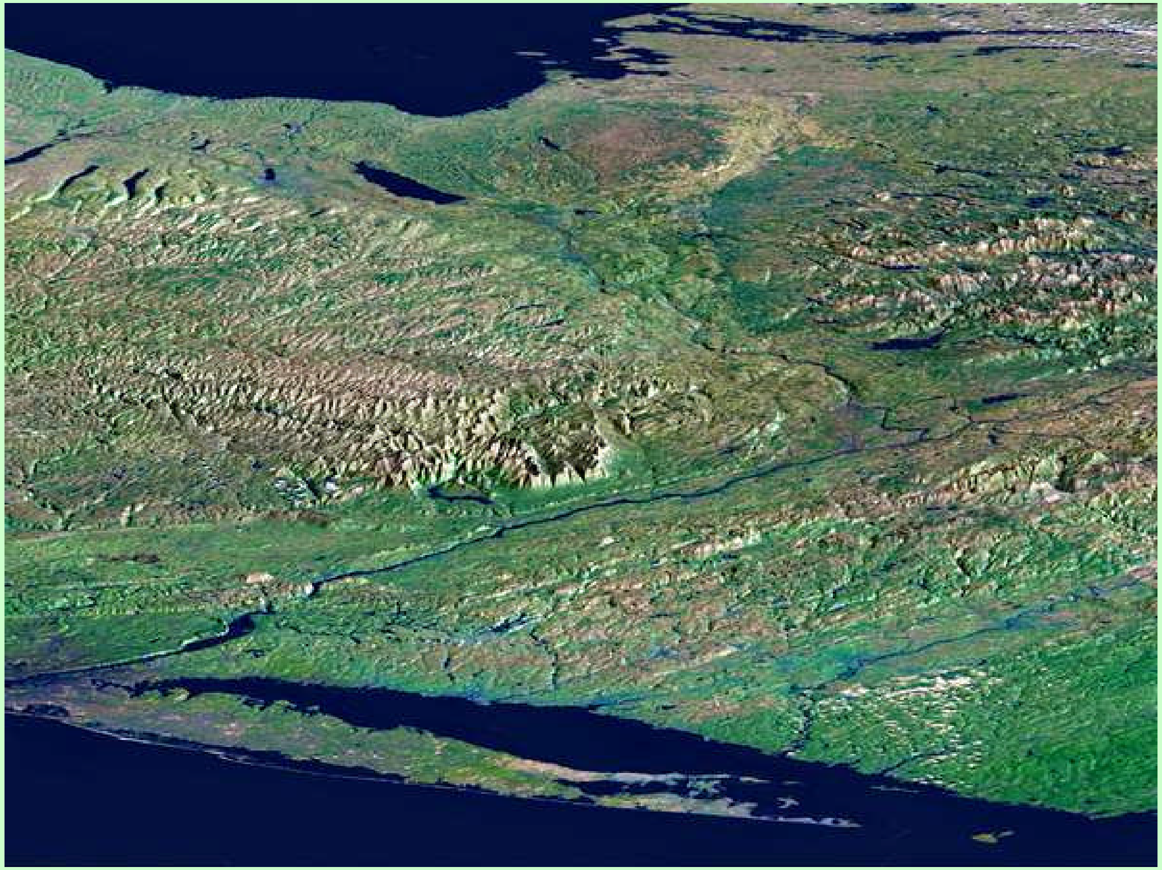
Cornell University
College of Agriculture and Life Sciences

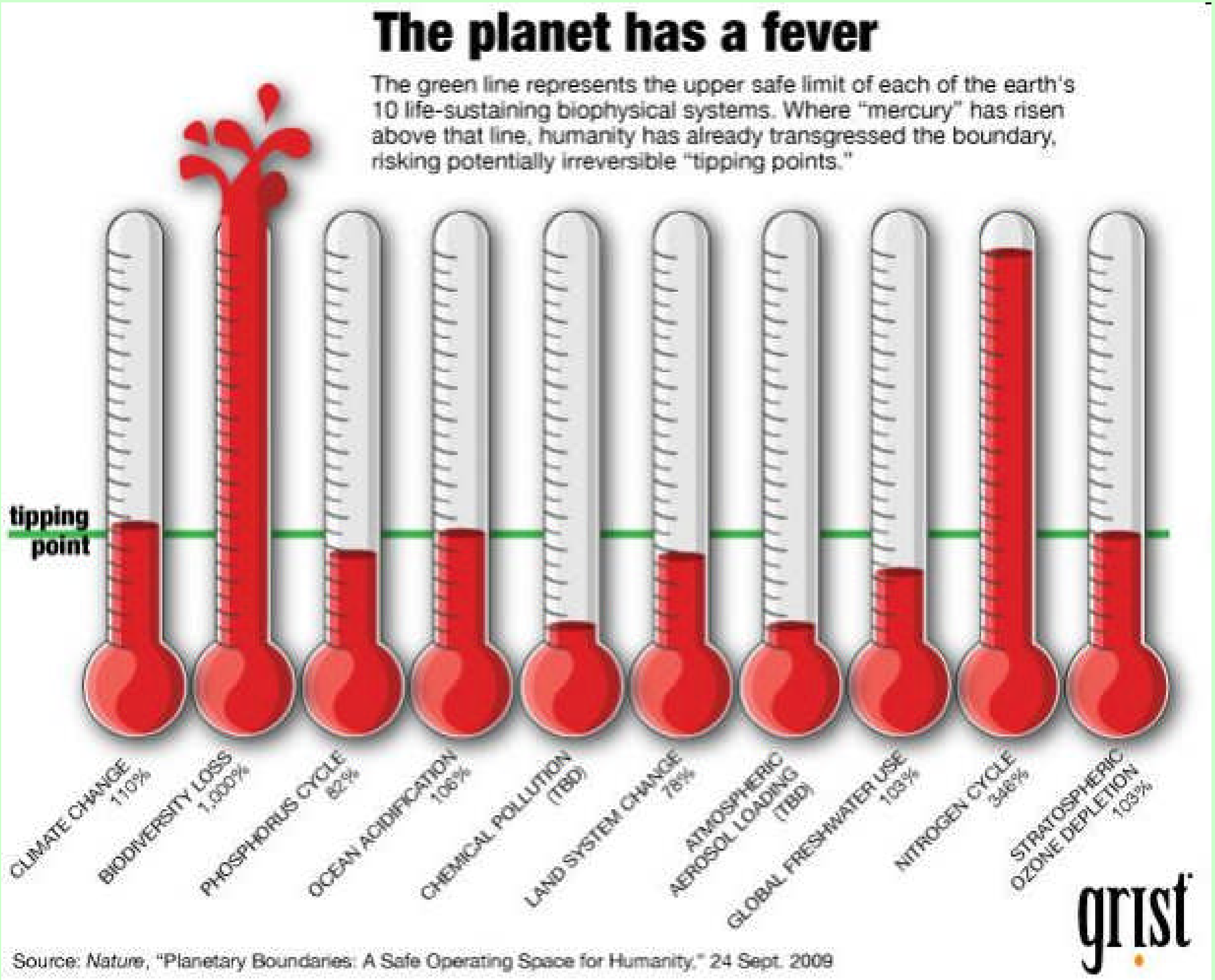
Human acceleration of the nitrogen cycle at regional to global scales

Bob Howarth
Ecology & Evolutionary Biology

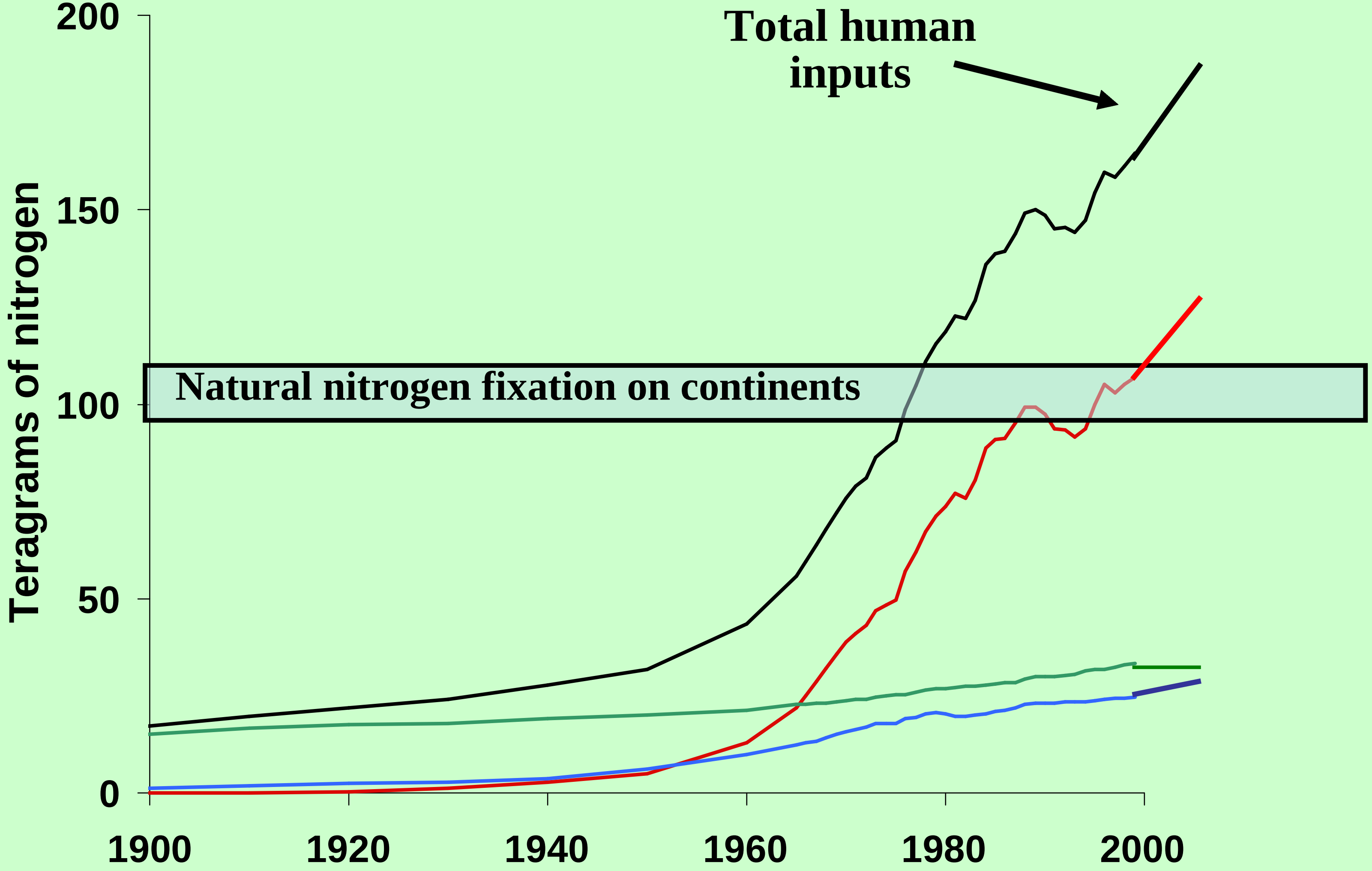
Computational Sustainability

10 March 2010




The planet has a fever
The green line represents the upper safe limit of each of the earth's 10 life-sustaining biophysical systems. Where "mercury" has risen above that line, humanity has already transgressed the boundary, risking potentially irreversible "tipping points."
tipping point
CLIMATE CHANGE 110%
BIODIVERSITY LOSS 1,000%
PHOSPHORUS CYCLE 82%
OCEAN ACIDIFICATION 106%
CHEMICAL POLLUTION (TBD)
LAND SYSTEM CHANGE 78%
ATMOSPHERIC AEROSOL LOADING (TBD)
GLOBAL FRESHWATER USE 103%
NITROGEN CYCLE 346%
STRATOSPHERIC OZONE DEPLETION 103%
grist
Source: Nature, "Planetary Boundaries: A Safe Operating Space for Humanity," 24 Sept. 2009

Global trends in nitrogen use per year – humans have doubled the natural supply



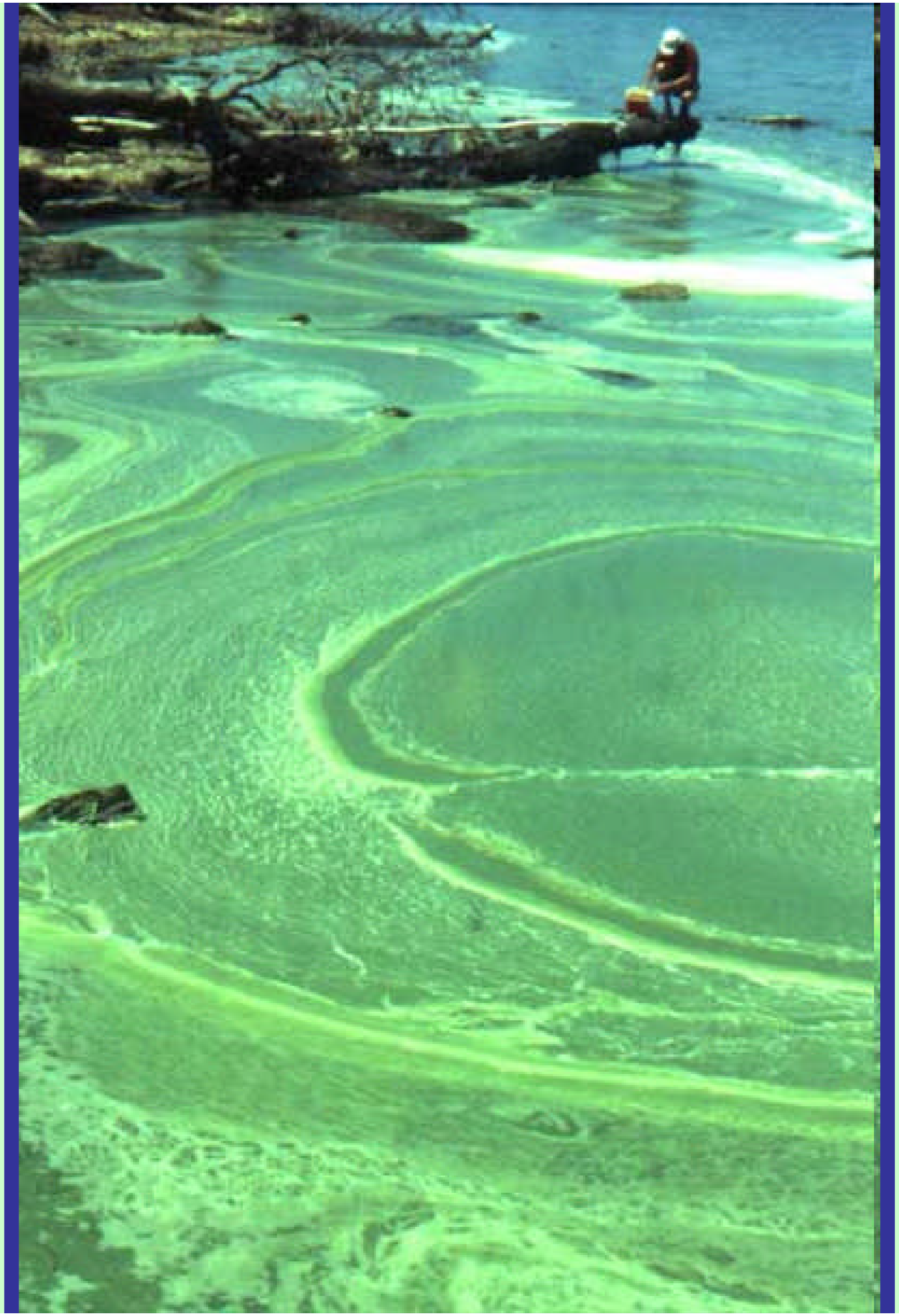
(modified from Howarth et al. 2005)

What’s the problem?

Nitrogen is a nutrient…

Nutrients are “things that nourish.”

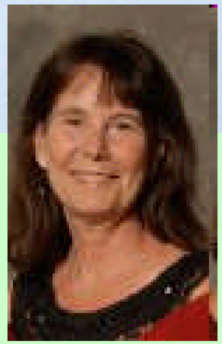
Too much of a good thing!

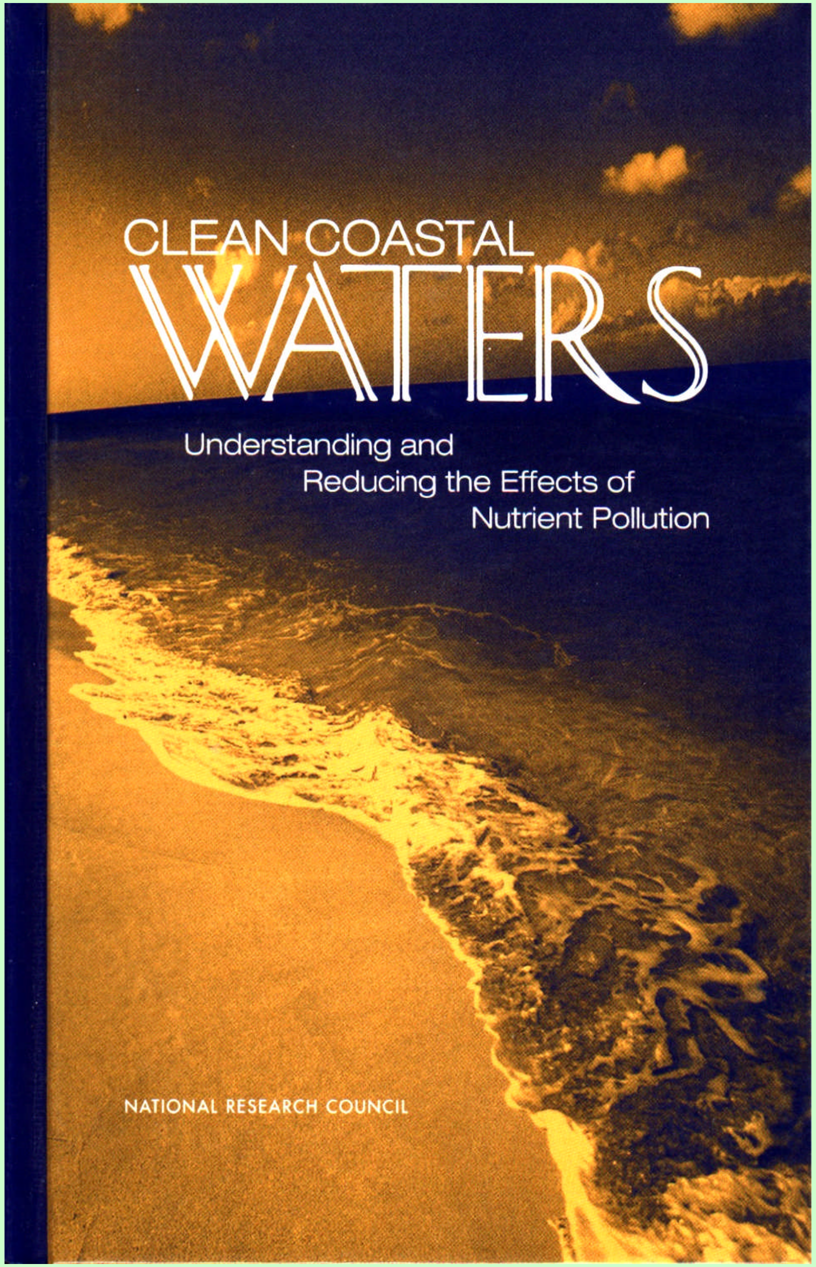



Yellowstone River
Missouri River
Mississippi River
Platte River
Illinois R.
Ohio River
St Louis
Arkansas River
Tennessee River
Red River
Mississippi River
New Orleans
0 200 KILOMETERS
0 200 MILES


15:08:06

“Dead Zone”



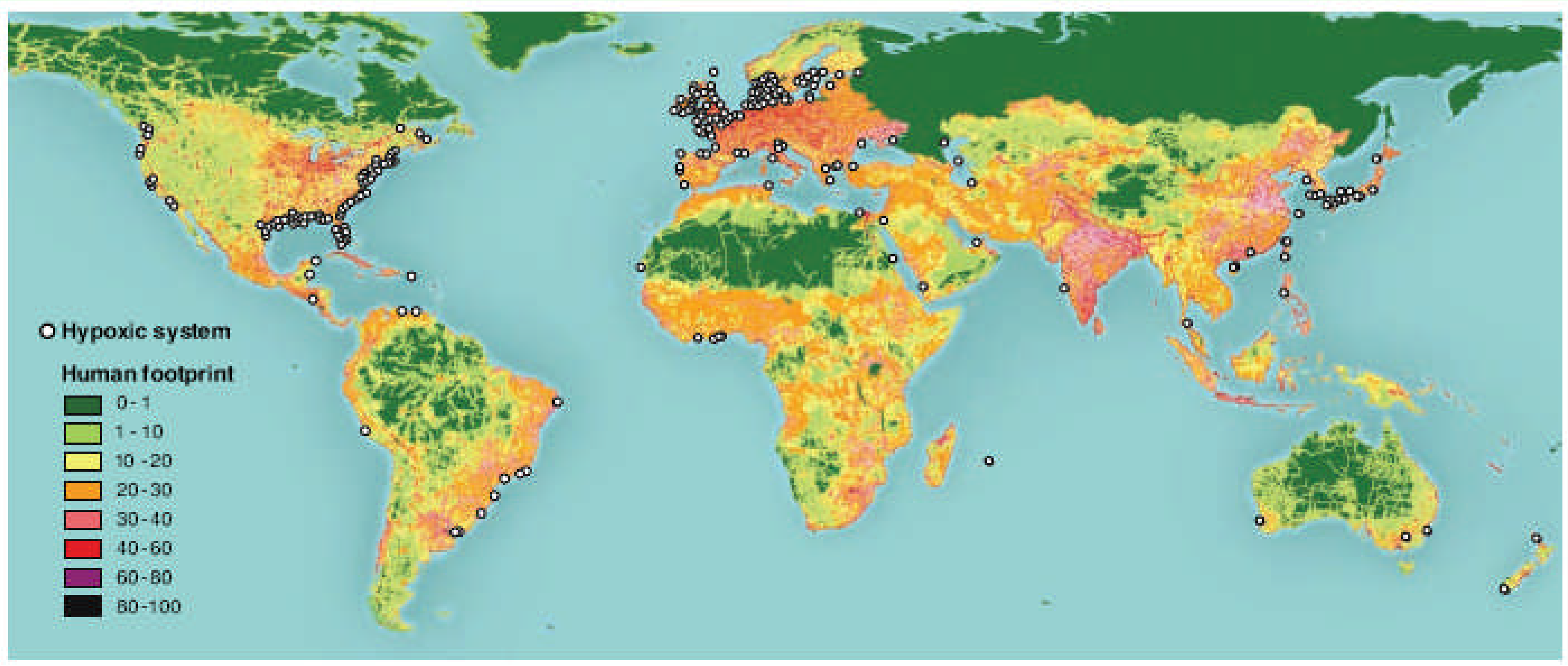


NRC 2000:

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

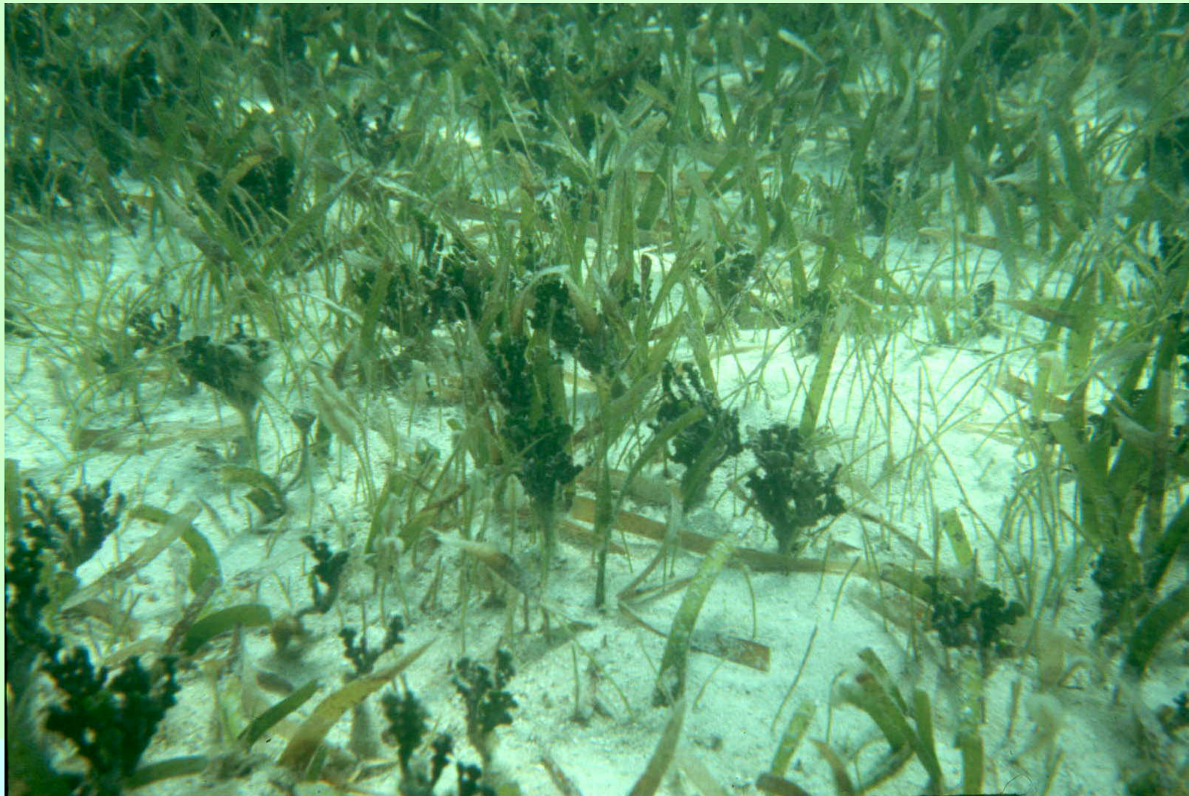
Two thirds of coastal rivers and bays are moderately to severely degraded from nitrogen pollution.

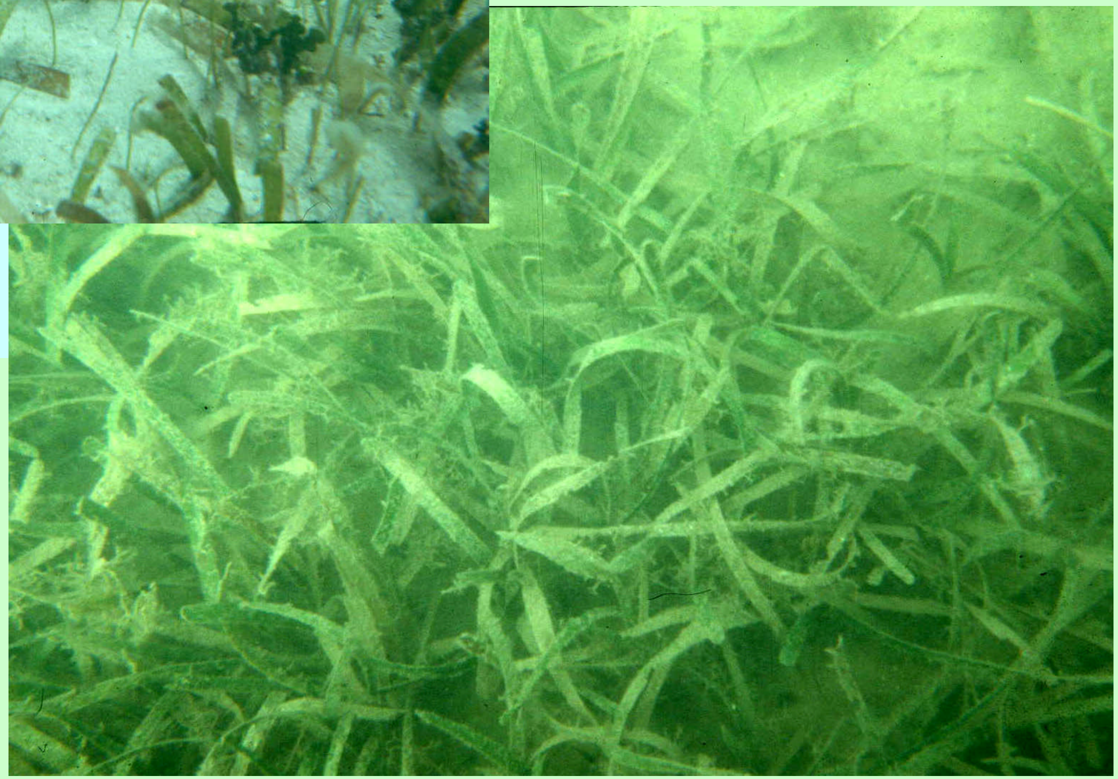
“Dead Zones” (low-oxygen waters) from Excess Nitrogen Pollution



United Nations Environmental Programme (2008)


WARNING . . .
TOXIC SHELLFISH
SHELLFISH FROM THIS AREA ARE UNSAFE TO EAT DUE TO PARALYTIC SHELLFISH TOXIN.
DO NOT EAT CLAMS, OYSTERS, MUSSELS OR SCALLOPS.
Red Tide Hotline
1-800-562-5632
Health





Townsend & Howarth (2010) Scientific American

Other environmental consequences of accelerated N cycle

- **Acid rain: damage to waters and soils**
- **Damage to growth of forests and agriculture, due to ozone pollution**
- **Over-stimulation of forest growth, leading to winter dieback**
- **Loss of biodiversity in forests, wetlands, etc.**

Other environmental consequences of accelerated N cycle

Species[a]	Concentrations[b] and their changes[c]: 2005	Change since 1998	Radiative Forcing[d]: 2005 ($W m^{-2}$)	Change since 1998 (%)
CO_2	379 ± 0.65 ppm	+13 ppm	1.66	+13
CH_4	1,774 ± 1.8 ppb	+11 ppb	0.48	-
N_2O	319 ± 0.12 ppb	+5 ppb	0.16	+11

Nitrous oxide gas (N_2O) – no laughing matter!

- greenhouse gas -- much lower concentration that CO_2, but 280-fold more powerful! Responsible for about 1/10th of warming currently, compared to CO_2
- creates ozone holes in stratosphere, letting high UV radiation hit surface of earth
- stays in the atmosphere for 120 years.

Nitrogen and Human Health

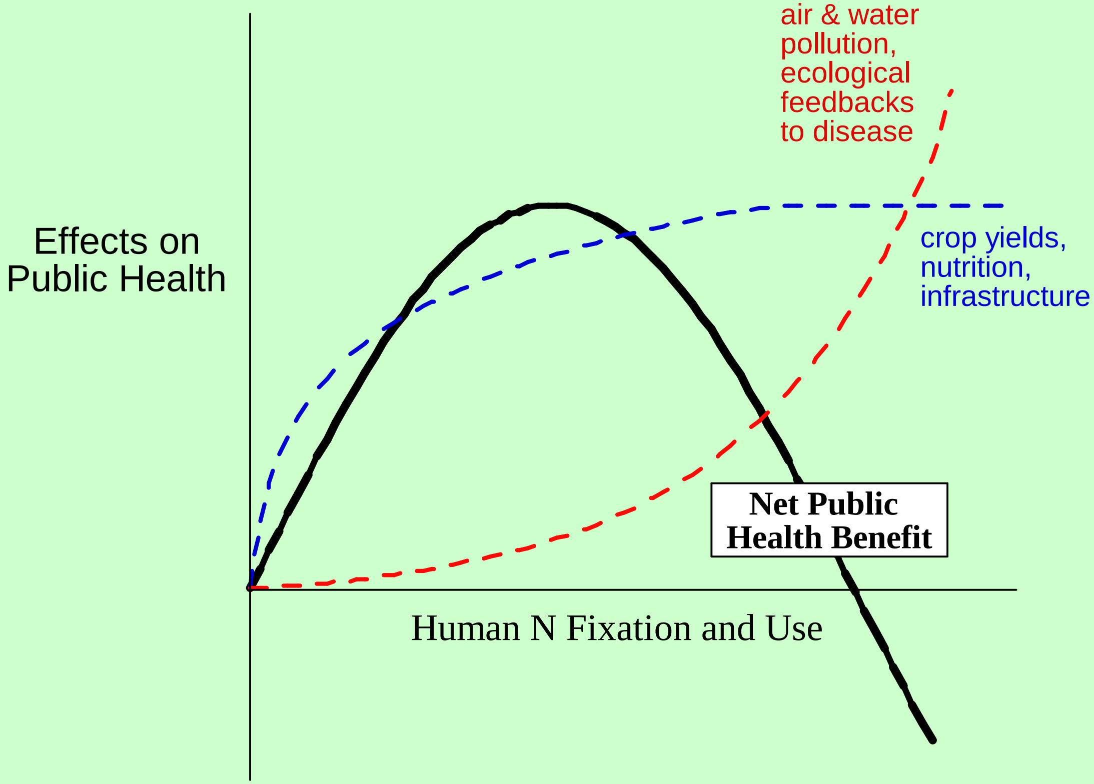
<u>Direct pollution effects</u>:

- **Heart disease and lung diseases (from gases and particles in air)**
- **Cancer (nitrogen in drinking water)**

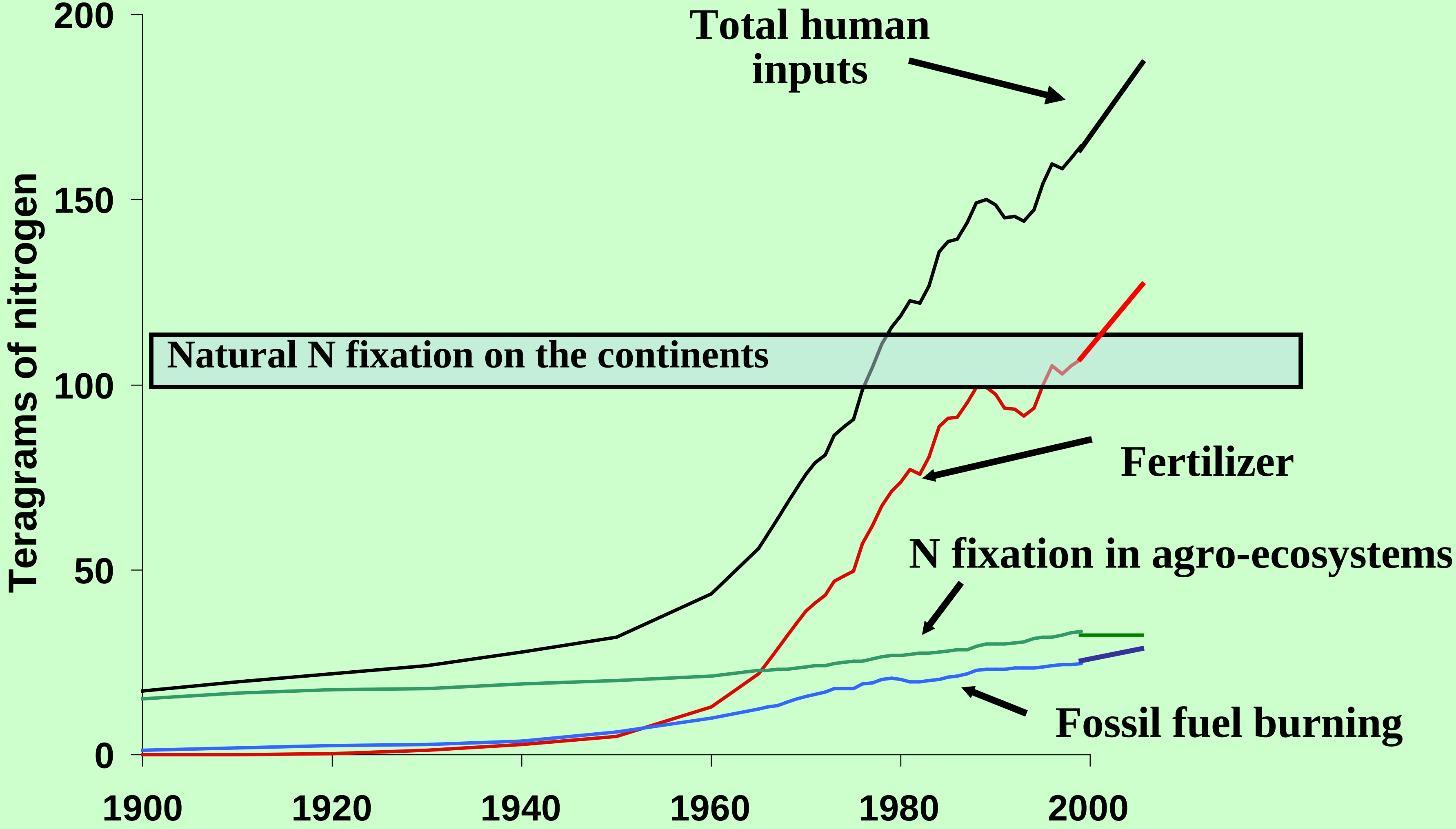
<u>Indirect pollution effects (from fertilization!)</u>:

- **Pollen and allergies**
- **Animals that carry diseases (mosquitoes, snails) such as malaria and schistosomiasis**

Townsend et al. (2003) *Frontiers in Ecology and Environment* 1: 240-246



Global trends in nitrogen use per year

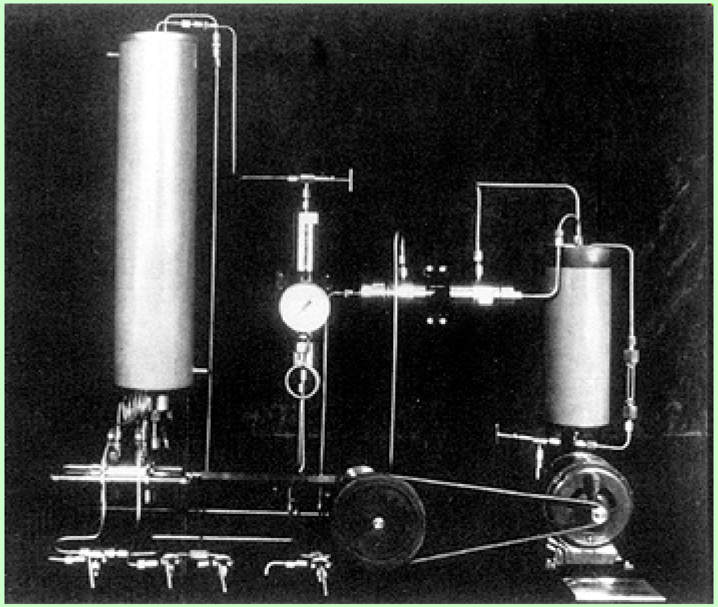


(modified from Howarth et al. 2005)

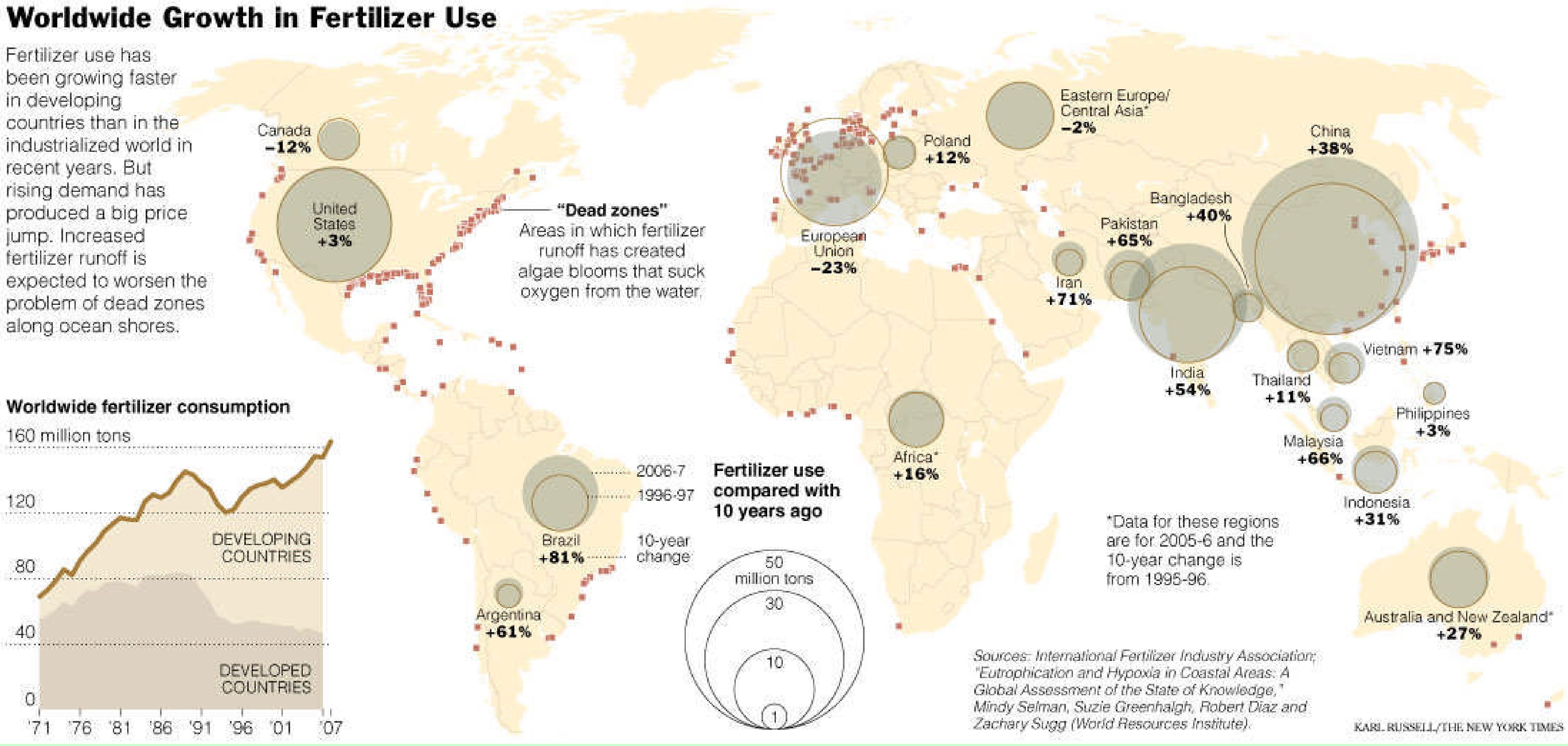
Fritz Haber discovered a way to make synthetic nitrogen fertilizer from atmospheric N_2 gas in 1909.

Today, this literally feeds the world!

80% of the nitrogen that supports food production comes from this industrial process (and 80% of the nitrogen in your proteins, if you eat like an average person).

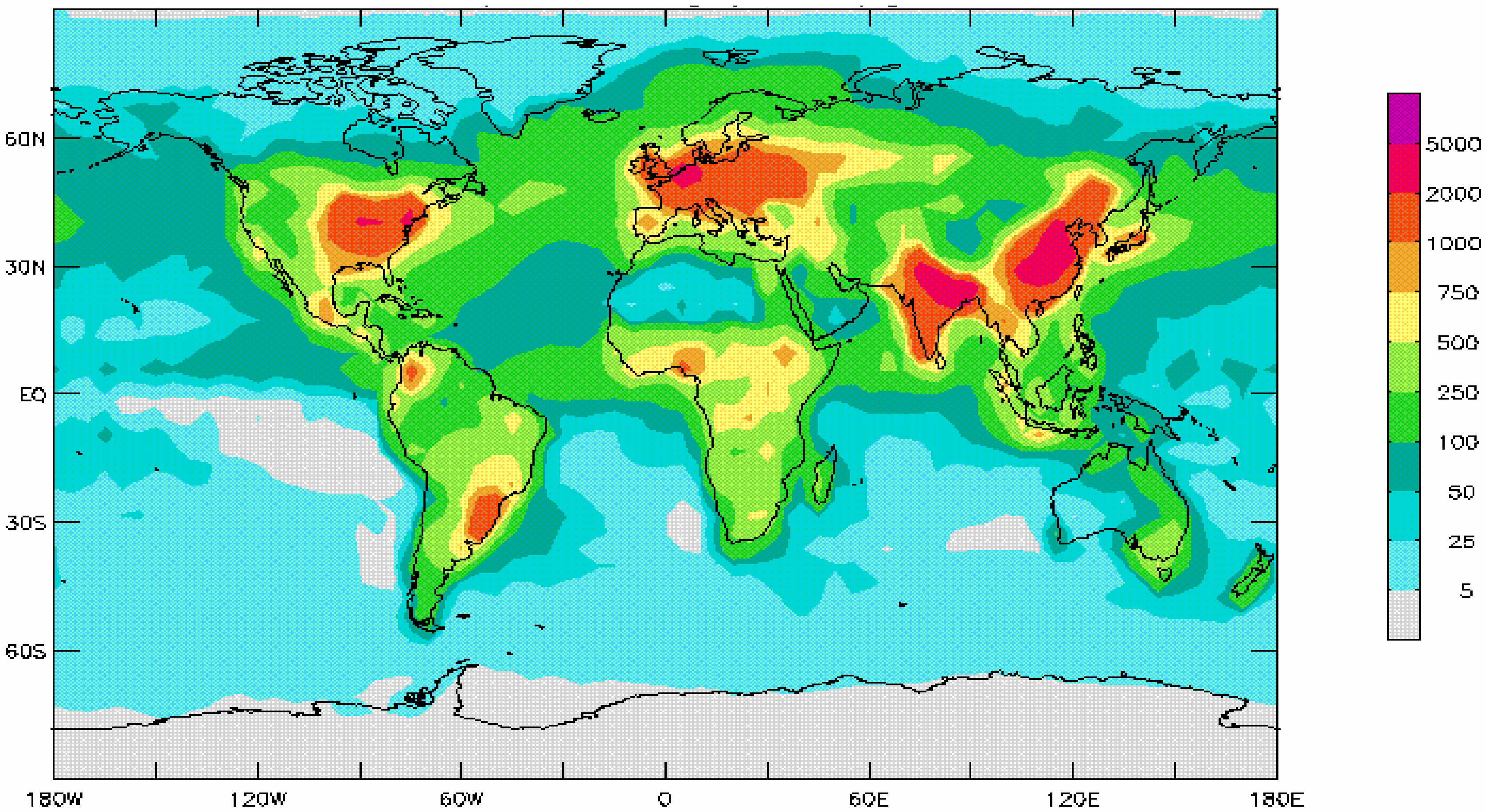


Burning of fossil fuels contributes…… and is a bigger problem that agriculture in some parts of the northeastern US. But in most of the world, agriculture is the biggest source of nitrogen pollution.

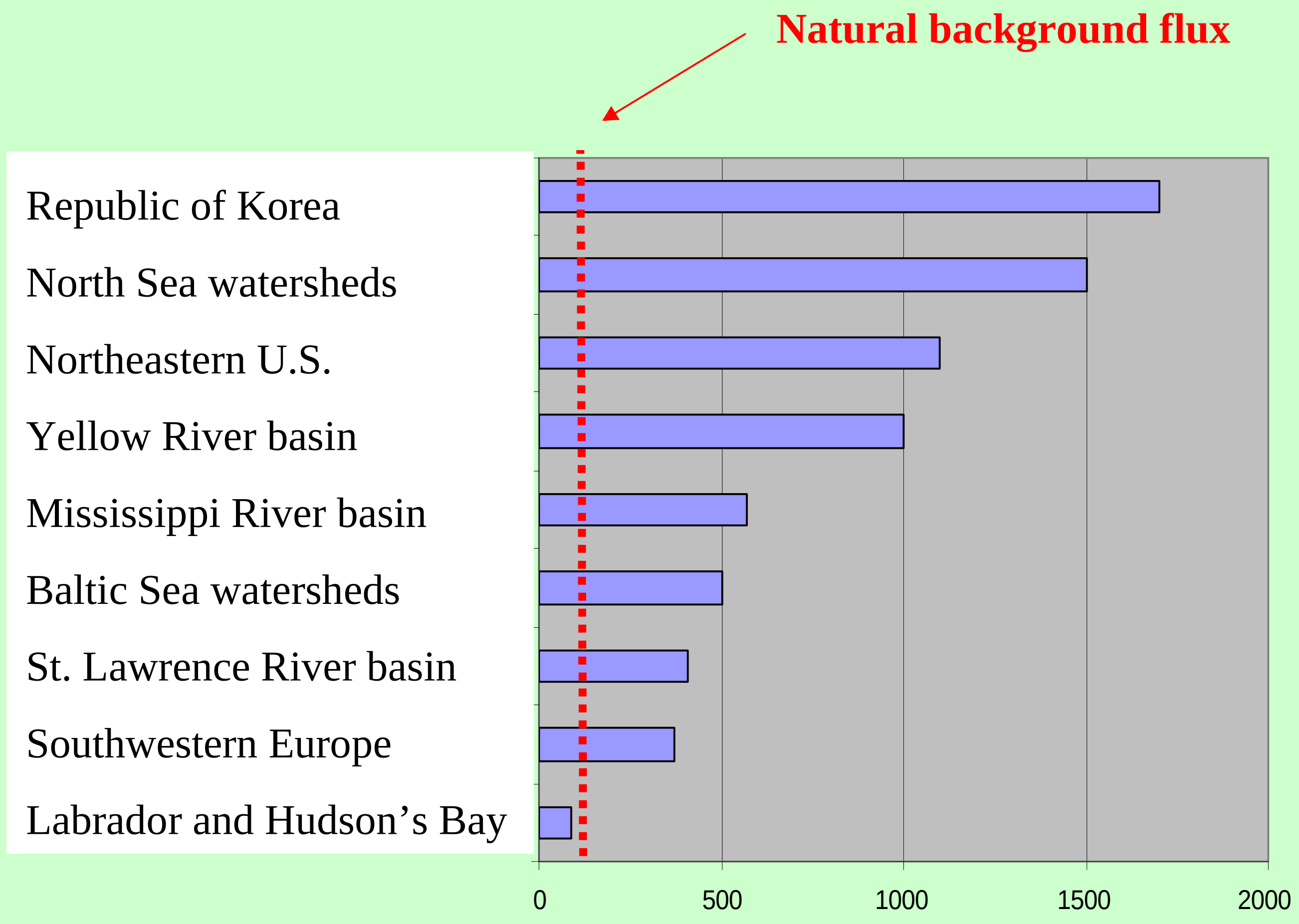


New York Times (4/30/08)

Total nitrogen deposition as of 1993
(kg km^{-1}yr^{-1})



Dentener 2000



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. 2005).

For particular regions and watersheds, where does the nitrogen come?

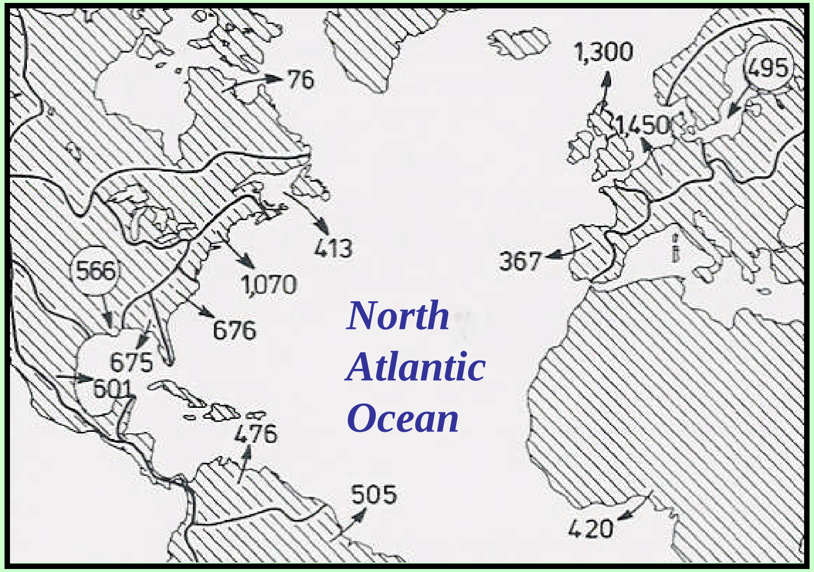
Only models provide an answer…..

For particular regions and watersheds, where does the nitrogen come?

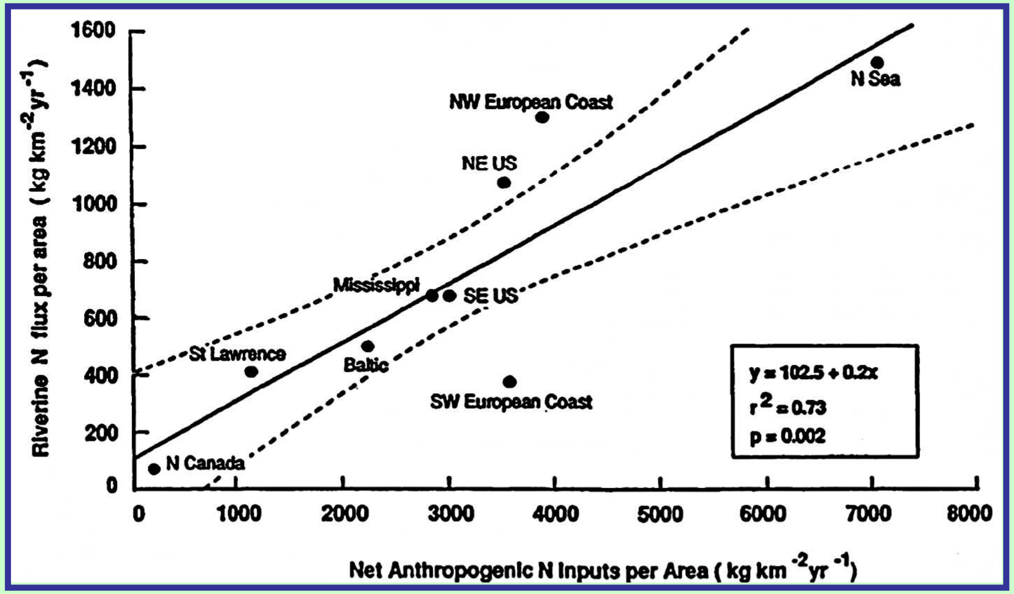
Only models provide an answer…..

Many available models, and we use a few different ones, of varying complexity. Today, I will focus on the simplest: large spatial scales, multiple-year average input data.

(This forms the basis for some of the more complicated models, which run at daily time scales and demand more types of data input).



Kg N km^{-2} $year^{-1}$

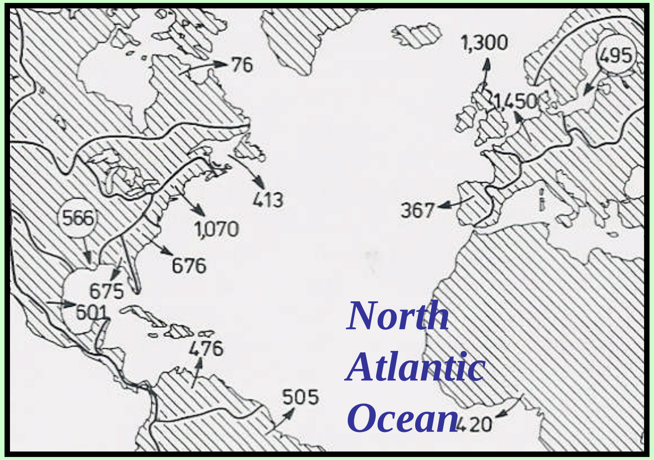


	NO_y deposition	Fertilizer	N fixation by crops	Net import (+) or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW Eutropean coast	460	3370	15	-65	3780

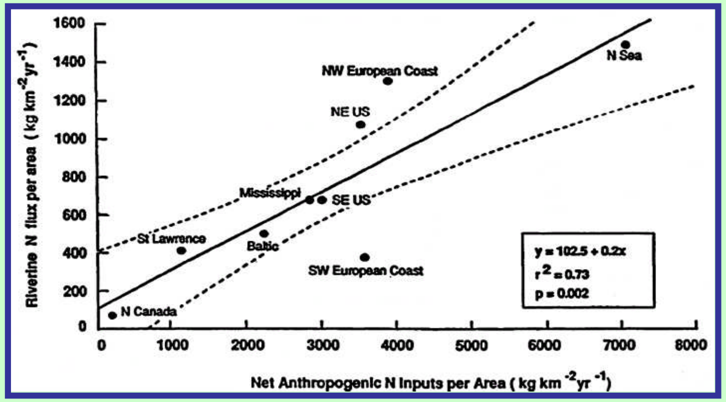
NANI

(net anthropogenic N inputs)

(Howarth et al. 1996)



Kg N km^{-2} year^{-1}

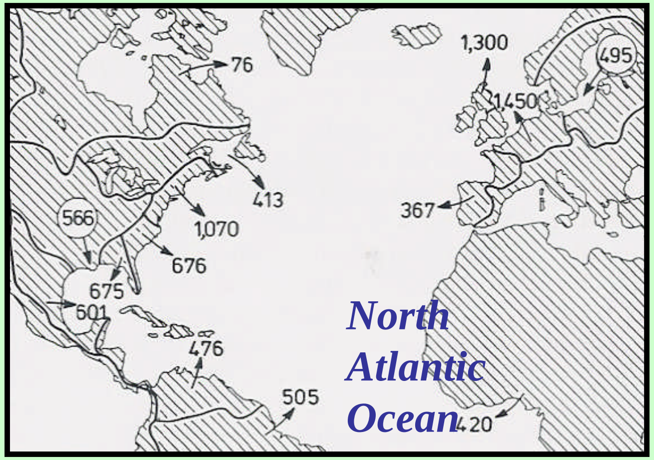


(Howarth et al. 1996)

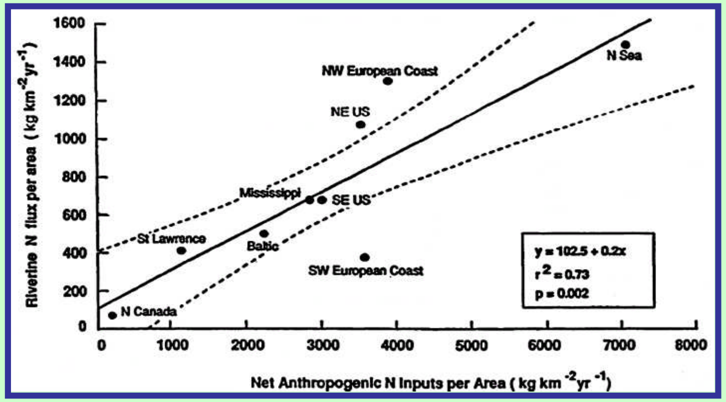
	NO_y deposition	Fertilizer	N fixation by crops	Net import (+) or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW Eutropean coast	460	3370	15	-65	3780

NANI:

- only 4 inputs
- deposition of NH_3 and NH_4^+, wastewater inputs, and manure are not included (these are considered recycling within region)



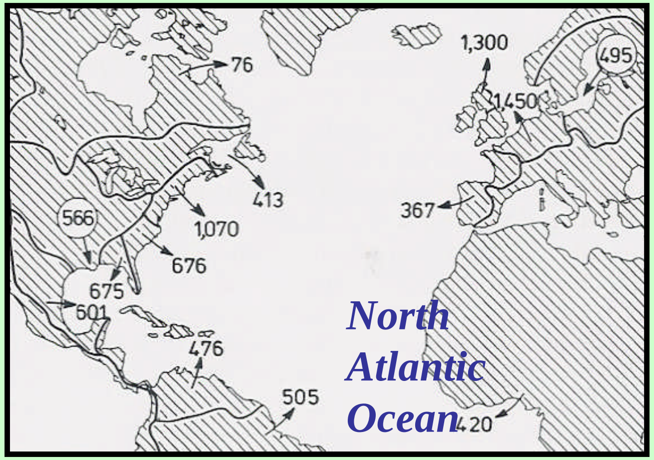
Kg N km^{-2} year^{-1}



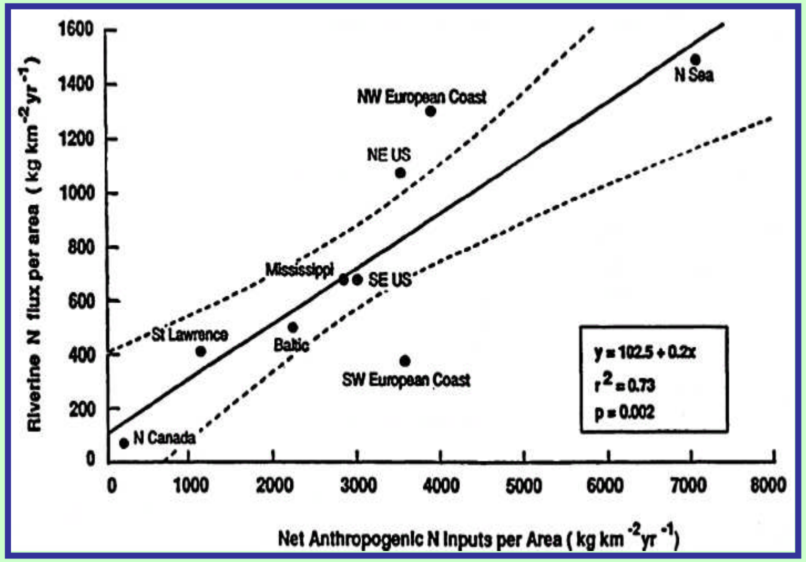
(Howarth et al. 1996)

	NO_y deposition	Fertilizer	N fixation by crops	Net import (+) or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW Eutropean coast	460	3370	15	-65	3780

These inputs are easier to estimate at larger spatial scales



Kg N km^{-2} $year^{-1}$

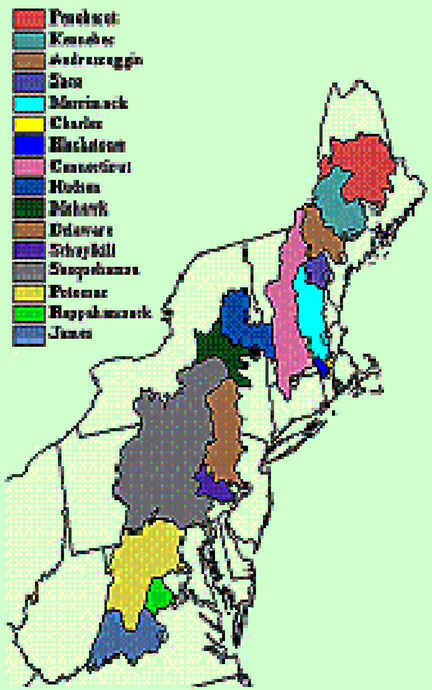


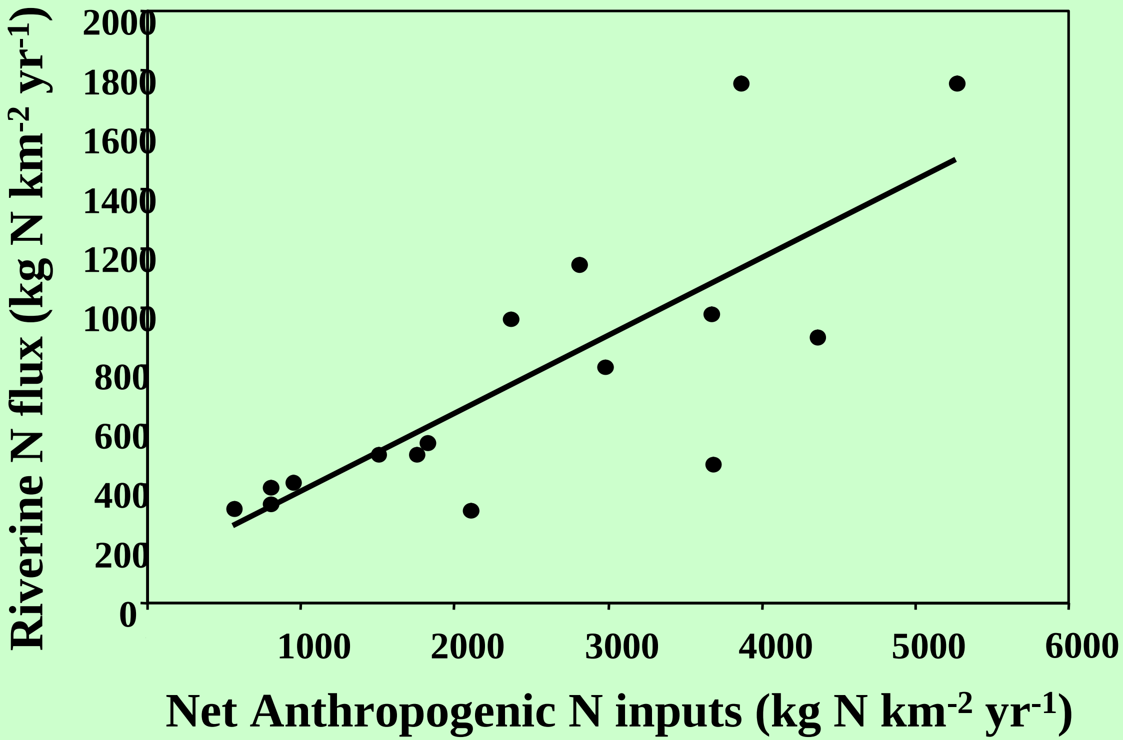
	NO_y deposition	Fertilizer	N fixation by crops	Net import (+) or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW Eutropean coast	460	3370	15	-65	3780

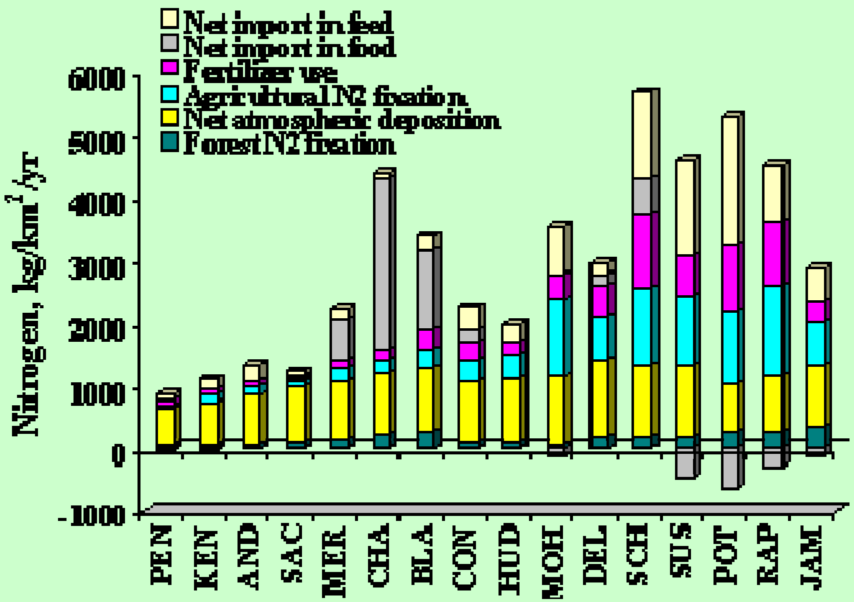
NANI compared to riverine TN flux to coast over periods of ~ 6 years, to average out year-to-year variability.

- **The simple NANI model compares extremely well with more complicated models for estimating N export from large watersheds and regions (Alexander et al. 2002; Boyer & Howarth 2008).**

- **We do even better by including a little more information (climate or hydrology).**

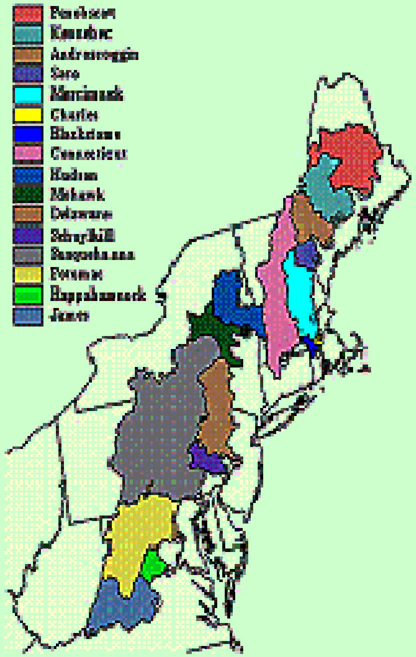




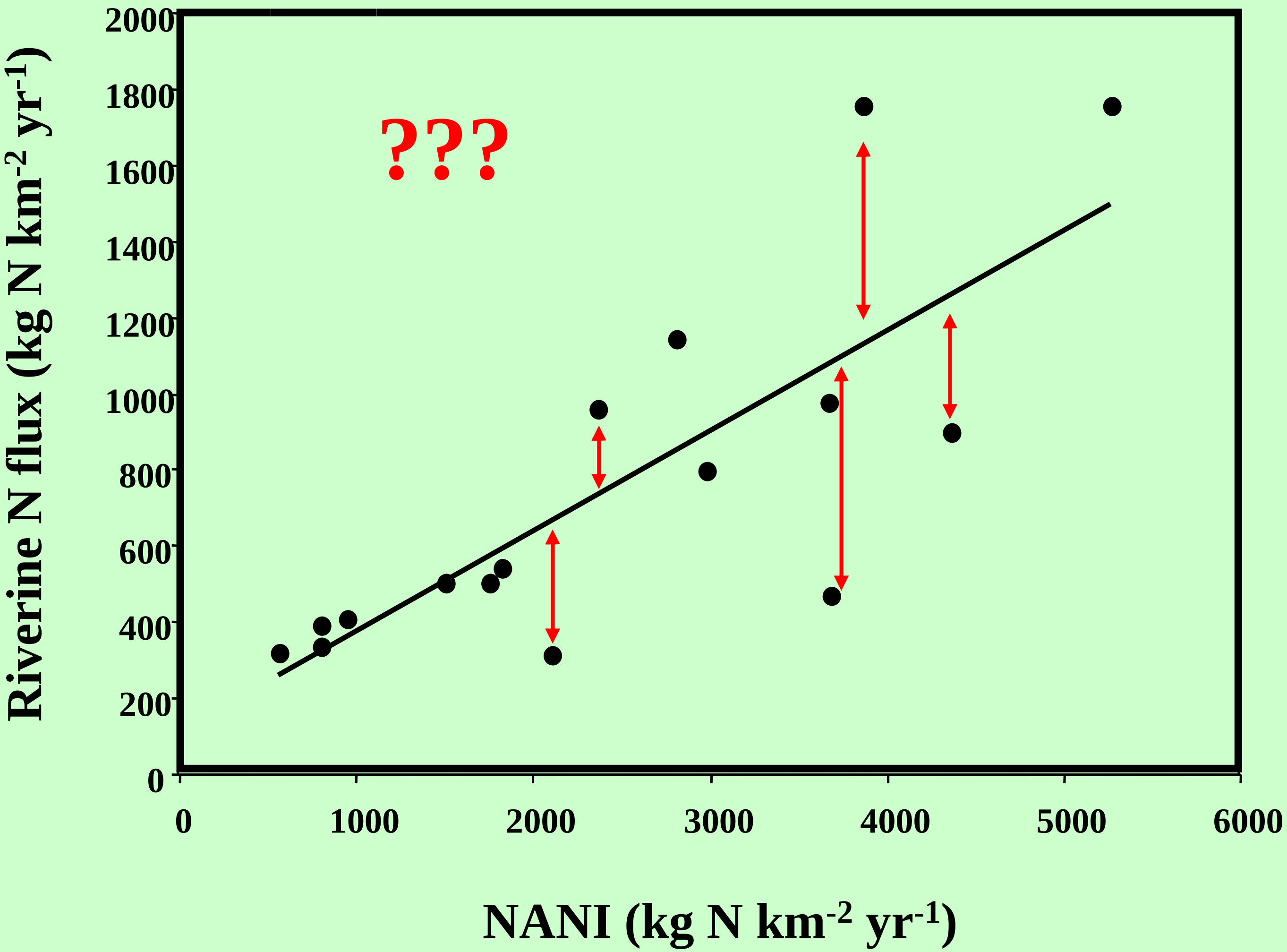


Application to individual watersheds in northeastern US

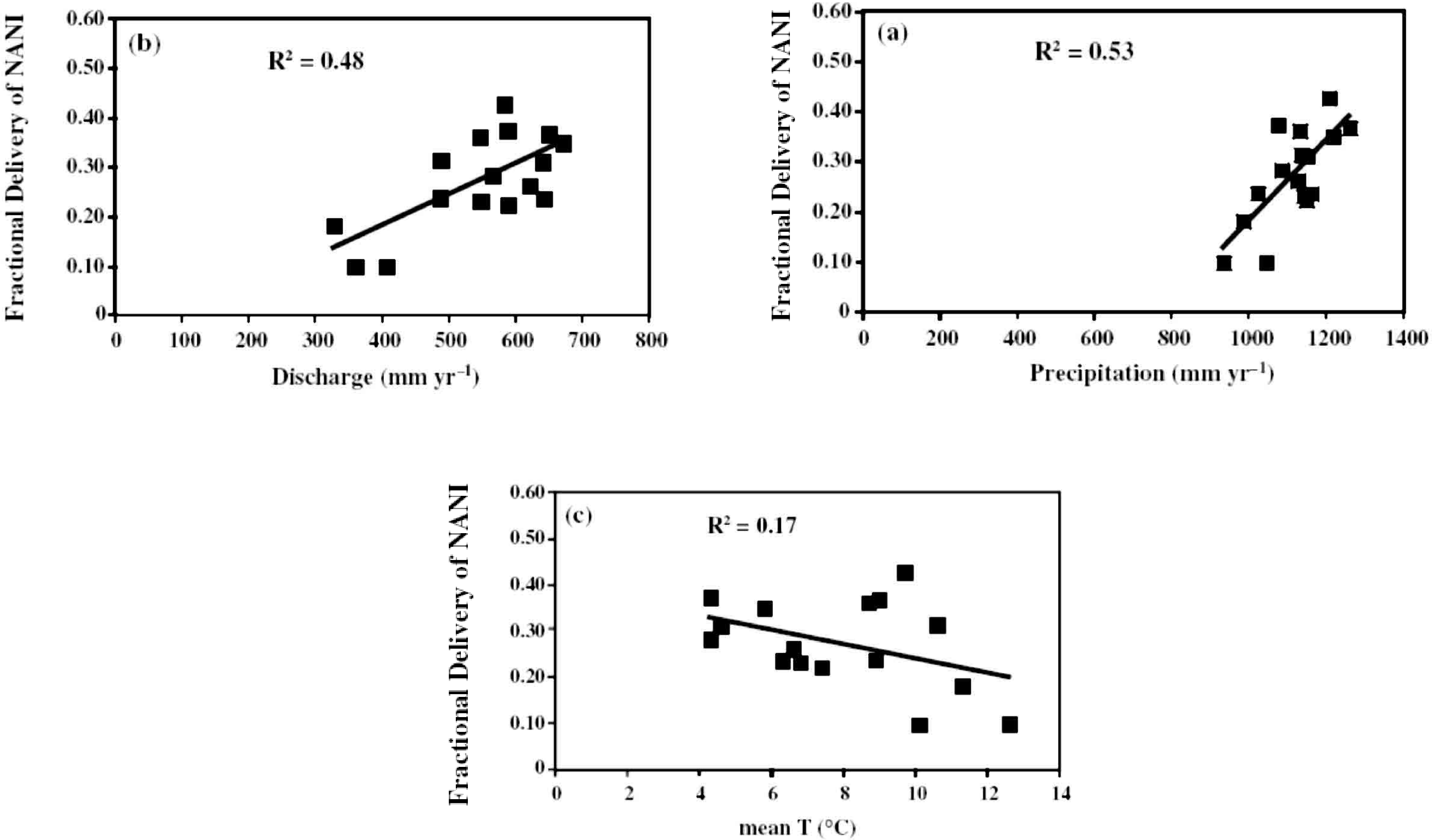
(Boyer et al. 2002; Howarth et al. 2006)



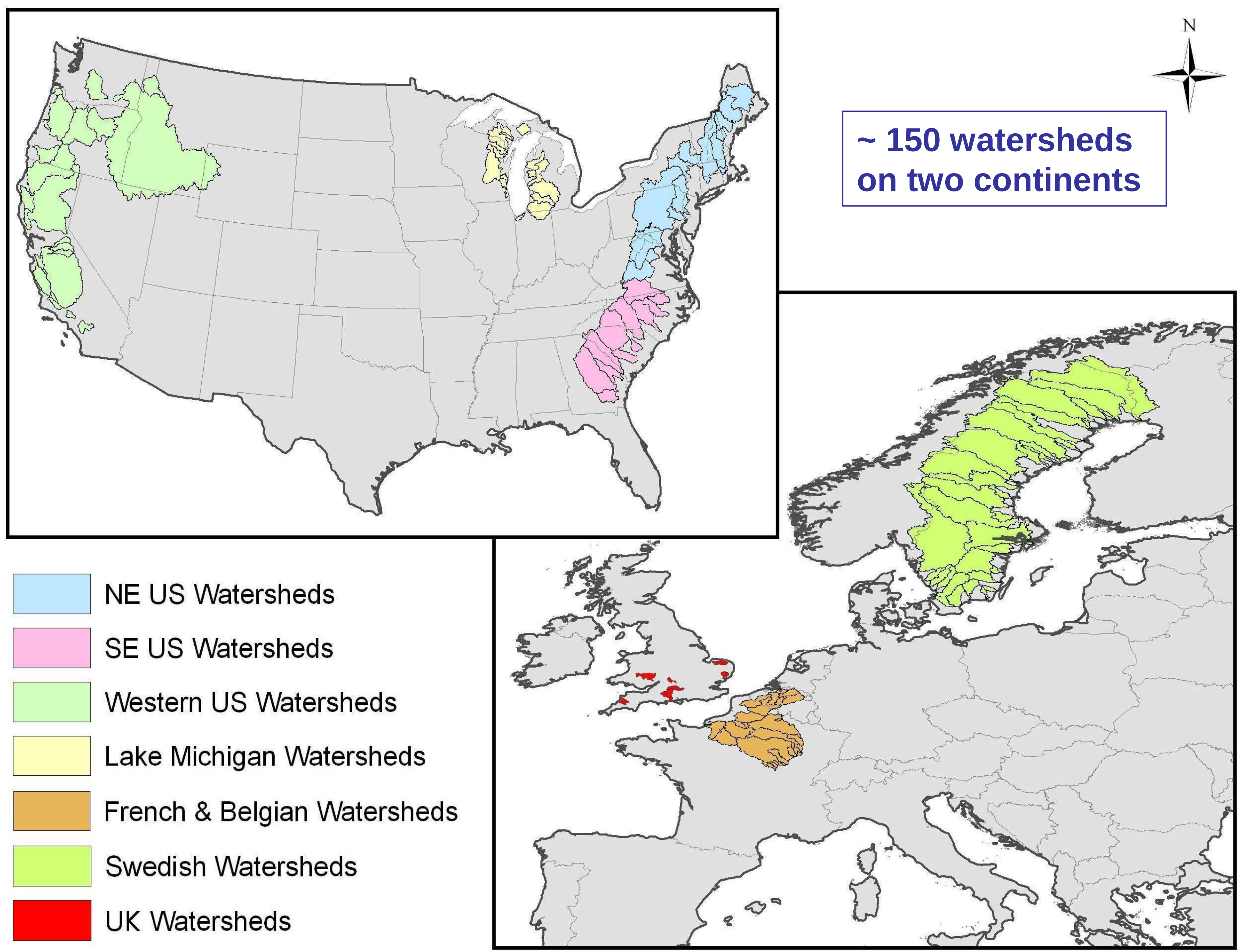
Is scatter attributable to climate differences?

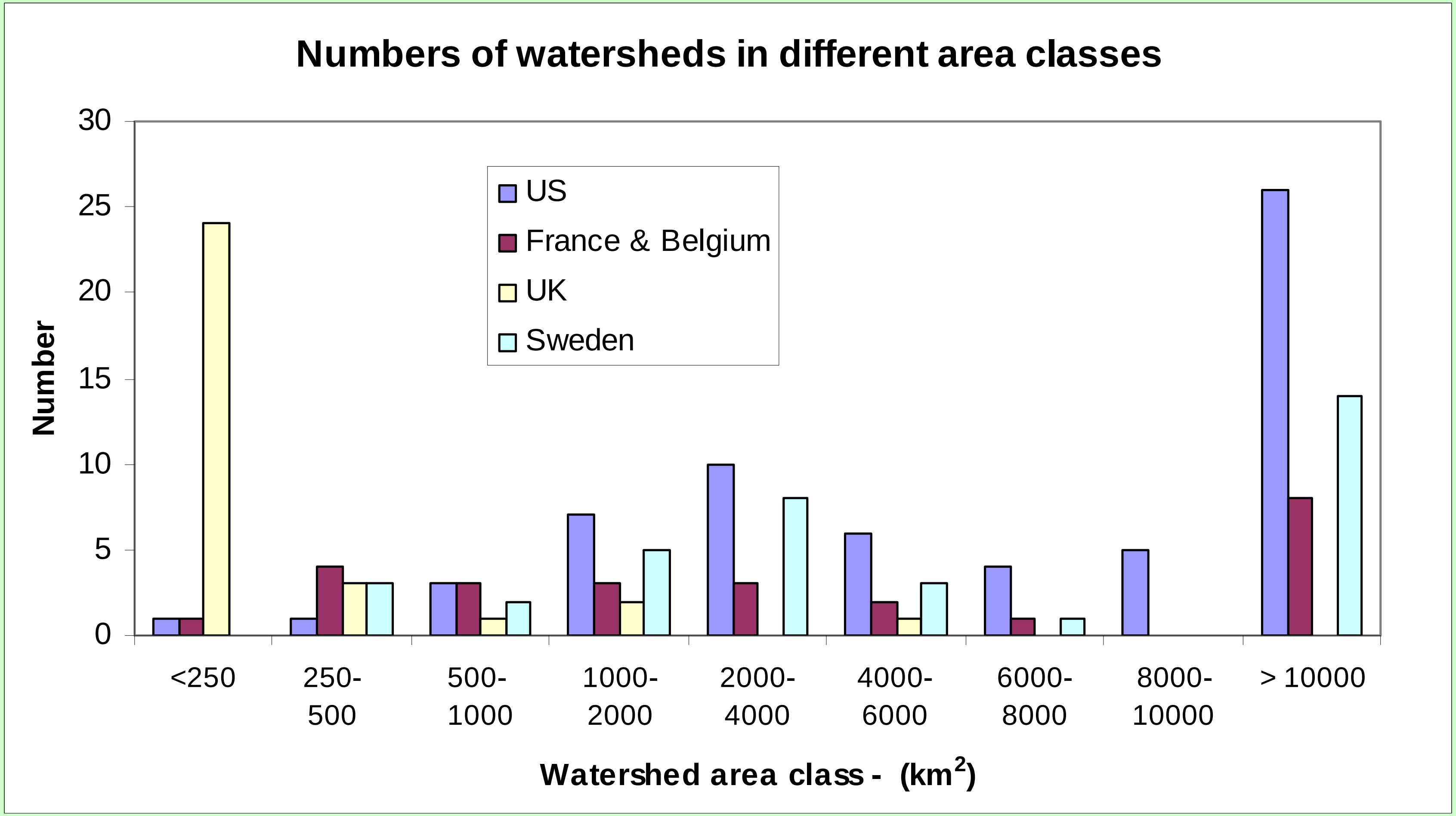


Fractional delivery = (river flux) / (N inputs)

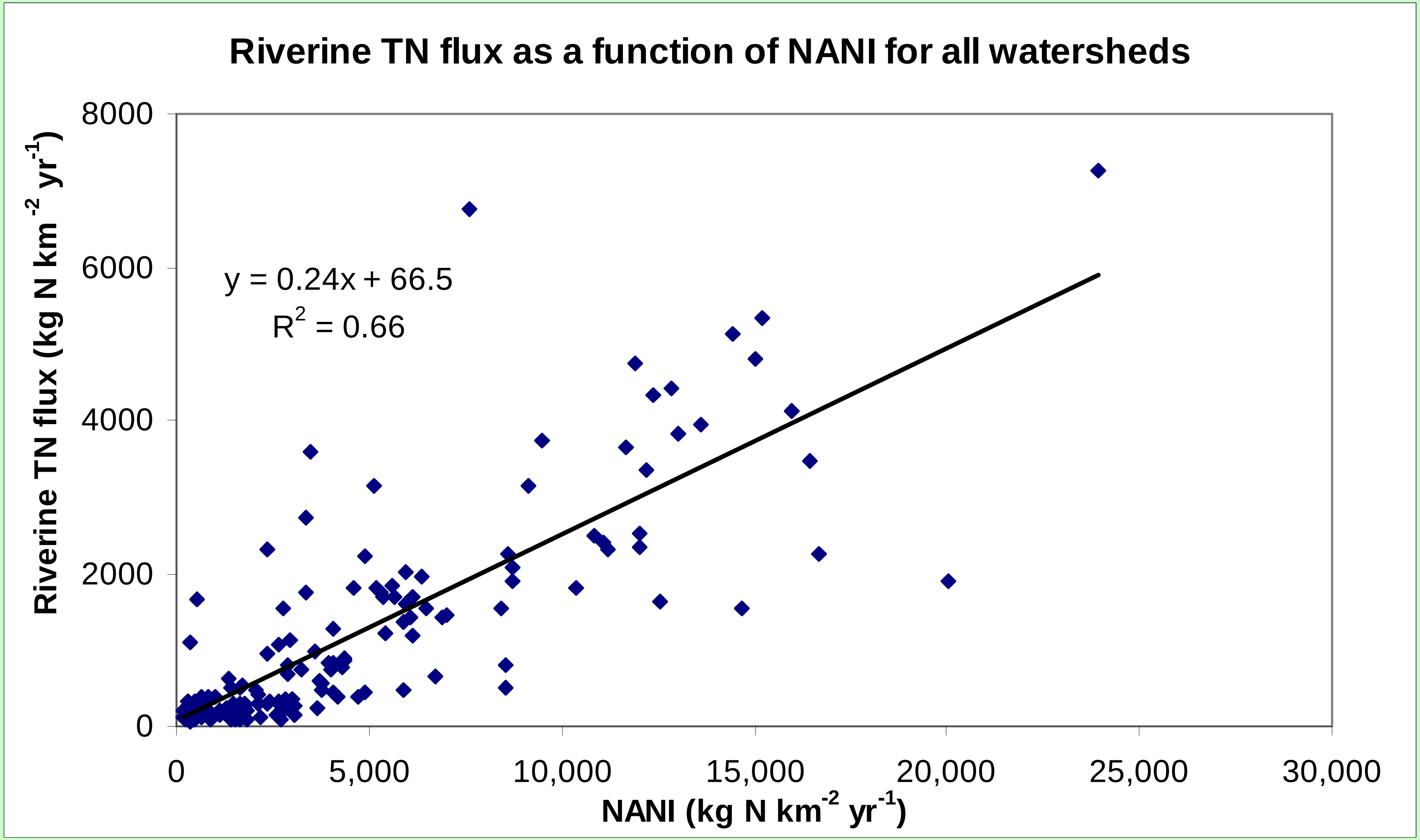


Howarth et al., 2006


N
~ 150 watersheds
on two continents
NE US Watersheds
SE US Watersheds
Western US Watersheds
Lake Michigan Watersheds
French & Belgian Watersheds
Swedish Watersheds
UK Watersheds

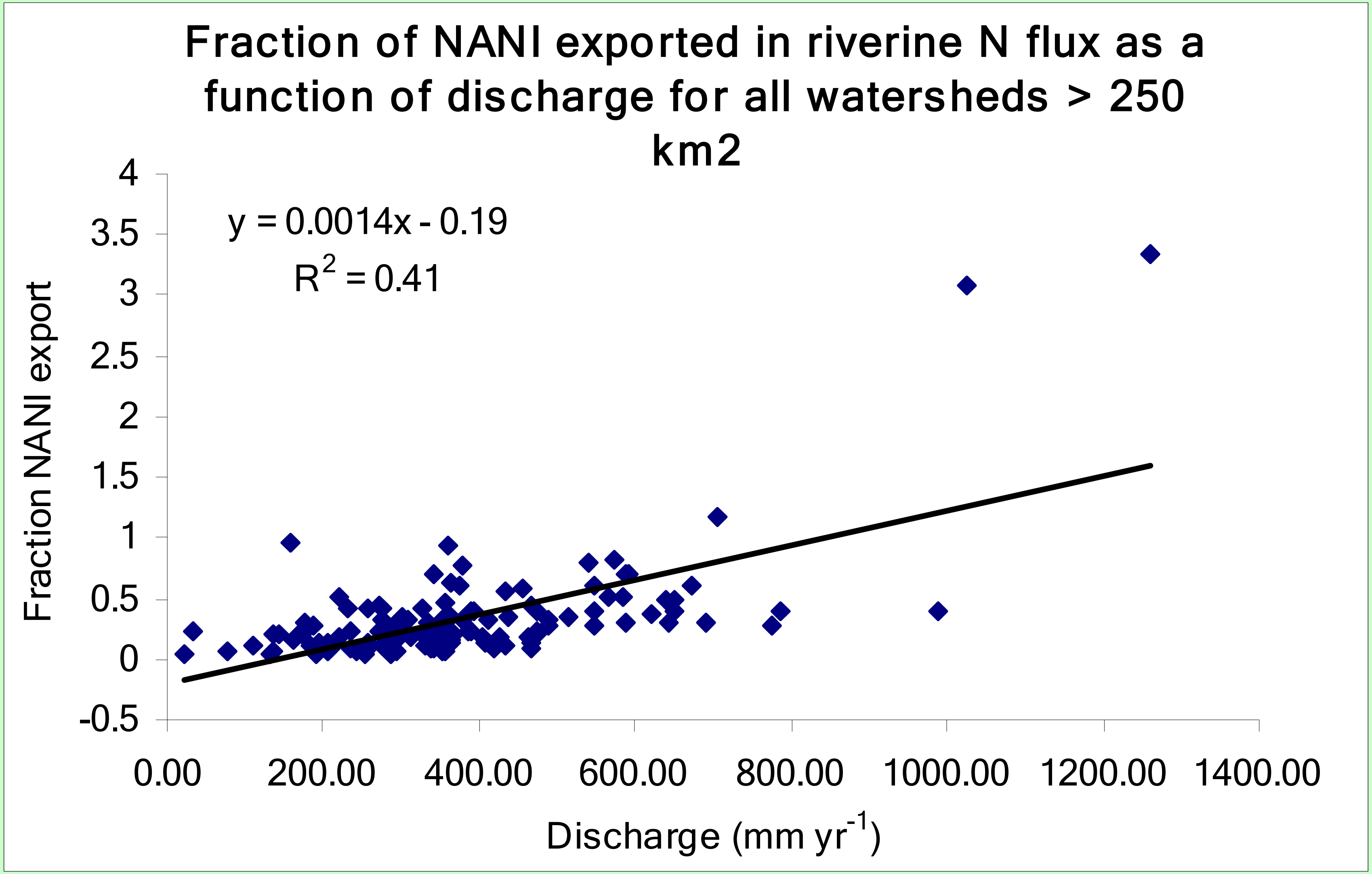


Numbers of watersheds in different area classes
Number
30
25
20
15
10
5
0
US
France & Belgium
UK
Sweden
<250
250-500
500-1000
1000-2000
2000-4000
4000-6000
6000-8000
8000-10000
> 10000
Watershed area class - (km^2)



Riverine TN flux as a function of NANI for all watersheds
y = 0.24x + 66.5
R2 = 0.66
Riverine TN flux (kg N km-2 yr-1)
NANI (kg N km-2 yr-1)
0
2000
4000
6000
8000
0
5,000
10,000
15,000
20,000
25,000
30,000

Fraction of NANI Export as a Function of Discharge



Models with intercepts set to zero:

#2) TN flux = b* NANI + c* NANI*Q + d* Temp (adj.R2 =0.86)

	NANI*Q	**NANI**	Temp
Coefficients	**0.00033**	**0.13**	-4.77
P-value	**6.5E-10**	**4.9E-07**	0.48

#4) TN flux = b* NANI + c* NANI*Temp+ d* Temp (adj.R2 =0.82)

	NANI	Temp	NANI*Temp
Coefficients	**0.355**	-3.16	-0.010
P-value	**6.95E-10**	0.71	0.064

#6) TN flux = b* NANI + c* NANI*Q (R2 =0.86)

	NANI*Q	**NANI**
Coefficients	**0.00034**	**0.118**
P-value	**3.08E-10**	**4.95E-08**

#8) TN flux = b* NANI + c* NANI*Q+ d* Q (R2 =0.86)

	NANI*Q	**NANI**	Q
Coefficients	**0.00032**	**0.116**	0.13
P-value	**5.6E-09**	**9.1E-08**	0.36

Models with intercepts set to zero:

#2) TN flux = b* NANI + c* NANI*Q + d* Temp (adj.R2 =0.86)

	NANI*Q	NANI	Temp
Coefficients	**0.00033**	**0.13**	-4.77
P-value	**6.5E-10**	**4.9E-07**	0.48

#4) TN flux = b* NANI + c* NANI*Temp+ d* Temp (adj.R2 =0.82)

	NANI	Temp	NANI*Temp
Coefficients	**0.355**	-3.16	-0.010
P-value	**6.95E-10**	0.71	0.064

#6) TN flux = b* NANI + c* NANI*Q (R2 =0.86)

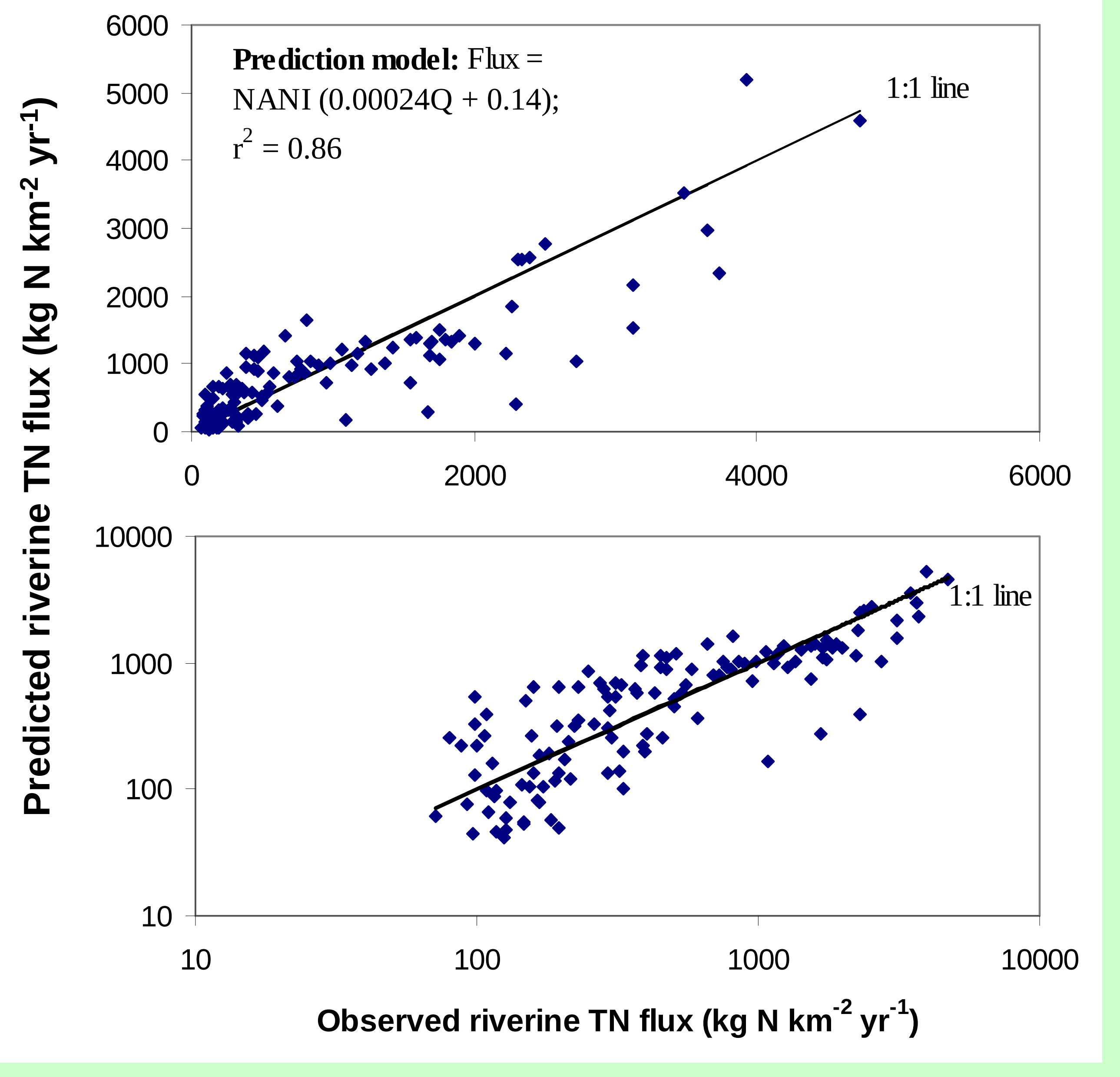
	NANI*Q	NANI
Coefficients	**0.00034**	**0.118**
P-value	**3.08E-10**	**4.95E-08**

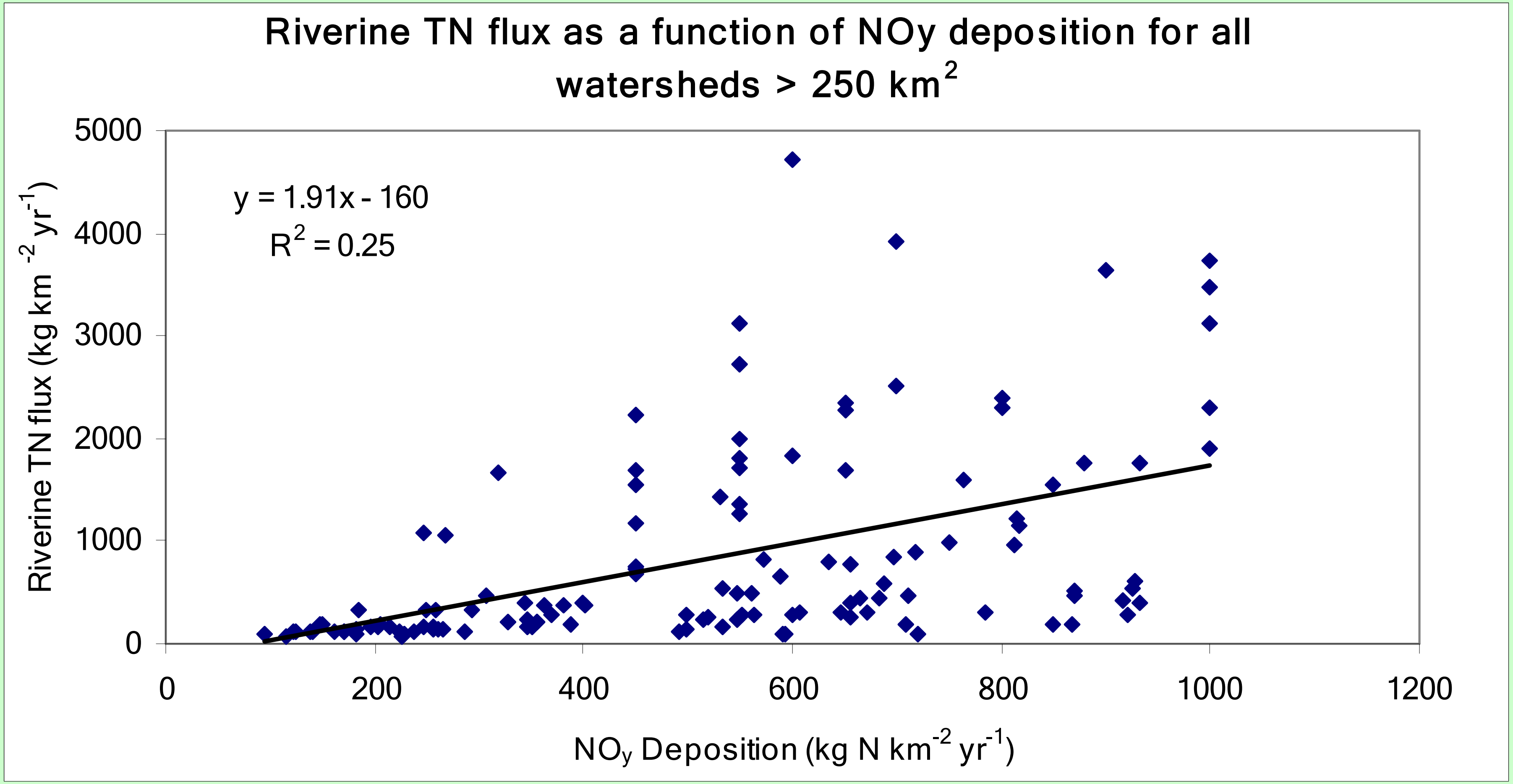
High R2 and all terms significant

#8) TN flux = b* NANI + c* NANI*Q+ d* Q (R2 =0.86)

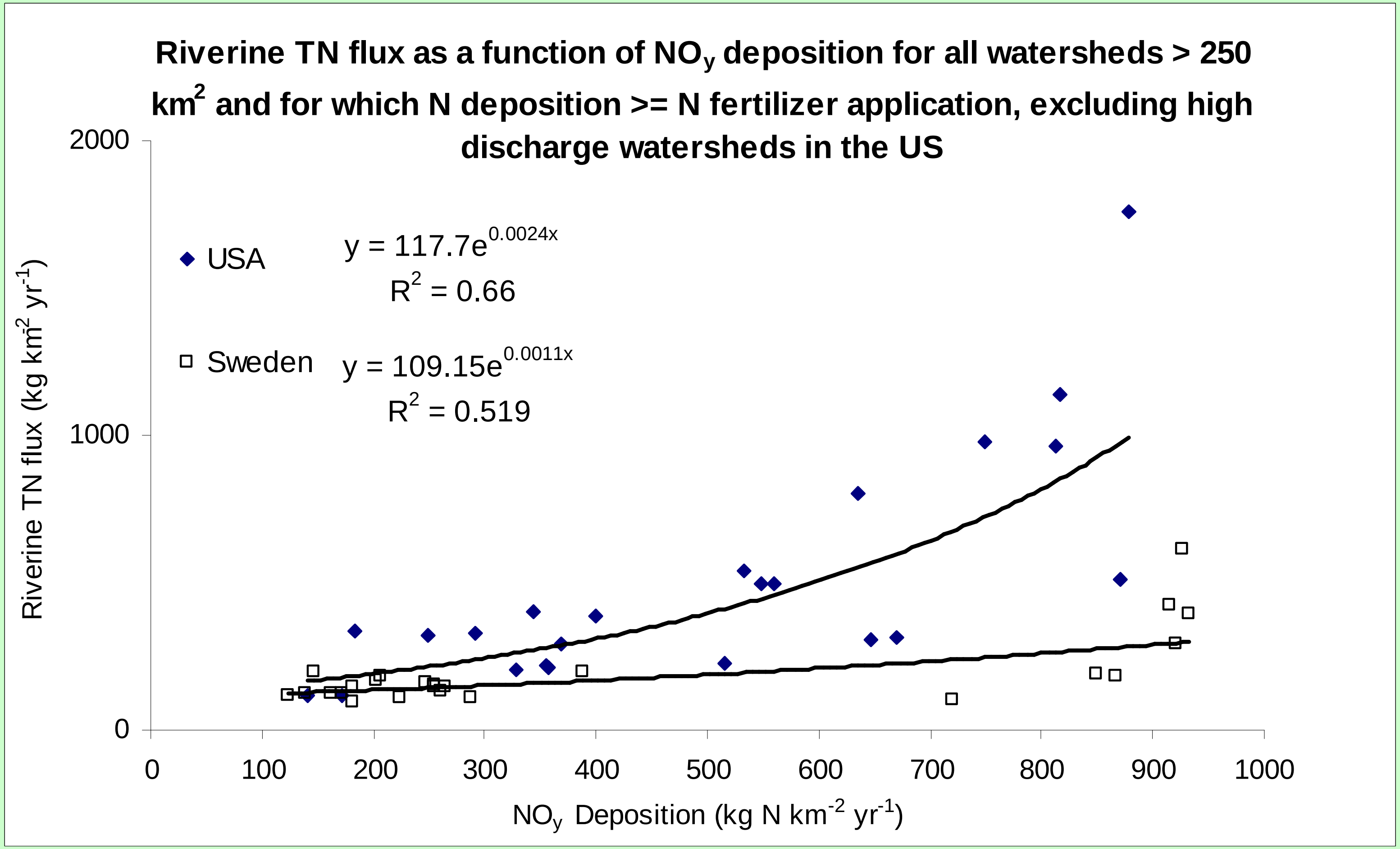
	NANI*Q	NANI	Q
Coefficients	**0.00032**	**0.116**	0.13
P-value	**5.6E-09**	**9.1E-08**	0.36

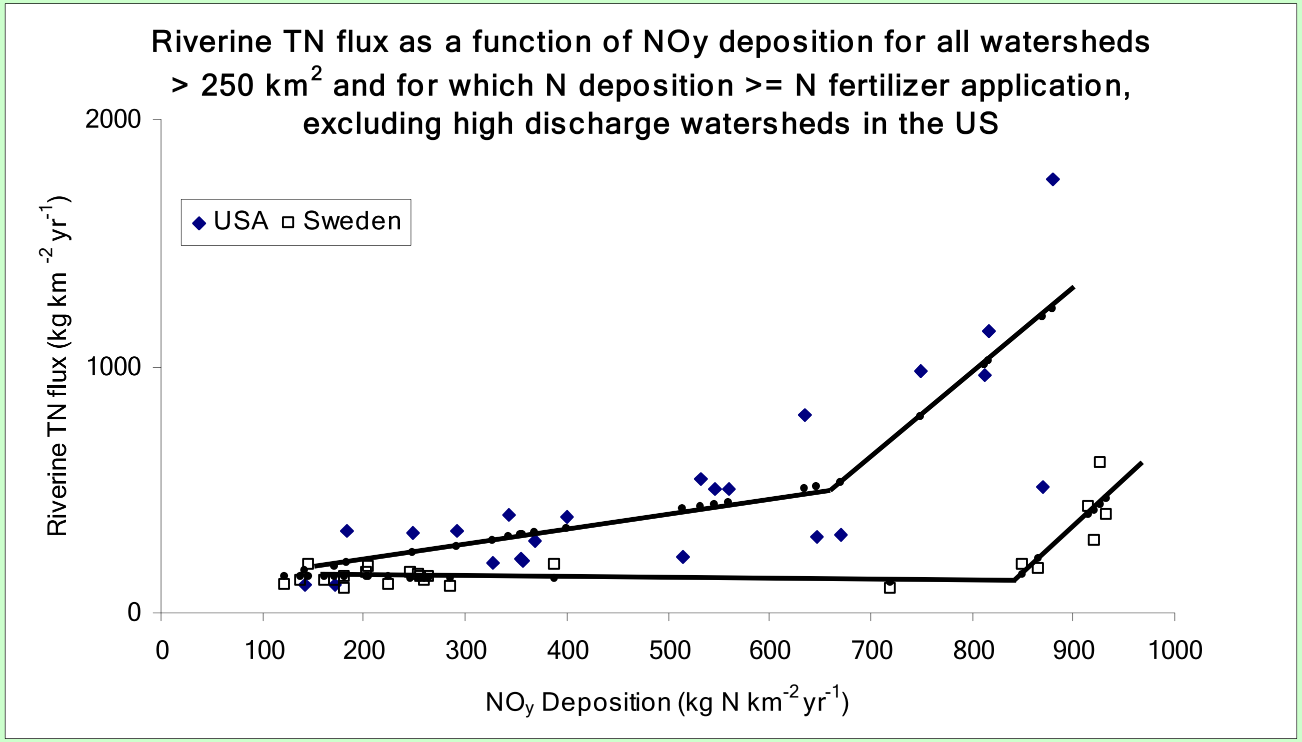
Predicted vs. Observed Riverine TN Flux for all watersheds >250 km^2





Riverine TN flux as a function of NOy deposition for all watersheds > 250 km2
y = 1.91x - 160
R2 = 0.25
Riverine TN flux (kg km -2 yr-1)
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
NOy Deposition (kg N km-2 yr-1)


Riverine TN flux as a function of NOy deposition for all watersheds > 250 km2 and for which N deposition >= N fertilizer application, excluding high discharge watersheds in the US
USA
y = 117.7e0.0024x
R2 = 0.66
Sweden
y = 109.15e0.0011x
R2 = 0.519
Riverine TN flux (kg km-2 yr-1)
NOy Deposition (kg N km-2 yr-1)
2000
1000
0
0
100
200
300
400
500
600
700
800
900
1000



The piecewise linear functions were fit by minimizing the sum of the squared differences between the data and the model.

The best fit:

	US	Sweden
r2	0.67	0.80
a	76.27	149.98
b	0.67	-0.04
c	3.39	3.64
x_t	670.73	838.91

$y = a + b\,x\,,\ x < x_t$ $\qquad$ $y = a + b\,x_t + c\,(x - x_t),\ x >= x_t$

parameters:

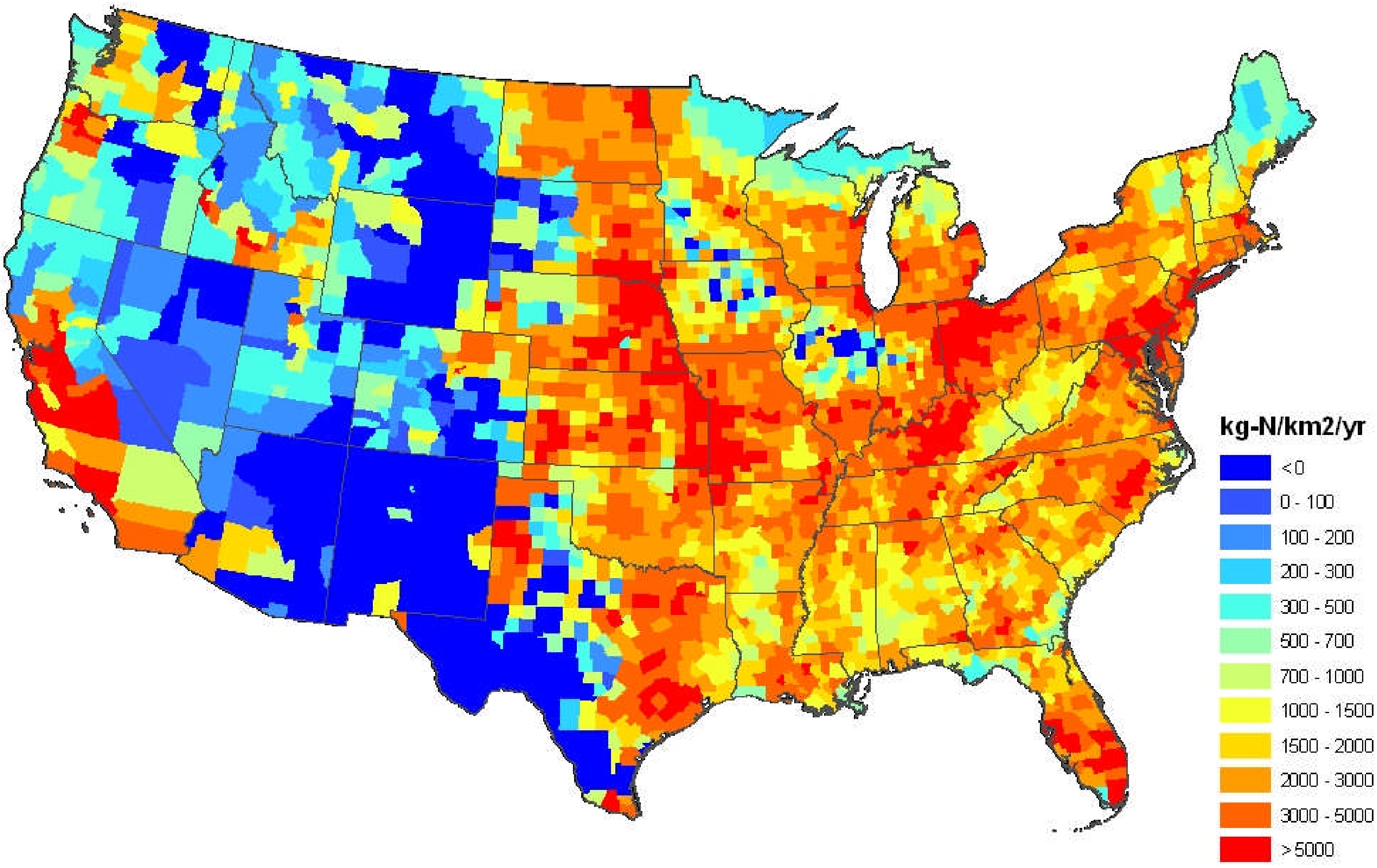
a y intercept

b slope of the first piecewise segment, $x < x_t$

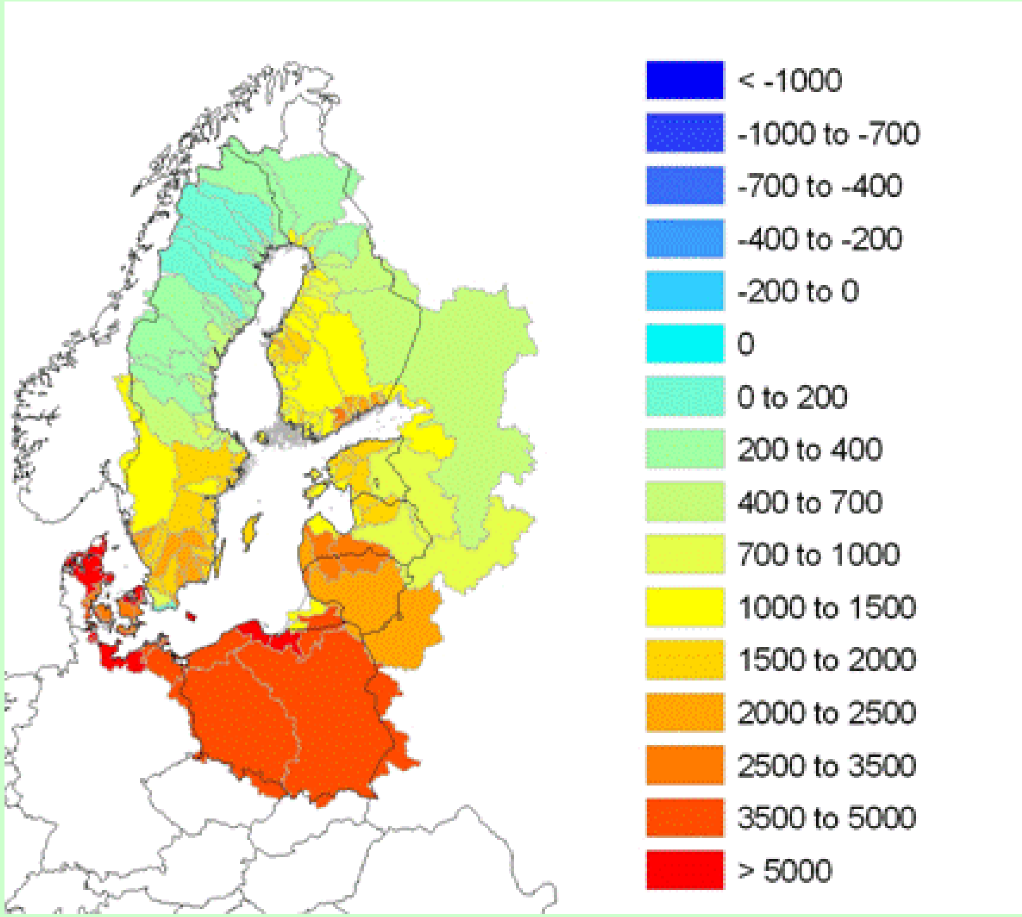
c slope of the second piecewise segment, $x >= x_t$

x_t threshold value of x at which the slope changes

Net anthropogenic nitrogen inputs (NANI) by county in the United States for 2002

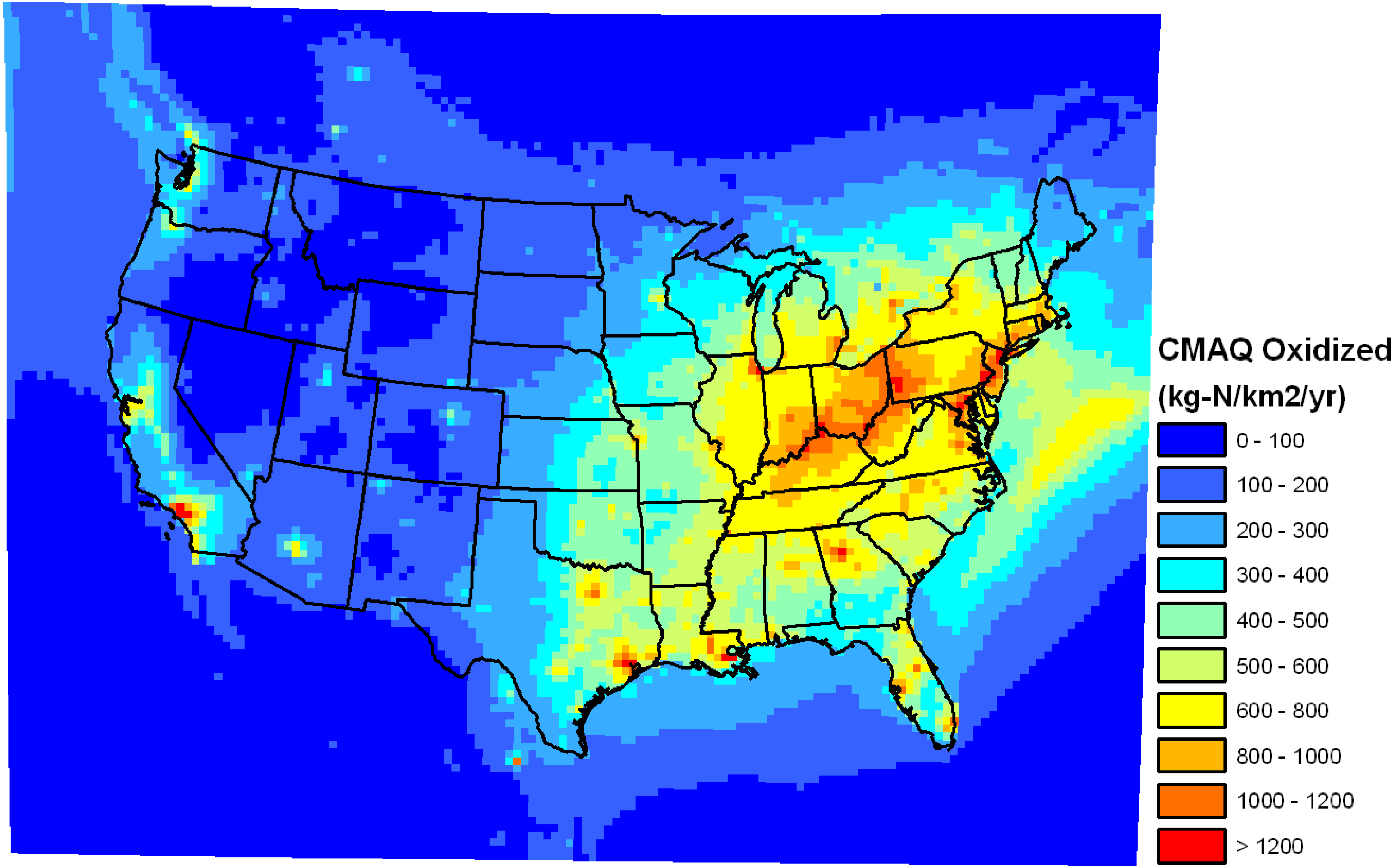


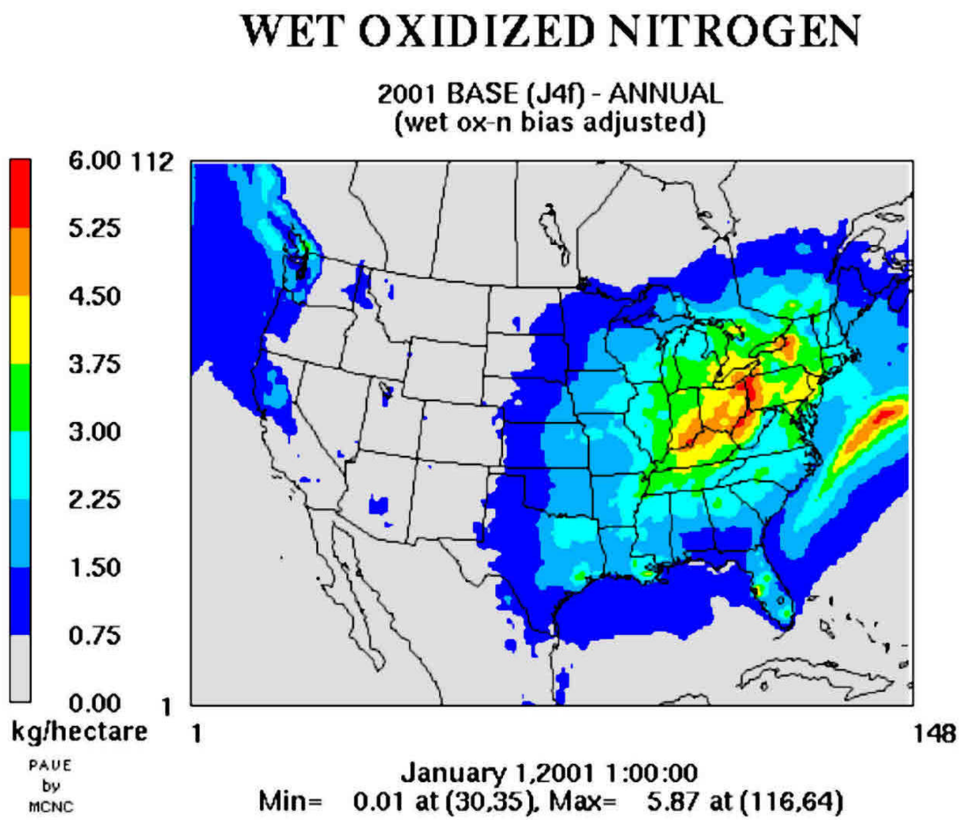
NANI (kg/km2/yr)
Baltic Basin

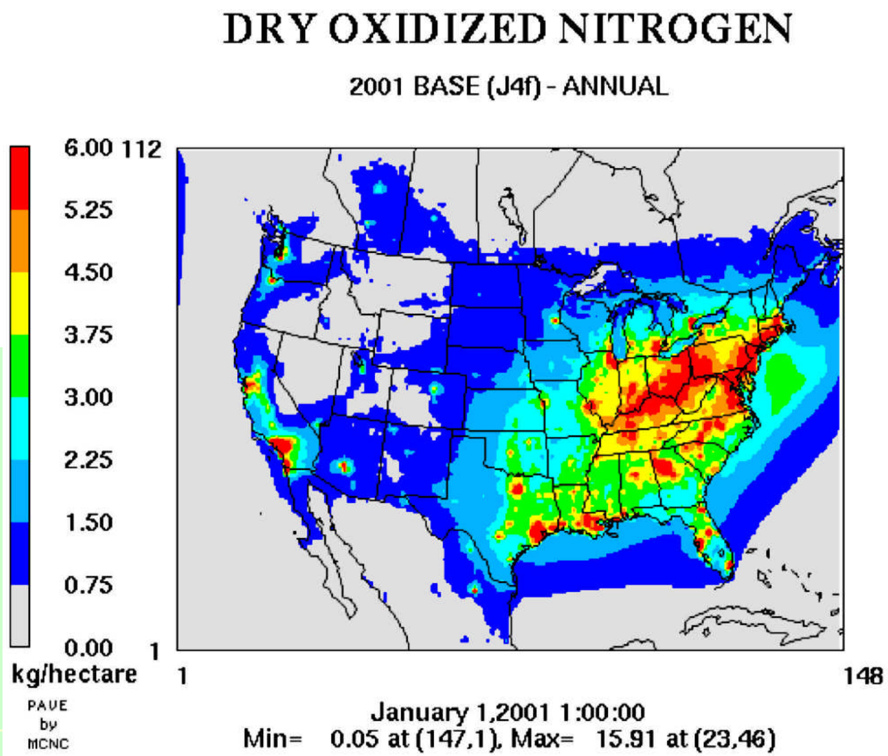


~2000

Atmospheric Deposition (wet + dry) of Oxidized Nitrogen estimated from CMAQ model

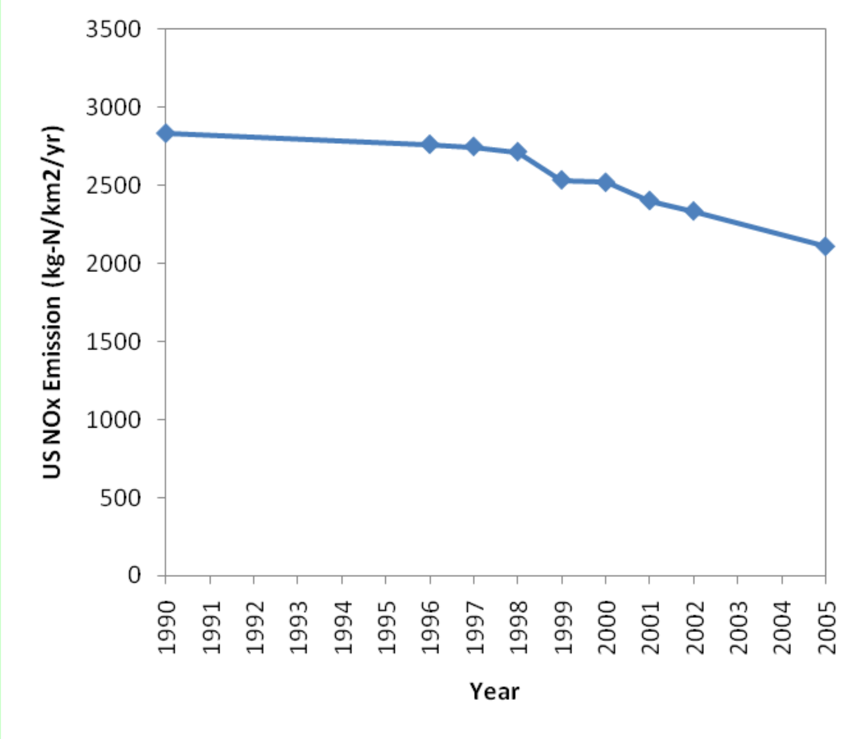




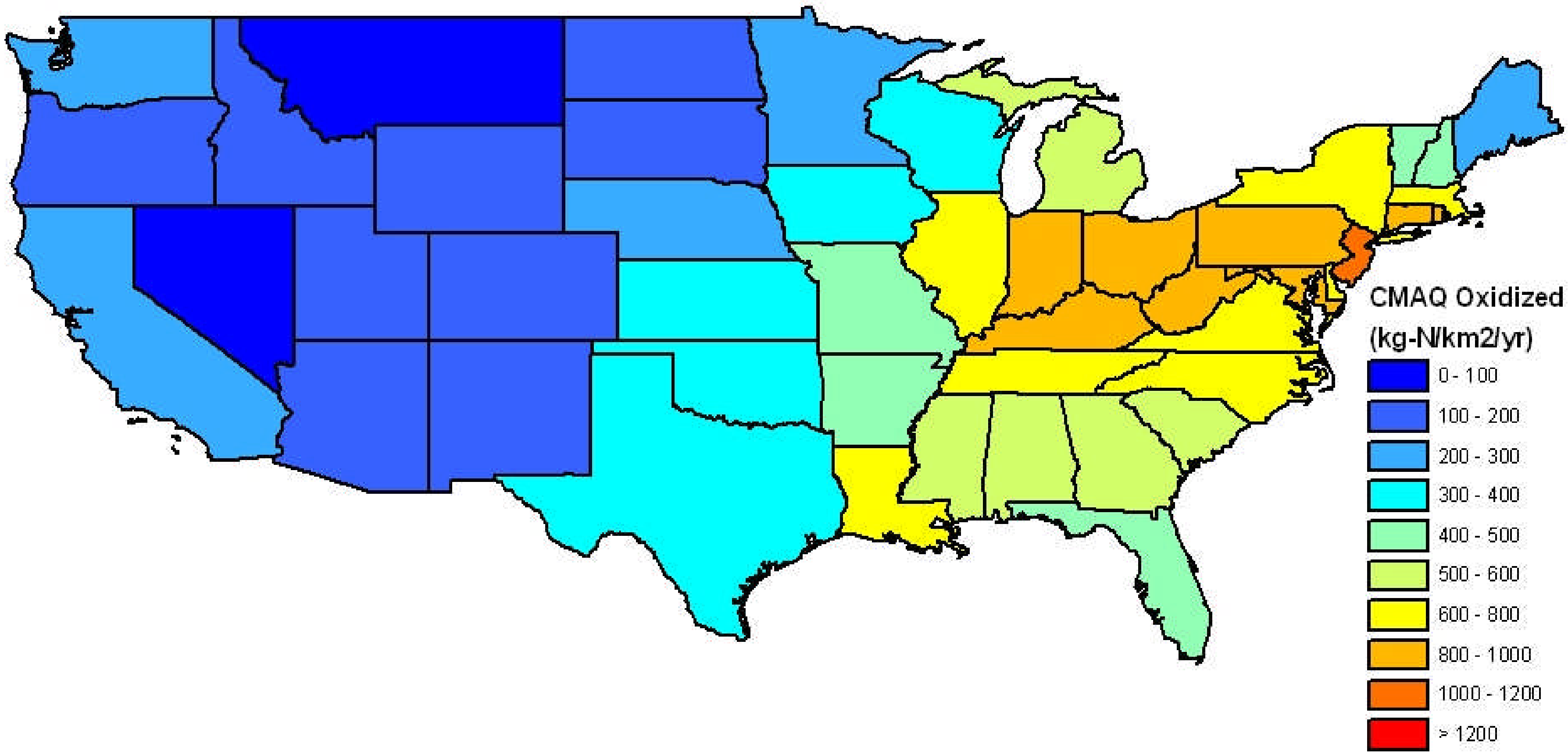


Beta version of CMAQ model (courtesy of Robbin Dennis, NOAA/EPA)

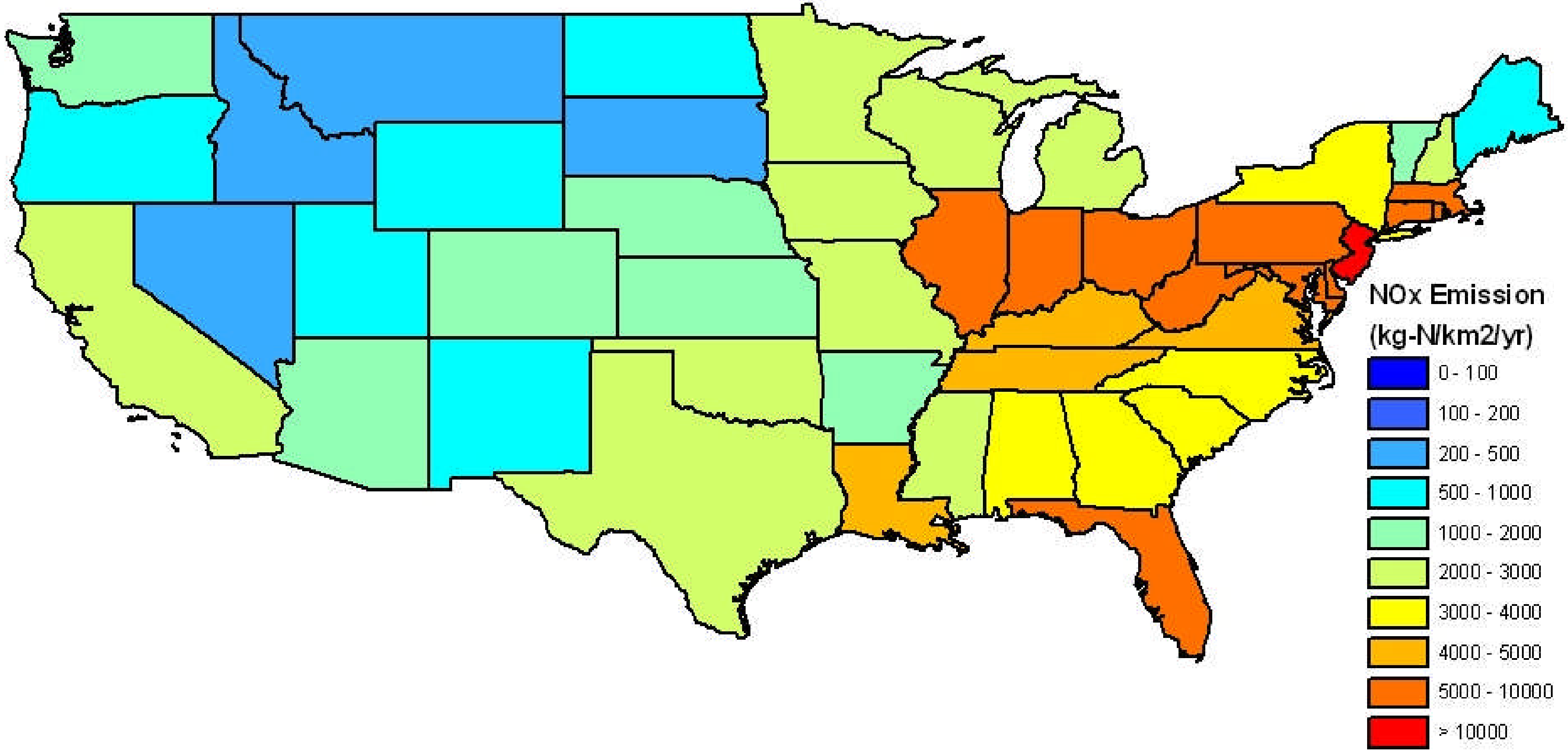
US oxidized N emissions



2002 estimated state level oxidized N deposition
(EPA CMAQ model estimates)



2002 state level oxidized N emissions



Summarizing complex models with relatively simple statistical relationships

Analyze relationship between state-level N emission and deposition components with ordinary least-squares regressions:

Using state-level data:

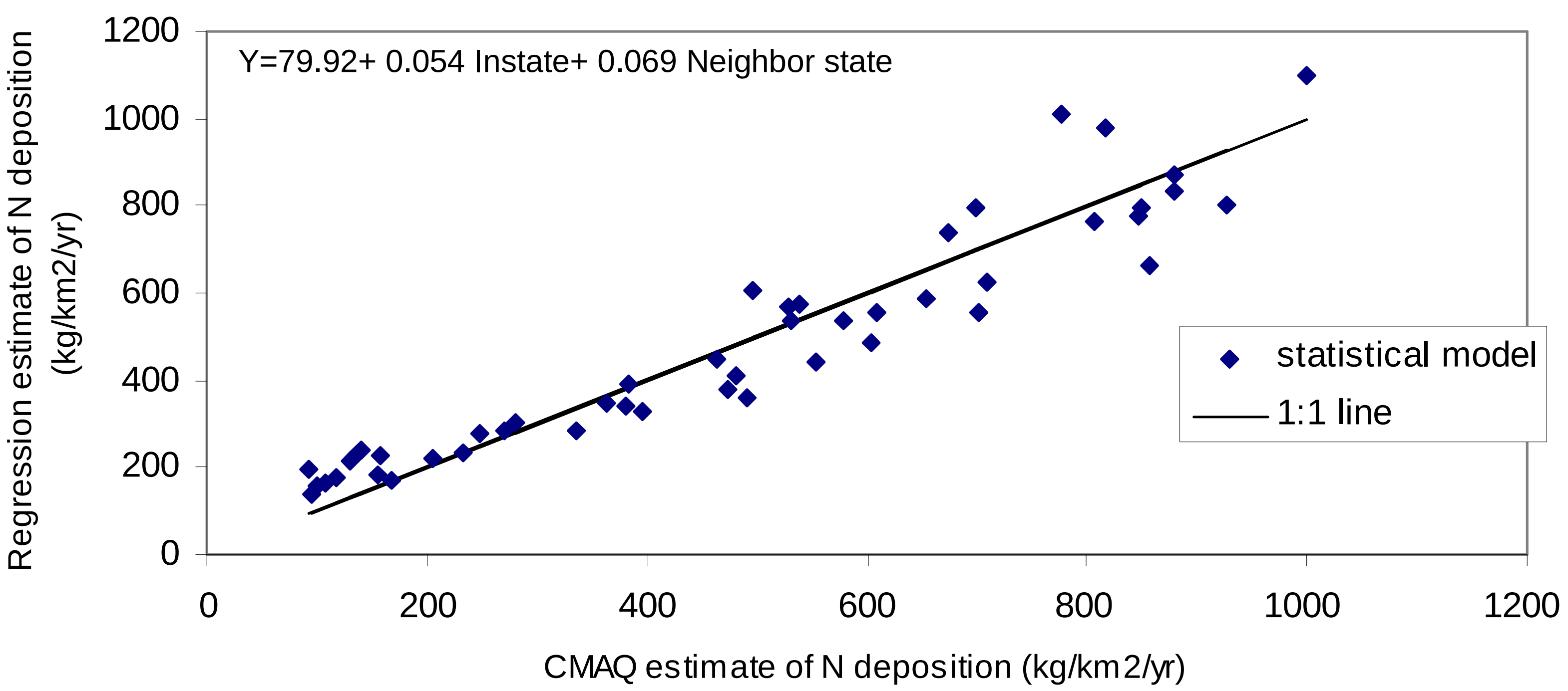
Oxidized N: $Ndep_{ox}$ = a + b *NO_X(instate)+ c NO_X(neighbor states)

NO_x = Oxidized N emissions (kg N km^{-2} yr^{-1})

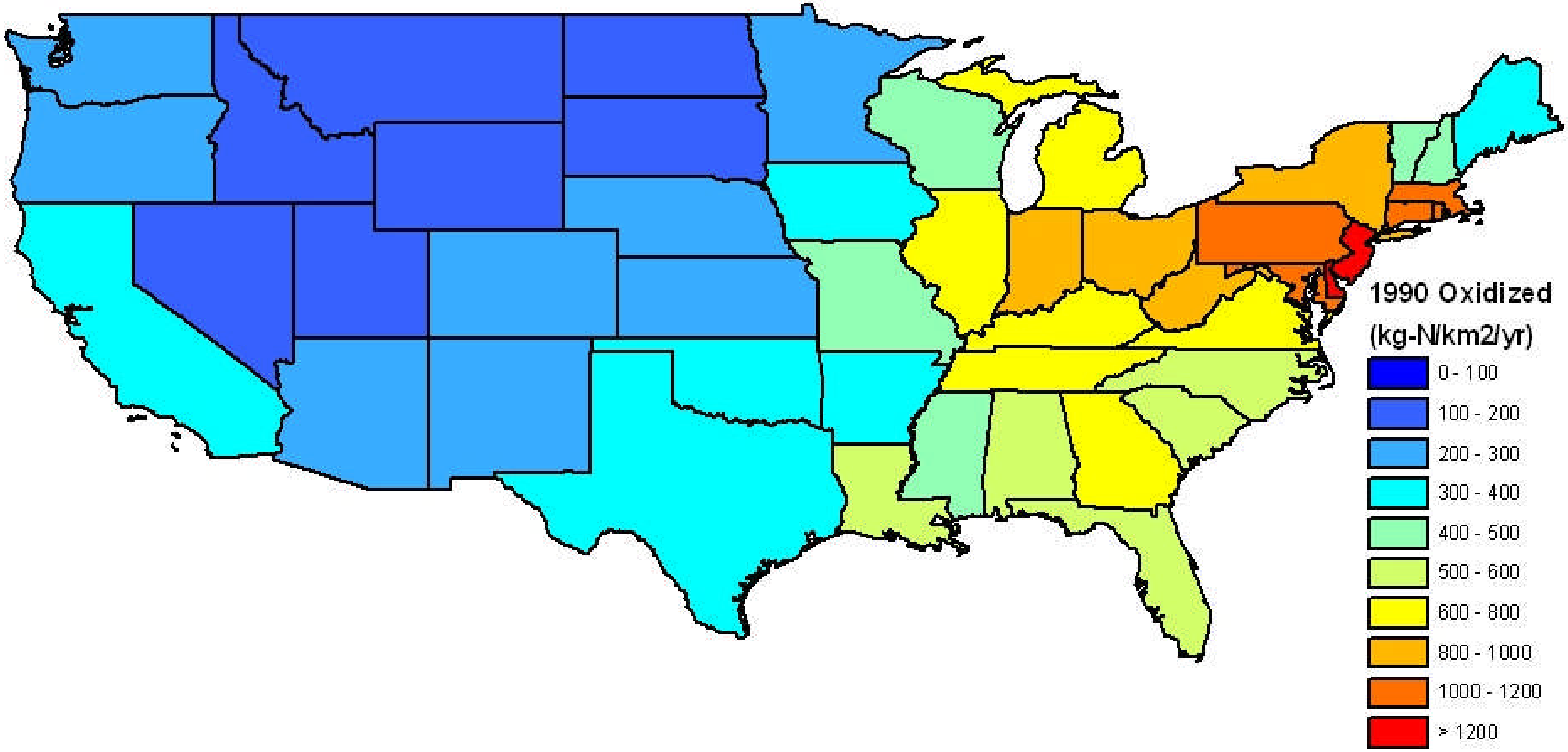
Oxidized N: a=79.92; b=0.0537; c=0.0688; r^2=0.90

* not significantly different from zero

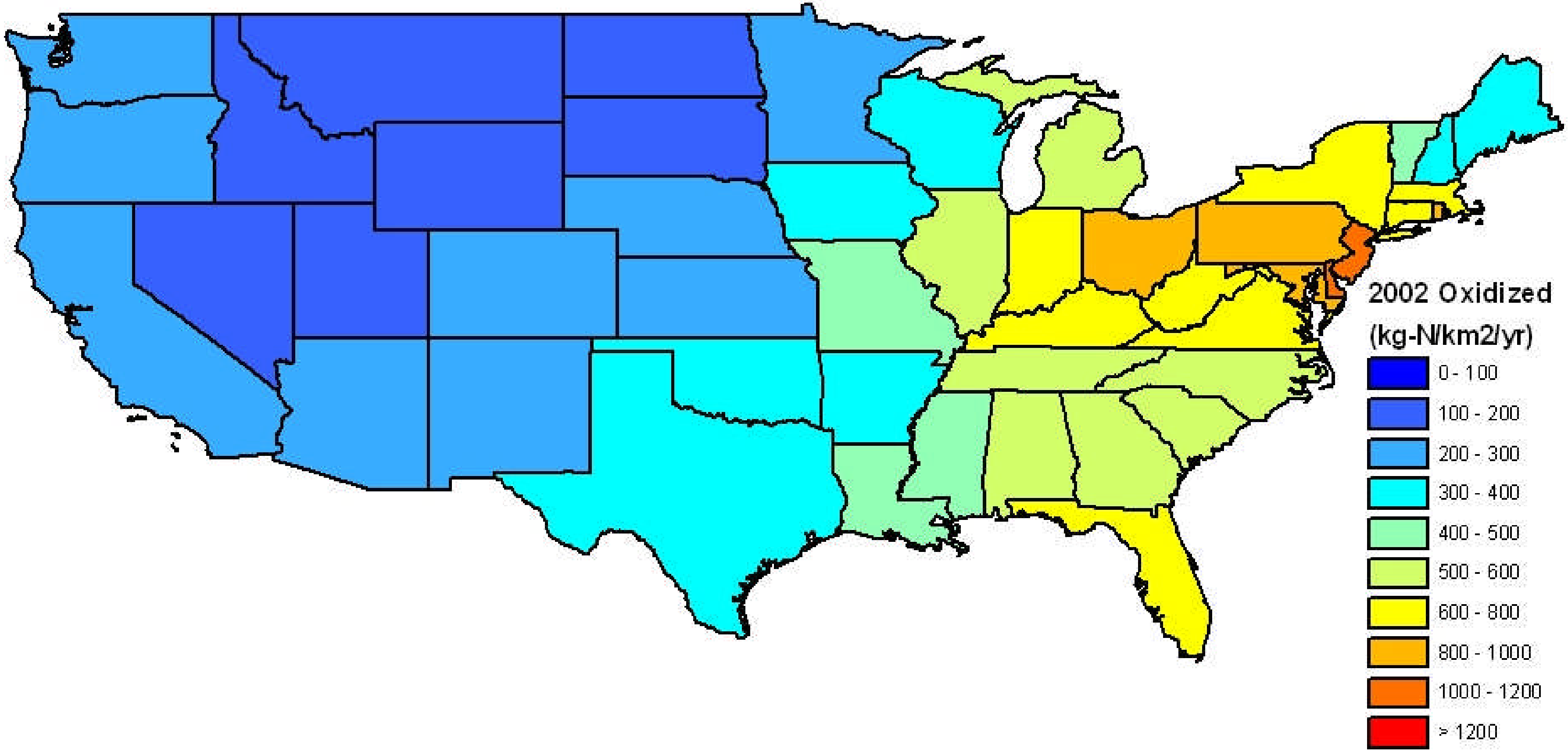
Estimated deposition of **oxidized** N from instate and neighbor state oxidized N emissions



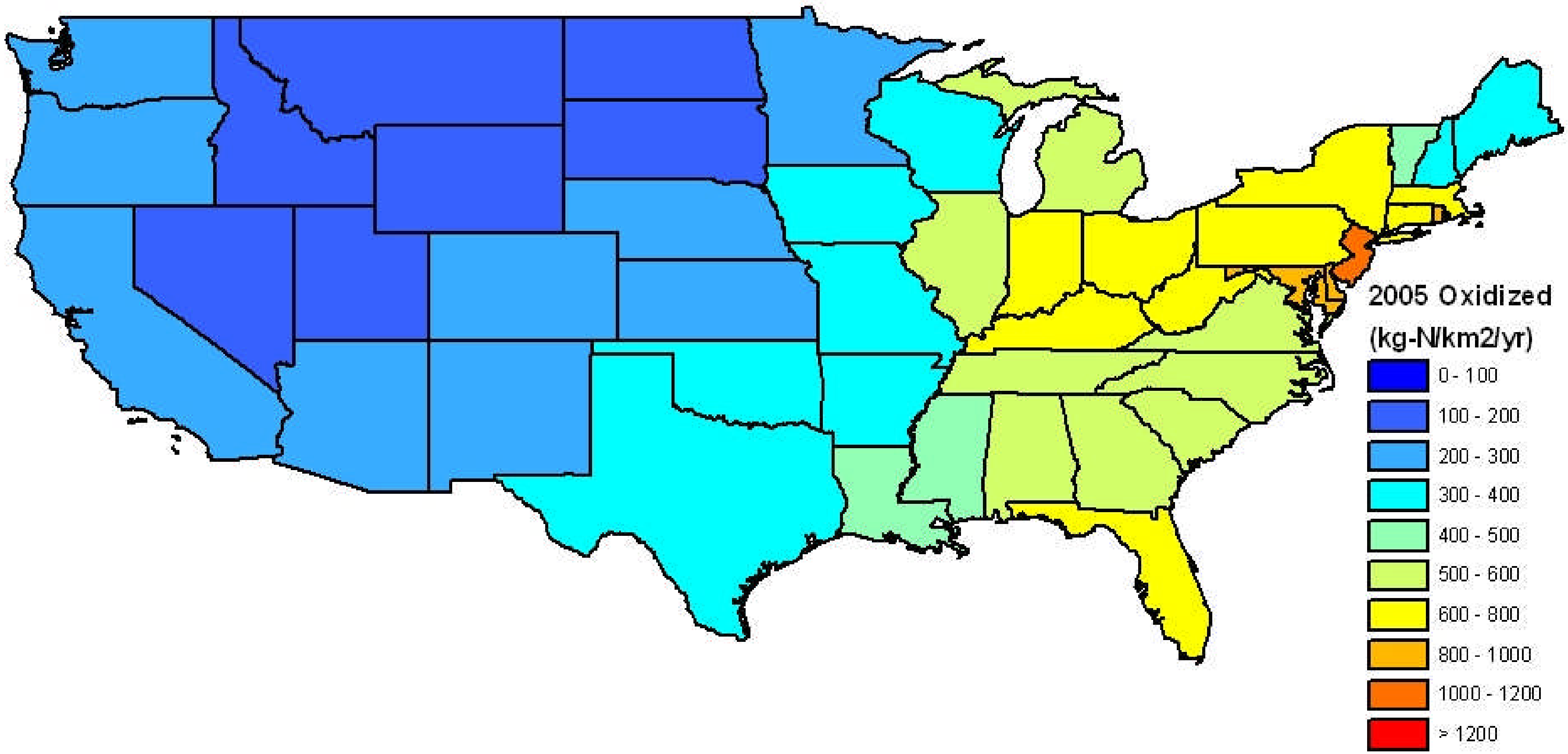
1990 predicted state level oxidized N deposition (from regression)



2002 predicted state level oxidized N deposition
(from regression)



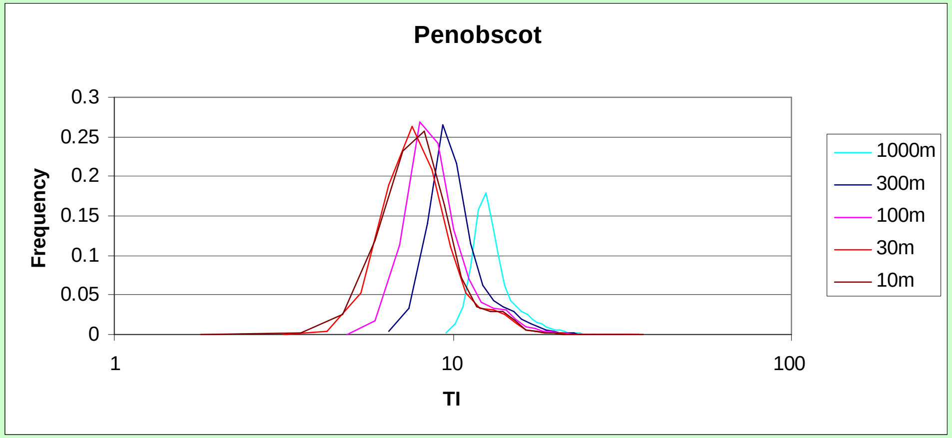
2005 predicted state level oxidized N deposition
(from regression)

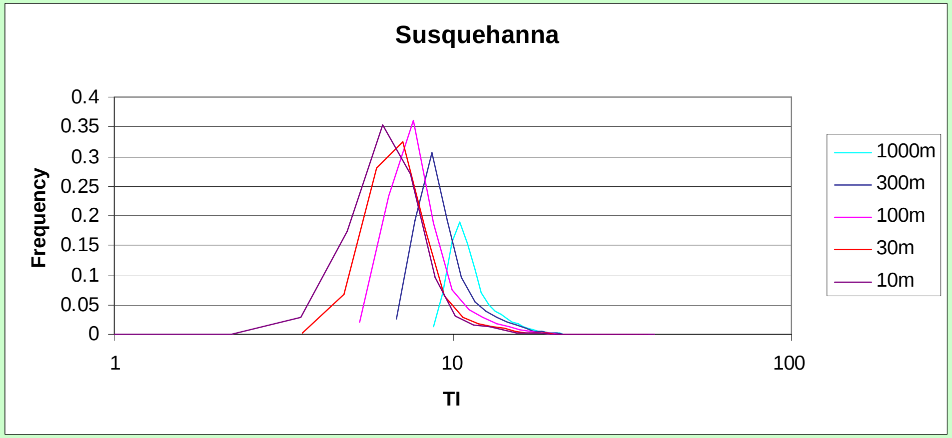


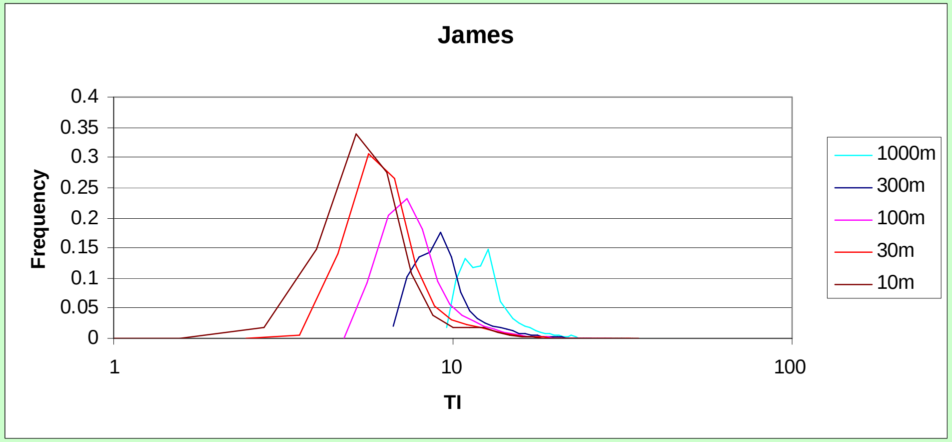
Topographic Index (Bevens and Kirkby, 1979):

$$TI_i = \ln\left(\frac{A_i}{s_i}\right)$$

Where: TI_i is the topographic index of grid cell i of the watershed, A_i is the contributing area of grid cell i of the watershed per unit contour length, s_i is the slope of grid cell i of the watershed

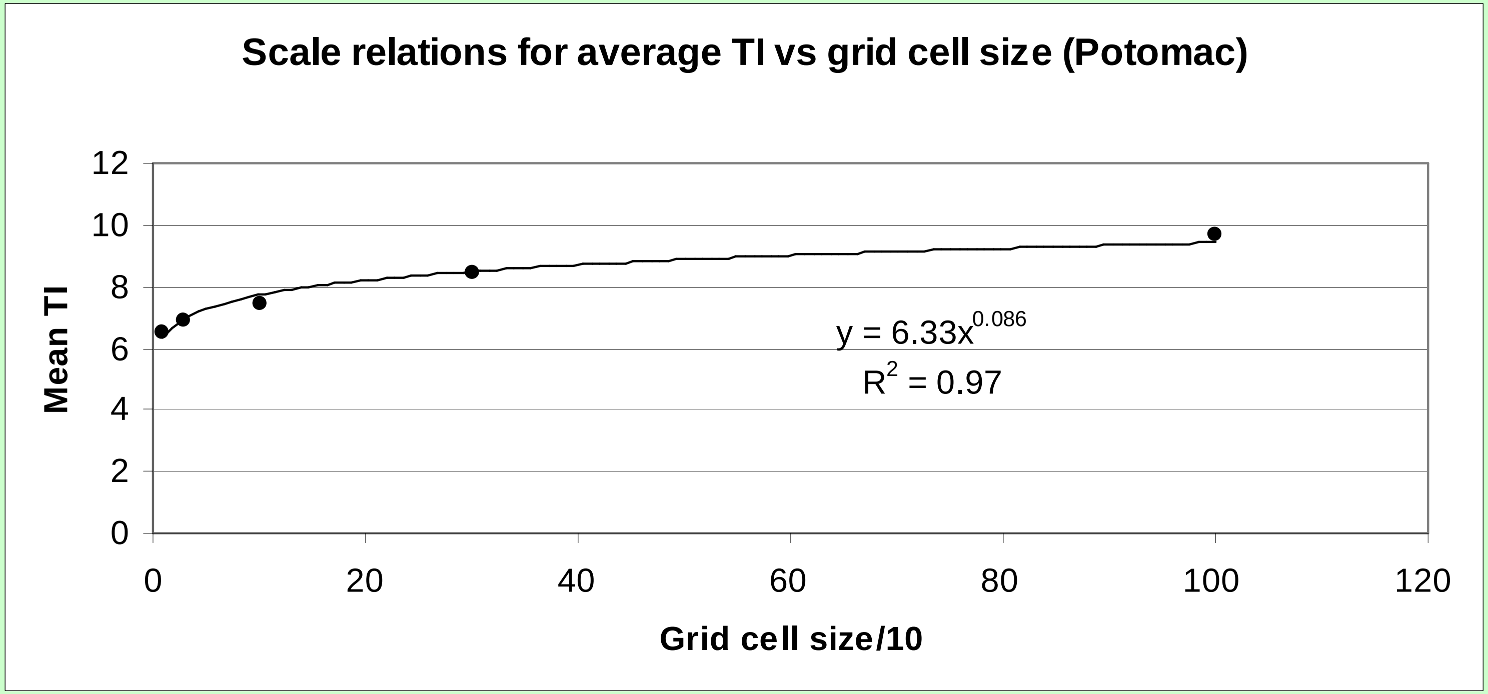




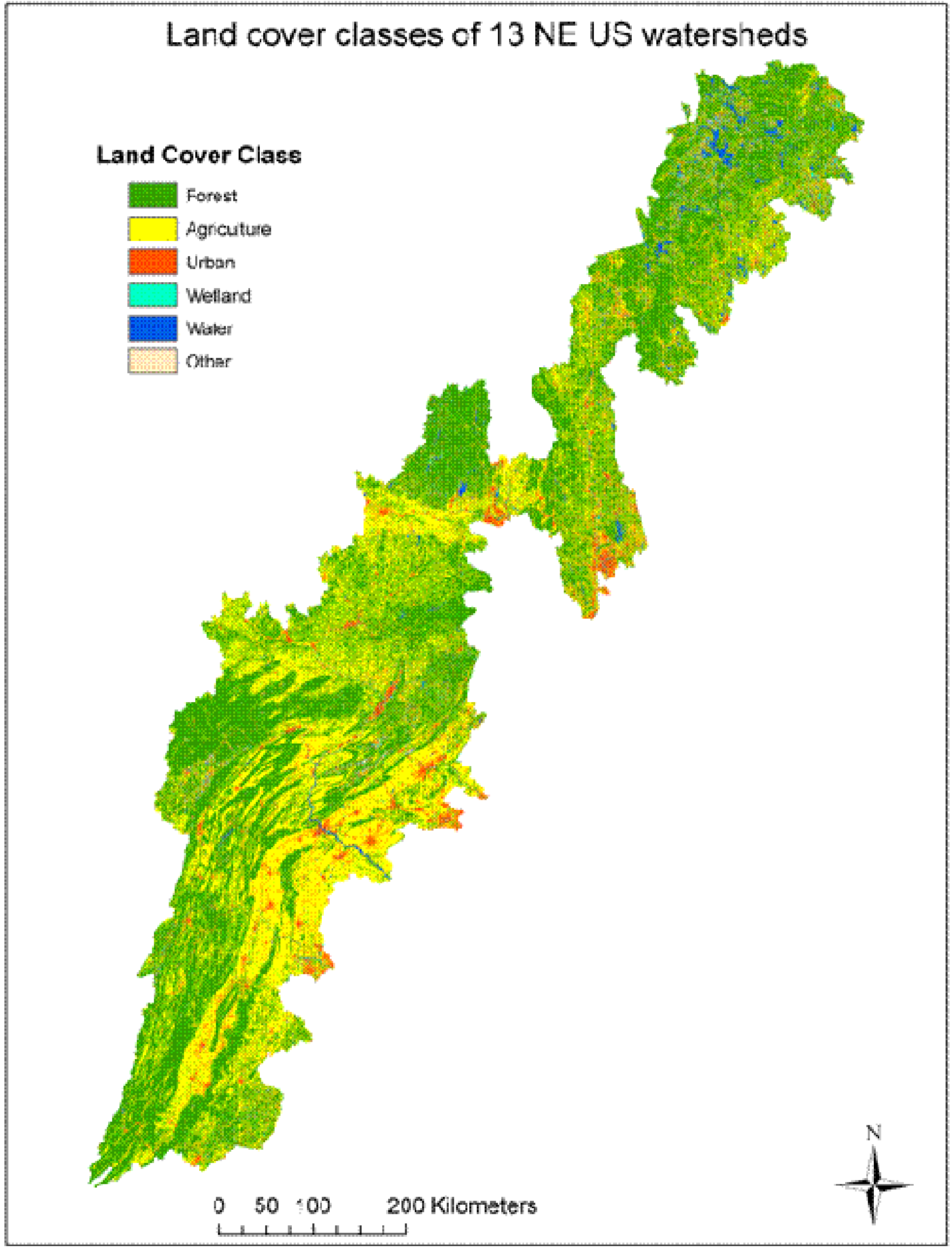


TI is scale-dependent.

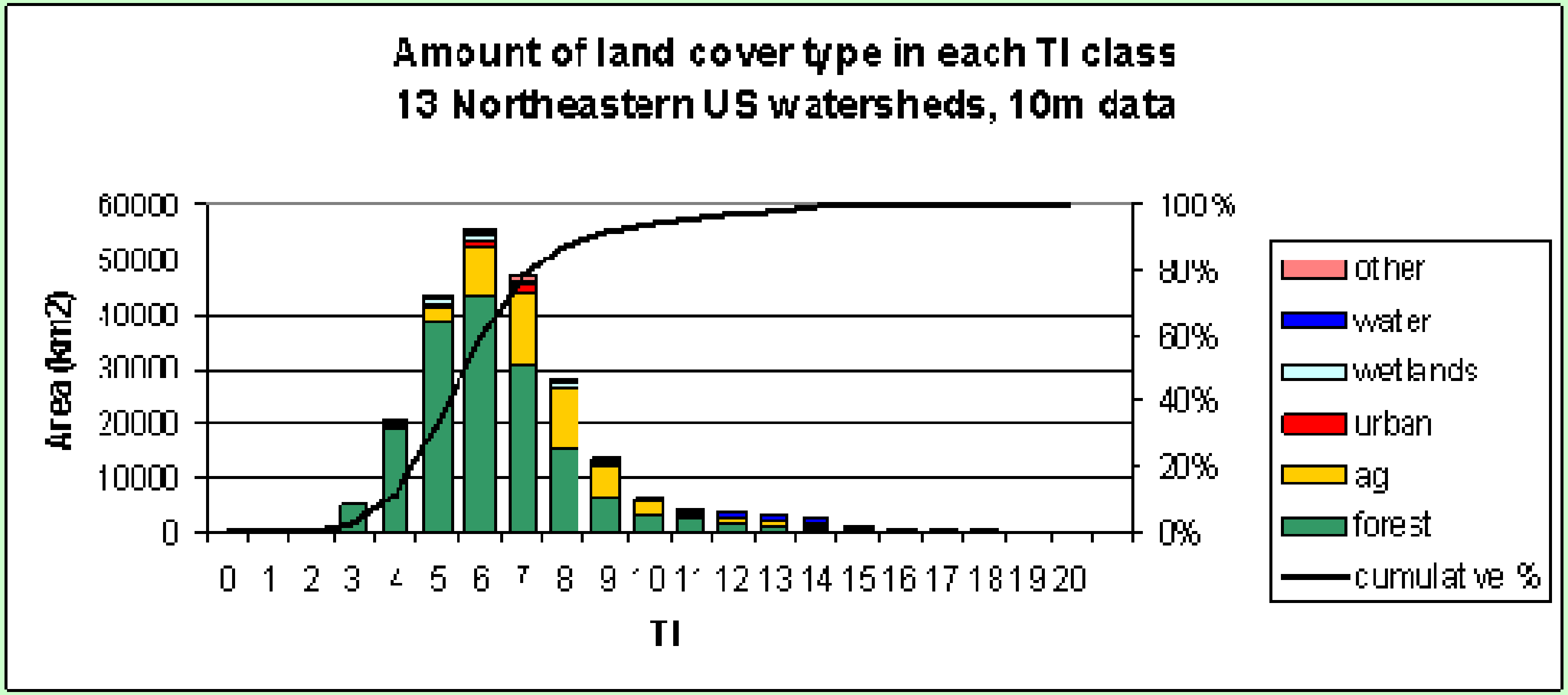
The distributions at the highest resolution are lognormal and have lower mean TI (are drier) than distributions calculated at coarser scale.



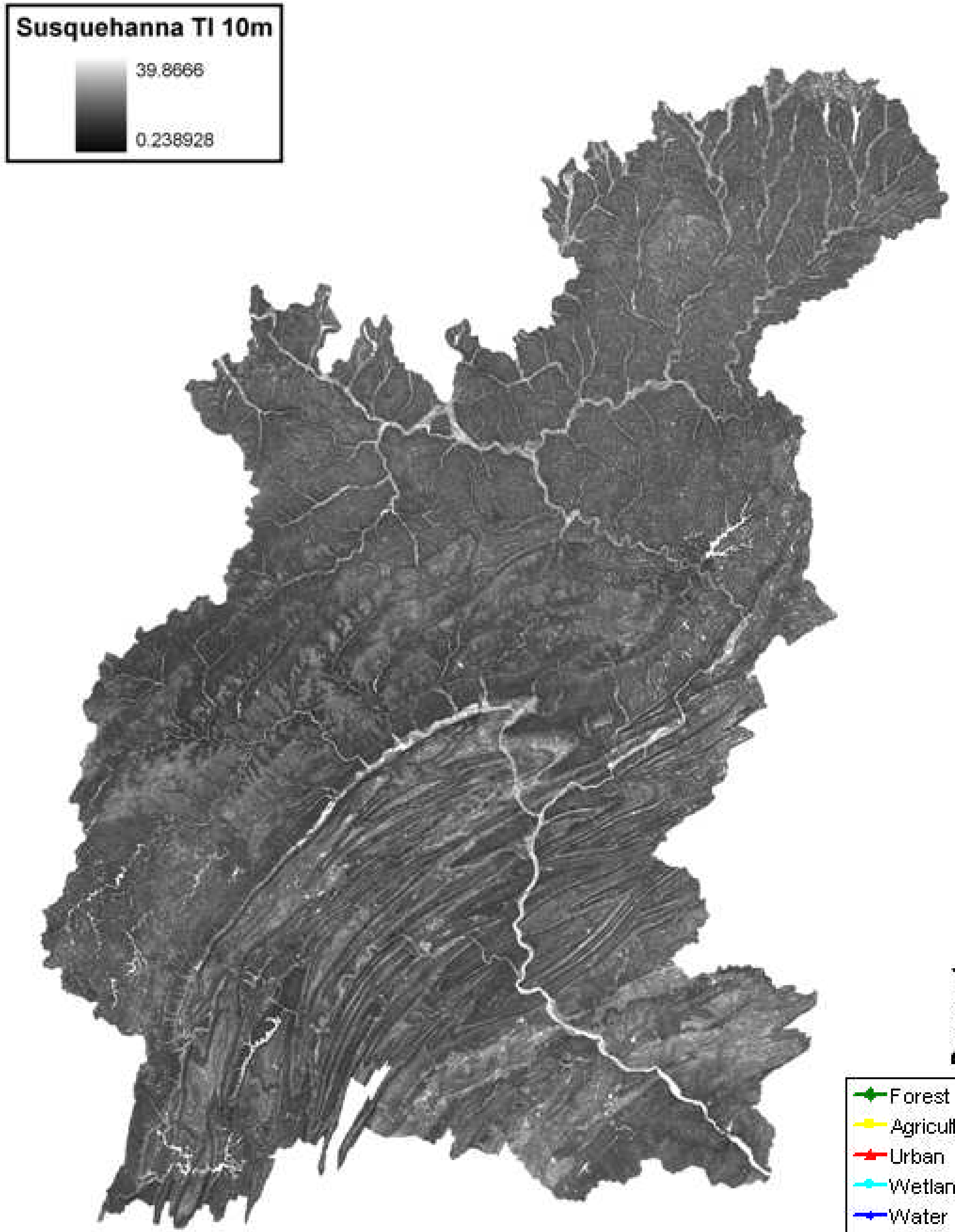
When necessary (ie in watersheds lacking fine-scale data), it may be possible to scale coarse-scale information to obtain statistics appropriate to fine-scale resolution based on scaling relations developed for these watersheds.

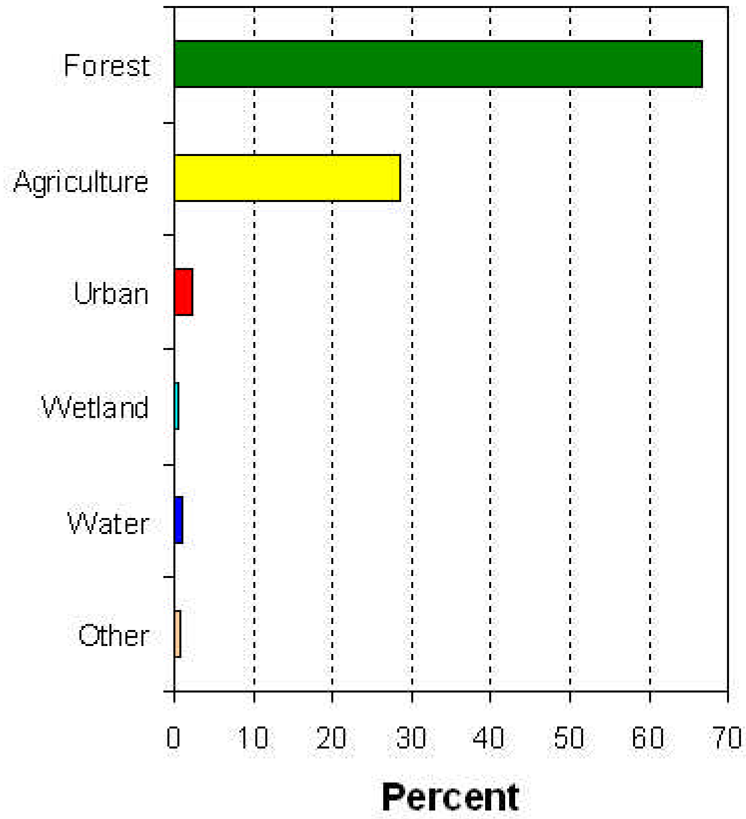


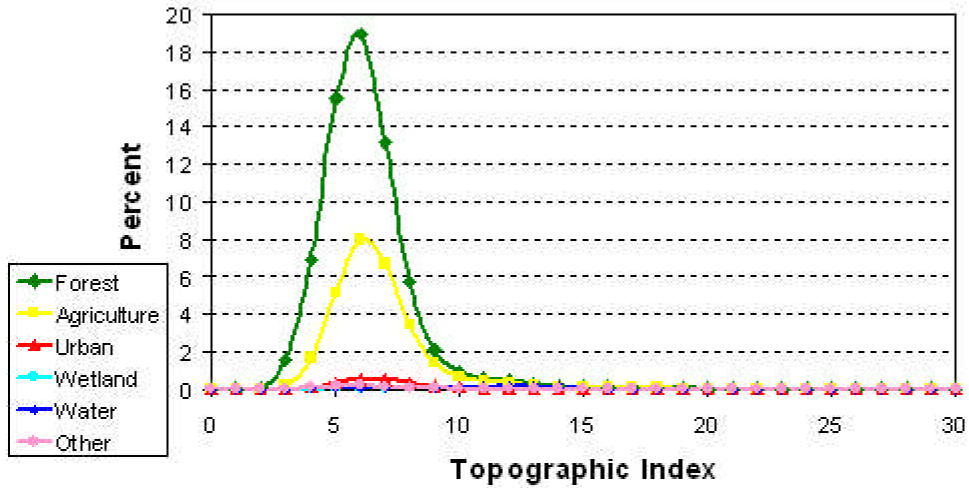
Land cover classes of 13 NE US watersheds
Land Cover Class
Forest
Agriculture
Urban
Wetland
Water
Other
0 50 100 200 Kilometers
N

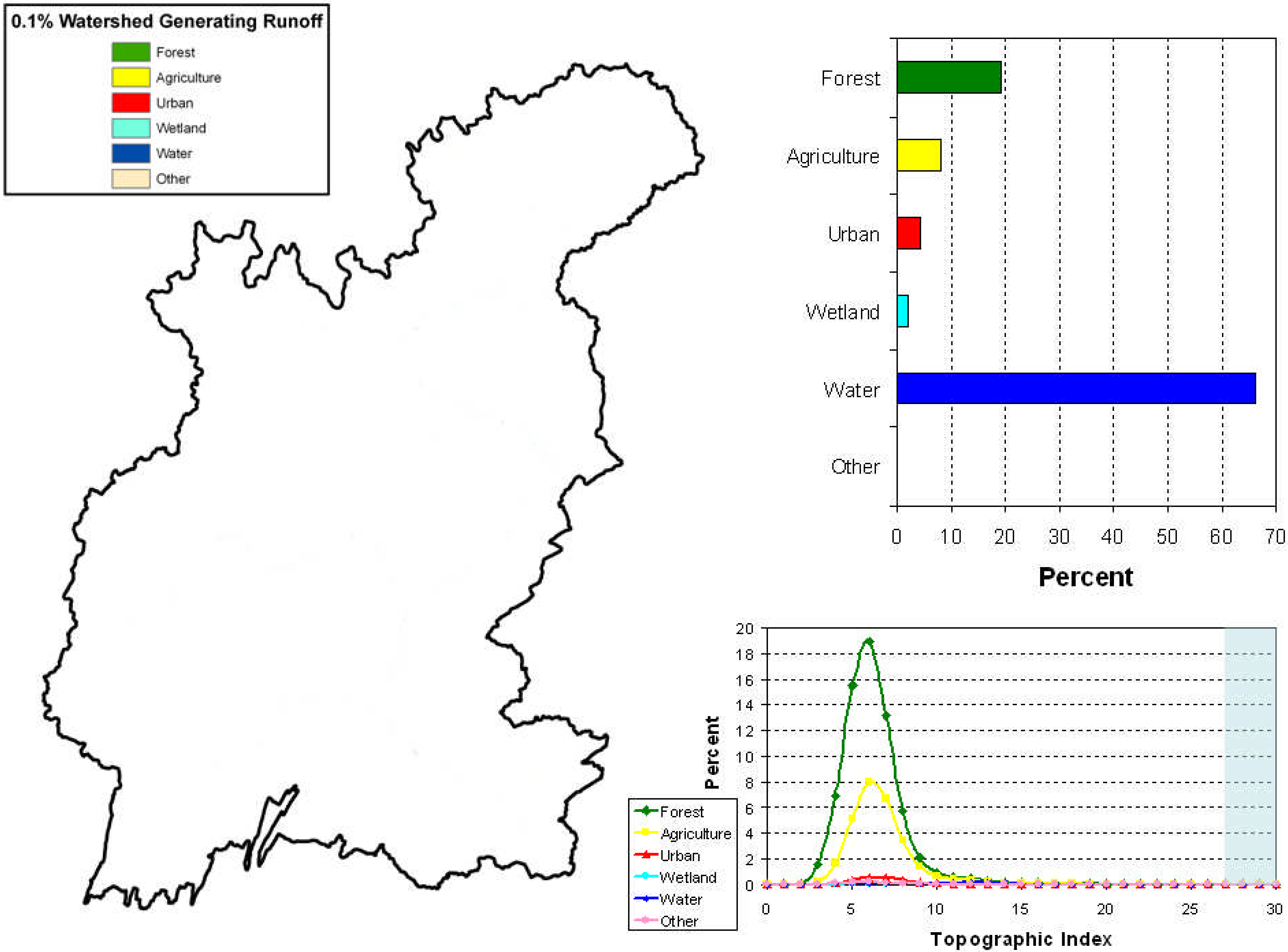


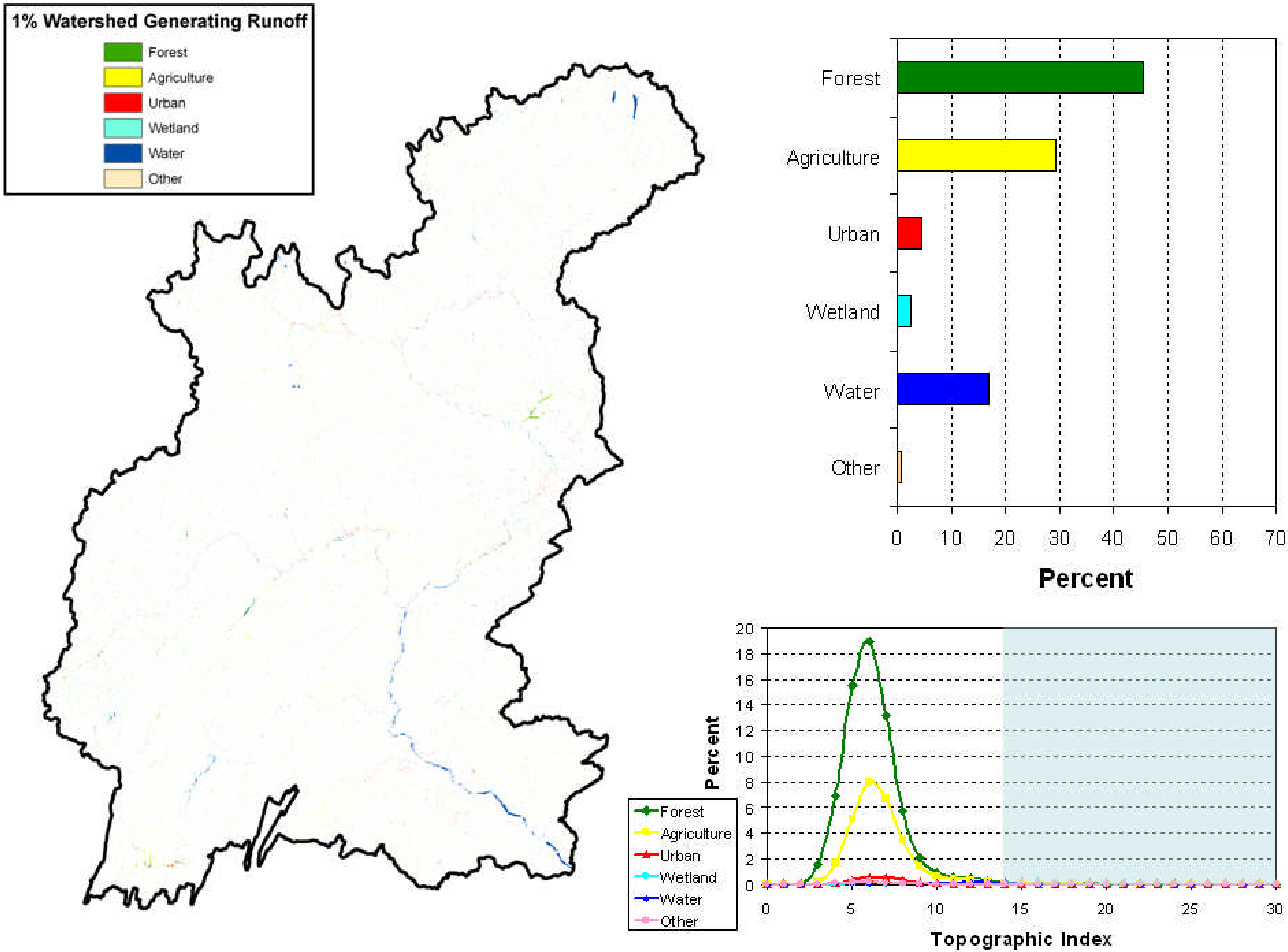
Distribution of topographic index over the 13 watersheds analyzed at 10m resolution. While a small proportion of large TI values (ie > 20) are present in the region, 99.9% of the occurrences fall between 0 and 20. High values of TI indicate wetter areas (with higher runoff potential); low values represent drier areas.

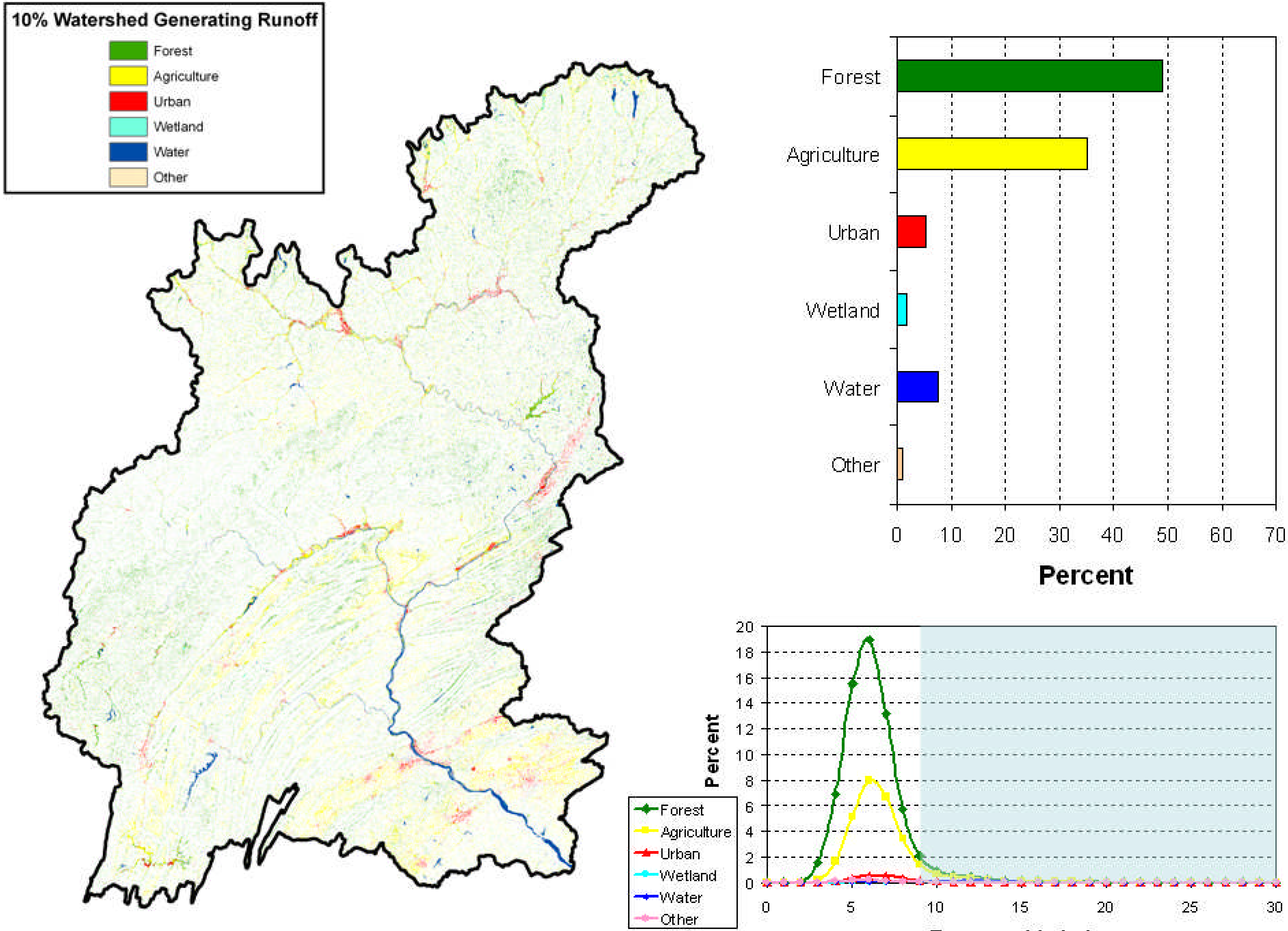

Susquehanna TI 10m
39.8666
0.238928


Forest
Agriculture
Urban
Wetland
Water
Other
0
10
20
30
40
50
60
70
Percent

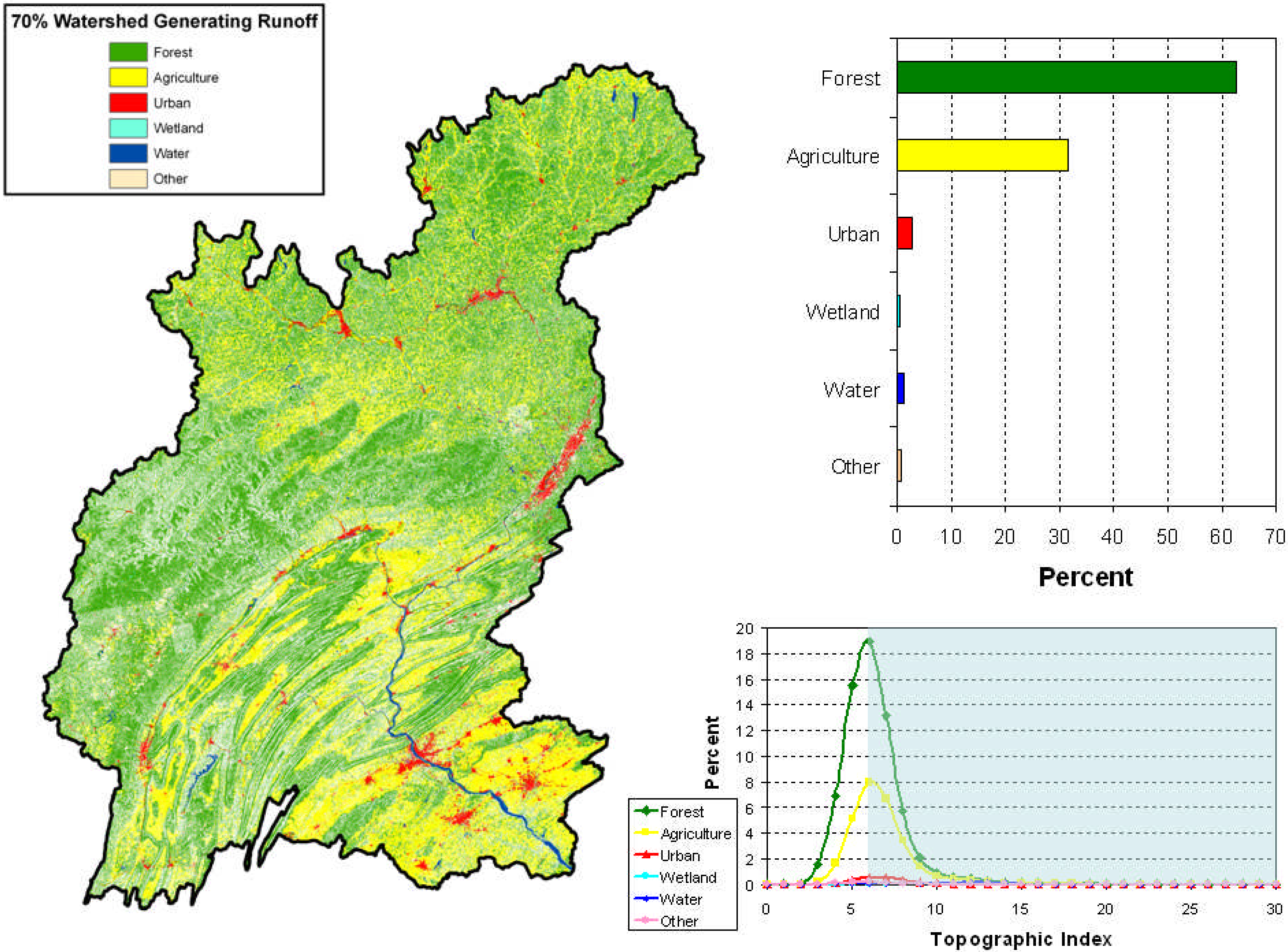

Percent
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
Topographic Index
Forest
Agriculture
Urban
Wetland
Water
Other


0.1% Watershed Generating Runoff
Forest
Agriculture
Urban
Wetland
Water
Other
Forest
Agriculture
Urban
Wetland
Water
Other
0
10
20
30
40
50
60
70
Percent
20
18
16
14
12
10
8
6
4
2
0
Percent
Forest
Agriculture
Urban
Wetland
Water
Other
0
5
10
15
20
25
30
Topographic Index

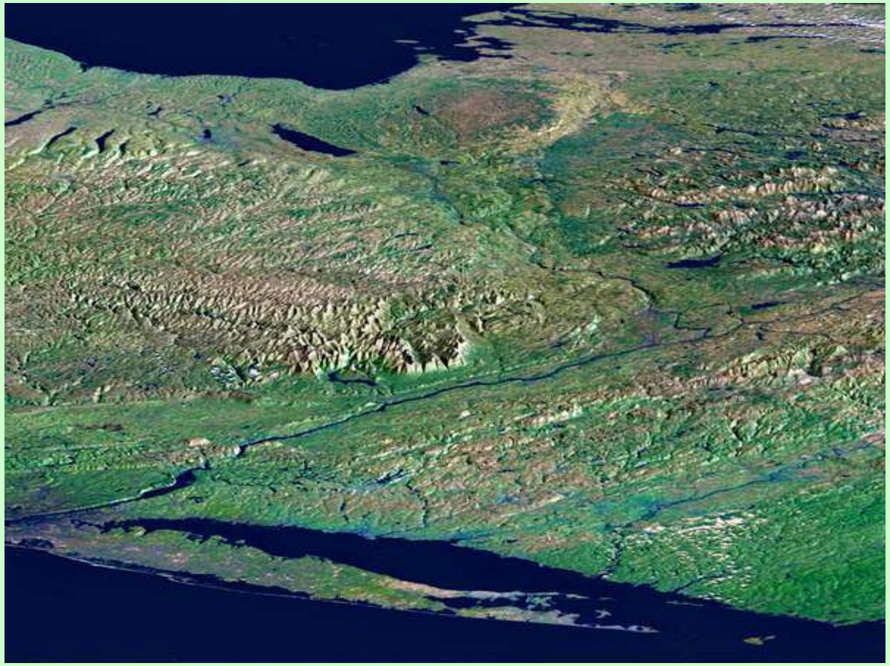

1% Watershed Generating Runoff
Forest
Agriculture
Urban
Wetland
Water
Other
Forest
Agriculture
Urban
Wetland
Water
Other
0 10 20 30 40 50 60 70
Percent
20 18 16 14 12 10 8 6 4 2 0
Percent
Forest
Agriculture
Urban
Wetland
Water
Other
0 5 10 15 20 25 30
Topographic Index



10% Watershed Generating Runoff
Forest
Agriculture
Urban
Wetland
Water
Other
Forest
Agriculture
Urban
Wetland
Water
Other
0 10 20 30 40 50 60 70
Percent
20
18
16
14
12
10
8
6
4
2
0
Percent
Forest
Agriculture
Urban
Wetland
Water
Other
0 5 10 15 20 25 30
Topographic Index

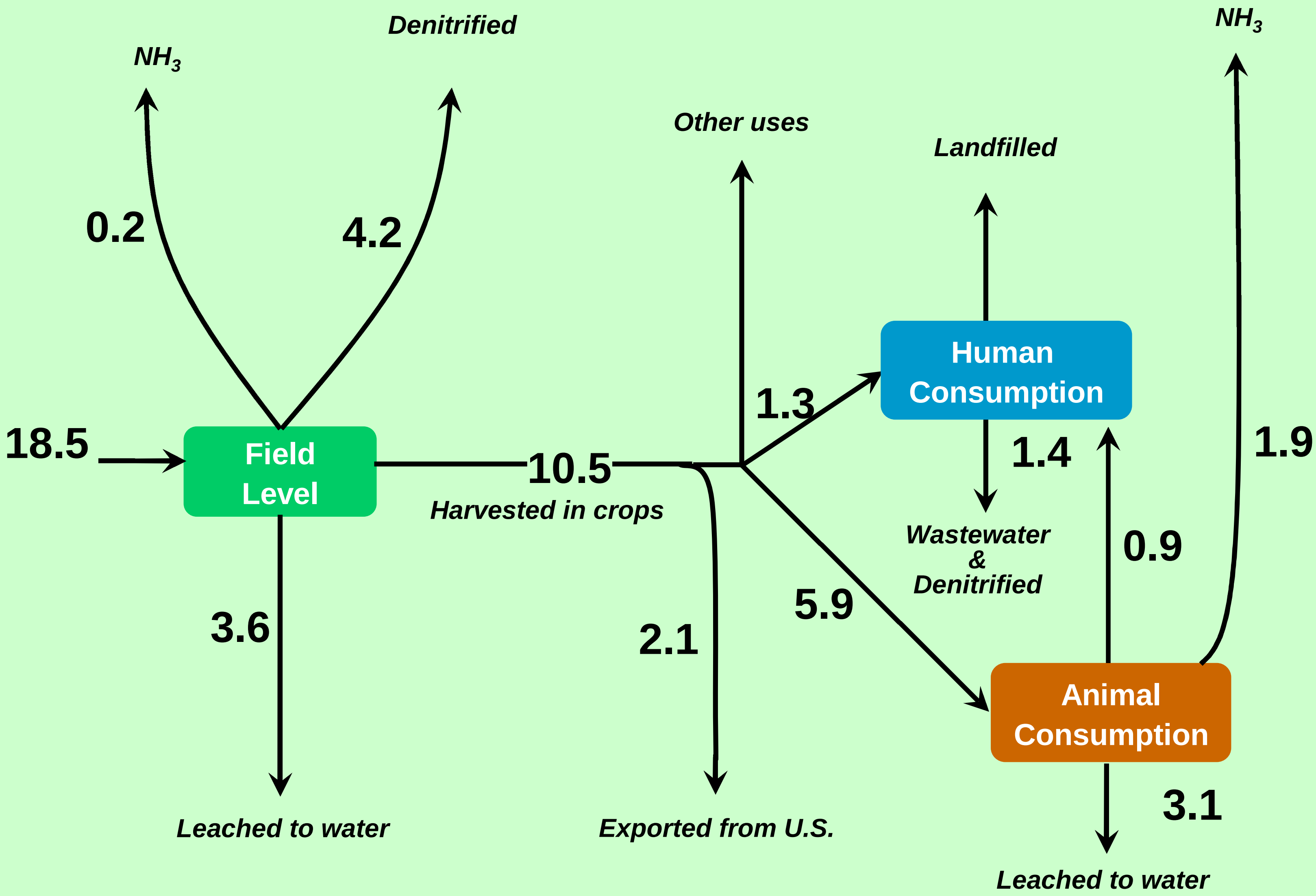

70% Watershed Generating Runoff
Forest
Agriculture
Urban
Wetland
Water
Other
Forest
Agriculture
Urban
Wetland
Water
Other
0
10
20
30
40
50
60
70
Percent
20
18
16
14
12
10
8
6
4
2
0
Percent
0
5
10
15
20
25
30
Topographic Index
Forest
Agriculture
Urban
Wetland
Water
Other

Cornell University
College of Agriculture and Life Sciences



Coastal Hypoxia Research Program

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



(Howarth et al. 2002)