Critical loads as a policy tool for protecting ecosystems from the effects of air pollutants

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Framing the effects of air pollutants on ecosystems in terms of a "critical load" provides a meaningful approach for research scientists to communicate policy-relevant science to air-quality policy makers and natural resource managers. A critical-loads approach has been widely used to shape air-pollutant control policy in Europe since the 1980s, yet has only rarely been applied in the US. Recently, however, interest in applying a critical-loads approach to managing sulfur and nitrogen air pollutants in the US has been growing, as evidenced by several recent conferences, a new critical-loads sub-committee within the National Atmospheric Deposition Program, and nascent efforts by several federal agencies to apply critical loads to land management. Here, we describe the critical-loads concept, including some of its limitations, and indicate how critical loads can better inform future air-pollutant control policy in the US.

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The concept of a "critical load" can facilitate communication between scientists who study the effects of air pollutants on ecosystems and those responsible for air-quality management and policy. Stated simply, a critical load (CL) is "the quantitative exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur, according to present knowledge" (Nilsson and Grennfelt 1988). Exceeding the CLs for nitrogen (N) and sulfur (S) can cause ecosystem acidification, nitrogen saturation, and biotic community changes, including a decline in forest health. Quantifying the pollutant loads at which a variety of ecosystem changes have occurred or may occur in the future can be a valuable method for characterizing ecosystem condition in a way that informs air-pollution control policy and program development, implementation, and assessment (Figure 1).

A CL approach to assessing air-pollution impacts has been used to evaluate the effects of acid precipitation on ecosystems in Canada and Europe since the 1980s. In Europe, this approach was formally adopted as a guiding principal in air-pollution management and policy, as part of the 1988 Sofia Protocol on the control of emissions of nitrogen oxides. The European CL approach also typically involves the calculation of a target load (ie target load, as the term is used in policy, not target-load functions, as it is known to CL modelers), which is determined by political agreement, and may be greater than or less than the critical load (Porter *et al*. 2005).

Thresholds of atmospheric-pollutant deposition for sensitive ecosystems in the US have been widely discussed in the scientific literature, beginning in the 1990s for sulfur (Gorham *et al*. 1984; Henriksen and Brakke 1988) and nitrogen (Aber *et al*. 1989). This work established that sulfate and nitrogen deposition were above levels at which damage occurs in many sensitive ecosystems in eastern North America. Although an extensive body of scientific literature was available at the time that policy makers were discussing how to address acid-rain effects, a CL approach was never formally incorporated into the Clean Air Act Amendments of 1990. Such an approach has yet to be broadly and formally applied to air-pollution control policy in the US (as it has in Europe and Canada), where it remains a potentially important but largely untapped tool for assessing ecosystem response to atmospheric deposition and for developing policies to promote ecosystem protection and recovery (Porter *et al*. 2005). While scientific studies of CL continue to be published in the US, most have a narrow geographic focus (Pardo and Driscoll 1996; Sullivan *et al*. 2003; Baron 2006).

In a nutshell:

- The critical load for an air pollutant defines a deposition level below which sensitive parts of an ecosystem are protected
- Critical loads have been widely and successfully applied in Europe and Canada, but not in the US
- Recent activity in the scientific and policy communities indicates increasing interest in applying critical loads in the US

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How CL can be applied to air-pollution control policy

CLs have primarily been applied to the atmospheric deposition of sulfur (S) and nitrogen (N), but the European community has applied a similar critical-levels approach to managing tropospheric ozone, as well as trace metals (Sliggers and Kakebeeke 2004). A CL approach could conceivably be used to manage the deposition of any air pollutant for which demonstrated ecological effects and thresholds can be determined, but here we will focus on its application in the case of atmospheric S and N deposition.

Atmospheric S and N are of concern because of their role in acidifying sensitive aquatic and terrestrial ecosystems (Driscoll *et al.* 2001). N deposition can also exceed the assimilation capacity of ecosystems (a condition commonly known as "N saturation") and can contribute to (1) the eutrophication of estuarine and alpine waters (Paerl 1997; Wolfe *et al.* 2003), and (2) shifts in species composition in alpine plant communities (Bowman *et al.* 2006), semi-arid coastal sage shrub communities (Egerton-Warburton and Allen 2000), and serpentitic grasslands (Weiss 1999). Acidification strips the base cations calcium and magnesium from sensitive soils, and replaces these cations with aluminum, which can cause stress and increase mortality in some tree species (Driscoll *et al.* 2001). Acidification of aquatic habitat eliminates sensitive organisms, including many species of fish, zooplankton, invertebrates, and diatoms (Schindler *et al.* 1989). Effects of excess N deposition are of great concern in the western US, and include shifts in terrestrial and aquatic species (Fenn *et al.* 2003) as well as indirect effects, such as increased susceptibility of these species to insects and disease (Throop and Lerdau 2004). In the eastern US, concerns include both acidification and N saturation (Aber *et al.* 1989; Figure 2).

Figure 1. *Coal-fired power plants are the principal source of the sulfur dioxide and nitrogen oxide emissions that are transported from upwind locations such as the Ohio River Valley, where they fall as acid precipitation in the mid-Atlantic and northeastern states. Recovery and protection of sensitive ecosystems in upland parts of these states has been a principal focus of critical-loads research in the US.*

Several of the aforementioned ecological changes in terrestrial and aquatic ecosystems resulting from S and N deposition readily lend themselves to a CL approach. For example, many aquatic organisms cannot thrive and successfully reproduce below certain pH values or above certain aluminum concentrations. Surface waters that become acidified to below-threshold pH values tend to lose these acid-intolerant species (Schindler *et al.* 1989). Commonly, either empirical data or models are used to predict the atmospheric N and S deposition rates that will allow the recovery of various species of interest in sensitive waters. In this manner, ecotoxicological data are combined with biogeochemical data and models to provide CL values to managers and policy makers. Scientists also know that simple atmospheric dose-responses and thresholds do not exist for some organisms in certain settings, either because key biogeochemical processes are not well understood or because of complex interactions among environmental variables that affect the survival of a given species or community. Also, landscape disturbance history (Foster *et al.* 1997), as well as a range of environmental stressors in addition to atmospheric deposition, can affect CL values, especially for nitrogen (Smithwick *et al.* 2005). In such situations, a range of CL values may be the best information that scientists can provide to policy makers.

Language does not exist in the Clean Air Act and its subsequent amendments that specifically permits the use of a CL approach, despite the tremendous potential for this approach to simplify complex scientific information

Figure 2. *Atmospheric deposition of sulfur and nitrogen has adversely affected aquatic fauna in many locations. Here, a scientist collects a kick sample of aquatic macroinvertebrates to evaluate ecosystem recovery from levels of acid deposition that have been decreasing in the northeastern US since the late 1970s.*

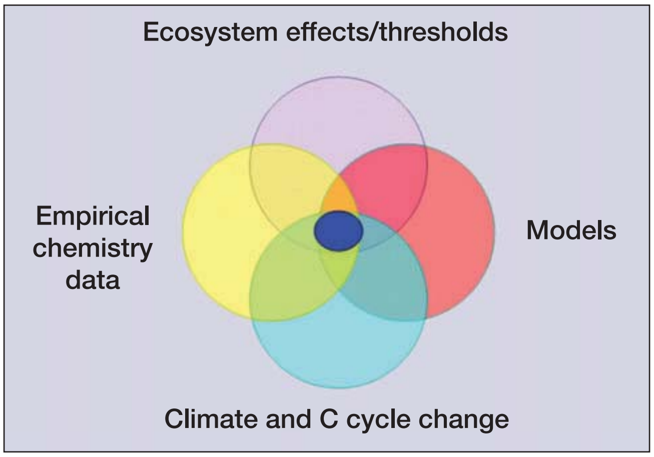

Figure 3. *A variety of scientific information on ecosystem effects and thresholds, empirical chemistry data, model results, and projected changes in climate and the carbon cycle are needed to determine critical loads of sulfur and nitrogen deposition. The air-quality and land-management policy communities lie within the dark blue oval at the intersection of these various sources of scientific information, where politically realistic target loads are developed and implemented.*

and effectively communicate it to the policy community. We believe that, despite a lack of statutory authority, the CL approach simply provides another lens through which to assess the results of current policies and programs and to evaluate the potential ecosystem-protection value of proposed policy options. Managers and policy makers must each decide how to incorporate CL information into policy evaluation and planning. For example, policy makers can translate a CL value into a target load of S or N deposition in a given region or ecosystem. This target load could be higher or lower than the CL, and might be based on the political and budgetary constraints within which air-quality managers must operate.

Recent developments

Recent efforts suggest that the attitude toward CL in the US may be changing. For example, between 2002 and 2006, several federal agencies convened conferences and workshops to review European CL experiences, discuss CL science and modeling efforts, and to explore the possible future role of CL in air-pollution control policy in the US. As a result of these meetings, agencies such as the National Park Service and US Forest Service developed specific recommendations for using CL as a tool to assist in managing US federal lands. More recently, a new CL ad-hoc subcommittee has formed within the National Atmospheric Deposition Program (NADP; http://nadp.sws.uiuc.edu/clad/). This sub-committee will promote information-sharing, scientific advances, and applied projects in an effort to explore the potential uses of CL in policy development and program implementation (Figure 3).

In 2004, the National Research Council recommended that the US Environmental Protection Agency (EPA) should consider using CL for ecosystem protection. In 2005, the EPA included in their Nitrogen Dioxide Increment Rule a provision that individual states may propose the use of CL information as part of their air-quality management approach, in order to satisfy requirements under Clean Air Act provisions regarding "prevention of significant deterioration" (US EPA 2005).

Several federal agencies, including the National Park Service and US Forest Service, are employing CL approaches to protect and manage sensitive ecosystems (Porter *et al.* 2005). For example, in Rocky Mountain National Park, Colorado, the National Park Service (NPS) has entered into a Memorandum of Understanding (MOU) with the Colorado Department of Public Health and Environment (CDPHE) and the EPA to address harmful impacts to air quality and other natural resources occurring in the Park and to reverse a trend of increasing nitrogen deposition. The MOU requires NPS to develop a resource management goal to protect Park resources and requires the CDPHE to develop an air management strategy that will help to meet Park goals. Based on research results that indicate deleterious effects on natural resources from current levels of atmospheric N deposition (Wolfe *et al.* 2003), NPS has established a resource-management goal, linked to a critical load for wet N deposition of 1.5 kg ha^{-1} yr^{-1} for high elevation aquatic ecosystems (Baron 2006). The Colorado Air Quality Control Commission has also established a "Rocky Mountain National Park Initiative Sub-committee" to involve stakeholders, review the research, identify information

Courtesy of J Marr, Niwot Ridge Long-Term Ecological Research site archives

Figure 4. *To apply a critical loads approach, scientists must know the current levels of atmospheric sulfur and nitrogen deposition. These values can be difficult to quantify, especially in high-altitude settings, such as that pictured here at Niwot Ridge, CO, where wind and extreme cold test the ability of instruments to document atmospheric loads. Photo taken at the D-2 Meteorological Station, ca 1953.*

needs, and discuss options for improving conditions in the Park (Figure 4).

Links to greenhouse gases and climate change

According to the Intergovernmental Panel on Climate Change (IPCC), human activities are primarily responsible for increased concentrations of greenhouse gases, such as CO_2, in the atmosphere, and these increases have caused the Earth's climate to warm substantially since the early 20th century (IPCC 2007). The IPCC further concludes that continued warming is likely, even if greenhouse-gas emissions remain constant. These conclusions have important implications for deriving critical loads for S and N, because the cycles of these elements have strong interactions with climate and the carbon cycle; the emission, transport, and cycling of S and N in the atmosphere and through ecosystems are affected by, and in turn affect, the climate and cycles of greenhouse gases (Brasseur and Roekner 2005; Magnani *et al.* 2007). Therefore, any future CL projections for S and N based on models should take into account these projected future changes in climate and the carbon cycle.

Conclusions

Given the acknowledged success of CL approaches in Europe, the US air-pollution science and air-quality policy communities should explore greater use of this policy-assessment and resource-management approach in the future. We would like to encourage greater research and application of CL in the science and policy communities in the US, welcome broad participation in the open-attendance CL ad-hoc sub-committee at NADP, and invite others to join us in 2008 for a planned multi-agency CL workshop. Those who are interested should check the NADP web site (http://nadp.sws.uiuc.edu/CLAD/) for further updates and information.

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