USDA

United States
Department of
Agriculture

Forest Service

**Northern
Research Station**

General Technical
Report NRS-80

Assessment of Nitrogen Deposition Effects and Empirical Critical Loads of Nitrogen for Ecoregions of the United States

L.H. Pardo, M.J. Robin-Abbott, C.T. Driscoll, editors




Abstract

Human activity in the last century has led to a substantial increase in nitrogen (N) emissions and deposition. This N deposition has reached a level that has caused or is likely to cause alterations to the structure and function of many ecosystems across the United States. One approach for quantifying the level of pollution that would be harmful to ecosystems is the critical loads approach. The critical load is defined as the level of a pollutant below which no detrimental ecological effect occurs over the long term according to present knowledge.

The objective of this project was to synthesize current research relating atmospheric N deposition to effects on terrestrial and aquatic ecosystems in the United States and to identify empirical critical loads for atmospheric N deposition. The receptors that we evaluated included freshwater diatoms, mycorrhizal fungi and other soil microbes, lichens, herbaceous plants, shrubs, and trees. The main responses reported fell into two categories: (1) biogeochemical, and (2) individual species, population, and community responses.

The range of critical loads for nutrient N reported for U.S. ecoregions, inland surface waters, and freshwater wetlands is 1 to 39 kg N ha^{-1} y^{-1}. This broad range spans the range of N deposition observed over most of the country. The empirical critical loads for N tend to increase in the following sequence for different life forms: diatoms, lichens and bryophytes, mycorrhizal fungi, herbaceous plants and shrubs, trees.

The critical loads approach is an ecosystem assessment tool with great potential to simplify complex scientific information and effectively communicate with the policy community and the public. This synthesis represents the first comprehensive assessment of empirical critical loads of N for ecoregions across the United States.

Cover Photos

Front, left to right, top: elevated nitrogen inputs to a prairie grassland in Minnesota (control) resulted in a decrease in species richness and an increase in invasive grasses (N addition). Photos by David Tilman, University of Minnesota, used with permission.

Front, left to right, bottom: elevated nitrogen inputs to a high elevation spruce fir forest (control) in Vermont resulted in decreased growth and increased mortality (high treatment). Photos by Linda Pardo, U.S. Forest Service.

Back top: The endangered checkerspot butterfly (*Euphydryas editha bayensis*). Photo by Stuart Weiss, used with permission.

Back bottom: The threatened purple pitcher plant (*Sarracenia purpurea* L.). Photo by Lingli Liu, used with permission.

Manuscript received for publication 25 February 2010

Published by:

U.S. FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073

May 2011

For additional copies:

U.S. Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: (740)368-0152
Email: nrspubs@fs.fed.us

Visit our homepage at: **http://www.nrs.fs.fed.us/**

Assessment of Nitrogen Deposition Effects and Empirical Critical Loads of Nitrogen for Ecoregions of the United States

Editors

L.H. Pardo

M.J. Robin-Abbott

C.T. Driscoll

LINDA H. PARDO, environmental engineer, U.S. Forest Service, Northern Research Station, 705 Spear St., South Burlington, VT 05403; lpardo@fs.fed.us

MOLLY J. ROBIN-ABBOTT, research assistant, Syracuse University, located at U.S. Forest Service, Northern Research Station, 705 S. Spear St., South Burlington, VT 05403

CHARLES T. DRISCOLL, professor, Syracuse University, Department of Civil and Environmental Engineering, 151 Link Hall, Syracuse, NY 13244.

Acknowledgments

This project was funded, in part, by the U.S. Environmental Protection Agency's Clean Air Markets Division. Initial work on this project was funded by the U.S. Forest Service Air Resource Management program. Funding was provided by the UCR Center for Conservation Biology and NSF grant DEB 04-21530. We appreciate the reviews of Suraj Ahuja, Allison Aldous, Mary Arthur, Jayne Belnap, John Blair, Tamara Blett, Matthew Brooks, Andrew Burton, William Currie, Daniela Cusack, Robert Edmonds, Heather Erickson, Ilka Feller, Benjamín Sánchez Gimeno, Rick Graw, Rick Haeuber, Cindy Huber, Randy Kolka, Steven Lindberg, Kathleen Lohse, Michelle Mack, Bill McDowell, Steve McNulty, Anne Mebane, Tom Meixner, John Melack, Kristi Morris, Bengt Nihlgård, Annika Nordin, Rock Ouimet, Michael Pace, Gareth Phoenix, Cindy Prescott, James Sickman, Jack Triepke, David Wedin, Trent Wickman, and Mark Williams. We would also like to thank Scott Collins, Robin Dennis, Amanda Elliot Lindsey, Ray Gomez, Robert Johnson, Duan Lei, and Bethany Zinni.

CONTRIBUTING AUTHORS

EDITH B. ALLEN, professor of plant ecology, Department of Botany and Plant Sciences and Center for Conservation Biology, University of California, Riverside, CA

JILL S. BARON, research ecologist, U.S. Geological Survey, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO

ROLAND BOBBINK, director/ senior consultant, B-WARE Research Centre B.V., Radboud Universiteit, Nijmegen, NL

WILLIAM D. BOWMAN, professor, Department of Ecology and Evolutionary Biology and Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO

CHRISTOPHER M. CLARK, AAAS science and technology policy fellow, Office of Research and Development, National Center for Environmental Assessment, Global Change Research Program, U.S. Environmental Protection Agency, Washington, D.C.

CHARLES T. DRISCOLL, professor, Syracuse University, Department of Civil and Environmental Engineering, Syracuse, NY

BRIDGET EMMETT, head of site, Centre for Ecology and Hydrology, Environment Centre Wales, Bangor, Gwynedd, UK

MARK E. FENN, research plant pathologist, U.S. Forest Service, Pacific Southwest Research Station, Forest Fire Laboratory, Riverside, CA

LINDA H. GEISER, ecologist, U.S. Forest Service, Pacific Northwest Region Air Program, Corvallis, OR

FRANK S. GILLIAM, professor, Department of Biological Sciences, Marshall University, Huntington, WV

CHRISTINE L. GOODALE, associate professor, Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY

TARA GREAVER, ecologist, Environmental Media Assessment Group, National Center for Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC

SHARON J. HALL, assistant professor, Ecology, Evolution, and Environmental Science, School of Life Sciences, Arizona State University, Tempe, AZ

ERIK LILLESKOV, research ecologist, U.S. Forest Service, Northern Research Station, Forestry Sciences Laboratory, Houghton, MI

LINGLI LIU, ORISE post-doctoral fellow, Environmental Media Assessment Group, National Center for Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC

JASON A. LYNCH, ecologist, Clean Air Markets Division, U.S. Environmental Protection Agency, Washington, D.C.

KNUTE NADELHOFFER, professor, Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI

LINDA H. PARDO, environmental engineer, U.S. Forest Service, South Burlington, VT

STEVEN S. PERAKIS, research ecologist, U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Corvallis, OR

MOLLY J. ROBIN-ABBOTT, research assistant, Syracuse University, located at U.S. Forest Service, South Burlington, VT

JOHN L. STODDARD, research life scientist, U.S. Environmental Protection Agency, Western Ecology Division, Corvallis, OR

KATHLEEN C. WEATHERS, senior scientist, ecosystem ecologist, Cary Institute of Ecosystem Studies, Millbrook, NY

CONTENTS

14 SOUTHERN SEMI-ARID HIGHLANDS

M.E. Fenn, E.B. Allen

14.1 Ecoregion description

Most of the Southern Semi-Arid Highlands ecoregion occurs in Mexico, but a portion centered on the Chiricahua Mountains of Arizona and New Mexico lies in the United States. The ecoregion description is adapted from CEC (1997). Rainfall is 300 to 600 mm, with biseasonal distribution (winter and summer). The mountains are volcanic in origin, with valleys and plains of alluvial sediments. The area lies at the intersection of the Sonoran and Chihuahuan Deserts, the Rocky Mountains, and the Sierra Madre (CEC 1997, Fig. 2.1). Consequently, this region is high in plant and animal diversity, having components of all four ecosystem types. Vegetation includes desert grassland interspersed with desert scrub (especially mesquite [*Prosopis* spp.] and acacia [*Acacia* spp.]) at low elevations, oak (*Quercus* spp.) and juniper (*Juniperus* spp.) at intermediate elevations, and coniferous forests at high elevations.

14.2 Ecosystem Responses to N Deposition

Potential nitrogen (N) deposition impacts to the southern highlands are likely to be similar to those described for Mediterranean California and North American Deserts ecoregions (Chapters 13 and 12), where similar vegetation types occur. In the lowlands, ecosystem responses to N deposition might include increases in exotic species, an effect which can lead to the accumulation of fire-sustaining fuel loads and thus increased fire frequency and severity. Other potential effects to lowland ecosystems include alteration of mycorrhizal fungal diversity, abundance, and functioning; shifts in lichen communities; and alteration of biotic crust composition as reported for other desert areas (see Chapter 12).

At intermediate elevations, ecosystem responses to N deposition might include alteration of lichen community composition or functional groups. Further increases in N deposition might affect mycorrhizae and herbaceous plant communities.

In the uplands, ecosystem responses to N at current deposition inputs likely include changes in lichen communities. We hypothesize that if N deposition increased two- to threefold (to approximately 12 to 18 kg ha^{-1} yr^{-1}), many effects reported for mixed conifer forests (see Chapter 13) would become apparent within a few years as N accumulates in the ecosystem. These expected effects would include elevated nitrate (NO_3^-) leaching and nitrogenous trace gas emissions from soil, impaired root production, altered mycorrhizal community composition and function, increased susceptibility to pests, and possible effects on understory biodiversity.

14.3 Range of Responses Observed

As we were not able to identify U.S. studies documenting a particular ecosystem response at a given level of N input for this ecoregion, we focus instead on the reported deposition for the U.S. ecoregion and documented ecosystem responses not linked to a specific N level.

The Chiricahua National Monument, a semi-arid site with sparse vegetation cover, is designated a Class I airshed under the Clean Air Act, with management objectives of clear views to 100 miles in any direction (NPS 2006). Threats to air quality include smelting and power plants in Mexico, but especially future plans for power plants within 50 miles of the border. Because both smelting and coal-fired power plants produce sulfur oxides (SO_x), the greater ecological threats in past decades may have come from sulfur (S) rather than N deposition. However, based on temporal trends in the National Atmospheric Deposition Program (NADP) and Clean Air Status and Trends Network (CASTNET) data at the Chiricahua site, N deposition is now greater than S deposition. Sulfur emissions have decreased in this area since around 1999 (US EPA 2008b), when smelters in Playas, New Mexico, and Cananea, Sonora, Mexico, closed. Total S deposition over the past several years as reported by NADP and CASTNET is approximately 1.2 kg ha^{-1} yr^{-1}. Even if the dry deposition of S is underestimated, S deposition levels would still be considered low.

The NADP and CASTNET data report total annual N deposition of 2 to 3 kg ha^{-1} yr^{-1} over the past 15 years at the Chiricahua site (US EPA 2008a). Average annual precipitation at the monitoring site is approximately 400 mm. Reported values of wet N deposition are three times greater than those for dry N deposition, suggesting that the CASTNET modeling approach is underestimating dry deposition and thus total deposition, as has been reported by CASTNET data for other semi-arid sites in the western United States (Fenn et al. 2009). According to NADP data, wet deposition of ammonium (NH_4^+) is similar to wet deposition of NO_3^-. However, dry deposition of ammonia (NH_3) is not measured, and as a result, total N deposition is almost certainly greatly underestimated.

In our judgment, bulk N deposition at the Chiricahua NADP site is likely closer to 4 to 5 kg ha^{-1} yr^{-1}. Depending on leaf area index, deposition to canopies in areas with significant vegetation cover would be even higher. Nitrogen deposition in this region was estimated to be 4 to 7 kg ha^{-1} yr^{-1}, by the Environmental Protection Agency's Models-3/Community Multiscale Air Quality (CMAQ) model (Byun and Schere 2006) and 2002 emissions data (Fenn et al. 2003b). Based on these estimates, we hypothesize that N deposition in the Chiricahua National Monument occurs at levels that can affect sensitive ecosystem components such as lichen community composition. Other possible effects of incipient N enrichment are community shifts of annual plant species (Fenn et al. 2003a). However, lichen communities likely have also been affected by historical S emissions from copper smelters in the region.

In the San Simon Valley, near Portal, Arizona, and adjacent to the Chiricahua National Monument, the winter annual plant community has undergone marked community change associated with the sustained proliferation of stork's bill (*Erodium cicutarium*), the Eurasian invasive winter annual plant (Schutzenhofer and Valone 2006). As a result, winter annual plant diversity has declined drastically and species composition has shifted. Possible factors contributing to these plant community changes are changes in climate, including decreased winter precipitation and more frequent drought, N deposition from agricultural fields and copper smelters (Bytnerowicz 2009[22]), and changes in the rodent community (Ernest et al. 2000). Preliminary atmospheric concentration data for NO_3^- and nitric acid (HNO_3) measured from December 2006 to January 2007 in the San Simon Valley were higher than expected for a remote site.[22]

14.4 Future Research Directions and Gaps in Data

Little is known about the effects of N deposition in the Southern Semi-Arid Highlands, as they have not been studied. N deposition needs to be measured within the major ecosystem types. Ecological effects should be investigated by surveying for sites showing N accumulation and enrichment associated with N deposition. Sulfur deposition levels and effects from past and current S deposition should also be evaluated. Where lichen communities occur, they can be surveyed for community shifts and S and N accumulation as early sentinels of ecosystem change and response to air pollution.

---

[22]Bytnerowicz, A. 2009. Personal communication. Ecologist, Pacific Southwest Research Station Forest Fire Laboratory, 4955 Canyon Crest Drive, Riverside, CA 92507.

LITERATURE CITED

Byun, D.; Schere, K.L. 2006. **Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system.** Applied Mechanics Reviews. 59: 51-77.

CEC (Commission for Environmental Cooperation). 1997. **Ecological regions of North America. Toward a common perspective.** Montreal, Canada: Commission for Environmental Cooperation. 71 p. Available at http://www.cec.org/files/pdf/BIODIVERSITY/eco-eng_EN.pdf (May 24, 2010).

Ernest, S.K.M.; Brown, J.H.; Parmenter, R.R. 2000. **Rodents, plants, and precipitation: spatial and temporal dynamics of consumers and resources.** Oikos. 88: 470-482.

Fenn, M.E.; Baron, J.S.; Allen, E.B.; Rueth, H.M.; Nydick, K.R.; Geiser, L.; Bowman, W.D.; Sickman, J.O.; Meixner, T.; Johnson, D.W.; and Neitlich, P. 2003a. **Ecological effects of nitrogen deposition in the western United States.** BioScience. 53: 404-420.

Fenn, M.E.; Haeuber, R.; Tonnesen, G.S.; Baron, J.S.; Grossman-Clarke, S.; Hope, D.; Jaffe, D.A.; Copeland, S.; Geiser, L.; Rueth, H.M.; Sickman, J.O. 2003b. **Nitrogen emissions, deposition, and monitoring in the western United States. BioScience.** 53: 391-403.

Fenn, M.E.; Sickman, J.O.; Bytnerowicz, A.; Clow, D.W.; Molotch, N.P.; Pleim, J.E.; Tonnesen, G.S.; Weathers, K.C.; Padgett, P.E.; Campbell.; D.H. 2009. **Methods for measuring atmospheric nitrogen deposition inputs in arid and montane ecosystems of western North America.** In: Legge, A.H., ed. Developments in environmental science. Relating atmospheric source apportionment to vegetation effects: Establishing cause effect relationships. Vol. 9. Amsterdam: Elsevier: 179-228.

NPS (National Park Service). 2006. **Chiricahua National Monument—air quality.** Washington, DC: U.S. Department of Interior, National Park Service, Chiricahua National Monument. Available at http://www.nps.gov/chir/naturescience/airquality.htm (Accessed May 12, 2010).

Schutzenhofer, M.R.; Valone, T.J. 2006. **Positive and negative effects of exotic *Erodium cicutarium* on an arid ecosystem.** Biological Conservation. 132: 376-381.

US EPA (U.S. Environmental Protection Agency). 2008a. **Clean air status and trends network—Chiricahua, total N.** Washington, DC: U.S. Environmental Protection Agency. Available at http://epa.gov/castnet/javaweb/charts/CHA467_totn.png (Accessed March 28, 2011).

US EPA (U.S. Environmental Protection Agency). 2008b. **Clean air status and trends network—Chiricahua, total S.** Washington, DC: U.S. Environmental Protection Agency. Available at http://epa.gov/castnet/javaweb/charts/CHA467_tots.png (Accessed March 28, 2011).