Evaluation of the Use of Critical Loads to Mitigate Effects of Acidic Deposition to Forest Ecosystems in the Northeastern U.S.

Critical loads are a tool used to guide air quality management to protect sensitive ecosystems from adverse effects. Based on dynamic modeling and empirical approaches, many forest and aquatic ecosystems in the Northeast exceed critical loads for acidity and nitrogen.

THEME 2:

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http://www.nsrcforest.org

Project Summary

- Air pollution effects on ecosystems have been an important environmental concern in the Northeast since the 1970s. The concept of critical loads (CLs)/target loads (TLs) has been widely used in Europe for air quality management since the 1980s. A critical load is the input of air pollutants below which adverse ecological effects do not occur. Agencies in the U.S., such as the Forest Service, the Park Service and the Environmental Protection Agencies, and states are interested in using critical loads to guide air quality management to protect ecosystems from acidic deposition and nitrogen deposition. Three approaches are commonly used to establish critical loads: empirical observations and experiments; the application of steady-state (time-invariant) models; and application of dynamic (time-dependent) models. This research involved three projects on the development and application of critical loads to forest and aquatic ecosystems in the Northeast and beyond. The application of a dynamic model, PnET-BGC, was used to determine critical loads of lake/watershed ecosystems in the Adirondack region of NY. PnET-BGC was applied to a watershed at the Hubbard Brook Experimental Forest, NH to examine how changing climate influences the values of critical loads. Empirical critical loads for effects of atmospheric nitrogen deposition were developed for ecosystem types and attributes based on ecoregions for the U.S. We found that critical loads of acidity and nitrogen are routinely exceeded in forest ecosystems of the northeastern U.S. Under changing climate at the Hubbard Brook Experimental Forest in New Hampshire for acidity and nitrogen, the sensitivity of the forest ecosystem to acidic and nitrogen deposition increases, decreasing the critical loads.

Background and Justification

- Acid deposition originates from emissions of sulfur dioxide, nitrogen oxides from fossil fuel combustion (see Photo 1) and ammonia from agricultural activities.
- Forest and aquatic ecosystems in the northeastern U.S. are sensitive to inputs of air pollution (see Figure 1) and have been impacted to high loading by atmospheric sulfur and nitrogen deposition.

Photo 1. Emissions from a power plant.

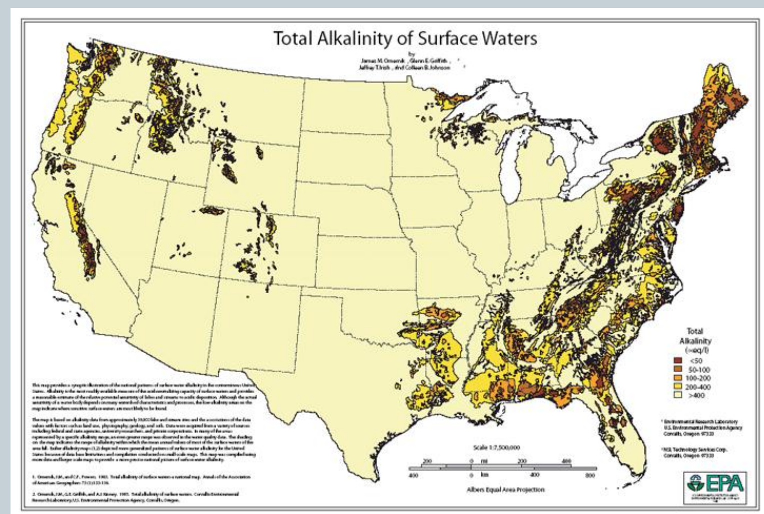

Figure 1. Map showing the acid sensitivity of waters in the U.S.

Background and Justification

- Effects of high acidic and nitrogen deposition include the acidification of forest soils and surface waters, and enhancing nitrogen cycling and availability and resulting in high nitrogen leaching. Sensitive terrestrial (lichens, sugar maple) and aquatic (aquatic invertebrates, fish) species may be impacted by elevated atmospheric deposition from air pollutants (see Photos 2 a,b).

Photo 2a. Brook trout, though relatively acid-tolerant, cannot survive in highly acidified streams and lakes. Photo: Barry Baldigo, USGS, Lovett et al. 2008.

Photo 2b. Sugar Maple (*Acer saccharum)* is sensitive to acidic soils and conditions of soil calcium depletion.

Background and Justification

- The concept of "critical loads" (CLs) and "target loads" (TLs) were introduced in the 1980s in Europe as an air pollution control strategy to protect sensitive ecosystems.
- A critical load is "the estimate of exposure to pollutants below which harmful effects on sensitive elements of the environment do not occur according to present knowledge." A critical load is a phenomenon that is realized over a long period (steady-state conditions).
- A target load is a load to protect an ecosystem that is undergoing change and not at steady-state with respect to inputs of atmospheric deposition.
- The U.S. Forest Service, the National Park Service, U.S. Environmental Protection Agency and some states have recently initiated critical loads programs.
- Ecosystems susceptible to effects of acidic deposition can be characterized by quantifying the extent to which current deposition exceeds the critical load.

  (exceedance = current deposition – critical Load).

Objectives

- Evaluate the use of critical load calculations as an approach to protect forest and aquatic ecosystems from effects of atmospheric deposition.
- Evaluate the response of lake/watersheds in the Adirondack region of New York to changes in acidic deposition and assess the landscape characteristics that influence sensitivity to acidic deposition.
- Evaluate if critical loads for northern forest ecosystems are altered under changing climate.
- Synthesize current research and develop empirical critical loads for ecosystem attributes for ecoregions across the U.S.
- Communicate results to policy makers and resource managers interested in developing secondary standards to protect sensitive ecosystems from air pollution disturbance.

Methods

- For this project, we used the dynamic model PnET-BGC to evaluate the response of forest watersheds to potential future changes in atmospheric deposition. PnET-BGC simulates energy, water and major elements (sulfur, nitrogen, calcium) in trees, soil and water in forest watersheds in response to meteorological inputs and atmospheric deposition (see Figure 2).

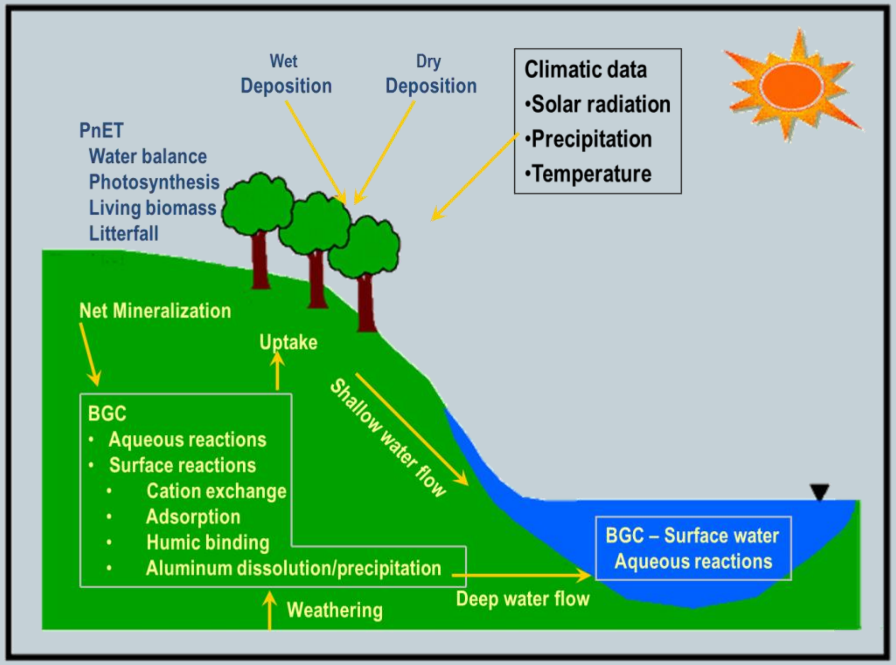

Figure 2. Conceptual diagram illustrating the processes depicted in the dynamic model PnET-BGC. PnET-BGC is a forest watershed model of energy, water and major element transformations.

Methods

- PnET-BGC was applied to 73 lake/watersheds in the Adirondack region of New York to assess the response of watersheds to proposals of controls of air quality emissions and resulting atmospheric deposition. The response of lake/watersheds were also evaluated in the context of landscape attributes that influence the sensitivity of forest watersheds to changes in acidic deposition (elevation, land cover, lake hydraulic residence time).

- We applied PnET-BGC to examine the influence of changing climate on the determination of critical loads of sulfate, nitrate and base cations to an acid impacted watershed at the Hubbard Brook Experimental Forest, NH.

- We synthesized available literature involving long-term measurements, gradient studies and nitrogen addition experiments to determine empirical critical loads of nitrogen for different ecosystem receptors for ecoregions across the U.S. The receptors evaluated included mycorrhizal fungi, lichens, herbaceous plants and shrubs, forest ecosystems and nitrate leaching.

Results and Outcomes

- Lake/watersheds in the Adirondacks should respond to additional controls on atmospheric sulfur and nitrogen emissions resulting in some recovery from the effects of elevated acidic deposition (see Figure 3).

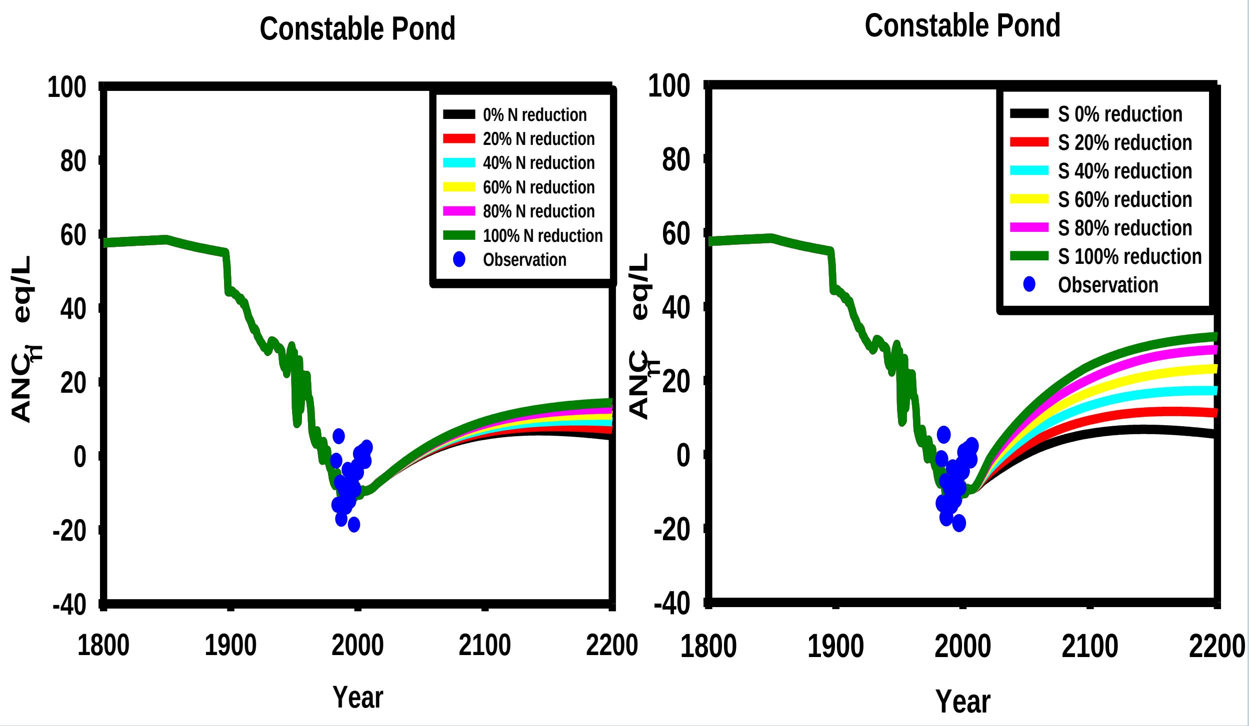

Figure 3. Hindcast and forecast simulations of acid neutralizing capacity (ANC) for Constable Pond in the Adirondacks. The figure depicts historical loss of ANC from increases in acidic deposition and potential future recovery under different loadings of sulfate and nitrate deposition.

Results and Outcomes

- Simulations project that over the next 50 years current and planned controls on atmospheric emissions will not be adequate to achieve full recovery of acid impacted lakes.

- The extent and rate of recovery of lake/watersheds appears to be influenced by elevation, forest cover and lake surface area.

- This work is described in Wu and Driscoll (2009) *Journal of Hydrology*, 378: 299-312.

Results and Outcomes

- Development of critical loads of acidity and nitrogen for ecosystems have rarely considered the effects of base cation deposition or changing climate.

- Three dimensional response surfaces for critical loads of sulfate, nitrate and base cation deposition were developed for the Hubbard Brook Experimental Forest, New Hampshire under current and potential future climate conditions (see Figure 4).

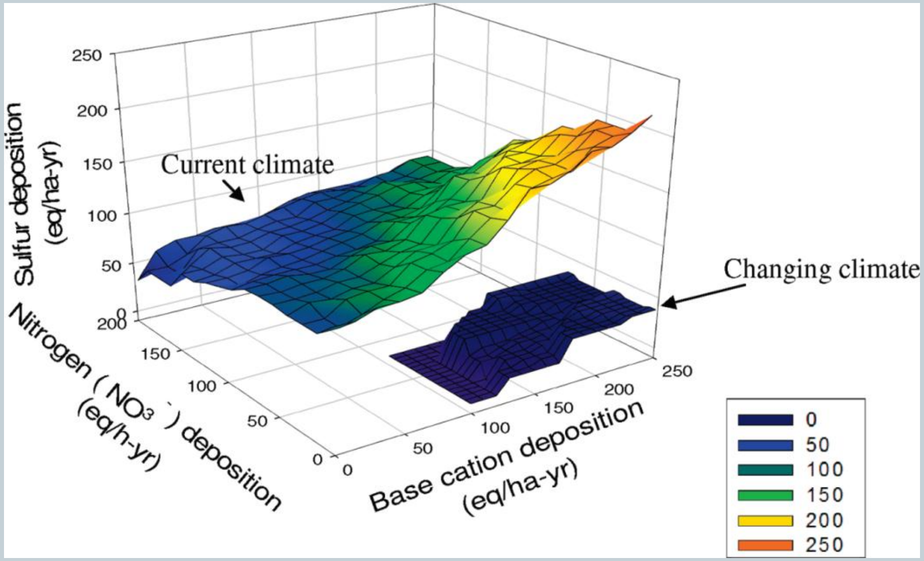

Figure 4. Three-dimensional response surfaces for ANC of 20 μeq/L for different sulfate, nitrate and base cation deposition under current and future climate change scenarios.

Results and Outcomes

- Our analysis shows that target loads for nitrate and sulfate will be lower under future climate conditions and under lower loading of base cation deposition.
- Greater emission controls may be needed to protect Northern Forest ecosystems from effects of atmospheric deposition under future changing climate.
- This work is summarized in Wu and Driscoll (2010) *Environmental Science and Technology* 44: 720-726.

Results and Outcomes

- The range of empirical critical loads of nitrogen for U.S. ecoregions, inland surface waters and freshwater wetlands range from 1-39 kg N/ha-yr, spanning the range of atmospheric nitrogen deposition for the U.S.
- Empirical critical loads of nitrogen increase for the following biotic indicators: diatoms, lichens and bryophytes, mycorrhizal fungi, herbaceous plants and shrubs, and trees.
- Maps for critical loads for nitrogen for ecosystems of the U.S. and their exceedances are shown for lichens and nitrate leaching (see Figures 5 a,b). For these and other ecosystem attributes exceedances largely occur in the eastern U.S.
- This work in summarized in Pardo et al. (2011) *Ecological Applications* 21: 3049-3082.

Results and Outcomes

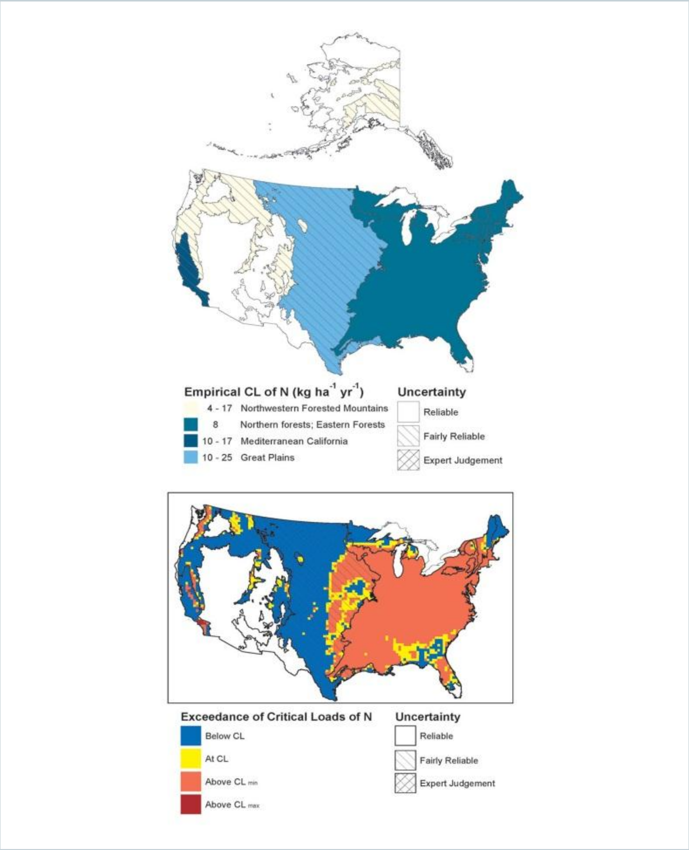

Figure 5a. Empirical critical loads of nitrogen for lichens and the exceedences of their critical loads.

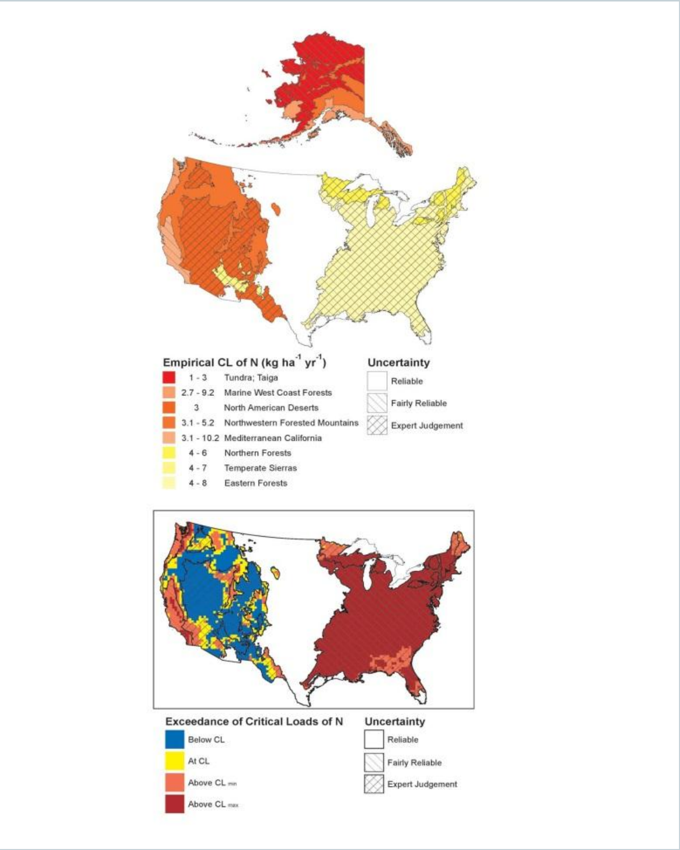

Figure 5b. Empirical critical loads of nitrogen for ecosystem nitrate leaching and the exceedences of their critical loads.

Implications and Applications in the Northern Forest Region

- The Northern Forest is sensitive to acidic deposition and has been highly impacted by acidic deposition.
- Soils and waters have been acidified by acidic deposition which has impaired ecosystem health. For example, 129 lakes in the Adirondacks are impaired due to elevated acidity (see Figure 6).

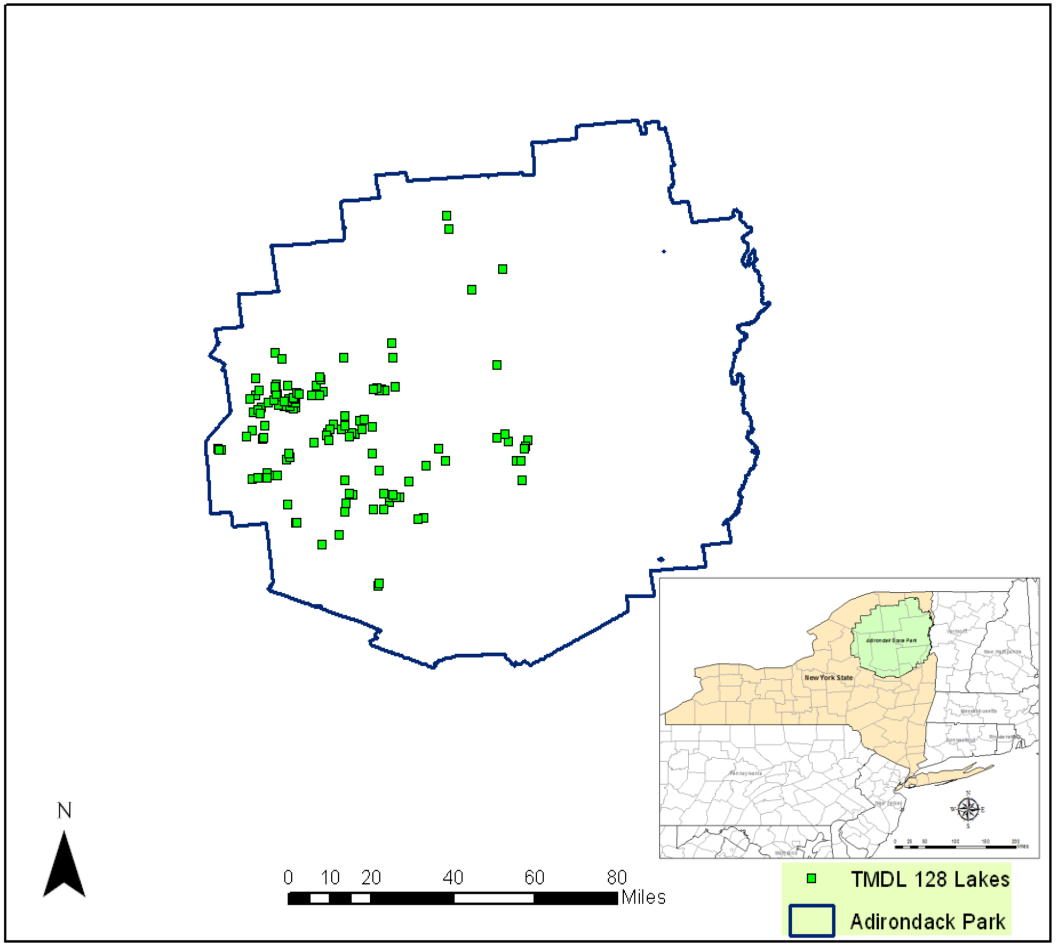

Figure 6. Location of lakes in the Adirondacks that are impaired due to acidity (pH < 6.0).

Implications and Applications in the Northern Forest Region

- Preliminary analysis shows that many watersheds in the Northern Forest exceed critical loads of sulfur and nitrogen, and that additional controls on emissions will be necessary to facilitate ecosystem recovery.

- Under future climate change, it is anticipated that watersheds will exhibit increased acid sensitivity due to the mobilization of legacy nitrogen that has accumulated in soil following decades of elevated atmospheric nitrogen deposition.

Future Directions

- Work on critical loads of acidity and nitrogen in the Northeast and elsewhere is continuing.
- Related research is being done working with States, the EPA and the Park Service to develop Total Maximum Daily Loads for acidity for watersheds in New York and Tennessee.
- Critical load studies are in progress for the Adirondacks and New Hampshire, and other regions.
- There is a need to develop an algorithm to depict changes in naturally occurring organic acids in response to changes in acidic deposition.

Journal Articles

- Wu W, Driscoll CT. 2009. Application of the PnET-BGC – an integrated biogeochemical model – to assess the surface water ANC recovery in the Adirondack region of New York under three multi-pollutant proposals. *Journal of Hydrology*, **378**: 299-312.
- Wu W, Driscoll CT. 2010. Impact of climate change on three-dimensional dynamic critical load functions. *Environmental Science and Technology*, **44**: 720-726.
- Baron JS, Driscoll CT, Stoddard JL, Richer E. 2011. Empirical critical loads of atmospheric nitrogen deposition for nutrient enrichment and acidification of sensitive US lakes. *BioScience*, **61**: 602-613.
- Pardo LH, Fenn M, Goodale CL, Geiser LH, Driscoll CT, Allen E, Baron J, Bobbink R, Bowman WD, Clark C, Emmett B, Gilliam FS, Greaver T, Hall SJ, Lilleskov EA, Liu L, Lynch J, Nadelhoffer K, Perakis S, Robin-Abbott MJ, Stoddard J, Weathers K, Dennis RL. 2011. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. *Ecological Applications*, **21**: 3049-3082.

Presentations

- "Critical Loads of Acidity at Hubbard Brook" presentation given at the Annual Hubbard Brook Meeting, West Thornton, NH, July 2009.
- "Watershed Modeling with PnET-BGC" presentation given to researchers and staff at the Great Smoky Mountain National Park", Gatlinburg, TN, 19 July 2009.
- "Modeling of the Hydrochemical Response of High Elevation Forest Watersheds to Climate Change and Atmospheric Deposition Using a Biogeochemical Model (PnET-BGC)" presentation given at the 2009 LTER All Scientists Meeting, Estes Park, CO, 13-16 September 2009.
- "The Response of Acid-Impacted Lake Watersheds in the Adirondack Region of New York to Decreases in Atmospheric Deposition" keynote speaker at the annual 2009 NADP Meeting and Scientific Symposium "Monitoring Change in Multi-Pollutant Deposition and Environmental Response: Bridging Air and Ecosystems", Saratoga Springs, NY, 6-8 October 2009.
- "Linkages among Acidic and Mercury Deposition and Climate Change in Ecosystems in the Adirondack Region of New York" presentation given at the annual Environmental Monitoring, Evaluation, and Protection (EMEP) NYSERDA Conference, Albany, NY, 14-15 October 2009.

Presentations (continued)

- "The Acid-base Chemistry and Biological Response of Lake/Watersheds in the Adirondacks to Changes in Acidic Deposition" presentation given to Syracuse University's Civil and Environmental Engineering Environmental Chemistry class (CIE 471), Syracuse, NY, 19 October 2009.
- "Trends in Atmospheric Deposition and Lake Chemistry and Fisheries in the Adirondacks" presentation given to the Laboratory Research Group, Syracuse University, Syracuse, NY, 30 October 2009.
- "Watershed Modeling with PnET-BGC" presentation given as a Distinguished International Scholar visitor to Queen's University for the Geography class, Kingston, Ontario, 7 April 2010.
- "The Road to Ecosystem Recovery from Acidic Deposition: Are We There Yet?" presentation given as a Distinguished International Scholar visitor to Queen's University for a Geography Seminar, Kingston, Ontario, 7 April 2010.
- "The Road to Ecosystem Recovery from Acidic Deposition: Are We There Yet?" presentation given for the Natural Science and Mathematics Seminar Series at Colgate University, Hamilton, NY, 5 November 2010.

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Presentations (continued)

- “The Road to Recovery from Acid Rain for the Adirondacks: Are We There Yet?” presentation given to the Harvard Business School Club, Syracuse, New York Chapter, Syracuse, NY 27 April 2011.
- “The Road to Recovery of Adirondack Lakes from Acidic Deposition: Are We There Yet?” presentation given as a Keynote Speaker for the Gordon Research Conferences Catchment Science: Interactions of Hydrology, Biology & Geochemistry, Bates College, Lewiston, ME, 10-15 July 2011.
- “Effects of Acid Rain on Sensitive Forest and Freshwater Ecosystems: Is the Problem Solved?” presentation given at the Institute of Marine Research “Workshop on acidification in aquatic environments: What can marine science learn from limnological studies of acid rain?” Tromso, Norway, 27-29 September 2011.
- "The Road to Recovery of Adirondack Lakes from Acidic Deposition: Are We There Yet?" presentation given at SUNY ESF’s Forest and Natural Resources Management Seminar Series of 2011, Syracuse, NY, 3 October 2011.

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Grants Resulting From NSRC Funding

- Critical Loads of Sulfur and Nitrogen Deposition to Protect and Restore Acid Sensitive Resources in the Adirondack Mountains (with T. Sullivan, E&S Environmental Chemistry Inc.), New York State Energy Research and Development Authority (9/1/08-8/31/11).
- Application of a Dynamic Watershed Biogeochemical Model (PnET-BGC) to Evaluate the Recovery of Sensitive Aquatic Resources at Great Smoky Mountains National Park From the Effects of Acidic Deposition, National Park Service (4/1/09-3/31/11).
- Hydrochemical Modeling of the Response of High Elevation Watersheds to Climate Change and Atmospheric Deposition (with J. Campbell, US Forest Service), U.S. Environmental Protection Agency STAR Program (8/1/09-7/31/12).
- Determining Total Maximum Daily Loads of Acidity for Adirondack New York Lakes, U.S. Environmental Protection Agency (1/1/11-12/31/12).