligotrophic lakes.	Nydick, K. R., Lafrancois, B. M. & Baron, J. S. (2004) NO3 uptake in shallow, oligotrophic, mountain lakes: the influence of elevated NO3 concentrations. Journal of the North American Benthological Society, 23, 397-415.
Rocky Mountain National Park (ROMO)	Pathways for nitrate release from an alpine watershed: Determination using delta N-15 and delta O-18	Snowpack, snowmelt, precipitation, surface water, and groundwater samples from the Loch Vale watershed in Colorado were analyzed for delta(15)N and delta(18)O of nitrate to determine the processes controlling the release of atmospherically deposited nitrogen from alpine and subalpine ecosystems. During snowmelt, delta(18)O((NO3)) indicated that about half of the nitrate in stream water was the product of microbial nitrification; at other times that amount was greater than half. Springs emerging from talus deposits had high nitrate concentrations and a seasonal pattern in delta(18)O((NO3)) that was similar to the pattern in the streams, indicating that shallow groundwater in talus deposits is a likely source of stream water nitrate. This study demonstrates the value of the nitrate double-isotope technique for determining nitrogen-cycling processes and sources of nitrate in small, undisturbed watersheds that are enriched with inorganic nitrogen.	Campbell, D. H., Kendall, C., Chang, C. C. Y., Silva, S. R. & Tonnessen, K. A. (2002) Pathways for nitrate release from an alpine watershed: Determination using delta N-15 and delta O-18. Water Resources Research, **38**, 9.
Rocky Mountain National Park (ROMO)	PROCESSES CONTROLLING THE CHEMISTRY OF 2 SNOWMELT-DOMINATED STREAMS IN THE ROCKY-MOUNTAINS	Time-intensive discharge and chemical data for two alpine streams in the Loch Vale watershed, Colorado, were used to identify sources of runoff, flow paths, and important biogeochemical processes during the 1992 snowmelt runoff season.	Campbell, D. H., Clow, D. W., Ingersoll, G. P., Mast, M. A., Spahr, N. E. & Turk, J. T. (1995) PROCESSES CONTROLLING THE CHEMISTRY OF 2 SNOWMELT-DOMINATED STREAMS IN THE ROCKY-MOUNTAINS. Water Resources Research, **31**, 2811-2821.

Rocky Mountain National Park (ROMO)	Relations between basin characteristics and stream water chemistry in alpine/subalpine basins in Rocky Mountain National Park, Colorado	Relations between stream water chemistry and topographic, vegetative, and geologic characteristics of basins were evaluated for nine alpine/subalpine basins in Rocky Mountain National Park, Colorado, to identify controlling parameters and to better understand processes governing patterns in stream water chemistry. Fractional amounts of steep slopes, unvegetated terrain, and young surficial debris within each basin were positively correlated to each other. These terrain features were negatively correlated with concentrations of base cations, silica, and alkalinity and were positively correlated with nitrate, acidity, and runoff. The fractional amounts of subalpine meadow and, to a lesser extent, old surficial debris in the basins were positively correlated to concentrations of weathering products and were negatively correlated to nitrate and acidity. The results indicate that in alpine/subalpine basins, slope vegetation (or lack thereof), and distribution and age of surficial materials are interrelated and can have major effects on stream water chemistry.	Clow, D. W. & Sueker, J. K. (2000) Relations between basin characteristics and stream water chemistry in alpine/subalpine basins in Rocky Mountain National Park, Colorado. Water Resources Research, 36, 49-61.
Rocky Mountain National Park (ROMO)	Timescales for migration of atmospherically derived sulfate through an alpine/subalpine watershed, Loch Vale, Colorado	Researchers measured Sulfur 35 in snowpack during 1993-1997 and at four locations within the Loch Vale watershed during 1995-1997. The four sites include the two main drainages in the watershed, Andrews Creek and Icy Brook. Concentrations ranged from a high of almost 50 mBq/L for a sample from Spring 19 in June 1996 to a concentration near the detection limit for a sample from Andrews Creek in April 1997. Snowpack had the highest S-35 concentration with an average concentration of 53 mBq/mg SO4-2, concentrations in the streams were much lower. A calculation of the seasonal flux indicated that about 40% of the sulfate that flowed out of the watershed was derived from atmospheric sulfate deposited during the previous year. Researchers suggest that sulfate retention in alpine watersheds like Loch Vale is very limited, and changes in sulfate deposition should be quickly reflected in stream chemistry.	Michel, R. L., Campbell, D., Clow, D. & Turk, J. T. (2000) Timescales for migration of atmospherically derived sulfate through an alpine/subalpine watershed, Loch Vale, Colorado. Water Resources Research, 36, 27-36.
Mercury and Airborne Toxics Deposition and Effects			
Rocky Mountain National Park (ROMO)	Atmospheric deposition of current-use and historic-use pesticides in snow at national parks in the Western United States	There is growing evidence that pesticides and other semi-volatile organic compounds (SOCs) are accumulating in remote high-elevation and high-latitude ecosystems, according to literature. The objectives of the study were to quantify and document the distribution of pesticides in seasonal snowpack samples from seven national parks in the Western U.S., to investigate potential factors that may influence the distribution of pesticides in these parks, and to estimate the percentage of total concentration due to regional sources versus long-range sources for each of the most frequently detected current and historic use pesticides detected at each park. The current-use pesticides detected in seasonal snowpack samples at national parks in this study were dacthal (DCPA), chlorpyrifos, endosulfans (I and II), ç-hexachlorocyclohexane (lindane), trifluralin, and triallate. The presence of these in remote ecosystems implies that they are persistent enough to undergo transport to remote ecosystems in national parks, according to the researchers.	Hageman, K. J., Simonich, S. L., Campbell, D. H., Wilson, G. R. & Landers, D. H. (2006) Atmospheric deposition of current-use and historic-use pesticides in snow at national parks in the Western United States. Environmental Science & Technology, **40**, 3174-3180.
Rocky Mountain National Park (ROMO)	Atmospheric Deposition of Nutrients, Pesticides, and Mercury in Rocky Mountain National Park, Colorado, 2002	Researchers measured atmospheric deposition during summers in Rocky Mountain National Park in Colorado, at Bear Lake area and Loch Vale watershed. Annual bulk nitrogen deposition in 2002 was 2.28 kg N/ha at Bear Lake and 3.35 kg N/ha at Loch Vale. Dry deposition may account for as much as 28 percent of annual nitrogen deposition. Annual deposition rates for three pesticides were estimated as 45.8 mg/ha for atrazine, 14.2 mg/ha for dacthal, and 54.8 mg/ha for carbaryl, with 80-90 percent of the annual pesticide deposition occurring during summer. Concentrations of nutrients in summer precipitation at Bear Lake ranged from less than 0.007 to 1.29 mg N/L for ammonium and 0.17 to 4.59 mg N/L for nitrate, similar to Loch Vale National Atmospheric Deposition Network station. At Bear Lake, carbaryl was present (0.0079 to 0.0952 µg/L, followed by atrazine (less than 0.0070 to 0.0604 µg/L), and dacthal (0.0030 to 0.0093 µg/L). Mercury was detected from Loch Vale in concentrations ranging from 2.6 to 36.2 ng/L. Additionally, mercury deposition to Loch Vale was estimated at 7.1 µg/m2.	Mast, M.A., Campbell, D.H., Ingersoll, G.P., Foreman, W.T., and Krabbenhoft, D.P., 2002, Atmospheric Deposition of Nutrients, Pesticides, and Mercury in Rocky Mountain National Park, Colorado, USGS Water-Resources Investigations Report 0
Rocky Mountain National Park (ROMO)	Mercury Loading and Methylmercury Production and Cycling in High-Altitude Lakes from the Western United States	Investigators sampled 90 mid-latitude, high-altitude lakes from seven national parks in the western United States in September 1999. Routine monitoring and experimental studies were conducted at one of the lakes (Mills Lake) to quantify MeHg flux rates and process rates such as photo-demethylation. Results show that high-altitude lakes have low total mercury (HgT) and methylmercury (MeHg) levels (1.07 and 0.05 ng L-1, respectively). Researchers found a good correlation of Hg to MeHg (r2= 0.82) suggesting that inorganic Hg(II) loading is a primary controlling factor of methylmercury levels in dilute mountain lakes. Positive correlations were also observed for dissolved organic carbon (DOC) and both Hg and MeHg, although to a much lesser degree. Levels of MeHg were similar among the seven national parks, with the exception of Glacier National Park where lower concentrations were observed (0.02 ng L-1), possibly related to naturally elevated pH values occurring there. Measured rates of MeHg photo-degradation at Mills Lake were quite fast according to the researchers.	Krabbenhoft, D.P., Olson, M.L., Dewild, J.F., Clow, D.W., Striegl, R.G., Dornblaser, M.M., and VanMetre, P. (2002) Mercury loading and methylmercury production and cycling in high-altitude lakes from the western United States. Water, Air, and Soil Pollution, **Focus 2**: 233-249.
Rocky Mountain National Park (ROMO)	Mercury transport in a high-elevation watershed in Rocky Mountain National Park, Colorado	Mercury (Hg) was measured in stream water and precipitation in the Loch Vale watershed in Rocky Mountain National Park, Colorado, during 2001-2002 to investigate processes controlling Hg transport in high-elevation ecosystems. Total Hg concentrations in precipitation ranged from 2.6 to 36.2 ng/L and showed a strong seasonal pattern with concentrations that were 3 to 4 times higher during summer months. Total Hg concentrations in streams ranged from 0.8 to 13.5 ng/L and were highest in mid-May on the rising limb of the snowmelt hydrograph. Stream-water Hg was positively correlated with dissolved organic carbon; researchers suggest organically complexed Hg was flushed into streams from near-surface soil horizons during the early stages of snowmelt. Methylmercury (MeHg) in stream water peaked at 0.048 ng/L just prior to peak snowmelt, and was at or below detection (< 0.040 ng/L) for the remainder of the snowmelt season.	Mast, M. A., Campbell, D. H., Krabbenhoft, D. P. & Taylor, H. E. (2005) Mercury transport in a high-elevation watershed in Rocky Mountain National Park, Colorado. Water Air and Soil Pollution, 164, 21-42.

Air Quality Effects to Sensitive Resources:			
Park	**Title**	**Project Summary/Findings**	**Citation**
		Climate Change Effects	
Rocky Mountain National Park (ROMO)	Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada	According to the researchers, changes in precipitation and temperature regimes or patterns have significant potential effects on the distribution and abundance of plants and animals. Changes in stream temperature regimes result in significant changes in community composition. Warming temperatures may geographically isolate cole water stream fishes in increasingly confined headwaters. The heat budgets of large lakes may be affected resulting in a change of state between dimictic and warm monomictic character. The authors conclude that regional climate models are needed to resolve the complexities of the high gradient landscapes. Also, extensive wilderness preserves and national park lands provide sensitive areas for differentiation of anthropogenic effects from climate effects; and future research should encompass both short-term intensive studies and long-term monitoring studies with comprehensive experiments of streams and lakes specifically designed to address the issue of anthropogenic versus climatic effects.	Hauer, F. R., Baron, J. S., Campbell, D. H., Fausch, K. D., Hostetler, S. W., Leavesley, G. H., Leavitt, P. R., McKnight, D. M. & Stanford, J. A. (1997) Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes, **11**, 903-924.
Rocky Mountain National Park (ROMO)	Effects of land cover, water redistribution, and temperature on ecosystem processes in the South Platte Basin	The project entailed using the RHESSys model to compare the changes in plant productivity and vegetation-related hydrological processes that occurred as a result of either land cover alteration or directional temperature changes (-2 degrees Celsius (C), +4 degrees C). Land cover change exerted more control over annual plant productivity and water fluxes for converted grasslands, while the effect of temperature changes on productivity and water fluxes was stronger in the mountain vegetation. Throughout the basin, land cover change increased the annual loss of water to the atmosphere by 114 mm via evaporation and transpiration, an increase of 37%. There is a large elevational range from east to west in the South Platte Basin, which encompasses the western edge of the Great Plains and the eastern front of the Rocky Mountains. Climate is increasingly dominated by winter snow precipitation with increasing elevation, and the timing of snowmelt influences tundra and forest ecosystem productivity, soil moisture, and downstream discharge.	Baron, J. S., Hartman, M. D., Kittel, T. G. F., Band, L. E., Ojima, D. S. & Lammers, R. B. (1998) Effects of land cover, water redistribution, and temperature on ecosystem processes in the South Platte Basin. Ecological Applications, 8, 1037-1051.
Rocky Mountain National Park (ROMO)	Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas	Researchers corroborate data from mesoscale climate model simulations using the Colorado State University Regional Atmospheric Modeling System (RAMS), projecting that modifications to natural vegetation in the plains produced lower summer temperatures in the mountains. The investigators corroborate the RAMS simulations with three independent sets of data: climate records from 16 weather stations, which showed significant trends of decreasing July temperatures in recent decades; the distribution of seedlings of five dominant conifer species in Rocky Mountain National Park, Colorado, which suggested that cooler, wetter conditions occurred over roughly the same time period; and increased stream flow, normalized for changes in precipitation, during the summer months in four river basins, which also indicates cooler summer temperatures and lower transpiration at landscape scales. Results showed that the effects of land use practices on regional climate may overshadow larger-scale temperature changes commonly associated with observed increases in CO2 and greenhouse gases.	Stohlgren, T. J., Chase, T. N., Pielke, R. A., Kittel, T. G. F. & Baron, J. S. (1998) Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. Global Change Biology, 4, 495-504.
Rocky Mountain National Park (ROMO)	Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO2	The objective of the study was to explore the hydrologic and ecological responses of a headwater mountain catchment, Loch Vale watershed, to climate change and doubling of atmospheric CO2 scenarios using the Regional Hydro-Ecological Simulation System (RHESSys). A slight (2 degrees Celsius) cooling, comparable to conditions observed over the past 40 years, led to greater snowpack and slightly less runoff, evaporation, transpiration, and plant productivity. An increase of 2 degrees C yielded the opposite response, but model output for an increase of 4 degrees C showed dramatic changes in timing of hydrologic responses. The snowpack was reduced by 50%, and runoff and soil water increased and occurred 4-5 weeks earlier with 4 degrees C warming. Alpine tundra photosynthetic rates responded more to warmer and wetter conditions than subalpine forest, but subalpine forest showed a greater response to doubling of atmospheric CO2 than tundra.	Baron, J. S., Hartman, M. D., Band, L. E. & Lammers, R. B. (2000) Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO2. Water Resources Research, **36**, 89-99.
		Ecosystem Effects from N or S Deposition	
Rocky Mountain National Park (ROMO)	ANALYSIS OF NITROGEN SATURATION POTENTIAL IN ROCKY-MOUNTAIN TUNDRA AND FOREST - IMPLICATIONS FOR AQUATIC SYSTEMS	Researchers used grass and forest versions of the CENTURY model under a range of N deposition values (0.02-1.60 g N m(-2) y(-1)) to explore the possibility that high observed lake and stream N was due to terrestrial N saturation of alpine tundra and subalpine forest in Loch Vale Watershed, Rocky Mountain National Park, Colorado. Model results suggest that N is limiting to subalpine forest productivity, but that excess leachate from alpine tundra accounts for the current observed stream N. Tundra leachate, combined with N leached from exposed rock surfaces, produce high N loads in aquatic ecosystems above treeline in the Colorado Front Range. The investigators concur that, while increased N deposition will worsen the situation, nitrogen saturation is an ongoing phenomenon.	Baron, J. S., Ojima, D. S., Holland, E. A. & Parton, W. J. (1994) ANALYSIS OF NITROGEN SATURATION POTENTIAL IN ROCKY-MOUNTAIN TUNDRA AND FOREST - IMPLICATIONS FOR AQUATIC SYSTEMS. Biogeochemistry, 27, 61-82.
Rocky Mountain National Park (ROMO)	Anthropogenic nitrogen deposition induces rapid ecological changes in alpine lakes of the Colorado Front Range (USA)	Recent sediments from two alpine lakes in the Colorado Front Range (USA) register marked and near-synchronous changes that are believed to represent ecological responses to enhanced atmospheric deposition of fixed nitrogen from anthropogenic sources. Directional shifts in sediment proxies include greater representations of mesotrophic diatoms and increasingly depleted delta N-15 values. These trends are particularly pronounced since similar to 1950, and appear to chronicle lake responses to excess N derived from agricultural and industrial sources to the east. The rate and magnitude of recent ecological changes far exceed the context of natural variability, as inferred from comparative analyses of a long core capturing the entire 14,000-year postglacial history of one of the lakes. Nitrogen deposition to these seemingly pristine natural areas has resulted in subtle but detectable limnological changes that likely represent the beginning of a stronger response to nitrogen enrichment.	Wolfe, A. P., Baron, J. S. & Cornett, R. J. (2001) Anthropogenic nitrogen deposition induces rapid ecological changes in alpine lakes of the Colorado Front Range (USA). Journal of Paleolimnology, 25, 1-7.

Rocky Mountain National Park (ROMO)	Aquatic ecosystems	This document is the product of an ongoing effort begun at a 4-day workshop sponsored by the Rocky Mountain Region of the USDA Forest Service, held in December 1990 in Estes Park, Colorado. Workshop participants worked on pollution impacts in three specific areas: aquatic ecosystems; terrestrial ecosystems; and visibility. The workshop provided the USDA Forest Service with information that may be used to identify and develop sensitive receptors and limits of acceptable change for assessing air pollution impacts on air quality-related values in wildernesses within the Rocky Mountain Region. The reports also address needs and recommendations relating to modeling or predictive techniques, monitoring, and research.	Baron, J., and J. Turk. 1998. Aquatic ecosystems. Pp. 4-18 in: Haddow, D., R. Musselman, T, Blett, R. Fisher, tech. Coords. Guidelines for evaluating air pollution impacts on wilderness within the Rocky Mountain Region: report of a works
Rocky Mountain National Park (ROMO)	Changes in the chemistry of lakes and precipitation in high-elevation national parks in the western United States, 1985-1999	Sixty-nine lakes in seven national parks sampled in the U. S. Environmental Protection Agency's Western Lake Survey were resampled during fall 1999 to investigate possible decadal-scale changes in lake chemistry. In most lakes, SO4 concentrations were slightly lower in 1999 than in 1985, consistent with a regional decrease in precipitation SO4 concentrations and in SO2 emissions in the western United States. Nitrate concentrations also tended to be slightly lower in 1999 than in 1985, in contrast with generally stable or increasing inorganic N deposition in the west. Results suggest that rain prior to sampling in 1985 may have caused elevated NO3 in some lakes due to direct runoff of precipitation and flushing of NO3 from alpine soils, which also may explain some of the decrease in NO3 concentrations observed in survey lakes.	Clow, D. W., Sickman, J. O., Striegl, R. G., Krabbenhoft, D. P., Elliott, J. G., Dornblaser, M., Roth, D. A. & Campbell, D. H. (2003) Changes in the chemistry of lakes and precipitation in high-elevation national parks in the western United States, 1985-1
Rocky Mountain National Park (ROMO)	Chemistry of selected high-elevation lakes in seven national parks in the western United States	A chemical survey of 69 high-altitude lakes in seven national parks in the western United States was conducted during the fall of 1999. Lakes in parks in the Sierra/southern Cascades (Lassen Volcanic, Yosemite, Sequoia/Kings Canyon National Parks) and in the southern Rocky Mountains (Rocky Mountain National Park) were very dilute; median specific conductance ranged from 4.4 to 12.2 mgrS cm-1 and median alkalinity concentrations ranged from 32.2 to 72.9 mgreqL-1. Regional patterns in lake concentrations of NO3 and SO4 were similar to regional patterns in NO3 and SO4 concentrations in precipitation, suggesting that the lakes are showing a response to atmospheric deposition. Concentrations of NO3 were particularly high in Rocky Mountain National Park, where some ecosystems appear to be undergoing nitrogen saturation.	Clow, D.W., Striegl, R.G., Nanus, L., Mast, M.A., Campbell, D.H., Krabbenhoft, D.P. (2002) Chemistry of selected high-elevation lakes in seven national parks in the western United States. Water, Air, and Soil Pollution, **Focus 2**:139-164.
Rocky Mountain National Park (ROMO)	Critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA	The researchers review a survey in 1995 of 91 high-elevation lakes in the central Rocky Mountains where water quality is being affected by inorganic N in wetfall throughout the region. From this survey, the researchers make a conservative recommendation to Federal Land Managers that critical loads of inorganic N in wetfall to Class 1 areas in the central Rocky Mountains be set at 4 kg/ha/yr. Target loads may be set at lower levels to protect extremely sensitive natural resources.	Williams, M. W. & Tonnessen, K. A. (2000) Critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA. Ecological Applications, **10**, 1648-1665.
Rocky Mountain National Park (ROMO)	Cumulative effects of nutrients and pH on the plankton of two mountain lakes	The researchers conducted enclosure experiments to examine the cumulative effects of nutrient enrichment and acidification on the plankton of two mountain lakes with differing nutrient conditions on the Colorado Front Range. The results showed that in both study lakes, changes in chlorophyll a were linked to addition of limiting nutrients regardless of pH, whereas shifts in phytoplankton species composition were apparently affected by both nutrient conditions and acidity. The most striking changes in species composition and biomass occurred in combined N plus acid plus P treatments, indicating that continued nutrient enrichment may interact with acidification to produce marked changes in the plankton of mountain lakes.	Lafrancois, B. M., Nydick, K. R., Johnson, B. M. & Baron, J. S. (2004) Cumulative effects of nutrients and pH on the plankton of two mountain lakes. Canadian Journal of Fisheries and Aquatic Sciences, **61**, 1153-1165.
Rocky Mountain National Park (ROMO)	Differences in Engelmann spruce forest biogeochemistry east and west of the Continental Divide in Colorado, USA	Researchers compared Engelmann spruce biogeochemical processes in forest stands east and west of the Continental Divide in the Colorado Front Range. Atmospheric nitrogen (N) deposition is 1-2 kg N ha(-1) y(-1) on the west side, as compared with 3-5 kg N ha(-1) y(-1) on the east side. Higher N deposition sites had significantly lower organic horizon Carbon (C):Nitrogen (N) and lignin:N ratios, lower foliar C:N ratios, as well as, greater percent N, higher N:Ca, N:Mg, and N:P ratios, and higher potential net mineralization rates. When C:N ratios dropped below 29, as they did in east-side organic horizon soils, mineralization rates increased linearly. The results showed current levels of N deposition, have caused measurable changes in Engelmann spruce forest biogeochemistry east of the Continental Divide in Colorado.	Rueth, H. M. & Baron, J. S. (2002) Differences in Engelmann spruce forest biogeochemistry east and west of the Continental Divide in Colorado, USA. Ecosystems, **5**, 45-57.
Rocky Mountain National Park (ROMO)	Ecosystem responses to nitrogen deposition in the Colorado Front Range	The researchers wanted to see if 3-5 kg N y(-1) atmospheric N deposition was sufficient to have influenced terrestrial and aquatic ecosystems of the Colorado Front Range by comparing ecosystem processes and properties east and west of the Continental Divide. Twelve old-growth stands of Engelmann spruce (*Picea engelmannii*) were selected for study, six east and six west of the Continental Divide on NADP site is Sunlight Peak and the NADP sites east of Continental Divide, Loch Vale and Niwot Saddle. Researchers used long-term sample collections at The Loch, an east side lake in Rocky Mountain National Park. East side forest stands had significantly greater percent foliar N (1.09% N) than west side stands (0.96% N). Results show that 75% of the increased east side soil N pool can be accounted for by increased N deposition due to human settlement. Nitrogen emissions from fixed, mobile, and agricultural sources have also increased dramatically. The findings indicate even slight increases in atmospheric deposition lead to measurable changes in ecosystem properties.	Baron, J. S., Rueth, H. M., Wolfe, A. M., Nydick, K. R., Allstott, E. J., Minear, J. T. & Moraska, B. (2000) Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystems, 3, 352-368.
Rocky Mountain National Park (ROMO)	Effects of Atmospheric Nitrogen Deposition on High Elevation Colorado Forests	Atmospheric nitrogen deposition from energy, automobile, and agricultural emissions acts as a fertilizer to these forests, but this fertilization also alters natural ecosystem processes. The authors compared old-growth forest characteristics from the east side of the Colorado Front Range, where nitrogen deposition ranges 3-6 kg N/ha/yr, to characteristics from the west side, and where nitrogen deposition is several times lower. Fertilization experiments were also conducted on east- and west-side forest stands. Higher nitrogen deposition has led to greater nitrogen accumulation in needles, greater soil microbial activity, and accumulation of N in soil floors. Fertilization of east-side forests caused microbial activity and nitrogen leaching to increase, since these forests are close to nitrogen saturation. Fertilization of west-side forests increased organic and foliar nitrogen concentrations. Understory vegetation differs across the east- and west-side plots, with east-side vegetation being much more diverse than west-side.	Baron, J.S., J.A. Botte, and R. Shory, 2004. Effects of Atmospheric Nitrogen Deposition on High Elevation Colorado Forests. pp. 10-14 in: Warren R. Keammerer and Jeffrey Todd, eds. Proceedings, HIGH ALTITUDE REVEGETATION WORKSH

Rocky Mountain National Park (ROMO)	Engelmann spruce nitrogen dynamics across a nitrogen deposition gradient in Colorado, USA	Researchers asked whether nitrogen (N) deposition has altered Engelmann spruce (*Picea engelmanni* i) biogeochemistry along the east side of the Colorado Front Range, USA. Twelve similar old-growth Engelmann spruce stands were sampled, six with low (1-2 kg N ha(-1) yr(-1)) and six with higher (3-5 kg N ha(-1) yr(-1)) N deposition inputs. The results suggest that current levels of N deposition (3-5 kg N ha(-1) yr(-1)) along the Colorado Front Range may be altering Engelmann spruce biogeochemistry. Even relatively low N inputs may cause measurable changes in forest biogeochemistry.	Rueth, H. M. & Baron, J. S. (2001) Engelmann spruce nitrogen dynamics across a nitrogen deposition gradient in Colorado, USA. Ekologia-Bratislava, **20**, 43-49.
Rocky Mountain National Park (ROMO)	Environmental characteristics and benthic invertebrate assemblages in Colorado mountain lakes	Twenty-two high-elevation lakes (>3000 in) in Rocky Mountain National Park and Indian Peaks Wilderness Area, Colorado, were surveyed during summer 1998 to explore relationships among benthic invertebrates, water chemistry (particularly nitrate concentrations), and other environmental variables. Presence/absence of benthic invertebrate taxa among the study lakes was best explained by elevation and presence of fish. Relative abundance and density of benthic invertebrate taxa were more strongly influenced by sampling date and water chemistry. Nitrate (NO3-) concentration, potentially on the rise due to regional nitrogen deposition, was unrelated to benthic invertebrate distribution regardless of sampling method or taxonomic resolution.	Lafrancois, B. M., Carlisle, D. M., Nydick, K. R., Johnson, B. M. & Baron, J. S. (2003) Environmental characteristics and benthic invertebrate assemblages in Colorado mountain lakes. Western North American Naturalist, 63, 137-154.
Rocky Mountain National Park (ROMO)	Hindcasting nitrogen deposition to determine an ecological critical load	The researcher reconstructed an N-deposition history at Loch Vale (Colorado, USA; NADP site CO98) using exponential equations that correlated well with EPA-reported NO, emissions from Colorado and from the sum of emissions of 11 western states, using an estimated background nitrogen (N) deposition value of 0.5 kg N(.)ha(-1.)yr(-1) in 1900, and a 19-year record of measured values. The mean wet N-deposition values for the period 1950-1964 was similar to 1.5 kg N(.)ha(-1.)yr(-1), corresponding to the reported time of alteration of diatom assemblages attributed to N deposition in alpine lakes in Rocky Mountain National Park (USA). This value becomes the critical load defining the threshold for ecological change from eutrophication. According to the investigator, if an N-deposition threshold for ecological change can be identified, and the date at which that threshold was crossed is known, hindcasting can derive the amount of atmospheric deposition at the time of change, at least for alpine lakes.	Baron, J. S. (2006) Hindcasting nitrogen deposition to determine an ecological critical load. Ecological Applications, 16, 433-439.
Rocky Mountain National Park (ROMO)	It's in the Air: The Ecological Effects of Nitrogen Deposition in Rocky Mountain National Park	Website of research on nitrogen Deposition in the Loch Vale watershed, by leading USGS researcher Jill Baron. The website includes project methods, maps, analysis and results of ongoing study of the ecological effects of Nitrogen deposition.	Baron, J.S. (Website, last accessed, May 16, 2007) It's in the Air: The Ecological Effects of Nitrogen Deposition in Rocky Mountain National Park. U.S. Department of the Interior | U.S. Geological Survey, Fort Collins Science Center.
Rocky Mountain National Park (ROMO)	Lake-specific responses to elevated atmospheric nitrogen deposition in the Colorado Rocky Mountains, USA	Investigators explored variability among subalpine lakes with similar climate and atmospheric conditions, but differing in watershed characteristics, hydrology, and food web structure. Nitrogen (N) dynamics was a focal point because the study area receives some of the highest levels of atmospheric N deposition in the Rocky Mountains. The researchers asked if the effect of regional N deposition is manifested uniformly among neighboring lakes both in terms of ambient conditions and responses to greater nutrient inputs. Results showed catchment vegetation appeared to be the main determinant of ambient nitrate (NO3), phosphate (PO4), and dissolved organic carbon (DOC) concentrations, although in-lake differences in recycling produced variable and contrasting NH4 levels. In most cases, phosphorus was limiting to phytoplankton growth, although the importance of N deficiencies was greater in lakes with forested watersheds and fringing wetlands.	Nydick, K. R., Lafrancois, B. M., Baron, J. S. & Johnson, B. M. (2003) Lake-specific responses to elevated atmospheric nitrogen deposition in the Colorado Rocky Mountains, USA. Hydrobiologia, **510**, 103-114.
Rocky Mountain National Park (ROMO)	Lessons learned from long-term ecosystem research and monitoring in alpine and subalpine basins of the Colorado Rocky Mountains, USA	Long-term ecosystem research and monitoring began in the Loch Vale watershed of Rocky Mountain National Park in 1983, after extensive survey work to identify the best location. The author makes clear that the objectives are to understand natural biogeochemical cycles and variability, in order to differentiate ecosystem changes from human-caused disturbances, such as atmospheric deposition of pollutants and climate change. The author notes that clear scientific objectives, even for long-term monitoring, are essential. Standardized methods, including rigorous quality assurance procedures should be adhered to from the start of the program. All data, even those collected routinely for background records, should be scrutinized and summarized at least once a year.	Baron, J. S. (2001) Lessons learned from long-term ecosystem research and monitoring in alpine and subalpine basins of the Colorado Rocky Mountains, USA. Ekologia-Bratislava, **20**, 25-30.
Rocky Mountain National Park (ROMO)	Loch Vale, Colorado, USGS Fact Sheet-164-99	Alpine and subalpine ecosystems are vulnerable to impacts from acidic deposition and changes in climate because they have a short growing season, and large amounts of snowmelt are released from deep seasonal snowpacks in the spring (Campbell and others, 1995). Research at the Loch Vale Watershed provides process-level information that augments synoptic and long-term monitoring of atmospheric deposition and water quality in other sensitive Rocky Mountain ecosystems. Together, these research and monitoring studies support policy decisions by other government agencies regarding natural resource management issues.	Clow, D. W., D. H. Campbell, M. A. Mast, R. G. Striegl, K. P. Wickland and G. P. Ingersoll. 2000. Loch Vale, Colorado, A water, energy, and biogeochemical budgets program site. USGS Fact Sheet-164-99
Rocky Mountain National Park (ROMO)	Nitrogen saturation in the Rocky Mountains	Lakes in the Rocky Mountains have a median value of NO3- concentrations less than 1 µequiv/ L, compared with other high-elevation lakes. Rocky Mountain ecosystems are relatively sensitive to changes in the flux of energy, chemicals, and water compared to downstream ecosystems. Niwot Ridge/Green Lakes Valley and Glacier Lakes annual minimum concentrations of NO3- in surface waters (growing season) have increased from below detection limits to close to 10 µequiv/L. The Loch Vale watershed, a second-order, 660-ha basin in Rocky Mountain National Park is N saturated, with annual minimum concentrations of NO3- in surface waters generally above 10 µequiv/L. At the three test basins in the Front Range, annual NO3- loading from wetfall increased in the late 1980s with higher loading rates being maintained. At NWT, there has been a 200% increase in NO3- loading from wet deposition over the last decade. According to the scientists, critical loads need to be reconsidered since only modest atmospheric loadings of N are sufficient to induce N leaching.	Williams, M. W., Baron, J. S., Caine, N., Sommerfeld, R. & Sanford, R. (1996) Nitrogen saturation in the Rocky Mountains. Environmental Science & Technology, **30**, 640-646.

Rocky Mountain National Park (ROMO)	NO3 uptake in shallow, oligotrophic, mountain lakes: the influence of elevated NO3 concentrations	Investigators conducted nutrient enrichment experiments in 1.2-m deep enclosures in 2 shallow, oligotrophic, mountain lakes. N-15-NO3 isotope tracer was used to compare the importance of phytoplankton and benthic compartments for NO3 uptake under high and low NO3 conditions. NO3 uptake approached saturation in the high-N lake, but not in the low-N lake. Phytoplankton productivity responded strongly to addition of limiting nutrients, and NO3 uptake was related to phytoplankton biomass and photosynthesis. The results suggest that phytoplankton are most sensitive to nutrient additions, but benthic processes are important for NO3 uptake in shallow, oligotrophic lakes.	Nydick, K. R., Lafrancois, B. M. & Baron, J. S. (2004) NO3 uptake in shallow, oligotrophic, mountain lakes: the influence of elevated NO3 concentrations. Journal of the North American Benthological Society, 23, 397-415.
Rocky Mountain National Park (ROMO)	PHYTOPLANKTON DYNAMICS IN 3 ROCKY-MOUNTAIN LAKES, COLORADO, USA	Investigators in 1984 and 1985 studied seasonal changes in phytoplankton in a system of three lakes in Loch Vale, Rocky Mountain National Park, Colorado. Seasonal phytoplankton dynamics in these lakes are controlled partially by the rapid flushing rate during snowmelt and the transport of phytoplankton from the highest lake to the lower lakes by the stream, Icy Brook. Measurement of photosynthetic rates at different depths during the three periods confirmed the rapid growth of *Aquilegia formosa* (Western columbine) during the spring. The decline in *A. formosa* after snowmelt may be related to grazing by developing zooplankton populations. The possible importance of the seasonal variations in nitrate concentrations were evaluated in situ enrichment experiments.	McKnight, D. M., Smith, R. L., Bradbury, J. P., Baron, J. S. & Spaulding, S. (1990) PHYTOPLANKTON DYNAMICS IN 3 ROCKY-MOUNTAIN LAKES, COLORADO, USA. Arctic and Alpine Research, 22, 264-274.
Rocky Mountain National Park (ROMO)	Recent loch vale watershed research - Preface	Abstract Unavailable	Baron, J. S. & Wiiliams, M. W. (2000) Recent loch vale watershed research - Preface. Water Resources Research, 36, 11-12.
Rocky Mountain National Park (ROMO)	Responses of Engelmann spruce forests to nitrogen fertilization in the Colorado Rocky Mountains	Scientists studied the response of two old-growth coniferous forests in Colorado, Fraser and Loch Vale, each with differing initial soil conditions to 4 years of low-level fertilization with ammonium nitrate. Fraser with an average initial organic horizon soil C:N ratio of 36 and nitrogen (N) pool of 605 kg/ha showed no significant increase in net N mineralization rates, though foliar and organic horizon soil percentage N increased significantly. In contrast, N mineralization rates and inorganic soil N increased significantly at Loch Vale with greater soil N (C:N of 24, N pool of 991 kg/ha), with no change in foliar N and soil percentage N in the organic layer. The researchers predict continued N inputs/fertilization at Fraser will narrow the soil C:N ratio. According to the researchers, the size of the organic soil N pool and C:N ratio of mature coniferous forests in Colorado controls the responsiveness of N pools and fluxes to fertilization, and found that even low levels of nitrogen initiate measurable biogeochemical changes.	Rueth, H. M., Baron, J. S. & Allstott, E. J. (2003) Responses of Engelmann spruce forests to nitrogen fertilization in the Colorado Rocky Mountains. Ecological Applications, **13**, 664-673.
Rocky Mountain National Park (ROMO)	Seasonal inorganic nitrogen release in alpine lakes on the Colorado western slope	In the Rocky Mountains, the association of increases in acidic deposition with increased atmospheric loading of sulfate and direct changes in surface water chemistry has been well established. The importance, though, of increased nitrogen (N) deposition in the episodic acidification of alpine lakes and N saturation in alpine ecosystems is only beginning to be documented. In alpine areas of the Colorado Front Range, modest loadings of N in deposition have been associated with leakage of N to surface waters. On the Colorado western slope, however, no leakage of N to surface waters has been reported. A 1995 study showed N leakage to surface waters in some western slope basins. NO3- leakage compounds the existing sensitivity to episodic acidification from low acid neutralizing capacity (ANC), which is less than 40 µequiv/L in those basins.	Inyan, B. J., Williams, M. W., Tonnessen, K., Turk, J. T. & Campbell, D. H. (1998) Seasonal inorganic nitrogen release in alpine lakes on the Colorado western slope. Physical Geography, **19**, 406-420.
Rocky Mountain National Park (ROMO)	Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO2	The objective of the study was to explore the hydrologic and ecological responses of a headwater mountain catchment, Loch Vale watershed, to climate change and doubling of atmospheric CO2 scenarios using the Regional Hydro-Ecological Simulation System (RHESSys). A slight (2 degrees Celsius) cooling, comparable to conditions observed over the past 40 years, led to greater snowpack and slightly less runoff, evaporation, transpiration, and plant productivity. An increase of 2 degrees C yielded the opposite response, but model output for an increase of 4 degrees C showed dramatic changes in timing of hydrologic responses. The snowpack was reduced by 50%, and runoff and soil water increased and occurred 4-5 weeks earlier with 4 degrees C warming. Alpine tundra photosynthetic rates responded more to warmer and wetter conditions than subalpine forest, but subalpine forest showed a greater response to doubling of atmospheric CO2 than tundra.	Baron, J. S., Hartman, M. D., Band, L. E. & Lammers, R. B. (2000) Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO2. Water Resources Research, **36**, 89-99.
Rocky Mountain National Park (ROMO)	Surface water acidification responses and critical loads of sulfur and nitrogen deposition in Loch Vale watershed, Colorado	Investigators evaluated the sensitivity of The Loch, a subalpine lake in Rocky Mountain National Park in Colorado, to acidification in response to increased atmospheric loading of sulfur (S) and nitrogen (N) using the Model of Acidification of Groundwater in Catchments (MAGIC). The loads of S deposition that would drive chronic lake water acid neutralizing capacity (ANC) to below 0 or 20 mµeq L-1 were estimated to be 11 and 8 kg S ha(-1) yr(-1), respectively, assuming constant future N deposition at current levels. Comparable loads for N deposition, assuming constant future S deposition, were estimated to be 21 and 12 kg N ha(-1) yr(-1), respectively. Modeling results for Andrews Creek, an alpine tributary to The Loch, suggest critical loads for surface water acidification averaged about one third lower. Researchers suggest the need for a regional analysis of critical loads for the larger population of acid-sensitive aquatic resources in order to make federally mandated land management decisions.	Sullivan, T. J., Cosby, B. J., Tonnessen, K. A. & Clow, D. W. (2005) Surface water acidification responses and critical loads of sulfur and nitrogen deposition in Loch Vale watershed, Colorado. Water Resources Research, 41, 15.
Rocky Mountain National Park (ROMO)	Temporal coherence of two alpine lake basins of the Colorado Front Range, USA	According to the researchers, information on synchrony in trends is important to determining regional responses of lakes to disturbances such as atmospheric deposition and climate change. They explored the temporal coherence of physical and chemical characteristics of two series of mostly alpine lakes in nearby basins of the Colorado Rocky Mountains, the Green Lakes Valley and Loch Vale Watershed, two steeply incised basins with strong altitudinal gradients. The investigators found the lakes in the two basins to be topographically close, however only some attributes are temporally coherent. Catchment and in-lake processes influence temporal patterns, especially for temperature, alkalinity and silica. Montane lakes with high altitudinal gradients may be particularly prone to local controls compared to systems where coherence is more obvious.	Baron, J. S. & Caine, N. (2000) Temporal coherence of two alpine lake basins of the Colorado Front Range, USA. Freshwater Biology, 43, 463-476.

Rocky Mountain National Park (ROMO)	The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA - a critical review	The Rocky Mountains of Colorado and southern Wyoming receive atmospheric nitrogen (N) deposition that ranges from 2 to 7 kg ha(-1) yr(-1), and some previous research indicates pronounced ecosystem effects at the highest rates of deposition. This paper provides a critical review of previously published studies on the effects of atmospheric N deposition in the region. Retention of N in atmospheric wet deposition is < 50% in some watersheds east of the Continental Divide, which reflects low biomass and a short growing season relative to the timing and N load in deposition. Relatively high rates of atmospheric N deposition east of the Divide may have altered nutrient limitation of phytoplankton, species composition of diatoms, and amphibian populations, but most of these effects have been inconclusive to date, and additional studies are needed to confirm hypothesized cause and effect relations. Projected future population growth and energy use in the west increase the likelihood that the effects of atmospheric N deposition will become more pronounced and widespread in the future.	Burns, D. A. (2004) The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA - a critical review. Environmental Pollution, 127, 257-269.
Rocky Mountain National Park (ROMO)	The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA—a critical review	This report provides a synthesis and critical assessment of published results on the effects of atmospheric nitrogen (N) deposition in the Rocky Mountains of Colorado and southern Wyoming. The report includes levels and trends in wet and dry atmospheric deposition of nitrogen, stream and lake nitrogen chemistry, subsurface nitrogen-cycling processes, and effects on terrestrial vegetation, aquatic biota, and amphibians. The Rocky Mountains of Colorado and southern Wyoming receive atmospheric nitrogen (N) deposition that ranges from 2 to 7 kg/ha/yr. Projected future population growth and energy use in Colorado and the west increase the likelihood that the subtle effects of atmospheric N deposition now evident in the Front Range will become more pronounced and widespread in the future.	Burns, D.A., 2002, The Effects of Atmospheric Nitrogen Deposition in the Rocky Mountains of Colorado and Southern Wyoming -- a Synthesis and Critical Assessment of Published Results: U.S. Geological Survey Water-Resources Investigations
Rocky Mountain National Park (ROMO)	Temporal coherence of two alpine lake basins of the Colorado Front Range, USA	According to the researchers, information on synchrony in trends is important to determining regional responses of lakes to disturbances such as atmospheric deposition and climate change. They explored the temporal coherence of physical and chemical characteristics of two series of mostly alpine lakes in nearby basins of the Colorado Rocky Mountains, the Green Lakes Valley and Loch Vale Watershed, two steeply incised basins with strong altitudinal gradients. The investigators found the lakes in the two basins to be topographically close, however only some attributes are temporally coherent. Catchment and in-lake processes influence temporal patterns, especially for temperature, alkalinity and silica. Montane lakes with high altitudinal gradients may be particularly prone to local controls compared to systems where coherence is more obvious.	Baron, J. S. & Caine, N. (2000) Temporal coherence of two alpine lake basins of the Colorado Front Range, USA. Freshwater Biology, 43, 463-476.
Rocky Mountain National Park (ROMO)	WINTER PHYTOPLANKTON DYNAMICS IN A SUB-ALPINE LAKE, COLORADO, USA	Investigators studied the temporal dynamics of phytoplankton in The Loch, a subalpine lake in Rocky Mountain National Park, over twi winter seasons of 1987 to 1989. The pattern of phytoplankton biovolume during ice-cover was consistent between the two years with maxima occurring in November/December and February/March. This pattern resulted principally from the contribution of *Asterionella formosa* HASS (euplankton). Algal composition changed throughout the winter and individual species varied in abundance with depth. Phytoplankton species composition continually fluctuated throughout the winter. The researchers suggest algal species succession was not driven by thermal regime or by wind induced changes in the mixed depth. Also, grazing by the winter zooplankton assemblage, composed nearly exclusively of cyclopoid copepods and rotifers, did not adequately explain the phytoplankton dynamics. Freeze concentration of water (concentration as ions are excluded in the formation of ice) in early winter may be responsible for the early phytoplankton bloom.	Spaulding, S. A., Ward, J. V. & Baron, J. (1993) WINTER PHYTOPLANKTON DYNAMICS IN A SUB-ALPINE LAKE, COLORADO, USA. Archiv Fur Hydrobiologie, **129**, 179-198.