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Translating science into policy: Using ecosystem thresholds to protect resources in Rocky Mountain National Park

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A collaborative approach between scientists and policymakers is described for addressing nitrogen deposition effects to Rocky Mountain National Park, USA.

Abstract

Concern over impacts of atmospheric nitrogen deposition to ecosystems in Rocky Mountain National Park, Colorado, has prompted the National Park Service, the State of Colorado Department of Public Health and Environment, the Environmental Protection Agency, and interested stakeholders to collaborate in the Rocky Mountain National Park Initiative, a process to address these impacts. The development of a nitrogen critical load for park aquatic resources has provided the basis for a deposition goal to achieve resource protection, and parties to the Initiative are now discussing strategies to meet that goal by reducing air pollutant emissions that contribute to nitrogen deposition in the Park. Issues being considered include the types and locations of emissions to be reduced, the timeline for emission reductions, and the impact of emission reductions from programs already in place. These strategies may serve as templates for addressing ecosystem impacts from deposition in other national parks.
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Keywords: Nitrogen; Atmospheric deposition; Critical load; Ecosystem threshold; Air quality related value

1. Introduction

There is growing evidence that tighter standards to protect sensitive ecosystems in the United States are needed, and an enhanced program of research on air pollution impacts on ecosystems is needed (National Research Council, 2004).

Science is a primary driver of air quality law and policy. Observations lead to inquiry, inquiry leads to study, and study—ideally—leads to political will and informed policy choices. In Los Angeles in the 1940s, severe air pollution problems came to be referred to as "gas attacks." In 1952, a 5-day temperature inversion in London trapped fog full of pollutants from coal combustion resulting in approximately 12,000 deaths in a 3-month period during and immediately following the episode (Bell and Davis, 2001; Bell et al., 2004). In 1955, the Federal Air Pollution Control Act provided for research on the effects of air pollution by the US Public Health Service (US Congress, 1955). In 1963, the Federal Clean Air Act provided for more research and encouraged, but did not require, emission standards for stationary sources such as power plants and steel mills (US Congress, 1963). Finally, in 1970, the Clean Air Act Amendments directed the Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS), which were promulgated in 1971. EPA required states to ensure their air quality met the NAAQS, a requirement that continues today (US Congress, 1970).

While early efforts at using research to develop air pollution regulations were driven by concerns over human health impacts, concerns over pollution impacts to ecosystems soon followed suit. Observations of acidity in some Northeastern lakes and streams in the 1970s prompted the passage of the

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Acid Deposition Act in 1980 (US Congress, 1980). That law established a research program under the auspices of the National Acid Precipitation Assessment Program to look at deposition trends, effects, atmospheric processes and potential control strategies. In the 1990 Clean Air Act Amendments, Congress responded to this research by establishing the Acid Deposition Control Program under Title IV of the Act (US Congress, 1990). This program requires fossil-fuel-fired power plants to reduce sulfur dioxide and nitrogen oxides (NO_x) emissions over time, and has resulted in significant reductions of sulfur and nitrogen (N) deposition in the eastern United States.

In 1995, in response to a request by Congress, EPA evaluated the feasibility of establishing and implementing acid deposition standards. EPA concluded that establishing standards for N and sulfur deposition was technically feasible, but the lack of guidance regarding appropriate resource protection goals and certain scientific unknowns precluded the agency from acting at that time (US EPA, 1995). Since then, US federal land managers for national parks, forests, and wilderness areas have established some general and specific resource protection goals for federally protected areas, published in the Federal Land Managers Air Quality Related Values Workgroup (FLAG) Report (FLAG, 2000; Porter et al., 2005). The FLAG Report provides guidance for evaluating air pollution impacts, including impacts from atmospheric deposition, on resources on federal lands. In addition, since 1995 considerable progress has been made in ecosystem research and certain ecosystem processes are now sufficiently understood to develop dose-response relationships. EPA continues to evaluate tools for ecosystem protection and has expressed interest in developing innovative approaches to achieve that end (US EPA, 2005).

Ecosystem impacts from atmospheric deposition of N compounds are well documented, and include acidification and excess nutrient fertilization of waters and soils. Comprehensive review articles discuss effects to ecosystems in Europe (Bobbink et al., 1998; Erisman and de Vries, 2000) and for both the eastern US (Aber et al., 2003; Driscoll et al., 2001, 2003) and the western US (Fenn et al., 2003a) across a variety of ecosystem types. Excess N has been found to disrupt soil nutrient cycling (Aber et al., 1998; Galloway et al., 2003; Gunderson et al., 1998; Lovett et al., 2000; Magill et al., 2000), change species composition and decrease biodiversity of vegetation (Bowman et al., 2006; Stevens et al., 2004; Suding et al., 2005; Wedin and Tilman, 1996), increase dominance of invasive and alien plants (Brooks, 2003), and affect forest tree health (McNulty et al., 1996). Nitrogen contributes to acidification and loss of biodiversity in streams and lakes (Driscoll et al., 2001; Vitousek et al., 1997) and eutrophication of coastal waters (Howarth et al., 2002; Paerl et al., 2002; Vitousek et al., 1997) and N-limited freshwaters (Bergstrom and Jansson, 2006), even at very low levels of atmospheric deposition (Baron et al., 2000; Baron, 2006; Saros et al., 2003; Wolfe et al., 2003).

Many national parks in the US contain ecosystems known or suspected to be sensitive to N deposition (FLAG, 2000), including oligotrophic lakes and streams, low-nutrient deserts and grasslands, high-elevation areas and tundra, and coastal ecosystems. Research on N deposition effects has been done at only a few parks; documented effects include changes in foliar chemistry and photosynthesis in spruce-fir forests in Great Smoky Mountains National Park (McLaughlin et al., 1991) and alterations in aquatic biota, water and soil chemistry, and vegetation in Rocky Mountain National Park (RMNP) in Colorado (Baron et al., 2000). Nitrogen also contributes to acidification of streams in Shenandoah National Park (Bulger et al., 2000; Hyer et al., 1995). Research on N effects to soils, water, and vegetation is underway at additional parks, including Big Bend, Joshua Tree, Grand Teton, Glacier, Yosemite, Sequoia, Mount Rainier, and North Cascades National Parks, and continues at Rocky Mountain and Great Smoky Mountains National Parks.

A growing body of evidence on N deposition dose-response relationships in RMNP, in fact, has become the basis for policy discussions to address N deposition effects on ecosystems. Observations and scientific research in RMNP have led to the collaborative process described in this paper among the National Park Service (NPS), federal and state regulators and stakeholders to develop policy responses to specifically address the issue of N deposition in RMNP. This collaborative process may serve as a template for addressing ecosystem impacts from air pollution in other national parks.

2. Critical loads

An important step in addressing the effects of deposition in parks is to quantify the relationship between deposition and ecosystem response (Porter et al., 2005). This relationship can be described by the critical load, defined as ‘‘the quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge’’ (Nilsson and Grennfelt, 1988). Critical loads are usually expressed as loading rates in kilograms per hectare per year (kg ha^{-1} $year^{-1}$). Critical loads for deposition have been developed for many areas of Europe, where they are used to guide emission control strategies to protect or restore natural and other resources (UNECE WGE, 2004). In North America, Canada has used critical loads for over 20 years to set emission targets (Jeffries et al., 2005); more recently, the Conference of the New England Governors and Eastern Canadian Premiers (NEG/ECP) has directed development of critical loads for acidification of forest soils and lakes in eastern Canada and the northeastern US (Dupont et al., 2005; Miller, 2006; Ouimet et al., 2001, 2006).

The US has no similar national program for critical loads; however, the US federal land management agencies and others recognize that critical loads—in conjunction with monitoring data—provide a valuable tool for assessing ecosystem conditions, setting management goals, communicating resource concerns, and guiding air pollution management decisions (Porter et al., 2005; National Research Council, 2004).

Critical loads are science-based and derived from modeling, empirical, and experimental approaches. Steady-state models have been used extensively in Europe and Canada to calculate critical loads, often using mass-balance equations with inputs and outputs of biogeochemical processes that affect certain resources or indicators (Henriksen and Posch, 2001). Dynamic models include a time component, calculating when a specific effect will occur (Wright, 2001; Larssen et al., 2003). Empirical approaches may use temporal or spatial gradients to derive the amount of deposition that causes changes in resources or indicators (Baron et al., 2000). Experimental approaches manipulate deposition loadings to examine dose-response relationships and determine thresholds for ecosystem changes (Bowman et al., 2006).

A critical load is specific to a certain resource or indicator, the "specified sensitive element," and a defined "significant harmful effect." Sensitive elements include ecosystem resources like forest soils and surface waters. Harmful effects include alterations in ecosystem function and structure such as N leaching from soils and loss of aquatic or terrestrial species. For a given national park, individual critical loads could be developed for a variety of ecosystem resources, including streams, forest soils, and alpine vegetation. For each resource, critical loads could be developed for different significant harmful effects. For example, relatively low levels of N deposition may increase N mineralization rates in forest soils, while higher levels may initiate nitrate leaching from the soils. Ecosystem modeling can predict the N loadings, or critical loads, that would induce either effect.

Although critical loads are science-based, it is the responsibility of land managers to determine which critical load will ensure resource protection consistent with the legal mandates and policies for a given area (Porter et al., 2005). For example, both increased soil mineralization rates and nitrate leaching caused by anthropogenic N deposition could be considered unnatural ecosystem changes that would be inconsistent with legal mandates for national park protection. To comply with these mandates, a national park manager might choose as a management goal a critical load that would prevent an increase in soil mineralization rates and nitrate leaching.

A target load may be used in conjunction with a critical load to ensure protection of a specific resource; a target load is based on policy, economic, temporal, or other considerations and represents an acceptable level of deposition. In an area where deposition is currently at a level below the critical load, a manager might set a target load lower than the critical load, with the intent of ensuring that the critical load is not reached or exceeded (Porter et al., 2005). In areas where the critical load is currently exceeded, an "interim target load" might be used. The interim target load would be a level of deposition between current loading and the critical load that would set a milestone for progress towards reducing deposition (Porter et al., 2005).

3. Rocky Mountain National Park

RMNP is situated along the Colorado Front Range 80 km northwest of Denver. The Continental Divide bisects the park, creating steep elevational gradients with a resulting range of ecosystem types, from high elevation talus slopes and permanent glaciers above 4000 m to lower grassy meadows at 2400 m. More than one-fourth of the park is above treeline (about 3500 m), with large expanses of tundra. The park has more than 60 peaks over 3600 m.

3.1. Atmospheric transport and precipitation

RMNP is in an area of prevailing westerly wind flow. Storms from the west generally lose moisture on the west side of the Continental Divide with the eastern slopes receiving relatively little precipitation from these storms (Mast et al., 2003). During winter, transport from the west and northwest dominates, but easterly upslope events can bring significant amounts of snow to the eastern side of the park (Baron and Denning, 1993; Mast et al., 2003). During spring and summer, easterly upslope winds from differential heating are more common (Losleben et al., 2000). Precipitation increases with elevation in the park, with high peaks receiving most of their moisture in the form of snow (Doesken et al., 2003).

3.2. Nitrogen sources

Potential emission sources that contribute to N deposition in Colorado include vehicles, power plants, other industries, and agricultural operations. Nitrogen-related emissions from vehicles, power plants, and industrial combustion sources are primarily dominated by NO_x, while fertilized croplands and livestock operations emit mainly reduced N in the form of ammonia (NH_3) or ammonium compounds (Fenn et al., 2003b). In the Colorado Front Range, the area east of the Continental Divide that encompasses Colorado's major urban areas of Fort Collins, Boulder, Denver, Colorado Springs, and Pueblo, population increased rapidly from 1980 (1.9 million) to 2000 (2.9 million). Also, both the Front Range and the eastern Colorado plains are host to numerous agricultural operations (Baron et al., 2004). Agricultural trends have been mixed. While cattle in Colorado have decreased 11% and sheep and goats have decreased 55% from 1980 to 2006, hogs have increased 174% during that same time period. And although many crops have decreased (e.g., wheat, corn for silage, oats, hay alfalfa), some have increased in the last few decades (e.g., rye, corn for grain, sunflower seeds, hay) (http://www.nass.usda.gov:8080/QuickStats/PullData_US).

The EPA's current emissions trends data indicate that nationwide, both NO_x and NH_3 emissions decreased about 15% from 1990 to 2001. In Colorado, NO_x emissions decreased 8.7% and NH_3 emissions decreased 25% during that time period (US EPA, 2006). EPA data from all western states (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming) also follow the trend of decreasing NO_x emissions reported (13% from 1990 to 2001), while reported NH_3 emissions have remained relatively steady, with a slight increase of less than 1% (US EPA, 2006).

3.3. Nitrogen deposition

Since 1978, the National Atmospheric Deposition Program (NADP) has been measuring the concentrations of major ions in precipitation, including nitrate and ammonium, at sites nationwide. RMNP has two NADP samplers that are both on the east side of the Continental Divide in the Park at Beaver Meadows (2490 m) and Loch Vale (3159 m). Deposition is not measured routinely on the west side of the Divide in the park, but there are NADP samplers in other areas of Colorado and southern Wyoming west of the Divide. A comparison of data from these samplers found that although precipitation is generally greater west of the Divide, annual average concentrations of nitrate and ammonium in precipitation are higher east of the Divide (Burns, 2003; Heuer et al., 2000) and annual N deposition is generally greater east of the Divide (Baron and Denning, 1993; Burns, 2003). From 1995 to 1999, wet inorganic N deposition at five NADP sites west of the Continental Divide in Colorado and southern Wyoming averaged 1.7 kg ha^{-1} $year^{-1}$; wet inorganic N deposition at the eight NADP sites east of the Divide averaged 2.7 kg ha^{-1} $year^{-1}$ (Burns, 2003). This analysis suggests that annual N deposition in RMNP also is higher on the east versus the west side of the Divide. NPS uses data from the high elevation NADP site at Loch Vale to characterize the most deposition-sensitive ecosystems in the park. Wet inorganic N deposition is currently estimated at 3.1 kg N ha^{-1} $year^{-1}$, based on a 5-year average (1999–2003) (Blett and Morris, 2004).

Inorganic N concentrations in deposition have been increasing over time at many NADP sites in the West, including RMNP. From 1985 to 2002, in large areas of the West ammonium concentrations increased over 50%, with an increase of 73% in RMNP; nitrate concentrations increased 25–50%, with an increase of 26% in RMNP (Lehmann et al., 2005). Wet inorganic N deposition has been increasing by about 2% per year from 1985 to 2000 at Loch Vale (Clow et al., 2003). Most of this increase is due to increases in ammonium concentrations in precipitation (Burns, 2003; Clow et al., 2003) and currently ammonium and nitrate contribute approximately equally to wet inorganic N deposition in the park (Blett and Morris, 2004).

Dry atmospheric deposition is estimated by the Clean Air Status and Trends Network (CASTNet), with a site in RMNP on the east side of the Divide at 2743 m, 400 m lower than the Loch Vale NADP site. Dry inorganic N deposition is estimated at 0.8 kg N ha^{-1} $year^{-1}$, based on a 5-year average (1999–2003) (Blett and Morris, 2004). The CASTNet model is designed for relatively simple terrain and this estimate may be low for higher elevation, exposed areas in the park like Loch Vale. Dry deposition is enhanced in exposed mountainous terrain due to turbulence and increased impaction rates (Hasselroth and Grennfelt, 1987). Also, the CASTNet method does not include NH_3 in its measurements, resulting in a further underestimate of dry deposition. A trend analysis for CASTNet dry deposition from 1995 to 2003 indicated that nitrate concentrations in the air increased during that period, while ammonium showed no trend (Blett and Morris, 2004). Results from an intensive monitoring study at sites near RMNP suggested that air concentrations of N species (nitric acid, nitrate, and ammonium) doubled from the mid-1980s to the mid-1990s (Sievering et al., 1996).

The reported decreases in NO_x and NH_3 emissions from 1990 to 2001 both nationwide and in Colorado are not consistent with the increasing trends in concentrations of nitrate and ammonium in wet deposition over approximately the same period, 1985–2002 (Lehmann et al., 2005), or the increasing trend in concentrations of dry N species from slightly different periods. Uncertainties in the NH_3 emissions inventory (Fenn et al., 2003b; Baron et al., 2004; National Research Council, 2004) may account for the inconsistency between EPA's inventory and the trend in ammonium concentrations in wet deposition. The inconsistency between the NO_x emissions inventory and the trend in nitrate concentrations in wet and dry deposition is less easily explained, but may be due to the somewhat different time periods available for comparison or to underestimates in the emissions inventory from certain source sectors that have experienced recent growth, including oil and gas development.

Total inorganic N deposition in the park can be estimated by adding wet (3.1 kg ha^{-1} $year^{-1}$) and dry (0.8 kg ha^{-1} $year^{-1}$) deposition for a total of 3.9 kg N ha^{-1} $year^{-1}$. This is the best estimate of total inorganic N deposition to high elevation ecosystems in the park, but is likely an underestimate, as the dry deposition estimate is probably low, as noted above, and organic N deposition is not included. Organic N deposition has not been reported for the park. At the Green Lakes Valley near the park, organic N contributed 16% to wet N deposition during a 1996–1998 study (Williams et al., 2001). While it is important to understand the role of organic N deposition in RMNP, methods for measuring organic N have not been standardized and incorporated into monitoring networks.

3.4. Nitrogen deposition effects research in RMNP

Fig. 1 shows the conceptual relationship between N emissions sources, atmospheric transport, N deposition, and ecosystem effects in RMNP. Stationary (point and area), mobile, and agricultural N emissions are carried by prevailing westerly or seasonal upslope winds and deposited as various N species into park ecosystems. More than 20 years of research in RMNP has documented effects from N deposition to high elevation soils, vegetation, and lakes (Baron et al., 2000). Several studies have examined spatial differences in ecosystem effects in the park. As noted in Section 3.2, wet N deposition is generally lower at NADP sites west of the Continental Divide and although deposition is not measured on the west side of the Divide in RMNP, it is likely that wet N deposition is lower on the west side than on the east side of the park. Ecosystem effects appear to reflect this difference. Engelmann spruce stands on the east side of the park were found to have significantly greater soil and foliar N and lower carbon to N ratios than spruce stands on the west side. Potential net soil mineralization rates were also higher on the east side, in

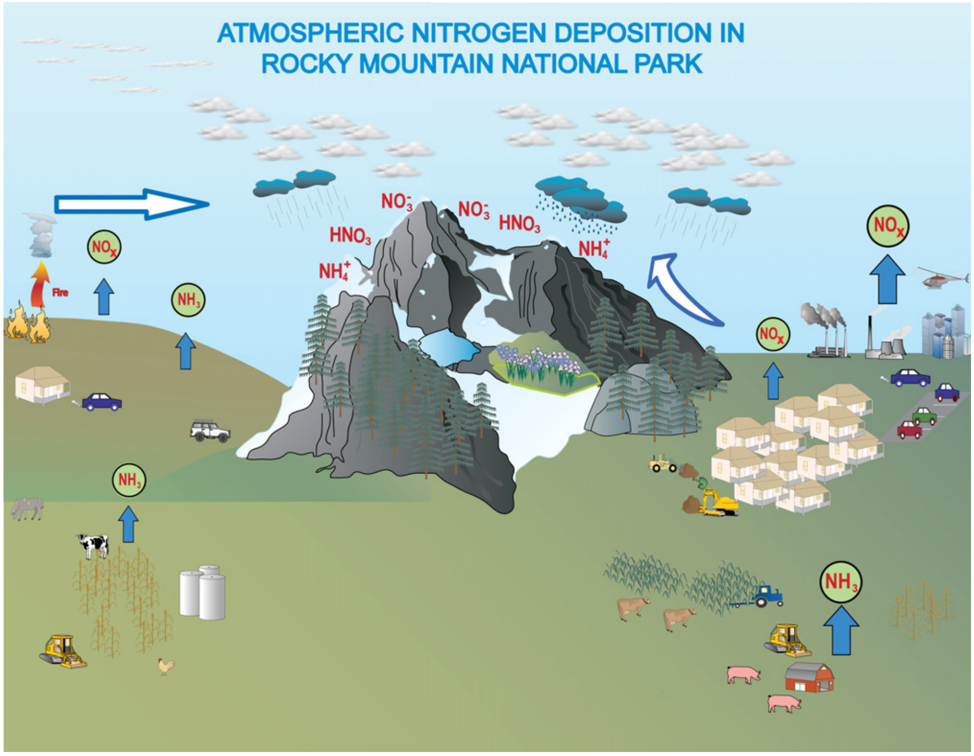

Fig. 1. Conceptual diagram of nitrogen deposition in Rocky Mountain National Park. (1) Vehicles, powerplants, industry, agriculture, and other sources emit nitrogen oxides and ammonia; (2) prevailing westerly or seasonal upslope winds from the east carry emissions to the park; (3) nitrates, nitric acid, ammonium, ammonia, and other compounds are deposited to park aquatic and terrestrial ecosystems; (4) in park ecosystems, nitrogen compounds may alter chemical and biological processes, resulting in changes in water and soil chemistry and species composition (Symbols courtesy of the Integration and Application Network (http://ian.umces.edu/symbols/), University of Maryland Center for Environmental Science).

response to higher percent organic soil N (Rueth and Baron, 2002; Rueth et al., 2003). These changes may be indicative of nutrient imbalances similar to those shown to increase forest sensitivity in other locations to factors such as frost and attacks by fungi (Erisman and de Vries, 2000).

A comparison of lake chemistry found that the mean nitrate concentration in lakes on the east side of the park is significantly higher than on the west side, and significantly higher than would be expected in these nutrient limited ecosystems (Baron et al., 2000). Lake sediment core analysis found that around 1950, a shift began to occur in planktonic taxa, resulting in a fundamental change indicative of eutrophication in high elevation aquatic ecosystems. Prior to this time, diatom assemblages were dominated by oligotrophic species typical of low nutrient lakes; around 1950, mesotrophic species typical of increased disturbance and eutrophication became more prevalent and diatom and chlorophyll concentrations increased. Although lakes on both side of the Continental Divide recorded these changes, the changes were most pronounced in lakes east of the Divide. Corresponding to these changes in aquatic biota was a change in the proportions of N isotopes in the cores, reflecting an increased contribution of anthropogenic N (Wolfe et al., 2001, 2003). In situ enclosure experiments confirmed that phytoplankton in low nutrient lakes in the park respond to small N additions with increased biomass and shifts in species composition (Lafrancois et al., 2004). These studies suggest that anthropogenic N deposition is a likely source of the aquatic biota changes in these high elevation lakes in the park.

The results from these ecosystem studies in the park provide evidence that excess N from atmospheric deposition is changing the structure and function of sensitive high elevation aquatic and terrestrial ecosystems in RMNP (Baron et al., 2000). Empirical research and ecosystem modeling suggest that if N deposition continues at current levels or increases, additional sensitive park ecosystems will be impacted. Significant increases in nitrophilous plant species have been documented in alpine ecosystems on Niwot Ridge, a Long-Term Ecological Research site about 10 km south of RMNP (Korb and Ranker, 2001) that experiences somewhat higher rates of N deposition than the Park (Burns, 2003). Fertilization experiments at Niwot Ridge found that additions of N favored the growth of grasses over forbs in alpine tundra and increased overall plant biomass (Bowman, 2000; Bowman et al., 2006). The fertilization experiments were used to estimate the lowest amount of N deposition that would alter alpine plant communities; this amount, 4 kg ha^{-1} $year^{-1}$ (Bowman et al., 2006), is similar to the level of total wet inorganic N deposition in alpine tundra in RMNP, as described in Section 3.2. Nitrogen deposition also contributes to episodic acidification in streams in the Green Lakes Valley below Niwot Ridge (Williams and Tonnessen, 2000) and ecosystem models predict that continued trends in increasing N deposition may eventually reduce acid-neutralizing capacity of sensitive lakes and streams in RMNP to levels that would allow episodic or chronic acidification (Sullivan et al., 2005).

Fig. 2 shows a theoretical continuum of existing and future effects from N deposition in the park. Existing effects include increased nitrate in lakes and streams, altered phytoplankton communities, and biogeochemical changes in soils and vegetation of Engelmann spruce forests (Baron et al., 2000). Current N deposition levels are comparable to those known to induce changes in tundra plant community species composition and abundance (Bowman et al., 2006). Potential future effects include episodic or chronic acidification of streams and lakes (Williams and Tonnessen, 2000; Sullivan et al., 2005).

This accumulation of evidence of fundamental and significant effects to park ecosystems has prompted NPS, state and federal air regulators, and stakeholders to initiate a process to address N deposition problems at RMNP.

4. Protection of air quality and air quality related values in RMNP: legal framework and governmental responsibilities

4.1. Resource protection

The responsibilities of federal land managers to protect resources under their care are rooted in the law. These laws have been interpreted and applied by the courts, reiterating the resource protection responsibility. The primary laws and interpretations follow.

- Congress established RMNP on January 26, 1915, to be "... set apart as a public park for the benefit and enjoyment of people of the United States," and directed implementing regulations to be "... primarily aimed at the freest use of the said park and for the preservation of the natural conditions and scenic beauties" (US Congress, 1915).
- The Organic Act of the NPS directs the agency to: "... conserve the scenery and the natural and historic objects and wild life therein... as will leave them unimpaired for the enjoyment of future generations" (US Congress, 1916).
- The Wilderness Act of 1964 directs that "[w]ilderness areas... shall be administered for the use of the American people in such a manner as will leave them unimpaired for future use and enjoyment as wilderness.... " (US Congress, 1964).
- Preservation mandates are necessarily carried out using all relevant scientific data and consultation with the scientific community. The NPS "Research Mandate" recognizes that the management of the National Park System must be "enhanced by the availability and utilization of a broad program of the highest quality science and information" (US Congress, 1998).

The responsibilities of the NPS with respect to resource protection have been the subject of litigation. Courts have held that the Interior Secretary's lack of action to protect resources is subject to judicial review, and the Secretary must take "reasonable steps in a reasonable time" to protect resources (*Sierra Club v. DOI*, 1976).

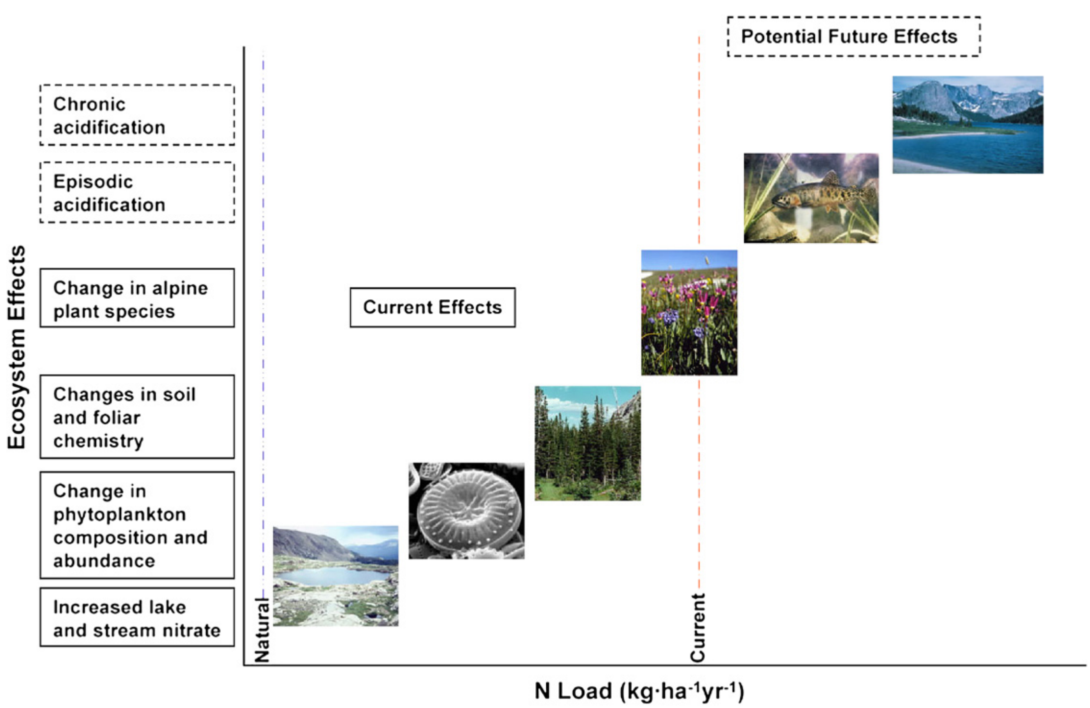

Fig. 2. Continuum of nitrogen deposition effects in Rocky Mountain National Park. Existing effects include increased lake and stream nitrate, changes in high elevation lake phytoplankton communities, and changes in Engelmann spruce forest soil and foliar chemistry. Current nitrogen deposition levels are similar to those known to cause changes in alpine plant species composition and abundance. Future effects may include episodic and chronic acidification of streams and lakes.

The NPS has a responsibility to protect resources within the borders of the lands it manages. This is a challenging mission; while the Service can regulate sources *inside* the parks, it has no legal authority over external sources from which the vast majority of air pollutants which deposit in the parks originate. To carry out its responsibilities with respect to protecting resources from air pollution, the NPS works in collaboration with regulators and stakeholders in the context of an established body of air quality law, specifically the Clean Air Act, that creates responsibilities for other federal and state agencies.

4.2. Air quality management

The Clean Air Act provides a framework for protecting air quality and ‘‘air quality related values’’ (AQRV). An AQRV is defined as a resource that may be adversely affected by a change in air quality and may include visibility or a specific scenic, cultural, physical, biological, ecological, or recreational resource for a particular area (FLAG, 2000). The Act established this framework—the Prevention of Significant Deterioration (PSD) Program—‘‘... to preserve, protect and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historic value’’ (US Congress, 1977). The EPA is responsible for developing regulations to implement the PSD program and approving state PSD programs. One such requirement is that regulations be developed to fulfill the Act’s goals and purposes including for the ‘‘protection of air quality values’’ (US Congress, 1977). These protections ‘‘may contain air quality increments, emission density requirements, or other measures’’ (US Congress, 1977).

After years of debate and litigation about how EPA was addressing N impacts through the PSD program, EPA ultimately revised the nitrogen dioxide increment rule. The new rule provides an opportunity for states and federal land managers to implement critical loads pilot projects to address ecosystem effects from N deposition, which ‘‘could lead to implementation plans that demonstrate protection against deterioration of AQRVs from nitrogen impacts....’’ (US EPA, 2005). In fact, EPA allows states to propose the use of critical loads as part of their air quality management approach, and EPA will determine whether that approach satisfies PSD requirements on a case-by-case basis (US EPA, 2005).

The nitrogen dioxide increment rule was EPA’s first formal suggestion that critical loads may have a place in the regulatory framework. Otherwise, EPA has been exploring using critical loads as an assessment tool, and has participated in several projects exploring critical loads issues including modeling, mapping, developing pilot projects and synthesizing the state of the science on indicators and monitoring ecosystem response to air pollution (http://www.epa.gov/airmarkets/cmap/linkdescs/).

These explorations are largely a result of suggestions from the National Research Council of the National Academy of Sciences that effective air quality management needs to include improved techniques for measuring ecosystem exposure and designing strategies for controlling the most significant sources (National Research Council, 2004). The National Research Council, reporting on air quality management in the US, recommended ways to improve the technical and scientific foundations for managing air quality. The Clean Air Act Advisory Committee, a senior-level policy committee established in 1990 to advise the EPA on issues related to implementing the Clean Air Act Amendments of 1990, developed a plan to prioritize and focus the National Research Council recommendations, which included substantial attention to ecosystem assessment and protection. That plan includes recommendations to develop measures to assess ecological impacts of air pollution and evaluate progress, including examining the possibility of using critical loads; and to evaluate alternative approaches for protecting ecosystems, with an emphasis on critical loads (http://epa.gov/air/caaac/aqm.html).

The implementation responsibilities under the PSD program primarily fall to the states (or tribes), or the EPA when a state agency does not have delegation or approval for the program, or fails to properly administer the program. Historically, PSD had been treated solely as a permitting program, where new sources of air pollution locating in or affecting relatively clean areas must show that their emissions will not cause significant air quality deterioration. Although the Act contemplates the need to manage air quality to avoid significant deterioration and protect AQRVs (US Congress, 1977), states have struggled with how to implement this air quality management direction in the Act. As a result, cumulative effects have not been examined in most states. Some western states, under the auspices of the Western States Air Resources Council (WESTAR) have begun discussions on how to use ecosystem effects information—specifically critical loads—as a measure and thus a driver of air quality management strategies (http://www.westar.org/Training/2005%20Training/Critical%20Load/Critical%20Loads%20Final%20Agenda.doc). Colorado is the first state to consider using critical loads in a specific policy application.

Colorado does have an approved PSD program, and as such is required to have a State Implementation Plan (SIP) that contains ‘‘measures as may be necessary... to prevent significant deterioration of air quality....’’ (US Congress, 1977). In general, any SIP shall be revised if any applicable provisions of the Act are not being complied with (US Congress, 1977). Additionally, Colorado has a state law (Colorado, 1994), the ‘‘State AQRV law,’’ that provides for a federal land manager to assert and verify impairment of an AQRV in an area managed by that federal land manager. Upon receipt of such information, the statute requires the state to initiate a formal proceeding to address the issue, involving data generation and verification, a peer review panel, and consultation process. The parties involved in the RMNP process agree that the State AQRV law provides for an adversarial process and should only be used as a last resort. The process described in the next section, on the other hand, is intended to be based on collaboration.

5. Interagency and stakeholder process to address nitrogen deposition in RMNP

In addition to evidence indicating ecosystems are being harmed by the deposition of air pollutants coupled with the legal responsibilities of various governmental agencies, the initiation of a policy process often requires external influence. In the case of RMNP, that influence was a petition in 2004, by Environmental Defense and Colorado Trout Unlimited to the US Department of the Interior (DOI), which oversees the NPS (http://www.cdphe.state.co.us/ap/rmnp/petition.pdf). Specifically, that petition requested the DOI to:

- Immediately declare adverse impacts on AQRVs at RMNP.
- Promptly establish a critical load standard for N deposition in RMNP and determine a pollution cap for NO_x and NH_3 to protect human health, plants and ecosystems, and scenic vistas in RMNP.
- Call for the EPA and the State of Colorado to fulfill their legal responsibilities to lower NO_x and NH_3 to protect human health, plants and ecosystems, and scenic vistas at RMNP and to fully mitigate N deposition above the identified critical load.

To respond to this petition and the body of evidence collected over the past 20 years, the NPS, Colorado's Air Pollution Control Division (APCD) and EPA Region 8 discussed an alternative to the relatively adversarial process set out in the State AQRV law. The agencies decided to approach the issue collaboratively.

5.1. Memorandum of understanding for interagency collaboration to address air quality issues affecting RMNP

The agencies memorialized the ultimate goal of the process, the collaborative intent, specific responsibilities of each agency and some process issues in a Memorandum of Understanding (MOU) that was signed in December, 2005. The purpose of the MOU is to:

> [E]stablish a collaborative, working relationship between the National Park Service (NPS), the State of Colorado's Department of Public Health and Environment (CDPHE), and the US Environmental Protection Agency (EPA) to assist in the development of air quality management policies and programs to address harmful impacts to air quality and other natural resources occurring in RMNP.

(http://www.cdphe.state.co.us/ap/rmnp/rmnpmoa.pdf). The MOU contains a specific N deposition goal: "to facilitate timely development and implementation of air management policies and programs, as determined necessary, to reverse the trend of increasing nitrogen-related compound impacts affecting RMNP". Also, the NPS will "[d]efine resource management goals related to nitrogen deposition (e.g., critical loads, sustainable conditions, desired future conditions) that would be protective of the Park's sensitive resources" (http://www.cdphe.state.co.us/ap/rmnp/rmnpmoa.pdf). While the MOU creates no rights or enforceable obligations on the part of the agencies, and commitments are subject to agency budget availabilities and priorities, the document has provided a framework, guidance and public accountability to move the process forward. The agencies to the MOU have formed technical committees such as Air, Water, and Agriculture to address the various relevant questions needing resolution to achieve the stated goals for RMNP. A steering committee with representatives from each of the three MOU agencies oversees the process and develops overall policy direction for the Initiative and interfaces with the State's Air Quality Control Commission (http://www.cdphe.state.co.us/ap/rmnp/orgchart.pdf).

5.2. Colorado Air Quality Control Commission subcommittee on RMNP

In Colorado, the Air Quality Control Commission (AQCC) is responsible for developing and adopting a regulatory framework to protect air quality in Colorado (Colorado, 1982a). The AQCC oversees the implementation of the air quality program, which is administered by the APCD in the CDPHE. The APCD also has enforcement authority, collects and analyzes data relating to the programs it administers, and provides technical advice to the AQCC and the regulated community (Colorado, 1982b). The APCD staff are involved in the MOU process, discussed above.

After being briefed on the air quality concerns at RMNP, the AQCC formed a subcommittee to address the issue. The subcommittee has provided a public forum for the agencies, AQCC, and stakeholders to review the research, identify further study needs and consider options for improving conditions. The goal of the subcommittee is to develop a plan to reverse the trend of increasing N deposition at the park and remedy N deposition effects. The subcommittee has been working in conjunction with the MOU agencies. The process as a whole is referred to at the Rocky Mountain National Park Initiative.

5.3. Policy goal: establishment of critical load for eutrophication in RMNP

The first objective under the MOU is that the "parties will work to develop a nitrogen deposition goal and/or a proposed air or water quality standard for making progress toward any resource management goal(s) established by the Park." Thus, the policy goal is based on the management goal established by the Park. The management goal for the park, in turn, is based on peer-reviewed scientific analyses (http://www.cdphe.state.co.us/ap/rmnp/rmnpmoa.pdf). As noted in Section 3.4, sediment cores from high elevation lakes on the east side of the Continental Divide in the park provide evidence that around 1950, a fundamental change in phytoplankton communities occurred that was indicative of N enrichment, or eutrophication. Phytoplankton species shifted from primarily oligotrophic to mesotrophic types, and overall phytoplankton and chlorophyll concentrations increased. This is the earliest documented change to RMNP ecosystems due to N deposition. As discussed in Section 3.4, N enrichment as indicated here leads to a multitude of other ecological effects. The estimate of N deposition at the time of this change defines an ecological threshold, or critical load. The relationship between post-1980 emissions and wet deposition, for which data were available, was used as a basis for hindcasting deposition for the period of phytoplankton change, approximately 1950–1964. Equations for hindcasting used mean annual precipitation values from 1984 to 2003, or VEMAP (Vegetation/Ecosystem Modeling and Analysis Project)-derived precipitation for 1900–1983. These precipitation values were used with both linear and exponential regressions of mean concentrations of nitrate and ammonium in precipitation to estimate wet N deposition back to 1900, when wet deposition was estimated at 0.5 kg N ha^{-1} $year^{-1}$. Using this approach, wet N deposition during 1950–1964 was estimated at 1.5 kg ha^{-1} $year^{-1}$ (Baron, 2006). This value defines the critical load for eutrophication in the park, that is, the deposition at which high-elevation aquatic communities were significantly altered (Baron, 2006).

The Park adopted this critical load and the Park Superintendent notified the director of the CDPHE in May 2006 that the critical load for eutrophication could provide the "benchmark that should be used at this time to link ecosystem protection goals of RMNP with air, and possibly water, management programs and policies administered by the State" (http://www.cdphe.state.co.us/ap/rmnp/rmnpCLLetter.pdf). Subsequently, the CDPHE as well as the EPA Region 8 formally responded with letters agreeing that the critical load identified did appear to be the "loading rate at which the Park's ecosystem began to shift," thus "endorsing" the critical load of 1.5 kg wet N ha^{-1} $year^{-1}$ set by the Park as a basis by which to set a N deposition goal as required by the MOU (http://www.cdphe.state.co.us/ap/rmnp/Ellisletter.pdf).

After using the critical load to set a deposition goal, the next step is identifying when that goal should be achieved. The parties are recommending that the achievement of the deposition goal in RMNP be patterned after the Regional Haze Rule, in which the endpoint—"natural background visibility" in many national parks and wilderness areas—is to be achieved in 2064. States are required to show progress along a glidepath at 5-year increments (US EPA, 1999).

The glidepath approach was chosen for this process in RMNP because it is an accepted regulatory and policy structure for long-term, goal-oriented air quality planning. Significant infrastructure (including emissions inventories, monitoring, modeling and other technical work) for the glidepath concept already exists in the state, and there is regional and national support for this concept in the context of the Regional Haze Rule. The slope of the glidepath for N deposition purposes identifies target loads along the timeline to be used to develop reduction strategies and assess progress. The endpoint and slope for the N deposition glidepath is under discussion. The MOU agencies recommend a shorter time line than the Regional Haze Rule because the existing N loading, which is cumulative, is degrading the ecosystem currently and the trend should be reversed as soon as possible to avoid further long-term damage and to help restore currently damaged resources. Visibility, on the other hand, is a function of atmospheric concentrations of pollutants, and responds more immediately to changes in emissions.

5.4. Policy implementation: geographic area and source category attribution

Given a deposition goal and timeline under which to achieve that goal, the overarching policy questions become what reductions are needed, from what source categories, from what geographic areas, and when? A related issue is the effect on N deposition of predicted emission reductions from programs already in place. For instance, federal mobile source standards are estimated to result in a 71% reduction in mobile source NO_x by 2022 in metro Denver. Combined with an estimated 33% growth in stationary source NO_x emissions and expected increases in area sources (e.g. oil and gas operations), a 28% reduction in NO_x in metro Denver is predicted (Silverstein and Taipale, 2006). Also important is what portions of the emissions are coming from Colorado versus neighboring states. While there are significant NH_3 emissions from agricultural activities in Eastern Colorado, for instance, there are even larger amounts of NH_3 generated in Kansas, Nebraska, and Iowa (Silverstein and Taipale, 2006).

There are numerous factors that affect atmospheric deposition of pollutants in a given geographic area: emissions in proximity to that area as well as emissions up to several hundred miles away, the physical height of those emissions, atmospheric chemical transformations of those emissions, topography, and local- and regional-scale meteorology including precipitation. Additionally, the N being deposited in RMNP contains both particulate and gaseous nitrate and ammonium (as well as gaseous NH_3) in roughly equal amounts. This implicates sources of NO_x as well as sources of NH_3. Because of this complexity, no single technical analysis will provide sufficient information regarding specific source attribution for the purpose of informing the policy process. Therefore, the parties plan to examine multiple existing and planned analyses and data sets to create a body of evidence—or "weight of evidence"—upon which policy decisions can be based, and to evaluate the effectiveness of those decisions.

The weight of evidence analysis in this case refers to a largely qualitative method by which evidence relevant to determining sources of deposition in the Park will be examined and the uncertainties and biases of that evidence identified. Relevant evidence includes emission inventories for NO_x and NH_3; data from wet and dry deposition, visibility, and state particulate matter monitoring networks, as well as data from special studies; and modeling studies that estimate atmospheric transport of pollutants into RMNP. For example, the Western Regional Air Partnership—a consortium of regulators and stakeholders convened to analyze regional haze issues—produced the "Attribution of Haze" reports (http://www.wrapair.org/forums/aoh/index.html).

These reports detail modeling analyses done to estimate each state's major emission source category contribution to visibility impacts at national parks and wilderness areas. Although the contribution to visibility impairment in RMNP from Colorado's various broad source categories has been estimated, correlating deposition to visibility impairment is uncertain. Visibility impairment reflects atmospheric concentrations of particulate pollutants which have been transported some distance and are still in transit, and may or may not deposit at the site at which the visibility impairment exists. Additionally, the attribution of haze studies were modeled on a 36-km grid size, which may be of insufficient resolution to capture smaller-scale variances in emissions, chemistry and transport characteristics. Although this resolution may not address transport in the complex terrain that makes up the eastern slope of the Continental Divide down to the Colorado Front Range area, these are peer-reviewed, relatively robust analyses that identify atmospheric transport of pollutants, and distinguish among geographic areas of origin and broad source categories.

5.4.1. Rocky Mountain atmospheric nitrogen and sulfur study

The NPS and CDPHE, in conjunction with Colorado State University are currently conducting a special study to identify source categories and source regions contributing pollutants, including N compounds, to RMNP. The study has two main components. First, field measurements in the Park and at other locations around the state of Colorado were taken for two intensive sampling periods in 2006. These periods were selected to be during times typically associated with precipitation events in the area—March through April and July through August. Measurements include fine and coarse particle concentrations (nitrate and ammonium), trace gas concentrations (nitrogen oxides, ammonia, and nitric acid), ion size distribution, wet deposition, particle light scattering and meteorology.

The contribution of a source or source region to deposition cannot be directly measured. Therefore, the second study phase involves data analysis and air quality modeling which simulates the atmospheric physiochemical processes and uses statistical inference techniques based on physical principles. Multiple source apportionment techniques will be applied and reconciled to minimize biases between modeled results and observations. In-state (distinguishing between the Front Range and rest of Colorado) and out-of-state source regions will be identified, as well as contributing source categories. Final results may not be available until 2008. The agencies, stakeholders and Colorado AQCC members engaged in the RMNP Initiative will continue to consider available evidence, discuss and debate the issues, and potentially develop some program components towards reversing the N deposition trend in the meantime.

5.5. The Rocky Mountain National Park Initiative: an ongoing policy process

Concurrent with conducting the technical analysis, the agencies are developing potential mitigation strategies and regulatory or programmatic pathways to achieve the policy goals. Potential mitigation strategies include attaining additional NO_x reductions when plans for regional haze are developed, statewide oil and gas industry controls, and voluntary reductions in the form of agricultural best management practices. The state, by law, is largely limited in regulating agriculture (Colorado, 1998). While mitigation strategies can be discussed, any new requirements will have to be supported by technical analysis.

Also, in addition to the glidepath approach discussed in Section 5.4, the agencies are exploring whether there are any water quality programs or regulatory options that would be appropriate to address the harmful impacts to aquatic ecosystems in RMNP from N deposition. Because most of the documented changes in water chemistry and aquatic biota occurred prior to designation of park waters as ‘‘outstanding natural resource waters’’ in 1981, and water chemistry in the Park has not exceeded any of the regulatory standards set for protection of drinking water, it is unclear whether the Total Maximum Daily Load process under Section 303(d) of the Clean Water Act could be of use in this instance.

6. Conclusions

Throughout the history of air quality management in the US, science has been an initial driver of air quality law and policy. For the Rocky Mountain National Park Initiative, the body of science of N effects to RMNP has driven the collaborative process between the NPS, CDPHE, and EPA to mitigate the adverse effects of air pollution on park ecosystems. The use of a critical load to define ecosystem thresholds for ‘‘significant harmful effect’’ has been instrumental in defining and setting management goals for Colorado's air quality planning. Hindcasting N deposition to estimate a critical load has proven to be very useful for an area in which the critical load has been exceeded, and historical ecosystems conditions can be estimated. Hindcasting is currently being evaluated by the National Park Service as a tool for estimating critical loads in other parks; other approaches being evaluated include ecosystem modeling, experimental manipulation, and deposition gradient studies.

On a national level, a growing body of science is driving the need for ecosystem protection on a broad scale. The National Research Council, EPA and the federal land managers have recognized that tools to evaluate ecosystem health are a natural starting point for this process. Strategies developed for the RMNP Initiative to establish the critical load, target load, glidepath, and plans for emissions reductions may serve as templates for mitigating air pollution impacts in other protected areas.

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