Nitrogen Pollution: from the Sources to the Sea

What is Hubbard Brook?

Hubbard Brook Experimental Forest

USDA Forest Service - 1955

Hubbard Brook Ecosystem Study

University scientists - 1963

Hubbard Brook Research Foundation

Non-profit Action/Think-tank - 1993
For forests and coastal waters...

1. What are the major sources of anthropogenic nitrogen in the Northeastern U.S.?

2. What are the ecological effects?

3. What are the most effective strategies for reducing anthropogenic nitrogen and its effects?
Northeast Population and Land Use Trends


Compiled by C. Goodale. HBRF 2003.
Nitrogen in a Pristine Landscape

Nitrogen Sources:
1. Lightning strikes
2. Fixation by plant-associated and soil bacteria

Nitrogen Fluxes:
3. Denitrification by bacteria
4. Atmospheric deposition
5. Watershed runoff

* A flux is the movement of nitrogen from one component of the ecosystem to another.
**Nitrogen in a Human-Altered Landscape**

**Nitrogen Sources:**
1. Imported food and feed
2. Vehicle emissions
3. Powerplant emissions
4. Fertilizer imports
5. Fixation in croplands
6. Agricultural emissions

**Nitrogen Fluxes:**
7. Atmospheric deposition
8. Wastewater from septic tanks and treatment plants
9. Agricultural runoff
10. Forest runoff
   - Urban runoff

* A flux is the movement of nitrogen from one component of the ecosystem to another.
Nitrate concentrations in runoff by land use

Global Population and Reactive Nitrogen Trends

Northeast Population and Land Use Trends

Nitrogen Cascade

Adapted from Galloway and Cowling, 2002.
In remote forested watersheds, such as the Hubbard Brook Experimental Forest, anthropogenic nitrogen sources are dominated by atmospheric emissions and deposition.

In large watersheds and coastal systems anthropogenic nitrogen sources are more diverse and are dominated by food.
Sources of Atmospheric Nitrogen Emissions

Primary airshed for LIS watershed (includes 65% of emissions to the watershed).

Distribution and Sources of Nitrogen Emissions

Map by G. Lawrence. HBRF 2001.

Legend

* Source area based on 21-hour back trajectory.

- Transportation NOx: 39%
- Electric utility NOx: 26%
- Animal waste NH3: 16%
- Area sources NOx: 8%
- Chemical fertilizer NH3: 8%
- Domestic animals NH3: 4%
- Human NH3: 2%
- Wastewater & septic NH3: 2%
- Industry NH3: 1%
How have emissions changed over time?

(Total U.S. NO\textsubscript{x} emissions)

Source: EPA National Air Pollution Emission Trends.
Nitrogen Wet Deposition

Wet Nitrate

- 1983-
- 1985

Wet Ammonium

- 1992-
- 1994

- 1995-
- 1997

kg NO$_3^-$/ha/yr

kg NH$_4^+$/ha/yr

NITROGEN TRENDS IN PRECIPITATION
HUBBARD BROOK EXPERIMENTAL FOREST, NH

Likens and Bormann 1995.
A recent analysis of 24 NADP sites in the Northeast and mid-Atlantic quantified the relationship between NOx emissions and concentrations of nitrate in precipitation.

Total Nitrogen Deposition

What environmental issues are linked to nitrogen pollution?

- Ground-level ozone
- Acid rain and forest effects
- Reduced visibility
- Groundwater contamination
- Climate change
• Ozone formation is dependent on nitrogen oxides.

• Decreases net photosynthesis and reduces forest productivity.

• Large areas in the Northeast exceed EPA health standards for ozone.
Ozone injury on white pine: Tip necrosis.
Source: NC Cooperative Extension.

Visible Ozone injury to ash: Purple stippling on upper leaf surface is due to ambient ozone. Source: National Park Service, Acadia National Park, ME.

Slide by S. Ollinger.
Isolating the Effects of Nitrogen Deposition
Harvard Forest, MA

Clockwise from left:

High treatment (150 kg N/Ha)

Low treatment (50 kg N/Ha)

Control

Slide by J. Aber.
Acidic deposition depletes nutrient cations and acidifies soils; these processes can be accompanied by increased plant stress from aluminum toxicity.

**Acid Deposition Effects on Trees**

Red Spruce
- Calcium leached from needle membranes
- Decreased cold tolerance
- Increased freezing injury

Sugar Maple
- Calcium & magnesium leached from soil
- Aluminum mobilized & taken up by tree
- Root function & nutrition impaired

Areas with 8 kg N/ha-yr or more tend to show high nitrate in streamwater.

36% of Northeast forests receive >8 kg N/ha-yr

Climatic data
• Solar radiation
• Precipitation
• Temperature

PnET
Water balance
Photosynthesis
Living biomass
Litterfall
Net Mineralization

BGC – Surface water
Aqueous reactions
Uptake
Deep water flow
Shallow water flow
Weathering
Wet deposition
Dry deposition

BGC
• Aqueous reactions
• Surface reactions
• Carbon exchange
• Adsorption
• Humic binding
• Aluminum dissolution/precipitation

PnET BGC (Biogeochemical) Model

Slide by C. Driscoll.
## Thresholds for Positive Chemical Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen deposition</td>
<td>&lt; 8 kg/ha-yr</td>
</tr>
<tr>
<td>Soil base saturation</td>
<td>&gt; 20%</td>
</tr>
<tr>
<td>Acid neutralizing capacity</td>
<td>&gt; 50 µeq/L</td>
</tr>
<tr>
<td>Stream pH</td>
<td>&gt; 6.0</td>
</tr>
<tr>
<td>Stream aluminum</td>
<td>&lt;2.0 µmol/L</td>
</tr>
</tbody>
</table>

From Aber et al. 2003 and Driscoll et al. 2001.
Emission Reduction Scenarios

- Base = 1990 Clean Air Act.

2. 75% reduction in electric utility NO_x from current levels.

3. 60-90% reduction in passenger vehicle NO_x (consistent with EPA Tier 2 regulations).

4. Aggressive vehicle reduction (90% reduction in passenger car emissions beyond Tier 2).

5. All of the above with a 34% reduction in agricultural NH_3 emissions by animal waste treatment.

Also, run with a 75% reduction in sulfur emissions from electric utilities beyond 1990 Clean Air Act requirements.
Improvement in Indicators at Hubbard Brook, NH

Driscoll et al. 2003.
From Driscoll et al. 2003.
Hubbard Brook Experimental Forest, NH

Results at year 50.

Slide by C. Driscoll.
Biscuit Brook, NY

Results at year 50.

1990 CAAA

Tier 2

Utility

Integrated

ANC (µeq/L)

Target ANC = 50 µeq/L

Slide by C. Driscoll.
Coastal Over-Enrichment

- Nitrogen is the primary nutrient that causes coastal over-enrichment.
- Over-enrichment can lead to low oxygen events that can cause fishkills.
- Over enrichment can lead to the loss of seagrass habitats.
Low Oxygen Events in Long Island Sound

Maximum area of hypoxia (km²)

Length of Hypoxic Event (days)

Days

Max. Area

Courtesy of Connecticut Department of Environmental Protection. 2001.
From Driscoll et al. 2003.
Nitrogen and the Food Cycle

1. Food imported

2. Food consumed

3. Nitrogen wasted

4. Nitrogen discharged by treatment plants

Meat: 7.7 grams N
Milk: 1.3 grams N
Bread: 0.4 grams N
Peas: 0.7 grams N

HBRF 2003.
Where does the nitrogen that enters watersheds go?

- Returned to atmosphere
- Stored in biomass
- Stored in soil
- Exported to groundwater
- Exported to estuaries

From Howarth et al. 2002.
From Driscoll et al. 2003.
Nitrogen sources to the Casco Bay watershed

- Utility and other point sources NOx: 24%
- Transportation NOx: 37%
- Animal waste NH3: 20%
- Area sources NOx: 7%
- Chemical fertilizer NH3: 5%
- Domestic animals NH3: 2%
- Human NH3: 2%
- WWTP and septic NH3: 2%
- Industry NH3: 1%

HBRF 2002.
Where is Nitrogen Deposited on the Land?

Wet Nitrate 1995-1997

kg NO$_3^-$ ha$^{-1}$ yr$^{-1}$

kg NH$_4^+$ ha$^{-1}$ yr$^{-1}$

Reduced Nitrogen Loading to Estuaries

- Reduced N emissions:
  - 75% reduction in utilities NO\textsubscript{x}.
  - EPA Tier 2 reductions in vehicle emissions.
  - 90% reduction above Tier 2 in NO\textsubscript{x} from cars.
  - 34% reduction in agriculture NH\textsubscript{3}.

2. Biological Nitrogen Removal for WWTPs.

3. Septic system improvements.

4. Offshore pumping of waste.

5. Agricultural BMPs (33% reduction in runoff N).
N Fertilization
N Fixation
Atmospheric Deposition
Livestock Waste

Crop Harvest
Animal Grazing
Ammonia Volatilization
Denitrification

Agricultural Lands
(Crops and Pastures)

Above Fall Line N Inputs

Watershed and Riverine Losses

Below Fall Line N Inputs

SWAT NPS Runoff
Point and NPS Septic Systems

Soil Climate N Fertilization Land Cover
Atmospheric Deposition

Human Population Wastewater N Discharge
Atmospheric Deposition Nitrogen Fixation

Upland Forests

Atmospheric N Deposition

Nitrogen Inputs to Estuary
REDUCTIONS IN NITROGEN LOADING TO LONG ISLAND SOUND AND CASCO BAY

From Driscoll et al. 2003.

BMPs = Best Management Practices
BNR = Biological Nitrogen Removal

Percent Reduction in N loading

75% utilities NOx
Agriculture BMPs
Mobile Tier 2
Aggressive Mobile
Animal Waste Treatment
Coastal Zone BNR
Basinwide BNR
Offshore pumping
Basinwide BNR + septic
Integrated
More WATERSN Results

Whitall et al. in review.
Conclusions: N Inputs

- Anthropogenic N inputs to upland forested watersheds are dominated by atmospheric emissions and deposition of nitrogen from transportation (39%) and electric utilities (26%).

- Atmospheric deposition of N to forests at the Hubbard Brook Experimental Forest has not decreased since measurements began in the 1960s.

- N to loading to downstream estuaries in the Northeast that were examined in this study is dominated by wastewater inputs (36-81%) derived from food and atmospheric deposition (14-35%).

- Runoff from agricultural and urban lands can be large inputs in some Northeast watersheds (up to 20% each).
Conclusions: N Effects

- Ambient ozone is projected to reduce forest productivity in the NE from 4-14%.

- 36% of forestland in the Northeast receive N deposition above 8 kg/ha/yr – a level which tends to result in elevated nitrate leaching.

- Nitrate is an increasing component of the acidity in acid rain and a key contributor to acid episodes that release Al to streams.

- Over-enrichment by nitrogen has caused low-oxygen, loss of habitat and algal blooms in some Northeast estuaries (such as Waquoit Bay, MA).
The 1990 Clean Air Act Amendments are not likely to reduce nitrogen deposition below 8 kg/ha-yr at Biscuit Brook, NY or Hubbard Brook, NH.

An additional 30% cut in total nitrogen emissions would likely bring deposition to levels that would reduce nitrogen leaching to streams.

The recovery thresholds for ANC, pH and soil base saturation are not achieved at either site under any N-only control scenarios.

ANC turns positive at Hubbard Brook under the ^ scenario.
Policies that include a 75% reduction in SO2 emissions from electric utilities achieve all the chemical thresholds at Biscuit Brook within 50 years, and approaches them at Hubbard Brook.

The PnET model does not evaluate effects of nitrogen emissions reductions on ground-level ozone.

Additional model runs show that seasonal reductions in N emissions may help with summertime ozone, but year-round controls are more effective in mitigating ecosystem effects.
Improved wastewater treatment results in the largest reduction in nitrogen pollution in our two case studies (up to 57% for Long Island Sound).

Emissions reductions of NO\textsubscript{x} from utilities and vehicles has the added benefit of reducing nitrogen pollution to coastal waters (up to 14% for Casco Bay).

An integrated management plan that includes nitrogen controls on several sources achieves maximum reductions in nitrogen pollution.
NYSERDA
Davis Conservation Foundation
Geraldine R. Dodge Foundation
Harold Whitworth Pierce Charitable Trust
Jessie B. Cox Charitable Trust
John Merck Fund
McCabe Environmental Fund of NHCF
Merck Family Fund
Sudbury Foundation
Switzer Environmental Fund of NHCF
Public Policy Activity

1. Power plant bills in Congress.

2. Tailpipe emissions standards at the state and federal levels.


4. Total maximum daily load planning.

5. Incentives for improved agricultural practices in the U.S. Farm Bill.