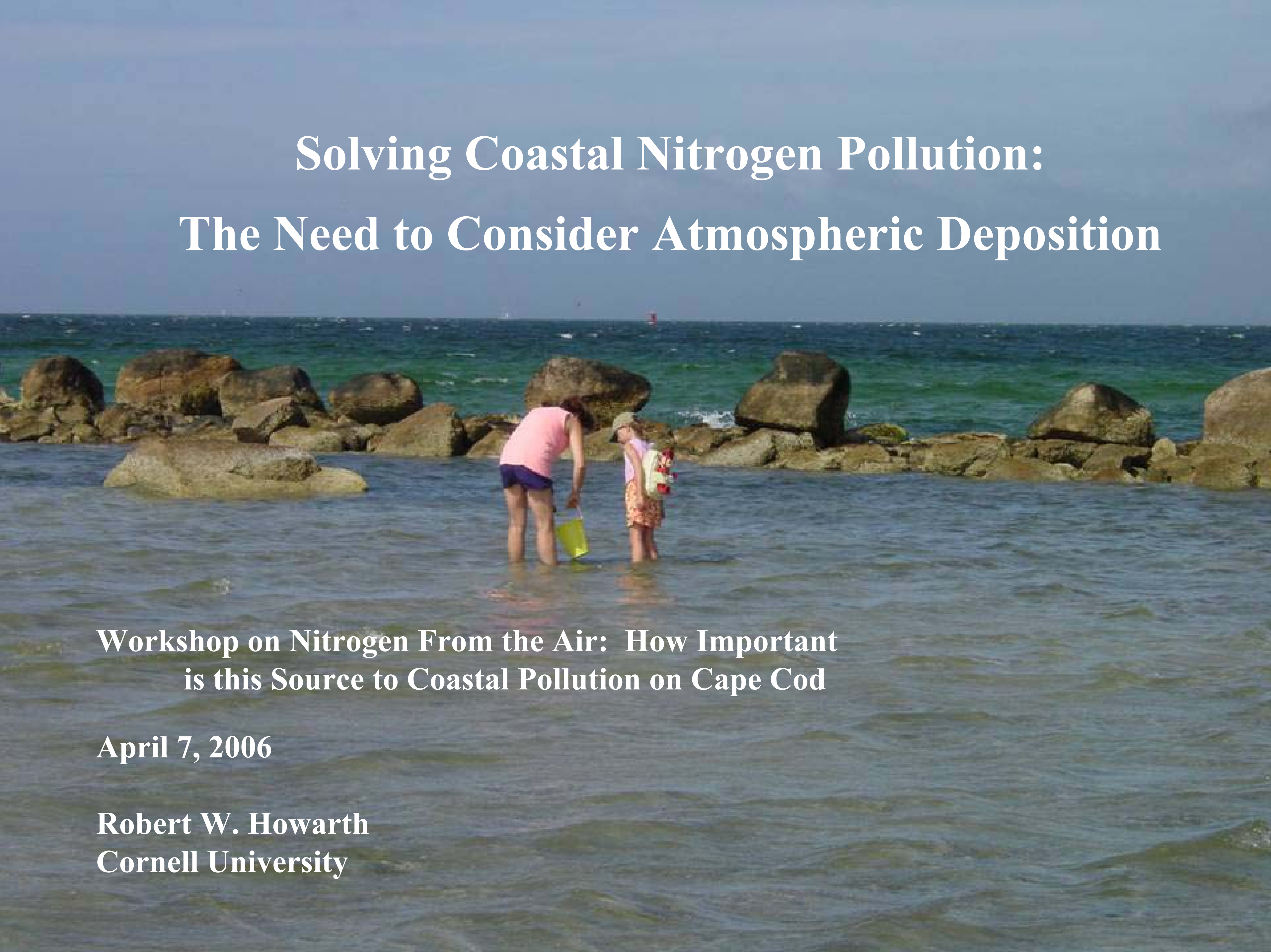
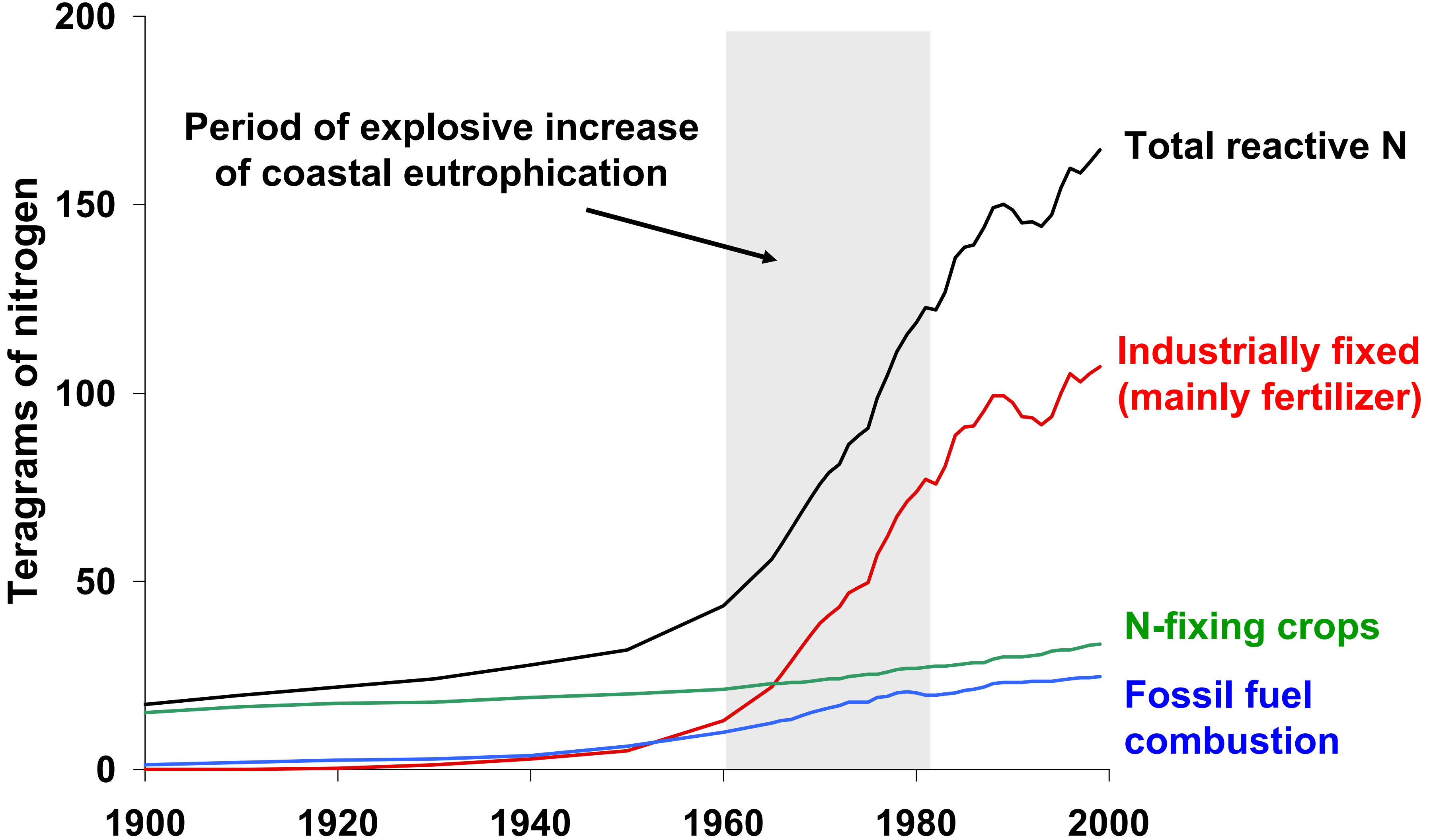


Solving Coastal Nitrogen Pollution: The Need to Consider Atmospheric Deposition

Workshop on Nitrogen From the Air: How Important is this Source to Coastal Pollution on Cape Cod

April 7, 2006

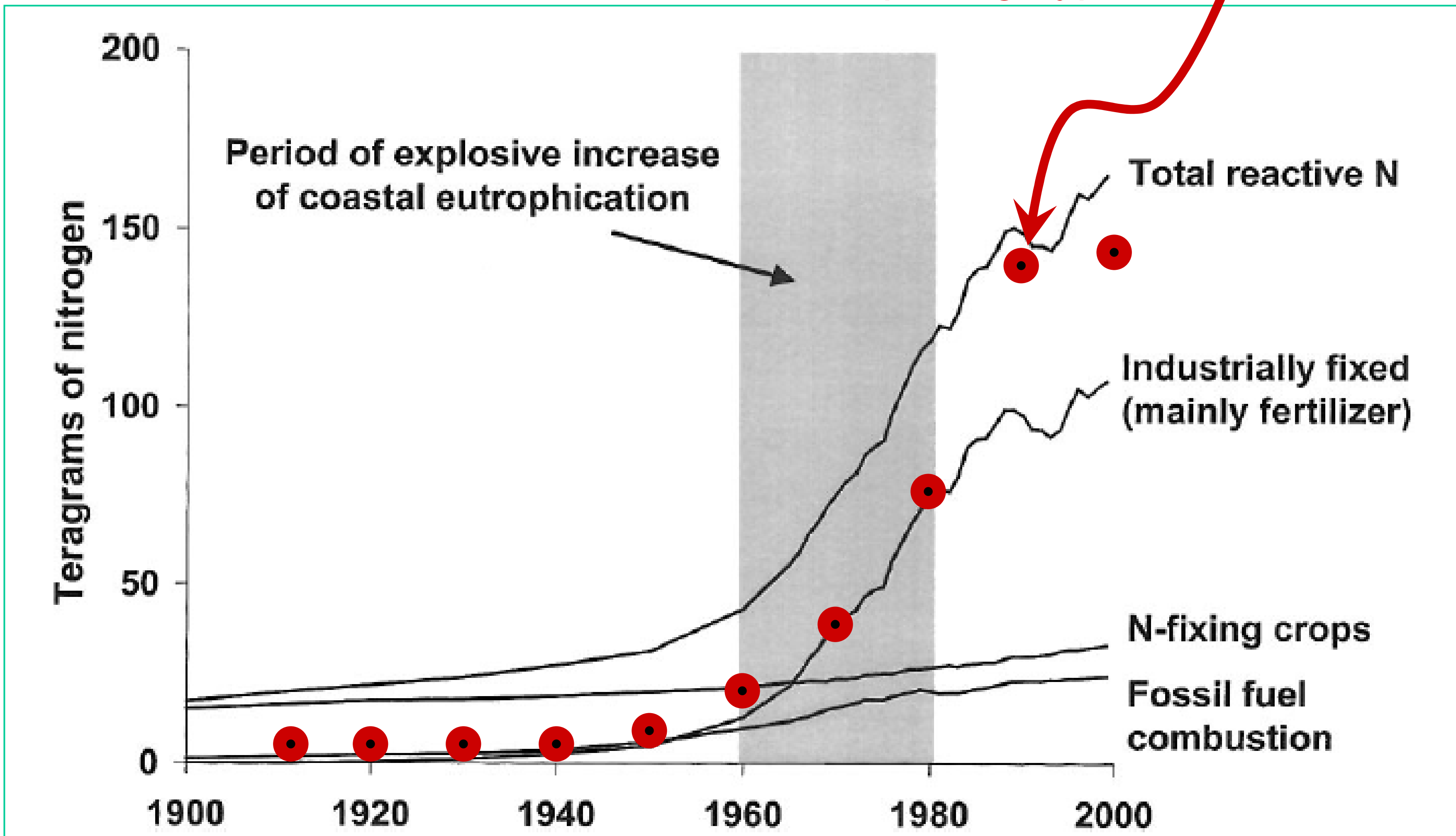
Robert W. Howarth
Cornell University



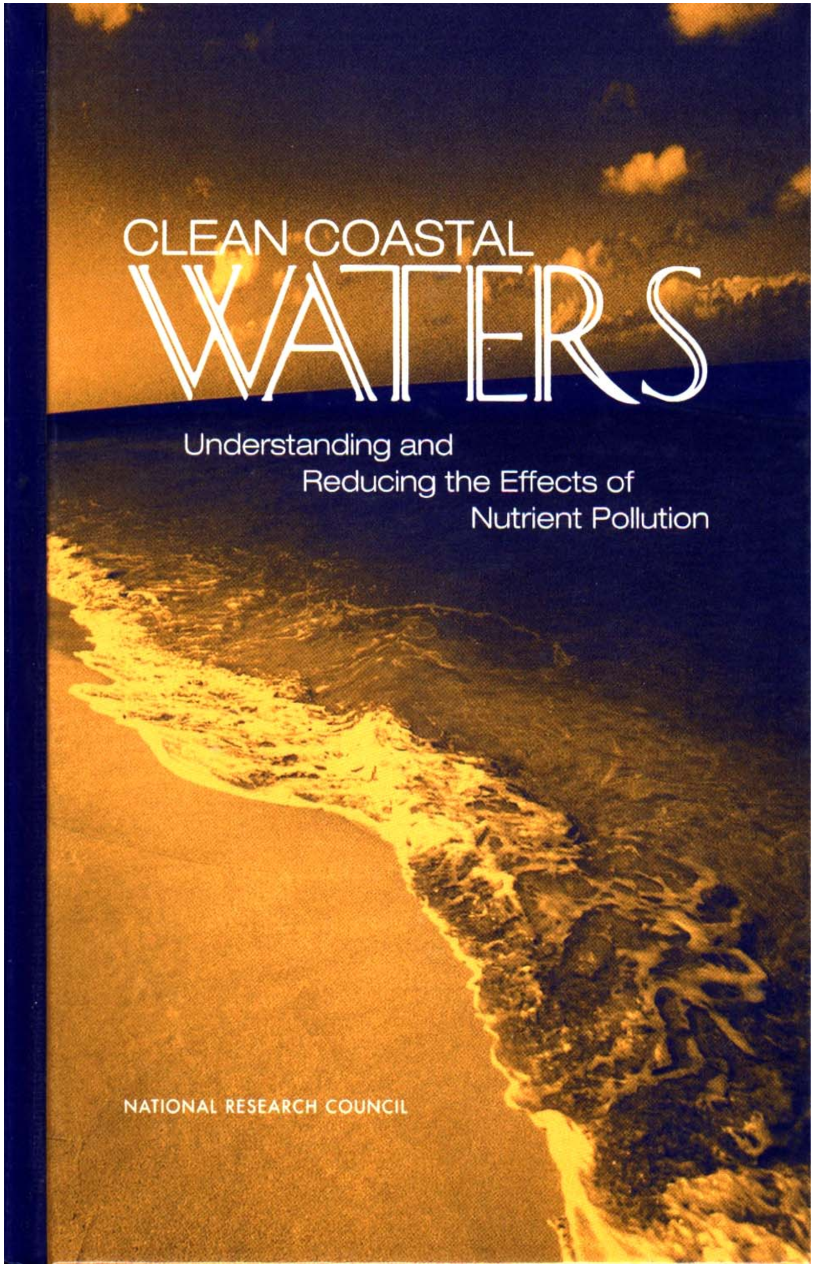
(Boesch 2002; Galloway et al., 2004)

Global Impacts

Cumulative number of systems reporting hypoxia



Modified from R. Diaz; courtesy of D. Scavia



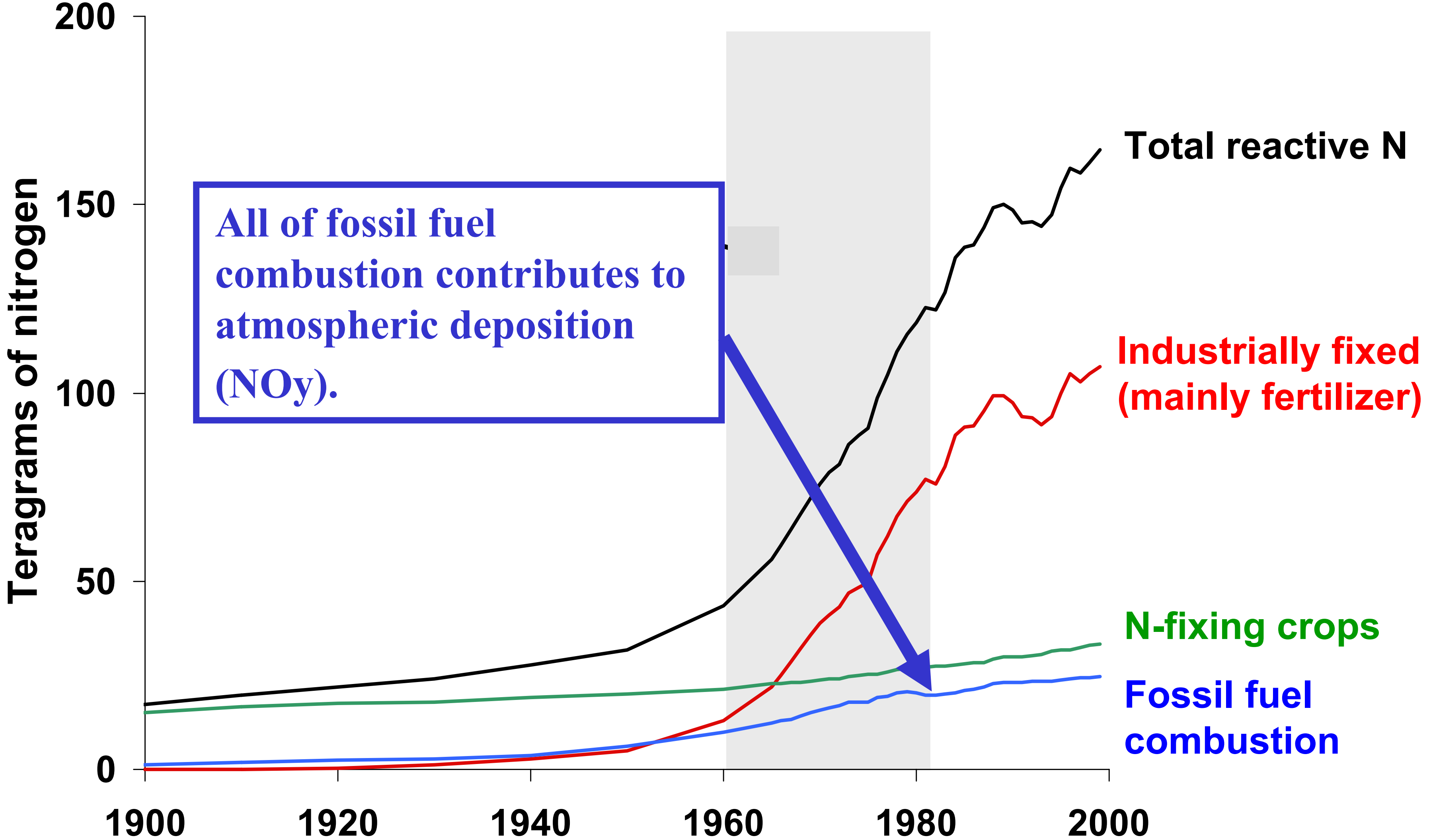
NRC 2000:

Nitrogen is now the largest pollution problem in the coastal waters of the United States.

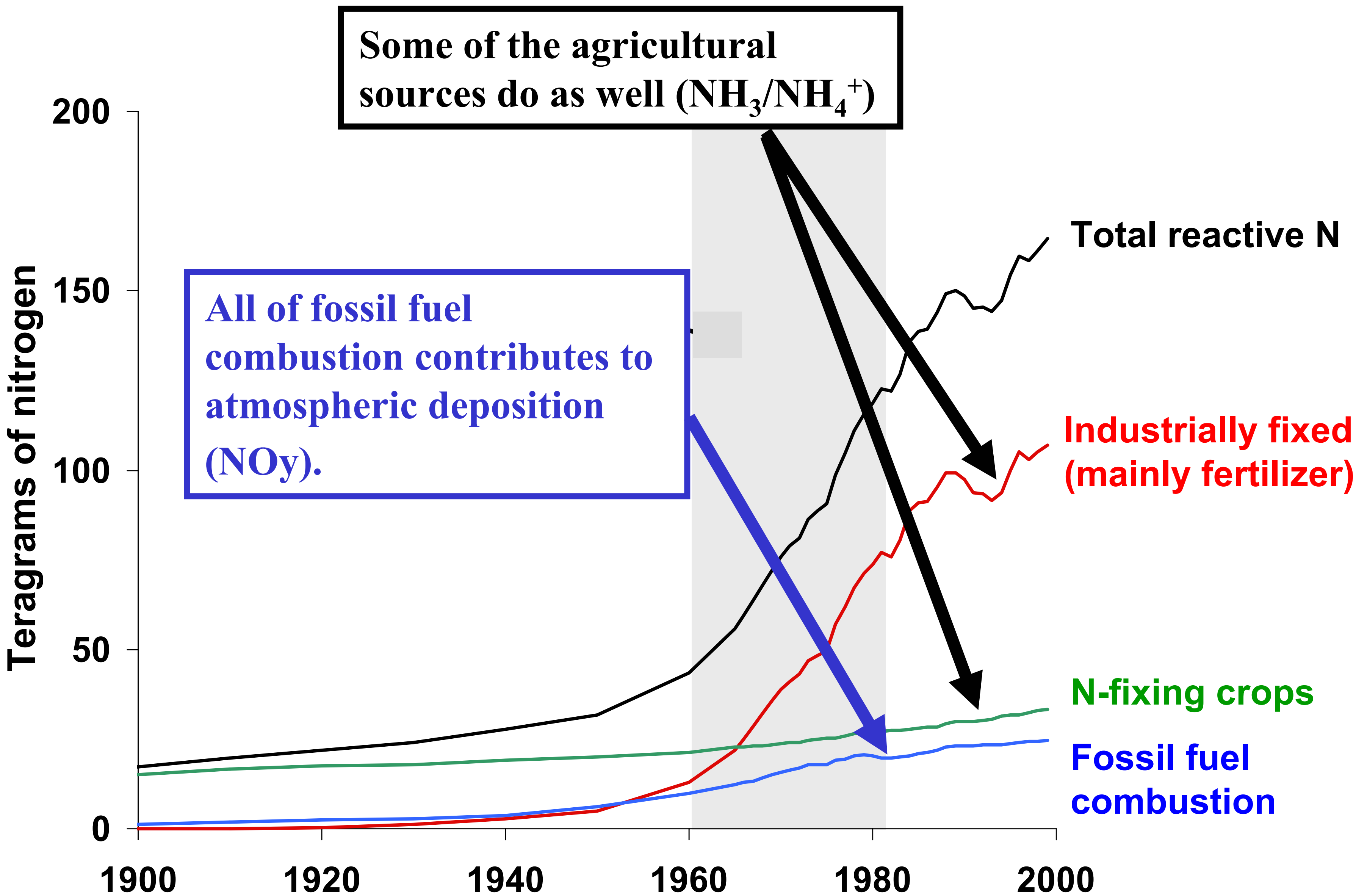
Two thirds of coastal rivers and bays are moderately to severely degraded from nitrogen pollution.

Nitrogen effects beyond hypoxia & anoxia ("dead zones"):

- **habitat degradation and alteration of ecological structure, loss of diversity**
- **increased incidence and duration of harmful algal blooms**

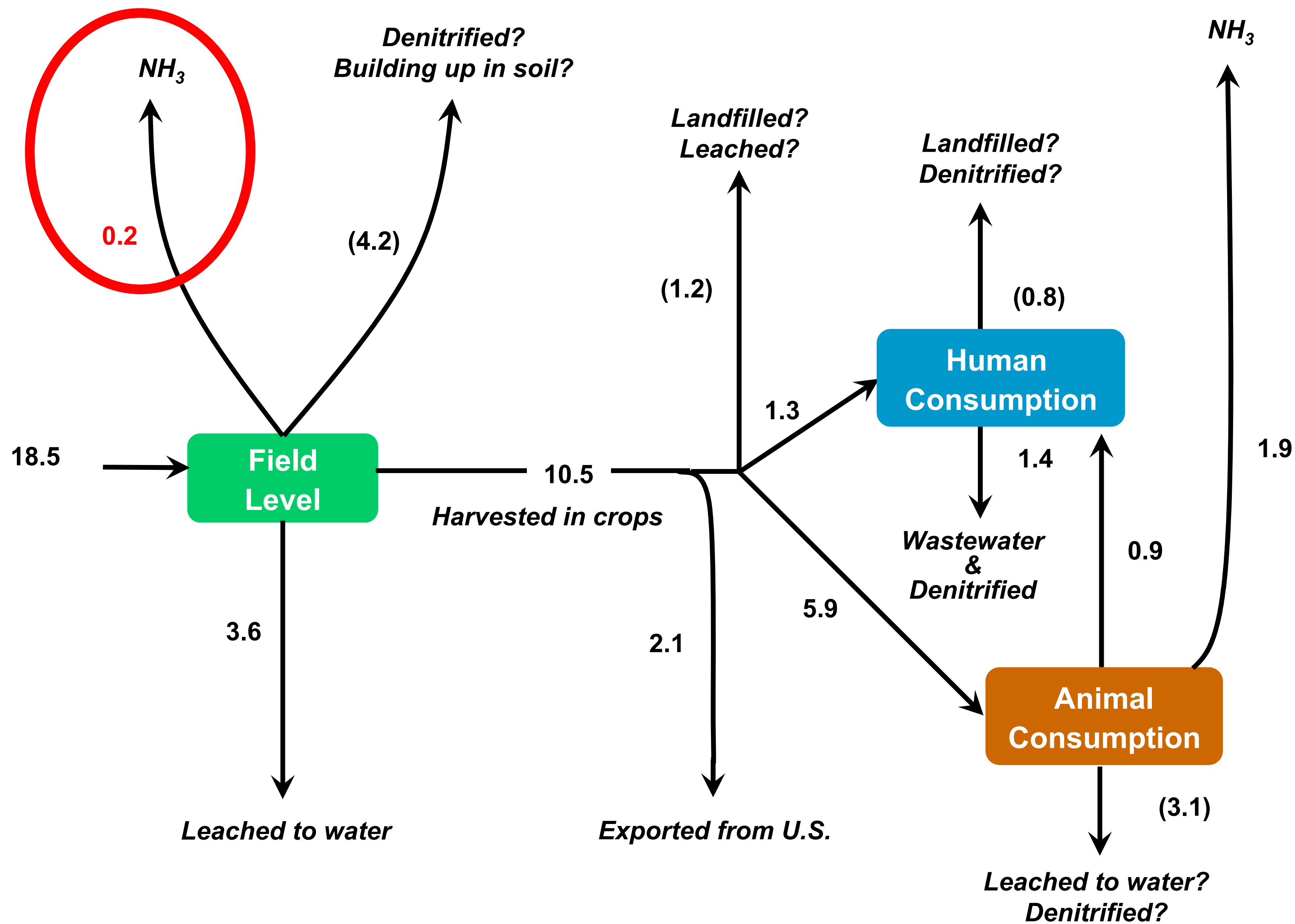


(Boesch 2002; Galloway et al., 2004)



(Boesch 2002; Galloway et al., 2004)

Farm nitrogen balance for US (~1995; Tg per year for entire US)



(Howarth et al. 2002)

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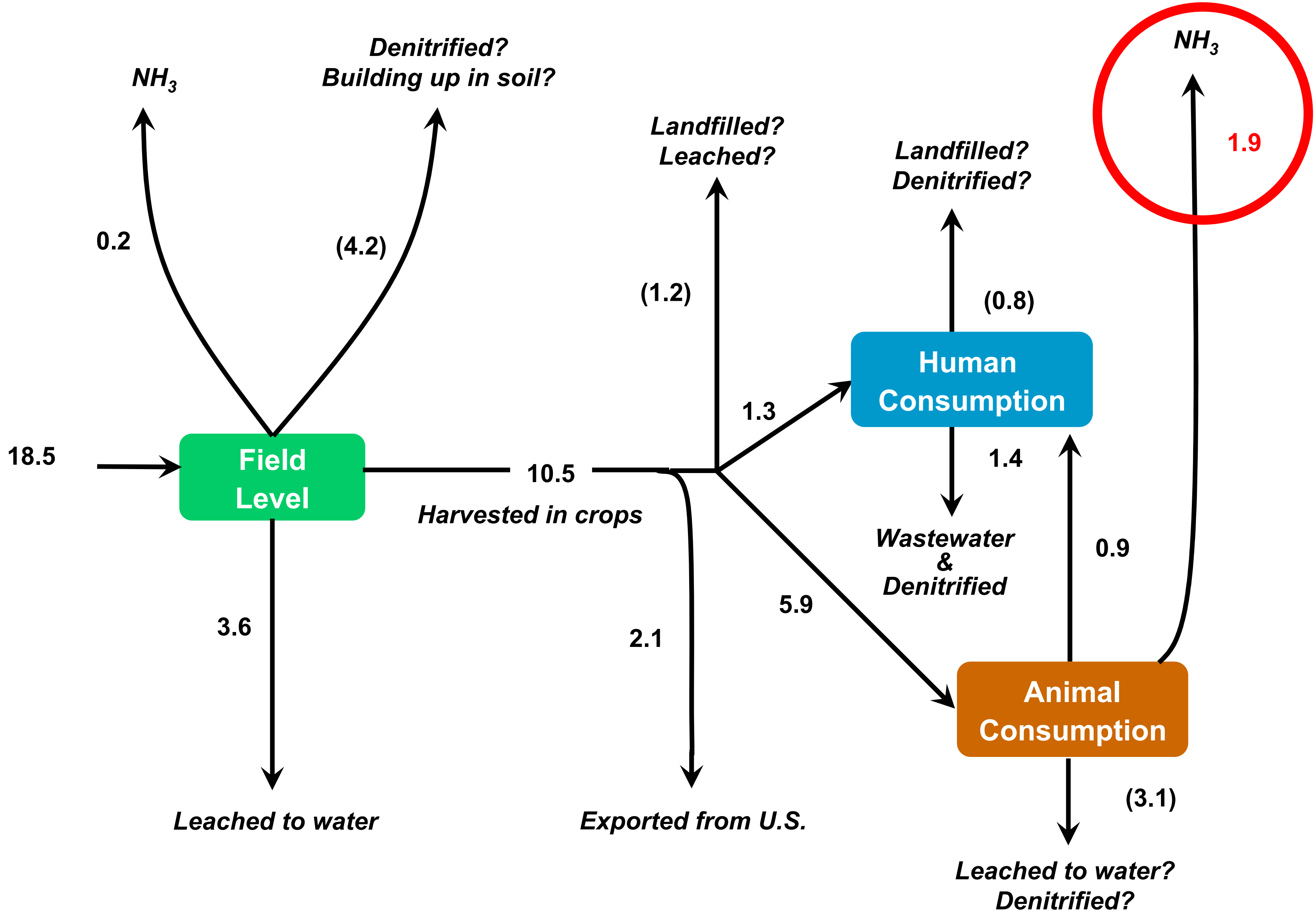
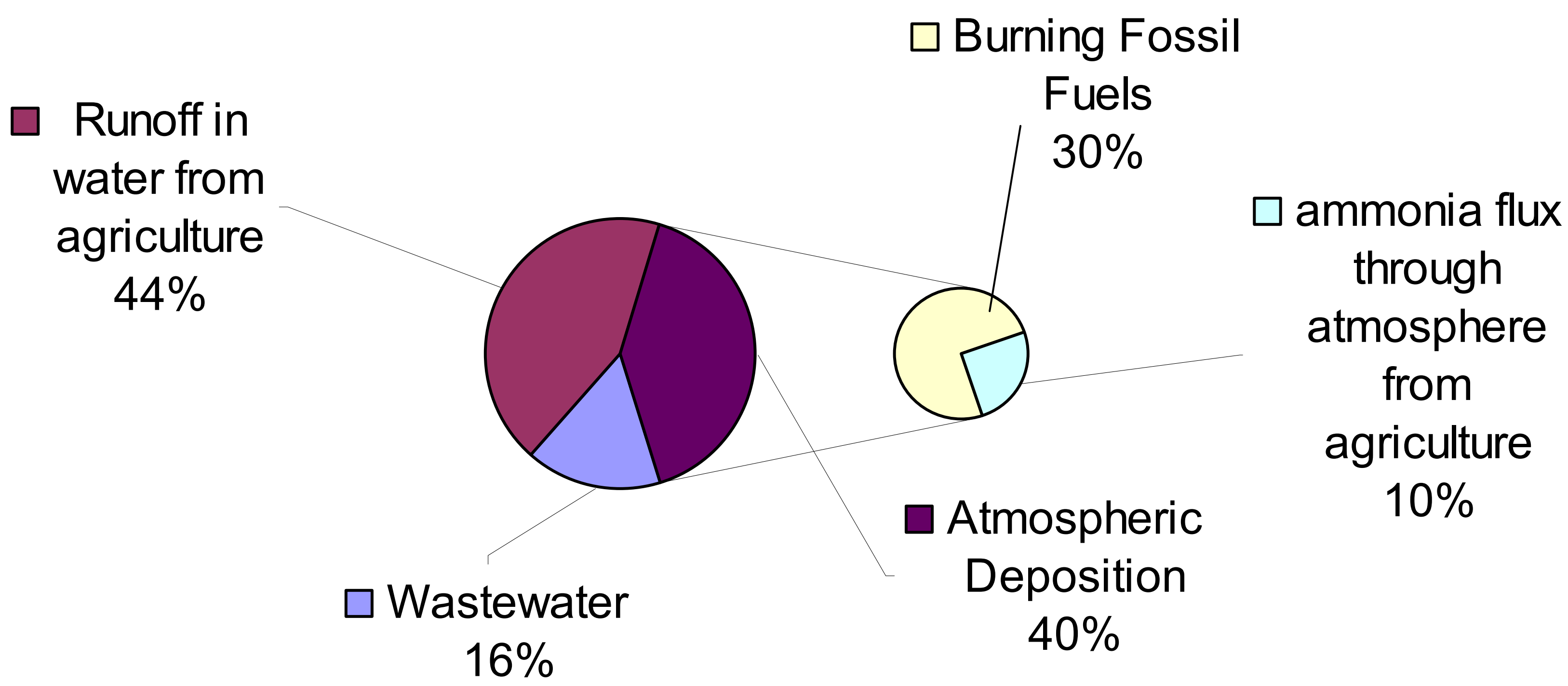


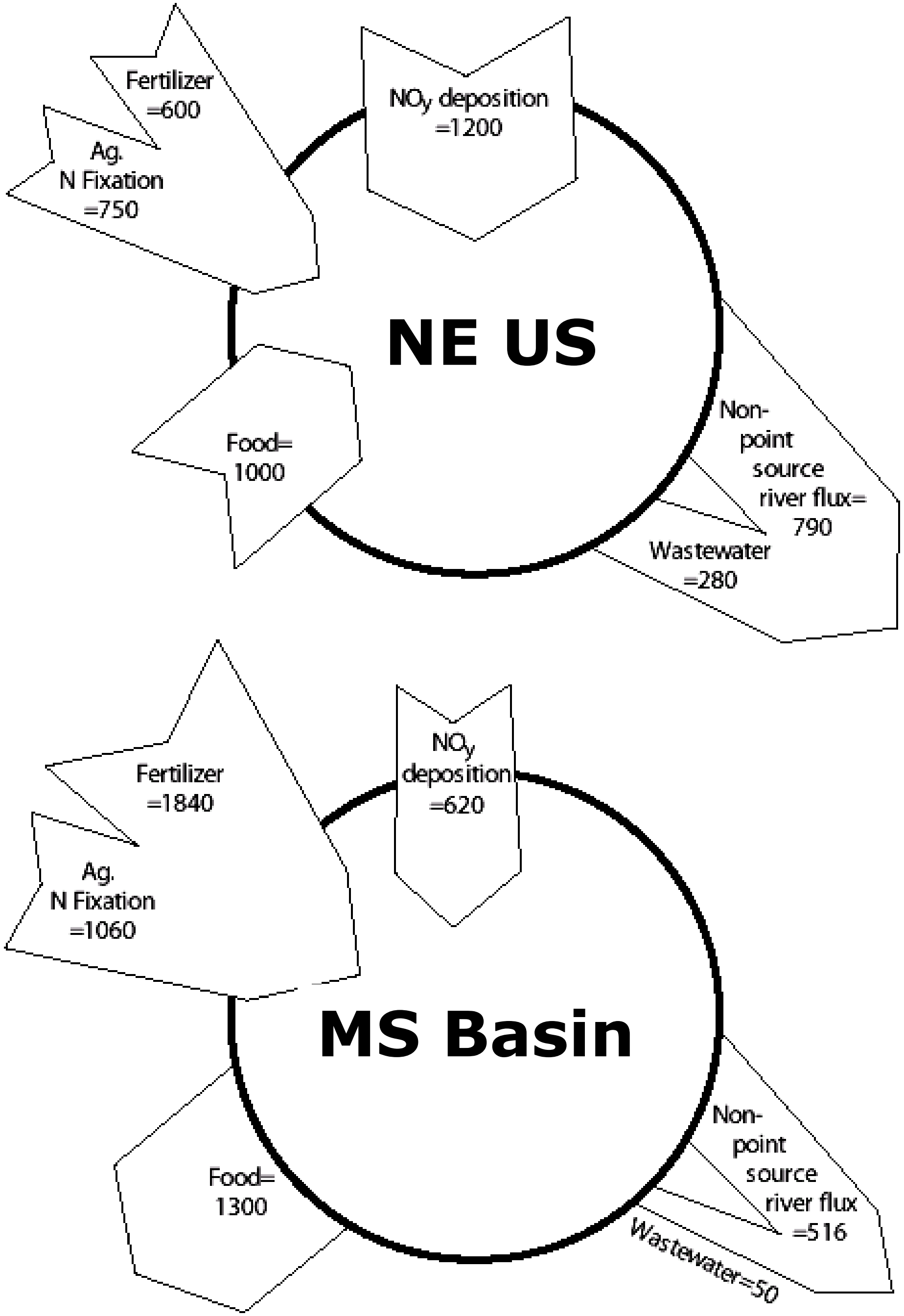
(Howarth et al. 2002)

Sources of Nitrogen Pollution to Coastal Rivers and Bays in the US on Average

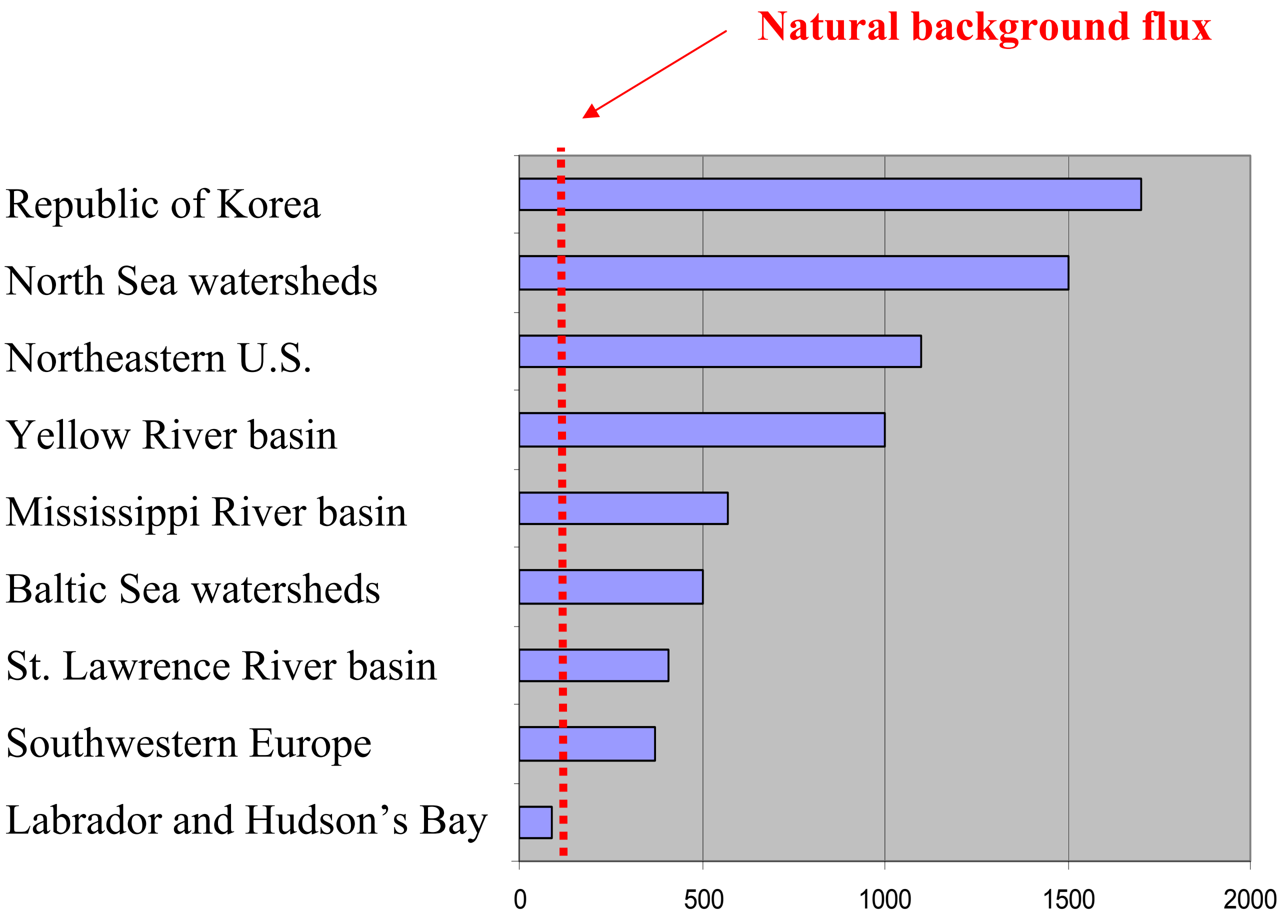


Howarth and Rielinger 2003

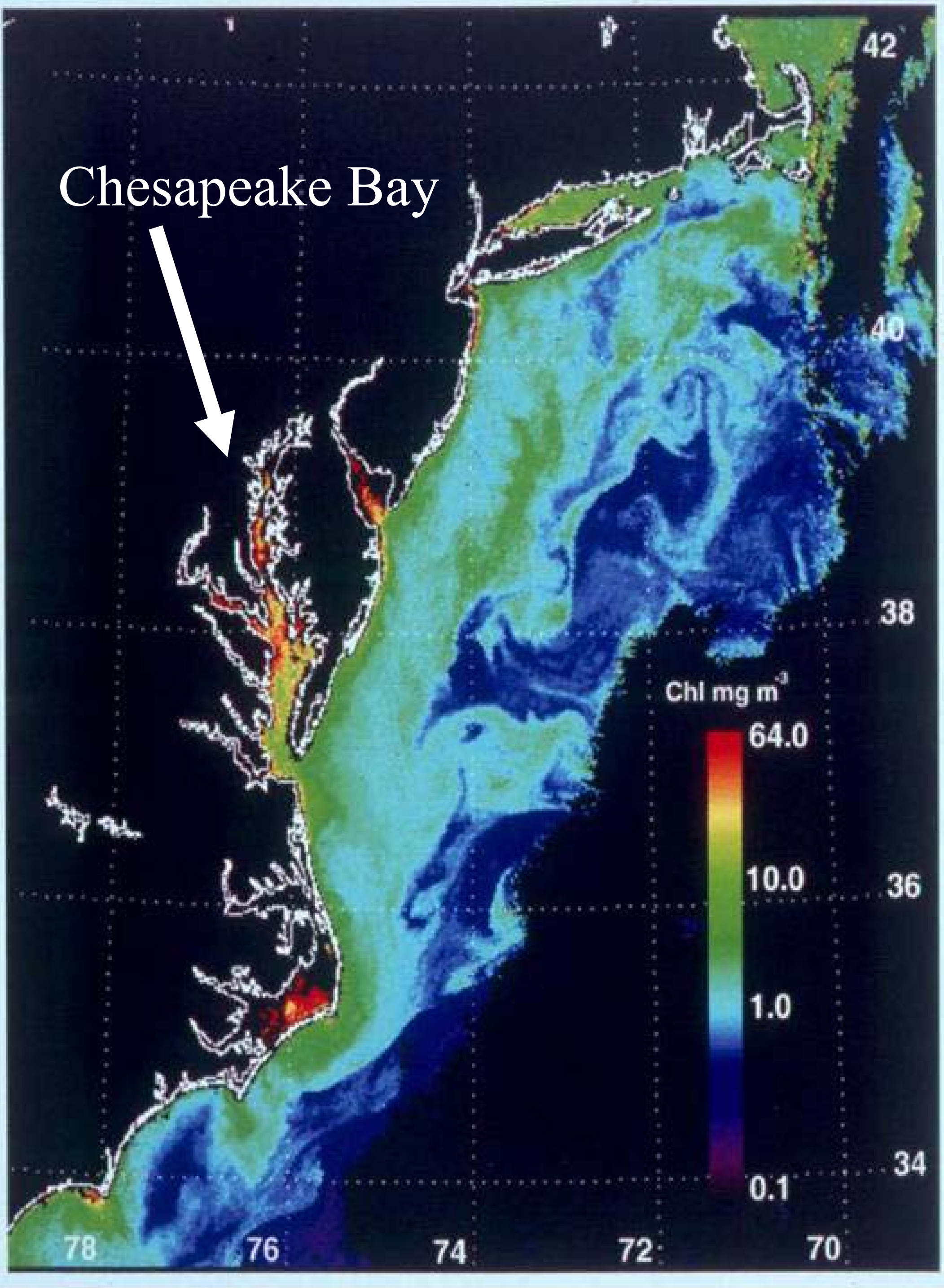
Regional Differences



Howarth et al. 2003



Flux of nitrogen from the landscape to coastal oceans in rivers for contrasting regions of the world in the temperate zone (kg per km2 of watershed area per year; from Howarth et al. 1996, 2002; Bashkin et al. 2002).



Much of the northeastern US is now highly eutrophic.

Note that variation in chlorphyll is only in part due to variation in nitrogen inputs…

large differences in sensitivity as well.

The role of atmospheric deposition as a source of nitrogen to coastal waters largely ignored, until Fisher and Oppenheimer (1991) suggested it may contribute ~ 40% of the nitrogen to Chesapeake Bay.

The role of atmospheric deposition as a source of nitrogen to coastal waters largely ignored, until Fisher and Oppenheimer (1991) suggested it may contribute ~ 40% of the nitrogen to Chesapeake Bay.

This suggestion not too widely believed at first ….
But increasing study of the process ever since.

And over past 15 years, estimates of importance of atmospheric deposition to Chesapeake Bay have steadily increased.

How important is atmospheric deposition to particular coastal rivers and bays?

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Several recent studies comparing across sites….

However, most just report what local teams have estimated; dramatically different methodologies and levels of rigor.

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However, most just report what local teams have estimated; dramatically different methodologies and levels of rigor.

How important is atmospheric deposition to particular coastal rivers and bays?

Consistent, comparative approaches are far preferable.

One of the best comparative approaches has used the USGS SPARROW model; a spatially explicit statistical model for water quality, based on sources of pollution as well as land use, stream residence times, etc.

For deposition, uses NADP wet deposition data only.

SPARROW-based estimates for importance of atmospheric deposition to fluxes of nitrogen from watersheds to estuaries in northeastern US

.	Atmosphere	Non-ag non-point	Wastewater
Casco Bay	22%	54%	13%
Great Bay	9	58	23
Merrimack River	28	43	20
Mass. Bay	4	6	88
Buzzards Bay	12	14	63
Narragansett Bay	10	19	62
LI Sound	35	33	17
Hudson River	26	21	40
Barnegat Bay	19	28	43
Delaware Bay	22	17	35
Chesapeake Bay	28	22	8

(Alexander et al. 2001)

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Chesapeake Bay	28	22	8

Pre-diversion

(Alexander et al. 2001)

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Probably low

(Alexander et al. 2001)

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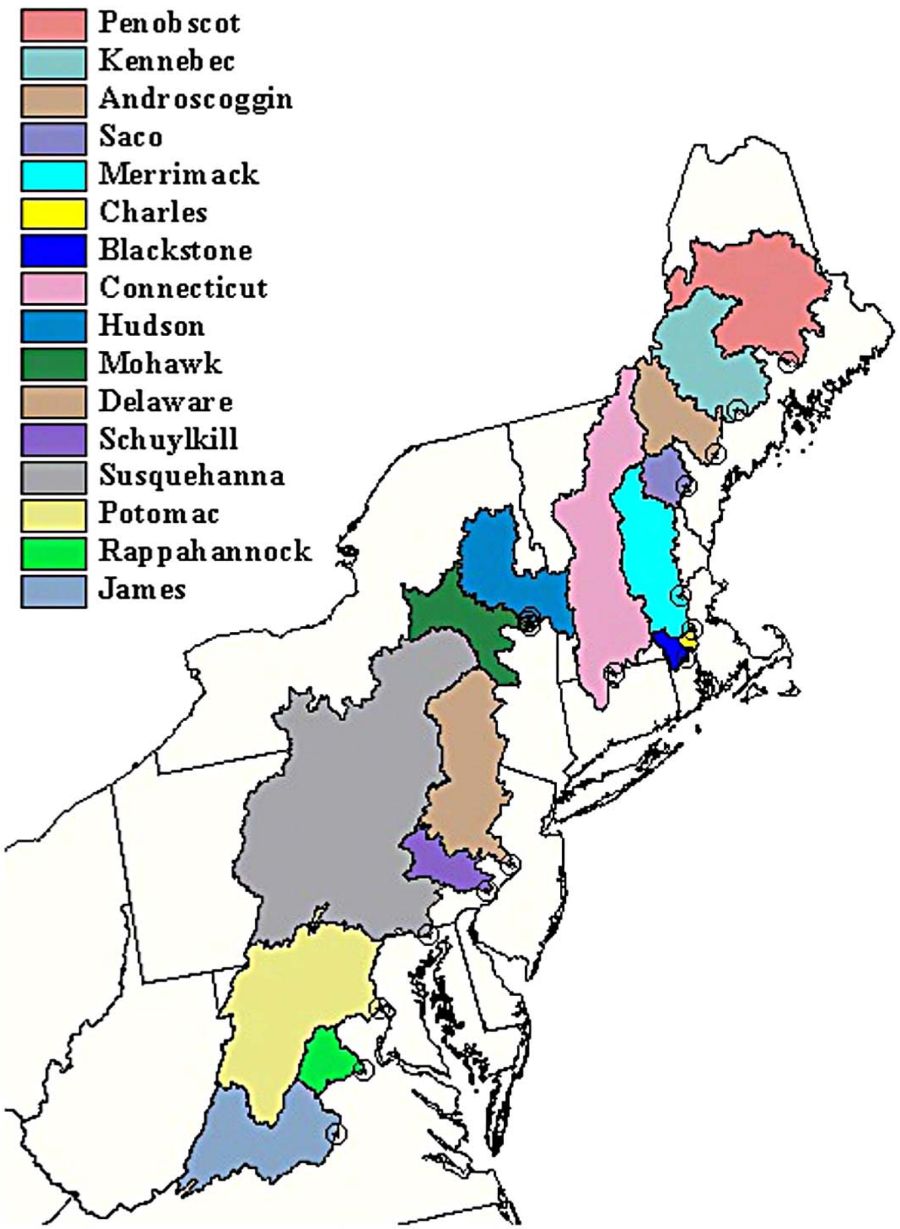
Chesapeake Bay	28	**22**	8

Is some or much of this from atmospheric depositon?

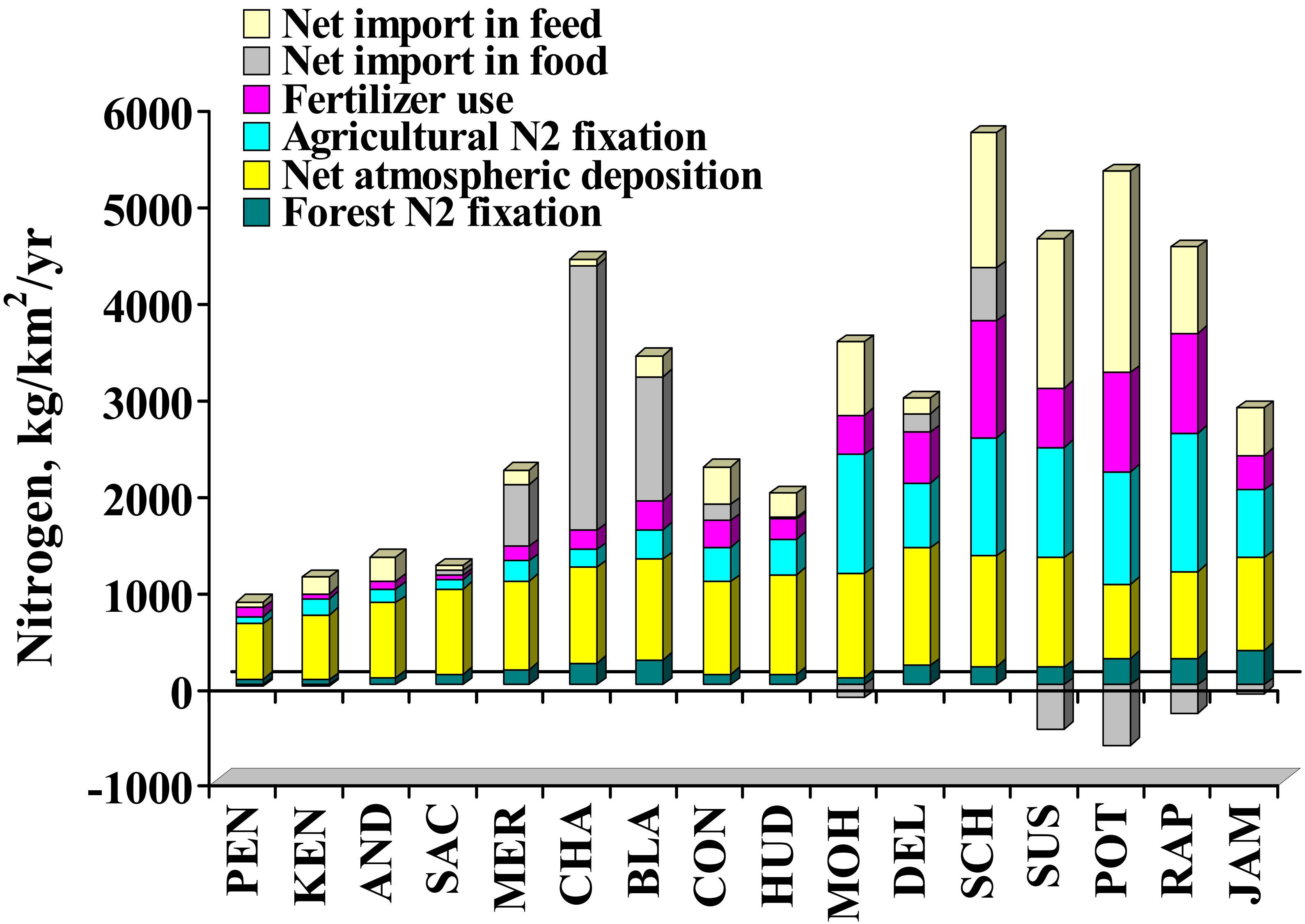
Another approach:

Mass balance assessment of nitrogen inputs to regions and large river basins.



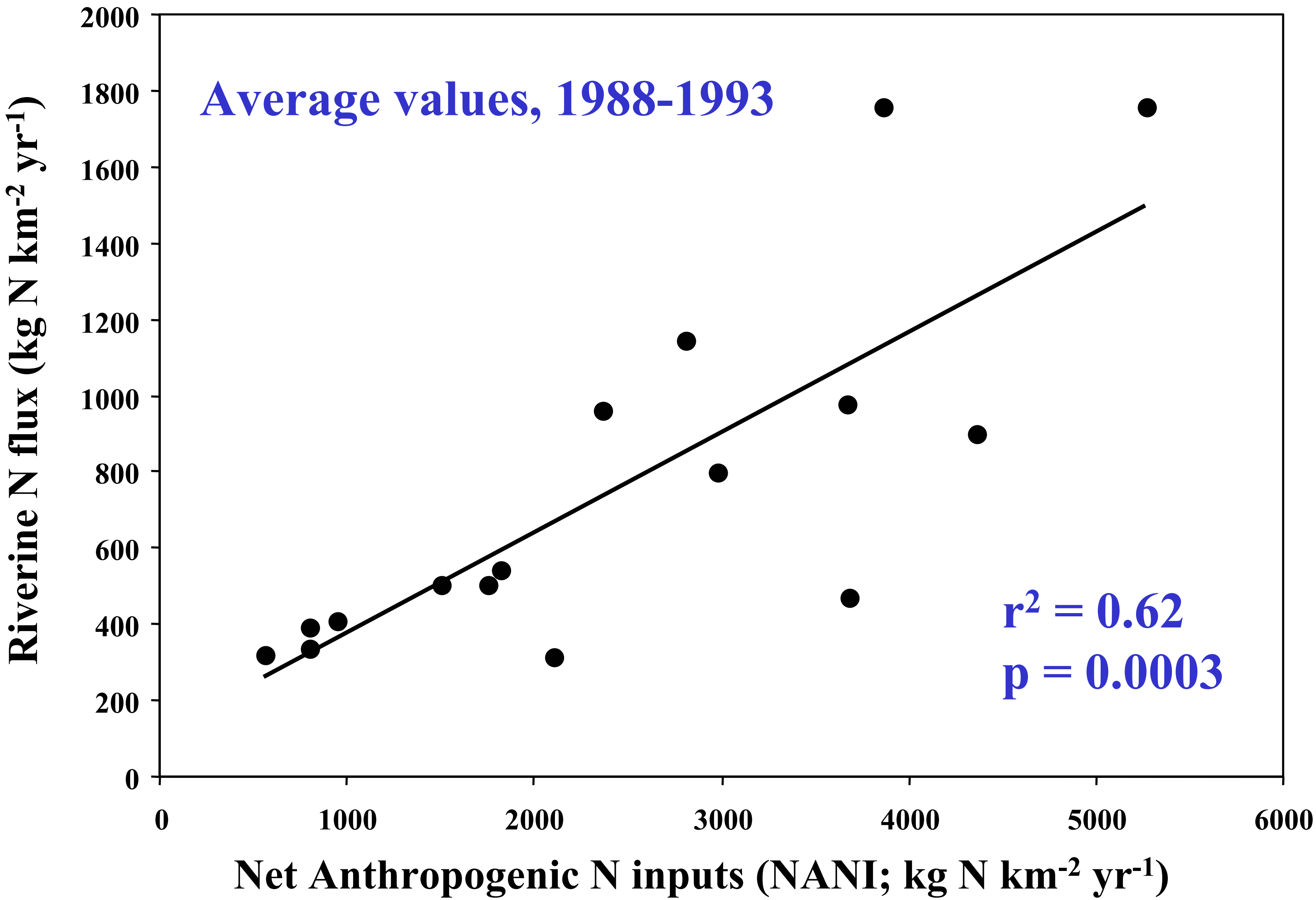
Boyer et al. 2002

Northeastern US watershed nitrogen inputs (1988-1993)



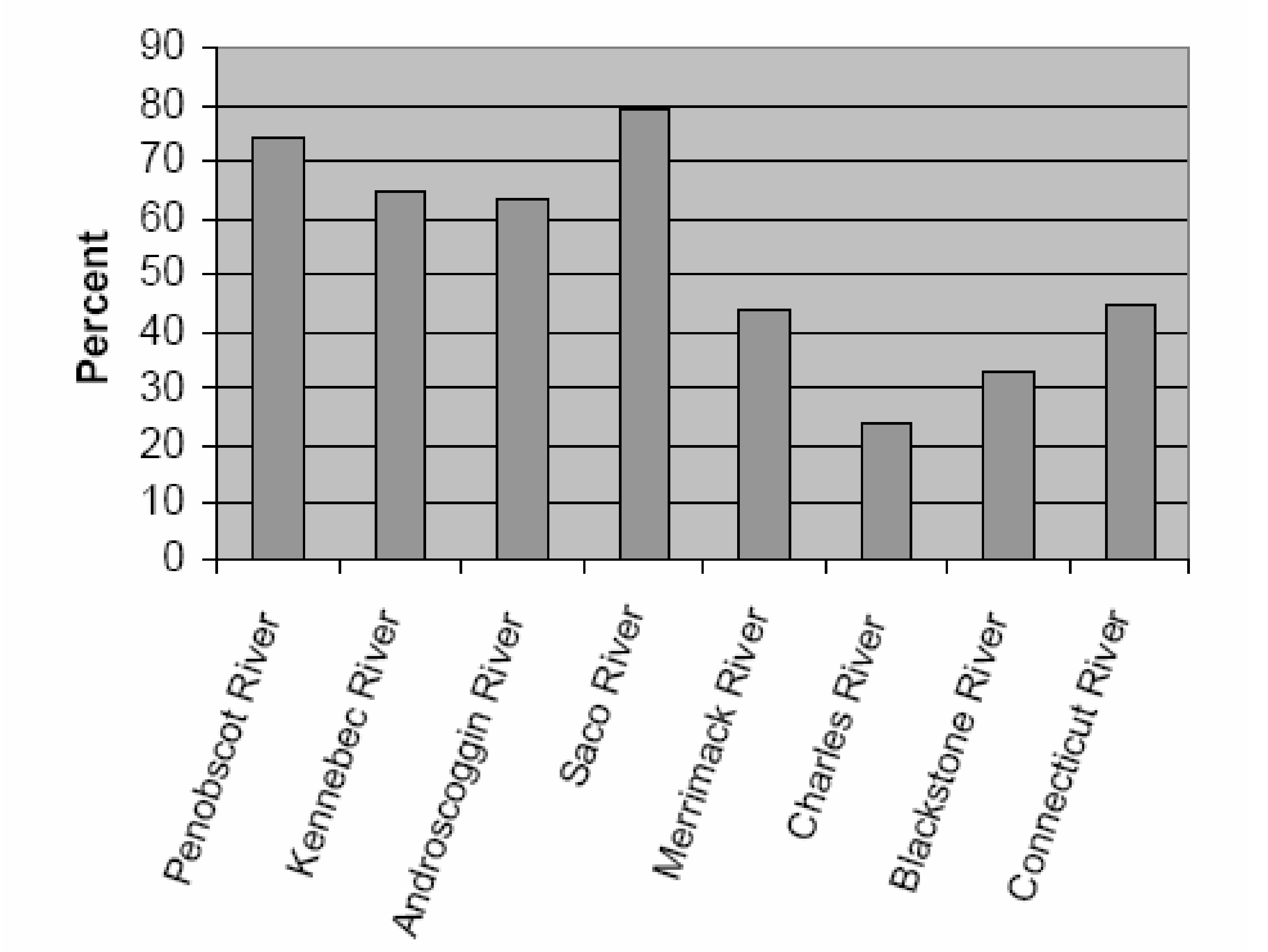
Boyer et al. 2002

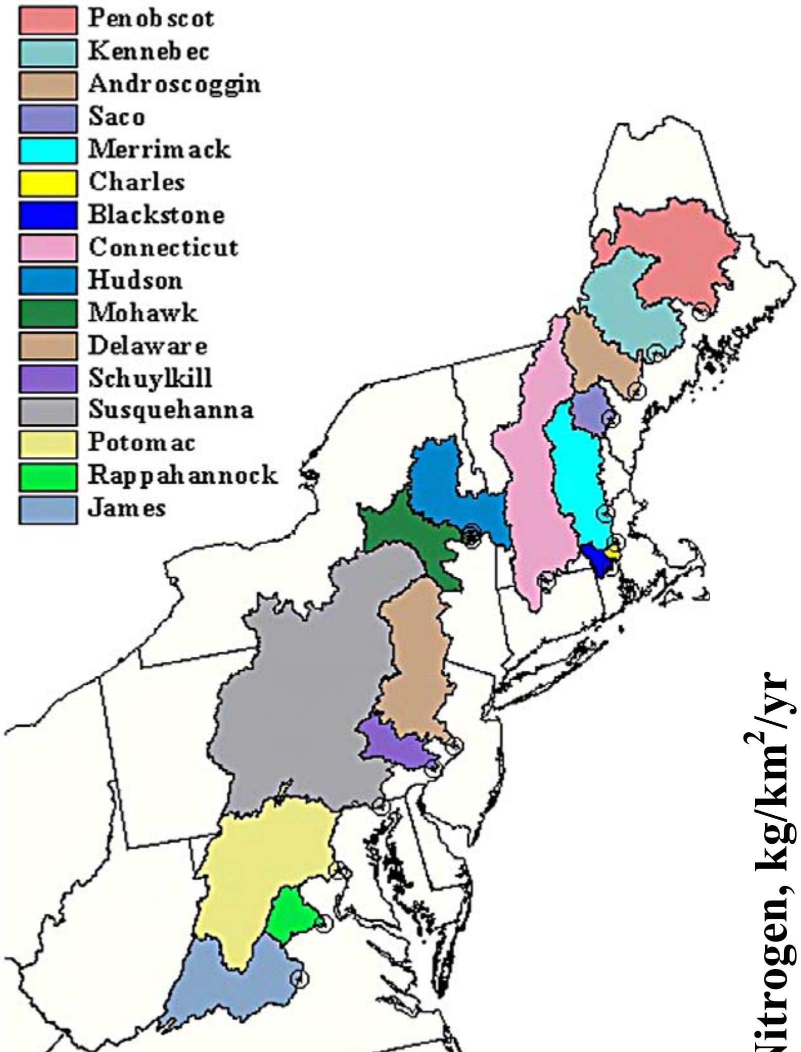
Approximately 25% of nitrogen inputs are exported in rivers.



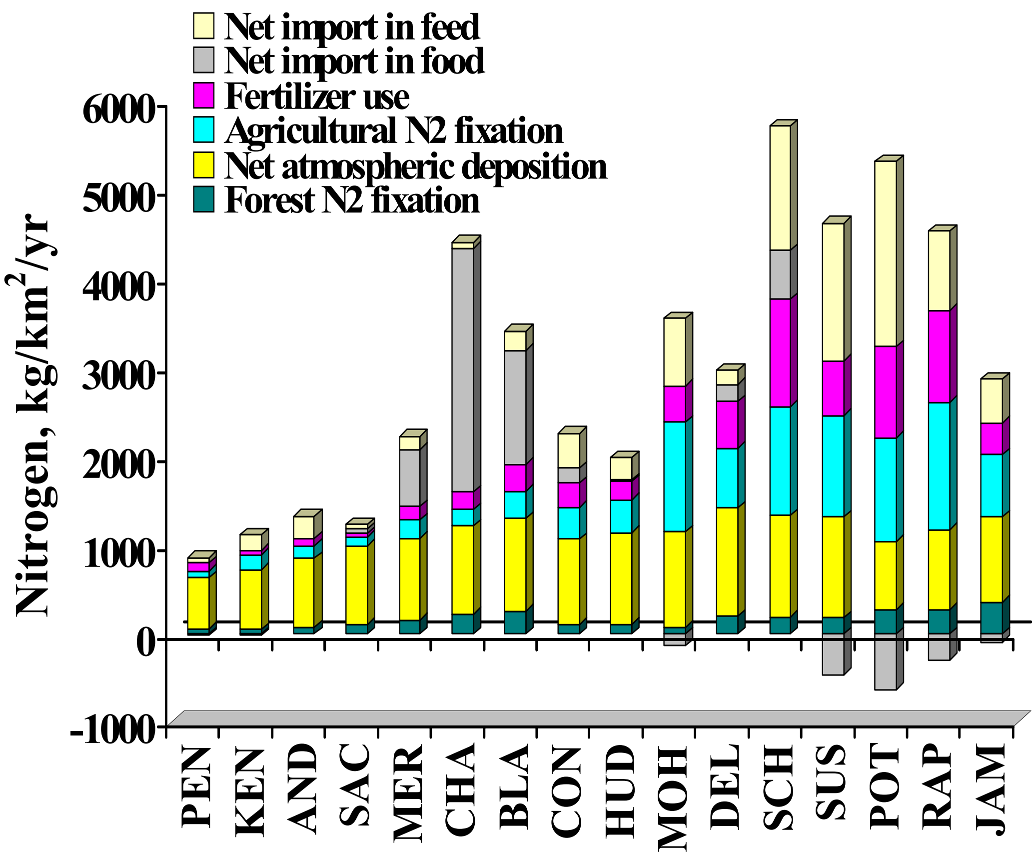
(Howarth et al. 2006, based on Boyer et al. 2002)

Percent contribution to total river nitrogen fluxes from atmospheric deposition of NOy



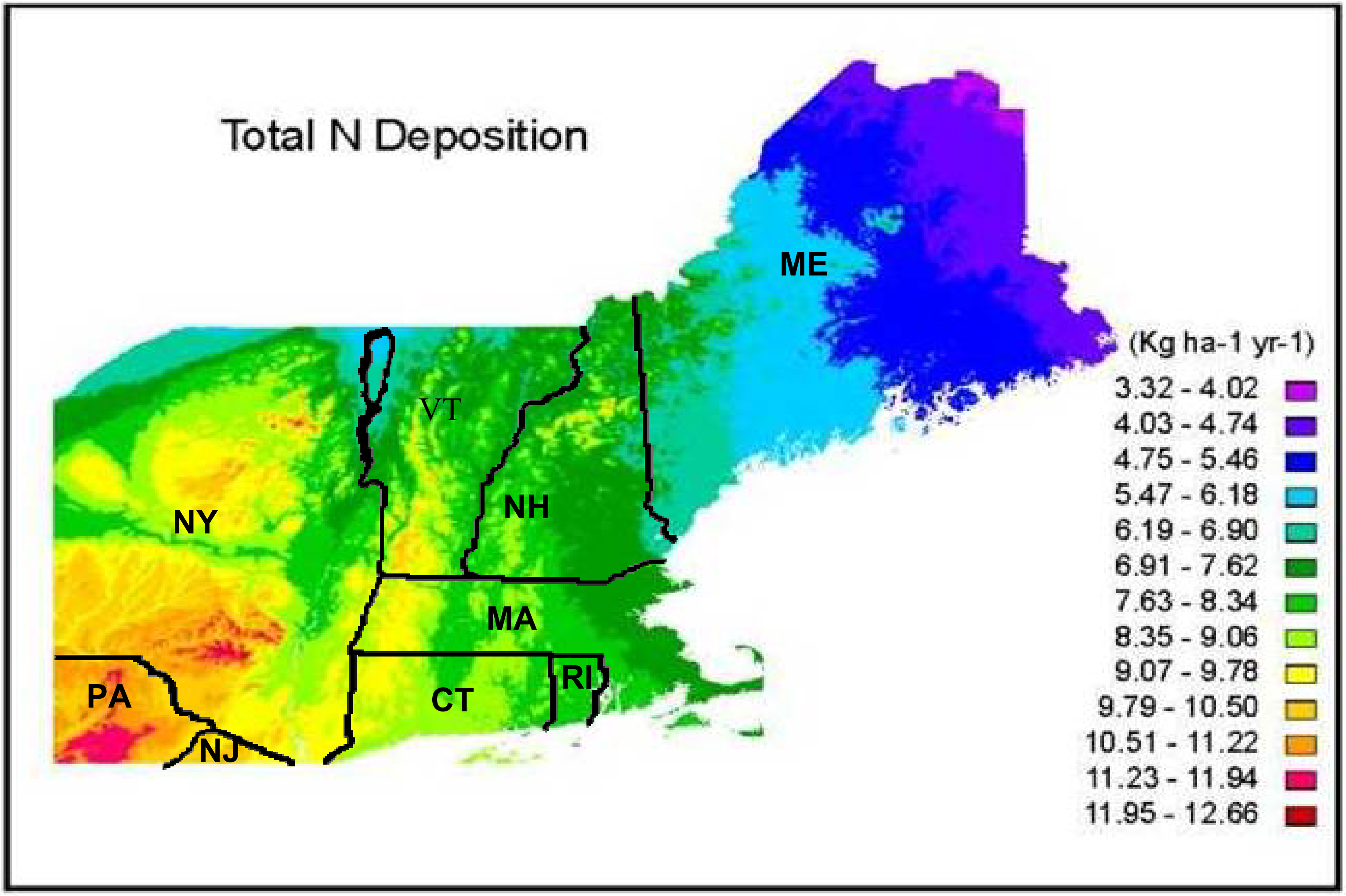


Deposition estimates based on NADP wet deposition data, with extrapolation for dry deposition (Boyer et al. 2002).

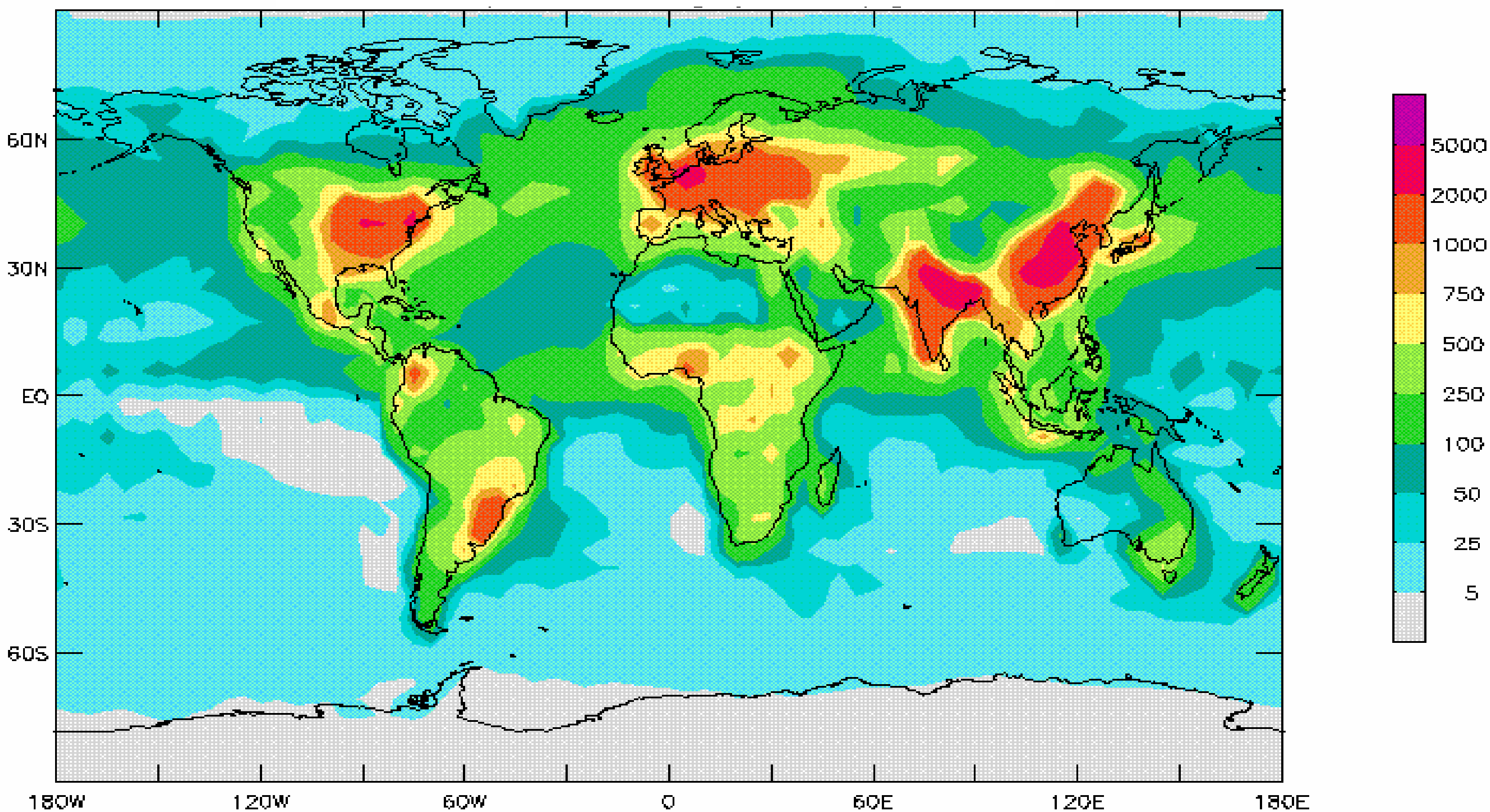


N Deposition in the US Northeast

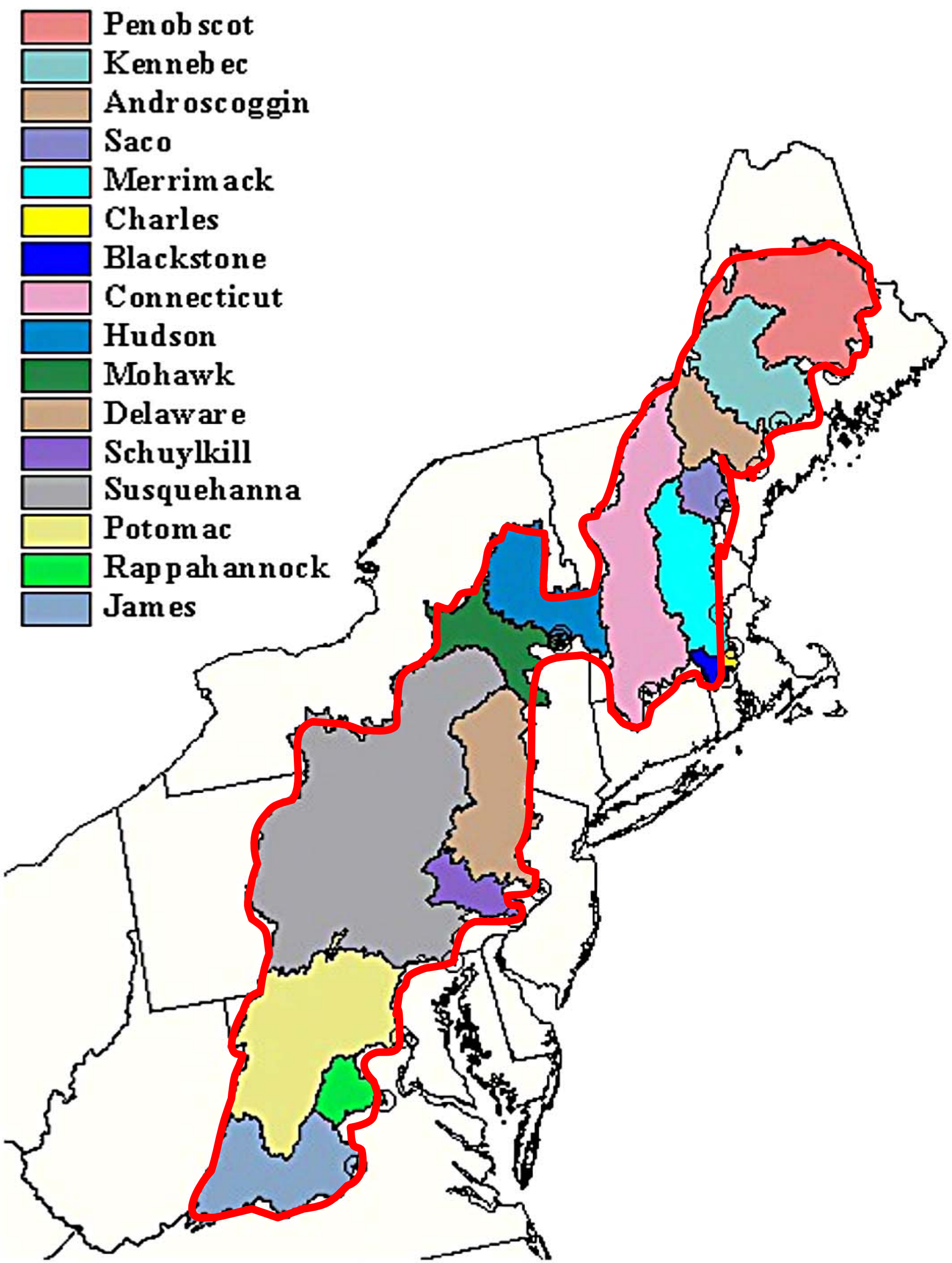
Provided by Scott Ollinger



1993 total nitrogen deposition (kg km^{-1} yr^{-1})



TM3 model of Dentener 2000: deposition estimated from emission estimates and atmospheric reactions and advection.

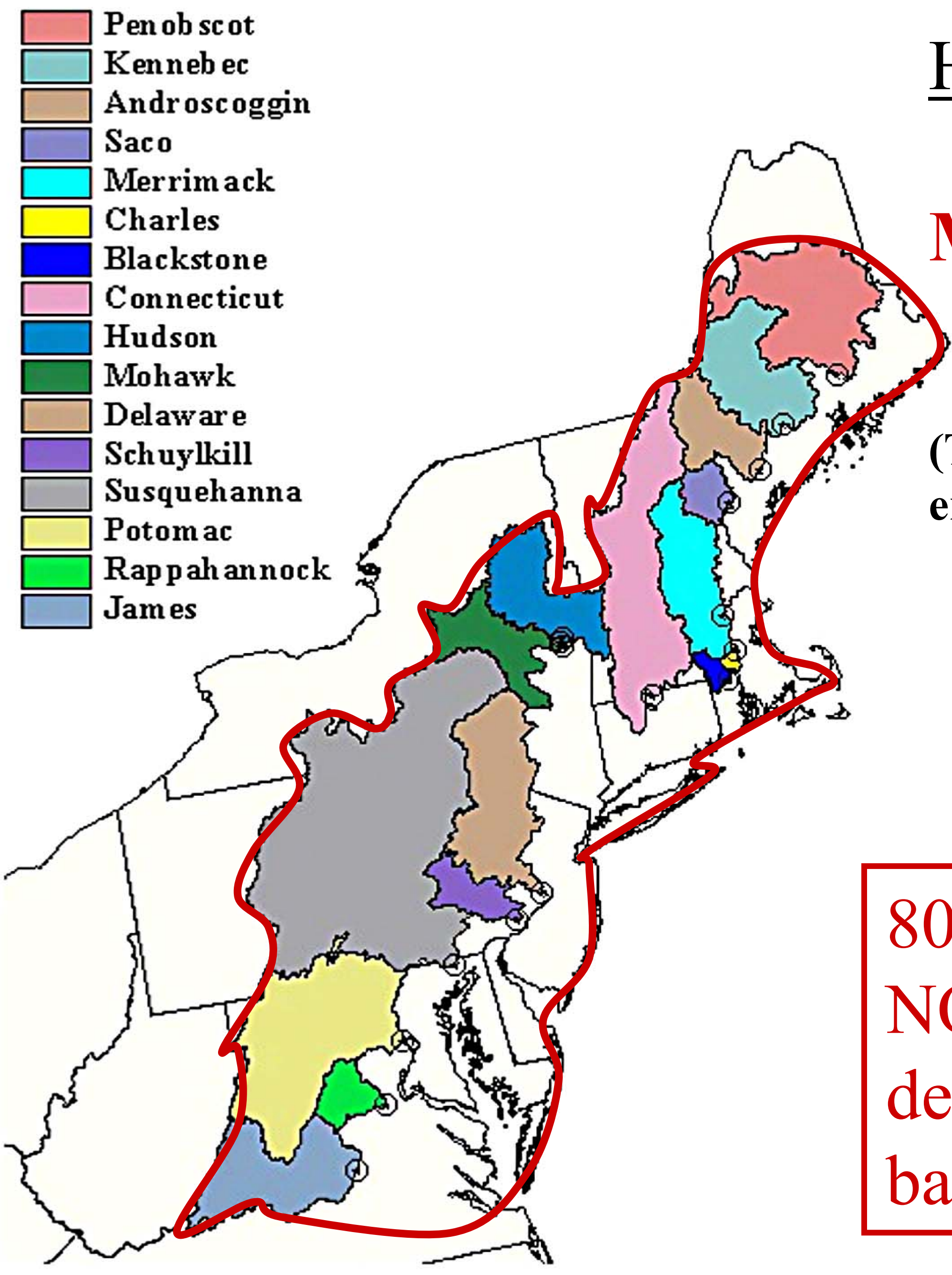


Boyer et al. (2002):

Mean NOy deposition for 16 watersheds:

~ 680 kg N km^{-2} yr^{-1}

(NADP monitoring data, with extrapolation for dry deposition; only watersheds above USGS gauging stations)

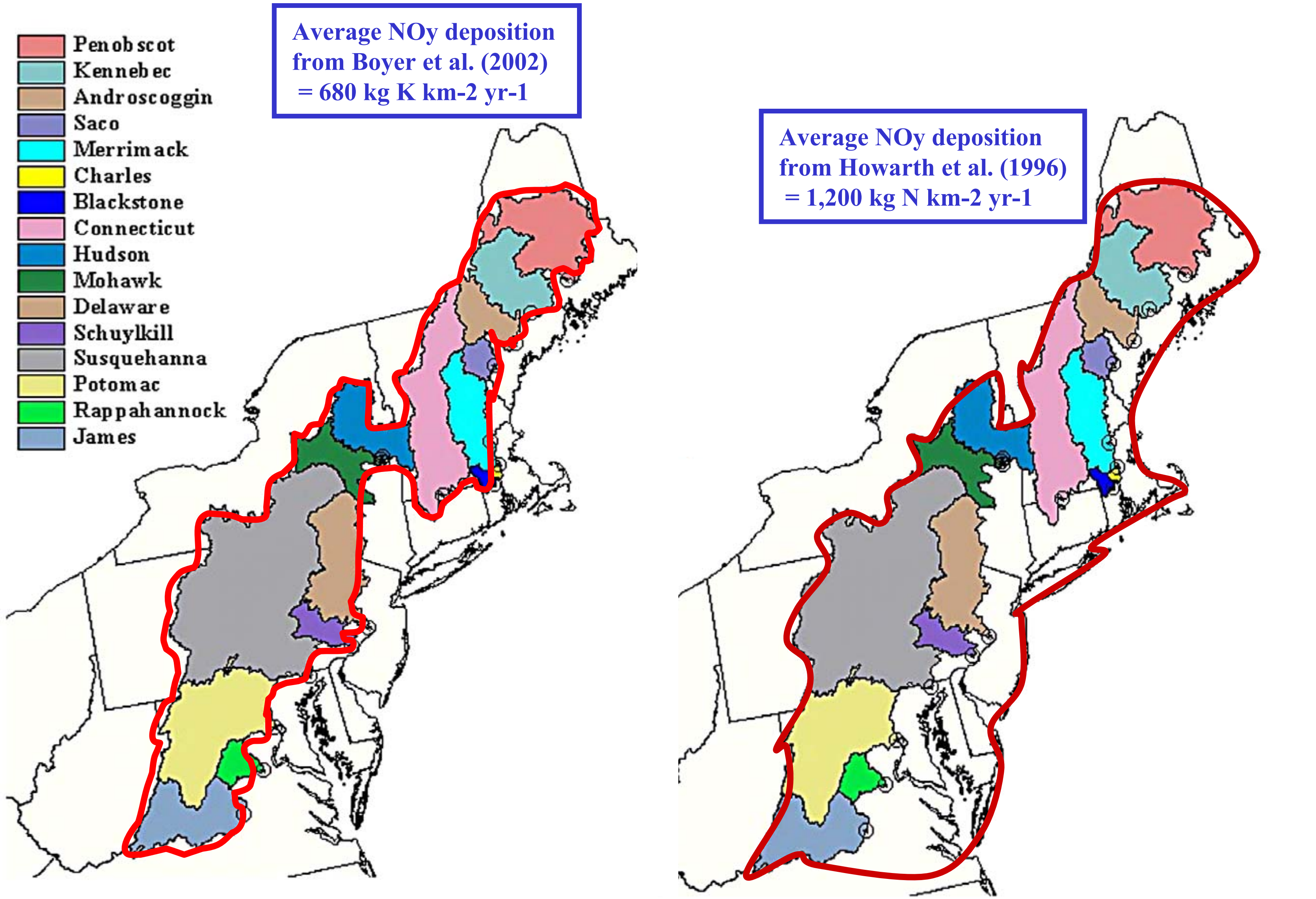


Howarth et al. (1996):

Mean for entire northeast:
~ 1,200 kg N km^{-2} yr^{-1}

(TM3-type model estimate based on emissions, reaction, and advection)

80% greater estimate of NOy atmospheric deposition using estimate based on emission data!



Penobscot
Kennebec
Androscoggin
Saco
Merrimack
Charles
Blackstone
Connecticut
Hudson
Mohawk
Delaware
Schuylkill
Susquehanna
Potomac
Rappahannock
James
Average NOy deposition from Boyer et al. (2002) = 680 kg K km-2 yr-1
Average NOy deposition from Howarth et al. (1996) = 1,200 kg N km-2 yr-1

Consider the issue from a local scale (Falmouth, Cape Cod):
Total N deposition estimated from two different approaches.

NADP and CASTnet data, spatially extrapolated = ~ 7 – 8 kg N ha^{-1} yr^{-1} (Ollinger et al.1993; Valiela and Bowen 2002)

Canopy througfall data = 13 kg N ha^{-1} yr^{-1} (Lajtha et al. 1995) ~ 75% greater than using "traditional" approach.

Or in Providence, RI:

NADP and CASTnet data, spatially extrapolated = ~ 8 kg N ha^{-1} yr^{-1} (Ollinger et al.1993)

Highway runoff = 17 kg N ha^{-1} yr^{-1} (Nixon et al. 1995) 2-fold greater than using "traditional" approach.

So, “traditional” approach of estimating deposition from extrapolation of NADP and dry deposition data seems to greatly underestimate N deposition in urban northeastern US.

Why?

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Why?

Generally underestimating dry deposition?

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Why?

Generally underestimating dry deposition?

Specifically underestimating gaseous dry deposition near emission sources?

According to Bruce Hicks (NOAA Air Resources Lab), the science of estimating dry deposition "remains immature."

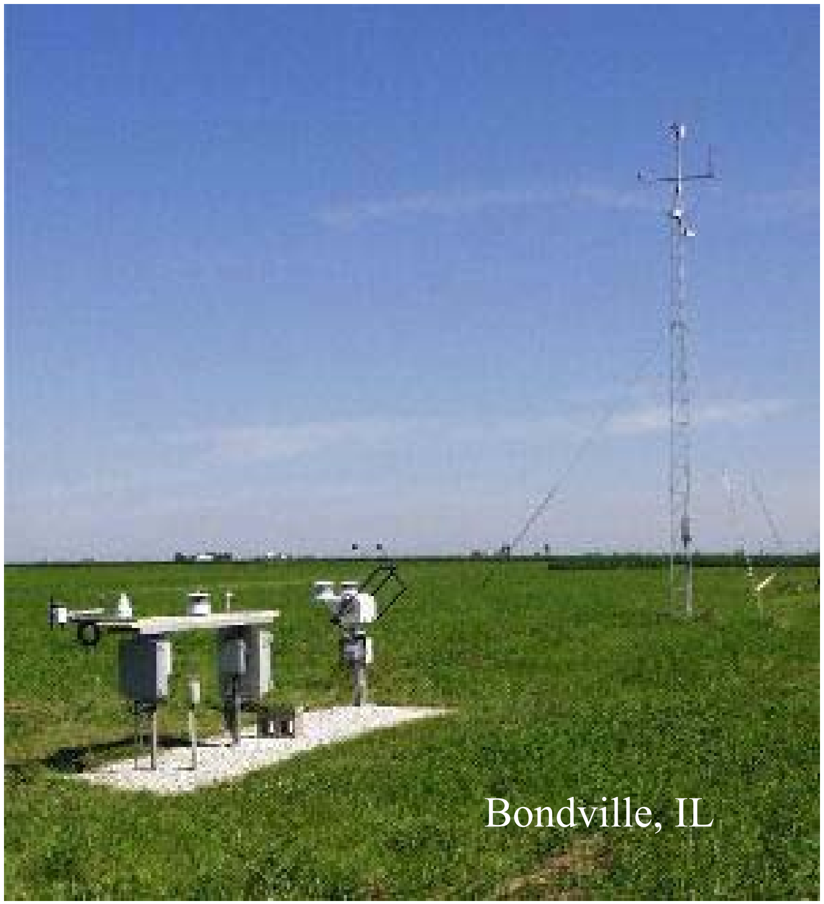
"For dry deposition, we can measure directly in some special situations, and infer results from other data in some cases. But how can we --

- estimate dry deposition to landscapes that are not homogeneous?
- address the situation of mountaintops and other complex terrain?
- bring these two together to address actual landscapes (coastal, e.g.)?

We often display unwarranted confidence.

We are simulating the world on the assumption that our understanding of special cases applies everywhere."

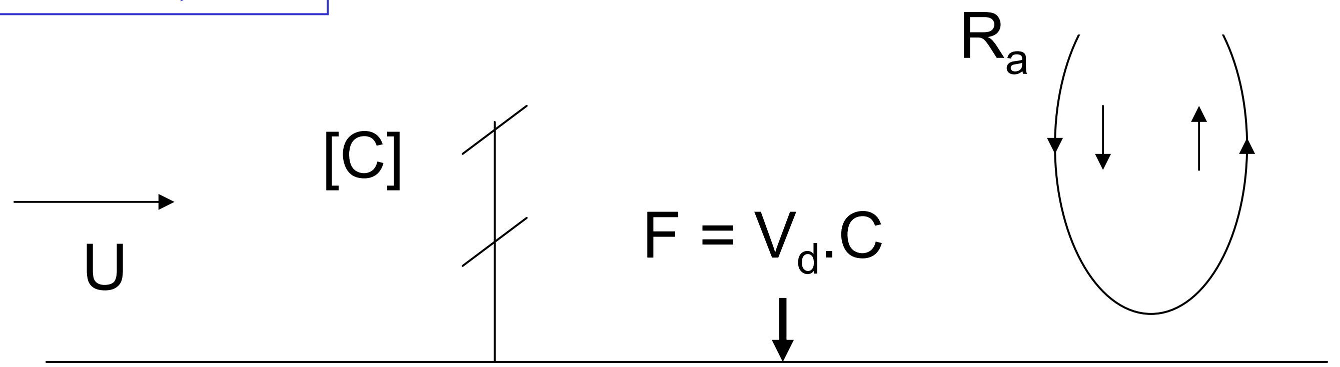
Micrometeorology has depended upon "outdoor laboratories" – flat and homogeneous so that the fluxes are the same everywhere.



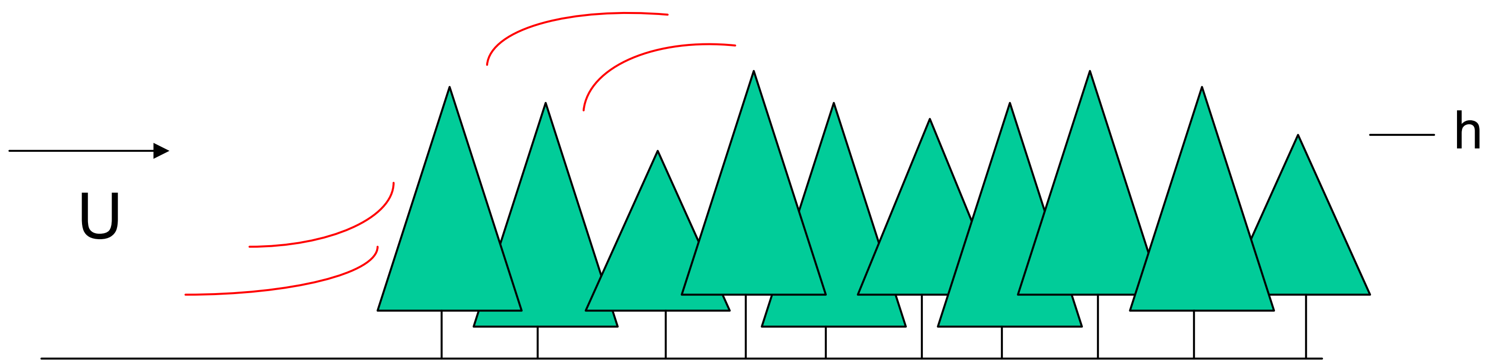
The "outdoor laboratory" sites are not selected to be spatially representative. Following micrometeorological convention, sites are selected so that the understanding derived from the long history of flat-earth field studies can be applied with confidence. The transfer from the air is solely via turbulent exchange affecting vertical gradients.

Modified from Bruce Hicks, NOAA

Courtesy of Bruce Hicks, NOAA



Horizontal, homogeneous surface, with $\partial C/\partial x = 0$.

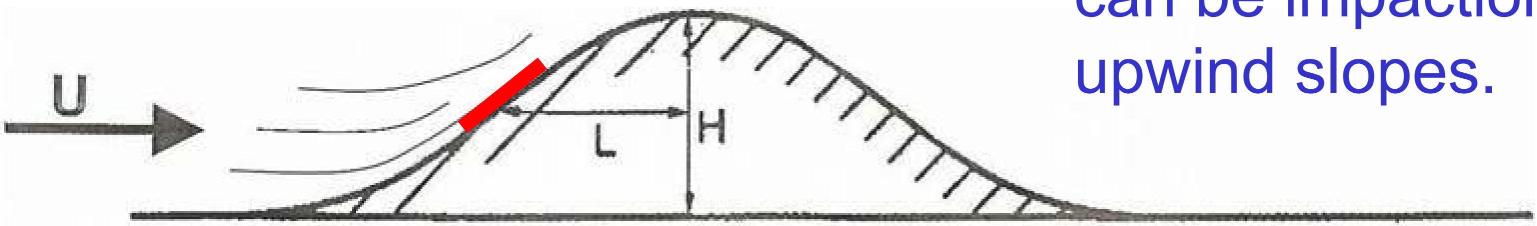


The rules are violated when we encounter a forest.

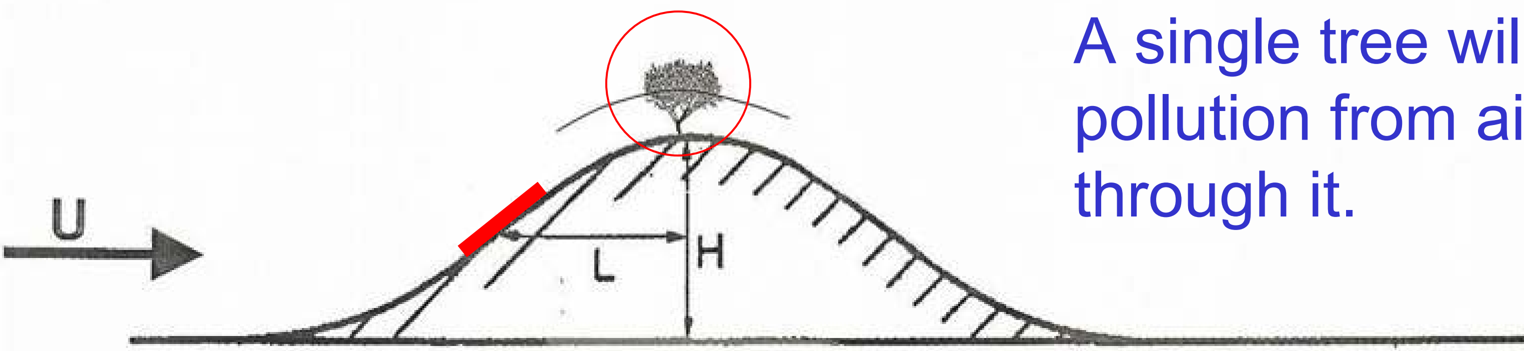
The leading edge serves as a filter, extracting material from the air without the imposition of an aerodynamic resistance.

Courtesy of Bruce Hicks, NOAA

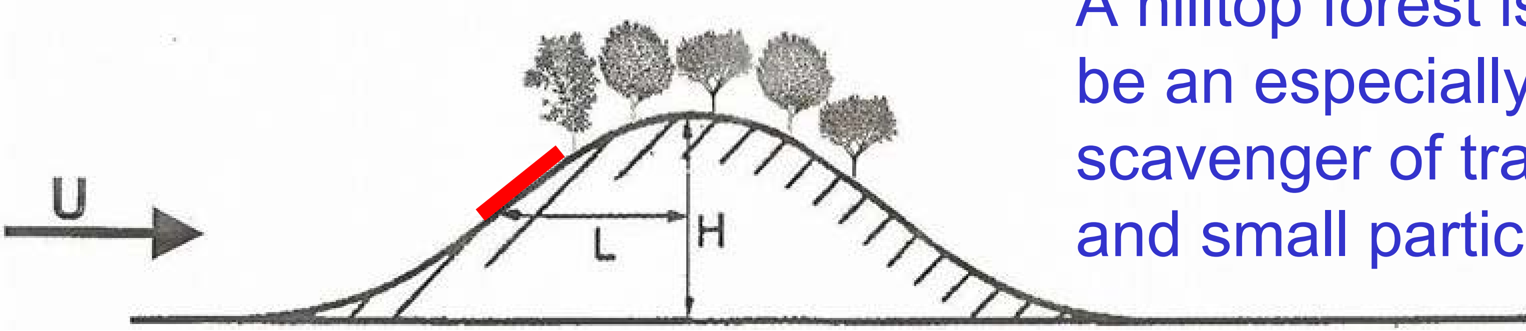
Now add the effects of complex topography --



For even a small hill, there can be impaction on the upwind slopes.



A single tree will scavenge pollution from air passing through it.



A hilltop forest is likely to be an especially effective scavenger of trace gases and small particles.

We are probably underestimating dry deposition in any complex terrain or forest…. But by how much?

We are only beginning to get a handle on this….

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We are only beginning to get a handle on this….

Kathleen Weathers, Samuel Simkin, Gary Lovett, & Steven Lindberg (2005). Empirical modeling of atmospheric deposition in mountainous landscapes. Ecological Application.

Detailed study of N (and S) deposition in Acadia and Great Smoky Mtns. National Parks. Deposition as estimated by throughfall showed great spatial variation at small scales (10-fold).

"Area-weighted deposition was found to be 70% greater than NADP plus CASTnet monitoring station estimates."

The additional problem: dry deposition monitoring sites such as CASTnet are purposefully located away from emission sources.

Is deposition (particularly dry deposition of nitrogen gases) near emission sources greater? (hypothesis #2)

Extremely poor monitoring of gas deposition near sources, or in fact anywhere for some gases (ie, NH_3)

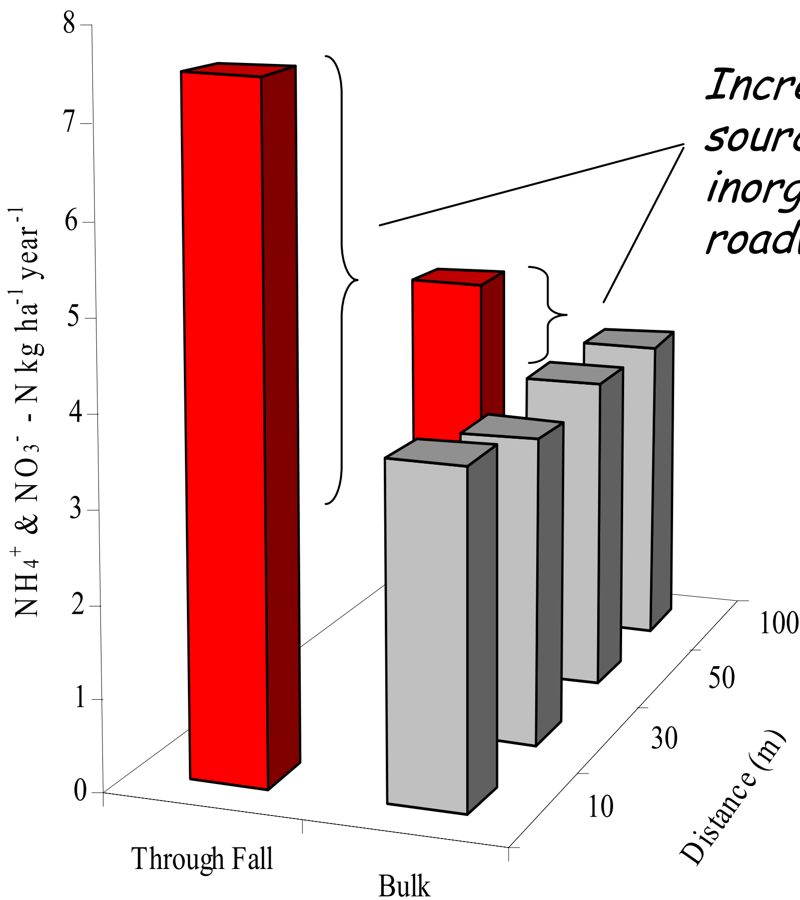
Lovett et al. (2002):

2-fold greater N deposition in New York City than 65 km to the north (measured by throughfall).

Cape et al. (2004):

Significantly greater deposition within 50 m of major roadways in the UK (NO_y and NH_3).

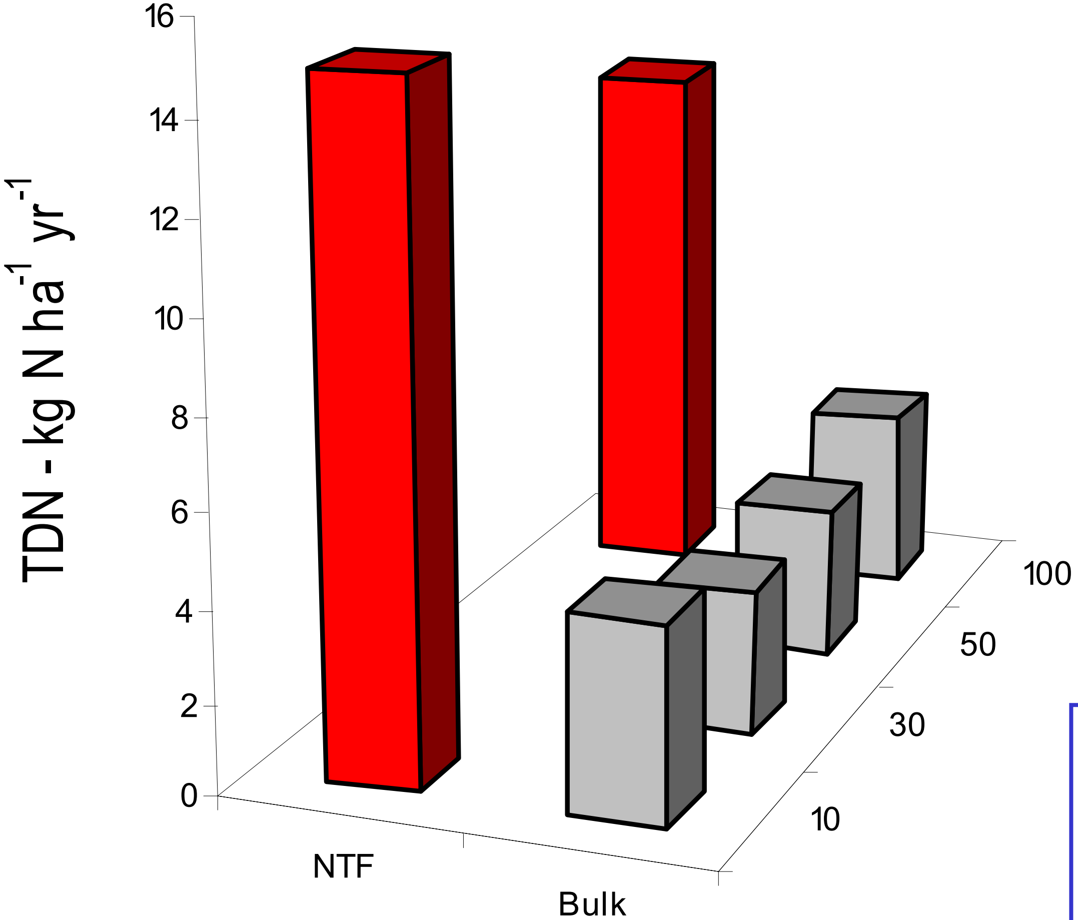
Some evidence that nitrogen emissions from vehicles are deposited very near to source (and not measured in normal precipitation collectors).



Increased deposition due to local vehicle sources. Note higher throughfall of inorganic N within just meters of a roadway

Unpublished data of Bettez, Marino, Howarth, and Davidson along roadways on Cape Cod; funded by Woods Hole SeaGrant; preliminary data – please do not cite.

Same pattern for total nitrogen….



Unpublished data of Bettez, Marino, Howarth, and Davidson. Very preliminary data. Please do not cite.

So, both hypotheses are reasonable:

Dry deposition in any complex terrain is probably underestimated.

And deposition of N gases near emission sources is probably underestimated.

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Dry deposition in any complex terrain is probably underestimated.

And deposition of N gases near emission sources is probably underestimated.

Need more research on both!

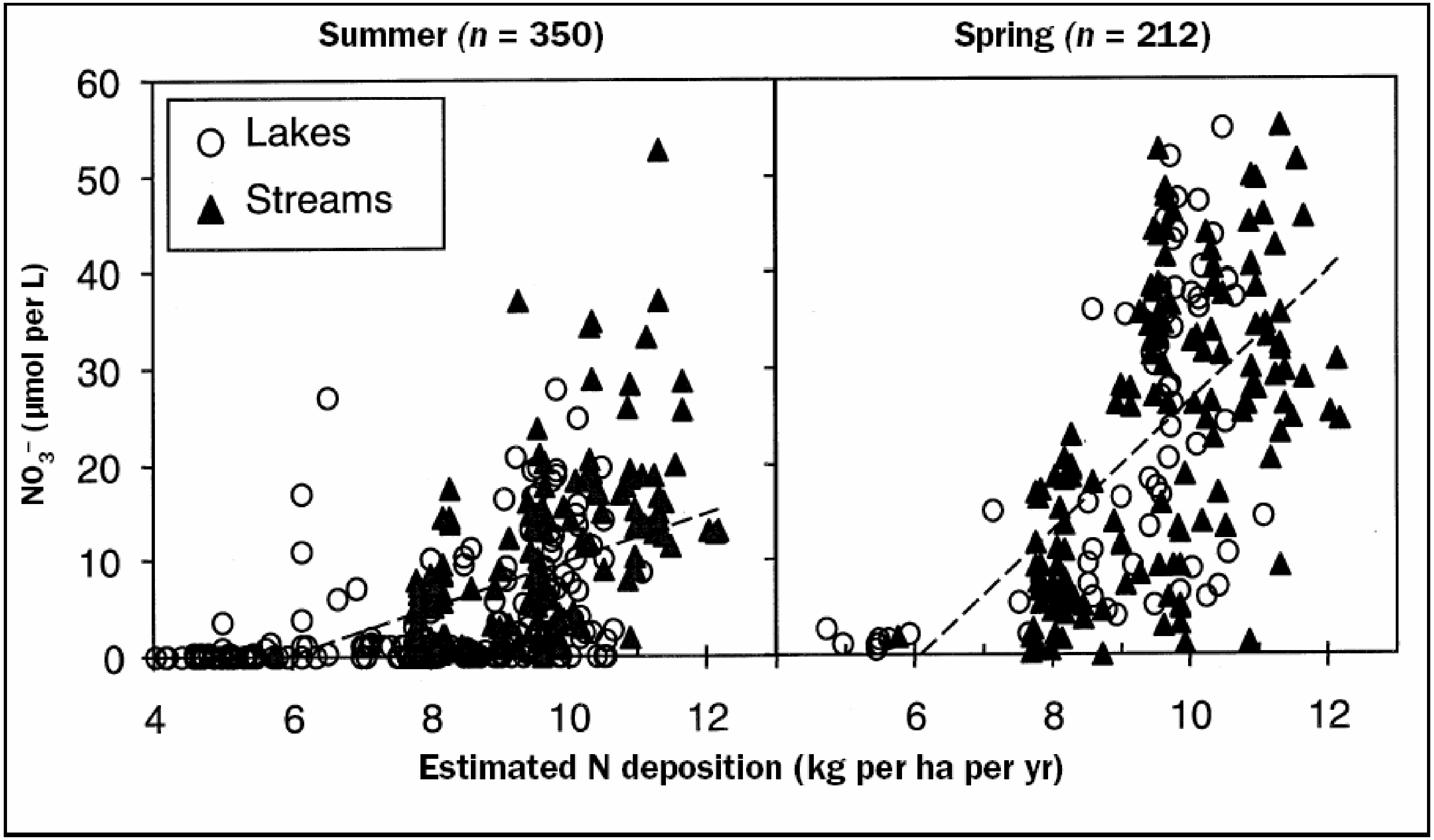
In the meanwhile, the most robust estimates for deposition are those based on emission and transport models….

In the meanwhile, the most robust estimates for deposition are those based on emission and transport models….

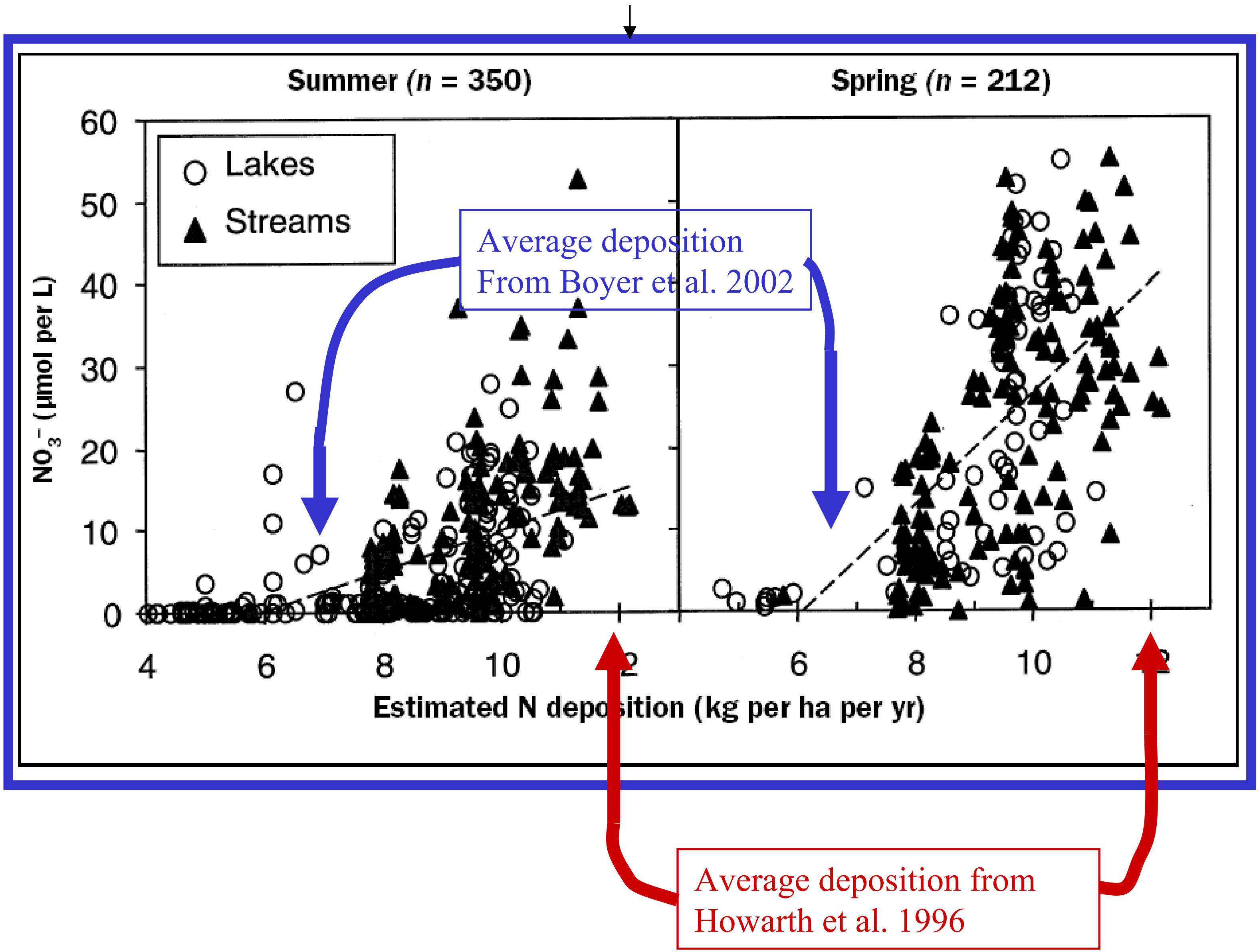
For northeastern US as a whole, this suggests NOy deposition is 80% greater than estimated by "traditional" methods.

The discrepancy is probably even greater for NH_3/NH_4^+ deposition…

(Aber et al. 2003)



Export of atmospheric deposition from forests in northeastern US. Export from disturbed systems and impermeable surfaces higher!!


Summer (n = 350)
Spring (n = 212)
Lakes
Streams
NO_3^- (µmol per L)
60
50
40
30
20
10
0
4
6
8
10
12
6
8
10
12
Estimated N deposition (kg per ha per yr)
Average deposition
From Boyer et al. 2002
Average deposition from
Howarth et al. 1996

Atmospheric Deposition and Nitrogen Inputs to Chesapeake Bay:

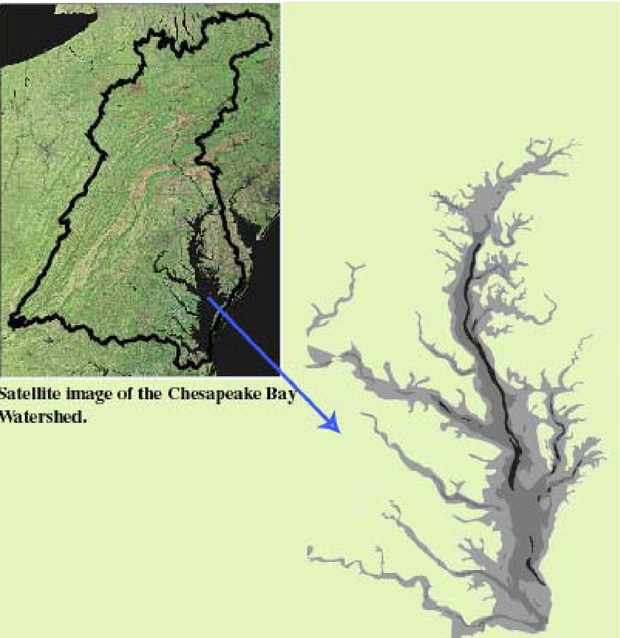
Chesapeake Bay model, standard run for 2000 conditions:

Total nitrogen input to Bay = 130,000 metric tons N yr^{-1}

Direct deposition to surface of Bay = 9,000 metric tons N yr^{-1}

Input to Bay from deposition onto watersheds with subsequent export = 25,000 metric tons N yr^{-1}

Total nitrogen input from deposition = 34,000 metric tons N yr^{-1} (26% of total inputs)



Atmospheric Deposition and Nitrogen Inputs to Chesapeake Bay:

What if deposition is actually 80% higher than assumed in Chesapeake Bay model (1,550 kg N km^{-2} yr^{-1}). Assume same retention in watersheds.

Total nitrogen input to Bay = 140,000 metric tons N yr^{-1} (8% more)

Direct deposition to surface of Bay = 12,000 metric tons N yr^{-1}

Input to Bay from deposition onto watersheds with subsequent export = 32,000 metric tons N yr^{-1}

Total nitrogen input from deposition = 44,000 metric tons N yr^{-1} (32% of total inputs)

Atmospheric Deposition and Nitrogen Inputs to Chesapeake Bay:

Again assume Chesapeake Bay model deposition rate, but lower retention in watersheds to 70%.

Total nitrogen input to Bay = 168,000 metric tons N yr^{-1}
(30% more)

Direct deposition to surface of Bay = 9,000 metric tons N yr^{-1}

Input to Bay from deposition onto watersheds with subsequent export = 63,000 metric tons N yr^{-1}

Total nitrogen input from deposition = 44,000 metric tons N yr^{-1}
(43% of total inputs)

Atmospheric Deposition and Nitrogen Inputs to Chesapeake Bay:

Assume higher rate of deposition (1,550 kg N km^{-2} yr^{-1}) and only 70% retention in watersheds.

Total nitrogen input to Bay = 188,000 metric tons N yr^{-1} (45% more)

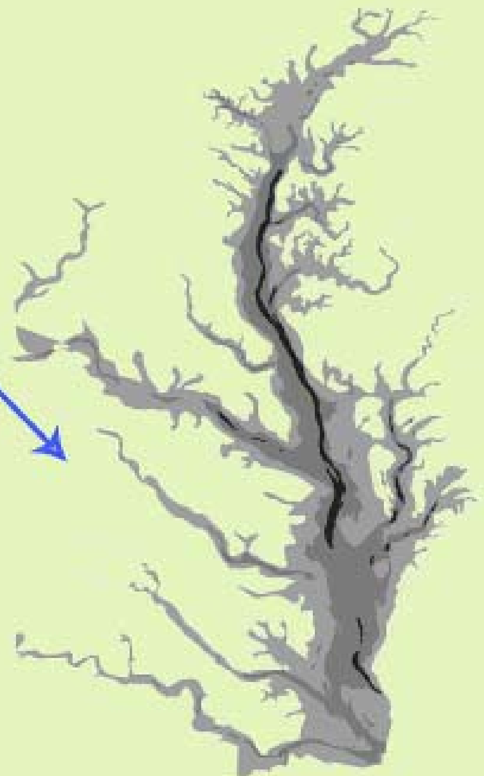
Direct deposition to surface of Bay = 12,000 metric tons N yr^{-1}

Input to Bay from deposition onto watersheds with subsequent export = 80,000 metric tons N yr^{-1}

Total nitrogen input from deposition = 92,000 metric tons N yr^{-1} (49% of total inputs)

Is it possible that nitrogen loads to Chesapeake Bay are 45% greater than predicted from Chesapeake Bay model (with half of the nitrogen coming from deposition?)

Satellite image of the Chesapeake Bay Watershed.



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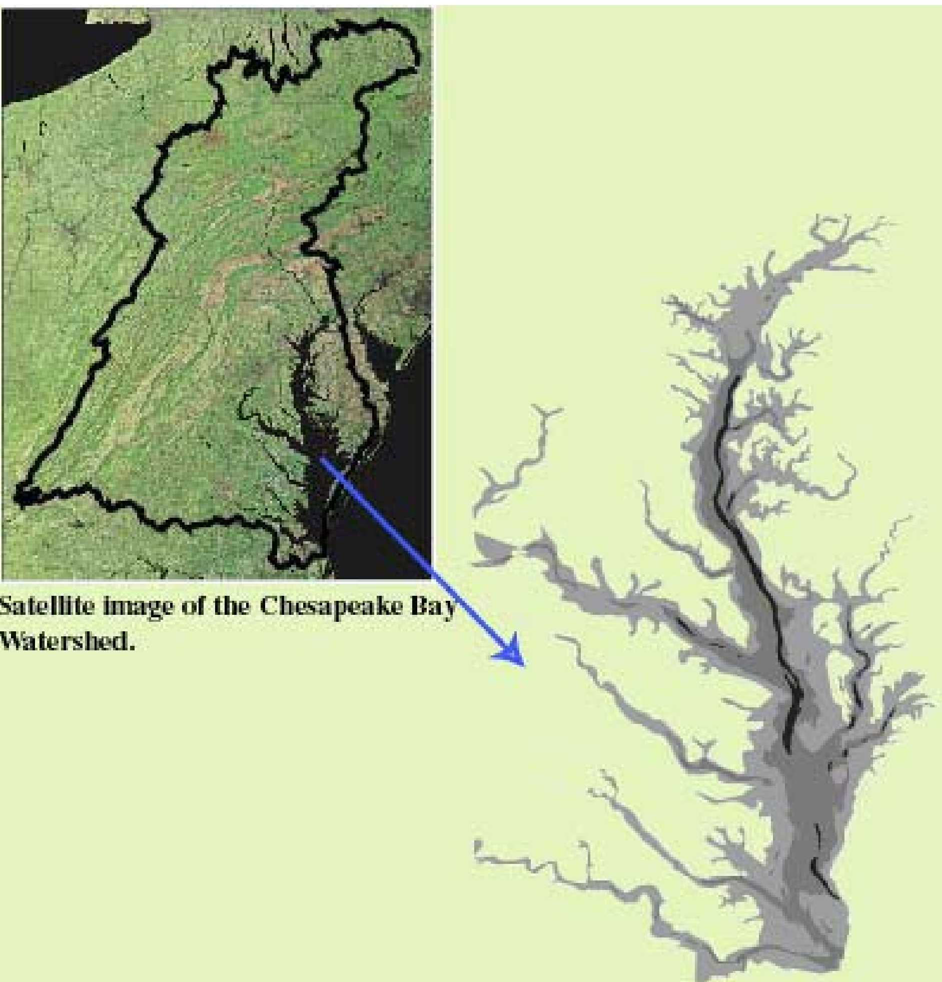
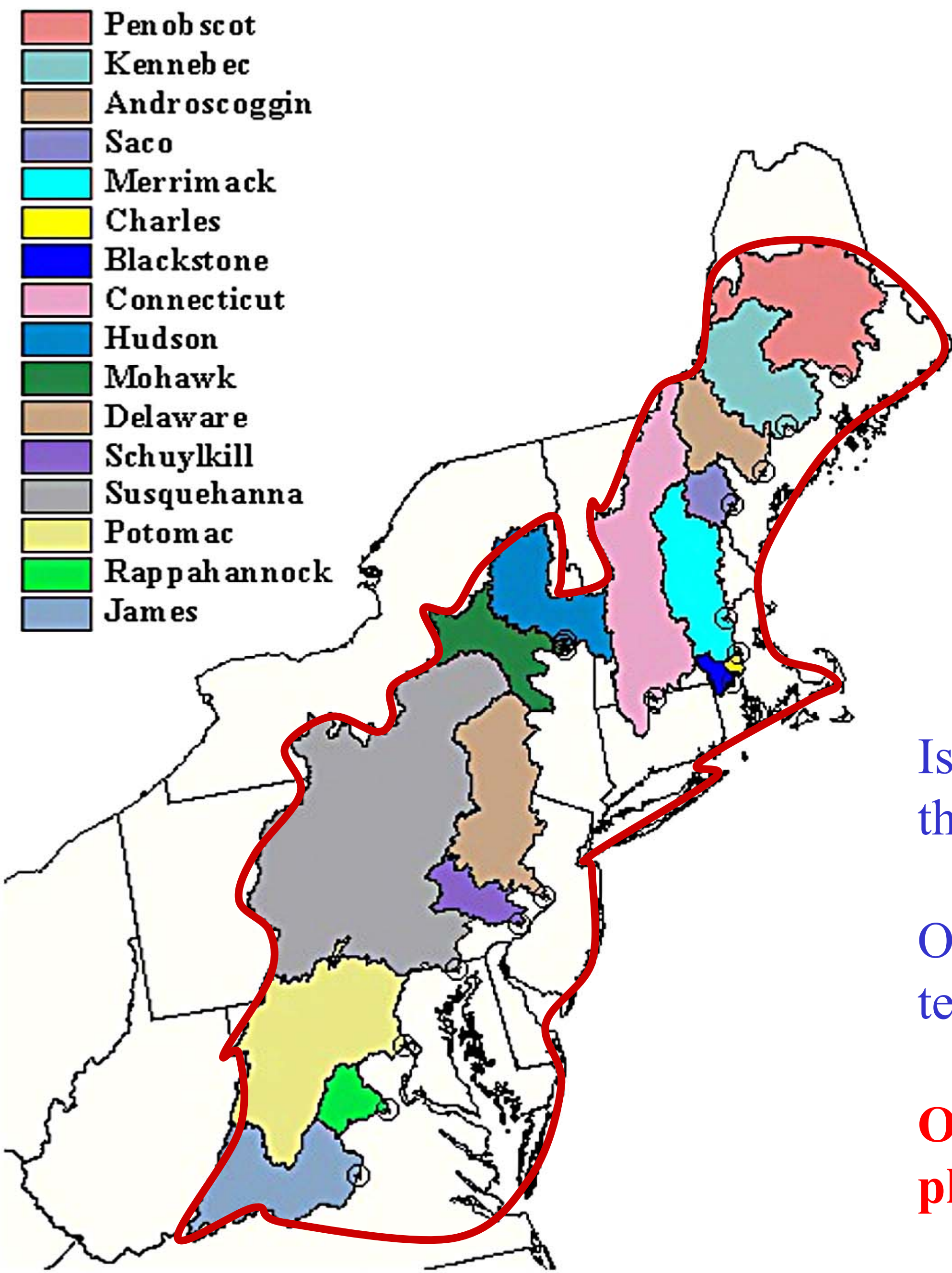


Satellite image of the Chesapeake Bay Watershed.

Maybe…. Loads down rivers to the Bay are well measured at USGS gaging stations. But all of these are up-river from tidal influences on the coastal plane.

Much of the watershed is very poorly monitored.

Atmospheric emissions are greatest in unmonitored urban areas near the Bay!!



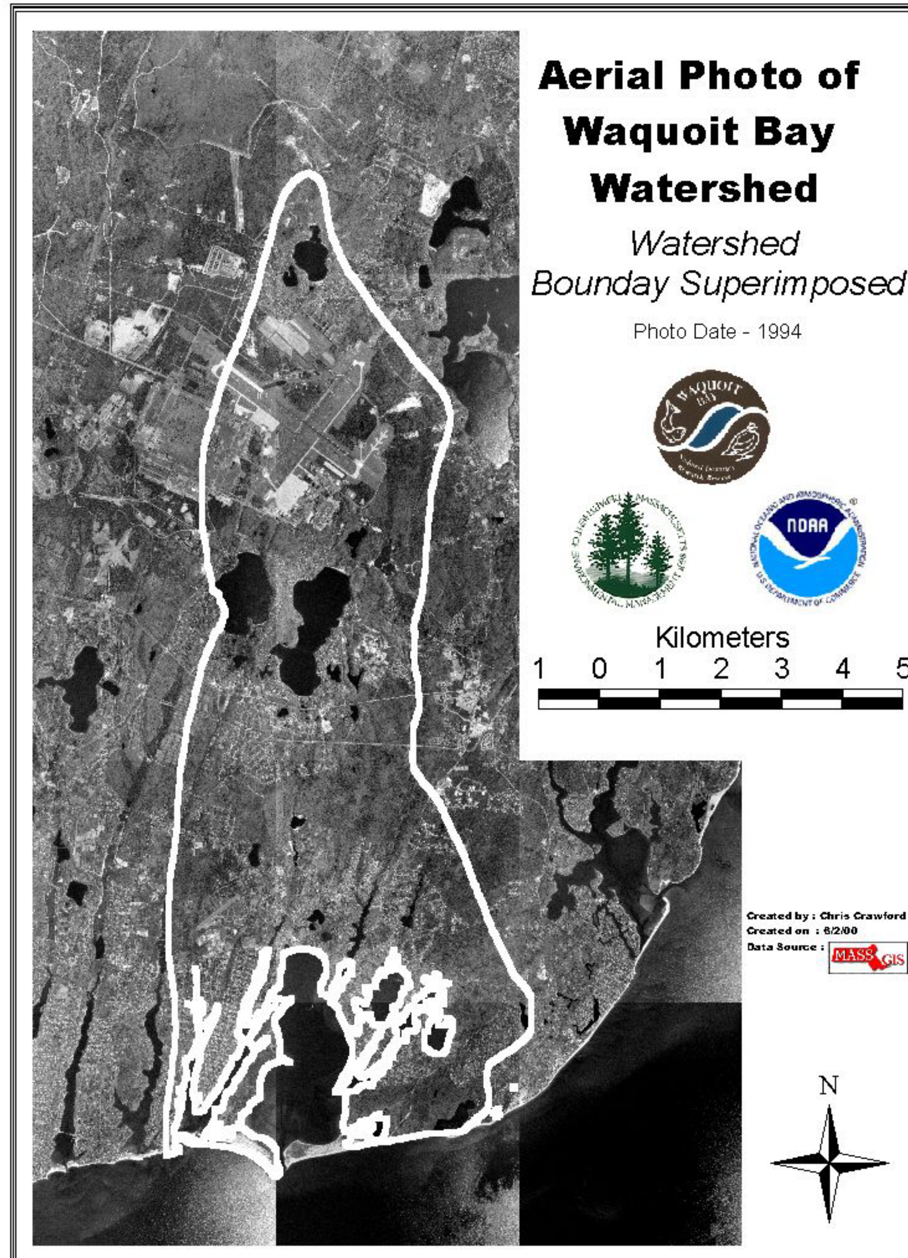
Is the “missing deposition” distributed throughout the northeast?

Or greater in the more mountainous terrain?

Or greater in the urbanized coastal plain where emissions are greater???

What about Cape Cod?

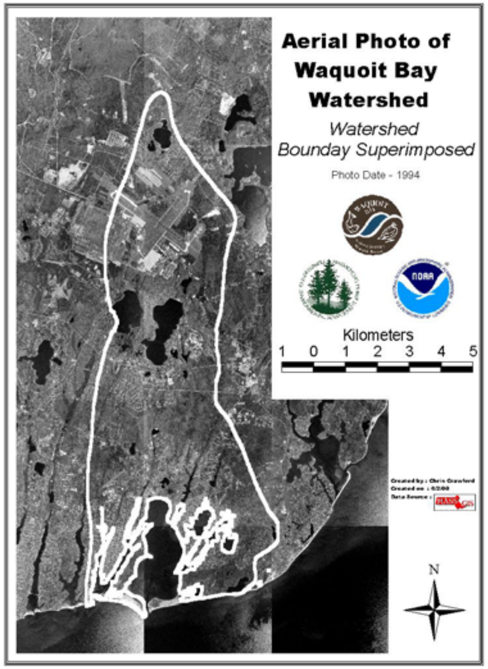
What about Cape Cod?



Nitrogen inputs to Waquoit Bay:

Total load from watershed = 23.1 metric tons N yr^{-1}

Wastewater = 48%
Fertilizer = 15%
Atmospheric deposition = 30%



(Valiela and Bowen 2002)

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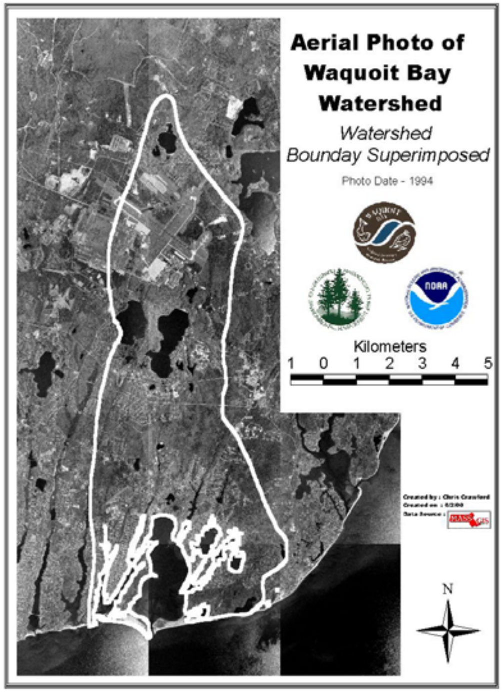

Wastewater = 48%
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Direct deposition of nitrogen to surface of Bay = 8.5 metric tons N yr^{-1}
(deposition of 13 kg ha^{-1} yr^{-1}; area = 656 hectares)

Nitrogen inputs to Waquoit Bay:

Therefore, total load from watershed and direct deposition
= 31.6 metric tons N yr^{-1}

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Retention of 70% to 80% may be more reasonable, given work of Lajtha et al. (1995), Howarth et al. (2002), and SPARROW model.

Nitrogen inputs to Waquoit Bay:

If we assume total load to Bay is accurate = 31.6 metric tons N yr^{-1}

Assume atmospheric deposition onto landscape = 13 kg ha^{-1} N yr^{-1}

And assume retention of atmospheric deposition in landscape is 75% (reasonably conservative),

Then percent contribution of atmospheric deposition is 66% of total load to Bay!!! **(wastewater = ~ 26%)**

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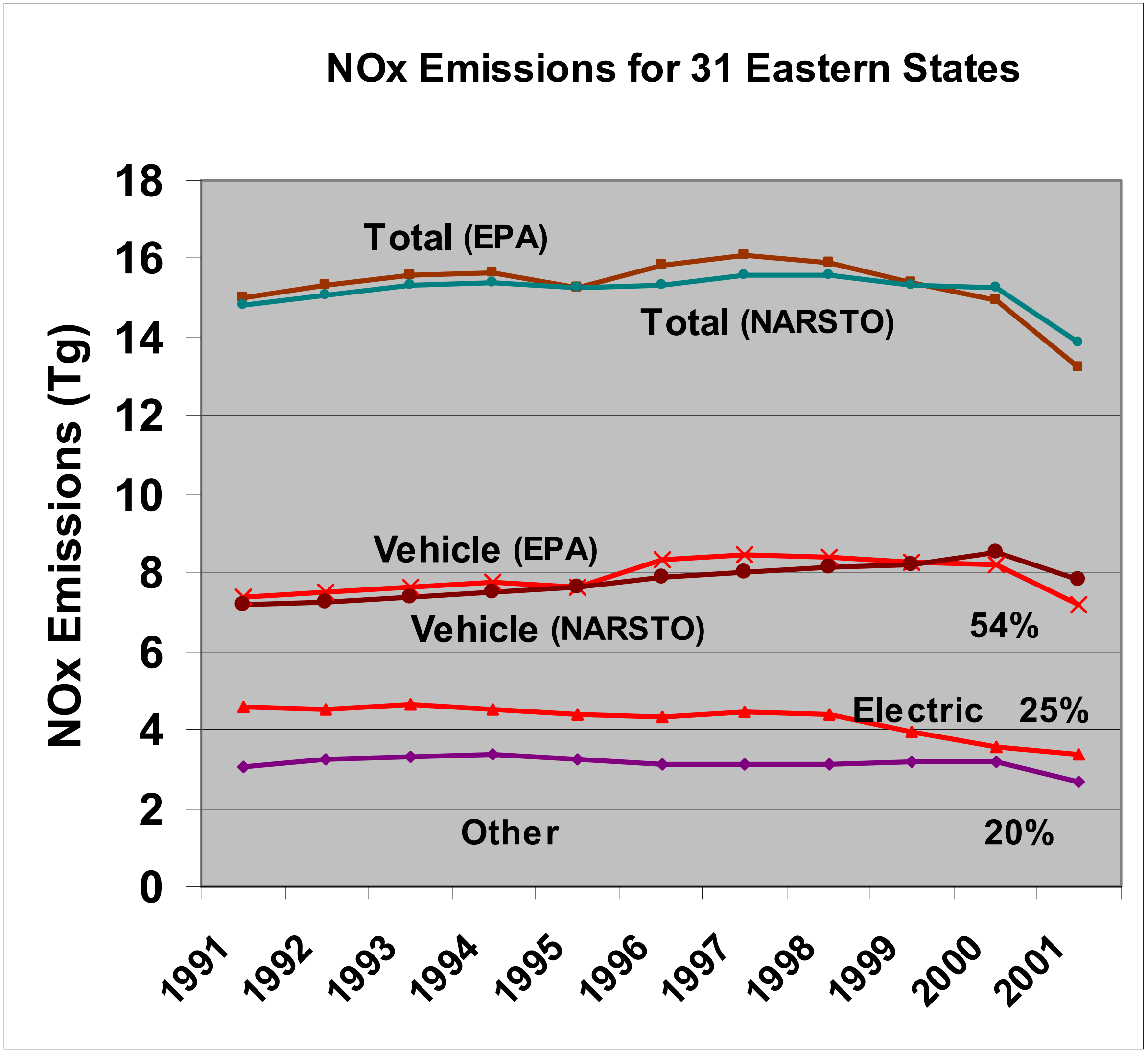
And assume retention of atmospheric deposition in landscape is 75% (reasonably conservative),

Then percent contribution of atmospheric deposition is 66% of total load to Bay!!! (wastewater = ~ 26%)

And this does not include near-source deposition from vehicle exhaust…… and the greater efficiency of transfer of nitrogen to the Bay, if deposition is higher.

Atmospheric deposition probably > 66% of total inputs!

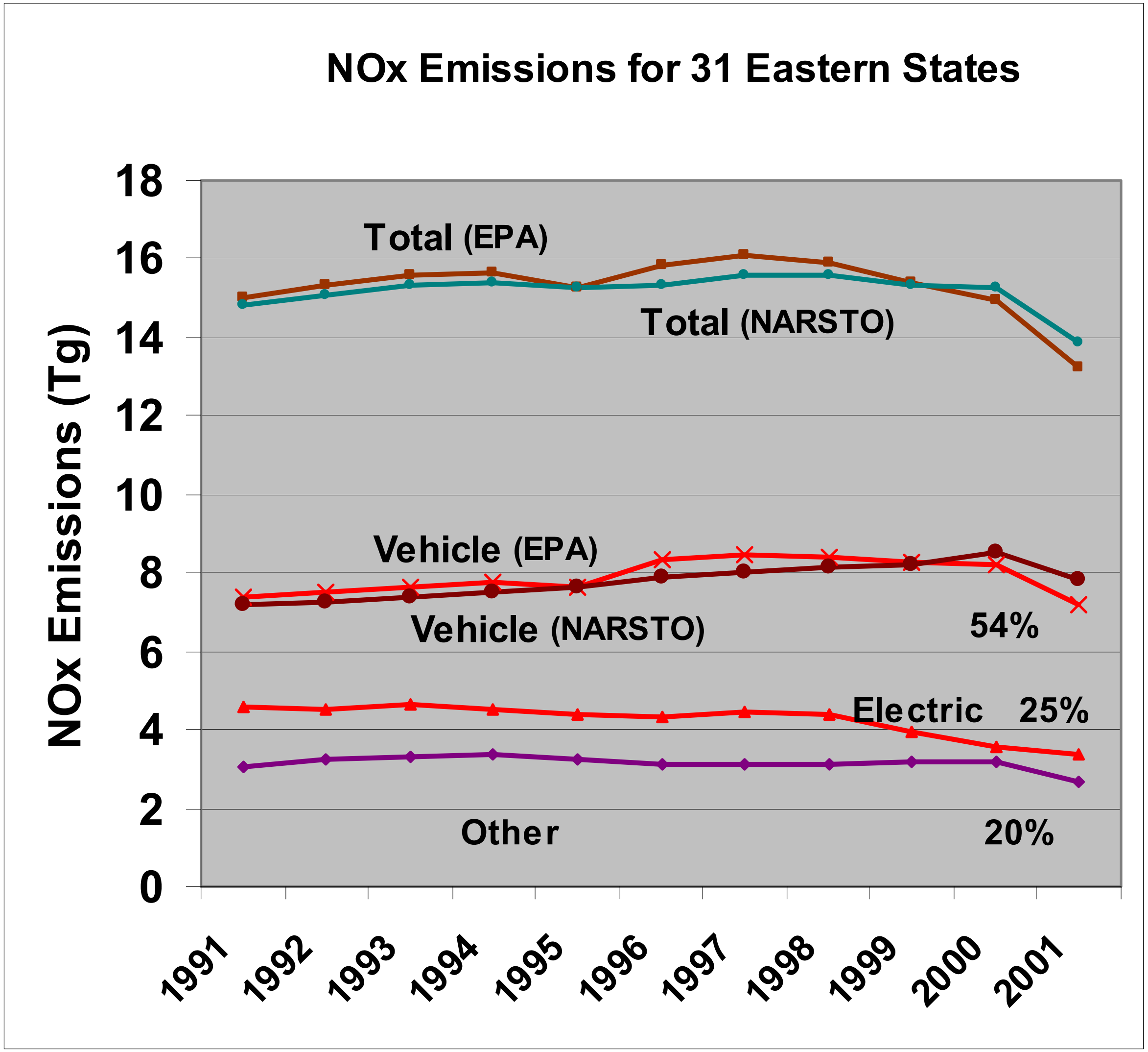
What can be done??



Trends are in the right direction….

But barely!

(Butler et al. 2005)

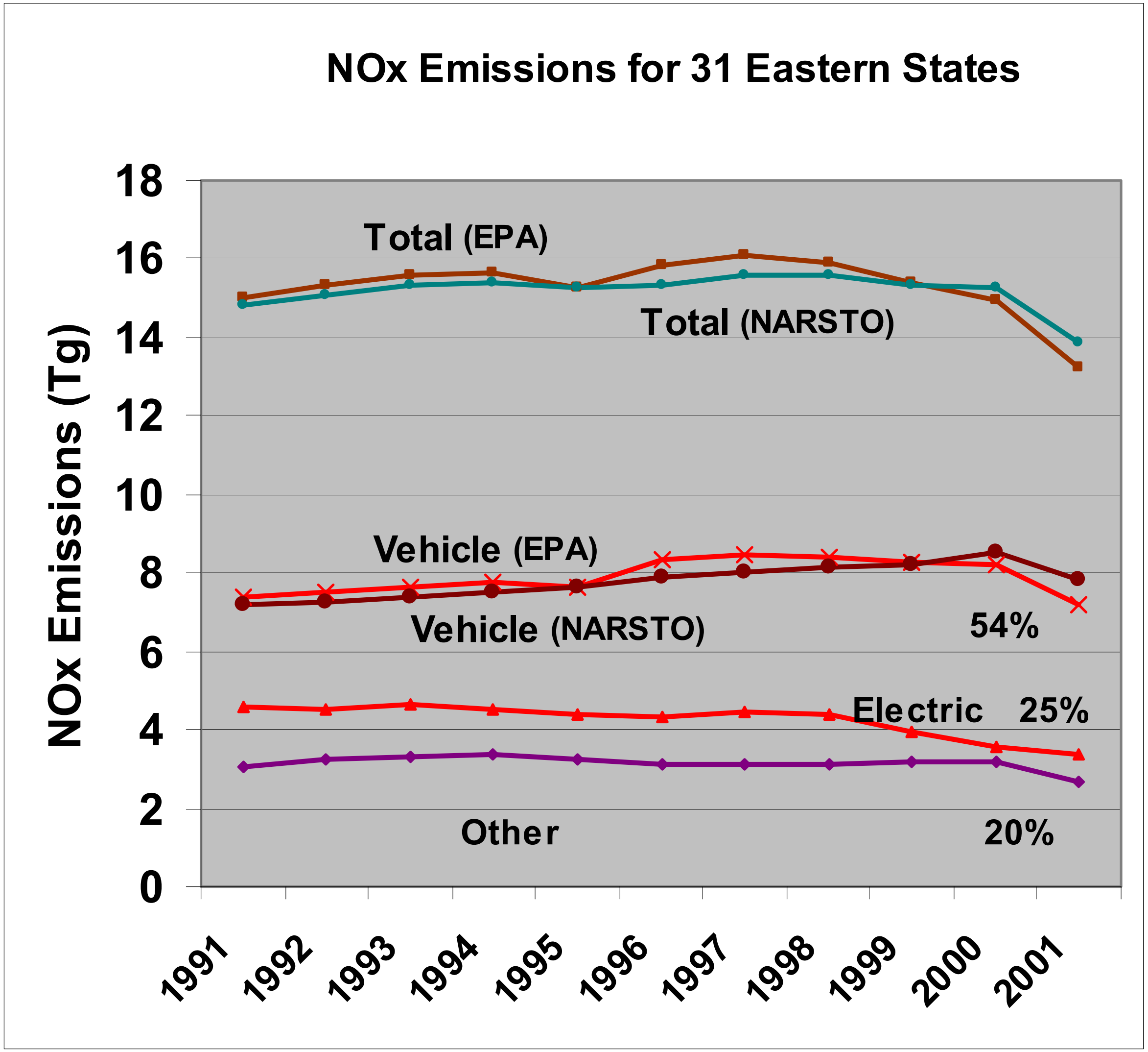


Electric power generation = ~ 20-25% of total.

Mostly coal-fired plants.

Need to apply Clean Air Act to "grandfathered" plants. Encouraging that federal courts have stopped Bush et al. from weakening Act.

(Butler et al. 2005)



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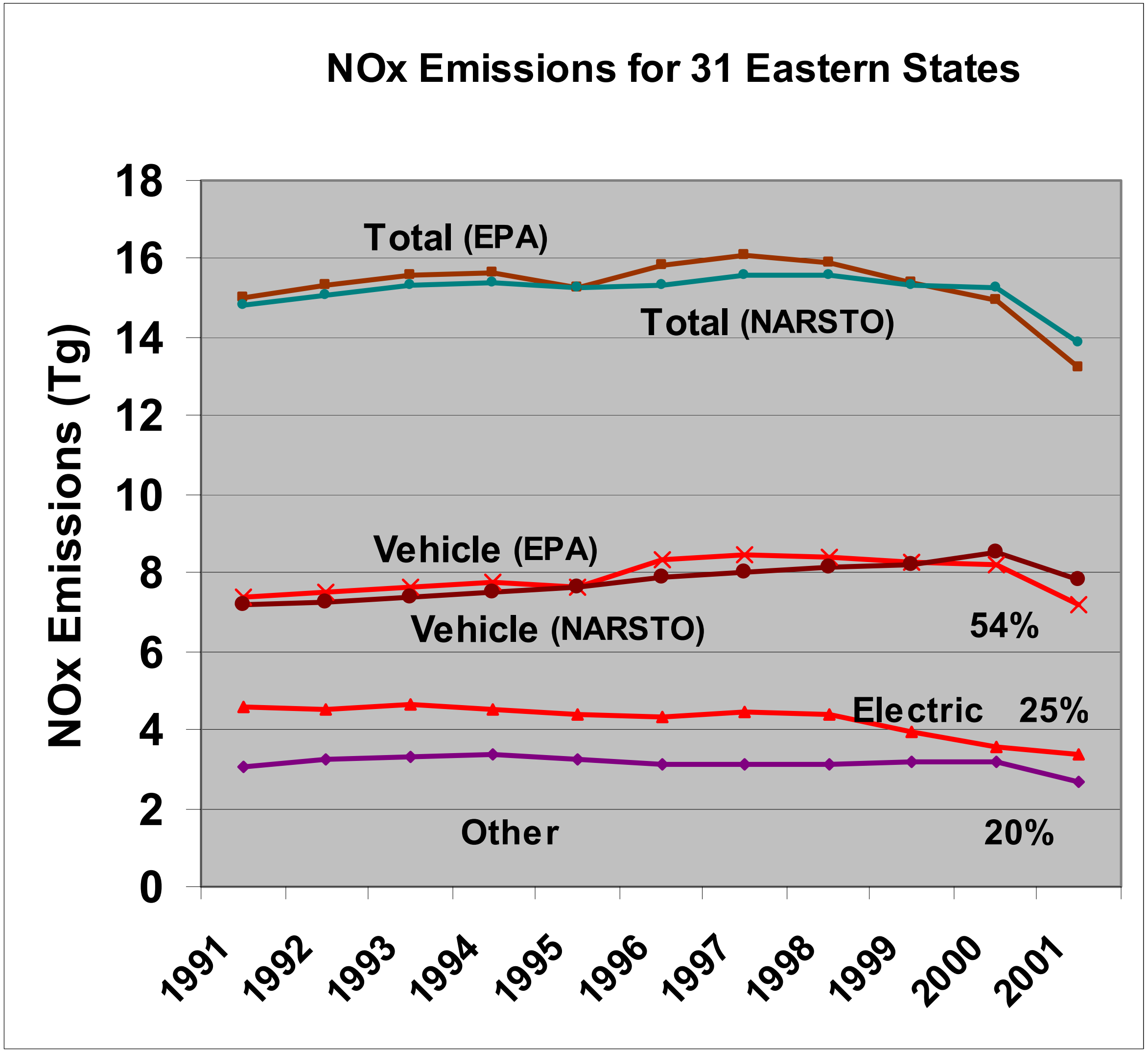
Apply emission standards year round (not just for summer ozone; NY is now doing this).

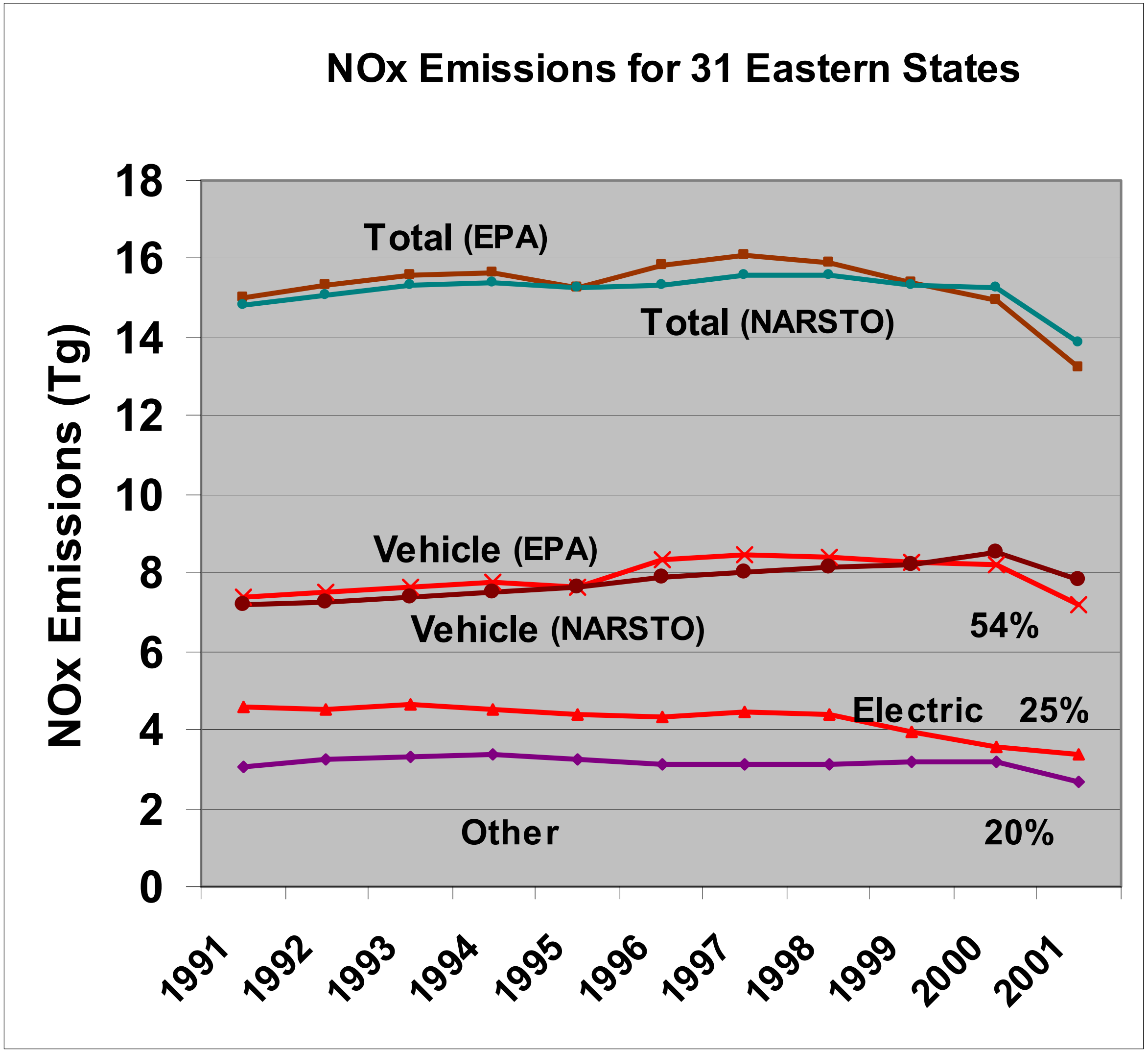
(Butler et al. 2005)



Electric power generation = ~ 20-25% of total.

Encourage wind power and other no-polluting alternative energy sources?

(Butler et al. 2005)



On-road vehicle exhaust is ~ 50% of the problem.

Another ~ 25% comes from boats, ships, tractors, construction equipment, lawn mowers, etc.

What can be done about these sources?

(Butler et al. 2005)

Encourage national policies:

- regulate SUVs and small trucks as if they are cars!
- encourage hybrid vehicles
- Encourage mass transit (particularly trains and light rail)

At local level:

- transportation planning (particularly in immediate coastal area, because of near-source deposition of vehicle exhaust)

- prohibit idling of truck and bus engines (and enforce this!)

- discourage impermeable surfaces (ie, require that parking lots be designed so as to allow infiltration of water)

- intercept runoff from roads and parking lots (retention ponds and wetlands)

- protect natural functioning of wetlands and low-order streams

Grant # R830882

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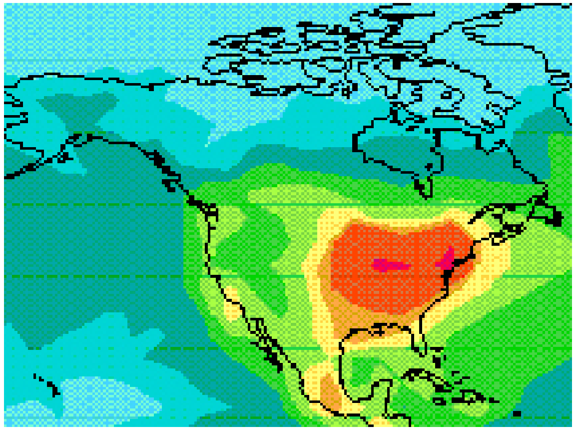

North American Nitrogen Center

One of 5 regional centers of the International Nitrogen Initiative, International Council of Science (SCOPE and IGBP).

www.eeb.cornell.edu/biogeo/nanc.nanc.htm

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