National Science Foundation Research Coordination Network: Reactive Nitrogen in the Biosphere

EAR-1049744/ DEB-1547041

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Objectives:

The objective of the RCN on reactive nitrogen (Nr) is to facilitate a community of researchers from a wide range of disciplines to exchange information and knowledge about Nr in the environment, thus fostering the creative science and synthesis needed to search for well-informed and integrative mitigation strategies. A parallel objective is to promote the communication of this science and synthesis to a broad audience of scientists and nonscientists.

Major activities since inception of the Reactive N RCN:

We have conducted seven workshops on diverse topics related to reactive nitrogen in the environment since the inception of this RCN in 2011. Each workshop has been multidisciplinary and has gathered together individuals who, despite their common interests in some aspect of nitrogen in the environment, would not likely have had reason to meet or work together had it not been for our workshops.

1. *July, 2011 – Workshop on climate-nitrogen interactions*, held at the Powell Center, Ft. Collins, CO. The main products were a technical report submitted to the National Climate Assessment (NCA) and publications of each of the seven chapters of that report in a special issue of *Biogeochemistry* (see list below). The technical report and the peer-reviewed papers were cited widely in the biogeochemistry chapter of the NCA.

Papers and reports emanating from the 2011 workshop:

National Climate Assessment Technical Report:

Suddick, E.C., and E.A. Davidson. 2012. The Role of Nitrogen in Climate Change and the Impacts of Nitrogen-Climate Interactions on Terrestrial and Aquatic Ecosystems, Agriculture, and Human Health in the United States: A Technical Report Submitted to the US National Climate Assessment. North American Nitrogen Center of the International Nitrogen Initiative (NANC-INI). Woods Hole Research Center, Falmouth, MA. Suddick & Davidson 2012

Biogeochemistry peer-reviewed papers (http://link.springer.com/journal/10533/114/1/page/1):

Suddick, E.C., P. Whitney, A.R. Townsend, E.A. Davidson (2012). The role of nitrogen in climate change and the impacts of nitrogen-climate interactions in the United States: Foreword to Thematic Issue. Biogeochemistry. DOI 10.1007/s10533-012-9795-z

Houlton, B.Z, E. Boyer, A. Finzi, J. Galloway, A. Leach, D. Liptzin, J. Melillo, T.S. Rosenstock, D. Sobota, A.R. Townsend (2012). Intentional vs. unintentional nitrogen use in the United States: Trends, efficiency, and implications. Biogeochemistry. DOI 10.1007/s10533-012-9801-5

Pinder, R.W., W.H. Schlesinger, G.B. Bonan, N.D. Bettez, T.L. Greaver, W.R. Wieder, E.A. Davidson (2012). Impacts of human alteration of the nitrogen cycle in the US on radiative forcing. Biogeochemistry, DOI: 10.1007/s10533-012-9787-z.

Robertson, G.P., T.W. Bruulsema, R. Gehl, D. Kanter, D. Mauzerall, A. Rotz, C. Williams (2012). Climate-nitrogen interactions in agriculture. Biogeochemistry. DOI 10.1007/s10533-012-9802-4

Baron, J.S., E.K. Hall, B.T. Nolan, J.C. Finlay, E.S. Bernhardt, J.A. Harrison, F. Chan, E.W. Boyer (2012) The Interactive Effects of Human-Derived Nitrogen Loading and Climate Change on Aquatic Ecosystems of the United States. Biogeochemistry. DOI 10.1007/s10533-012-9788-y

Porter, E., W.D. Bowman, C.M. Clark, J.E. Compton, L.H. Pardo, J. Soong (2012). Nitrogen, climate and biodiversity. Biogeochemistry. DOI 10.1007/s10533-012-9803-3

Peel, J., R. Haeuber, V. Garcia, L. Neas, A.G. Russell (2012). Implications of nitrogen-climate interactions for ambient air pollution and human health. Biogeochemistry. DOI 10.1007/s10533-012-9782-4

2. *November, 2012 – Workshop on human health impacts of excess nitrogen in air and water*, held in Bethesda, MD. This workshop included water and air quality experts from environmental sciences, epidemiologists, and human physiology researchers.

3. *August, 2013 – Conference entitled "Improving Nitrogen Use Efficiency in Crop and Livestock Production Systems: Existing Technical, Economic, and Social Impediments and Future Opportunities,"* cosponsored by the Soil Science Society of America (SSSA), American Geophysical Union (AGU), International Plant Nutrition Institute (IPNI), and The Fertilizer Institute (TFI), was held in Kansas City.

Peer-reviewed papers in the *Journal of Environmental Quality* emanating from the 2013 Kansas City conference, many of which are available as open access:

Journal of Environmental Quality Special Issue

David, M.B., C.G. Flint, L.E. Gentry, M.K. Dolan, G.F. Czapar, R.A. Cooke and T. Lavaire (2015). Navigating the Socio-Bio-Geo-Chemistry and Engineering of Nitrogen Management in Two Illinois Tile-Drained Watersheds. Journal of Environmental Quality. DOI: 10.2134/jeq2014.01.0036

Davidson, E.A., E.C. Suddick, C.W. Rice, and L.S. Prokopy. 2015. More food, low pollution (Mo Fo Lo Po): A grand challenge for the 21st century. Journal of Environmental Quality 44:305–311.

Fabián G. Fernández, Richard E. Terry and Eric G. Coronel (2014). Nitrous Oxide Emissions from Anhydrous Ammonia, Urea, and Polymer-Coated Urea in Illinois Cornfields. Journal of Environmental Quality. DOI: doi:10.2134/jeq2013.12.0496

Ferguson, R.B. 2015. Groundwater Quality and Nitrogen Use Efficiency in Nebraska's Central Platte River Valley. Journal of Environmental Quality. DOI: 10.2134/jeq2014.02.0085

Fernández, F.G., R.E. Terry, and E.G. Coronel. 2015. Nitrous oxide emissions from anhydrous ammonia, urea, and polymer-coated urea in Illinois cornfields. J. Environ. Qual. doi:10.2134/jeq2013.12.0496.

Jarecki, M.K., J.L. Hatfield and W. Barbour (2015). Modeled Nitrous Oxide Emissions from Corn Fields in Iowa Based on County Level Data. Journal of Environmental Quality. DOI: 10.2134/jeq2014.03.0100

Kanter, D.R. X. Zhang and D.L. Mauzerall (2015). Reducing Nitrogen Pollution while Decreasing Farmers' Costs and Increasing Fertilizer Industry Profits. Journal of Environmental Quality. DOI: 10.2134/jeq2014.04.0173

Lacey C. and S. Armstrong (2015). The Efficacy of Winter Cover Crops to Stabilize Soil Inorganic Nitrogen after Fall-Applied Anhydrous Ammonia. Journal of Environmental Quality. DOI: doi:10.2134/jeq2013.12.0529

McCrackin, M.L., J.A. Harrison and J.E. Compton (2015). Future Riverine Nitrogen Export to Coastal Regions in the United States: Prospects for Improving Water Quality. Journal of Environmental Quality. DOI: 10.2134/jeq2014.02.0081

Osmond, D.L., K. Hoag, A.E. Luloff, D.W. Meals and K. Neas. Farmers' Use of Nutrient Management: Lessons from Watershed Case Studies (2015). Farmers' Journal of Environmental Quality. DOI: 10.2134/jeq2014.02.0091

Perez, M. 2015. Regulating farmer nutrient management: A three-state case study on the Delmarva Peninsula. J. Environ. Qual. 44: 402–414. doi:10.2134/jeq2014.07.0304

Powell, M. and C. Rotz. 2015. Measures of nitrogen use efficiency and nitrogen loss from dairy production systems. J. Environ. Qual. 44: 336–344. doi:10.2134/jeq2014.07.0299

Soares, J., H. Cantarella, V.P. Vargas, J.B. Carmo, A.A. Martins, R.M. Sousa, C.A. Andrade (2015). Enhanced-Efficiency Fertilizers in N2O Emissions from Urea Applied to Sugarcane. Journal of Environmental Quality. DOI: 10.2134/jeq2014.02.0096

van Grinsven, H.J.M., L. Bouwman, K.G. Cassman, H.M. van Es, M.L. McCrackin, A.H.W. Beusen (2015). Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050. Journal of Environmental Quality. DOI: 10.2134/jeq2014

Weber, C. and L. McCann (2015). Adoption of Nitrogen-Efficient Technologies by U.S. Corn Farmers. Journal of Environmental Quality. DOI: 10.2134/jeq2014.02.0089

Zhang, X., D. Mauzerall, E.A. Davidson, D. Kanter, R. Cai (2015). The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. Journal of Environmental Quality. DOI: 10.2134/jeq2014.03.0129

A consensus statement from the conference was developed and posted:
Consensus Statement

A third product of the KC conference is a brochure for policy makers and the public, which is available on line at: NUE Brochure
In March 2014, the PI collaborated with colleagues from the SSSA, TFI, and the World Resources Institute (WRI) to brief policy makers about the conference and the consensus statement. We met with the following groups:

1. USDA
2. EPA
3. Staff of House and Senate agriculture committees
4. The Farm Bureau
5. NGOs convened by WRI

4. *February, 2015: A workshop on "Air Quality and Ecosystem Services"* was hosted by the US Park Service Santa Monica National Recreation Area, Thousand Oaks CA. The rationale and purpose of the workshop were as follows:

- Air pollution has negative effects on the environment and the organisms within the environment. The critical load concept has been used to help characterize the levels of pollution, particularly nitrogen deposition, that initiate damage to a variety of natural resources.
- Environmental policy and management decisions must often consider how changes to the environment, including those induced by excess air pollution, affect human welfare. The concept of ecosystem services is now being used to describe the benefits provided by nature and valued by people.
- The purpose of this workshop is to use our current understanding of critical loads of nitrogen to describe the impacts of air pollution and nitrogen deposition on specific ecosystem services.

The products of this workshop identified links between atmospheric deposition effects on sensitive natural resources and the ecosystem services they provide. Specifically, air pollution critical loads (CLs) were linked to specific final ecosystem goods and services (FEGS), using the STEPS (Stressor–Ecological Production function–final ecosystem Services) Framework to link changes in a biological indicator of a stressor to final ecosystem services. The STEPS Framework produces "chains" of ecological components that explore the breadth of impacts resulting from the change in a stressor. Chains are comprised of the biological indicator, the ecological production function, and the user group who directly uses, appreciates, or values the component. The effort required participation by scientists, resource managers, economists, and policy makers with expertise in aquatic ecology, water and soil biogeochemistry, plant physiology, modeling of environmental effects of pollution, and economics. The work products had two very different audiences: complex diagrams to provide details of interest to scientists and subject matter experts, and simple stories for management and public audiences. This dual approach was important as the stories are able to refine

the complex interactions into a few discrete steps ending in a biological unit that produced emotional connection and resonance with the audience. The stories and the detailed diagrams are valuable products from this workshop which, when used in combination, can serve to fill the gaps between science and policy in connecting air quality and ecosystem services. The STEPS framework has great potential in setting the foundation to provide the information that EPA needs to help set secondary NAAQS standards.

A detailed workshop report was published as a technical report by the National Park Service:

Blett, TF, Bell, MD, Clark CM, Bingham, D, Phelan, J., Nahlik, A., Landers, D., Irvine, I., and A. Heard.2016. Air Quality and Ecosystem Services Workshop Report: Santa Monica Mountains National Recreation Area, Thousand Oaks, CA- February 24-26, 2015. Natural Resource Report NSP/NRSS/ARD/NRR/2016/1107. National Park Service. Fort Collins, Colorado.
AQES Workshop Final Report Part 1
AQES Workshop Final Report Part 2

Four manuscripts from this workshop have been published in a special section in *Ecosphere*:

http://esajournals.onlinelibrary.wiley.com/hub/issue/10.1002/(ISSN)2150-8925.SF-AQ/

Bell, Michael D., Jennifer Phelan, Tamara F. Blett, Dixon Landers, Amanda M. Nahlik, George Van Houtven, Christine Davis, Christopher M. Clark, Julie Hewitt (2017). A framework to quantify the strength of ecological links between an environmental stressor and final ecosystem services. *Ecosphere*. 8 e01806. DOI: 10.1002/ecs2.1806

Chris Clark, Mike Bell, Eric Davidson, Christine Davis, Laurence Jones, Mark Fenn, Linda Geiser, Jim Boyd, Jana Compton, Tamara Blett (2017). Nitrogen-induced terrestrial eutrophication: Cascading effects and impacts on ecosystem services. *Ecosphere*. 8 e01877. DOI: 10.1002/ecs2.1877

Claire B. O'Dea, Sarah Anderson, Timothy Sullivan, Dixon Landers, and C. Frank Casey (2017). Impacts to ecosystem services from aquatic acidification: using FEGS-CS to understand the impacts of air pollution. *Ecosphere*. 8 e01807. DOI: 10.1002/ecs2.1807

Irvine, Irina, Tara Greaver, Jennifer Phelan, Robert D. Sabo, and George Van Houtven. (2017). Terrestrial acidification and ecosystem services: Effects of acid rain on bunnies, baseball and Christmas trees. *Ecosphere*. 8 e01857. DOI: 10.1002/ecs2.1857

5. *January 2016: A World Café session entitled "Managing Nutrients, Water, and Energy for Producing More Food with Low Pollution (MoFoLoPo); What Would Success Look Like?"* was held in Washington DC at the 16th National Conference of the National Council on Science and the Environment (NCSE).

Growing more food while conserving water and air resources has been called a "wicked problem" because the interactions among sectors and stakeholders are complex, and there are many stakeholders who stand to win and lose from evolving environmental, economic, energy, and food security policies. The objective of this World Café session was to explore what success for this wicked problem would look like from the varying perspectives of several stakeholders, including farmers, crop advisors, industry representatives, and researchers.

A summary of the workshop was published by Baron (2016). Baron 2016

Baron, J.S. 2016. Managing nutrients, water, and energy for producing more food with low pollution (MoFoLoPo); What would success look like? Environmental Development, 18:52–53.

A white paper was also produced prior to the workshop and published with open access in the Journal of

Environmental Studies Science Nutrients in the Nexus

Davidson, E.A., R.L. Nifong, R.B. Ferguson, C. Palm, D.L. Osmond, and JS. Baron. 2016. Nutrients in the nexus. Journal of Environmental Studies Science, DOI 10.1007/s13412-016-0364-y.

6. *October 2016: A Workshop to Develop a Nooksack Basin Nitrogen Assessment and Management Program* was held October 24-26, 2016, at Western Washington University, Bellingham WA. The goal was to kick start a demonstration project in Bellingham Bay and the Nooksack watershed as part of the International Nitrogen Management System. This watershed includes both British Columbia and Washington state and includes agricultural and municipal inputs and long-range transport deposition of N, with resultant pollution problems, including the estuary itself.

Subsequently, these workshop participants have organized a working group that has monthly calls and that organized a follow-on workshop in September 2017. They have continued data analysis and are attempting to raise their own research funds. In January 2018, they formed an organizational charter representing regional 8 academic institutions, 18 state, provincial and federal government agencies, 2 tribes and first nations, and 7 NGOs.was the starting point for creation of a new interdisciplinary regional project on nitrogen assessment and management. According to their charter, adopted in January 2018: "The Nooksack-Fraser Transboundary Nitrogen (NFT-N) Project is a collaboration of local constituents with a shared concern about nitrogen management in the airsheds and watersheds of the Nooksack River, Lower Fraser Valley, and the associated Sumas-Abbotsford aquifer. The Project gathers scientists and stakeholders from the U.S., Canada, and tribes/First Nations to work collaboratively to understand and address problems and opportunities associated with modern beneficial uses of nitrogen (N). While locally-driven, it also has broad regional participation as a North American demonstration project of a global network, designed to share experiences and strategies among regions with similar nitrogen use and management paradigms (International Nitrogen Initiative, http://www.initrogen.org/; International Nitrogen Management System, http://www.inms.international/)." The group's steering committee is comprised primarily of participants of the original 2016 workshop, which gathered this group together for the first time. This project is an excellent example of transdisciplinary analysis and co-learning by multiple stakeholder groups.

A poster on this project was presented at the 2017 AGU annual meeting in New Orleans by J. Lin and 13 workshop participants entitled: "Nitrogen Assessment in the Nooksack-Abbotsford-Sumas Transboundary Watershed."

https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/284233

An abstract was also submitted in early 2018 to the 6th Annual Interagency Conference on Research in Watersheds (ICRW), entitled: "Nitrogen inventories in the Nooksack-Fraser Transboundary Watershed: North American demonstration for the International Nitrogen Management System"

7. *December 2017: A workshop entitled: "Regional and Global N Input Datasets and Global N_2O Modeling" jointly sponsored by the Global Carbon Project – International Nitrogen Initiative Global N_2O Budget Workshop,* was held in New Orleans, LA.

Participants included ecologists, agronomists, and modelers from North America, China, Japan, Europe, and Africa and also included representative from United Nations Food and Agriculture Organization and the International Fertilizer Industry Association. The workshop had two major components with interacting goals and objectives: (1) Understanding and harmonizing N input datasets, and (2) Reviewing progress on a model inter-comparison of global N_2O emissions (NMIP). The first of these was the focus of the RCN

component of the workshop. Nitrogen input data is essential for studying and modeling many ecosystem functions, including carbon sequestration, NO and N_2O emissions from soils, hydrologic export of DON and DIN, and agricultural nitrogen use efficiency (NUE). Therefore, a variety of ecosystem, earth system, biogeochemistry, climate, and agricultural models require temporal and spatial datasets on N inputs to ecosystems, often including fertilizer and manure applications, N deposition, and biological N fixation (BNF). Similarly, compilations and synthesis of budgets of various forms of N at national and global scales require similar input data. When these analyses, whether model simulation outputs or budget synthesis, differ among studies and their publications, it is important to determine if those differences are due to use of different input datasets or due to different methods, assumptions, novel analysis, model structures, etc. Unfortunately, the use of available input datasets is often either inconsistent or less than entirely transparent. For example, the FAOSTAT datasets often require some manipulation or augmentation before they can be used in modeling or budgeting activities, but those modifications may differ among studies and could account for some differences in their respective findings. A key objective of this workshop was to provide clarity to the status of regional and global datasets on spatial and temporal variation in the estimated input rates of fertilizer and manure, N deposition, and BNF either by crop or non-crop associations. A Nitrogen budget data comparison working group was established, which has since assembled multiple N input datasets and is evaluating them to understand differences.

Coda

Since at least the 1980s, many scientists have studied human alteration of the global nitrogen cycle and its impacts. These efforts have made incremental progress in informing policy makers of the huge perturbation of the N cycle that has immense consequences for human health, ecosystem health, and economic prosperity. This RCN project contributed to advancing the search for sustainable solutions to the challenges of managing nitrogen wisely for producing abundant and nutritious food while minimizing unintended consequences of environmental pollution and human disease. By contributing to the US National Climate Assessment (2011 workshop product), partnering with the agronomic community and fertilizer industry to create a consensus statement (2013 workshop product), linking ecosystem critical loads with economic and non-economic values of ecosystem services (2015 workshop products), publishing an overview for environmental studies students (2016 World Cafe product), and organizing a trans-boundary regional effort of multiple stakeholders (2016 workshop outcome), we have assembled the kinds of partnerships among diverse disciplines and stakeholder groups needed to address this wicked problem with rigorous scientific investigation and cross-disciplinary communication and collaboration.

Other book chapters and peer-reviewed publications from the RCN project:

Davidson, E.A., M. B. David, J. N. Galloway, C. L. Goodale, R. Haeuber, J. A. Harrison, R. W. Howarth, D. B. Jaynes, R. R. Lowrance, B. T. Nolan, J. L. Peel, R. W. Pinder, E. Porter, C. S. Snyder, A. R. Townsend, and M. H. Ward. 2012. Excess nitrogen in the U.S. environment: trends, risks, and solutions. *Issues in Ecology*, Report Number 15, Ecological Society of America.
Davidson et al. 2012

Davidson, E.A., D. Kanter, E.C. Suddick and P. Syntharalingham. 2013. Chapter 3: N_2O: Sources, Inventories, Projections. In J. Alcamo, S.A. Leonard, A.R. Ravishankara, and M. A. Sutton (eds.). Drawing Down N_2O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report. United Nations Environment. Programme (UNEP), Nairobi, Kenya, ISBN: 978-92-807-3358-7 DEW/1748/NA
Davidson et al. 2013

Davidson, E.A. J.N. Galloway; N. Millar, A.M. Leach. 2014. N-related greenhouse gases in North America: Innovations for a sustainable future. Current Opinion in Environmental Sustainability, 9–10:1–8.
Davidson et al. 2014

Davidson EA and D Kanter. 2014. Inventories and scenarios of nitrous oxide emissions. Environmental Research Letters 9, doi:10.1088/1748-9326/9/10/105012.