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FOCUS: A pilot study for national-scale critical loads development in the United States

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ABSTRACT

The development and use of critical loads of air pollutant deposition in the U.S. is gaining momentum, and recent research efforts in the U.S. have produced valuable data for calculating critical loads. Critical loads are used to quantify the levels of air pollutants that are expected to impact forest health, soil fertility, aquatic biota condition, and other ecosystem responses. In addition, model refinements for improving critical loads estimates, and maps for illustrating critical loads for acidification and nitrogen saturation and eutrophication resulting from excess nutrient nitrogen, have been developed at various scales. However, prior to the effort described here, no cohesive process existed to provide a national-scale critical loads database and maps as a unified product representing all U.S. ecosystems. The FOCUS (Focal Center Utility Study) Project was initiated to coordinate the development and implementation of a clear, consistent, repeatable process for calculating and mapping critical loads within the U.S. In the FOCUS Phase I Pilot Study, empirical and calculated critical loads data for the U.S. were synthesized from dozens of regional and national-scale monitoring networks, research projects and publically available databases following an approach similar to that used in Europe. The United Nations Economic Commission for Europe (UNECE), through its International Cooperative Programme on Modelling and Mapping of Critical Levels & Loads and Air Pollution Effects, Risks and Trends (ICP-M&M) collects, analyzes and maps critical loads data. Countries participating in the Convention on Long-range Transboundary Air Pollution (CLRTAP) use a Critical Loads "Focal Center" in each country to serve as the point of contact for submitting regional and national-scale critical loads data to the ICP-M&M. One of the purposes of this study was to develop a foundation for interacting with other Focal Centers by assembling critical loads data, creating a database, establishing modeling protocols, and developing infrastructure within the U.S to report and update critical loads on a national scale. Because the U.S. does not currently have an officially designated Focal Center, critical loads data were provided as an informal, unofficial submission to the Coordination Center for Effects (CCE) of the ICP-M&M in March 2011, in the interest of international cooperation and exchange of information on the effects of atmospheric deposition of pollutants on ecosystems. We envision that

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these data will enable U.S. scientists, land managers, and environmental policymakers to enter into a productive and meaningful dialogue within the US, and also with the international scientific community on methods for estimating, calculating, mapping, interpreting, and refining critical loads for the effects of acidification and excess nutrient nitrogen on terrestrial and aquatic ecosystems. This paper describes the process used to develop national-scale critical loads in the U.S., summarizes the FOCUS Phase I approach and database development effort, and presents some initial national-scale critical loads mapping products.

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1. Introduction

1.1. *Development of a U.S. critical loads approach*

Air pollution impacts on sensitive ecosystems in the United States (U.S.) have been widely documented at local and regional scales; impacts include acidification due to nitrogen (N) and sulfur (S) inputs, eutrophication, declines in plant health, alterations in species composition, and increases in invasive species (Baron et al., 2000; Driscoll et al., 2003; Fenn et al., 2003; Pardo et al., 2011a). However, systematic use of the data to inform air quality and land management policies has not yet been achieved on a national basis. Although a critical loads framework for the U.S. was proposed in the early 1990s (Hunsaker et al., 1993; Strickland et al., 1993), implementation has only recently become possible now that comprehensive and integrated datasets are accessible (U.S. EPA, 1995). Several recent assessments are now available which provide sufficient data to inform policy and land management applications of critical loads (Baron et al., 2011; Burns et al., 2011; Pardo et al., 2011a,b).

Following a series of critical loads workshops held in the U.S. from 2003 to 2005, the Critical Loads of Atmospheric Deposition Science Committee (CLAD) under the National Atmospheric Deposition Program (NADP) was formed in 2006 to facilitate enhanced collaboration on critical loads topics (Burns et al., 2008). While CLAD has been successful in providing a communications venue for scientists, land managers, air quality regulators, and others working on developing critical loads, CLAD discussions early on revealed that most of the U.S. efforts to develop critical loads were disjointed: data were scattered amongst universities, agencies and others, various methodologies were utilized, and impacts were assessed at different scales. CLAD members concluded that the next frontier in U.S. critical loads progress should be to develop a comprehensive, national-scale critical load database and maps. They recommended that synthesis be conducted of multiple critical loads research efforts across the country, and protocols developed to provide a consistent approach to critical loads that would be useful in policy and land management decision-making.

1.2. *International collaboration*

CLAD established early on that efforts to assemble critical loads information for the U.S. into a comprehensive database would be most effective and efficient if the expertise and experience of others who had conducted similar previous assessments could be engaged. CLAD's collaborative work with the United Nations Economic Commission for Europe International Cooperative Programme on Modelling and Mapping of Critical Loads and Levels and Air Pollution Effects, Risks and Trends (ICP-M&M) highlighted the advantages in adapting protocols and processes for critical loads (UBA, 2004) and coordinating approaches with the European effort (CCE, 2011). The process the ICP-M&M employs to collect, analyze, and map critical loads data from participating countries utilizes a "Focal Center" in each country to serve as a point of contact for regional and national-scale critical loads data. CLAD initiated the FOCUS project as a small scale prototype of a U.S. Focal Center to coordinate and manage the development and implementation of a clear, consistent repeatable process for standardized, mappable critical loads within the U.S. Iterative collaboration between scientists and researchers from public and private institutions was employed to assemble existing critical loads and acquire data that could be used to calculate additional critical loads to produce a national critical loads database. As a result, these critical loads and supporting information were provided to the ICP-M&M Coordination Center for Effects (CCE) in March 2011 (CCE, 2011).

1.3. *Assessment goals*

Critical loads are currently being utilized as an approach in the U.S. to simplify complex scientific information and effectively communicate air pollution thresholds for ecosystems to the policy community and the public (Burns et al., 2008, 2011). Federal land managers and air quality regulators are increasingly relying on critical loads frameworks to quantify the levels of air pollutants that are expected to impact forest health, soil fertility, aquatic biota condition, and other ecosystem responses (Burns et al., 2011; Porter et al., 2005). In addition, activities utilizing current and exploring future uses of critical loads in decision making processes are increasing, such as setting of air quality health and welfare standards, exploring options for multi-pollutant strategies, developing land management plans, and developing site specific goals for natural resource protection from air pollutant emissions. Efforts are also underway by NADP to develop estimates of total deposition (wet and dry), for the U.S., based on monitored and modeled data, which will enable more accurate calculation of critical loads exceedances. The

Table 1 – Definitions of critical load terminology.

Acidification	The process by which pH of water or soil solution declines
Acid neutralizing capacity (ANC)	Ability of a solution to neutralize inputs of strong acid to a preselected equivalence. An important chemical parameter used in critical loads calculations.
Biological indicator	Selected organism(s) or population sensitive to chemical effects resulting from changing loading of deposition
Chemical criterion	The chemical parameter (e.g. ANC; ratio of base cations to aluminum) used to assess biological response
Critical threshold	The value of a critical chemical parameter, or combination of parameters, that does not cause a significant harmful response in a biological indicator
Eutrophication	The process by which a body of water becomes enriched in dissolved nutrients that stimulate the growth of aquatic plant life
Nitrogen saturation	The availability of mineral nitrogen in excess of biotic demand

effort described here represents the first coordinated work by the U.S critical loads community to develop a comprehensive national-scale critical loads database and maps that will help assess the extent of current and future risk of acidification of forest soils and surface waters; and the extent of current and future risk of excess nutrient nitrogen to eutrophication of surface waters and changes in aquatic and terrestrial biodiversity.

2. Methods

Existing data and information on critical loads were solicited for this effort through a call for critical load data and supporting information by CLAD to U.S. researchers, particularly staff from the National Park Service (NPS), the U.S. Forest Service (FS), the U.S. Environmental Protection Agency (EPA), university faculty, and environmental monitoring consultants. The call for data focused on obtaining steady-state calculated critical loads for acidity of surface waters and forest ecosystems, and empirical critical loads for nutrient nitrogen in natural areas (agricultural and urban lands were excluded).

Critical loads were compiled from a variety of sources representing different spatial scales. Detailed metadata describing differences in assumptions, methodologies, data origins, and modeling protocols were also obtained and are described in more detail in Lynch et al. (2013). Definitions of key critical loads terms are provided in Table 1. The following sections provide an overview of the data sources, models, and significant input variable choices that were selected to facilitate development of the database and the first approximation national-scale maps depicting U.S. critical loads.

2.1. *Aquatic critical loads for acidity*

Over 9500 steady-state critical loads for acidity of surface waters for streams (40%) and lakes (60%) are represented in the database. In some regions of the U.S., aquatic critical loads had already been calculated in previous studies. The critical loads for these 1470 locations were based on three different approaches for estimating base cation weathering: modified F-factor (Miller, 2011), regional regression model (McDonnell et al., 2012), and the MAGIC model (Sullivan et al., 2010). Where water quality data were available but critical loads had not yet been determined, a modified F-factor approach (Brakke et al., 1990; U.S. EPA, 2009a,b) was used. For sites with multiple sample dates, water quality data means from the most recent five years of measurements were used to calculate critical loads. Data were obtained primarily from the U.S. Geological Survey; the U.S. Forest Service Air Program; and the EPA's Long Term Monitoring (LTM) sites, regional lake surveys, Environmental Monitoring and Assessment (EMAP) Evaluations, and National Stream Surveys (NSS) (Table 2). Basic water quality information needed for estimating critical loads includes: base cations (Ca^{2+}, Mg^{+}, K^{+}, and Na^{+}), acid anions (SO_4^{-} and NO_3^{-}), and surface water runoff (m/year). The sites in the database represent a wide range of acid neutralizing capacity (ANC) from −101 to 20,529 microequivalents per liter (μeq/L) with an average value of 575 μeq/L. Lakes and streams with SO_4^{2-} values > 400 μeq/L were screened out to avoid water bodies affected by acid mine drainage. The critical threshold used for all aquatic critical loads modeling was an ANC of 50 μeq/L based on providing overall ecosystem protection from expected ecological effects to aquatic biota (Driscoll et al., 2001) as described in Table 3.

2.2. *Terrestrial critical loads for acidity*

Critical loads of acidity for forest ecosystems included in the FOCUS database were calculated by McNulty et al. (2007) and Duarte et al. (2011, 2013) using a steady-state Simple Mass Balance (SMB) model described in detail elsewhere (UBA, 2004). Critical loads of acidity were calculated by McNulty et al. (2007) for forested lands across the continental U.S. using a geographic information system (GIS) approach where each SMB model parameter was represented by geospatial data on a 1 km^2 grid system. Duarte et al. (2013) calculated critical loads of acidity at roughly 4000 sample sites within the northeastern U.S.

Although the model is "simple," parameterization is fairly complex. Two parameters that most influence the critical load calculation are base cation weathering and the critical ANC leaching rate. Base cation weathering was estimated using the clay correlation substrate method (Sverdrup et al., 1990). Selection of the chemical criterion and critical threshold that relate to a desired threshold of resource protection is key to the critical load calculation. For forest ecosystems, the commonly utilized chemical criterion is the ratio of base cation concentration [BC] to aluminum concentration [Al] in soil solution because it represents the level below which decreased growth and/or harm to sensitive tree species may occur (McNulty et al., 2007). This ratio is used to determine the

Table 2 – Water quality data sources used to develop surface water critical loads.

Program name, sampling period	Collecting group	Web link	References	Number of points
EPA long term monitoring (LTM) – Adirondacks – annual average from 1992 to 2010	ALSC	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	60
EPA long term monitoring (LTM) – Maine – annual average 1992–2007	UNH	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	30
EPA long term monitoring (LTM) – Vermont – annual average 1992–2007	State of VT	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	37
EPA long term monitoring (LTM) – Catskills – annual average 1992–2007	USGS	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	4
EPA long term monitoring (LTM) – Pennsylvania – annual average 1992–2007	PSU	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	5
EPA long term monitoring (LTM) – VTSSS – annual average 1992–2007	UVA	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	68
EPA long term monitoring (LTM) – Upper Midwest	EPA	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Eilers et al. (1988)	28
EPA long term monitoring (LTM) – Colorado	EPA	http://www.epa.gov/airmarkt/assessments/TIMELTM.html	Stoddard et al. (2003)	10
Eastern Lakes Survey dataset (ELS) 1984	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/els.html	U.S. EPA (1988a)	1564
EPA-EMAP Northeast Lake Survey 1991–1994	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/nelakes.html	U.S. EPA (1993)	322
EPA Regional EMAP (RMAP) Program 1993	EPA	http://www.epa.gov/emap2/remap/html/one/data/index.html	DiFranco et al. (1995)	333
EPA-EMAP Mid-Appalachian Highland Assessment (MAHA) 1994–1996	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/mastreams/9396/index.html	U.S. EPA (2000)	433
EPA-EMAP Mid-Atlantic Integrated Assessment (MAIA) 1997–1998	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/mastreams/9798/index.html	Stoddard et al. (2005a)	131
EPA National Stream Survey (NSS) 1986	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/nss.html	U.S. EPA (1988b)	844
Virginia Trout Stream Sensitivity Study (VTSSS) Surveys 1987 and 2000	UVA	http://swas.evsc.virginia.edu/		366
EPA National Wadeable Stream Survey (WSA) 2007	EPA	http://www.epa.gov/owow/streamsurvey/web_data.html	U.S. EPA (2006)	771
EPA Western Lake Survey (WLS) 1985	EPA	http://www.epa.gov/emap2/html/data/surfwatr/data/wls.html	Eilers et al. (1987) and U.S. EPA (1987)	704
EPA-EMAP Western Stream & River Survey 2000–2004	EPA	http://www.epa.gov/esd/land-sci/water/streams.htm	Stoddard et al. (2005b)	180
EPA National Lake Survey 2010	EPA	http://www.epa.gov/lakessurvey	U.S. EPA (2009a)	753
USFS Forest Service Water Quality Data	USFS	http://views.cira.colostate.edu/web/SiteBrowser/fswq.aspx		1772
USGS Water-Quality Data for the Nation	USGS	http://waterdata.usgs.gov/nwis/qw		1975
Washington/Oregon Coastal Streams and Yakima River Basin 1994–1995	EPA	http://www.epa.gov/emap2/remap/html/ten/data/		44
Multiagency Critical Loads Research Project: Virginia and West Virginia	E&S Environmental Chemistry	http://www.esenvironmental.com/projects_multiagency.htm	Sullivan et al. (2010) and Driscoll et al. (2001)	515
Multiagency Critical Loads Research Project: Northeast	Ecosystems Research Group, Ltd.	http://www.ecosystems-research.com/index.htm	Miller (2011)	1423

Table 3 – Aquatic status categories in the U.S. (Burns et al., 2011; U.S. EPA, 2009b).

ANC levels	Expected ecological effects
<0 microequivalents per Liter (μeq/L)	Complete loss of fish populations is expected. Planktonic communities have extremely low diversity and are dominated by acidophilic forms. The numbers of individuals in plankton species that are present are greatly reduced.
0–20 μeq/L	Highly sensitive to episodic acidification. During episodes of high acid deposition, brook trout populations may experience lethal effects. Diversity and distribution of zooplankton communities declines sharply.
20–50 μeq/L	Fish species richness is greatly reduced (more than half of expected species can be missing). On average, brook trout populations experience sub-lethal effects, including loss of health and reproduction (fitness). Diversity and distribution of zooplankton communities decline.
50–100 μeq/L	Fish species richness begins to decline (sensitive species are lost from lakes). Brook trout populations are sensitive and variable, with possible sub-lethal effects. Diversity and distribution of zooplankton communities begin to decline as species that are sensitive to acid deposition are affected.
>100 μeq/L	Fish species richness may be unaffected. Reproducing brook trout populations are expected where habitat is suitable. Zooplankton communities are unaffected and exhibit expected diversity and distribution.

critical ANC leaching rate applied in the SMB equation. McNulty et al. (2007) used a molar [BC]:[Al] ratio of 1 for deciduous forests and 10 for coniferous forests, Duarte et al. (2013) used a molar ratio of 10 for all forest types. The critical chemical threshold of 10 was selected to be more protective of the forest ecosystems (Pardo et al., 2011b) and in general would result in a lower calculated critical load.

2.3. *Empirical critical loads of nitrogen*

The database was populated with empirical (observation-based) critical loads of nitrogen from two primary sources. Critical load values for mycorrhizal fungi, herbaceous vegetation and shrubs, and forest ecosystems were based on a variety of different types of responses to nitrogen deposition inputs as summarized in Table 4 (Pardo et al., 2011a,c). A geospatial analysis was conducted to describe these critical loads for each Level 1 ecoregion (adapted from the classification for North America by Omernik (1987). Ecological regions at the coarsest level (Level I) in the U.S. include: Tundra, Taiga, Northern Forests, Northwestern Forested Mountains, Marine West Coast Forests, Eastern Temperate Forests, Great Plains, North American Deserts, Mediterranean California, Southern Semi-Arid Highlands, Temperate Sierras, and Tropical Wet Forests.

Empirical critical loads of nitrogen for lichens were determined using the approach described in Geiser et al. (2010). This methodology uses ''air scores'' which mark the transition from natural ''clean air'' to polluted air for each Level 1 ecoregion as determined by shifts from oligotroph to eutroph-dominated lichen communities. Lichen critical loads for nitrogen were calculated using the minimum threshold air scores, by ecoregion, combined with the annual average precipitation from each 4 km × 4 km grid cell estimated through geospatial analysis (PRISM, 2010). Average annual precipitation amounts were determined using 1961–1990

Table 4 – The range of empirical critical loads of nitrogen for each ecoregion summarized from Pardo et al. (2011a). Biological and chemical indicators used to determine the critical loads are described in each column. The low end of the range was used in developing the critical loads map shown in Fig. 3a. ''>'' and ''<'' symbols indicate that critical load estimates are based on gradient studies where the inflection point of ecosystem impact was not clear. The symbol ## estimates the critical loads as ''reliable;'' # as ''fairly reliable;'' and (#) as ''expert judgment (Pardo et al., 2011a; UBA, 2004).

Ecoregion level I	Empirical critical loads for N (kg/ha/year)		
	Mycorrhizal Fungi (changes in community structure; or declines in fungal diversity or activity)	Herbaceous species and shrubs (changes in foliar nitrogen, cover, or community composition; loss of species; decline in native forbs; or increased invasive grasses)	Forest ecosystems (nitrate leaching; changes in forest root biomass; decreased tree growth or survivorship; increased foliar nitrogen; net nitrogen mineralization; crown thinning; or chlorotic foliage)
Tundra		1–3 ##	
Taiga	5–7 (#)	6 ##	
Northern Forests	5–7 #	>7 and <21 #	>3 #
Northwestern Forested Mountains	5–10 (#)	4–10 ##	4 ##
Marine West Coast Forests	5 (#)		5 ##
Eastern Temperate Forests	5–10 (#)	<17.5 (#)	>3 #
Great Plains	12 (#)	5–15 #	
North American Deserts		3–8.4 #	
Mediterranean California	7.8–10 #	6 ##	17 N/A
Tropical Humid Forests			<5–10 (#)

climatic normals (arithmetic average over a 30 year period) at 4 km resolution. Lichen critical loads ranged from 2.7 to 9.2 kgN/ha/year.

2.4. *Critical load maps*

Critical loads for each category (modeled acidity for surface waters, or forests, or empirically derived effects of excess nutrient nitrogen) were mapped at 12 km × 12 km or 36 km × 36 km resolution. Scales were chosen to match map grids used in EPA deposition modeling and to be large enough for multiple critical load values to fall within a given grid cell. Critical loads of acidity for forest ecosystems and empirical critical loads for nutrient nitrogen were mapped at the 12 km × 12 km grid scale. Aquatic critical loads were mapped at the 36 km × 36 km scale to allow for more critical loads per grid cell which serves to enhance the display quality. The average and minimum critical load values within each grid cell were calculated and mapped by category.

The number of critical load values averaged per cell grid varied depending on the category of critical load. The number of critical load values per grid for aquatic acidification depended on the number of water quality sampling points located in a particular grid cell. For forest ecosystems, critical loads for acidity were calculated using all values present within each 4 km × 4 km grid. There were more values in the northeastern U.S. where both McNulty et al. (2007) and Duarte et al. (2011) calculated critical loads of acidity, than for other locations in the U.S. For empirical critical loads of nitrogen the minimum values for all receptors within a 4 km x 4 km grid cell were combined to create the composite average or minimum values that were mapped. Minimum values were used to create these initial maps because land managers were particularly interested in understanding critical loads for the most sensitive species. The number of values per grid for empirical critical loads of nitrogen was extremely variable as data from many different research and monitoring efforts characterizing effects on mycorrhizal fungi, lichens, herbaceous vegetation and forests were utilized. For empirical critical loads of nitrogen, urban and agriculture areas were excluded from the mapped area (shown as white areas) using the National Land Cover Database (NLCD, 2001).

3. Results

The FOCUS Phase I project created a database that contains 365,053 estimates of empirical critical loads for nitrogen (mapped into the 92,400 grid cells that make up the 12 × 12 grids across the continental U.S.); 242,670 estimates of forest acidification critical loads for sulfur and nitrogen; and 124,476 surface water acidification critical loads for sulfur and nitrogen. Maps in this report have been created to illustrate a range of possibilities of maps that could be developed based on the existing critical loads data in the database. The maps in Figs. 1 and 2 represent minimum and averaged aggregated critical loads estimates for acidity for surface waters and forest ecosystems. The maps in Fig. 3 represent minimum and averaged empirical critical loads for nutrient nitrogen based on the range of values present in each grid cell. The choice of statistical indicator (e.g. average, minimum) used to develop critical loads maps from the database is dependent upon the purpose of the map, and the amount of available data. For the analyses described here, minimum values were used to depict potential impacts to the most sensitive resources. Average values were selected to reduce the effect of the higher uncertainty surrounding some critical loads. Percentiles (i.e. 95%, as is used in many European critical loads map products to illustrate the critical load at which 95% of the water bodies in the grid cell do not exceed critical thresholds) were not calculated or mapped in this analysis for two reasons: many biological and chemical indicators did not have a sufficient number of data points across regional and national spatial scales to reliably develop these estimates, and because selection of the desired percentile (e.g. 98%, 95%, 90%) is a policy decision that has not yet been agreed upon in the U.S. Displaying average and minimum values as map products is particularly elucidating to natural resource managers and air regulators because it illustrates how policy strategies might differ if emissions reductions efforts focused on protecting average critical loads, or the most sensitive resources (lowest critical loads) from deposition impacts. For example, the surface water acidification maps show a clear pattern of higher sensitivity (low critical loads) in mountainous areas across the country using minimum values (Fig. 1a), while spatial patterns are less pronounced using the average values for surface water acidification (Fig. 1b). This difference helps policy makers better understand the extent to which emissions reduction strategies are likely to improve the condition of natural resources.

4. Discussion

Developing a unified approach to deliver national scale critical load data and maps is important in a variety of ways. It facilitates international exchange of critical loads information between U.S. and European scientists; it supports the longer-term goal of federal agencies implementation of critical loads in their land management and regulatory programs; and it assists in improving our understanding of large-scale linkages between air pollution and ecosystem effects in the U.S. The FOCUS Phase I effort and submission to the 2011 CCE "Call for Critical Loads Data" was important because it provided a catalyst to begin comprehensive database development and established a foundation for future refinement (FOCUS Phase II) and improvement of critical loads estimates in the U.S.

4.1. *Critical loads for international collaborative efforts*

The FOCUS Phase I project was an interagency and multi-stakeholder effort to assemble critical load information for the U.S. in a format that could be shared both nationally and internationally. Critical loads represent an international and widely accepted scientific approach to determine atmospheric deposition thresholds below which pollutants are not anticipated to cause undesirable effects to sensitive ecosystems. The U.S. is a party under the United Nations Economic Commission for Europe–Convention on Long Range Transport of Air Pollution Protocols (UNECE-CLRTAP). In contrast to other

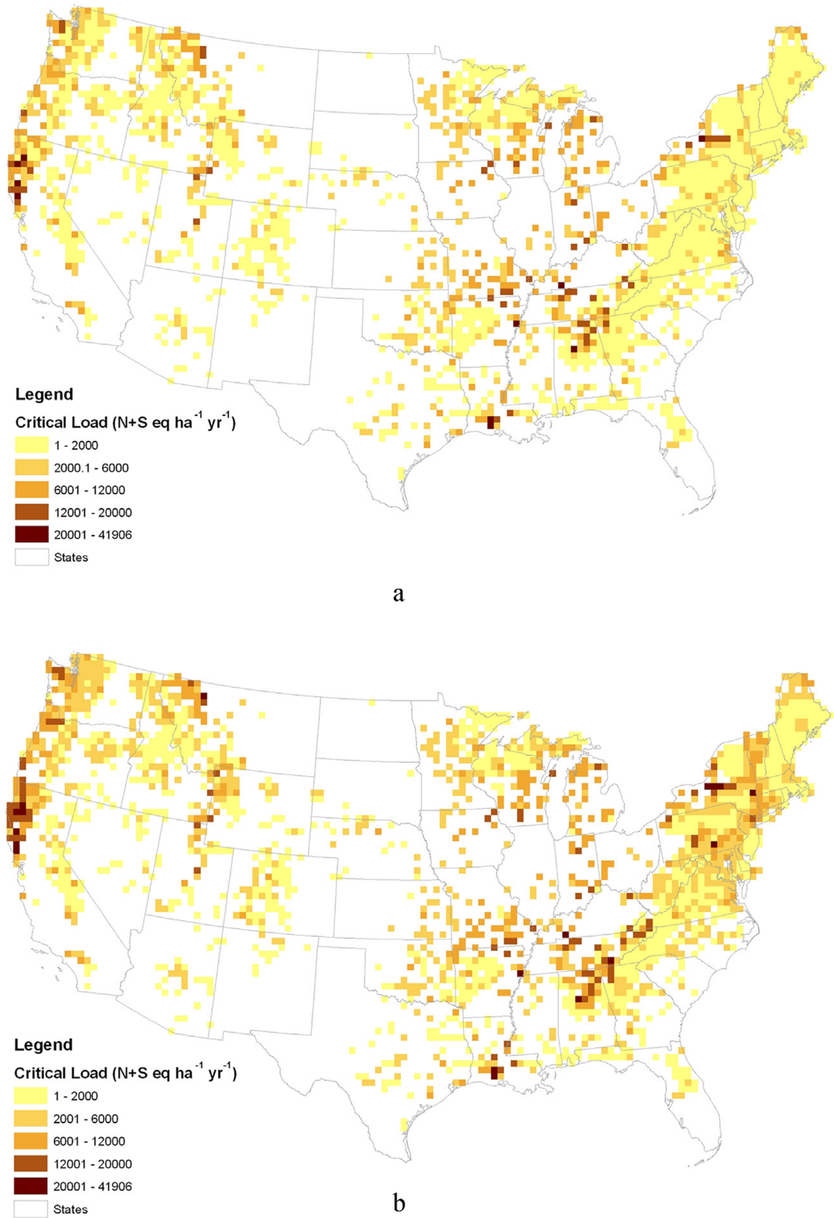

Fig. 1 – (a) Minimum critical loads of surface water acidity for nitrogen and sulfur. Grids represent the minimum calculated critical load from all data within the 36 × 36 km grid cell. The critical chemical criterion used was an acid neutralizing capacity (ANC) of 50 μeq/L. (b) Mean critical loads of surface water acidity. Grids represent the average calculated critical load from all data within the 36 km × 36 km grid cell. The critical chemical criterion used was an acid neutralizing capacity (ANC) of 50 μeq/L.

signatories of CLRTAP, the U.S. does not have a history of using critical loads data to support environmental policy and land management decisions or a record of submitting critical loads data to the UNECE. Because the U.S. did not have a history of implementing strategies to develop consistent regional or national scale critical loads, no unified approach existed to conduct these tasks prior to the FOCUS Phase I effort. Collaboration with the ICP-M&M and use of their protocols and processes for submitting critical loads data to the CCE provided a streamlined mechanism to develop a critical loads database and initial map products for U.S. ecosystems.

4.2. *Critical loads for management and policy applications*

The database developed through the FOCUS Phase I project was used to make an initial series of critical loads maps to illustrate potential outputs. However, these maps should not be considered the definitive critical loads for the U.S., as the "minimum" and "average" critical loads values displayed represent only two of many possibilities, both of which were developed to show outputs of specific interest to natural resources managers and air quality regulators. Additionally, CLAD and associated critical loads researchers are still

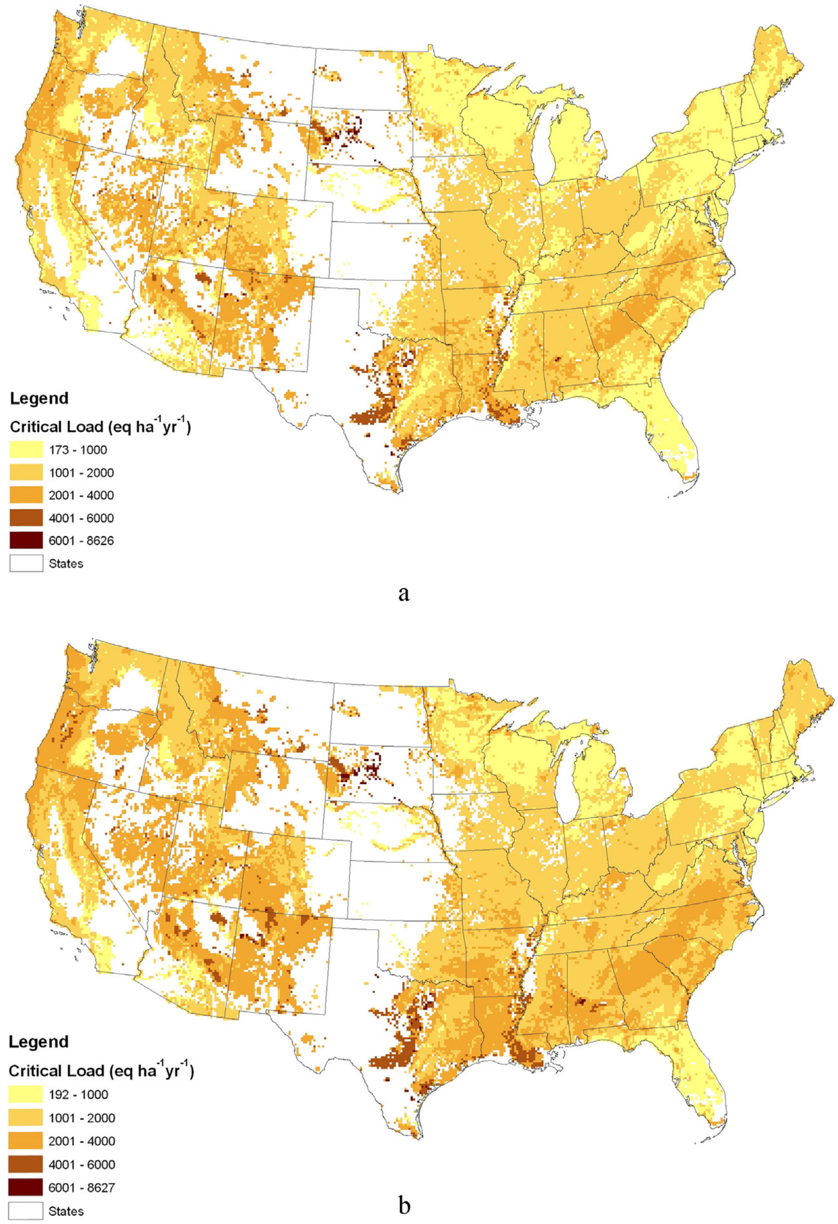

Fig. 2 – (a) Critical loads (CL) of acidity (sulfur and nitrogen) for forests. This map represents the minimum CL calculated by McNulty et al. (2007) or Duarte et al. (2011, 2013) within the 12 km × 12 km mapping unit. The base cation to aluminum ratio for forest soils was selected as the critical chemical criterion in these CL calculations (molar [BC]:[Al] ratio of 1 for deciduous forests and 10 for coniferous forests for McNulty et al., 2007, ratio of 10 for Duarte et al., 2011). (b) Critical loads (CL) of acidity (sulfur and nitrogen) for forests. This map represents the average of CLs calculated by McNulty et al. (2007) or Duarte et al. (2011, 2013) within the 12 km × 12 km mapping unit. The base cation to aluminum ratio for forest soils was selected as the critical chemical criterion in these CL calculations (molar [BC]:[Al] ratio of 1 for deciduous forests and 10 for coniferous forests for McNulty et al., 2007, ratio of 10 for Duarte et al., 2011).

working to refine estimates, improve methods, and collect additional data.

The critical loads database could be used to address a variety of issues and concerns. For example, U.S. air regulators may want to link critical loads to secondary air quality standards by asking, for example: ''what are the critical loads for acidity that will allow 95% of streams in U.S. ecosystems to maintain healthy biodiversity?'' Conversely, U.S. land managers may wish to combine all critical loads data layers to ask the question: ''what is the lowest (most protective) critical load for acidification and excess nitrogen that will prevent degradation to all sensitive ecosystems in my park, forest or refuge?'' The critical loads database can be used to address many types of scientific and policy questions, by allowing end users to select various thresholds, endpoints, and map display characteristics to produce their own critical

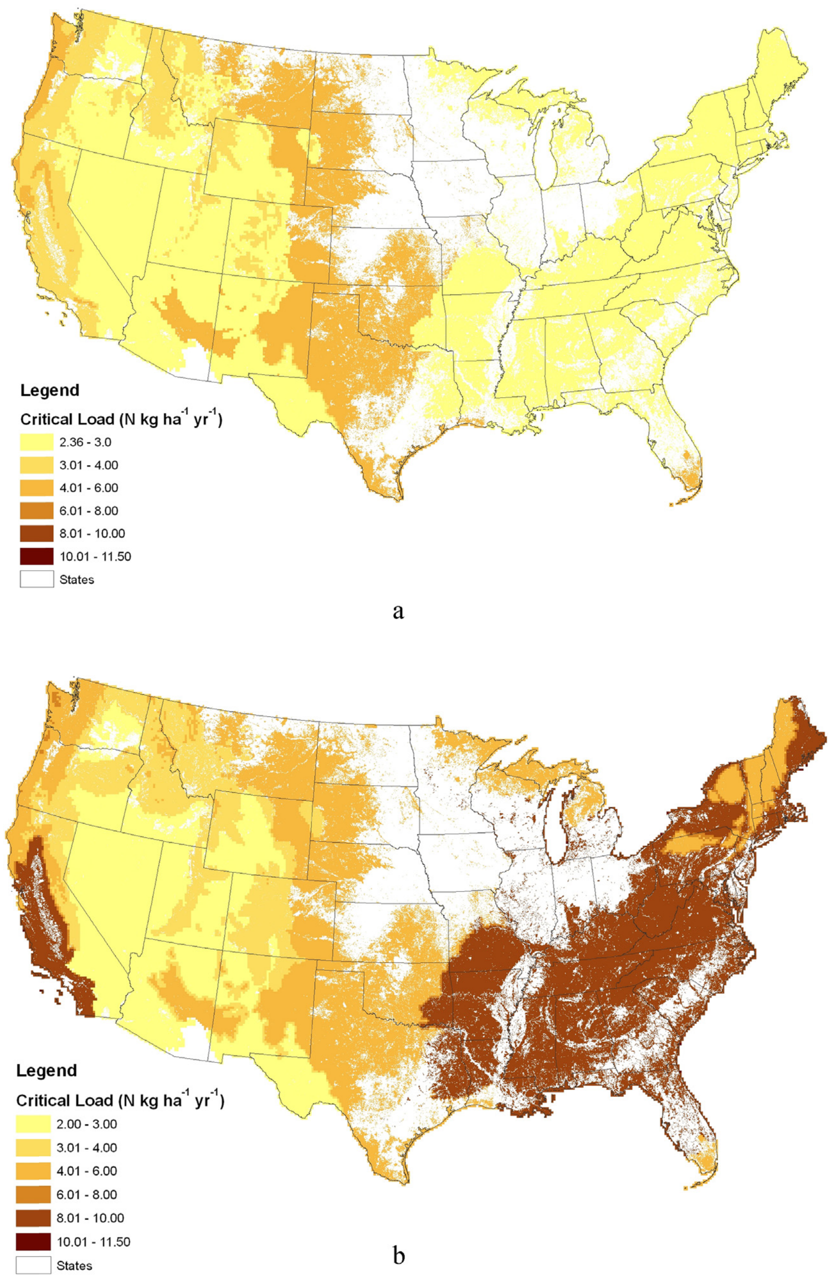

Fig. 3 – (a) Empirical critical loads (CL) of nitrogen (N) for all endpoints: mycorrhizal fungi, lichens, herbaceous vegetation, and forests. This figure represents the minimum of all estimated CL values for each 12 km × 12 km mapping unit (Pardo et al., 2011c; Geiser et al., 2010). (b) Empirical critical loads (CL) of nitrogen (N) for all endpoints: mycorrhizal fungi, lichens, herbaceous vegetation, and forests. This figure represents the average of all estimated CL values for each 12 km × 12 km mapping unit (Pardo et al., 2011c; Geiser et al., 2010).

loads maps and other products (http://nadp.sws.uiuc.edu/committees/clad/focus.aspx).

4.3. *Next steps*

The critical loads community in the U.S. has much work remaining in order to facilitate continued development and refinement of comprehensive national-scale critical loads (Fig. 4). Ecosystem research and monitoring, deposition monitoring and modeling, refinement of critical loads model parameters, protocol development, database infrastructure, and policy and management support are ongoing needs if U.S. critical loads efforts are to continue. Critical loads exceedances can only be evaluated where reliable estimates of current and future deposition can be established and compared to critical loads. Efforts to develop exceedance maps have recently begun, and will be refined as deposition estimates for areas of complex terrain are improved.

Significant uncertainties remain in this first approximation of national-scale critical loads for acidification and the effects

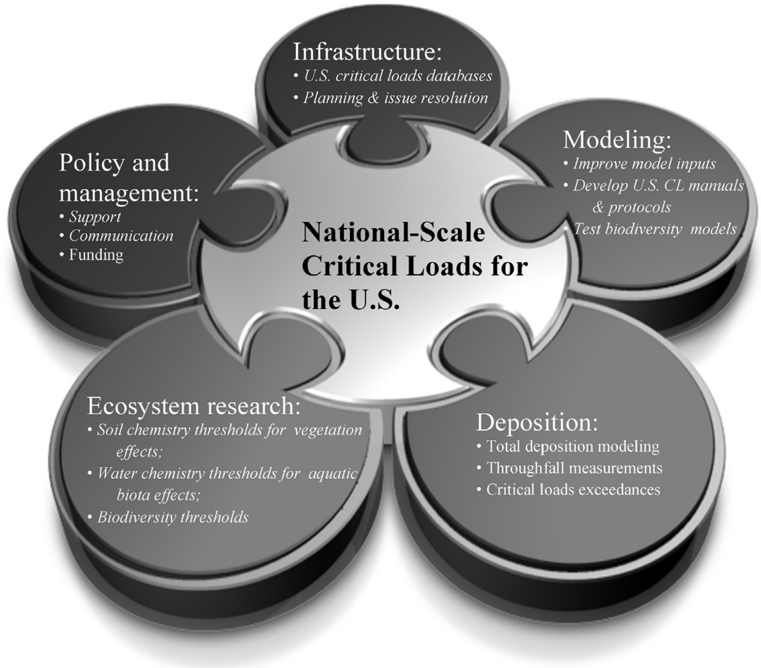

Fig. 4 – Areas of coordination and "next steps" needed to enable development and refinement of U.S. critical loads science and policy. Areas currently being addressed by FOCUS Phase II work groups are shown in italics.

of excess nitrogen. Improvement is needed in steady state model parameterization (i.e. weathering rates, acceptable nitrate leaching and nitrogen immobilization terms) and for a broader range of endpoints and geographic extent of data used to develop empirical N estimates. Efforts are currently underway in FOCUS-Phase II to evaluate and modify critical load calculation parameters to best represent the environmental conditions in the US, identify and fill data gaps, and evaluate and reduce uncertainty associated with critical load estimates. Expert work groups have been formed to work on the following specific topics that were identified for priority attention:

- Review and provide recommendations on the base cation weathering estimates for U.S. ecosystems used in the SMB model.
- Review and provide recommendations for improving the denitrification, and acceptable nitrate leaching, and soil N immobilization parameters of the SMB equation.
- Assess current knowledge and data linking soil chemistry and vegetation response, and provide recommendations on the critical thresholds used to determine the critical ANC and acceptable nitrate leaching rates used in the SMB model.
- Develop a model that relates lichen response to deposition for each forested Level I ecoregion in the United States using existing monitoring data.
- Conduct a pilot study in the northeastern U.S. to refine the spatial resolution of empirical critical loads of N from the Level I ecoregion to a 4 km $\times$ 4 km grid cell scale.
- Compare different modeling approaches for surface water critical loads, with particular focus on improving estimates for the weathering component, and quantifying uncertainty.
- Assess approaches that could be used by the U.S. to address the effects of atmospheric deposition on biodiversity.
- Maintain the critical load database and incorporate additional datasets as they become available.

5. Conclusions

Beginning in 2006, the primary forum for critical loads research and development coordination in the U.S. has been the CLAD of the NADP. From Fall 2010 through Spring 2011, CLAD's FOCUS Pilot Study – Phase I project was used to gather and synthesize empirical and calculated critical loads data from dozens of regional and national-scale projects. CLAD members provided that data as an informal, unofficial submission to the CCE in the interests of international cooperation and exchange of information on the effects of atmospheric deposition on ecosystems. By completing the Phase I project, CLAD hopes to actively join a productive and meaningful dialogue with the international scientific community on methods for estimating, calculating, mapping, interpreting, and refining critical loads. In addition, development of this database and mapping work represents a significant step forward in consolidating critical loads data in one place such that U.S. scientists, land managers and policy makers can effectively utilize them in decision-making processes. This effort represents the first phase in an anticipated future iterative process of developing and refining national-scale U.S. critical loads for surface water acidity, forest ecosystem acidity, and the detrimental effects of excess nitrogen.

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