Nitrogen Pollution: from the Sources to the Sea

C. Driscoll, D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence, S. Ollinger

What is Hubbard Brook?

Hubbard Brook Experimental Forest

USDA Forest Service - 1955

Hubbard Brook Ecosystem Study

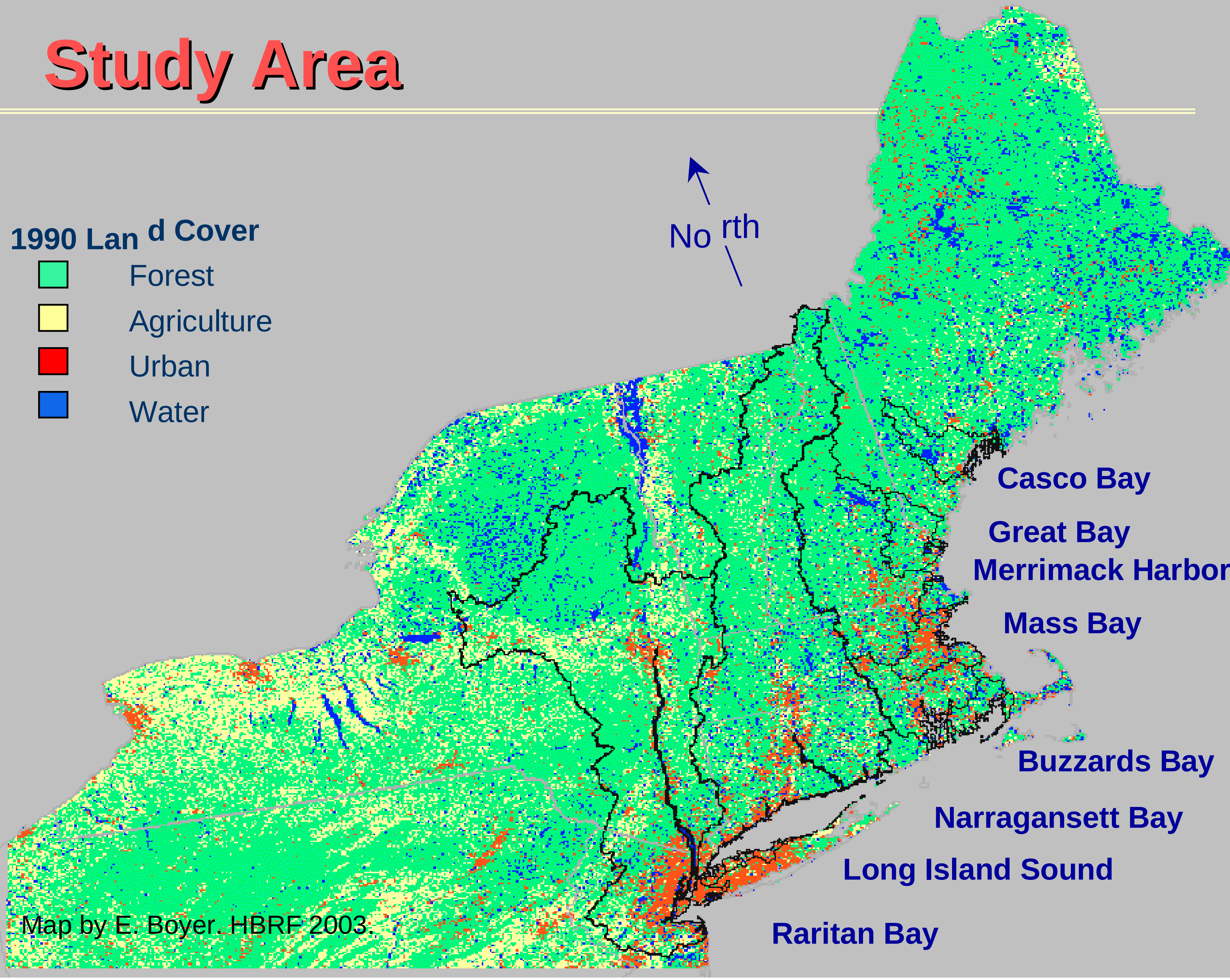
University scientists - 1963

Hubbard Brook Research Foundation

Non-profit Action/Think-tank - 1993

H B R F

Study Area


1990 Land Cover
Forest
Agriculture
Urban
Water
North
Casco Bay
Great Bay
Merrimack Harbor
Mass Bay
Buzzards Bay
Narragansett Bay
Long Island Sound
Raritan Bay
Map by E. Boyer. HBRF 2003.

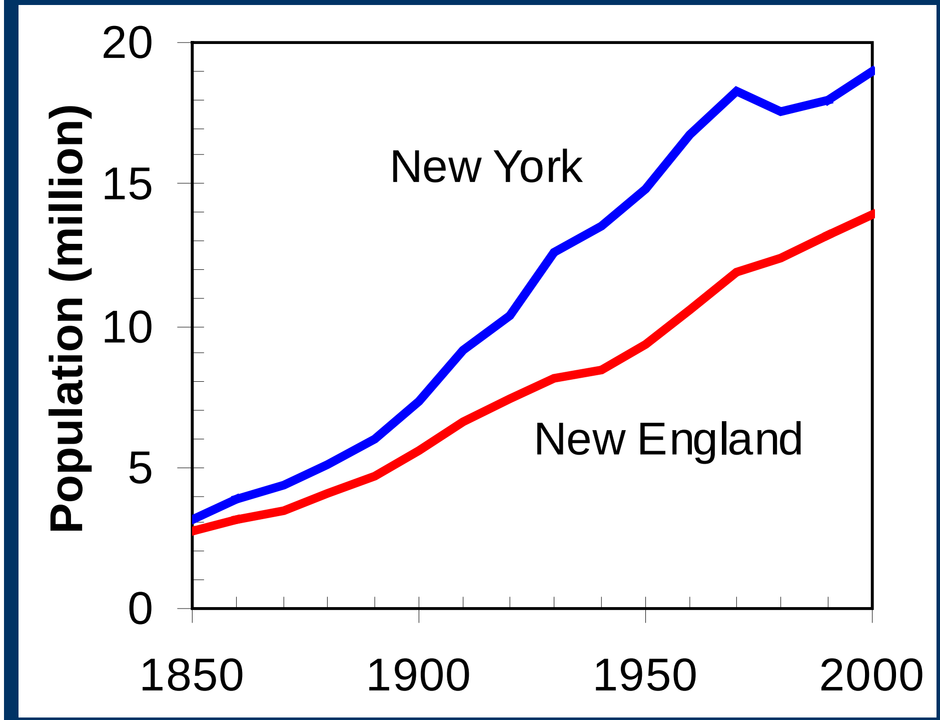
For forests and coastal waters…

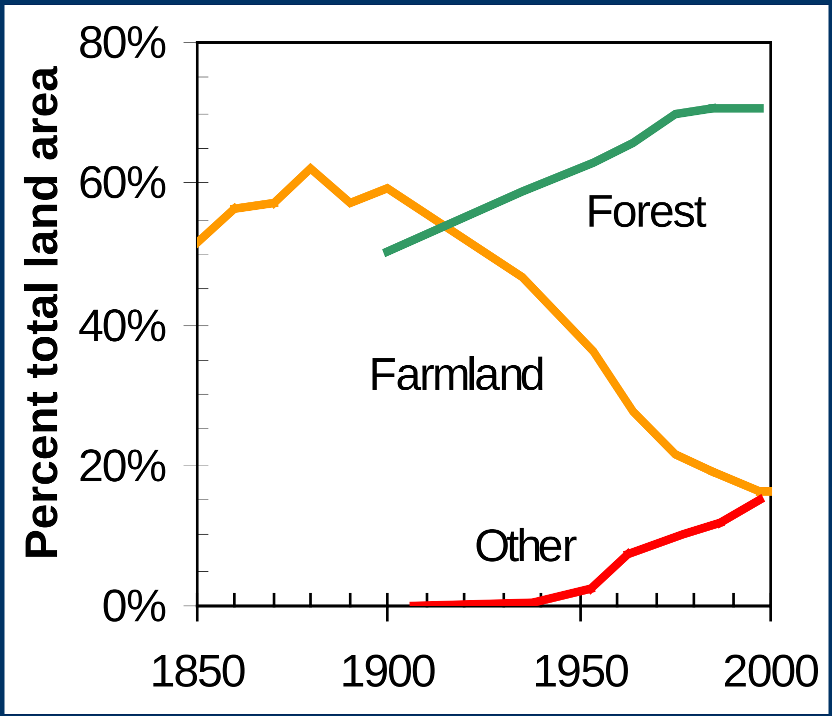
1. What are the major sources of anthropogenic nitrogen in the Northeastern U.S.?

2. What are the ecological effects?

3. What are the most effective strategies for reducing anthropogenic nitrogen and its effects?

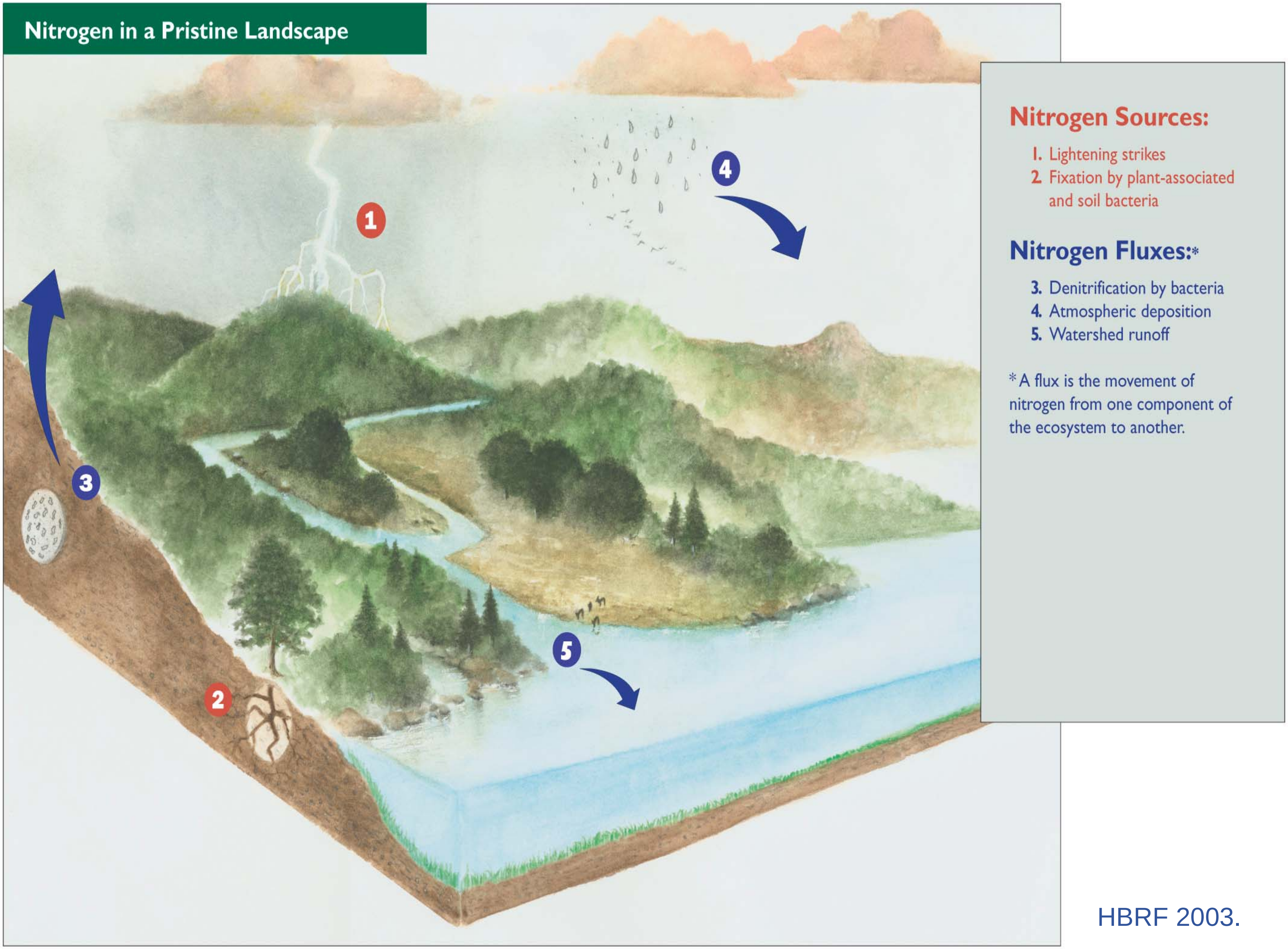
Northeast Population and Land Use Trends



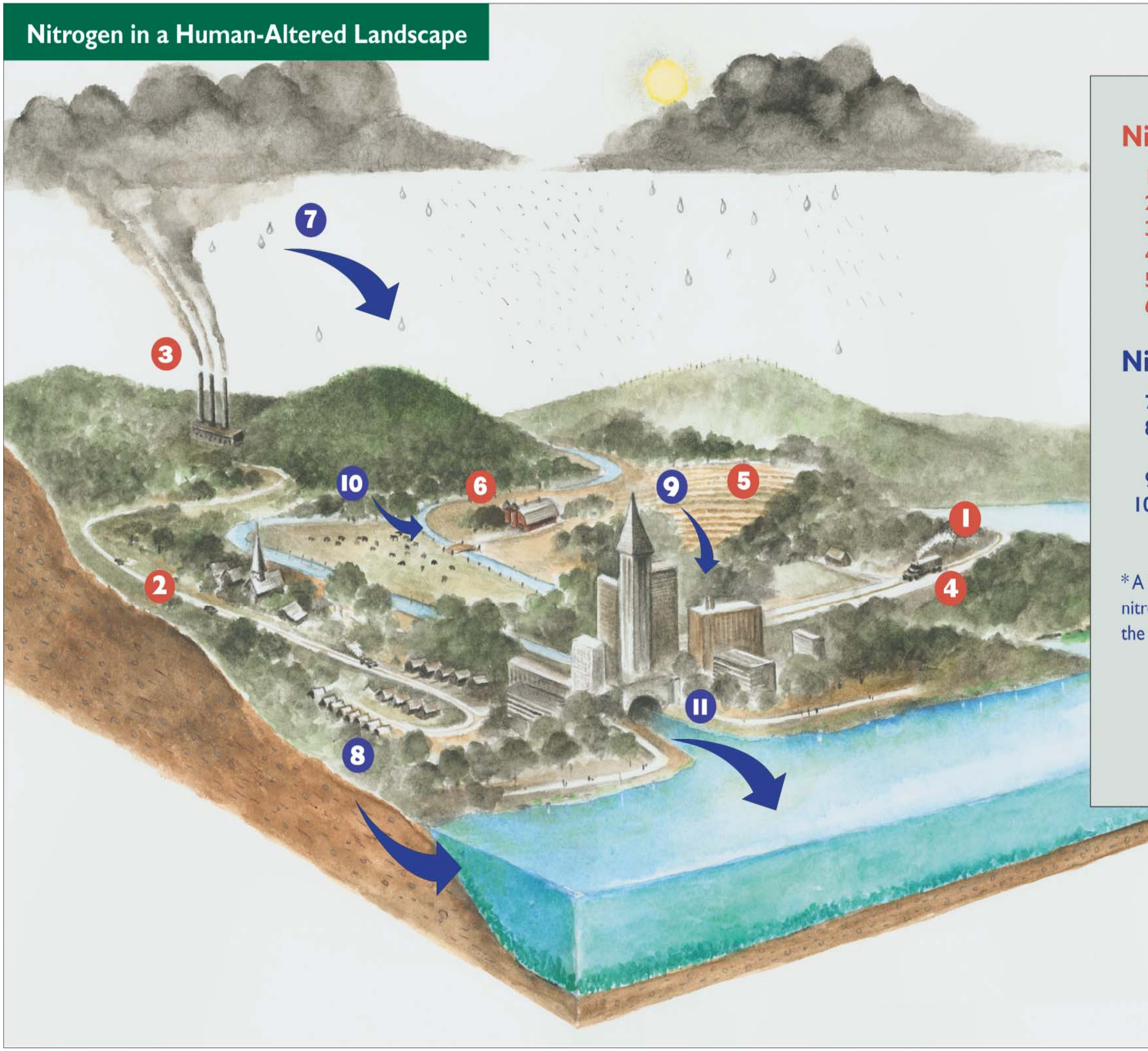


A) U.S. Bureau of Census, 1996. B) USDA 1997, NASS 1999.

Compiled by C. Goodale. HBRF 2003.


Nitrogen in a Pristine Landscape
1
2
3
4
5
Nitrogen Sources:
1. Lightening 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.

HBRF 2003.



Nitrogen Sources:

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

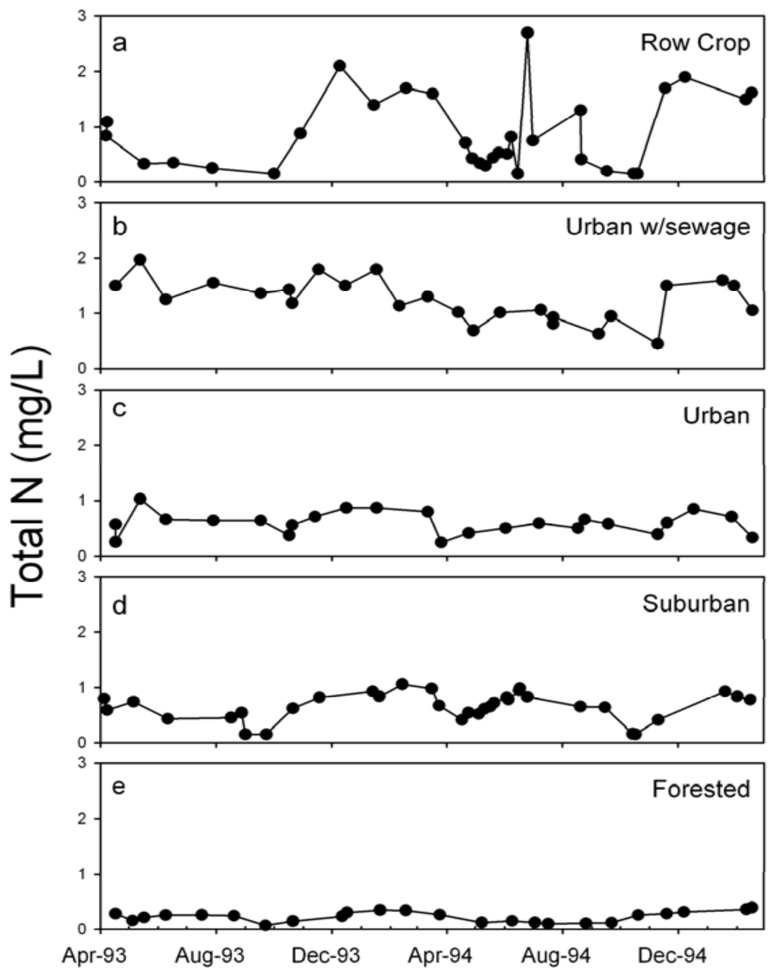
Nitrogen Fluxes:*

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.

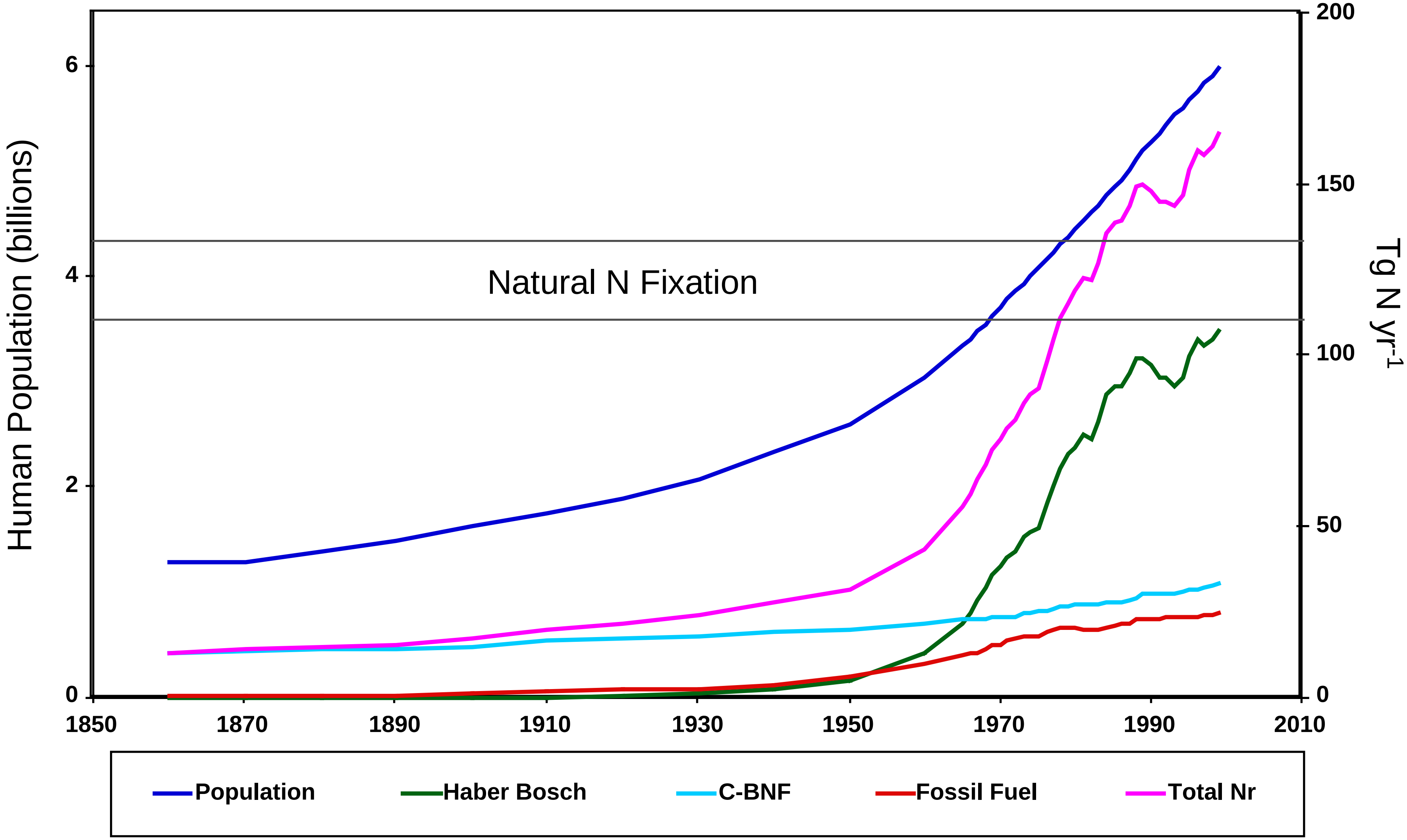
HBRF 2003.

Nitrate concentrations in runoff by land use



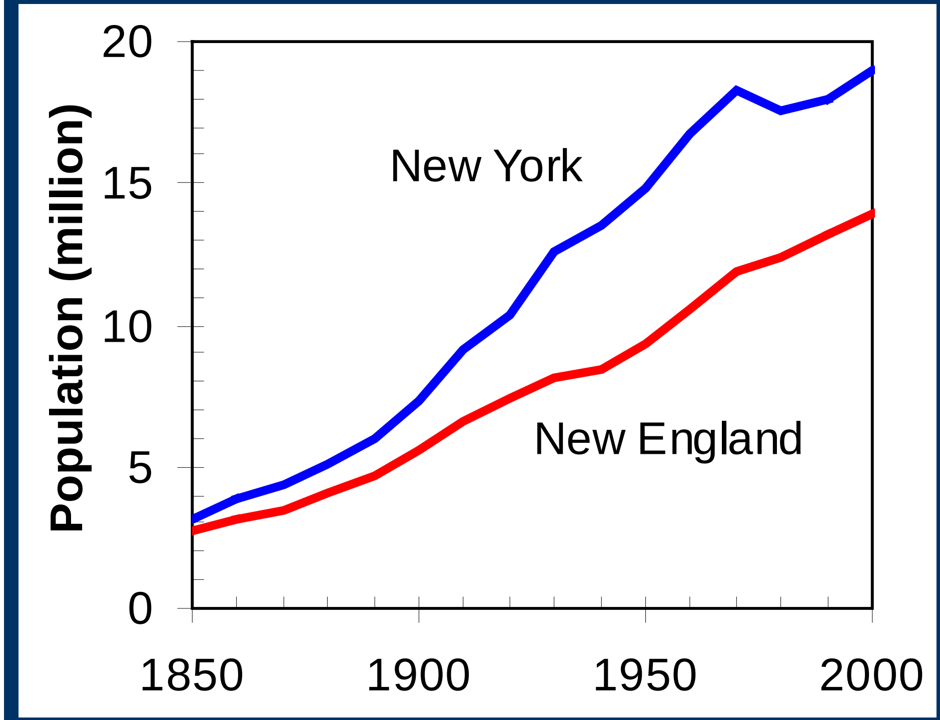
Driscoll et al. 2002. In review.

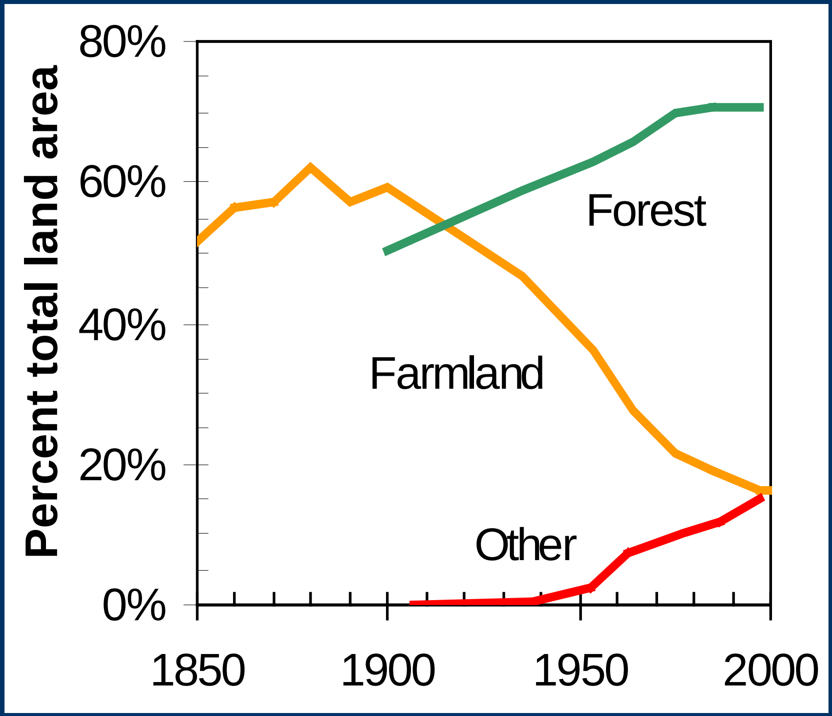
Global Population and Reactive Nitrogen Trends



From Galloway et al. 2002. In review.

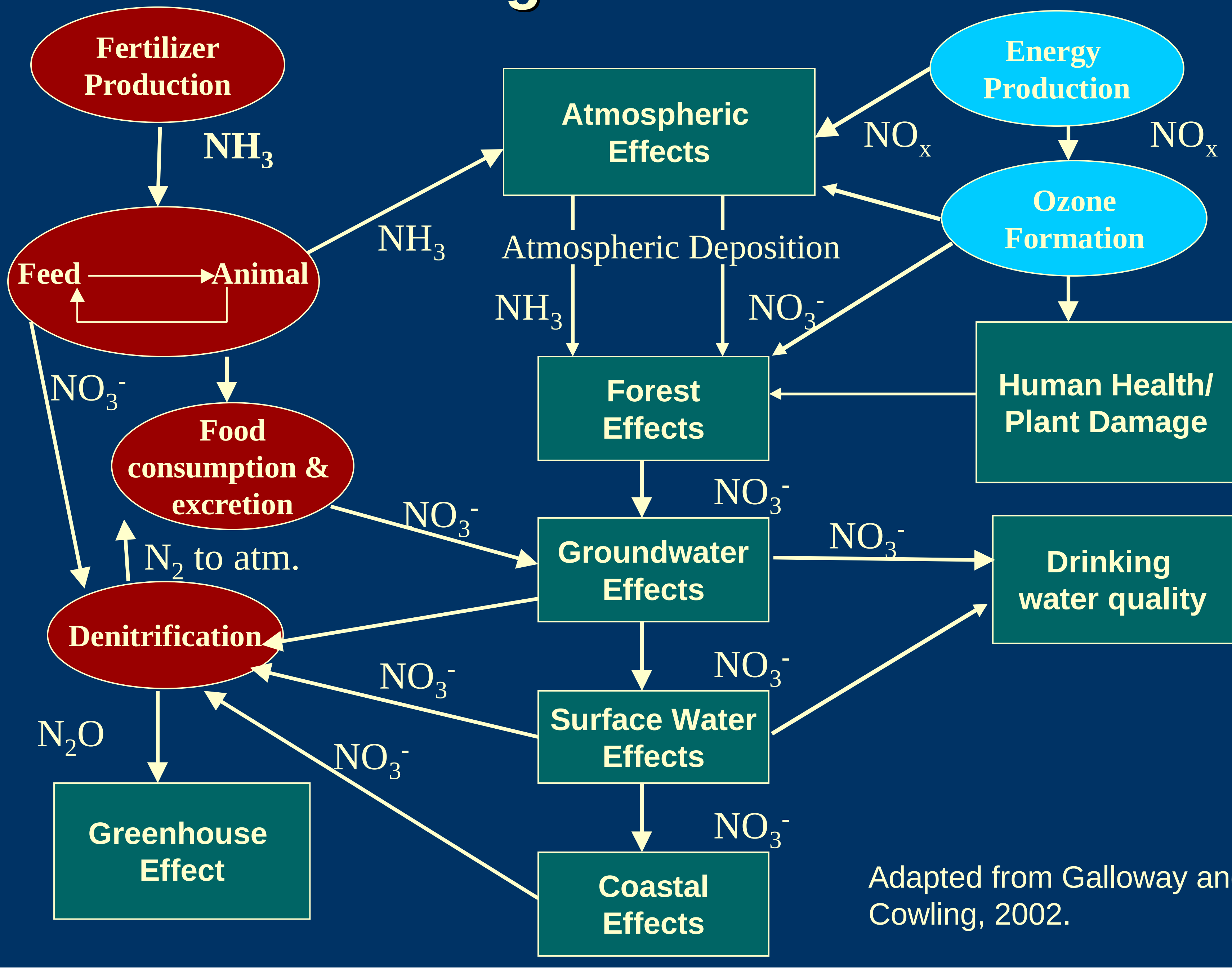
Northeast Population and Land Use Trends





A) U.S. Bureau of Census, 1996; B) USDA 1997, NASS 1999.

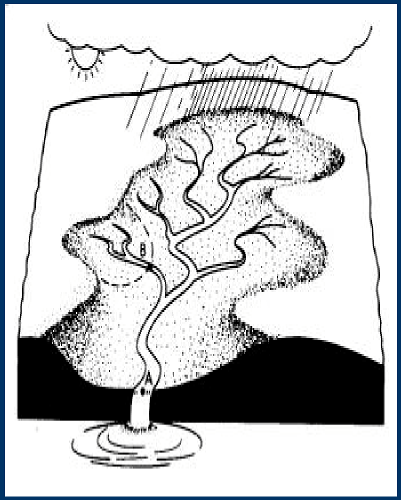
Nitrogen Cascade



Adapted from Galloway and Cowling, 2002.

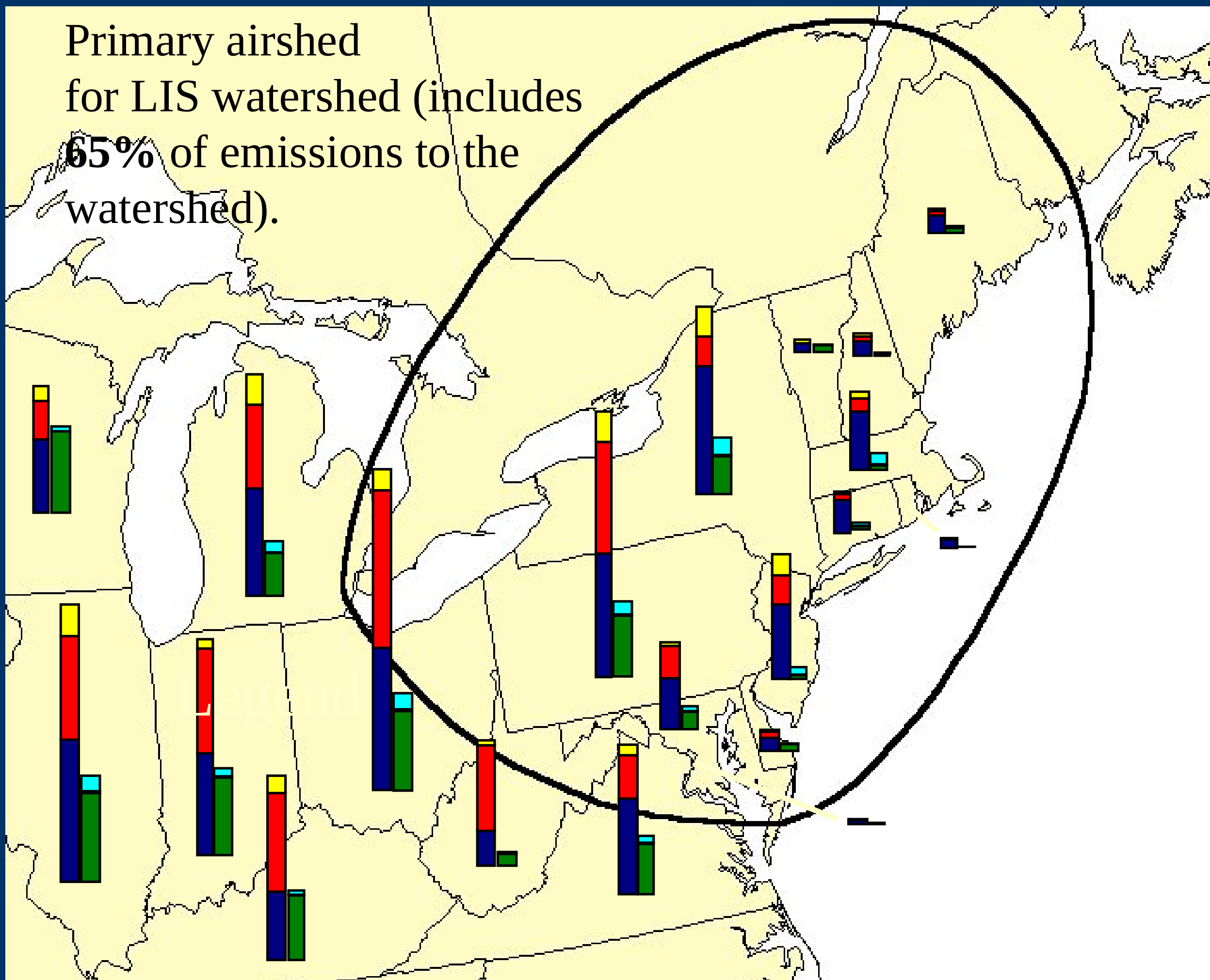
Sources of Nitrogen

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

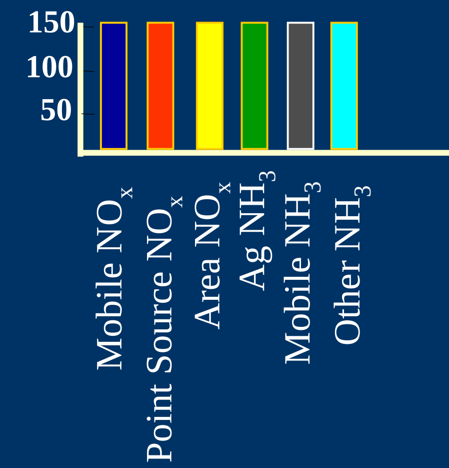


In large watersheds and coastal systems anthropogenic nitrogen sources are more diverse and are dominated by food.

Sources of Atmospheric Nitrogen Emissions

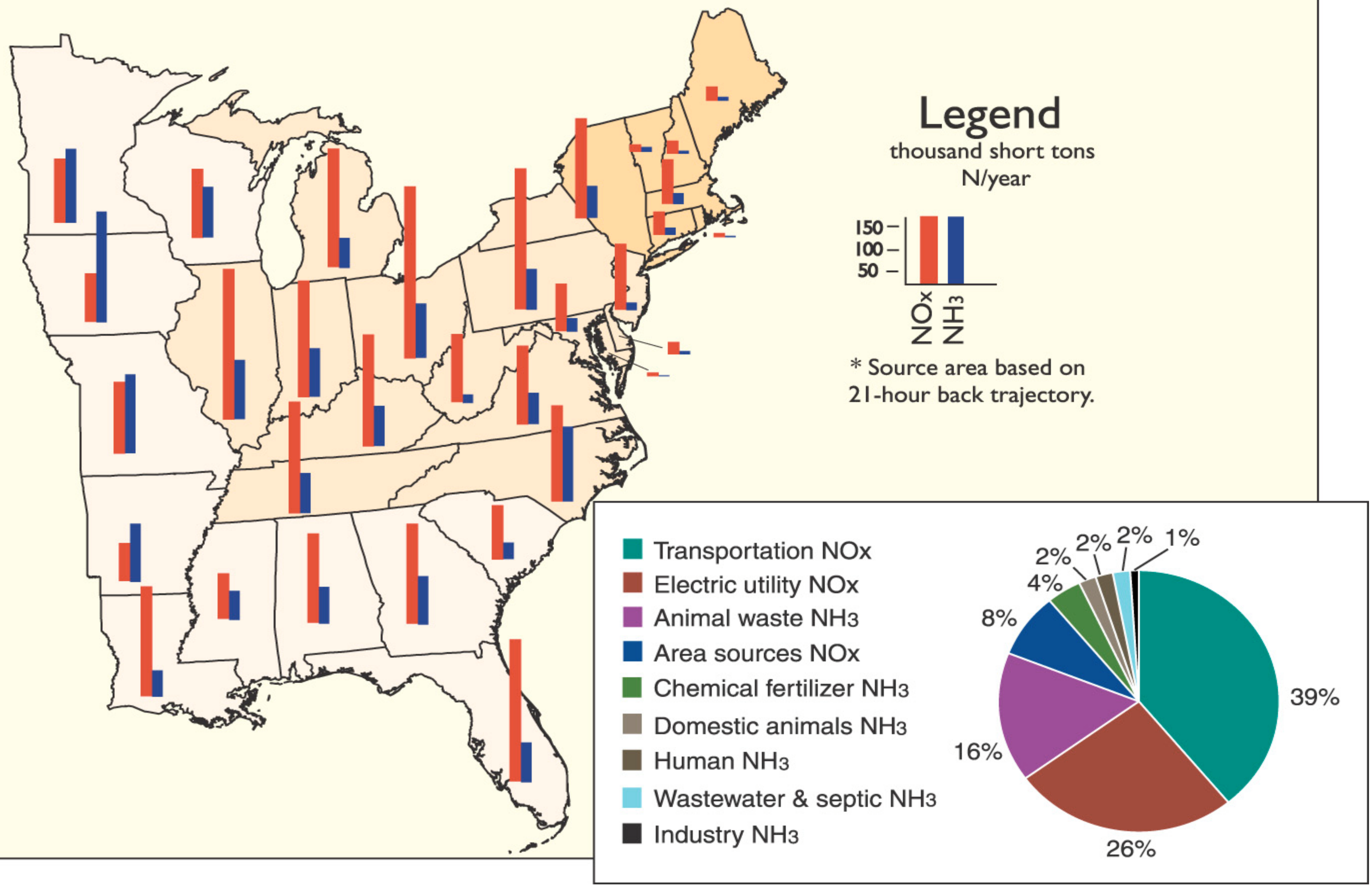


Atmospheric N Emissions thousand kt N/yr



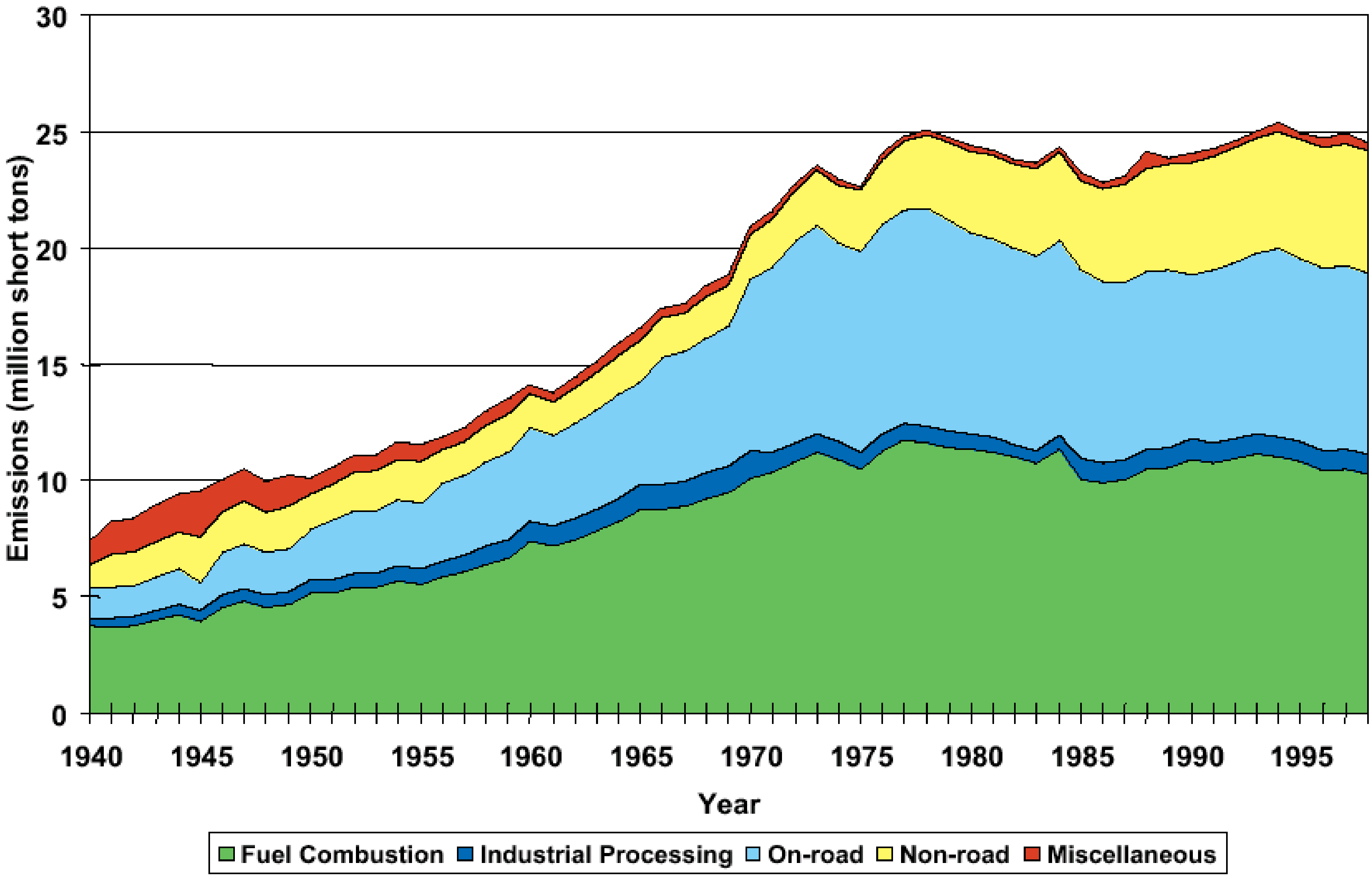
Driscoll et al. 2002. In review.

Distribution and Sources of Nitrogen Emissions



How have emissions changed over time?

(Total U.S. NO_x emissions)



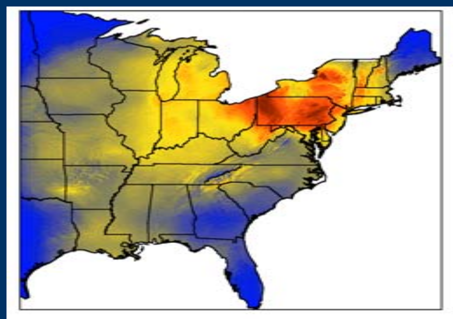
Source: EPA National Air Pollution Emission Trends.

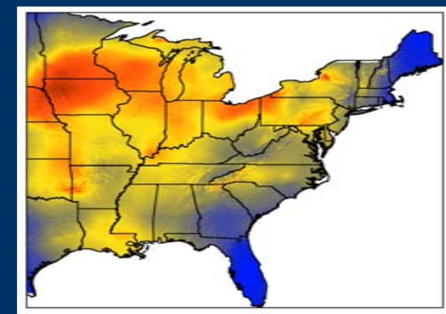
Nitrogen Wet Deposition

Dep

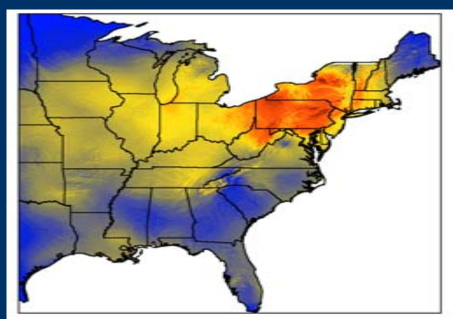
Wet Nitrate

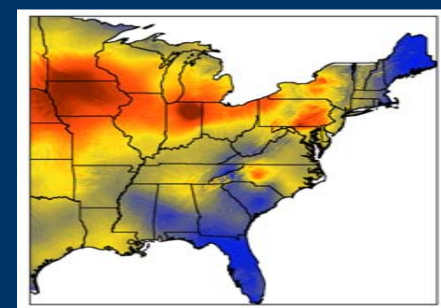
Wet Ammonium



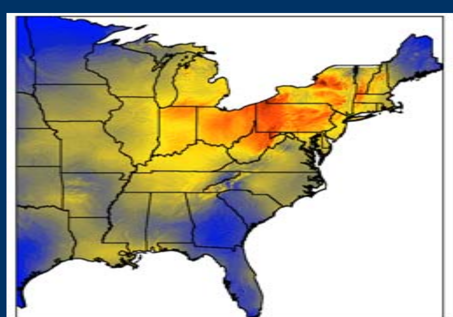


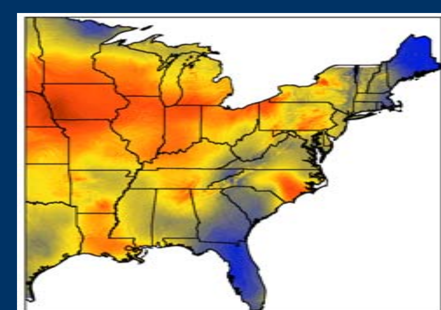
1983-
1985





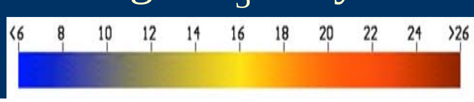
1992-
1994



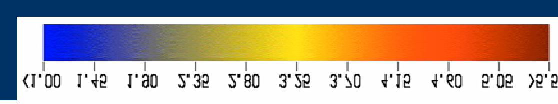


1995-
1997

kg NO_3^-/ha/yr

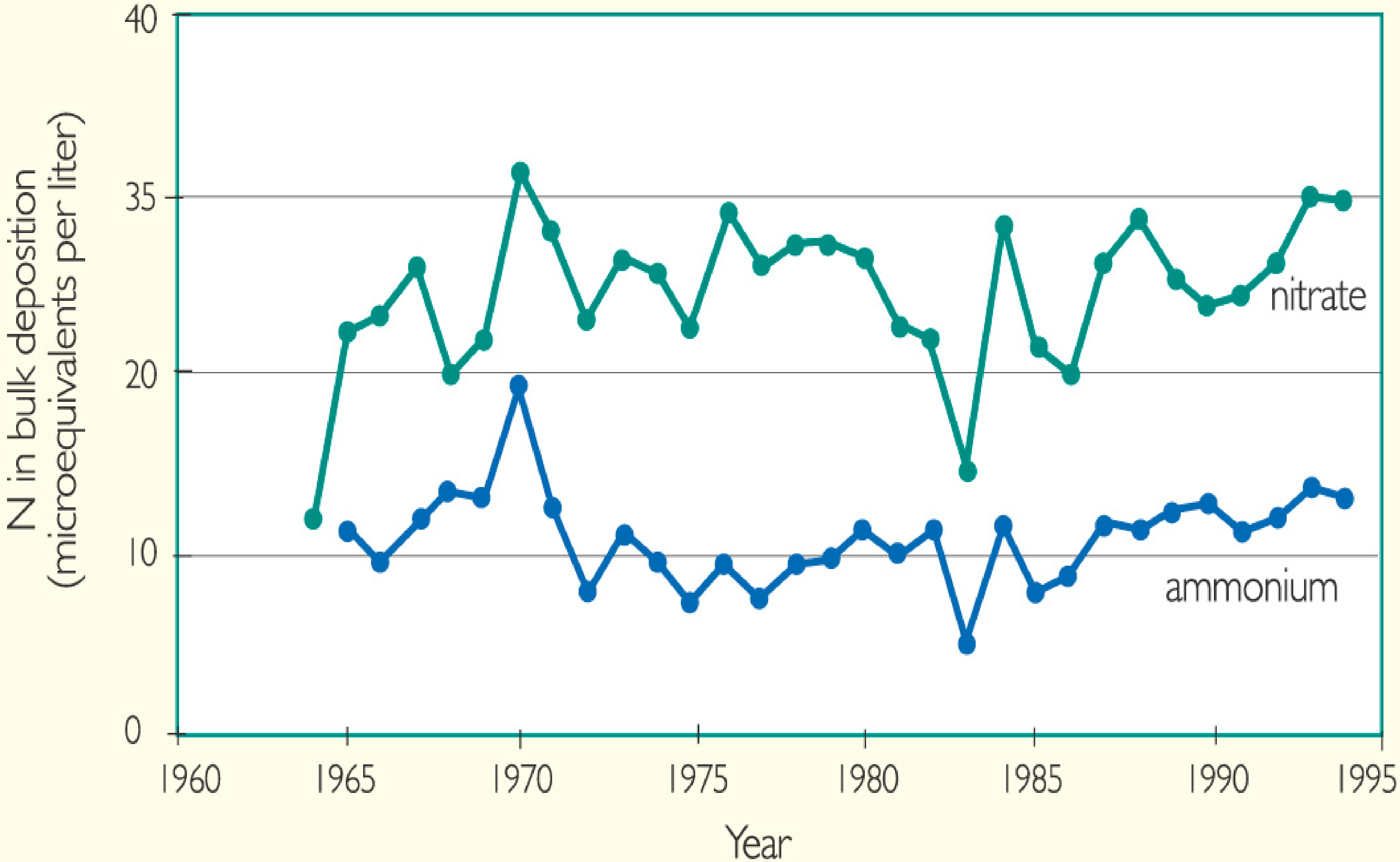


kg NH_4^{+-}/ha/yr



Lynch and Grimm, 1997.

Nitrogen Trends in Precipitation
Hubbard Brook Experimental Forest, NH

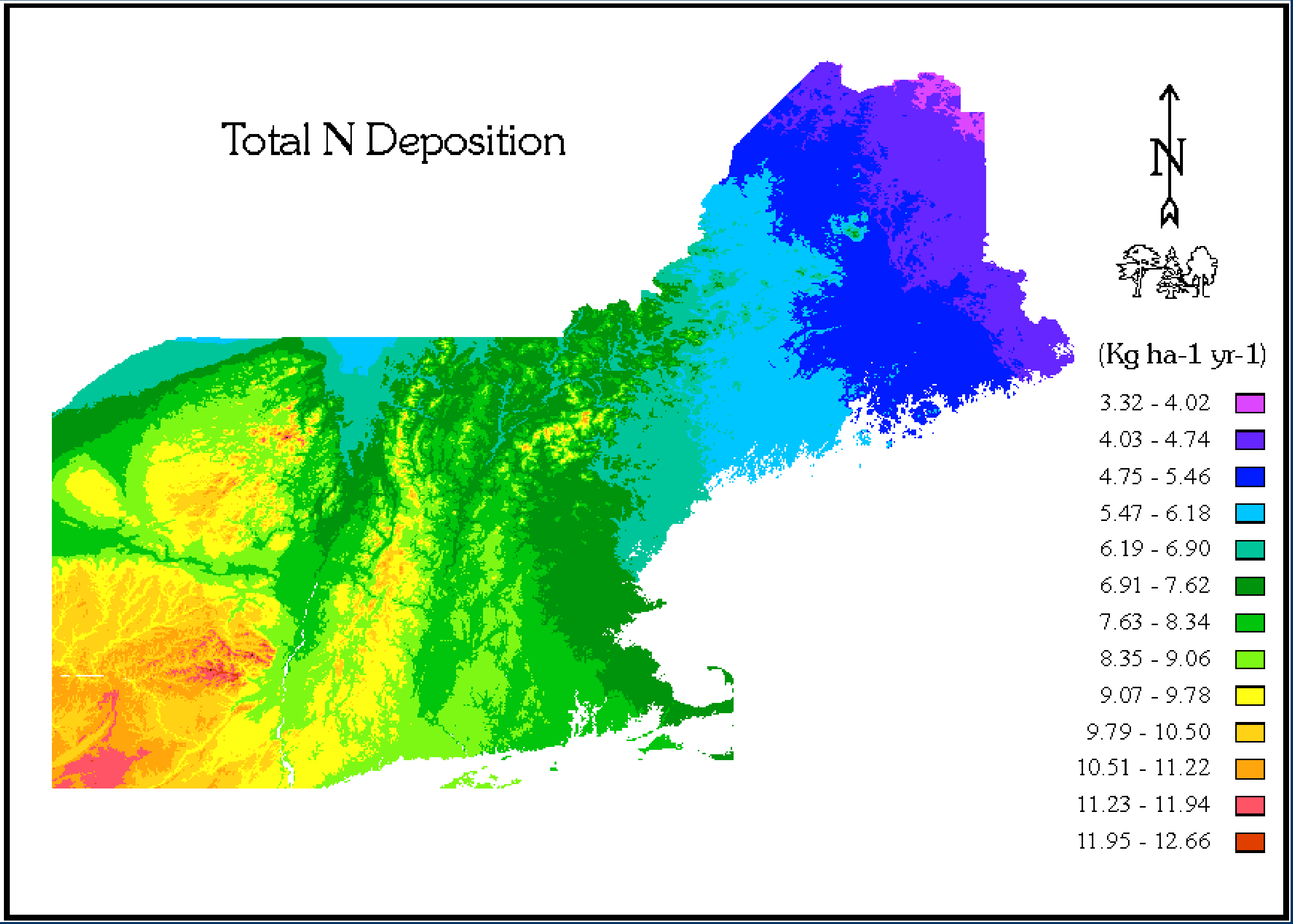


Likens and Bormann 1995.

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.

Butler, Likens, et al. Atmospheric Environment, 2003.

Total Nitrogen Deposition



Ollinger et al. 1993.

What environmental issues are linked to nitrogen pollution?

- Ground-level ozone
- Acid rain and forest effects
- Reduced visibility
- Groundwater contamination
- Climate change

Ground-level ozone

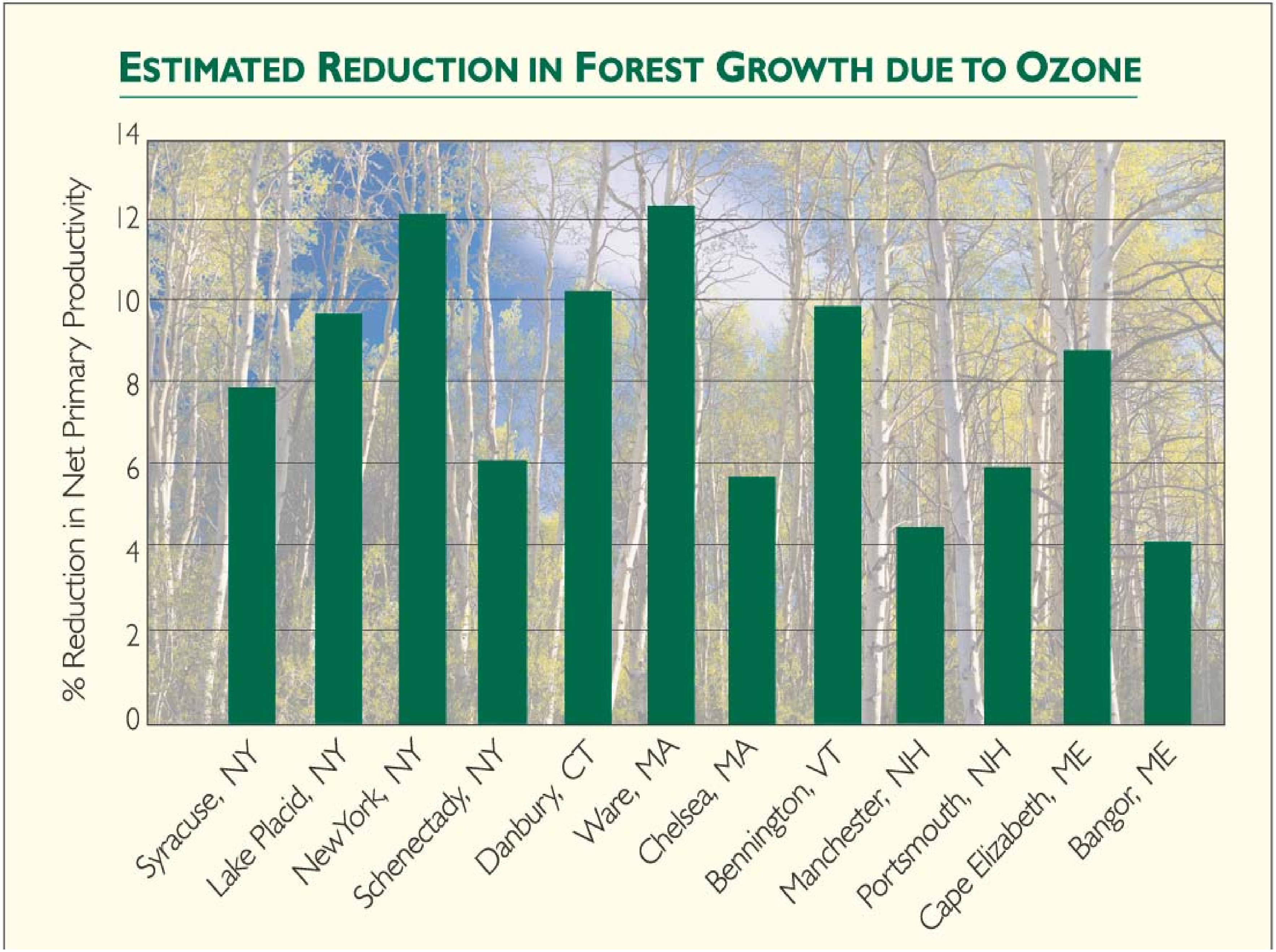
- Ozone formation is dependent on nitrogen oxides.
- Decreases net photosynthesis and reduces forest productivity.
- Large areas in the Northeast exceed EPA health standards for ozone.

Slide by S. Ollinger.

Foliar Ozone Injury

Ozone injury on white pine: Tip necrosis.
Source: NC Cooperative Extension.

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



From Ollinger et al. 1997. In HBRF 2003.

Isolating the Effects of Nitrogen Deposition

Harvard Forest, MA

Clockwise from left:

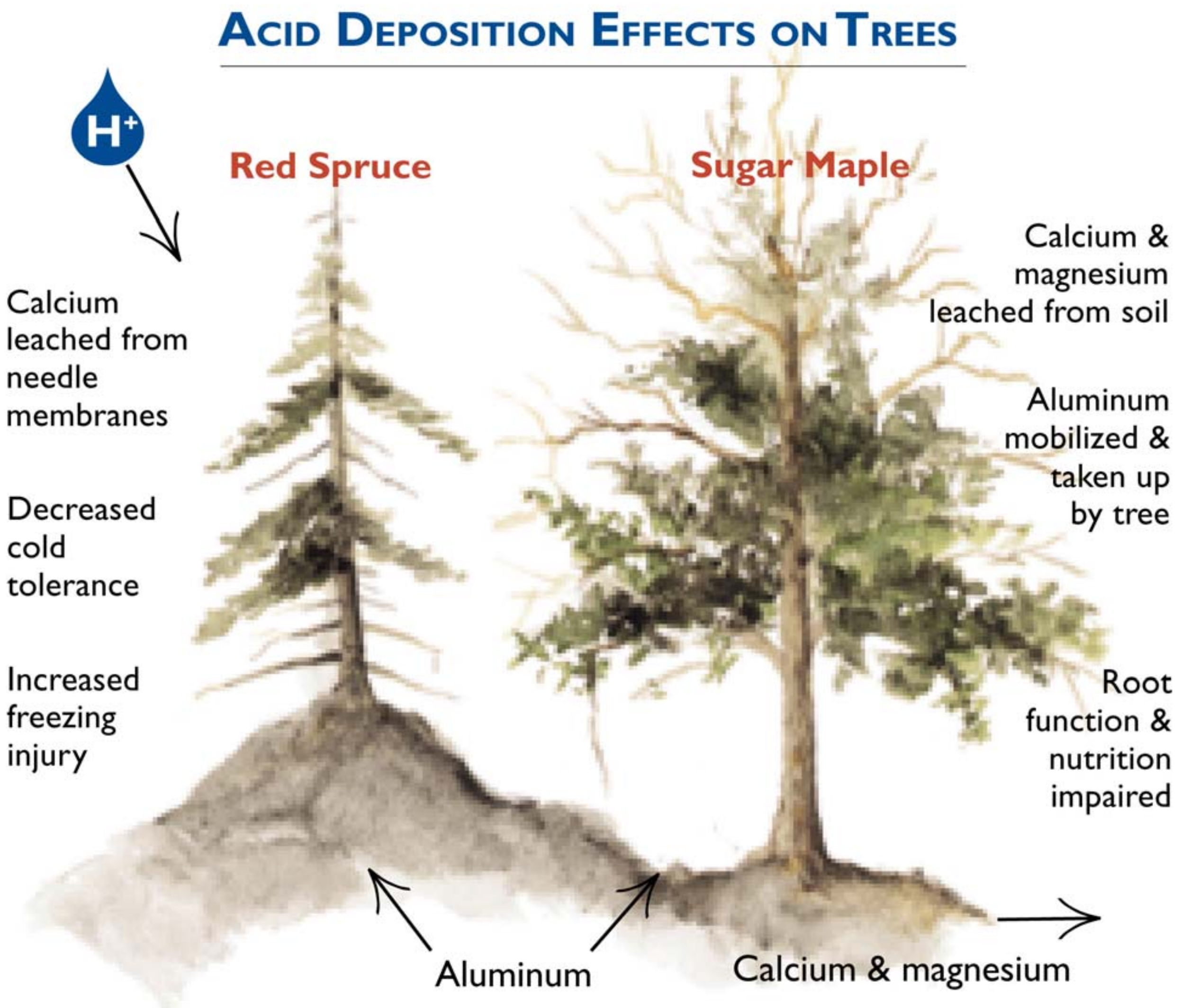
High treatment *(150 kg N/Ha)*

Low treatment *(50 kg N/Ha)*

Control

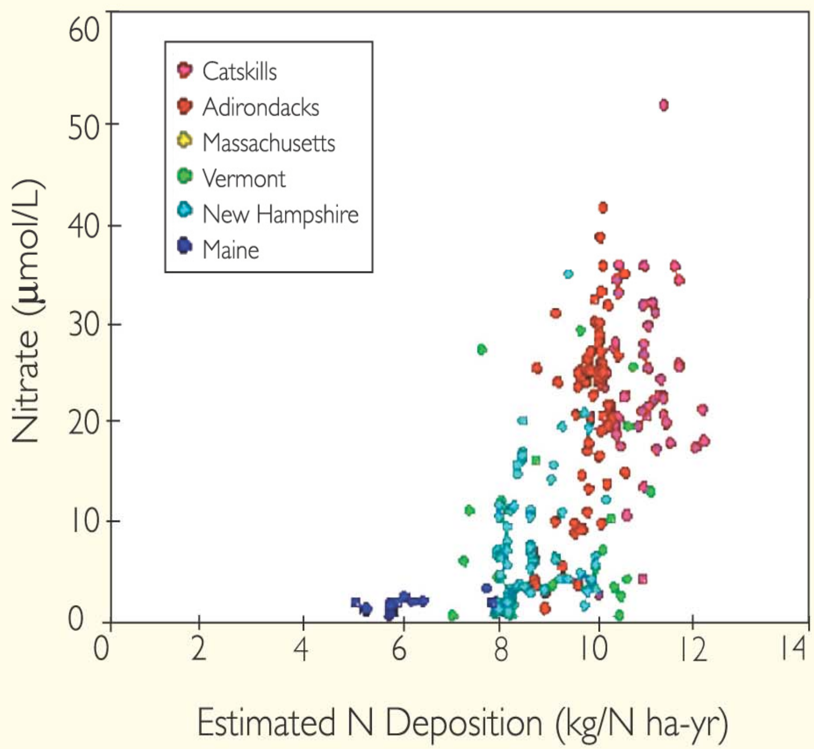
Slide by J. Aber.

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



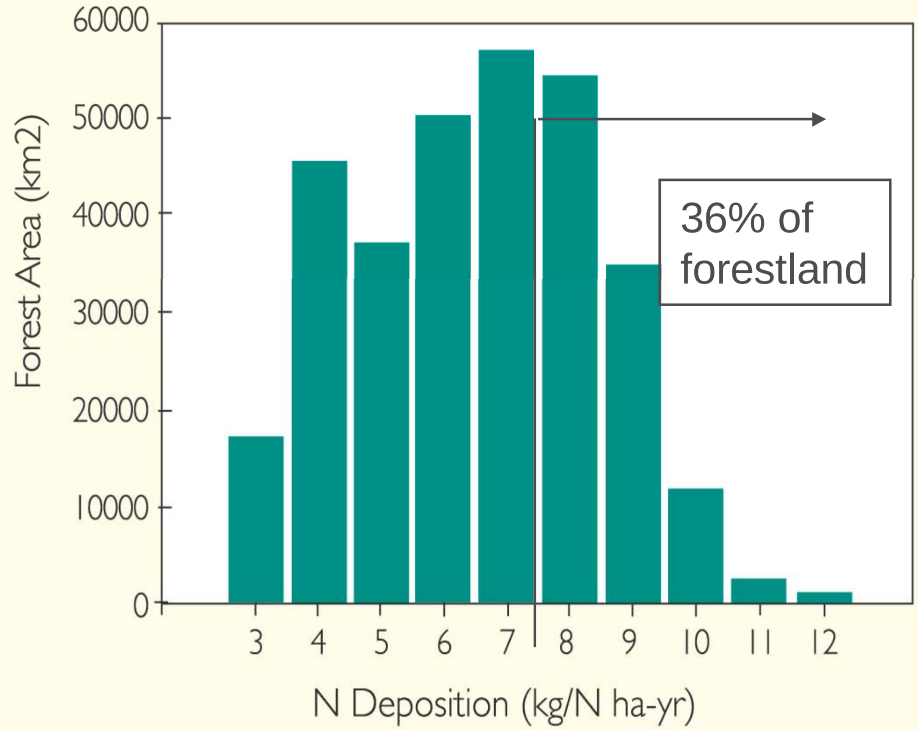
HBRF 2001.

N Deposition and Streamwater Nitrate



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

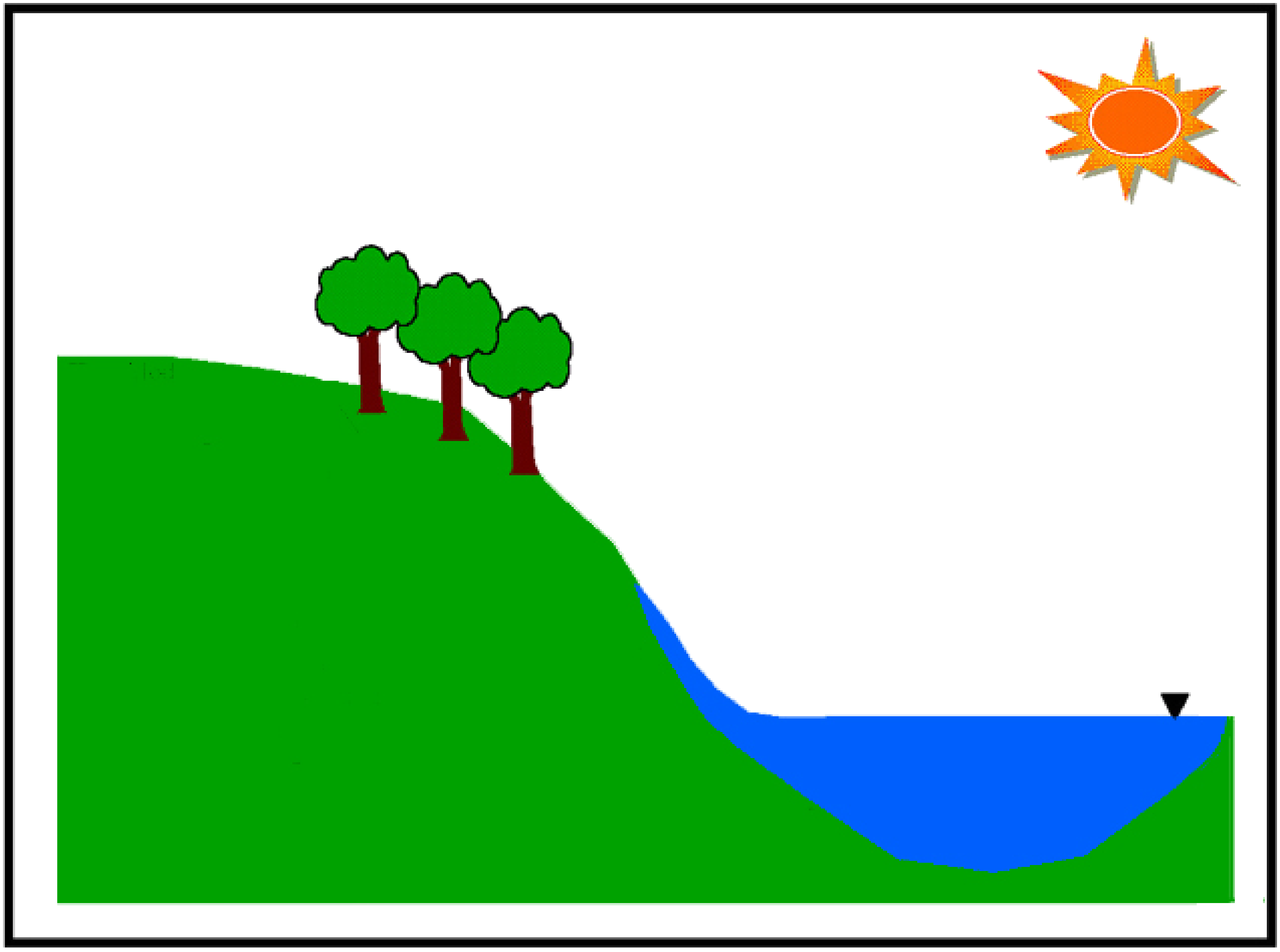
N Deposition in Northeast Forests



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

From J. Aber et al. 2003 and S. Ollinger. In HBRF 2003.

PnET BGC (Biogeochemical) Model



Slide by C. Driscoll.

Thresholds for Positive Chemical Conditions

Nitrogen deposition	< 8 kg/ha-yr
Soil base saturation	> 20%
Acid neutralizing capacity	> 50 µeq/L
Stream pH	> 6.0
Stream aluminum	<2.0 µmol/L

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.

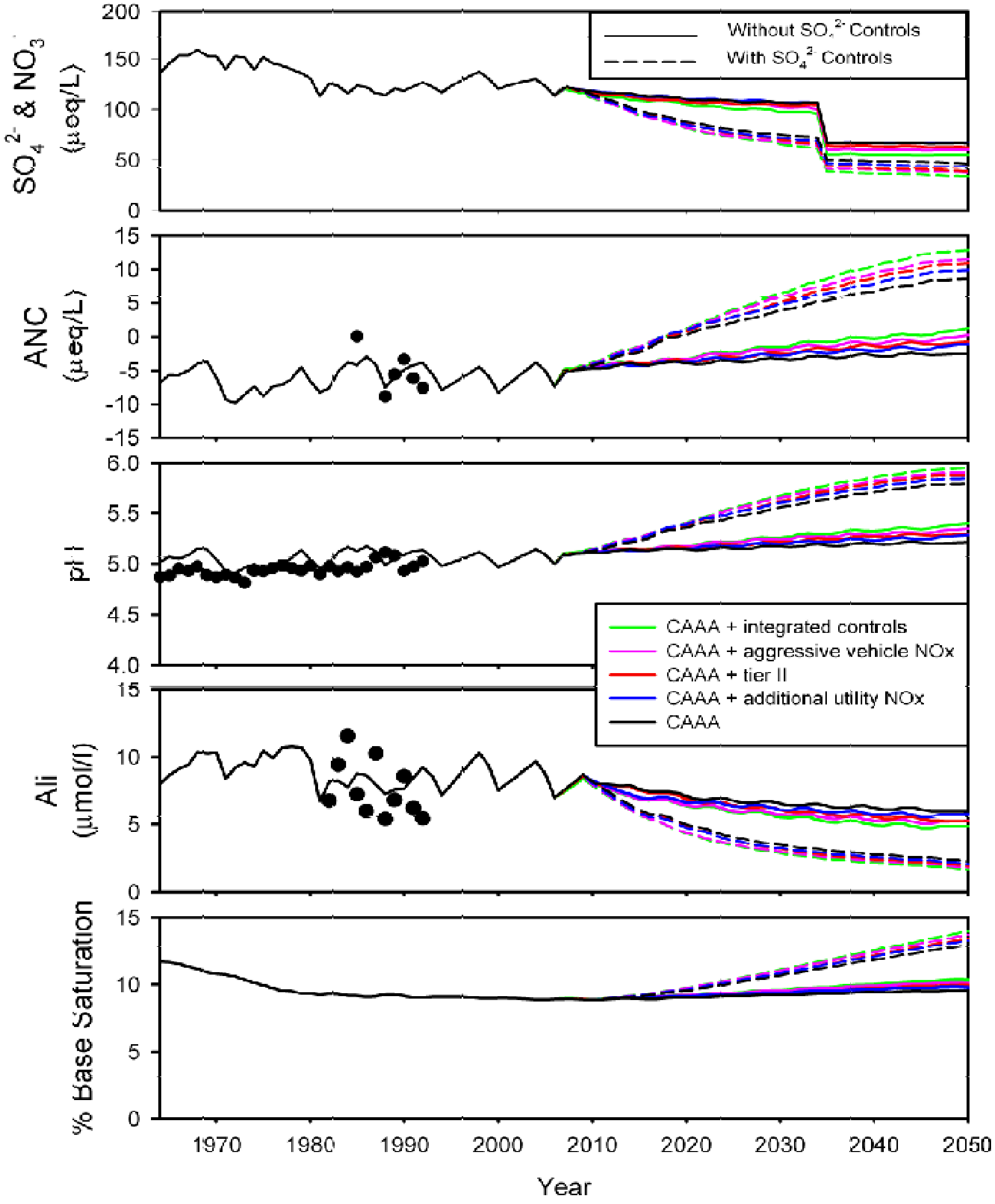
3. 60-90% reduction in passenger vehicle NO_x (consistent with EPA Tier 2 regulations).

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

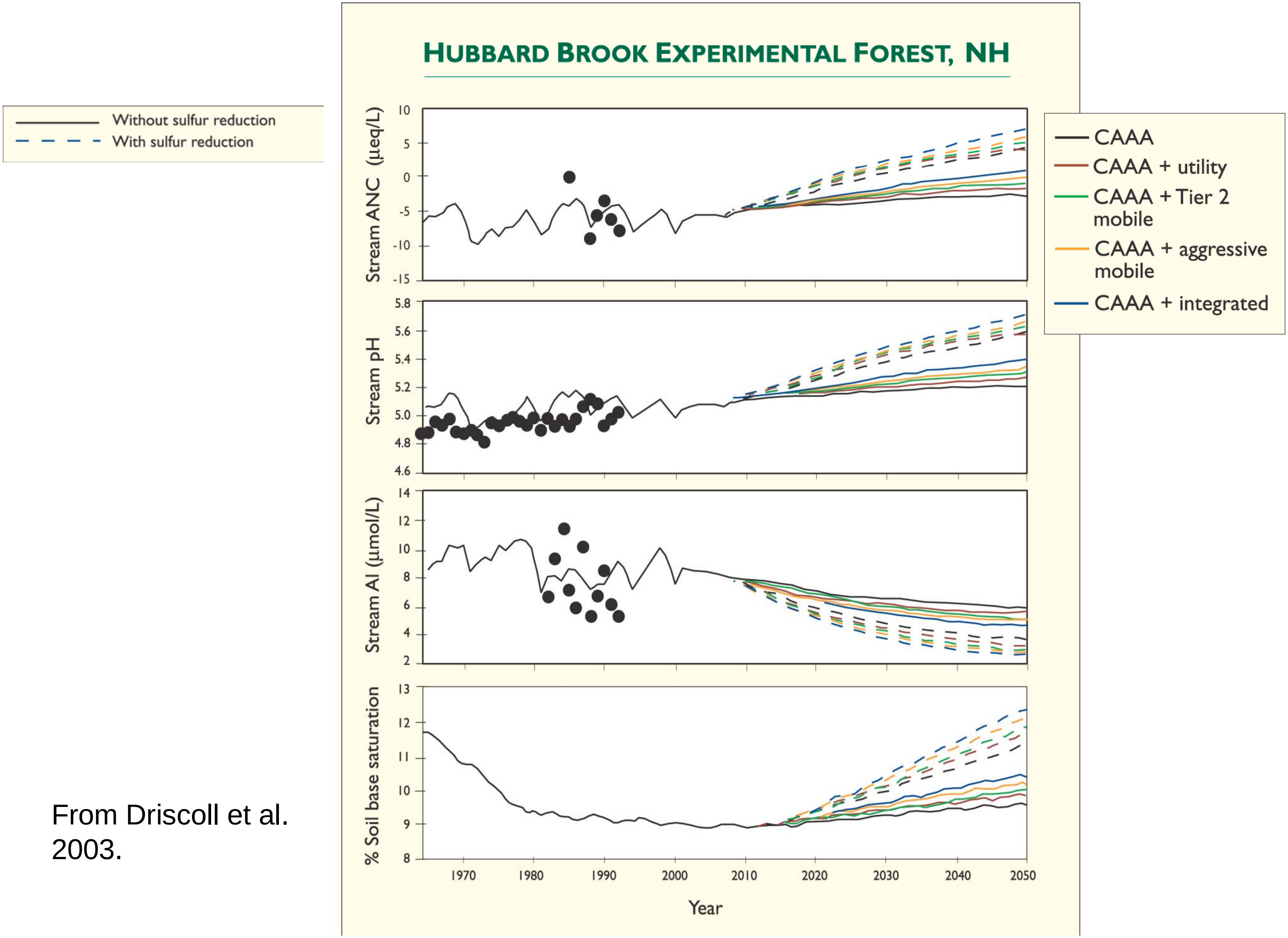
5. All of the above with a 34% reduction in agricultural NH_3 emissions by animal waste treatment.

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

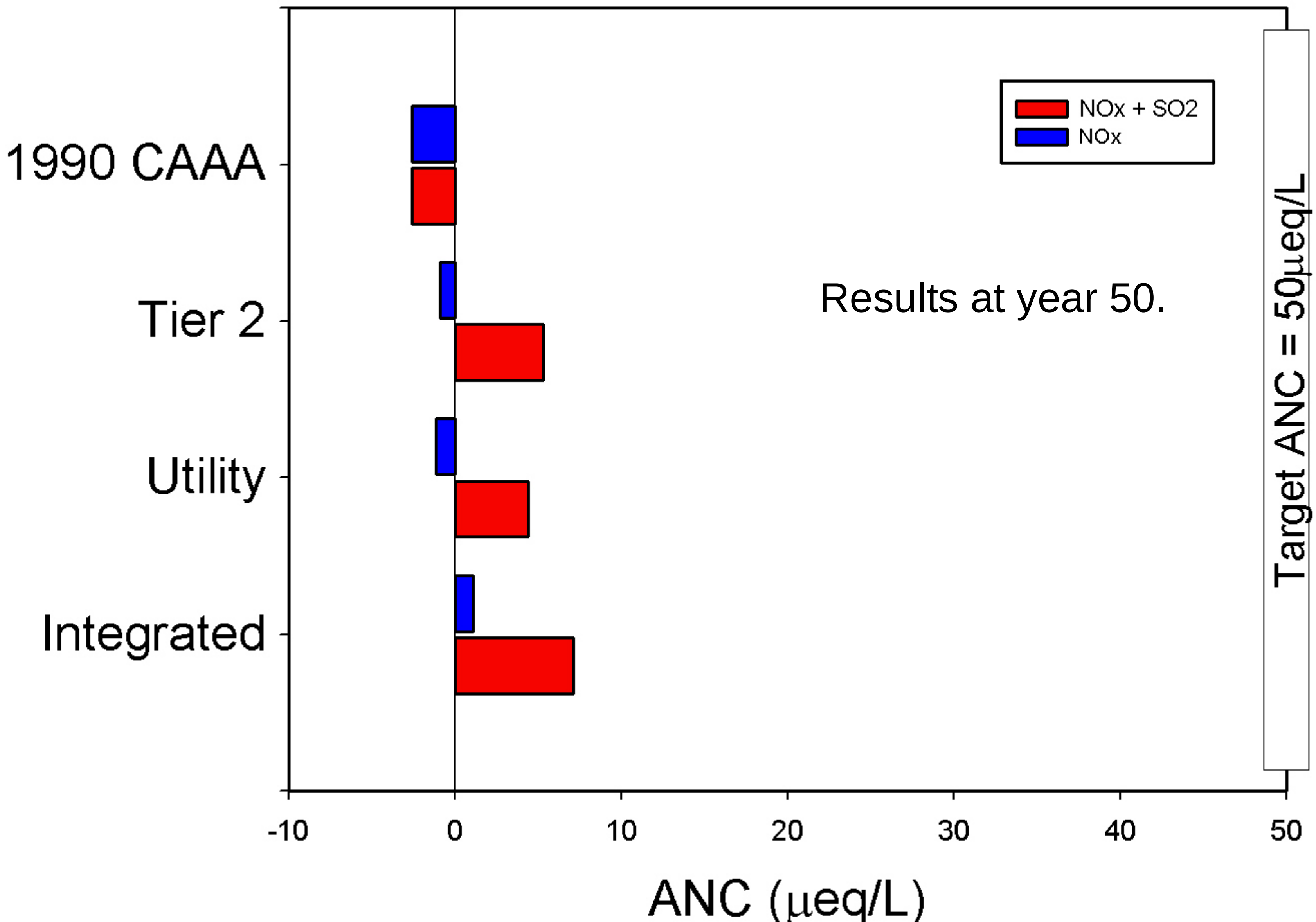


Driscoll et al. 2003.



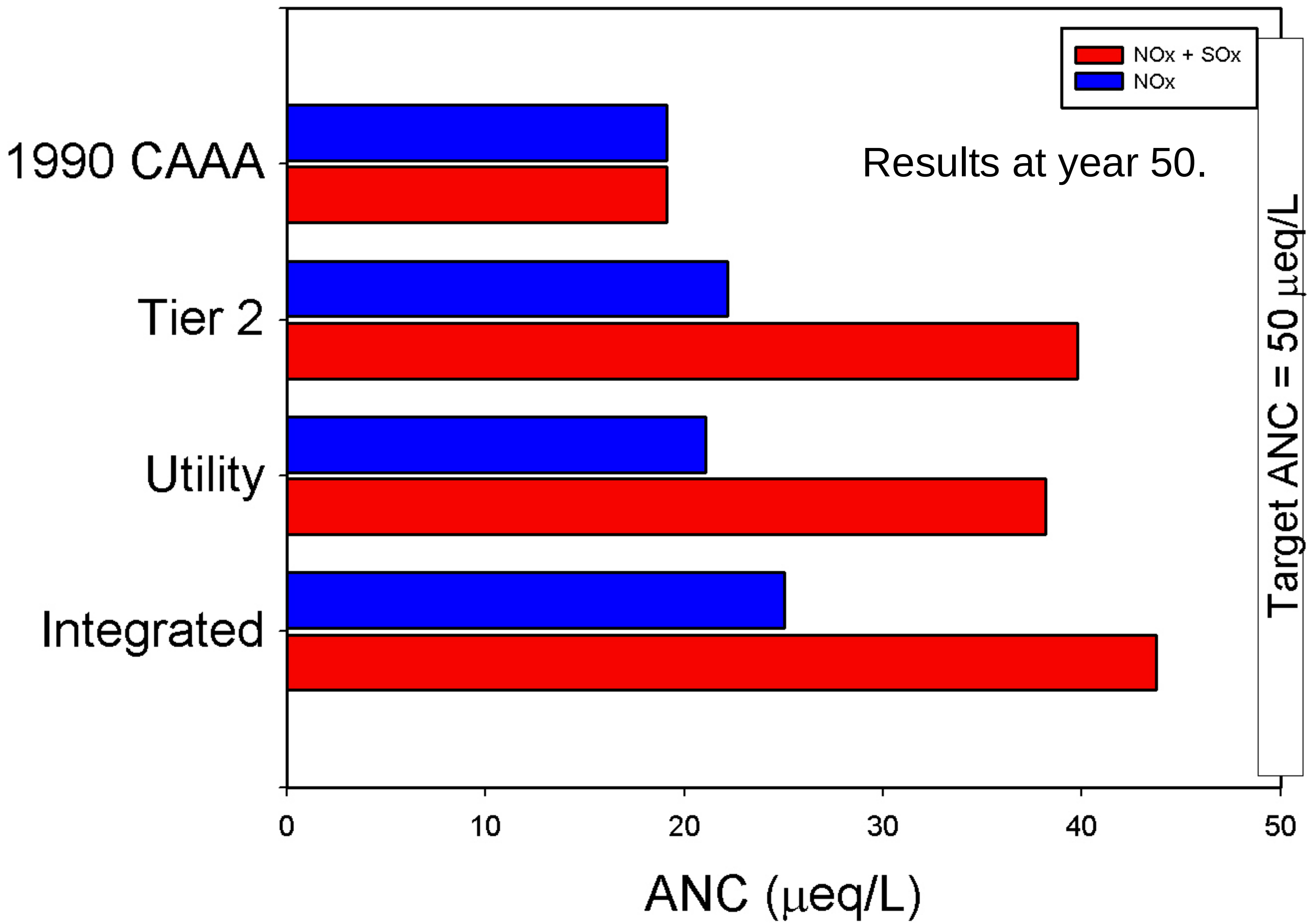
From Driscoll et al. 2003.

Hubbard Brook Experimental Forest, NH



Slide by C. Driscoll.

Biscuit Brook, NY



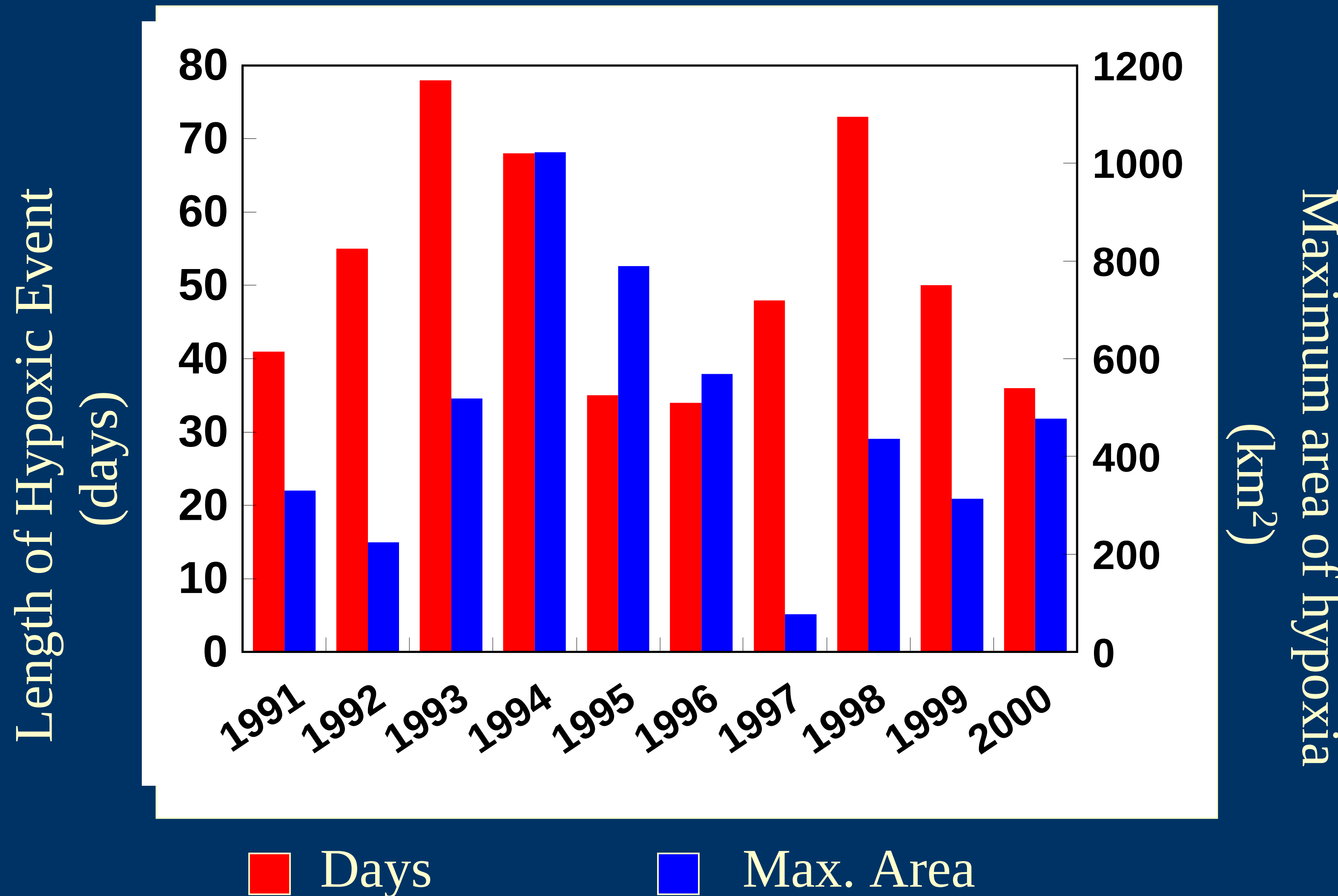
Slide by C. Driscoll.

Coastal Over-Enrichment

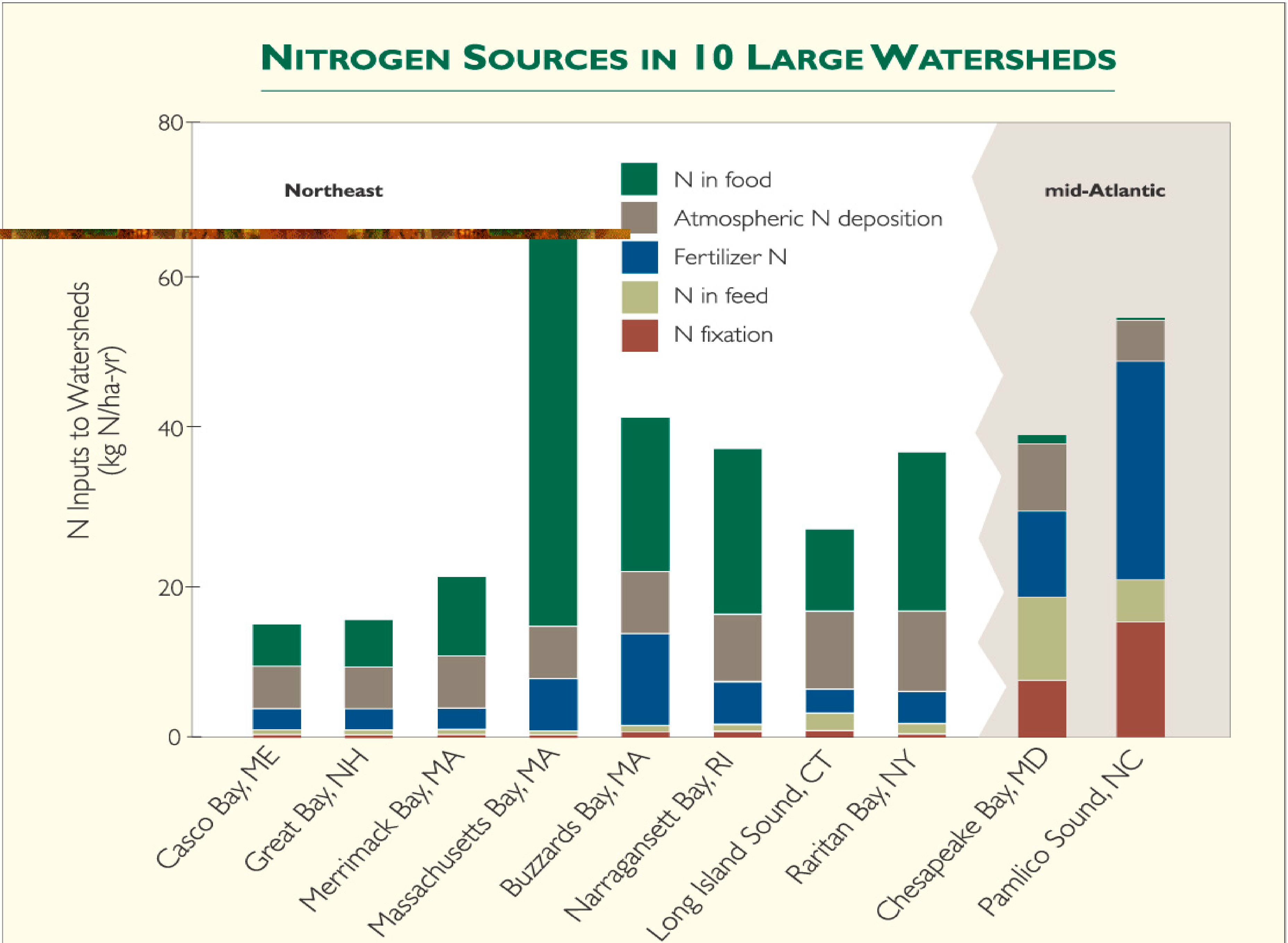
Photo W. Bennett

- 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

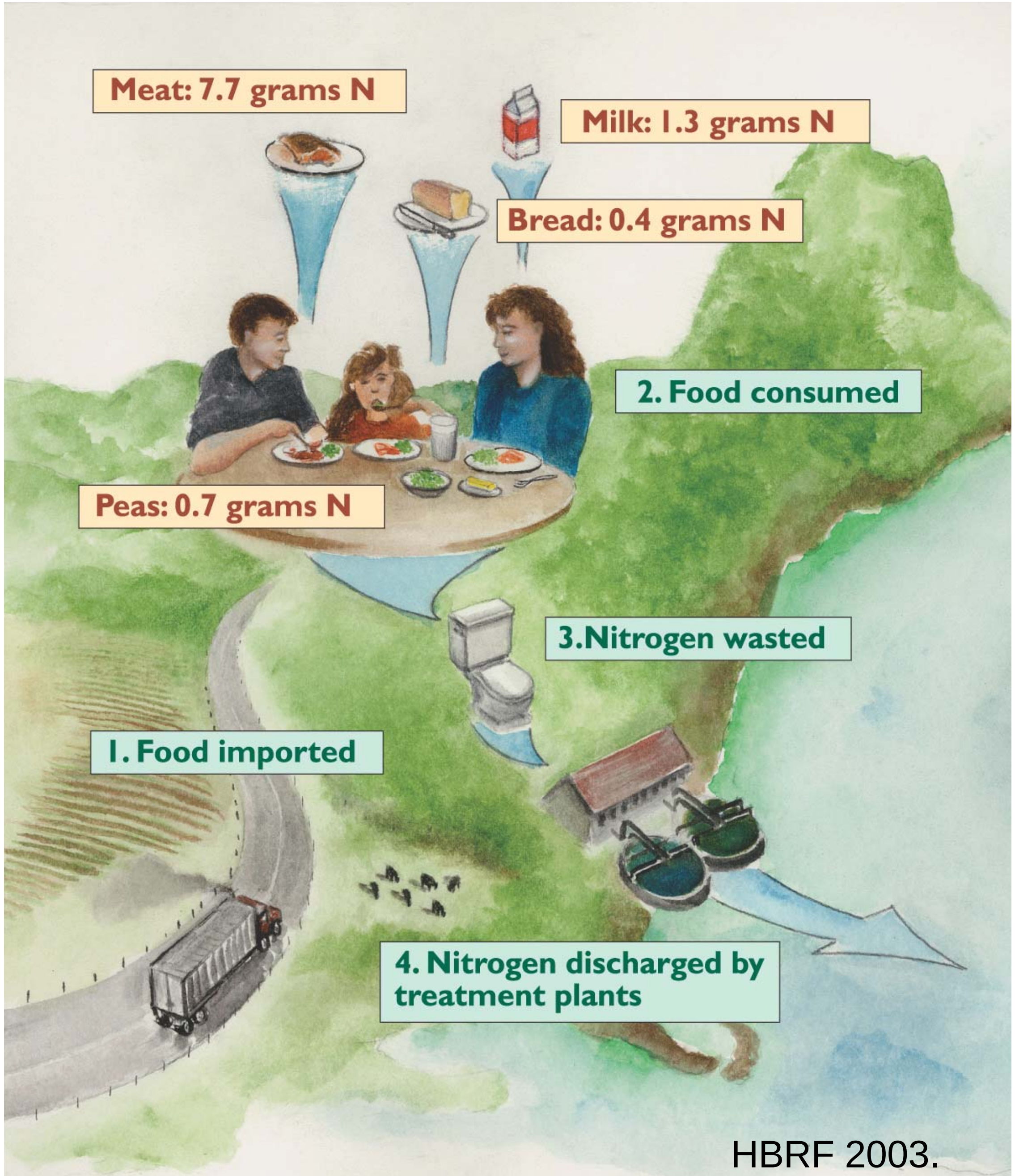


Courtesy of Connecticut Department of Environmental Protection. 2001.



From Driscoll et al. 2003.

Nitrogen and the Food Cycle

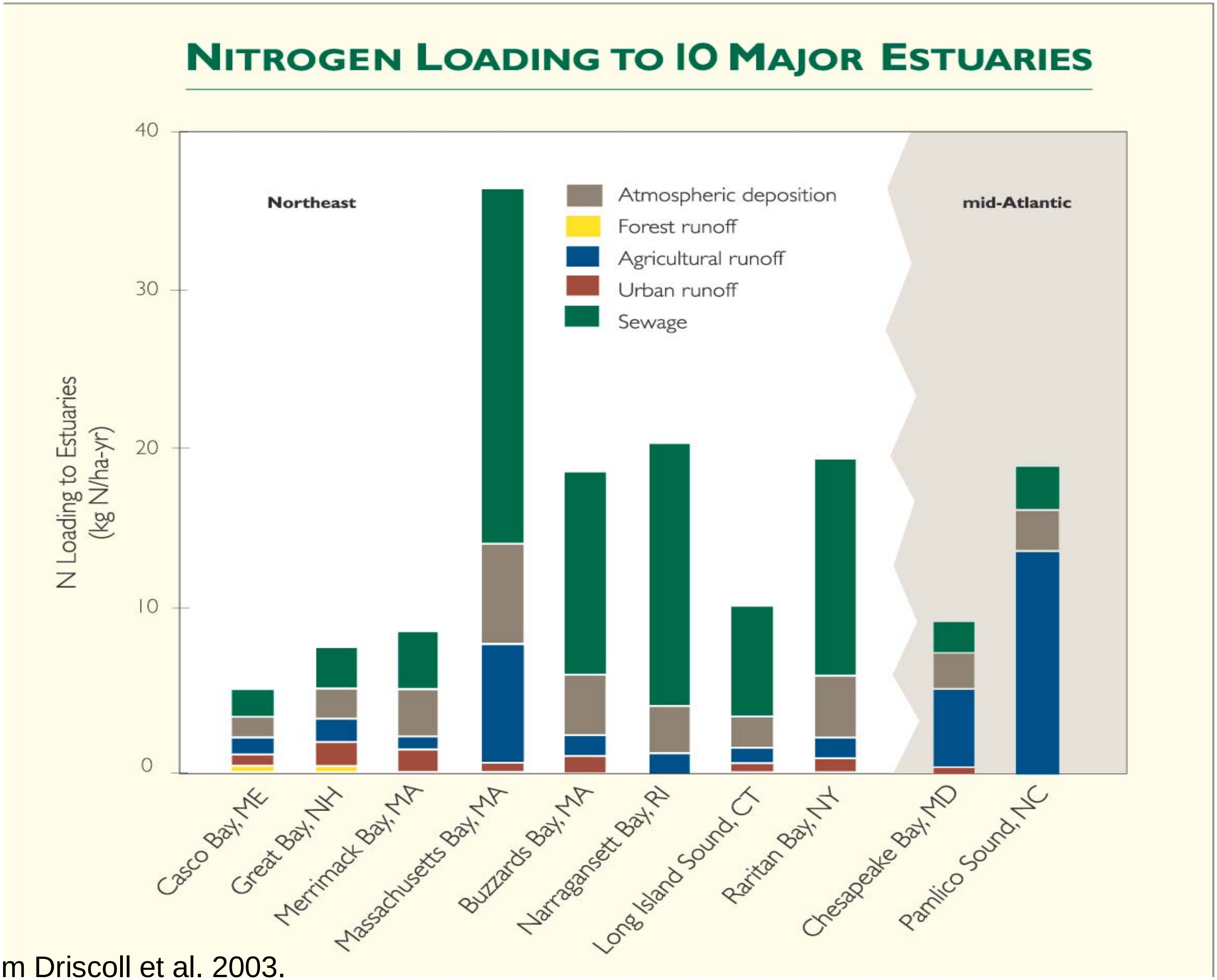


HBRF 2003.

Where does the nitrogen that enters watersheds go?

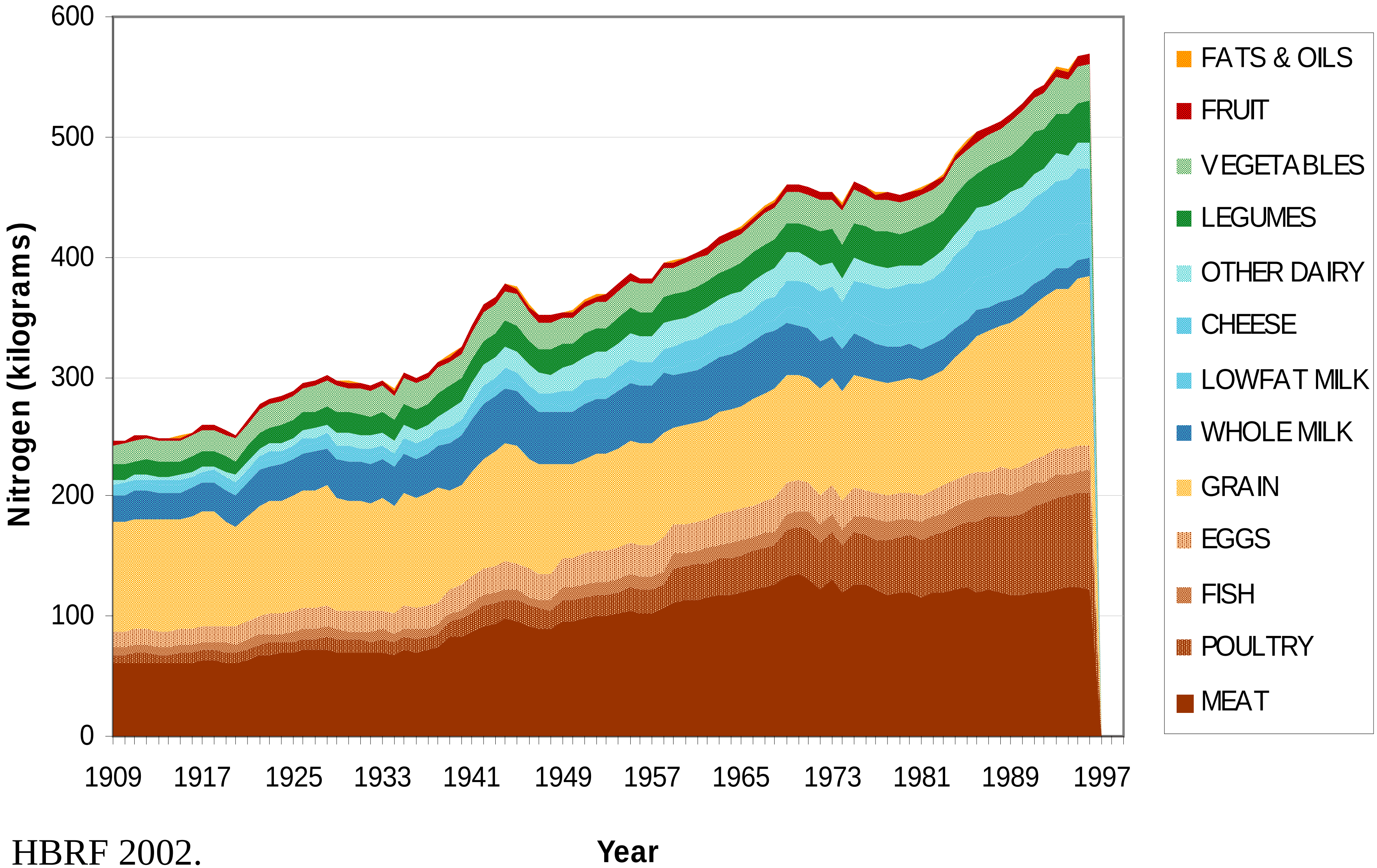
- Returned to atmosphere
- Stored in biomass
- Stored in soil
- Exported to groundwater
- **Exported to estuaries**

From Howarth et al. 2002.



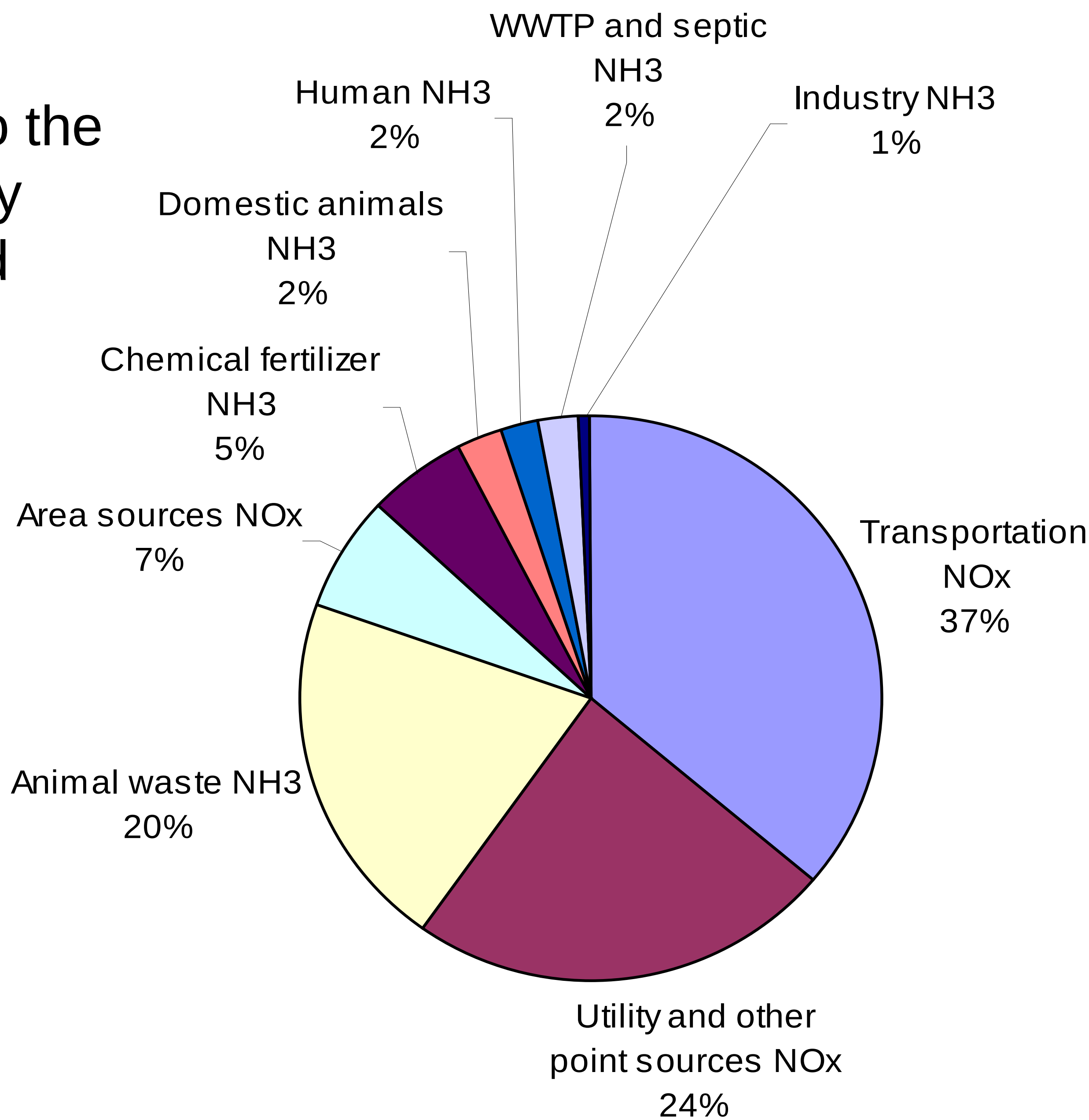
From Driscoll et al. 2003.

Daily Nitrogen Consumption in Food
New England and New York, 1909-1997



HBRF 2002.

Nitrogen sources to the Casco Bay watershed



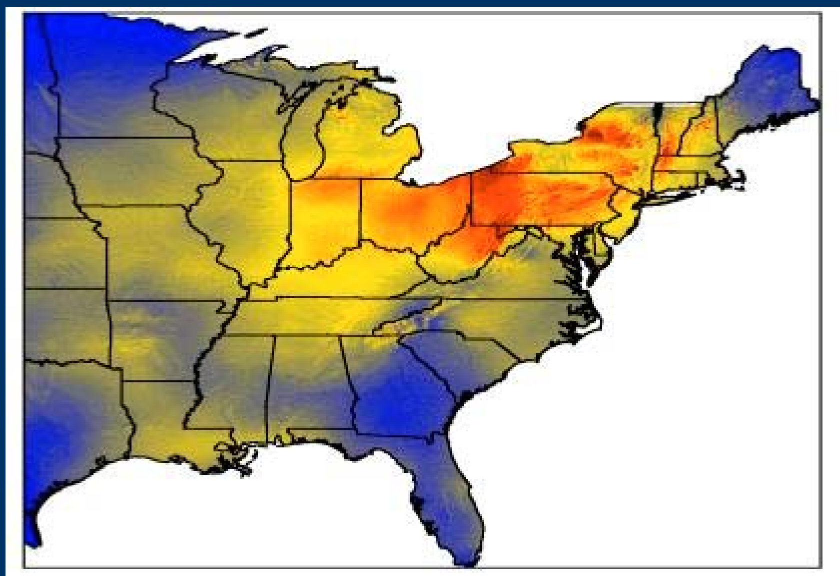
HBRF 2002.

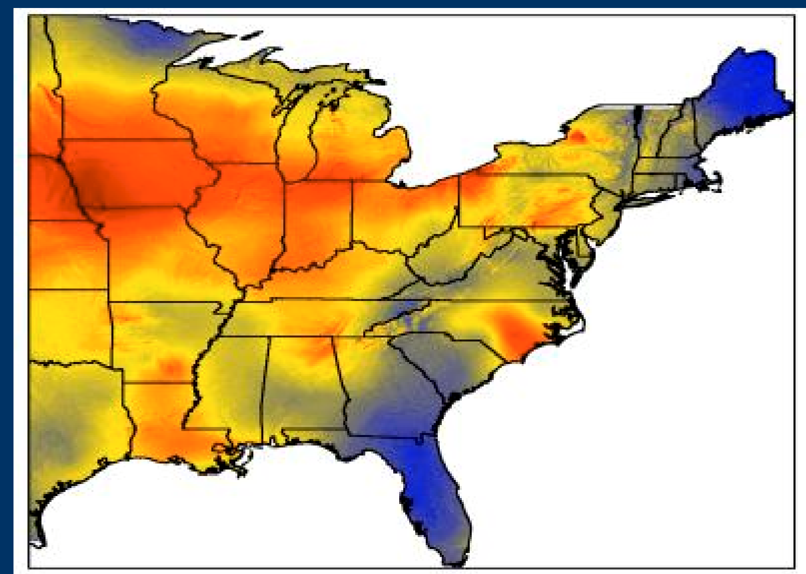
Where is Nitrogen Deposited on the Land?

Wet Nitrate

1995-1997

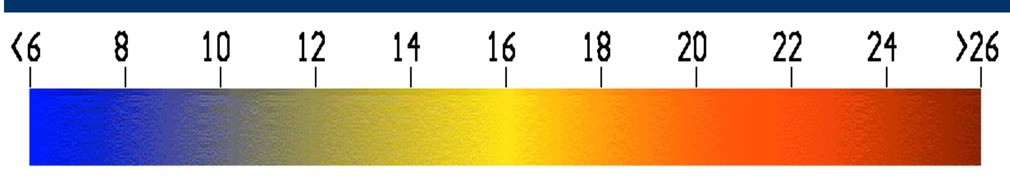
Wet Ammonium

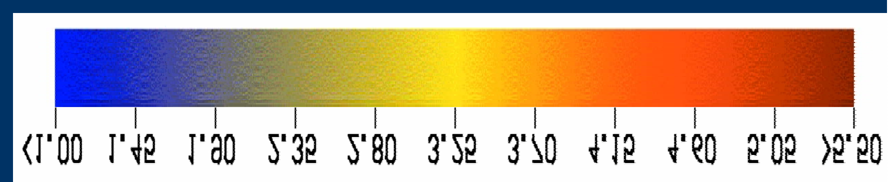




kg NO_3^- ha $^{-1}$ yr^{-1}

kg NH_4^+ ha^{-1} yr^{-1}





Lynch and Grimm, 1997.

Reduced Nitrogen Loading to Estuaries *Estuaries*

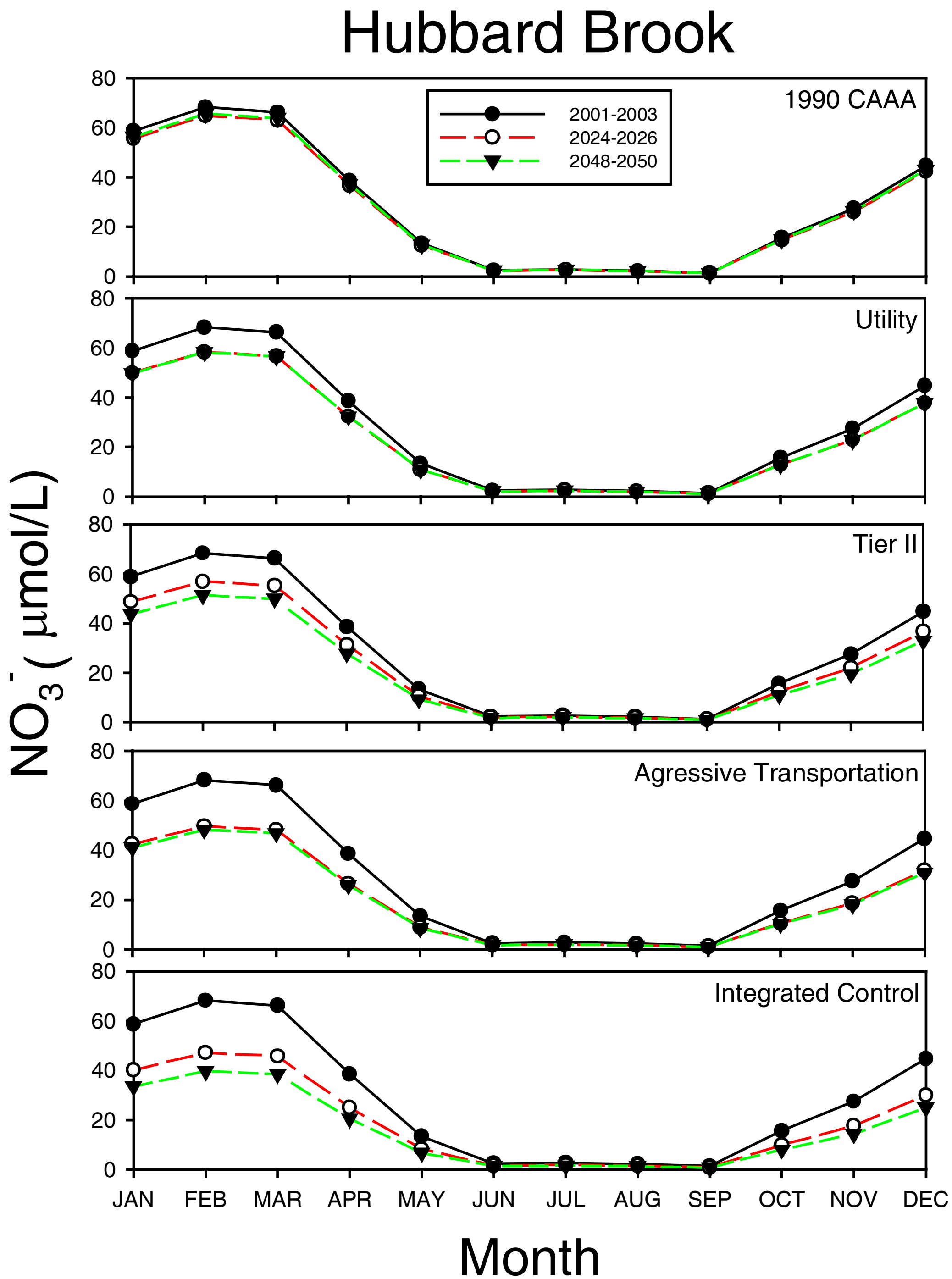
- Reduced N emissions:
  75% reduction in utilities NO_x .
  EPA Tier 2 reductions in vehicle emissions.
  90% reduction above Tier 2 in NO_x from cars.34% reduction in agriculture NH_3.

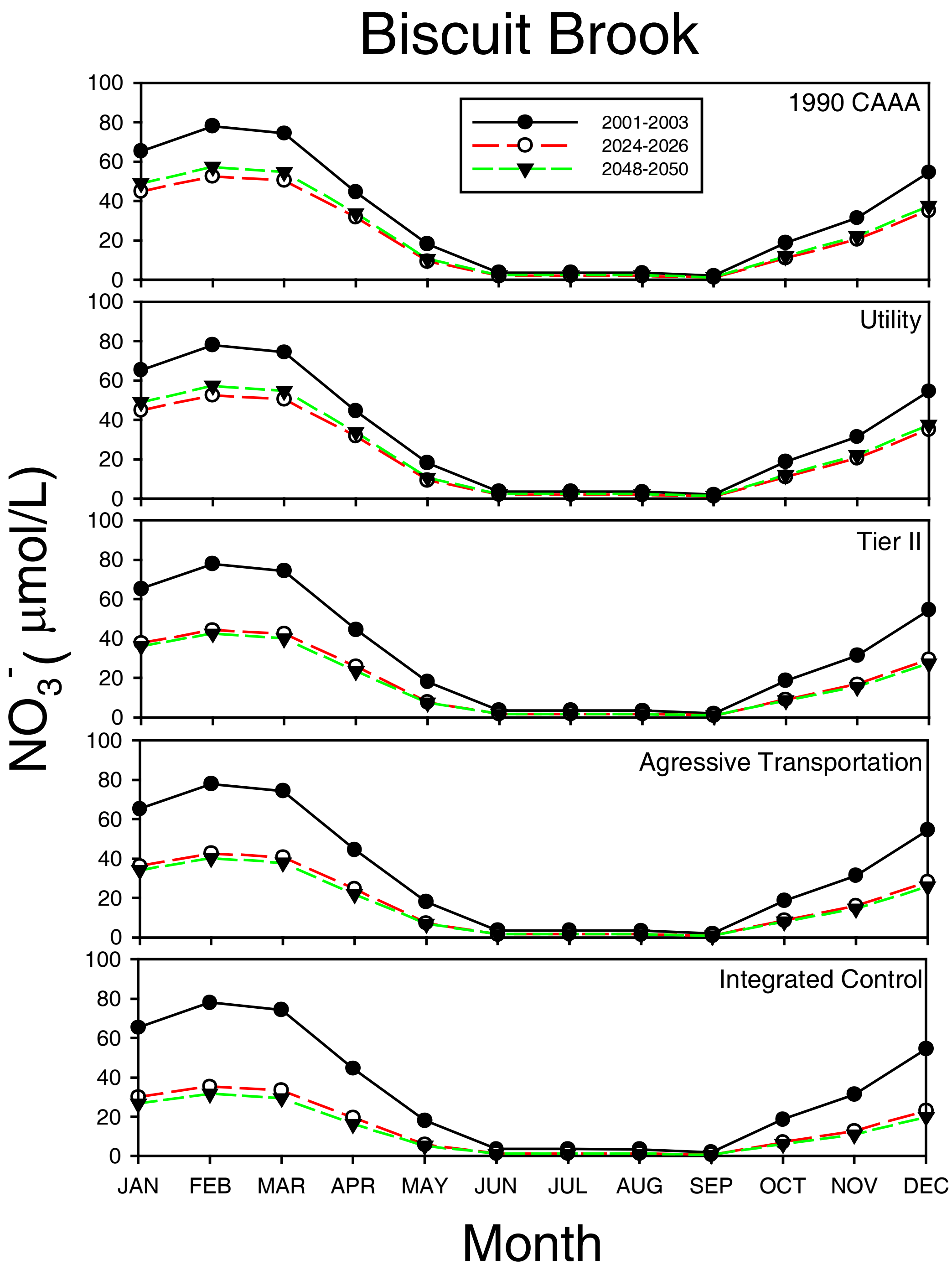
2. Biological Nitrogen Removal for WWTPs.

3. Septic system improvements.

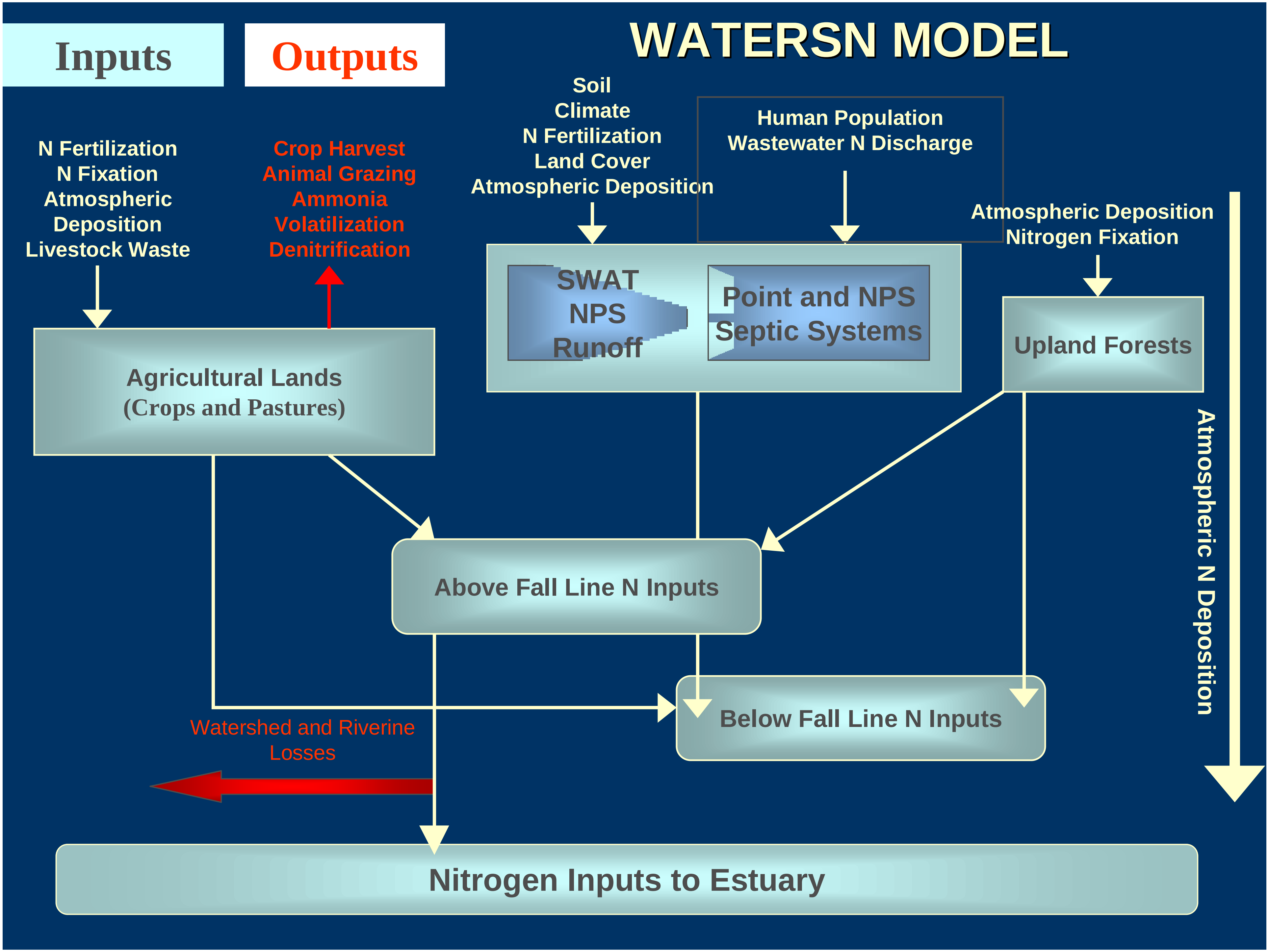
4. Offshore pumping of waste.

5. Agricultural BMPs (33% reduction in runoff N).

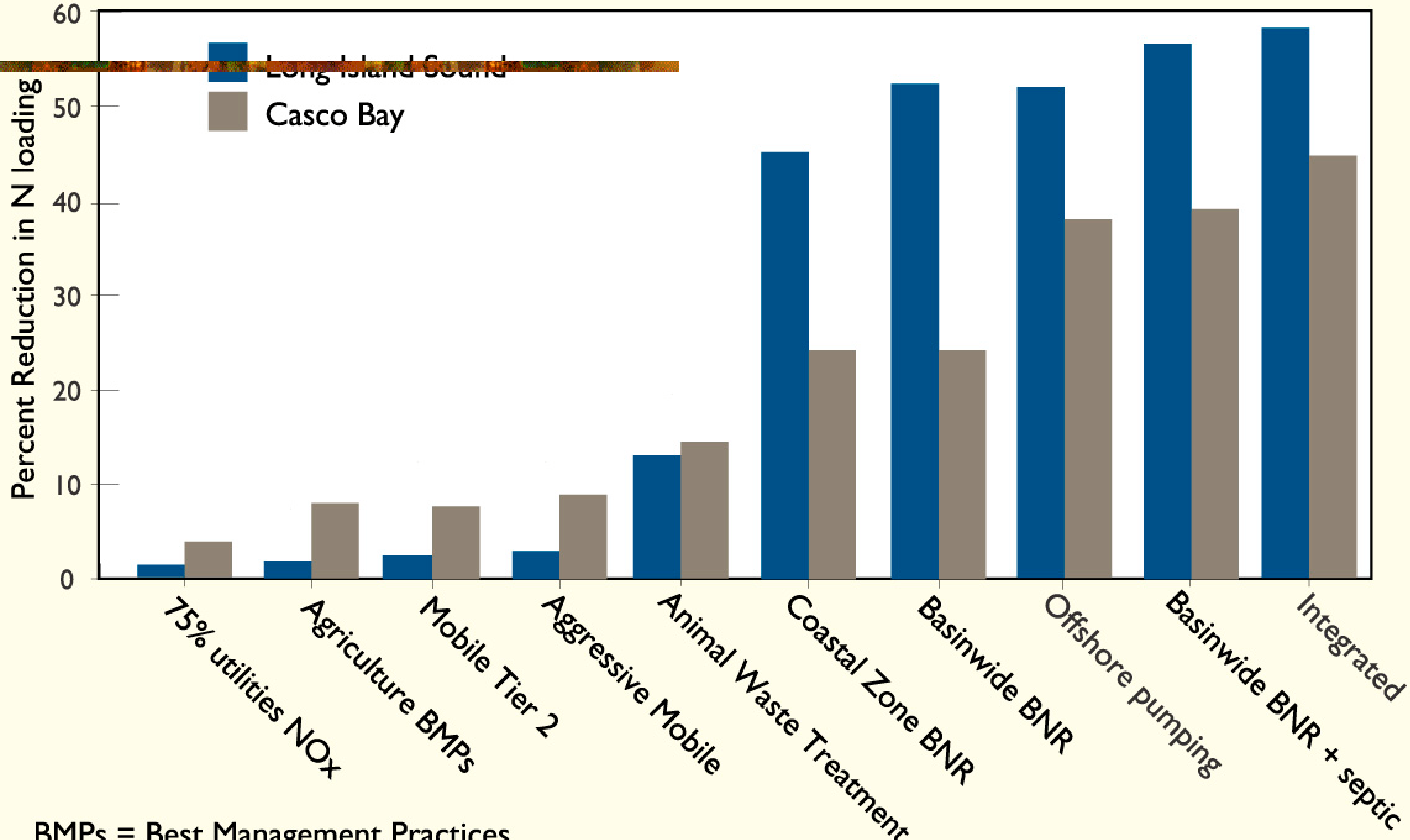

Hubbard Brook
1990 CAAA
Utility
Tier II
Agressive Transportation
Integrated Control
2001-2003
2024-2026
2048-2050
NO3- (μmol/L)
Month
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
0
20
40
60
80



Biscuit Brook
1990 CAAA
Utility
Tier II
Agressive Transportation
Integrated Control
2001-2003
2024-2026
2048-2050
NO_3^- (μmol/L)
Month
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
0
20
40
60
80
100


Inputs
Outputs
WATERSN MODEL
N Fertilization
N Fixation
Atmospheric Deposition
Livestock Waste
Crop Harvest
Animal Grazing
Ammonia Volatilization
Denitrification
Soil
Climate
N Fertilization
Land Cover
Atmospheric Deposition
Human Population
Wastewater N Discharge
Atmospheric Deposition
Nitrogen Fixation
SWAT NPS Runoff
Point and NPS Septic Systems
Upland Forests
Agricultural Lands
(Crops and Pastures)
Above Fall Line N Inputs
Below Fall Line N Inputs
Watershed and Riverine Losses
Atmospheric N Deposition
Nitrogen Inputs to Estuary

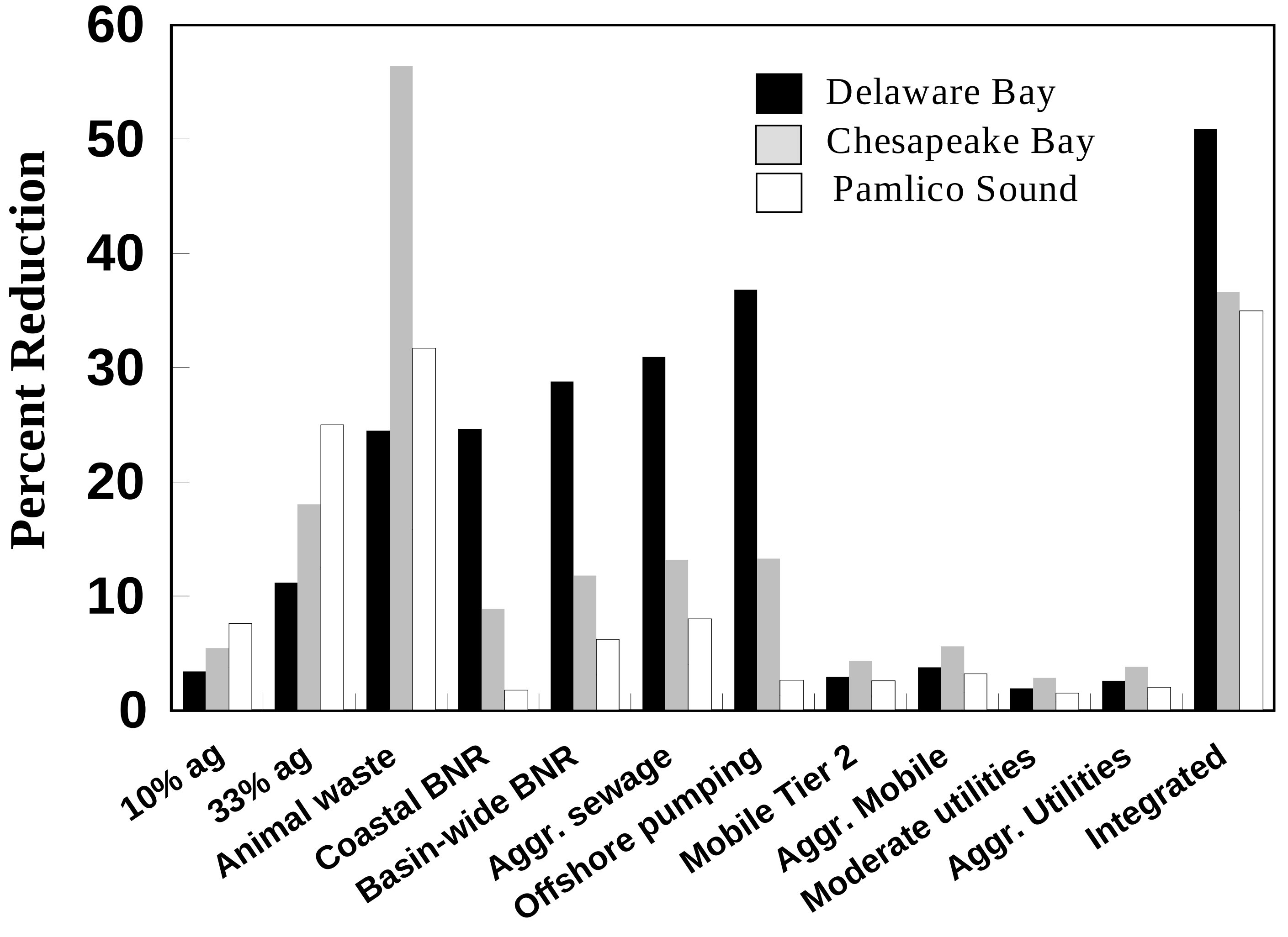
Reductions in Nitrogen Loading to Long Island Sound and Casco Bay



BMPs = Best Management Practices
BNR= Biological Nitrogen Removal

From Driscoll et al. 2003.

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).

N Management – Emissions & Deposition

- 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.

N Management – Emissions & Deposition

- 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.

N management - Coastal waters

- 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_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.

HBRF Science Links funding provided by:

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

Hubbard Brook Research Foundation

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Public Policy Activity

1. Power plant bills in Congress.

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

3. Federal funding bills for wastewater treatment.

4. Total maximum daily load planning.

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