Protecting Resources on Federal Lands: Implications of Critical Loads for Atmospheric Deposition of Nitrogen and Sulfur

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Critical loads are a potentially important tool for protecting ecosystems from atmospheric deposition and for promoting recovery. Exceeding critical loads for nitrogen and sulfur can cause ecosystem acidification, nitrogen saturation, and biotic community changes. Critical loads are widely used to set policy for resource protection in Europe and Canada, yet the United States has no similar national strategy. We believe that ecosystem science and resource protection policies are sufficiently advanced in the United States to establish critical loads for federal lands. Communication and interaction between federal area managers and scientists will ensure that critical loads are useful for assessing ecosystem conditions, influencing land management decisions, and informing the public about the status of natural resources. Critical loads may also be used to inform air pollution policy in the United States, regardless of whether critical loads are directly linked to air quality regulations and emissions reductions agreements, as they are in Europe.

Keywords: atmospheric deposition, critical load, target load, ecosystem threshold, land management

A critical load has been 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). Although critical loads can be developed for a variety of pollutants, we focus our discussion on sulfur (S) and nitrogen (N) compounds, because of their documented consequential and widespread effects on ecosystem components and processes. Critical loads describe thresholds for ecosystem sensitivity to S and N that are based on specific indicators of ecological change, including episodic and chronic acidification of streams and rivers, chemical changes in soils and vegetation, and nutrient enrichment and eutrophication (Driscoll et al. 2001, 2003, NPS 2002, Aber et al. 2003, Fenn et al. 2003a). Critical loads are expressed as loading rates in kilograms (kg) or equivalents of S and N per hectare (ha) per year. Critical loads are calculated for specific receptors, such as forest soils or surface waters, often using a dose-response relationship.

Federal area managers are beginning to use critical loads as tools for quantifying harmful pollution levels and setting goals for resource protection or restoration on federal lands. The federal areas administered by the National Park Service (NPS), the US Department of Agriculture Forest Service (USDA FS), and the US Fish and Wildlife Service (FWS) comprise nearly 142 million ha in the United States. Each agency has its own unique mission and responsibilities, but all three land management agencies are directed by their enabling legislation and federal statutes to protect resources for the benefit of future generations.

Resources on federal lands have been, and continue to be, affected by air pollutants. Most pollution sources are outside federal lands. The federal area managers have no regulatory authority over these sources, but they do have a consultative role in the air regulatory process. In this role, the federal area managers advise states and the US Environmental Protection Agency (EPA) regarding resources sensitive to air pollution

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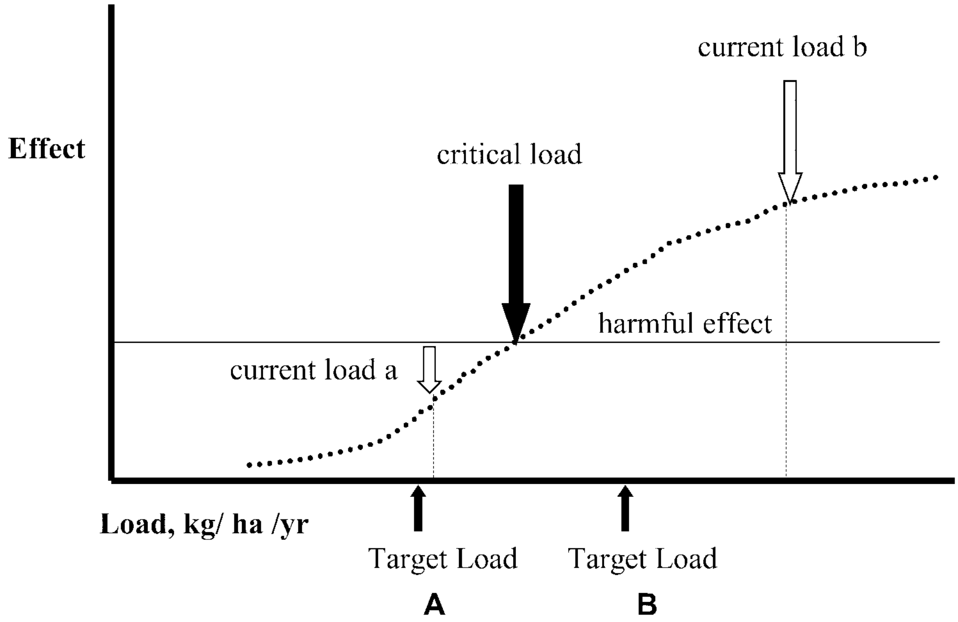


Figure 1. Target loads for atmospheric deposition. Target loads represent a policy or management decision about the amount of deposition that would result in an acceptable level of resource protection. Target load A is lower than the critical load to prevent degradation in more pristine environments or to provide a safety margin. Target load B represents a level of deposition between current loading and the critical load. Target load B could be regarded as an interim target load that would set a benchmark for progress toward reducing deposition to a level at or below the critical load. Adapted from Hultberg and colleagues (1994).

on federal lands. States and the EPA often ask federal area managers to identify pollution levels that are harmful to resources in order to facilitate permitting and planning, and to ensure resource protection. Critical loads would define these harmful pollution levels and could be used by air regulators to develop strategies to reduce air pollution emissions.

Target loads may also be selected to ensure protection or set restoration goals for federal areas. Target loads are usually based on critical loads and represent a policy or management decision about the amount of deposition that could be allowed without jeopardizing resource protection. For federal resources, the acceptable level, or target load, for resource protection would be somewhat below the critical load, because the critical load defines a level of pollution at which harmful effects may begin to occur. It would be inconsistent with federal resource protection mandates to advocate a level of deposition that might cause harmful effects. State and federal air regulatory agencies are guided by different mandates. For areas where the critical load has been exceeded, air regulatory agencies could choose an interim target load that is higher than the critical load in consideration of political, economic, and social goals, in addition to resource protection concerns. Figure 1 illustrates the relationship between the critical load and target load. The federal area manager would set a “target load A” somewhat below the critical load, to define protection goals consistent with mandates for resource protection and for planning and evaluation purposes. An air regulator might choose a “target load B” above the critical load if the current deposition load were above the critical load. This interim target load, which would represent a level of deposition between current loading and the critical load, would set a benchmark for progress toward reducing deposition. This “glide path” concept for reducing emissions is currently used by air regulatory agencies developing progress plans under the EPA’s Regional Haze Rule, under which states must demonstrate progress in reducing haze caused by anthropogenic air pollution in certain parks and wilderness areas. Visibility improvement will be evaluated at 10-year intervals, and emissions reduction targets adjusted accordingly, to achieve natural visibility conditions by the year 2064 (USEPA 2003). A similar strategy could be used to manage N and S deposition in areas where current deposition exceeds the critical load.

In this article we describe a strategy for developing critical loads. We discuss why communication and coordination between federal area managers and scientists are desirable to identify sensitive resources, define criteria for harmful effects, and calculate critical loads. We present case studies for two federal areas and discuss possible future directions and strategies for the development, communication, and use of critical loads in the United States. The success of the concept of critical loads in the United States will also depend on the consideration of critical loads in air regulatory policy decisions for developing pollution emission strategies at national, regional, state, and local levels.

Critical loads: History and policy

The critical load concept has been widely adopted in Europe as a tool for integrating information about the effects of air pollution on ecosystems, land management objectives, and regulation of atmospheric pollution. The United Nations Economic Commission for Europe, Convention on Long-Range Transboundary Air Pollution (Working Group on Effects), has established International Cooperative Programmes (ICPs) to address the effects of air pollution on ecosystems, human health, and cultural resources across Europe. Information from ICP monitoring of forests, waters, and natural vegetation has been used to calculate critical loads, set target loads, and support emission control policies throughout the continent (UNECE WGE 2004). Deposition critical loads are also increasingly available for areas outside Western Europe, such as Siberia (Bashkin et al. 1995), China (Duan et al. 2001), Thailand (Milindalekha et al. 2001), and South Africa (Van Tienhoven et al. 1995).

North America has no equivalent multinational program to broadly develop and adopt critical loads. Canada has led the way, developing critical and target loads that inform S deposition reductions to protect or restore lakes from acidification (RMCC 1990). A collaborative US–Canadian project to calculate critical loads has been initiated by the Conference of New England Governors and Eastern Canadian Premiers. Their Acid Rain Action Plan includes strategies for mapping forest sensitivity to S and N deposition in eastern Canada and the northeastern United States (NEG ECP 2001). These maps will be used to set critical loads for maintaining forest health and productivity and to identify acceptable levels of deposition (target loads) to be considered in S and N emissions reductions strategies.

In the early 1990s, the EPA considered setting acid deposition standards for the United States, similar to critical loads, as benchmarks for regulatory action. However, the EPA's Acid Deposition Effects Subcommittee advised against setting standards at that time, because of two critical barriers. First, "policy decisions regarding appropriate or desired goals for protecting sensitive aquatic and terrestrial resources" were needed to help guide the EPA; second, "key scientific unknowns, particularly regarding watershed processes leading to nitrogen acidification and remaining times to watershed saturation," still existed (USEPA 1995). Furthermore, the EPA was concerned that national deposition standards would not account for regional differences in ecosystem sensitivity. Now, a decade later, many policy decisions based on congressional mandates have been made by federal area managers regarding the goals of natural resource protection (NPS 2000); in addition, significant scientific advances have been made toward understanding N and S deposition processes (Driscoll et al. 2001, 2003, Aber et al. 2003, Fenn et al. 2003a). These policy decisions and science advances pave the way for critical loads to be calculated and implemented as tools for resource protection at local, state, regional, and national levels in the United States.

Federal area protection: Mandates and policy

Federal area managers are responsible for deciding what to protect and what degree of protection to provide on federal lands. These decisions are based on responsibilities mandated by the Clean Air Act (42 USC 7470[2] and 42 USC 7475[d][2]), the Wilderness Act (16 USC 1131–1136), the NPS Organic Act of 1916 (16 USC 1–4), the National Wildlife Refuge System Improvement Act of 1997 (PL 105-57), and the National Forest Management Act (16 USC 1600–1614).

A major milestone in making these decisions was the publication of the Federal Land Managers' Air Quality Related Values Workgroup (FLAG) Phase I Report (NPS 2000), which provided a consistent approach among agencies for evaluating air pollution effects on natural resources. Federal area managers recognized that critical loads should be specific to their wilderness areas or parks, should protect the most sensitive resources within each federal area, and should be based on the best science available. The FLAG report noted that the federal area managers were committed to fostering development of critical loads.

Federal area managers have identified the resources at risk from or sensitive to air pollution for many parks and wilderness areas (see *www2.nature.nps.gov/air/Permits/ARIS* and *www.fs.fed.us/r6/aq/natarm*). Qualitative descriptions of these resources have also been completed. This information is specific to each wilderness area or park, because of the tremendous diversity in ecosystem characteristics, sensitivities, and stressors on federal lands. In many areas, specific parameters have been selected for monitoring changes in these sensitive resources. The USDA FS has established broad protection thresholds for sensitive aquatic and terrestrial resources in wilderness areas that it manages (*www.fs.fed.us/r6/aq/natarm*). In some cases, "limits of acceptable change" (box 1) for these resources have been quantified. These thresholds describe resource protection criteria of interest to federal area managers and can serve as a basis for development of critical and target loads. The NPS and FWS have developed "deposition analysis thresholds" that are used to evaluate new sources of air pollution (box 1). Deposition analysis thresholds define a deposition rate below which the NPS and FWS would consider a new source's emissions to be insignificant. Deposition analysis thresholds are based on estimates of background deposition for the eastern and western United States and are described in "Guidance on Nitrogen and Sulfur Deposition Analysis Thresholds" (*www2.nature.nps.gov/air/Permits/flag/NSDATGuidance.htm*).

Critical loads: Advances in science

Scientific advances continue to be made in understanding ecosystem thresholds for the effects of acidification and N enrichment. Effects of acidification on aquatic systems can include changes in community structure, biodiversity, reproduction, decomposition, and other aspects of biogeochemical cycles. Effects of acidification on terrestrial systems include disruption of soil nutrient cycling processes, reduction of essential plant nutrients such as calcium, and alu-

Box 1. Terms related to resource protection and critical loads.

Acid-neutralizing capacity (ANC): A measure of buffering capacity, the ability of a solution to neutralize acids and therefore to resist changes in pH. Surface waters with ANC greater than 50–100 microequivalents per liter (µeq per L) are usually capable of supporting healthy aquatic biota.

Critical load: 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).

Deposition analysis threshold: The additional amount of nitrogen or sulfur deposition to an area below which estimated impacts from a proposed new or modified source of air pollution are considered insignificant.

Glide path: A quantitative route of progress from existing conditions to desired conditions (e.g., from current visibility impairment to natural visibility conditions for a specific park or wilderness area, or from current deposition above a critical load to the target load).

Indicator: A measurable physical, chemical, or biological characteristic of a resource that may be adversely affected by a change in air quality (e.g., ANC).

Interim target load: A level of deposition between current loading and the critical load that would set a benchmark for progress toward reducing deposition in areas where current deposition exceeds the critical load.

Limit of acceptable change: The amount of change that could occur without significantly altering a resource that is sensitive to air pollution.

Resource protection criterion: Quantitative value of a resource indicator that will adequately protect a resource from the effects of air pollution (e.g., ANC of 100 µeq per L to protect aquatic biota from acidification).

Sensitive resource: A resource that is easily affected by an air pollutant of concern (e.g., a high-elevation lake in Rocky Mountain National Park that is sensitive to nitrogen deposition).

Target load: The level of exposure to one or more pollutants that results in an acceptable level of resource protection based on policy, economic, or temporal considerations.

minum mobilization. (Overviews of recent progress in understanding the effects of S and N deposition in the eastern United States can be found in Driscoll and colleagues [2001, 2003] and Aber and colleagues [2003].) Ecosystems in the eastern United States have been more strongly affected by acidification than ecosystems in the western United States. Nitrogen enrichment is generally of greater concern than acidification for the western United States (Fenn et al. 2003a). Deleterious effects of N enrichment include N saturation, eutrophication, and changes in biotic communities. (Fenn and colleagues [2003a] present a discussion of the ecological effects of N deposition in the West.) Nitrogen causes a sequential cascade of effects that lie along a continuum from sublethal (e.g., nutrient enrichment) to lethal (e.g., chronic acidification), depending on the amount of deposition and the sensitivity of the resource (Galloway et al. 2003).

An increased understanding of the ecological changes resulting from deposition has heightened interest in quantifying the levels of deposition responsible for such changes. Critical loads can be used to quantify levels of deposition that cause harmful changes. A critical load can be calculated by a variety of methods. Critical loads may be based on empirical data from comparative research (spatial studies) and long-term ecological research (Williams and Tonnessen 2000). These types of studies use spatial and temporal gradients of deposition to assess thresholds for ecosystem response. Alternatively, critical loads can be calculated using the results of experimental manipulations that control deposition loading to identify specific effects of atmospheric deposition (Wright et al. 1994, Norton and Fernandez 1999, Baron et al. 2000). Steady-state mass balance models have also been used extensively in Europe, and to some extent in the United States, to estimate changes in ecosystem response based on increases or decreases in deposition loading (Henriksen and Posch 2001). All three approaches assume steady-state conditions, consistent with the concept of a critical load as static; that is, a critical load corresponds to a specific effect on a sensitive resource at a given time. However, ecosystems are dynamic in nature, and historical inputs of atmospheric deposition will affect the response of sensitive resources so that a critical load changes through time. Dynamic models address this problem by including a time component and have been used to estimate the critical load that will produce a specific effect at a specific time (Cosby et al. 1985a, 1985b, Johnson et al. 2000, Wright 2001, Larssen et al. 2003).

A critical load is often expressed in terms of the deposition required to induce a change to a chemical, physical, or biological indicator. For example, the response of aquatic ecosystems to deposition inputs is often described in terms of changes to acid-neutralizing capacity (ANC). The lake or stream is the sensitive resource, and ANC is the indicator. ANC is a measure of buffering capacity and is particularly useful as an indicator in calculating critical loads, because it can be linked to biotic response thresholds such as the condition and health of aquatic biota (Bulger et al. 2000, Henriksen and Posch 2001). Terrestrial ecosystem responses are a greater challenge to use in the development of critical loads. Terrestrial ecosystem indicators for which critical loads have been developed include soil carbon-to-nitrogen (C:N) ratio, soil solution aluminum-to-base-cation ratio, N leaching, and percentage base saturation. Links between changes to these indicators and effects of concern to federal area managers (e.g., reduced tree growth, reduced viability of threatened or endangered species, or changes in plant community composition) are not always available. However, these links are important if critical loads are to be used effectively to describe the condition of terrestrial resources.

In addition to resource information, data about current N and S loading rates are needed to make critical loads useful for evaluating deposition impacts. While wet deposition has been characterized at over 200 sites in the United States for over 20 years (Lamb and Bowersox 2000), important components for calculating total loading rates, such as dry deposition and cloud deposition, are labor-intensive and costly and, as a result, are not well quantified. For example, the Clean Air Status and Trends Network (CASTNet) estimates dry deposition rates for approximately 70 sites in the United States using an inferential model that requires input of extensive data on atmospheric concentrations of pollutants, meteorology, land use, vegetation, and surface conditions (Baumgardner et al. 2002). Cloud water chemistry has been measured at only a few sites, including three high-elevation sites in the eastern United States that were part of the Mountain Acid Deposition Program (Baumgardner et al. 2003). In contrast, relatively inexpensive throughfall measurements have commonly been used in Europe to determine total loading of deposition (Dise and Wright 1995, Bleeker et al. 2003) and are increasingly being used at sites in the United States. Throughfall deposition includes inputs from wet, dry, and cloud deposition and represents the deposition of pollutants through the canopy to the soil. Throughfall measurements are less labor-intensive and less costly than current dry and cloud deposition measurements and may be the method of choice in certain areas. However, throughfall measurements are best done under a canopy, and are not as effective in unforested areas, such as alpine and desert ecosystems. In addition, total N may be underestimated in throughfall because of canopy uptake (Fenn et al. 2003b). Total deposition can also be estimated with atmospheric models. Predicting deposition with these models has improved over time because of advances in predicting long-range transport, quantifying atmospheric emissions, and modeling chemical transformations (Fenn et al. 2003b).

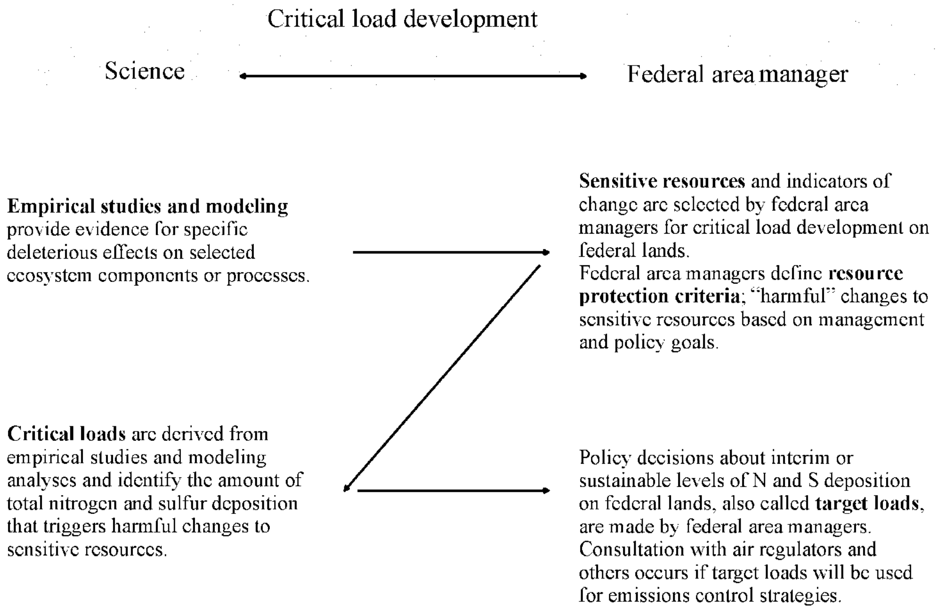
An additional step needed for critical loads to be accepted in the United States is to describe and quantify the levels of scientific uncertainty that are acceptable in establishing critical loads. Uncertainty still exists in understanding nutrient cycling and retention, and gradients in environmental conditions, for a large number of ecosystems in the United States. However, using the best available knowledge and systematically updating critical loads as new information becomes available may be a way of credibly proceeding with identification of critical loads even for those areas where uncertainty may be high.

Applying the concept of critical loads

Although there is no nationally coordinated strategy in the United States to develop and utilize critical and target loads, we believe that, based on federal land management and resource protection mandates, it is prudent to begin developing and using critical loads on a site-by-site basis to prevent future impacts, and remedy existing impacts, from N and S deposition on federal lands. The development and implementation of critical loads for resource protection on federal lands will best be accomplished by increased coordination between federal area managers and scientists to (a) identify resources sensitive to N and S deposition, (b) select resource protection criteria to meet management goals, and (c) estimate critical loads for sensitive resources. For critical loads to have maximum effectiveness, federal area managers should communicate land management goals to scientists to ensure that research and modeling efforts focus on resources of concern to federal area managers. The respective roles of federal area managers and scientists in developing critical loads are illustrated in figure 2. Scientists, using empirical and modeling approaches, identify potentially sensitive resources; federal area managers, guided by this scientific information, select sensitive resources of concern; federal area managers define harmful changes to those resources, guided by legal mandates and management goals to protect and preserve resources unimpaired for future generations; and scientists calculate critical loads for harmful changes to those sensitive resources.

The scientific literature provides information about the types of ecosystems and resources that may be sensitive to N and S deposition (Vitousek et al. 1997, Driscoll et al. 2001, 2003, Aber et al. 2003, Fenn et al. 2003a). These include ecosystems in the Rocky Mountains, the Cascades, the Sierra Nevada, southern California, and the Adirondack and Appalachian Mountains; other sensitive areas include the upper Midwest, New England, and Florida (Baker et al. 1990). Freshwater lakes, streams, ponds, and surrounding watersheds in these areas, including associated biota, may be vulnerable to acidification and nutrient enrichment. Shallow bays and estuaries along the Atlantic and the Gulf Coast may be sensitive to nutrient enrichment and eutrophication (Paerl et al. 2002, Galloway et al. 2003). Federal area managers can use this general information to identify ecosystems and resources on federal lands that are potentially sensitive to atmospheric deposition. Data on water and soil chemistry, bedrock geology, and biotic communities can be used to further refine inventories of deposition-sensitive resources.

These inventories will enable federal area managers to focus critical load development on the most sensitive resources. A critical load developed for the most sensitive resources should help protect all resources in the area. After identifying the most sensitive resources, the federal area manager selects resource protection criteria that conform to management goals to prevent significant harmful effects. Resource protection criteria are measures of physical, chemical, or biological indicators. For example, if a management goal for an area is to maintain healthy aquatic biota in freshwater lakes and streams, the federal area manager may select an ANC of 100–200 microequivalents (μeq) per liter (L) as the resource protection criterion. These levels have been cited as levels of ANC below which certain streams or lakes may be susceptible to acidification and subsequent harm to aquatic biota (Baker et al. 1990). Certain federal lands are not managed for their natural or wilderness characteristics, but rather for other purposes, including recreation and timber harvest. For these areas, resources and resource protection criteria may be



Empirical studies and modeling provide evidence for specific deleterious effects on selected ecosystem components or processes.

Sensitive resources and indicators of change are selected by federal area managers for critical load development on federal lands.
Federal area managers define **resource protection criteria**; "harmful" changes to sensitive resources based on management and policy goals.

Critical loads are derived from empirical studies and modeling analyses and identify the amount of total nitrogen and sulfur deposition that triggers harmful changes to sensitive resources.

Policy decisions about interim or sustainable levels of N and S deposition on federal lands, also called **target loads**, are made by federal area managers. Consultation with air regulators and others occurs if target loads will be used for emissions control strategies.

Figure 2. Conceptual diagram illustrating the roles of scientists and federal area managers in the development of critical and target loads. Abbreviations: N, nitrogen; S, sulfur.

selected to meet specific management goals, and may be different from those in national parks and wilderness.

When federal area managers and scientists have identified the most sensitive resource, or the resource of concern, and appropriate resource protection criteria that will prevent significant harmful effects, critical loads may be estimated by empirical, modeling, or experimental methods. In the absence of a nationally coordinated and supported program, individual federal agencies may use different approaches to critical load development, depending on available resource information and agency support. For example, USDA FS research scientists are collecting data at two demonstration sites (Fernow Experimental Forest, West Virginia, and Kings River Experimental Watershed, California) to test the European ICP model for calculating critical loads for terrestrial ecosystems. The ICP model may then be used to calculate critical loads for other areas. In Colorado, scientists are using empirical studies and modeling to calculate critical loads for sensitive ecosystems in Rocky Mountain National Park. In many areas across the country, federal and university scientists have used dynamic models, including PnET-BCG (Driscoll et al. 2001) and MAGIC (model for acidification of groundwater in catchments; Cosby et al. 1985a), to predict stream and lake chemistry response to deposition and to estimate critical loads. These areas include Absaroka Beartooth Wilderness, Montana; Fitzpatrick Wilderness, Wyoming; Grand Teton National Park, Wyoming; Joyce Kilmer Wilderness, North Carolina; Mount Rainier National Park, Washington; Rocky Mountain National Park, Colorado; Selway Bitterroot Wilderness, Montana; Sequoia National Park, California; Shenandoah National Park, Virginia; Shining Rock Wilderness, North Carolina; and Weminuche Wilderness, Colorado. For some areas, models were used not to estimate the absolute critical load for lakes and streams, but to estimate the deposition loading that would result in certain ANC end points over specified time periods. These time-based estimates are useful in setting recovery goals for areas where the critical load has been exceeded, or in evaluating the effects of proposed emission management strategies.

Case studies

Decades of research have been conducted at Shenandoah and Rocky Mountain National Parks to evaluate the effects of N and S deposition. Data on water, soils, and vegetation indicate that harmful changes have occurred to sensitive resources. The NPS has worked with scientists to identify resources that are most sensitive to deposition, according to the current state of science, and to select resource protection criteria consistent with congressional mandates, NPS policy, and management goals. Scientists are exploring methods of calculating critical loads for specific sensitive resources at each park. The following case studies illustrate the types of information and decisions that are needed to determine critical loads.

Rocky Mountain National Park. In the Colorado Front Range, decades of research document the effects of N deposition on terrestrial and aquatic ecosystems. Total annual atmospheric (wet and dry) N deposition at high-elevation sites in Rocky Mountain National Park ranges from 3 to 5 kg per ha (Baron et al. 2000), and total annual N deposition for the Colorado Front Range varies by site, from 2 to 7 kg per ha (Burns 2003). High-elevation sites throughout the Front Range show increasing trends in wet N deposition (Burns 2003). At several long-term study sites, empirical evidence shows that significant ecosystem changes attributable to N deposition have occurred. In Rocky Mountain National Park, changes in diatom species, lake ANC and nitrate concentrations, and forest soil and foliage chemistry in old-growth Engelmann spruce forests have been attributed to anthropogenic N deposition (Baron et al. 2000).

Many journal articles have been published on various aspects of the biogeochemistry of high-elevation ecosystems in the Colorado Front Range (*www.nrel.colostate.edu/projects/lvws/pages/publications/publications.htm*). Only one of these publications has recommended a critical load for acidification in the Colorado Front Range (Williams and Tonnessen 2000). None of the publications has suggested a specific critical load for nutrient (i.e., N) additions to high-elevation ecosystems in Rocky Mountain National Park, although a substantial body of literature documents ecological changes there that are attributable to N deposition. Nitrogen saturation, changes in soil and tree chemistry, and diatom community shifts have already occurred at deposition rates that are lower than those predicted to cause acidification (Williams et al. 1996, Baron et al. 2000, Fenn et al. 2003a).

To determine whether critical loads have been exceeded, it is necessary to decide which resources are "specified sensitive elements" and what "significant harmful effects" may be using the accepted definition for critical loads ("significant harmful effects on specified sensitive elements"; Nilsson and Grennfelt 1988). Scientists have identified resources in the park that are sensitive to deposition, including surface waters, aquatic biota, and high-elevation soils (see *www2.nature.nps.gov/air/Permits/ARIS/romo/index.htm*). Effects on these resources include elevated nitrate in lake waters; changes in the species composition of aquatic biota; and higher percentages of N, lower C:N ratios, and higher N mineralization rates in soils (Baron et al. 2000). Scientists are using lake sediment core analyses, water and soil chemistry data, and modeling to calculate the historical N deposition rate that induced these effects. The deposition rate that initiated harmful changes to sensitive resources would approximate the critical load for those resources. The NPS and the State of Colorado Department of Public Health and Environment are examining potential strategies for reducing N deposition in the park.

Shenandoah National Park. There is extensive documentation of S deposition and deposition effects on aquatic ecosystems in the Appalachian Mountains of the southeastern United States (Feldman and Connor 1992, Herlihy et al. 1993, Bulger et al. 2000). Perennial and intermittent streams have been identified by the NPS as sensitive resources for Shenandoah National Park (*www.nature2.nps.gov/air/Permits/ARIS/index.htm*) and by the USDA FS for wilderness areas in the southeast United States (*www.fs.fed.us/r6/aq/natarm*).

Research and monitoring at Shenandoah National Park have shown that long-term elevated levels of S deposition have resulted in chronic acidification of several streams and episodic acidification of others. Macroinvertebrate communities in low-ANC streams have been altered by changes in surface water chemistry. Modeling and bioassays suggest that several park streams have lost fish species because of anthropogenic acidification caused by S deposition (Sullivan et al. 2003). Impacts at Shenandoah National Park are typical of those found throughout the higher elevations of West Virginia and Virginia.

The critical S load for ANC loss has not been calculated for Shenandoah streams. However, recent dynamic modeling using MAGIC calculated a range of 45 different S deposition loadings that would result in various ANCs over different lengths of time in five streams that are very sensitive to deposition (table 1). These sensitive streams are poorly buffered as a result of bedrock geology (i.e., siliciclastic bedrock), and all have lost significant ANC. Their ANCs have decreased from preindustrial estimates of 66–91 μeq per L to 1990 measured values of 0–26 μeq per L (table 1). Average total S deposition in the park from 1988 to 1992 was 12.9 kg per ha per year. Total S deposition in the park over a recent 5-year period (1997–2001) averaged 10.4 kg per ha per year. The range of loads in table 1, from less than 0 to 22 kg per ha per year, represents the S deposition loads that would result in ANCs of 0, 20, or 50 μeq per L over 30, 50, or 110 years. A loading rate of less than 0 kg per ha per year indicates that, even if S deposition were to be reduced to zero, the ANC end point could not be achieved within the time period selected (Sullivan et al. 2003).

The data in table 1 can be used to suggest an interim target load for S in the park in order to reach resource protection goals. First, the resource protection criteria for the streams would have to be selected. ANCs of 0 or 20 μeq per L would most likely result in chronic or episodic acidification, conditions inconsistent with mandates for resource protection. Federal area managers, therefore, would probably select an ANC recovery goal of 50 μeq per L, since this protection criterion would have the greatest potential to yield "healthy aquatic biota" in these waters if recovery to this level could be attained (Bulger et al. 2000). Table 1 shows that a range in deposition rates for S of 0 to 4 kg per ha per year would restore some of the sensitive streams to an ANC of 50 μeq per L within 50 years. Although S deposition is declining, it significantly exceeds these rates, which would allow ANC recovery. In addition, the 50 μeq per L ANC considered to represent recovery does not restore the streams to their former ANC levels of 66–91 μeq per L (Sullivan et al. 2003). Modeling has not been done to calculate the actual critical loads for these streams (i.e., the level of deposition below which harmful effects would not have occurred). However, an interim deposition load may be used as a benchmark for progress in deposition reductions. Complete recovery of ecosystems altered by deposition may be unlikely even with deposition reductions, and monitoring over time will help determine whether goals for ecosystem recovery can be met. After 5–10 years, federal area managers and state air regulators could evaluate stream chemistry changes and adjust deposition loads needed for ANC recovery.

Table 1. Sulfur target loads for sensitive surface waters in Shenandoah National Park, based on dynamic modeling using MAGIC (model for acidification of groundwater in catchments) for acid-neutralizing capacity (ANC) end points and time frames.

	ANC (μeq per L)		Sulfur target load (kg per ha per yr)								
			ANC = 0			ANC = 20			ANC = 50		
Stream	**1990**	**Pre-1990**	**2020**	**2040**	**2100**	**2020**	**2040**	**2100**	**2020**	**2040**	**2100**
Meadow Run	0	69	9	9	9	2	5	6	< 0	< 0	1
Deep Run	2	78	14	13	12	5	8	9	< 0	< 0	3
Paine Run	7	91	16	15	14	11	11	11	1	4	6
Two Mile Run	16	81	20	17	15	11	12	11	< 0	1	5
White Oak Run	26	66	22	15	10	5	6	6	< 0	< 0	< 0

Note: Sensitive surface waters in the park are those on siliciclastic bedrock. A target load of < 0 indicates that the ANC end point could not be achieved within the time period selected even if sulfur deposition were reduced to 0 μeq per L.

Source: Sullivan et al. 2003.

Future directions for critical loads

Although federal area managers have begun to work with researchers to develop critical loads for sensitive resources at a few sites, critical loads need to be developed for many additional sites. The NPS manages 270 parks with significant natural resources, the USDA FS manages 155 national forests and 406 wilderness areas, and the FWS manages over 500 national wildlife refuges, including 71 wilderness areas. These areas have diverse ecosystems and site characteristics, and information on critical loads would be extremely valuable for each area. There are several issues that must be addressed in order to accomplish this:

- Federal area managers have identified sensitive resources and resource protection criteria for some areas, but need to complete the process for all areas that are sensitive to N and S deposition. In many cases, additional research and monitoring is needed to determine resource sensitivity and dose-response relationships.

- Information on aquatic resources and protection criteria is fairly robust. However, information on terrestrial resources is not as well developed. Although a number of suitable indicators have been identified for terrestrial ecosystems, researchers need to develop thresholds for specific ecosystems and indicators based on dose-response relationships.

- Acidification effects and indicators are well documented, but N enrichment effects and indicators are not as well developed. Research should identify indicators of N enrichment and site-specific dose-response thresholds for aquatic and terrestrial ecosystems.

- Appropriate models must be selected to develop critical loads for sensitive resources in aquatic and terrestrial systems. Models that take into account community interactions and food web effects may be useful for addressing complex ecosystems. Ecosystem monitoring should be conducted to collect data needed for optimal model performance.

- Methods for estimating total N and S deposition need refinement. Wet deposition is relatively well characterized, but dry deposition and deposition from fog and clouds are not as well quantified.

- Opportunities for using critical loads in air regulatory planning processes (e.g., review of new air pollution sources, Clean Air Act implementation planning, and development of secondary air pollution standards) at the local, state, and federal levels need to be discussed with EPA and state air regulators. Air regulatory agencies may have opportunities for maximizing ecosystem benefits (i.e., reducing N and S deposition) when developing plans for compliance with the Regional Haze Rule and air pollution standards for ozone and fine particulate matter.

- Federal area managers need to develop a systematic approach in working with federal and state regulators to select target loads in areas where critical loads have been exceeded and in areas where current deposition is below critical loads to provide a safety margin.

- Federal area managers should develop communication, education, and outreach tools to inform the public about cases where critical loads have been exceeded on public lands and about the subsequent effects on natural resources.

Conclusions

Critical and target loads for N and S deposition have been successfully developed and implemented in Europe, Canada, and other areas. They are used to evaluate resource condition, to establish benchmarks for resource protection and ecosystem recovery, and to set policy for reductions in air pollution emissions. We believe that critical loads can be used to protect resources on federal lands in the United States, and that sufficient information is available to develop critical loads for certain parks and wilderness areas. Scientific research on critical loads will be most useful to federal area managers when it specifically addresses sensitive resources and resource protection criteria and goals identified by federal area managers. Significant progress has been made by federal area managers in identifying these resources, criteria, and goals over the last decade. Milestones include (a) the development of the Federal Land Managers' Air Quality Related Values Work Group (FLAG) phase I report, (b) USDA FS regional workshops establishing general protection thresholds for aquatic resources, and (c) the development of USDA FS, NPS, and FWS Web sites describing air pollution–sensitive resources in many federal areas. Federal area managers recognize that establishing critical loads will be a dynamic process. The European experience shows that thresholds for N and S deposition may need to be adjusted as additional information becomes available regarding ecosystem thresholds and responses. Although current air pollution legislation in the United States does not directly link critical loads to air quality regulations, critical loads can be used to inform decisions about air pollution policy at local, state, and national levels.

Developing critical loads for federal lands will require a concerted effort by federal area managers and scientists. The current state of science, congressional mandates for resource protection, and agency goals provide the foundation for this effort. The success of this process will depend in large part on how well federal area managers communicate management goals to the research community, and how scientists design and conduct research to address these goals.

Of equal if not greater importance will be the collaboration between federal area managers and air regulatory agencies in incorporating critical loads into planning processes. The successful implementation of critical loads will depend on the federal area managers' ability to communicate resource protection goals and the value of critical loads to state and federal regulatory agencies, and on the response of those agencies. Federal area managers anticipate working with regulatory agencies to develop target and interim target loads, based on critical loads, to incorporate into air quality management decisions that will eventually result in the long-term health of ecosystems on federal lands for the benefit of future generations.

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