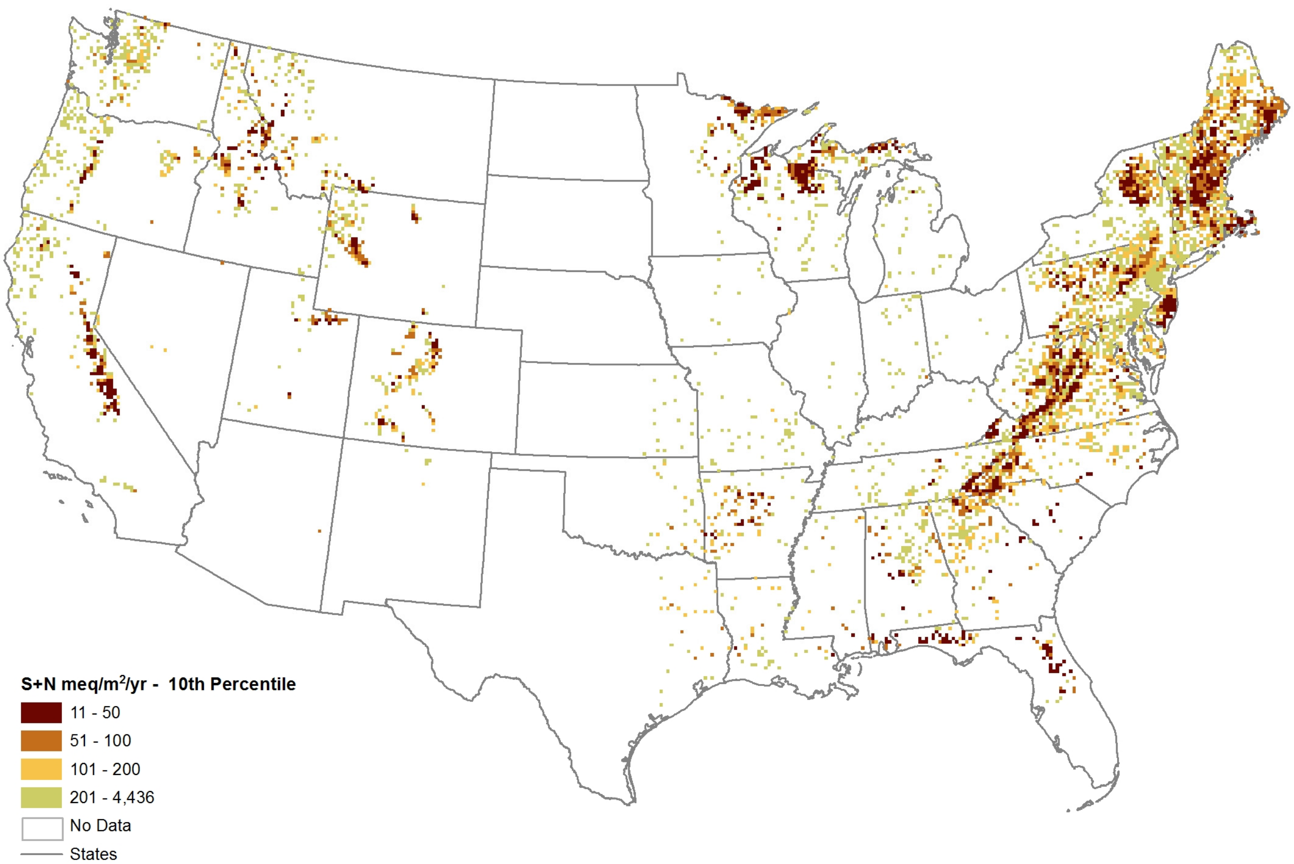
National Atmospheric Deposition Program

Critical Loads of Atmospheric Deposition Science Committee

2015 Summary of Critical Load Maps



On the cover: Surface Water Critical Loads for Acidity. Average aggregation for 12 km^2 grid cell with S + N (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).

Use Condition and Citation; please use the following: The intended use of this database is for scientific, policy-related, or educational purposes. Any published use of the CLAD database information must acknowledge the original sources for the data used. Each critical load value in the database can be linked to its origin using the RefID field. The proper citations for each RefID can be found in Table 7 of the database (Citation for all critical load values). In addition, whenever a data user presents and/or publishes research based on critical load values in the database, CLAD and NADP must be acknowledged. A suggested acknowledgement is:

"We acknowledge the Critical Loads of Atmospheric Deposition (CLAD) Science Committee of the National Atmospheric Deposition Program (NADP) for their role in making available CLAD_CL_ACID_v2.5 and CLAD_CL_N_v2.5accdb datasets."

Contents

Background

In April 2010, the National Atmospheric Deposition Program (NADP) Executive Committee formed the Critical Loads of Atmospheric Deposition Science Committee (CLAD). This committee evolved from an ad hoc group originally formed in 2006.The purpose of CLAD is to discuss current and emerging issues regarding the science and use of critical loads for effects of atmospheric deposition on ecosystems in the United States. The goals of CLAD are to:

- Facilitate technical information sharing on critical load topics within a broad multi-agency/entity audience;
- Fill gaps in critical loads development in the US;
- Provide consistency in development and use of critical loads in the US;
- Promote understanding of critical load approaches through development of outreach and communications materials.

For more information regarding CLAD, please visit the NADP-CLAD web page at http://nadp.sws.uiuc.edu/committees/clad/.

Starting in 2010, the “FOCUS Pilot Study” project gathered and synthesized both empirical and calculated critical loads data and information from dozens of regional- and national-scale projects (See Blett et al. 2014). CLAD members submitted data to this cooperative effort as a productive and meaningful way to share information to improve methods for estimating, calculating, mapping, interpreting, and refining critical loads. The first round of critical load data synthesis formed the foundation for an informal, unofficial submission to the UNECE Coordinating Center on Effects (CCE) in 2011. This unofficial submission to the European critical loads community represented a maturing of interest in the United States’ critical loads science community.

What is a critical load?

Air pollution emitted from a variety of sources is deposited from the air into ecosystems. These pollutants may cause ecological changes, such as long-term acidification of soils or surface waters, soil nutrient imbalances affecting plant growth, and loss of biodiversity. The term “critical load” is used to describe the threshold of air pollution deposition that causes change to sensitive resources in an ecosystem. A critical load is technically 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 are not expected to occur according to present knowledge” (Nilsson and Grennfelt 1988). Critical loads are typically expressed in terms of kilograms per hectare per year (kg/ha/yr) or equivalents per hectare per year (eq/ha/yr) of wet or total (wet + dry) deposition. Critical loads can be developed for a variety of ecosystem responses, including shifts in microscopic aquatic species, increases in invasive grass species, changes in soil chemistry affecting tree growth, and lake and stream acidification to levels that can no longer support fish. When critical loads are exceeded, the environmental effects can extend over great distances. For example, excess nitrogen can change soil and surface water chemistry, which in turn can cause eutrophication of downstream estuaries.

Critical loads describe the point at which a natural system is impacted by air pollution. For ecosystems that have already been damaged by air pollution, critical loads help determine how much improvement in air quality would be needed for ecosystem recovery to occur. In areas where critical loads have not been exceeded, critical loads can identify levels of air quality needed to protect ecosystems in the future. U.S. scientists, air regulators, and natural resource managers are currently developing critical loads for areas across the United States and collaborating with scientists developing critical loads in Europe and Canada.

Once critical loads are established, they can then be used to assess ecosystem health, inform the public about natural resources at risk, evaluate the effectiveness of emission reduction strategies, and guide a wide range of management decisions.

This summary is a collection of critical load maps for the U.S., developed by CLAD members using critical load data that are publically available as part of the NADP CLAD National Critical Load Database (NLCD). The full set of critical load maps can be downloaded at the following link: http://nadp.sws.uiuc.edu/committees/clad/db/

About the Maps and National Critical Load Database (NCLD)

The critical load maps provided here represent a compilation of empirical and calculated critical load values from a variety of regional- and national-scale projects. The intended uses of these maps are for scientific, policy-related, or educational purposes. These maps illustrate critical loads in the National Critical Load Database (NCLD) and help to identify spatial gaps in information, as well as additional research needs.

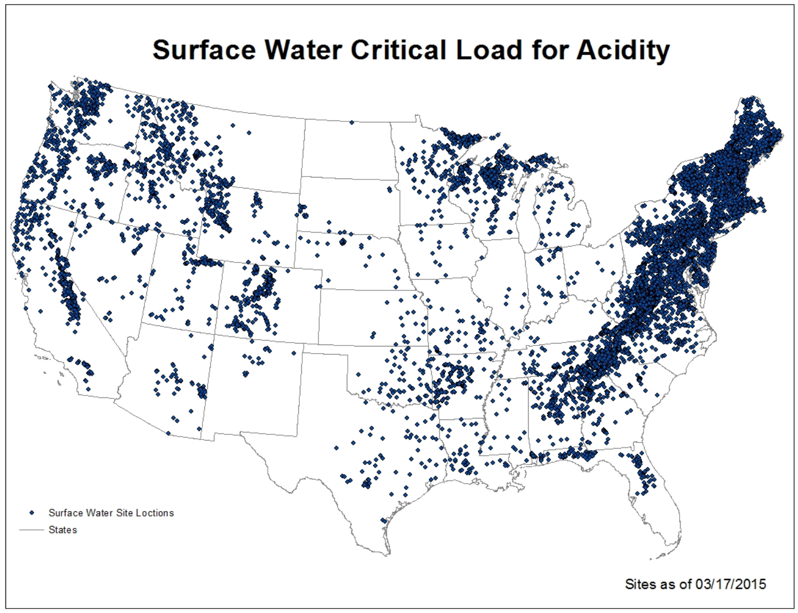
These maps focus on critical loads of sulfur and nitrogen deposition and the effects on terrestrial and aquatic environments:

- Surface Water Critical Loads for Acidity
- Forest Ecosystem Critical Loads for Acidity
- Empirical Critical Loads for Nitrogen (i.e., eutrophication).

The critical load values and maps were developed cooperatively with individuals or groups sharing critical load information and are not intended to be comprehensive of all known critical load values and data for the U.S. While substantial efforts have been made to ensure the accuracy of data and documentation contained in the NCLD database, complete accuracy of the information cannot be guaranteed. The qualities and accuracy of the critical load values are best described in the individual associated research publications. It is important to review material in the cited papers prior to using critical load information from these maps and the NCLD. In addition, any opinions, findings, conclusions, or recommendations drawn from these maps and datasets do not necessarily reflect the views of the National Atmospheric Deposition Program (NADP), the Critical Loads of Atmospheric Deposition Science Committee (CLAD), or its member affiliations.

Stoney Brook, North Central Pennsylvania. Photo courtesy of Jason Lynch

Surface Water Critical Loads for Acidity



For this series of maps, the critical loads represent the combined deposition load of sulfur and nitrogen, or the deposition load of sulfur only, to which a lake or stream could be subjected to and still maintain a healthy aquatic systems. These critical loads are calculated for specific waterbodies (e.g., an alpine lake) based on simple mass balance models that incorporate present-day surface water chemistry data from monitoring locations. Mass balance approaches consider the net loss or accumulation of acids, nutrients, and base cations in soils and surface waters necessary to maintain the surface water acidity (e.g., Acid Neutralizing Capacity (ANC)) above a pre-selected level or "chemical threshold," likely to allow ecosystem sustainability over the long term. The steady-state approach does not estimate how long it will take for ecosystem response (improvement or decline) to occur; rather, it estimates the critical load of deposition that will allow ecosystem sustainability over the long term.

Data from over 12,500 streams and lakes (Lynch et al. 2014) were used to develop steady-state surface water critical loads for acidity. Multiple approaches were employed for estimating steady-state acid-base balance load (e.g., Sullivan et al. 2010; McDonnell et al. 2012; Scheffe et al. 2014). The chemical threshold for ANC was set at 20 μeq/L for waterbodies in the western U.S. and 50 μeq/L for waterbodies in the eastern U.S., which best reflects the natural acidity conditions in these regions. The "Aquatic Ecosystem Concern Levels and Ecological Effects" table below generally describes the expected ecological effects for the eastern U.S. at given ranges of ANC. Critical loads for sulfur and nitrogen (S+N) and Sulfur (S) deposition are expressed in terms of ionic charge balance as milliequivalents per square meter per year (meq/m^2/yr). See National Critical Load Database (NLCD) metadata 2015 for a more complete description of the methods (Lynch et al. 2014).

Critical loads are based on water quality data collected from a range of years from the 1980s to the present. Not all waterbodies with surface water data are suitable for calculating critical loads for acidity. The following were excluded from critical load calculations: (1) insufficient or unsound data such that the mass-balance estimates were compromised (e.g., waterbodies with runoff rates > 0.15 mm/yr), (2) sulfate values exceeding 400 μeq/L, which suggest a non-atmospheric source of sulfur, such as mine drainage or sulfur-bearing bedrock, (3) imbalanced chloride and sodium concentrations, which suggest the water body was influenced by salt contamination, or (4) the size of the watershed at the sampling point was greater than 160 km^2.

The maps on pages 8 through 12 show aggregated critical loads at the 12 and 36 km^2 grid cells. Waterbodies having more than one calculated critical load value were averaged to produce a single value for each waterbody. These single critical load values per waterbody were then aggregated into a summary value for each grid cell. Aggregations maps are shown for the "average" and 10th percentile critical load based on recommendation of CLAD. A 10th percentile critical load represents the most sensitive 10 percent data available for a grid cell.

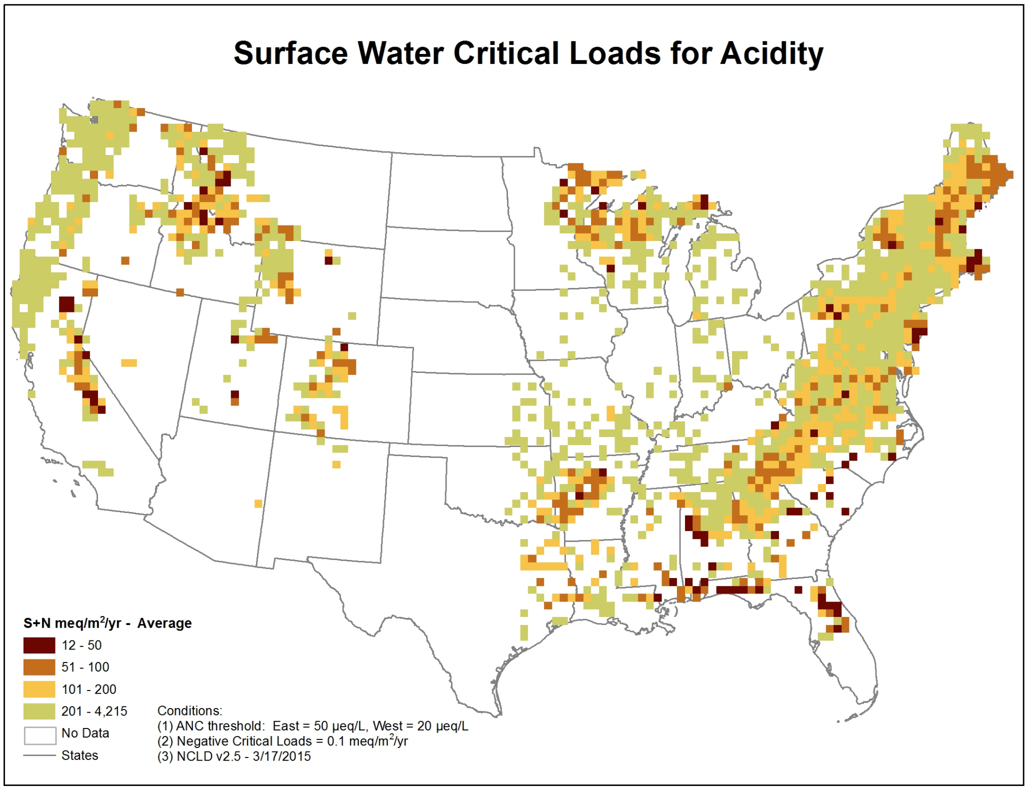
Uncertainty estimates for maps on pages 8 through 12 are not available at this time. Instead, the number of critical loads per grid cell gives a qualitative measure of reliability for the aggregated critical load: An aggregated critical load based on more values is assumed to be more reliable. The number of critical loads per 36 km^2 grid is presented on page 13. The number of critical load values in each grid cell varies depending on the availability of data for a particular area (see the critical load values per grid map). The Mid-Atlantic and Appalachian Mountains have considerably more critical load values then other regions. In addition, the critical load values in the database are not necessarily a representative sample of all waterbodies found in each grid cell. Instead, this mapping exercise provides a representation of the availability of data in a particular grid cell.

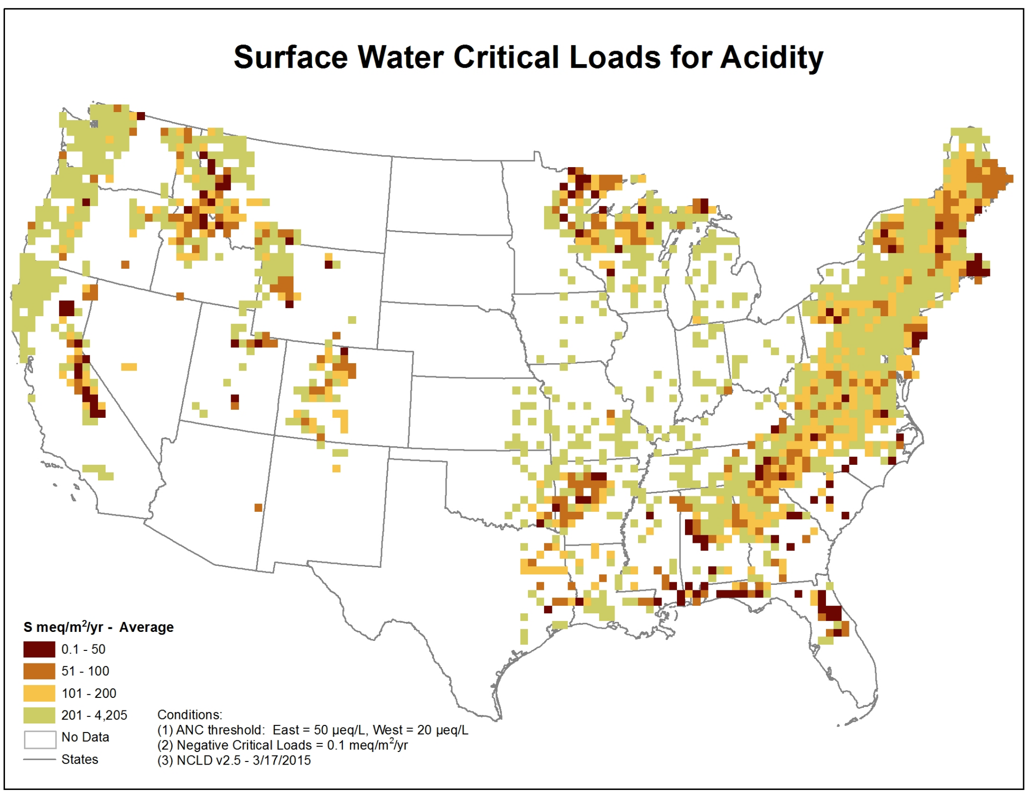
Maps contain critical load data through 3/17/2015 (NCLD 2.5); however, the NCLD is continuously being updated.

Aquatic Ecosystem Concern Levels and Ecological Effects

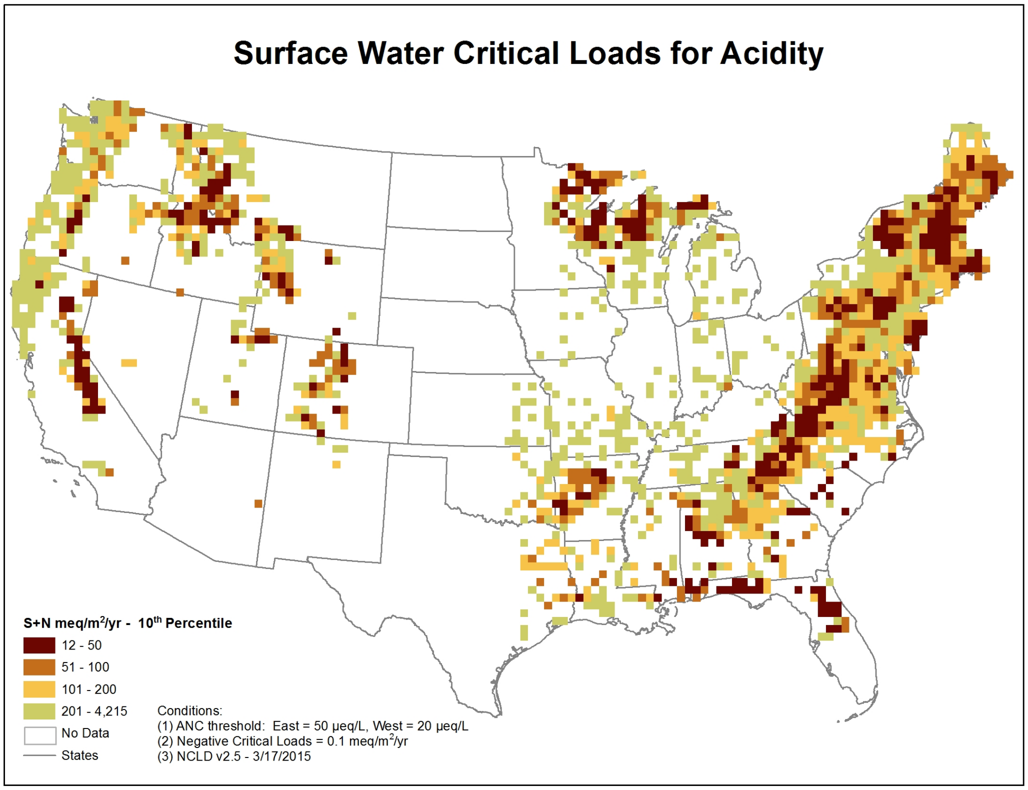
Category Label	ANC Level (µeq/L)	Expected Ecological Effects
Acute Concern	Less than 0	Near-complete loss of fish populations is expected. Planktonic communities have extremely low diversity and are dominated by acid-tolerant forms. The numbers of individuals in plankton species that are present are greatly reduced.
Elevated Concern	0 to less than 50	Fish species richness is greatly reduced (e.g., more than half of expected species are missing). On average, brook trout populations experience sublethal effects, including loss of health and reproduction (fitness). During episodes of high acid deposition, brook trout populations may experience lethal effects. Diversity and distribution of zooplankton communities decline.
Moderate Concern	50 to less than 100	Fish species richness begins to decline (e.g., sensitive species are lost from lakes). Brook trout populations are sensitive and variable, with possible sublethal effects. Diversity and distribution of zooplankton communities begin to decline as species that are sensitive to acid deposition are affected.
Low Concern	Greater than or equal to 100	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.

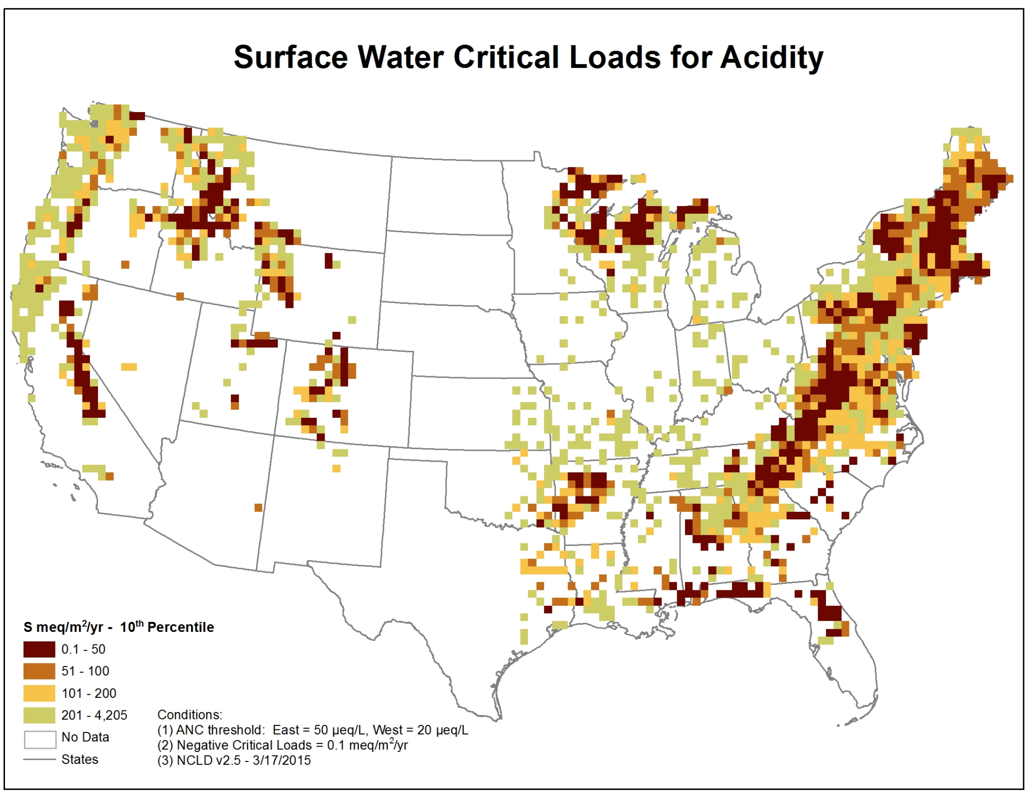
From Burns et al. 2011



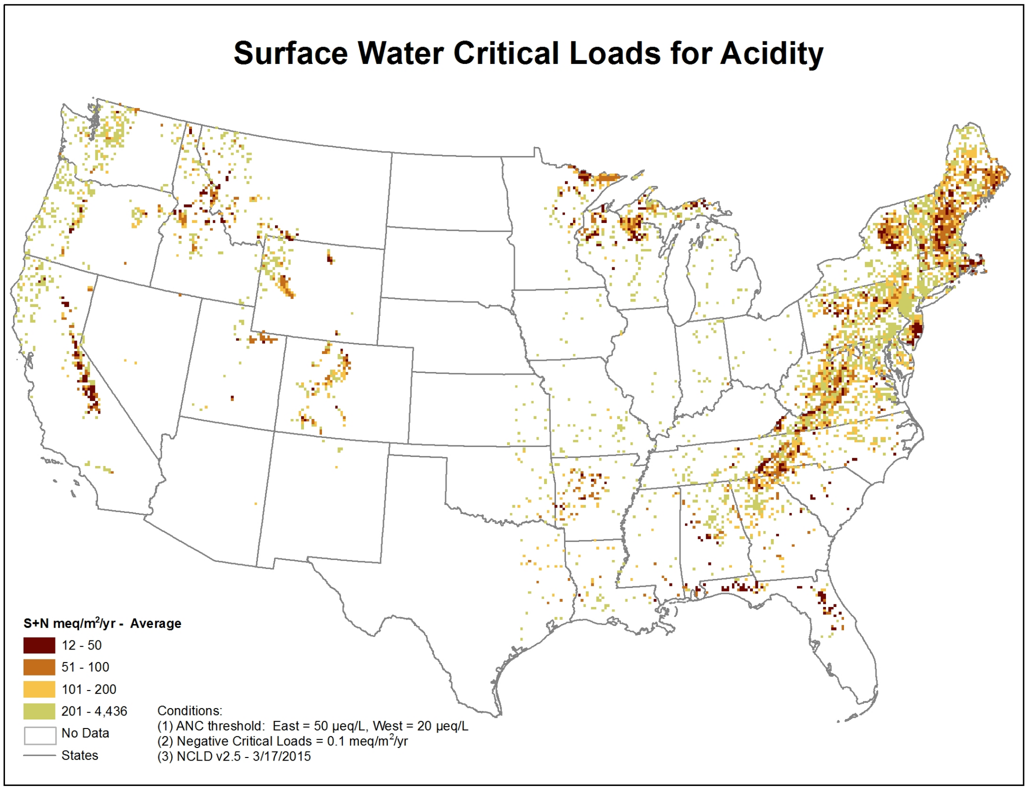


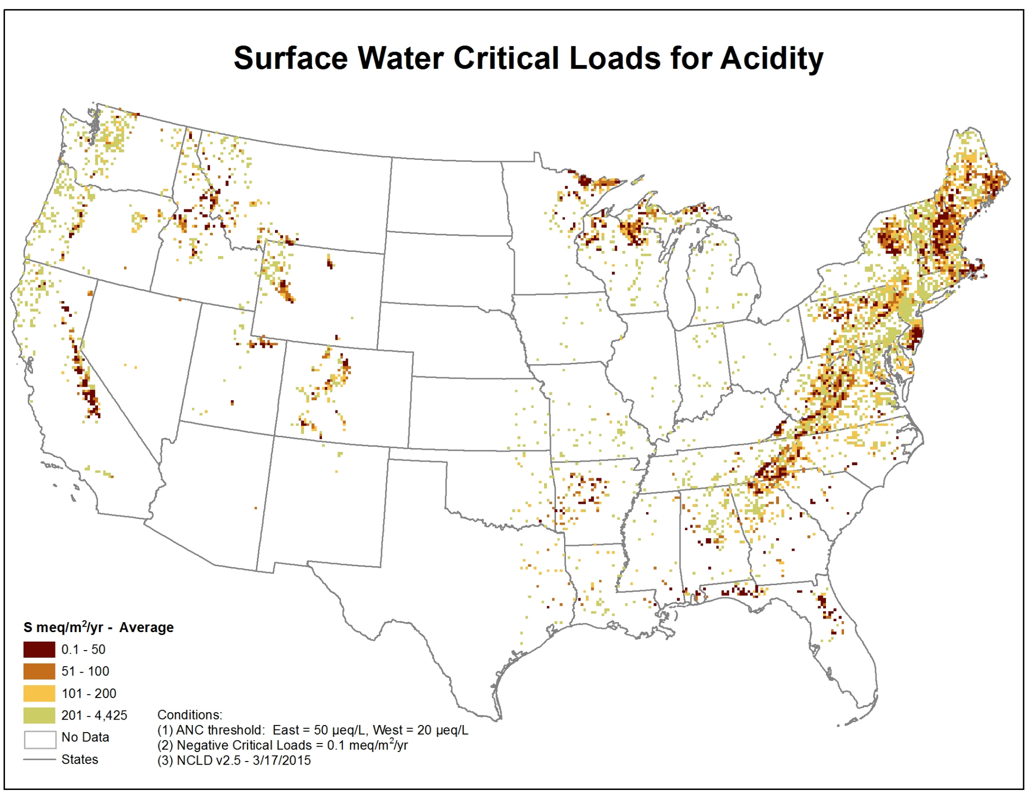
Surface Water Critical Loads for Acidity. Average aggregation for 36 km^2 grid cell with S + N (top) and S only (bottom) (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).



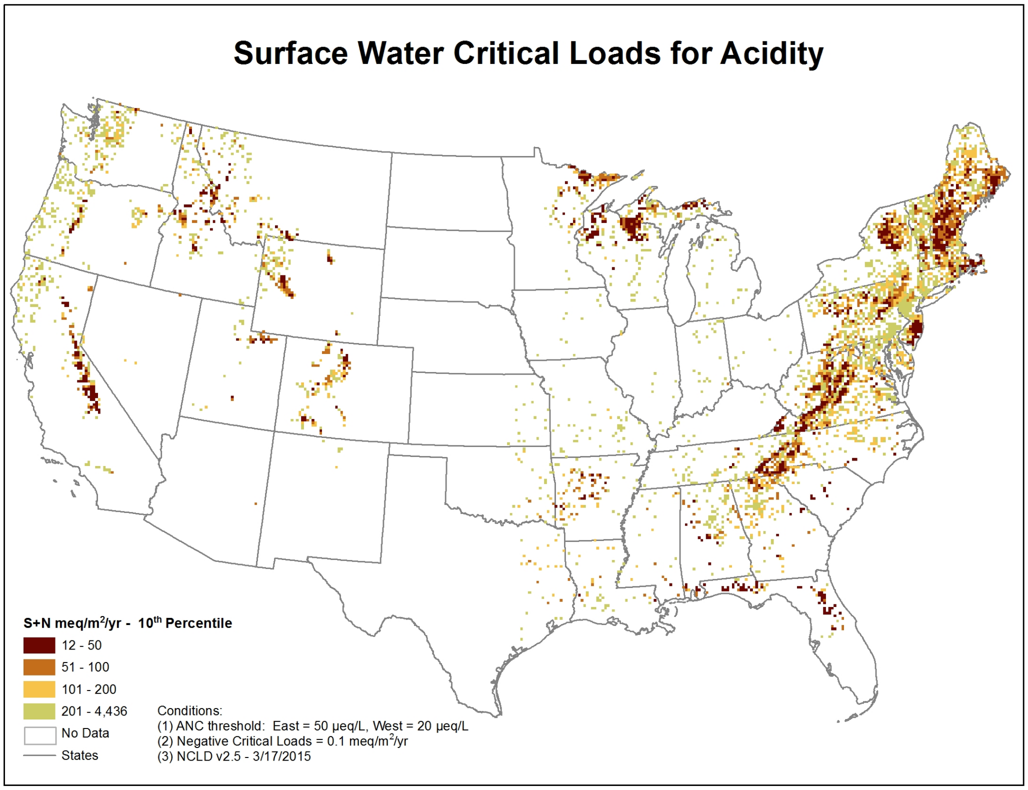


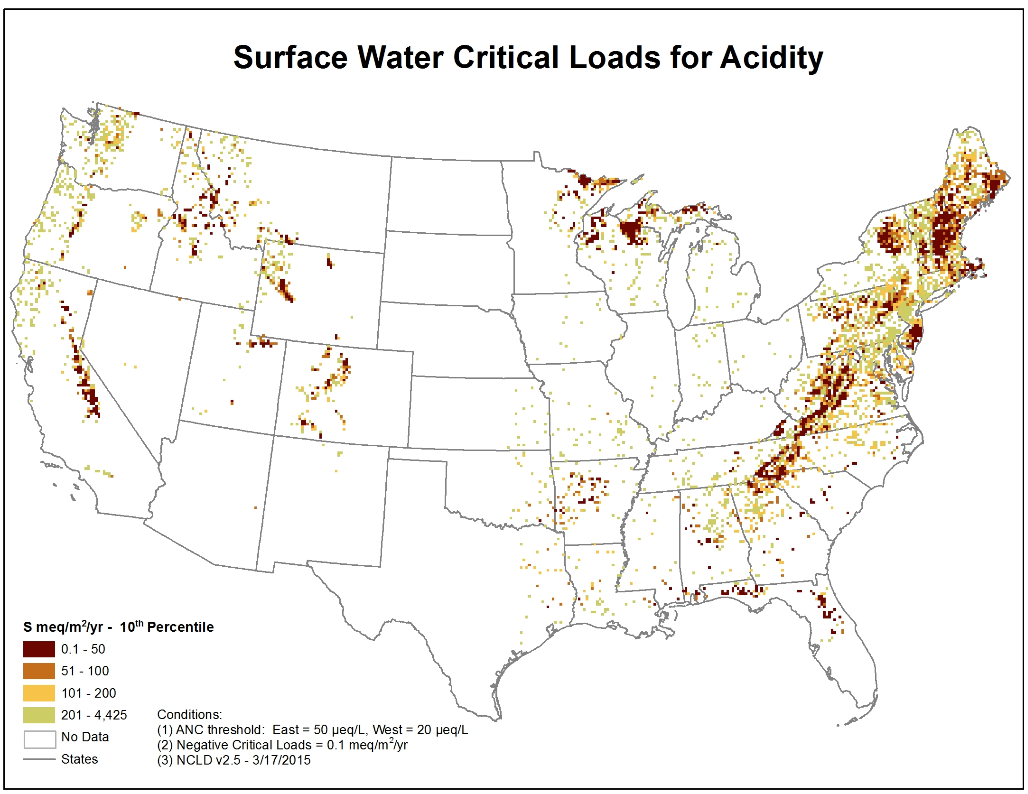
Surface Water Critical Loads for Acidity. 10th percentile aggregation for 36 km^2 grids with S + N (top) and S only (bottom) (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).



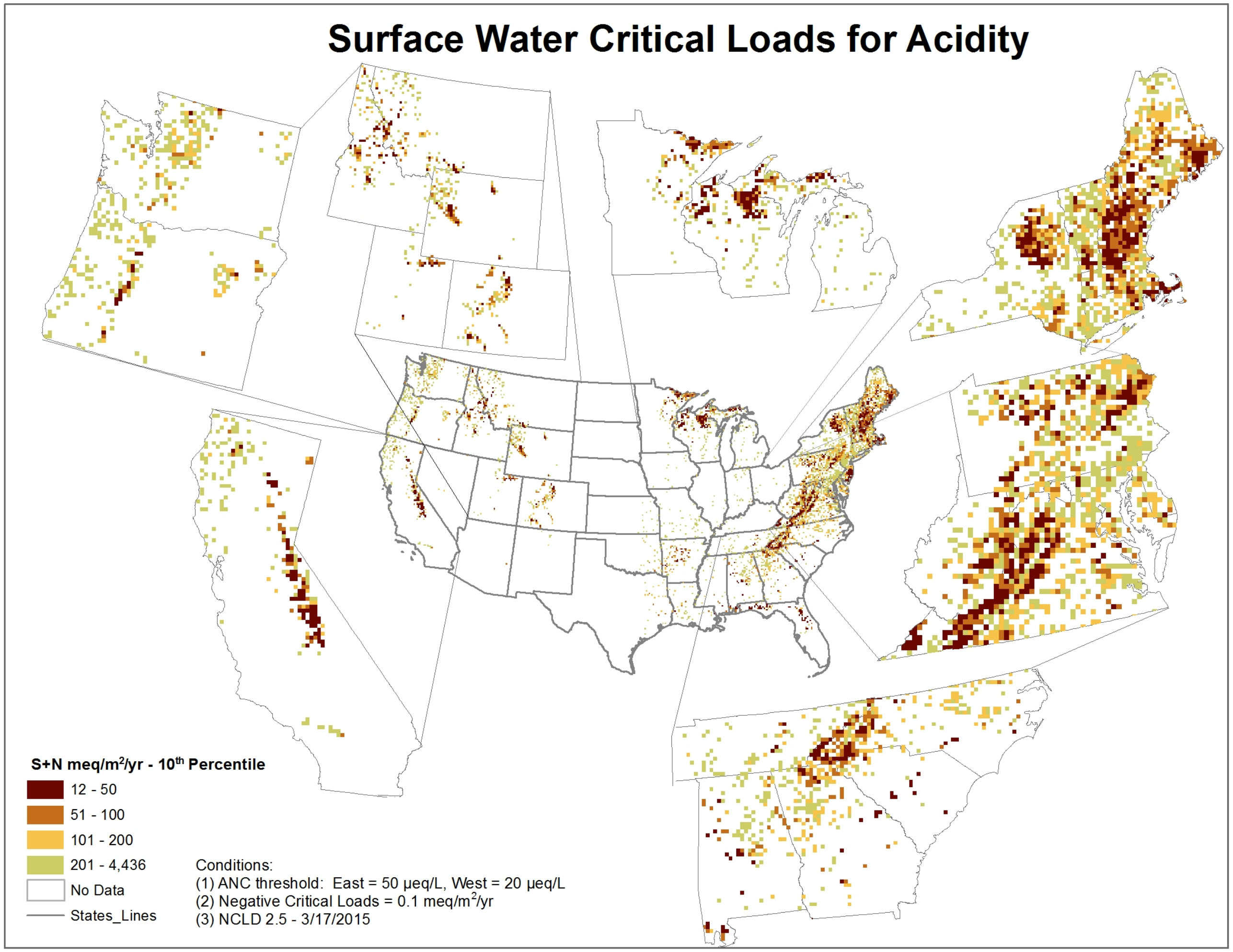


Surface Water Critical Loads for Acidity. Average aggregation for 12 km^2 grid cell with S + N (top) and S only (bottom) (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).

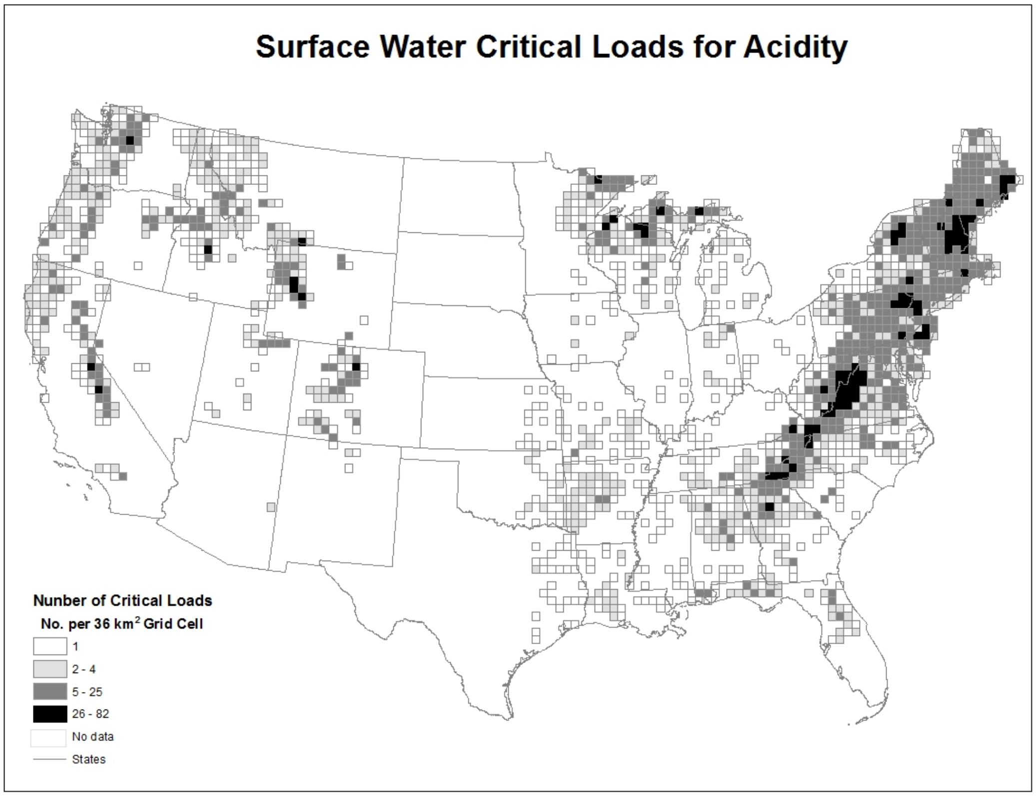




Surface Water Critical Loads for Acidity. 10th percentile aggregation for 12 km^2 grid cell with S + N (top) and S only (bottom) (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).



Surface Water Critical Loads for Acidity. 10th percentile aggregation for 12 km^2 grid (McDonnell et al. 2014; Scheffe et al. 2014; Sullivan et al. 2014; unpublished data).



Number of critical loads per 36 km^2 grid cell.

Forest Ecosystem Critical Loads for Acidity

Mapped terrestrial forest ecosystem critical loads for acidity are obtained from McNulty et al. (2007, 2013), Duarte et al. (2012, 2013), Sullivan et al. (2011a, 2011b), McDonnell et al. (2013), and Phelan et al. (2014). All of these studies calculated steady-state critical loads for forest ecosystems using the simple mass balance (SMB) approach (UBA 2004). Steady-state models are used to calculate critical loads that will allow ecosystem sustainability over the long term. Water and soil chemistry, mineral soil weathering rates, deposition data, and an understanding of ecosystem responses to chemical changes are all used in these models. The steady-state approach does not estimate how long it will take for ecosystem response (improvement or decline) to occur; rather, it estimates the critical load of deposition that will allow ecosystem sustainability over the long term.

Base cation weathering rates were estimated using various methods among the studies. McNulty et al. (2007, 2013) and Duarte et al. (2012, 2013) used the clay percent-substrate method. Sullivan et al. (2011a, 2011b) and McDonnell et al. (2013) used the Model of Acidification of Groundwater In Catchment (MAGIC) on a watershed bases, using an input-output mass balance approach. Phelan et al. (2014) used the PROFILE model, which integrates soil mineralogy and other environmental properties.

The base cation to aluminum [BC]: [Al] ratio was selected as the chemical criterion for McNulty et al. (2007, 2013), Duarte et al. (2011, 2013, and Phelan et al. (2014). McNulty et al. (2007, 2013) used the following critical thresholds for the molar [BC]: [Al] ratio: 1 for conifer forests and 10 for deciduous forests. The critical threshold used by Duarte et al. (2012, 2013) and Phelan et al. (2014) was a [BC]: [Al] molar ratio of 10 for all forest types. Sullivan et al. (2011a, 2011b) and McDonnell et al. (2013) used various chemical criterions, which included [BC]: [Al] molar ratio of 1 and 10, calcium to aluminum [BC:]: [Al] molar ratio of 1 and 10, and base saturation of 5 and 10 percent. A base saturation of 5 percent was used in the map on page 16.

See McNulty et al. (2007, 2013), Duarte et al. (2012, 2013), Sullivan et al. (2011a, 2011b), McDonnell et al. (2013), and Phelan et al. (2014), and National Critical Load Database (NCLD) metadata 2015 for more detail on methods used to calculate the critical loads of acidity (Lynch et al. 2014).

The maps on page 16 show critical loads mapped at 1 km^2 (McNulty et al. 2007, 2013), at 4 km^2 (Duarte et al. 2012, 2013), at the watershed scale (Sullivan et al. 2011a, 2011b and McDonnell et al. 2013), and at the sample site (Phelan et al. 2014). Critical loads are estimated for forest areas only and are expressed in terms of an ionic charge balance as equivalents per hectare per year (eq/ha/yr).

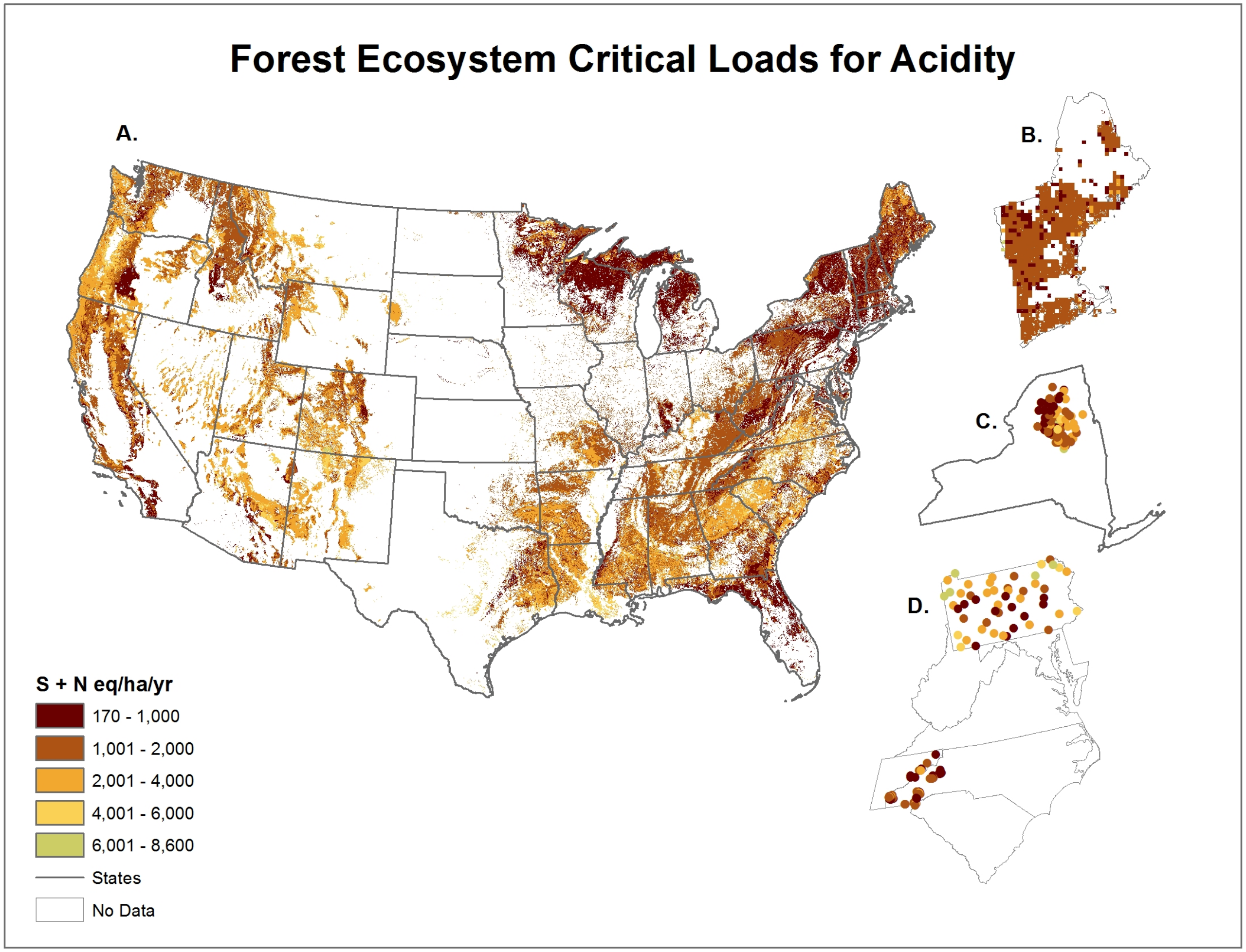
The strength of the SMB approach is that it provides a means for comparing forest soil susceptibility to acidification across the conterminous U.S. (McNulty et al. 2007, 2013). However, the McNulty et al. (2007, 2013) results should be considered preliminary due to the uncertainty in the underlying data, which is related to data quality, spatial heterogeneity, natural variability, and model suitability (Li and McNulty et al. 2007). The Li and McNulty 2007 analysis indicates that uncertainty in the SMB approach comes primarily from the components of base cation weathering and the estimate of acid-neutralizing leaching.

Improvement in these two parameters would considerably improve these critical load estimates (Duarte et al. 2013). Base cation weathering rates used by McNulty et al. (2007, 2013) may be more uncertain in the south and west regions of the U.S., given the suitability of the model used to estimate the base cation weathering for those regions. The maps on page 16 show critical loads calculated by (McNulty et al. 2007, 2013) but with a 20 and 40 percent increase in base cation weathering, indicating the relative sensitivity of these modeled estimates to base cation weathering rates.

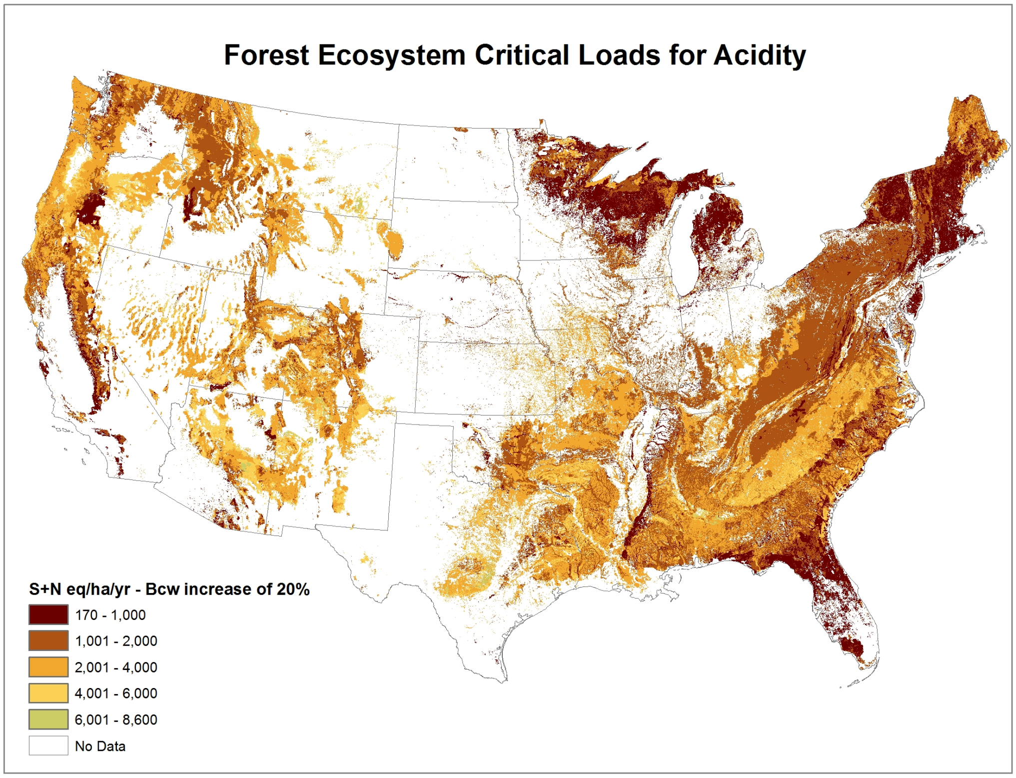
Phelan et al.'s (2014) application of the PROFILE model was a preliminary test of the ability of this model to estimate base cation weathering rates in forested ecosystems in the U.S., using the recently released USGS National Landscapes Project dataset http://minerals.cr.usgs.gov/projects). While their application was successful, the critical load calculations were restricted to only 51 sampling sites in Pennsylvania.

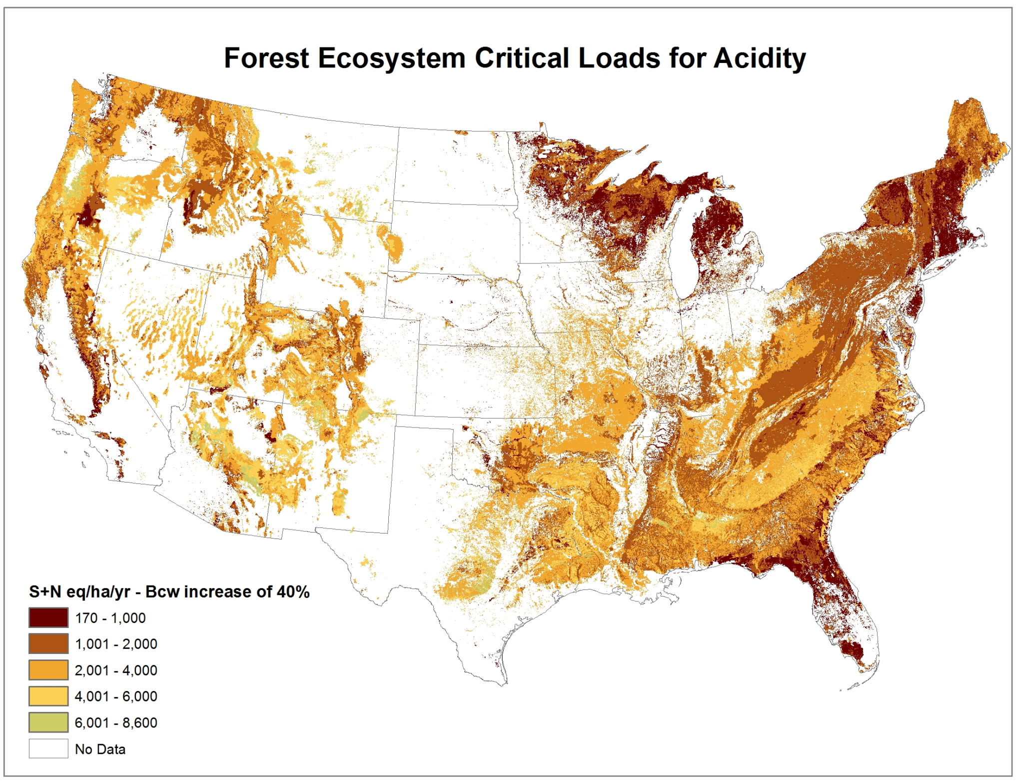
Critical loads calculated by Sullivan et al. (2011a, 2011b) and McDonnell et al. (2013) are technically "target" loads because they specify a year by which to achieve the chemical criterion; however, the year of 2300 (longest period of simulation) best approximates the steady-state "critical" load condition. In addition, the MAGIC model application was based on soil data from a single sampling site within each watershed. Each critical load represents the entire watershed area.

Lastly, the SMB model approach provides only point-in-time estimates of forest soil acidity, not a prediction of how the soils may change over time. The relative coarse spatial scale provides a general pattern of soil acidity. A more systematic analysis of model inputs and measures is still needed in order to identify areas of forest health concerns.



Forest Ecosystem Critical Loads for Acidity. (A.) McNulty et al. (2007, 2013) critical loads are mapped at 1 km^2 grids (center map). The color scheme presented here is different from the original McNulty et al. (2007, 2013) publications. For uncertainty, see Li and McNulty (2007); (B.) Duarte et al. (2012, 2013) critical loads are mapped at 4 km^2 grids; (C. and D.) Phelan et al. (2014) critical loads are mapped for each sampling site (Pennsylvania). Sullivan et al. (2011a, 2011b) and McDonnell et al. (2013) critical loads are mapped as a single point at the center point of the watershed (New York and North Carolina).

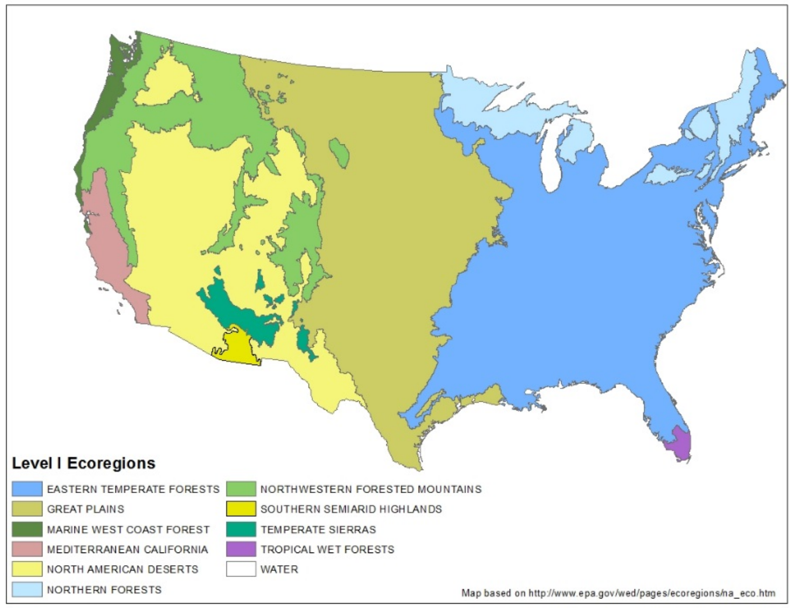




Forest Ecosystem Critical Loads for Acidity with base cation weathering increased by 20% (top) and 40% (bottom) (McNulty et al. 2013). Color scheme presented here is different from the original McNulty et al. (2007, 2013) publications.

Empirical Critical Loads for Nitrogen

Empirical approaches are based on the observation of ecosystem responses (such as changes in plant diversity, soil nutrient levels, or fish health) to specific deposition levels at a given point in time. These relationships are developed using dose-response studies or by measuring ecosystem responses to increasing gradients of deposition over space or time. Empirical information can be used to develop site-specific critical loads or generalized to estimate critical loads over similar areas.



The maps on pages 20 and 21 show empirical critical loads developed by Pardo et al. (2011a, 2011b). These empirical critical loads are defined by ecoregion and include a range of values representing different responses by various receptors based on the best scientific information available at the time. Maps are for receptors, including mycorrhizal fungi, lichens, herbaceous species and shrubs, and forest ecosystems, and are mapped at the Level 1 Ecoregion scale (http://www.epa.gov/wed/pages/ecoregions/na_eco.htm). See Pardo et al. (2011a, 2011b) for more details about how critical loads were determined.

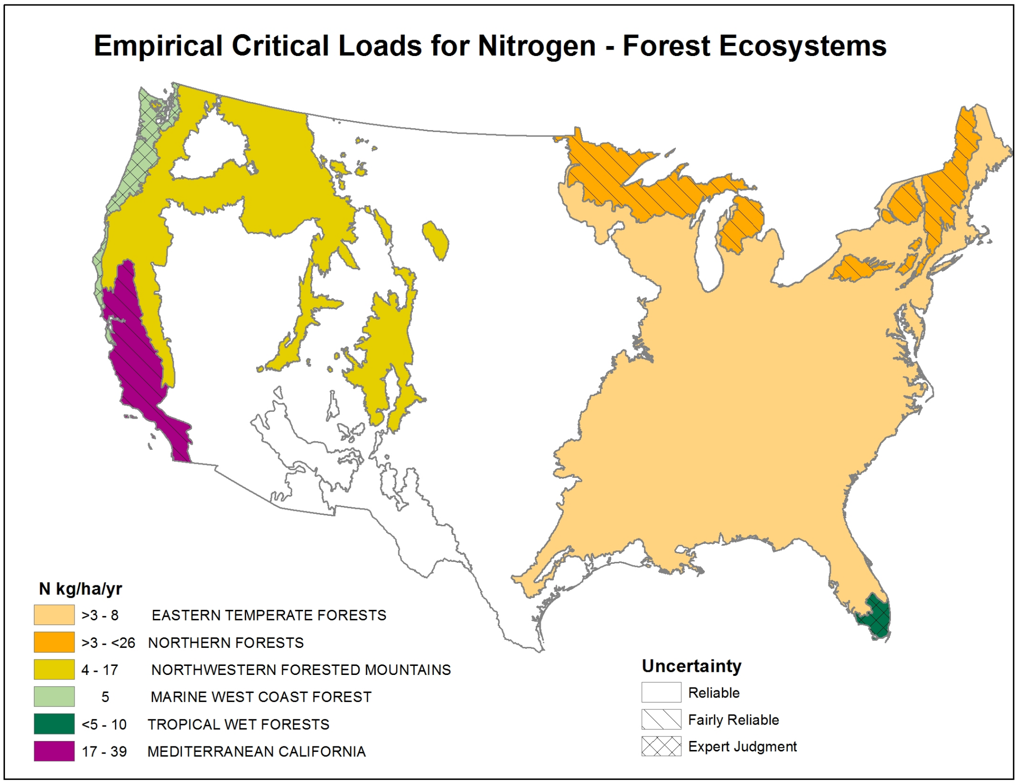
The maps on page 22 show empirical critical loads for lichen using methods developed by Geiser et al. (2010) and Root et al. (2015) and aggregated at the 4 km^2 grid. Root et al. (2015) estimated critical loads for the mountain regions in Washington, Oregon, Idaho, and Montana. Maps on page 22 represent a high and low critical load range, which is based on the minimum and maximum critical load presented in Geiser et al. (2010) and Root et al. (2015). Agriculture and urban areas, based on the 2001 National Landover Database (NLCD), were removed from the maps below and depicted as white spaces. See Geiser et al. (2010) and Root et al. (2015) for more details about how critical loads were estimated.

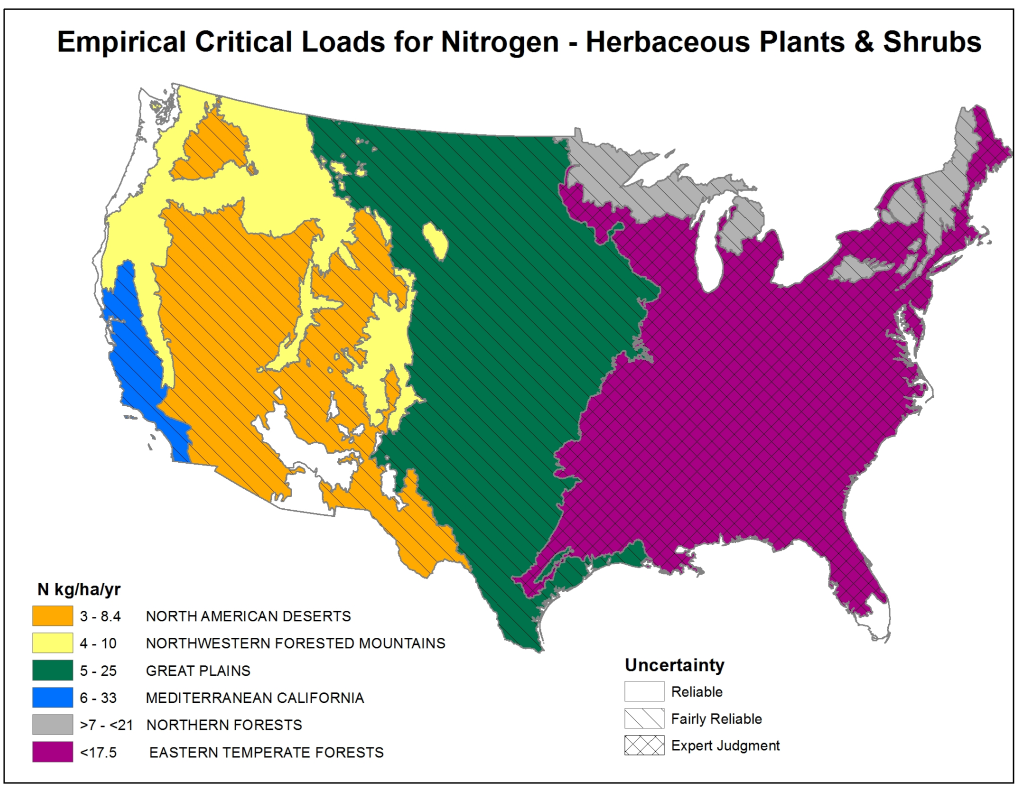
These empirical critical loads represent nutrient nitrogen impacts (eutrophication) of total nitrogen deposition (wet and dry) expressed in terms of kilograms of nitrogen deposition per hectare per year (N kg/ha/yr).

Minimum and maximum critical load values are specified; however, these values may represent different impacts (for example, a minimum critical load for lichen may be based on changes in community composition, while a maximum critical load for lichen may be based on changes to lichen chemistry which impact an individual species). Because a range of responses was reported for each receptor, the low end of the range provides a somewhat conservative critical load estimate.

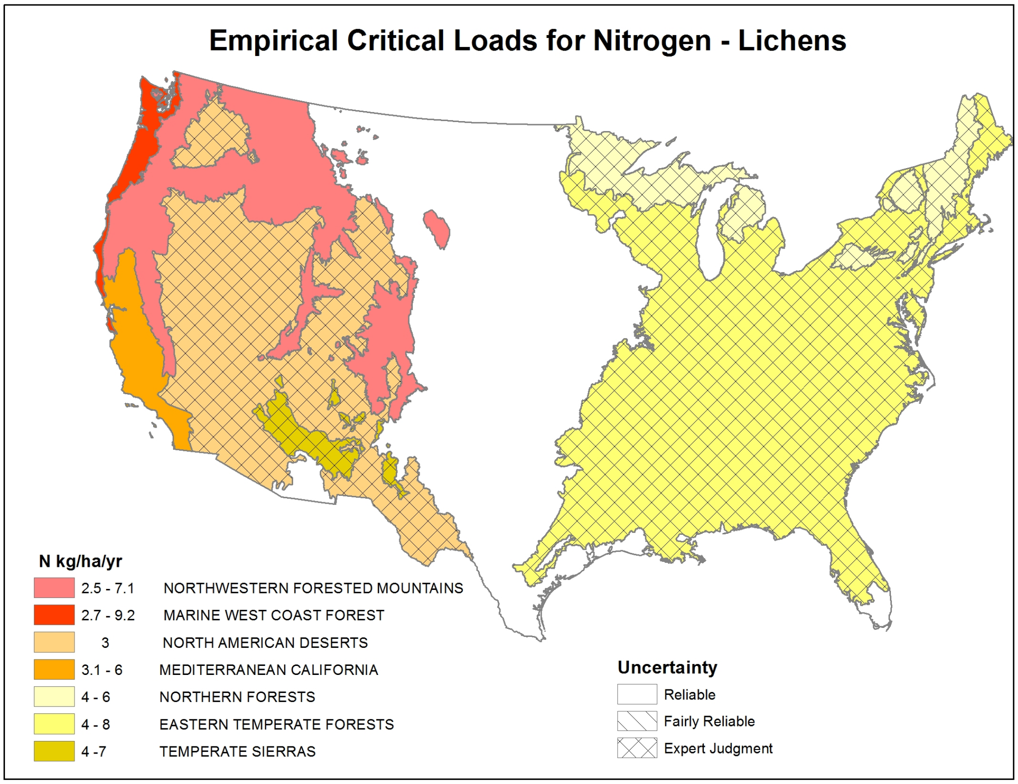
These critical loads represent a specific point in time and are mapped at a course scale. Because of the mapping scale, a receptor for a given map may not actually be present locally; site-specific data are therefore needed to verify the presence of the receptor. For example, the forest ecosystem receptor applies only to areas where forests occur. In addition, other environmental and biological factors (soil pH, species composition, etc.) may affect the critical load range for a given area. Additional empirical critical loads are being developed that account for more site-specific factors and will represent a much smaller geographic area.

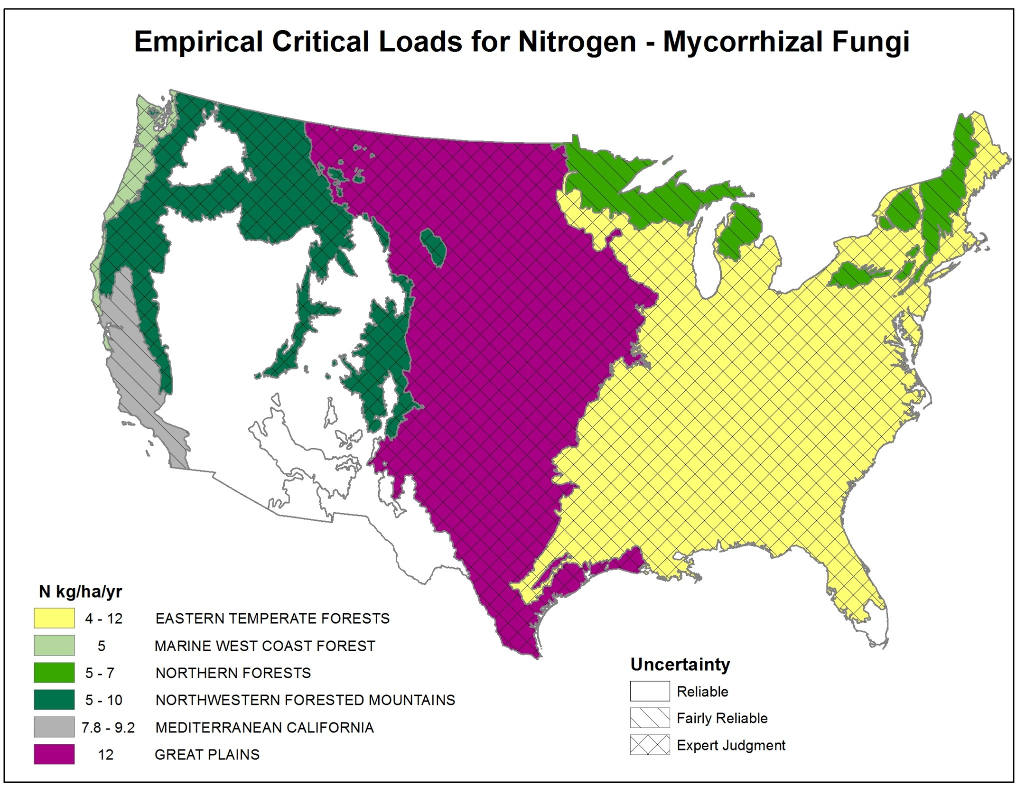
Uncertainty for maps on pages 20 and 21 are based on the strength of the scientific literature for each critical load receptor. Uncertainty is expressed as "reliable," "fairly reliable," and "expert judgment" (see Pardo et al., 2011a, 2011b for more details). Uncertainty for maps on page 22 is currently not available.



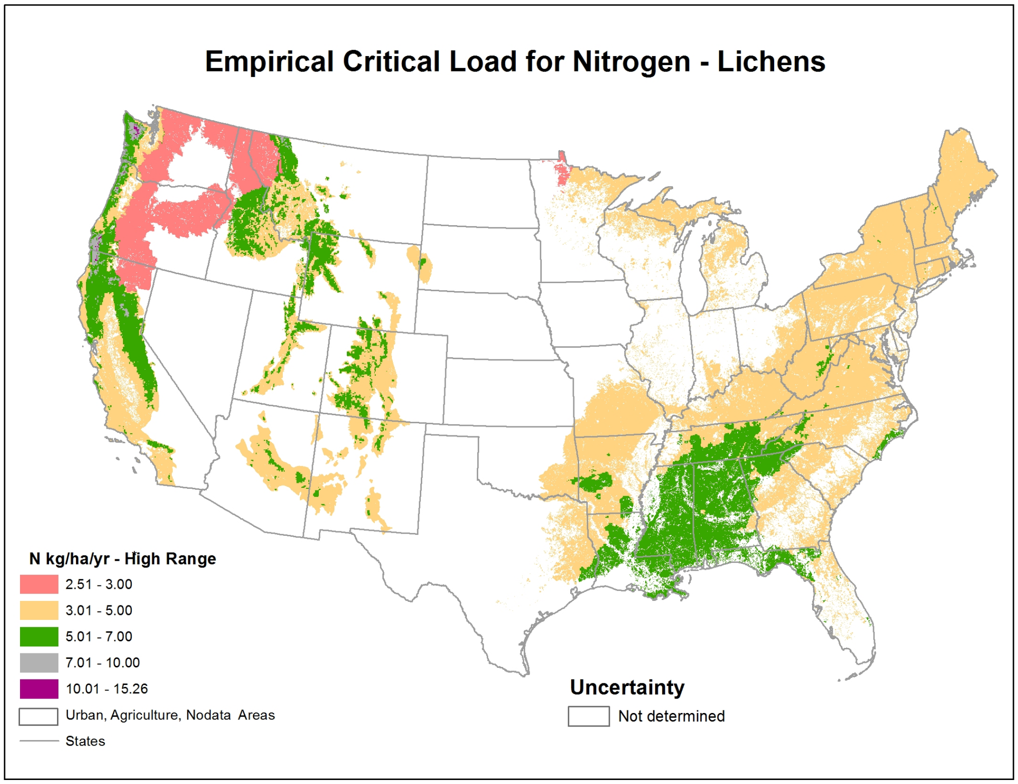


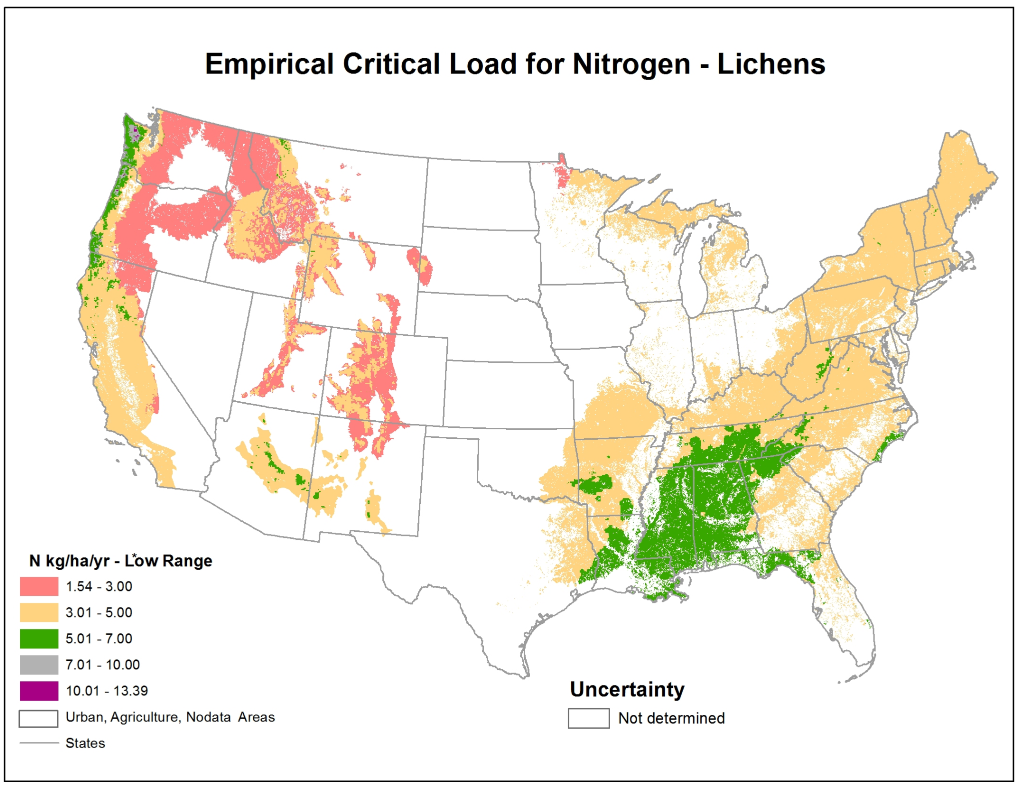
Empirical Critical Loads for Nitrogen for Forest Ecosystems (top) and Herbaceous Plants and Shrubs (bottom) (Pardo et al. 2011a, 2011b). The color scheme presented here is different from the original (Pardo et al. 2011a, 2011b) publication.





Empirical Critical Loads for Nitrogen for Lichens (top) and Mycorrhizal Fungi (bottom) (Reference: Pardo et al. 2011a, 2011b). The color scheme presented here is different from the original (Pardo et al. 2011a, 2011b) publication.





Empirical Critical Loads for Nitrogen for Lichens high range (top) and low range (bottom) (Geiser et al. 2010; Root et al. 2015).

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