Is Nitrogen Deposition Altering the Nitrogen Status of Northeastern Forests?

John D. Aber, Christine L. Goodale, Scott V. Ollinger, Marie-Louise Smith, Alison H. Magill, Mary E. Martin, Richard A. Hallett, and John L. Stoddard

Reasons for this study

• Dramatic increase in mobility & deposition of reactive forms of N due to human activities
  – NE United states: 5 – 10 fold increase in atmospheric deposition
  – 60 – 80% of deposited N as Nitrate

• 1990 CAAA Title IV, Sec. 407:
  – reduction of stationary source NO\textsubscript{x} emissions from 1980 levels by 2 million tons
  – limitation on emission rates from stationary coal-fired boilers & mobile sources (http://www.epa.gov/air/caa/caa407.txt)

• Predicted increase in power generation & vehicle miles traveled

→ Unlikely that NO\textsubscript{x} emissions will decrease significantly without further regulartory action

Nina Finger
Regional N deposition

- strong gradient of N deposition across NE United States
- southern New York & Pennsylvania:
  - High rates of wet/dry N deposition
  - 10 – 12 kg ha\(^{-1}\)yr\(^{-1}\)
- eastern Maine:
  - Low depositions
  - <4 kg ha\(^{-1}\)yr\(^{-1}\)
- Different source areas
  - Wet deposition: West-to-east gradient
    - declines with increasing distance from industrial areas
  - Dry deposition: South-to-north gradient
    - declines with increasing distance from coastal urban corridor
- Local storm paths and elevational effects can cause substantial regional variation in N deposition

Nina Finger
Chronic N additions

• Nihlgard (1985): damage of forest ecosystems due to excessive N deposition

• International research efforts

• Characteristics of N saturation
  – initial fertilization effects
  – followed by negative impacts on plant function and growth
  → Non-linear changes over time

• Two hypotheses for N saturation
  1) based on forest processes
  2) based on seasonal changes in $\text{NO}_3^-$ concentrations in surface waters

• Primary indicators for N saturation
  – $\text{NO}_3^-$ production in soils through net nitrification
  – Increasing N concentrations in foliage
  – Changes in C:N ratios in soils
  – Changes in quantity and seasonality of $\text{NO}_3^-$ concentrations in surface waters

http://harvardforest.fas.harvard.edu/research/nitrogensat.html
Theory suggests that [NO3] in stream water should be the primary indicator of N-deposition

Is this true for all forests in the Northeast?

<table>
<thead>
<tr>
<th>Location</th>
<th>N-Deposition</th>
<th>[NO3] in streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubbard Brook</td>
<td>stable @ 6-8kg/ha/yr</td>
<td>declined erratically (peak 70s)</td>
</tr>
<tr>
<td>Fernow Experimental Forest (WV)</td>
<td>stable @ 10-12kg/ha/yr</td>
<td>long-term increase</td>
</tr>
<tr>
<td>Schoharie Creek (NY)</td>
<td></td>
<td>increase (cyclical)</td>
</tr>
<tr>
<td>Lakes and streams in Adirondack &amp; Catskills</td>
<td></td>
<td>increases</td>
</tr>
<tr>
<td>New England Surface Waters</td>
<td></td>
<td>no significant trends</td>
</tr>
</tbody>
</table>

Factors causing the irregular trends:

1. Climate gradients and variations
2. Species Effects
3. Hydrologic Processes
4. Disturbance

Priscilla Cole
Climate Gradients and Variations

- Inter-annual variations in climate may cause as much as 20% difference in foliar \([N]\)
- Spikes in \([NO_3]\) caused by cold December with low snow cove
- Soil freezing causes increases in \([NO_3]\)
- Significant relationship between mean annual temperature and \([NO_3]\)

Priscilla Cole
Species Effects

- Different species respond differently to N-deposition, due to different N-cycling patterns
- Hardwoods with the same N-mineralization rates have different N-foliar concentrations

- Most of the differences in the spatial pattern in surface waters [NO3] in Catskills from different tree species driving different C:N

Priscilla Cole
Hydrologic Pathways

- NO3 can be either consumed or produced in streams, riparian areas, groundwater, hyporheic zones, and wetlands
- Spatial distribution & hydrologic connectivity = Differences in patterns of biotic and abiotic process
  - drivers of N retention
- Deep groundwater with high concentrations of [NO3]
  - may be an important source of N in Catskill surface waters
  - especially during base flow periods

Priscilla Cole
Disturbance

- Stream [NO3] losses increase following a disturbance
- Stream [NO3] losses maintained at low levels during forest regrowth
- Insect defoliation: spikes in [NO3] stream losses - similar with ice damage
- Land clearing for agriculture may reduce forest N-pools for N-cycling
- Plowing decreases soil C:N & increases nitrification for decades
- Forest fires reduce net nitrification rates and [NO3] losses
- Further human land uses complicate pattern of [NO3] in surface waters

Priscilla Cole
Long-term exposure to excess N from atmospheric deposition

• NERC (Natural Environment Research Council) workshop sponsored by EPA in 2001
• Status of N saturation in NE United States
  – Three key indicators: foliar, soil and surface water chemistry
  – data sets examined for spatial patterns in foliar, soil, or stream chemistry
• Simple question but complex to answer

• Northeast includes region from West Virginia to Maine
• Do foliar, soil and surface water chemistry respond in ways expected by theories if N saturation?

→ Spatial and temporal variations across the region
  – Climate
  – Species composition
  – Disturbance effects

Nina Finger
Approach

• Synthesis of existing data sets on stream, soil, and foliar chemistry in NE United States

• N deposition
  – modeled by using dry deposition coefficients
  – usage of published values

• Mean annual temperature
  – Monthly max & min calculated in consideration of latitude, longitude, elevation
  – Mean temperatures for each month were averaged
  – 12 monthly values were averaged for MAT

• Attempt to overcome confounding factors

• Direct relationship between N deposition and forest or surface water characteristics expected to be noisy

• Significant relationships may emerge as a result of large sample size
Expected results

- **Foliage**
  - Increase in foliar N concentrations
  - Decrease in foliar lignin to N

- **Soils**
  - Increased nitrification
  - Decrease in soil C:N ratio

- **Surface waters**
  - Increased NO$_3^-$ concentrations
  - Especially during dormant season

- Absence of significant trends would suggest there is no real effect of N deposition on N status
  \[ \rightarrow \] N deposition effects are small compared with variations resulting from
  - Disturbance
  - Climate variation
  - Species effects
  - Other factors

Nina Finger
Foliage
Foliar Study

- 362 different forest plots
- Red Spruce & Red Maple
- Relationships of Leaf Chemistry with respect to:
  - Latitude
  - Longitude
  - Elevation
  - Nitrogen Deposition
  - Mean Annual Temperature
  - Mean July Precipitation

Figure 2. Distribution of foliar chemistry sampling plots across the northeastern United States. Box plots indicate the median, quartiles, and range of measured foliar nitrogen (N) concentration and lignin:N ratios for red spruce and sugar maple in the growing season along an east-to-west longitudinal gradient, in Maine (ME), New Hampshire and Vermont (NHVT), Massachusetts (MA), eastern New York (NYE), western New York and Pennsylvania (NYW), and West Virginia (WV).
Two Major Forest Types in the NE: Spruce-Fir & Hardwood

Red Spruce: needle-leaved

Sugar Maple: broad-leaved deciduous

Priscilla Cole
Lignin is found in all vascular plants, mostly between the cells, but also within the cells, and in the cell walls. It makes vegetables firm and crunchy, and gives us what we call "fiber" in our food. It functions to regulate the transport of liquid in the living plant (partly by reinforcing cell walls and keeping them from collapsing, partly by regulating the flow of liquid). It is bonded in complex and various ways to carbohydrates in wood.

Priscilla Cole
Foliar Study: Significant Trends

- Differences in leaf-chemistry most strongly associated with elevation and climatic variables (predictable with elevation)
- Sugar Maple: Relationship observed in Percentage of N (foliar-N(g)/100g of leaves)
- Red Spruce: Strongest Relationship observed in Lignin:N with climate & elevation
  - Followed by N-Dep

<table>
<thead>
<tr>
<th>Variable</th>
<th>Red spruce</th>
<th>Sugar maple</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percent N</td>
<td>Lignin:N</td>
</tr>
<tr>
<td></td>
<td>(n = 203)</td>
<td>(n = 202)</td>
</tr>
<tr>
<td>Latitude</td>
<td>NS</td>
<td>0.06</td>
</tr>
<tr>
<td>Longitude</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td>Elevation</td>
<td>NS</td>
<td>0.38</td>
</tr>
<tr>
<td>Nitrogen deposition</td>
<td>NS</td>
<td>0.33</td>
</tr>
<tr>
<td>Mean annual temperature</td>
<td>NS</td>
<td>0.36</td>
</tr>
<tr>
<td>Mean July precipitation</td>
<td>NS</td>
<td>0.37</td>
</tr>
</tbody>
</table>

N, nitrogen; NS, not significant.
Note: Values expressed as R². All values shown are significant at p < 0.01.

Priscilla Cole
Triangles: Red Spruce  
Squares: Sugar Maple

- Sugar Maples have a much higher correlation between nitrogen% and both elevation and N-Deposition  
- Red Spruce have a higher correlation between their Lignin:N for both elevation and N-Dep

Priscilla Cole
Soils
Sites of data:

Fig: Distribution of Soil samples and % Nitrification in forest soil and mineral soil as a result of N deposition

Sudarshan Kumar Dutta
Fig: Nitrate deposition scenario in USA

Blett et al. 2004
Fig: Ammoniacal Nitrogen deposition scenario in USA

Sudarshan Kumar Dutta

Blett et al.

2004
The Sites varied in

- Vegetation type (Conifer vs. Hardwood)
- Elevation
- Soils
Fig: Soil C:N ratios (forest floor plus top 10 cm mineral soil) in relation to net mineralization and nitrification

Sudarshan Kumar Dutta

Ollinger et al. 2002
Fig: Nitrification increases with increase in temperature

http://cropwatch.unl.edu/nitrogenissue/nitrogen.pdf

Sudarshan Kumar Dutta
Fig: Overall view of Soil organic matter related to temperature and Rainfall

http://cropwatch.unl.edu/nitrogenissue/nitrogen.pdf

Sudarshan Kumar Dutta
## Table: Soil Carbon Mineralization and Soil Carbon to Nitrogen (C:N) Data sets

### Sudarshan Kumar Dutta

<table>
<thead>
<tr>
<th>Site</th>
<th>Forest type</th>
<th>Number of plots</th>
<th>Forest floor</th>
<th>Mineral soil depth (cm)</th>
<th>Incubation location</th>
<th>Duration (days)</th>
<th>C:N</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fernow, WV</td>
<td>HW</td>
<td>16</td>
<td>All</td>
<td>10</td>
<td>Field</td>
<td>56</td>
<td>O + M</td>
<td>1997</td>
<td>Christ et al. 2002</td>
</tr>
<tr>
<td>Fernow, WV</td>
<td>HW</td>
<td>21</td>
<td>NA</td>
<td>5</td>
<td>Field</td>
<td>365</td>
<td>M</td>
<td>1993</td>
<td>Gilliam et al. 1996</td>
</tr>
<tr>
<td>Huntington, NY</td>
<td>HW and conifer</td>
<td>4</td>
<td>Oe + Oa</td>
<td>15</td>
<td>Field</td>
<td>365</td>
<td>O + M</td>
<td>NA</td>
<td>Ohru et al. 1999, Bischoff et al. 2001</td>
</tr>
<tr>
<td>NE transect</td>
<td>Conifer</td>
<td>12</td>
<td>0a</td>
<td>10</td>
<td>NA</td>
<td></td>
<td></td>
<td>1992-1993</td>
<td>David and Lawrence 1996</td>
</tr>
<tr>
<td>NE transect</td>
<td>Conifer</td>
<td>31</td>
<td>Oe + Oa</td>
<td>10</td>
<td>Lab</td>
<td>28</td>
<td>O + M</td>
<td>1995</td>
<td>Lovett and Rusth 1999</td>
</tr>
<tr>
<td>NE transect</td>
<td>Conifer</td>
<td>11</td>
<td>Oe + Oa</td>
<td>NA</td>
<td>Lab</td>
<td>28</td>
<td>0</td>
<td>1988</td>
<td>McNulty et al. 1991</td>
</tr>
<tr>
<td>Montague Plain, MA</td>
<td>HW and conifer</td>
<td>16</td>
<td>NA</td>
<td>15</td>
<td>Field</td>
<td>42</td>
<td>M</td>
<td>1994</td>
<td>Compton et al. 1998</td>
</tr>
<tr>
<td>White Mountains, NH</td>
<td>HW and conifer</td>
<td>32</td>
<td>Oe + Oa</td>
<td>10</td>
<td>Field and lab</td>
<td>28-365</td>
<td>O + M</td>
<td>1998</td>
<td>Ollinger et al. 2002</td>
</tr>
<tr>
<td>White Mountains, NH</td>
<td>HW</td>
<td>36</td>
<td>Oe + Oa</td>
<td>10</td>
<td>Lab</td>
<td>28</td>
<td>O + M</td>
<td>1996</td>
<td>Goodale and Aber 2001</td>
</tr>
<tr>
<td>Maine (statewide)</td>
<td>Conifer</td>
<td>20</td>
<td>Oe + Oa</td>
<td>5</td>
<td>Lab</td>
<td>28</td>
<td>O + M</td>
<td>1999</td>
<td>Ivan Fernandez, University of Maine, Orono, ME, personal communication, 2001</td>
</tr>
<tr>
<td>Maine (statewide)</td>
<td>HW and conifer</td>
<td>28</td>
<td>Oe + Oa</td>
<td>NA</td>
<td>Lab</td>
<td>28</td>
<td>0</td>
<td>1995</td>
<td>Fernandez et al. 2000</td>
</tr>
<tr>
<td>Bear Brook, ME</td>
<td>HW and conifer</td>
<td>4</td>
<td>Oe + Oa</td>
<td>5</td>
<td>Lab</td>
<td>28</td>
<td>O + M</td>
<td>1998</td>
<td>Parker et al. 2001; Lindsey Rustad, USDA Forest Service, Durham, NH, and Ivan Fernandez, University of Maine, Orono, ME, personal communications, 2001</td>
</tr>
<tr>
<td>Acadia National Park, ME</td>
<td>HW and conifer</td>
<td>2</td>
<td>Oe + Oa</td>
<td>5</td>
<td>Lab</td>
<td>28</td>
<td>O + M</td>
<td>1998</td>
<td>Parker et al. 2001; Lindsey Rustad, USDA Forest Service, Durham, NH, and Ivan Fernandez, University of Maine, Orono, ME, personal communications, 2001</td>
</tr>
</tbody>
</table>

1. "Samples collected" indicates forest floor subhorizons and mineral soil sampling depths.
2. C:N indicates the soil horizon at which C:N ratios were calculated (O, organic layer; M, mineral layer).
Considerations:

• Methods for soil analysis are consistent
• Analytical methods for C and N concentration are relatively straightforward and consistent across the sites
• Net nitrification can be measured as a part of net mineralization
Fig: Net nitrification and net nitrogen mineralization in mineral soil in low deposition and high deposition sites

Sudarshan Kumar Dutta

Fenn et al. 2005
Ollinger et al. 2002
Findings:

- Across all the sites the C:N ratios varied from 15 to 48 in the forest floor and from 10 to 39 in the mineral soil. It is higher in coniferous than in deciduous stand.

- In forest floor the C: N ratios were significantly and inversely correlated with estimated nitrogen deposition. This trend differs between deciduous and coniferous.

- Trends between nitrogen deposition and C:N ratio in forest soils were significant and inverse correlation between % nitrification and soil C:N ratio is strong. But in mineral soil the trend is weaker.
Figure 5. (a) Measured ratios of carbon to nitrogen (C:N) in the forest floor in relation to estimated nitrogen deposition, showing different trends for hardwood and conifer stands (hardwood stands, $R^2 = 0.19, P < 0.001$; conifer stands, $R^2 = 0.27$, $P < 0.001$). Trends were weaker or nonsignificant in mineral soils (see table 4). (b) Percent nitrification in combined organic and mineral soils in relation to soil C:N ratio. Study areas and sampling methods are described in table 3. Trends were significant ($P < 0.001$) in organic, mineral, and combined soil layers, but data for combined soils are shown here because several studies did not report nitrification rates for individual horizons.
Findings (continued..)

- In mineral soils, trends between nitrification and C:N ratio were weaker or non significant.
- Both the soil horizons showed strong inverse correlation between C:N ratios and nitrification with in the threshold limit of 20 and 25
- N deposition patterns across the region have had a measurable effect on soil organic matter and net nitrification
- The C:N ratios were significantly correlated with elevations and estimated mean annual temperature (MAT) in forest soils of coniferous stand, not so much for deciduous stand
Table 4. Results of multiple linear regression analysis of soil carbon-to-nitrogen ratio and percent nitrification versus nitrogen deposition, mean annual temperature, and elevation.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean annual temperature</th>
<th>N deposition</th>
<th>Elevation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardwood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C:N—organic</td>
<td>103</td>
<td></td>
<td>X</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>C:N—mineral</td>
<td>103</td>
<td>X</td>
<td>X</td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td>Percent nitrification—organic</td>
<td>105</td>
<td>X</td>
<td>X</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>Percent nitrification—mineral</td>
<td>97</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Conifer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C:N—organic</td>
<td>48</td>
<td>X</td>
<td></td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>C:N—mineral</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>C:N—total</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Percent nitrification—organic</td>
<td>54</td>
<td></td>
<td>X</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Percent nitrification—mineral</td>
<td>41</td>
<td></td>
<td>X</td>
<td>X</td>
<td>0.42</td>
</tr>
</tbody>
</table>

NS, not significant; X, significant contribution to final equation.
Findings (Continued..)

• In mineral soil, although N deposition is not significant, but elevation and MAT were significant factors.

• In forest floor, % nitrification increased significantly with increasing N deposition; the trend was stronger in deciduous than coniferous forest.

• Trends between % nitrification in the forest floor and elevation or MAT were non significant or weakly significant.
Figure 4. Measured foliar $N$ concentration for (a) deciduous and (b) evergreen components of field plots in relation to the plot-level mean value estimated using AVIRIS.
Surface waters
Surface Waters

Data:
- 354 upland forested catchments
- lake & stream chemistry
- mid- to late 1990s

Main problems with data set:
- Unevenly distributed
- Variations in sampling frequencies
- Sometimes only summer sampled
Seasonal trends

- $\text{NO}_3^-$ concentrations generally peak during snow melt
- $\text{NO}_3^-$ concentrations are lowest during the growing season
  $\rightarrow$ highest biotic uptake
- Changes in seasonal pattern of stream $\text{NO}_3^-$ concentrations
  $\rightarrow$ indicators for identifying stages of N saturation

Nina Finger
Spatial trends

- Mean annual $\text{NO}_3^-$ concentrations decreased across NE United States
  - 20 – 25 $\mu$mol/l in Adirondacks & Catskill Mountains, NY
  - 10 $\mu$mol/l in Green Mountains, VT
  - 5 $\mu$mol/l in White Mountains, NH
  - 1 $\mu$mol/l in lakes ME

- Closely parallels spatial pattern of N deposition

- Increase both during growing and dormant season

- Increase steeper during dormant season (reduced plant uptake)
Three important trends

1) Watersheds receiving less than 7 kg N ha\(^{-1}\) yr\(^{-1}\) at their base or 9 – 13 kg N ha\(^{-1}\) yr\(^{-1}\) for whole watershed
   → \(\text{NO}_3^-\) concentrations rarely exceed 1 \(\mu\text{mol/l}\)
2) Relatively high N inputs
   → Lakes & streams with relatively high \(\text{NO}_3^-\) concentrations
      - High variability due to factors such as:
        - Species composition
        - Land use history
        - Bedrock mineralogy
        - Flow paths
   → Low \(\text{NO}_3^-\) losses unless N inputs are elevated to several times above pre-industrial conditions
3) As N deposition increased, variance in \(\text{NO}_3^-\) concentrations increased along with the mean
   → Differences among watersheds in \(\text{NO}_3^-\) leaching and its effects are more pronounced in areas of higher N deposition
Comparison to foliage & soil data

- Surface water data free from confounding covariation between N deposition, elevation, and climate factors

- Relationships between N deposition and NO$_3^-$ concentrations were far stronger than between elevation and spring or summer NO$_3^-$ concentrations

- Clear pattern across the region
  - Stream NO$_3^-$ export increased from Maine to West Virginia

- Watershed inorganic N retention
  - Little N deposition: > 90% retention
  - Large N deposition: 50 – 60% retention
Comparison to European forests

- Relationship between N deposition and NO$_3^-$ export observed for NE United States is similar to those for European forests.

- NE United States watersheds don’t receive N deposition as high (up to 30 kg N/ha yr$^{-1}$).

- Threshold of approx. 10 kg N ha$^{-1}$ yr$^{-1}$ is similar to observations from NE US.

ACD Annual Scientific Report 2004
www.asr.ucar.edu/2004/ACD/Achievements.htm
Limitations:

• The source of data is the previously collected data sets where method of soil sample collections were different in some cases.

• For net N mineralization there is no acceptable way to normalize data obtained from different incubation methods.

• Mineral soil nitrification showed an inverse relationship with N deposition.

• The large range of sites have variations in vegetation, elevation and soils.

Sudarshan Kumar Dutta
Limitations (Continued..)

• Although most of the wildly distributed species are included, foliar data sets are least evenly distributed over the study region

• Although soil characteristics do not change rapidly over time, they are also subject to large variation over very short spatial scales

• Decadal changes in surface water

Sudarshan Kumar Dutta
Conclusions:

“Is the nitrogen status of northern forests being altered by N deposition?” - YES

• Surface water data- Strong relationship between NO$_3^-$ concentration and flux across the nitrogen deposition gradient

• Soil data- Strong relationship between N deposition, soil C:N ratio and nitrification with some limitations

• Foliar Data- significant relationship between foliar data and N deposition

• Among these more emphasis has given surface water yield
  The climatic variation, disturbance, species composition and hydrologic pathways should also be considered as these affects the foliar, soil and stream chemistry at different spatial and temporal scale
Thank You