Rapid shift in nitrogen inputs and fluxes across the contiguous United States

This research highlights the capacity for society to quickly change the source and magnitude of N inputs and fluxes across the landscape through market, regulatory, and policy actions.

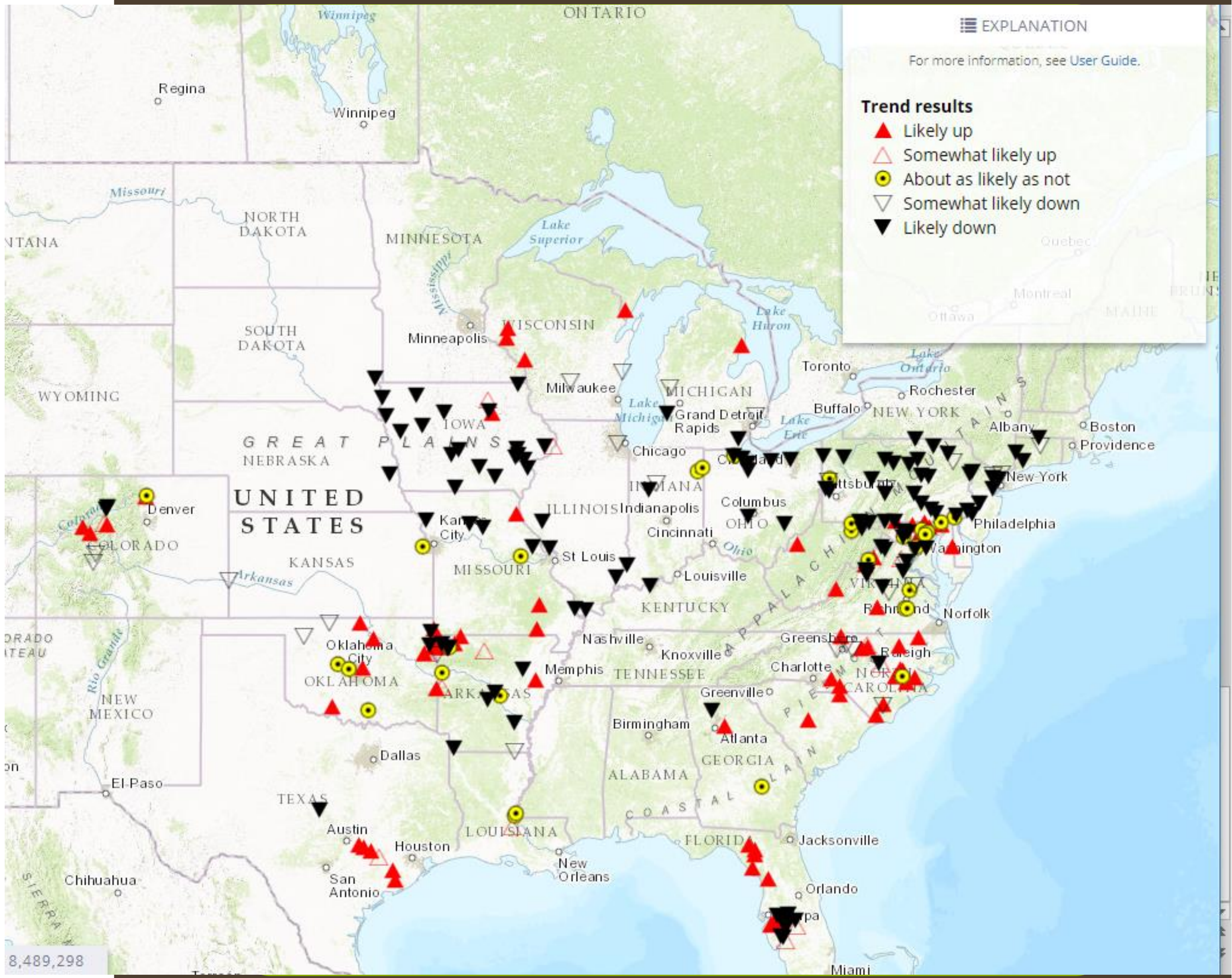
Robert D. Sabo, Christopher M. Clark, and many others!

Good news for N management in USA!

- Increased cropland nitrogen use efficiency across the United States (Zhang *et al.*, 2015)
- Decreased NO_x deposition stemming from stationary and mobile emissions (Lloret & Valiela, 2016)
- Lots of wastewater treatment plant upgrades
- Coordinated efforts to implement BMPs (García *et al.*, 2015)

Nitrogen management is still a national challenge

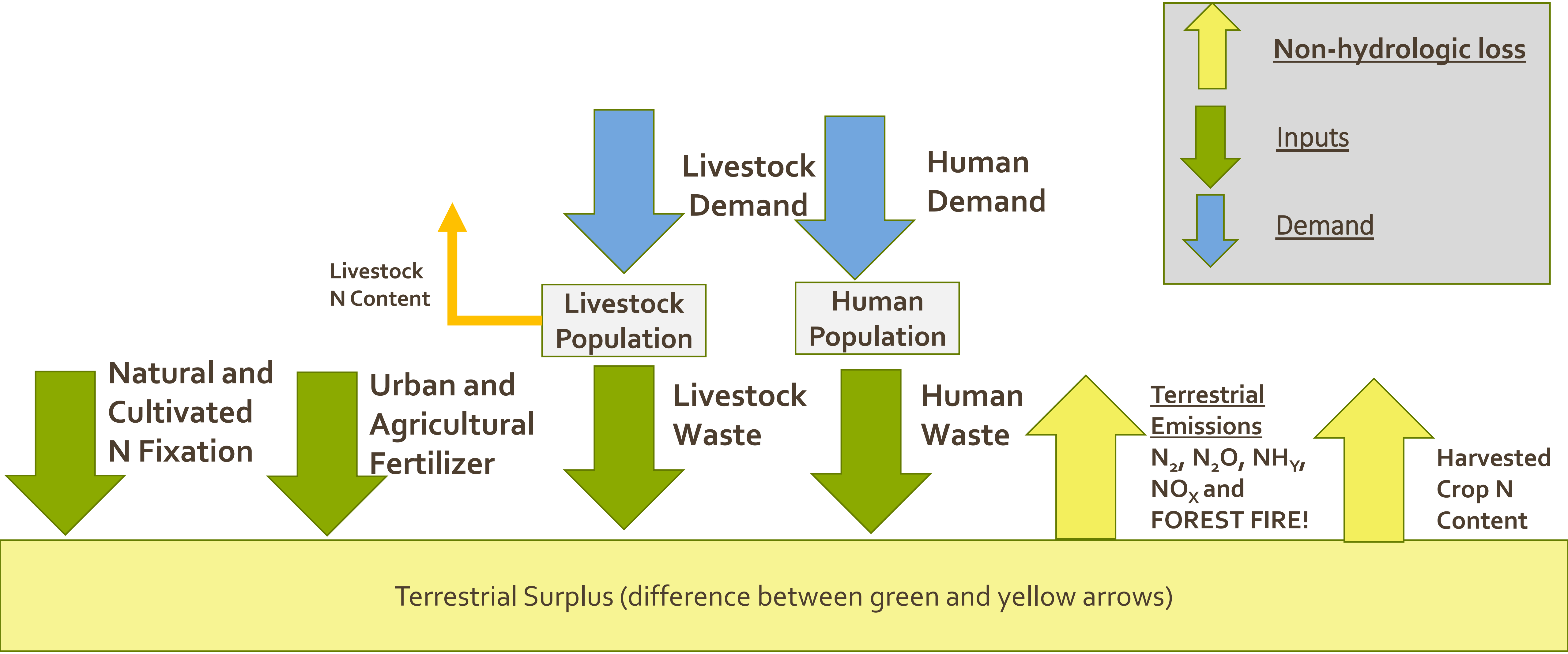
- Eutrophication, harmful algal blooms, and hypoxia still persists in many of the nation's estuaries, bays, and lakes (EPA, 2015; Clark *et al.*, 2017)
- Episodic acidification of headwater lotic systems (Lawrernce *et al.*, 2015)
- Nitrate contamination of drinking water supplies (Garcia *et al.*, 2017)
- Periodic high exposure to fine particles (PM) and ground level ozone (Di *et al.*, 2016)
- No clear decline in N export has been observed nationally in the nation's rivers and streams (Oelsner *et al.*, 2017)



https://nawqatrends.wim.usgs.gov/swtrends/

Brief overview of the inventory

- What is the spatial extent and for what years is the inventory compiled?
  - Currently 2002, 2007, and 2012 inventories have been constructed for the contiguous USA (CONUS), but many of the individual fluxes are available annually
- What is the spatial resolution?
  - The current inventory was constructed at the HUC-8 subbasin scale (~1,800 km^2, about ½ the size of Rhode Island), but the majority of the estimated fluxes are available at finer resolutions (Table S-1 upon request)
- How can I access the data?
  - A simple tabular database will be available that can be simply linked to corresponding HUC-8 shape files



Also estimate emissions from fossil fuel combustion (stationary and mobile) along with recovered and applied manure

Objectives

With these input-output datasets we determined:

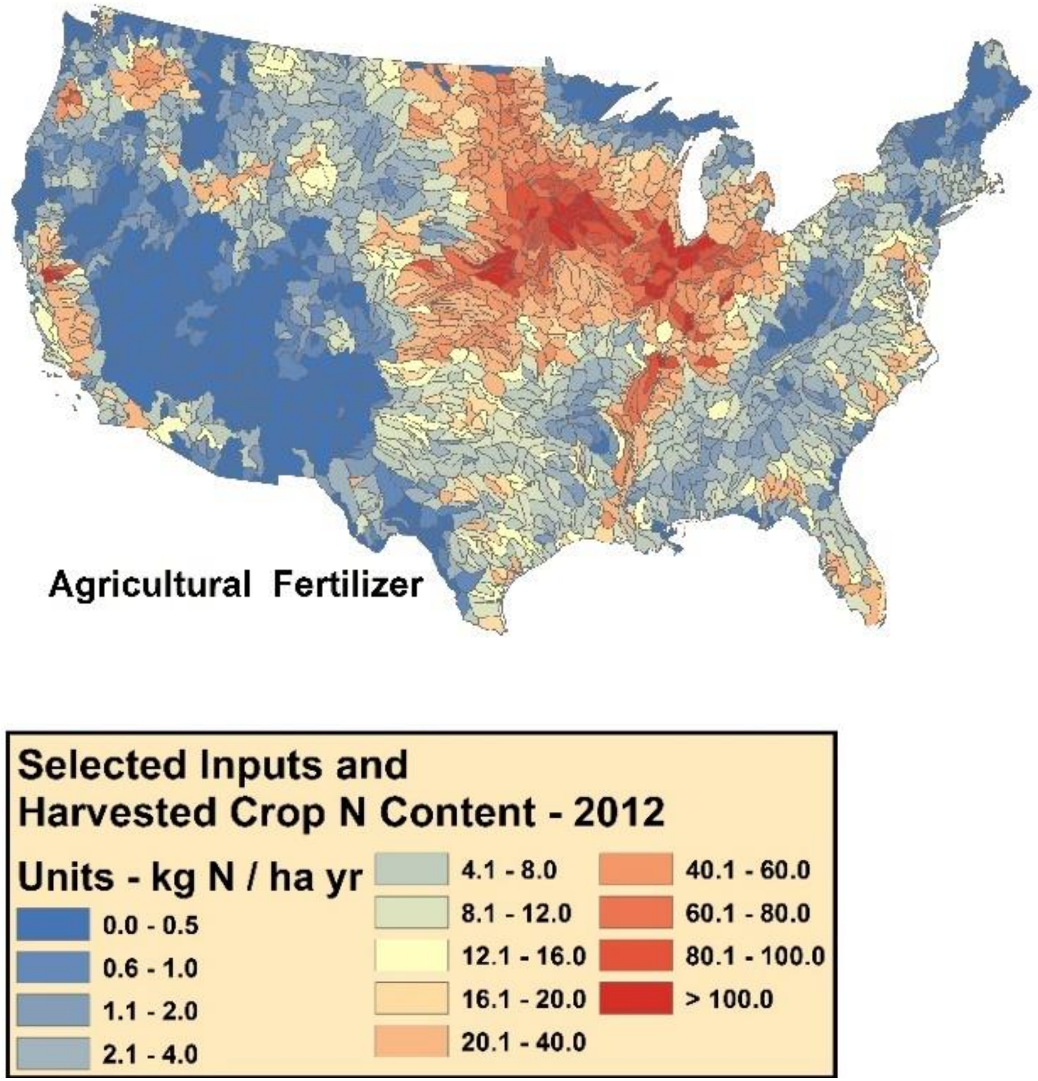
1) total inputs, total non-hydrologic losses, and terrestrial surpluses (i.e., total inputs – non-hydrologic losses) for all HUC-8s of CONUS

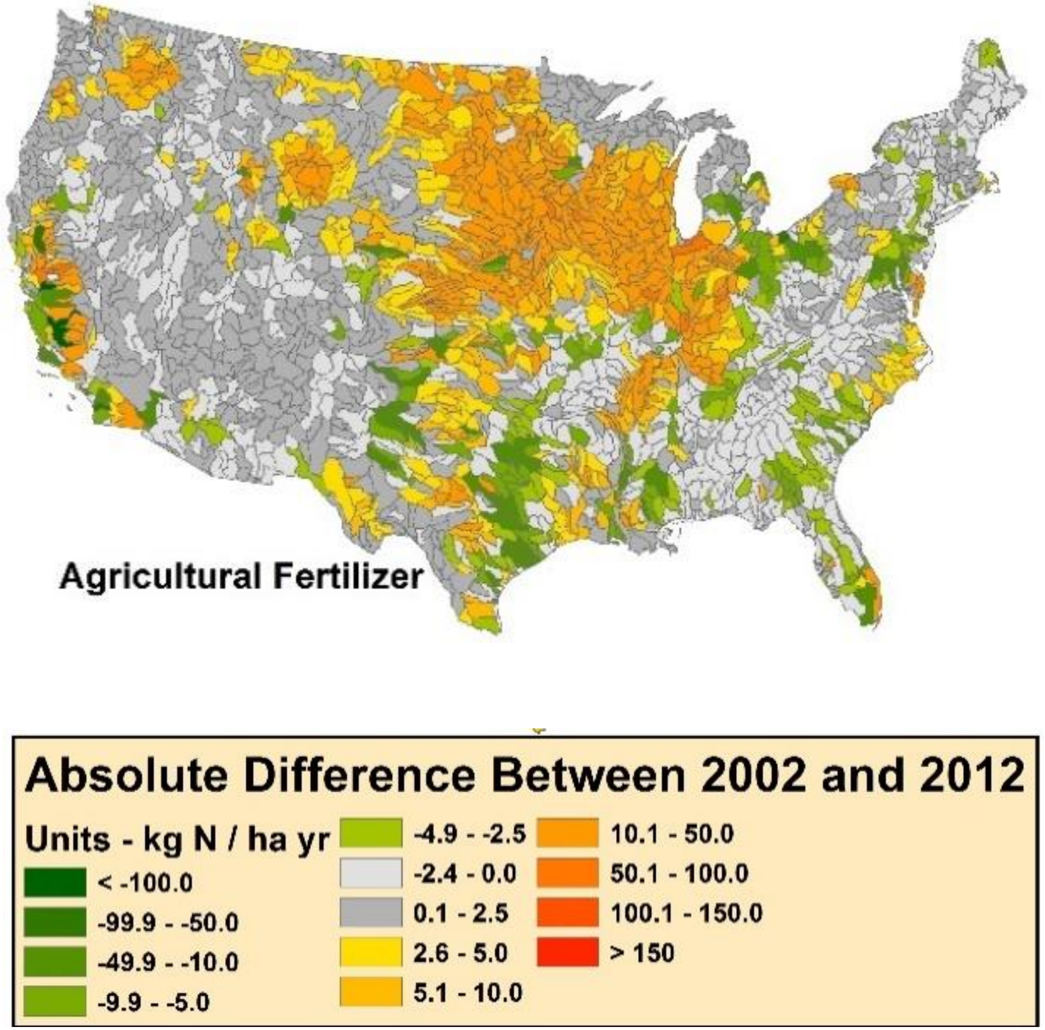
2) differences through time by comparing the 2002 and 2012 inventories.

Nitrogen inputs remained stable

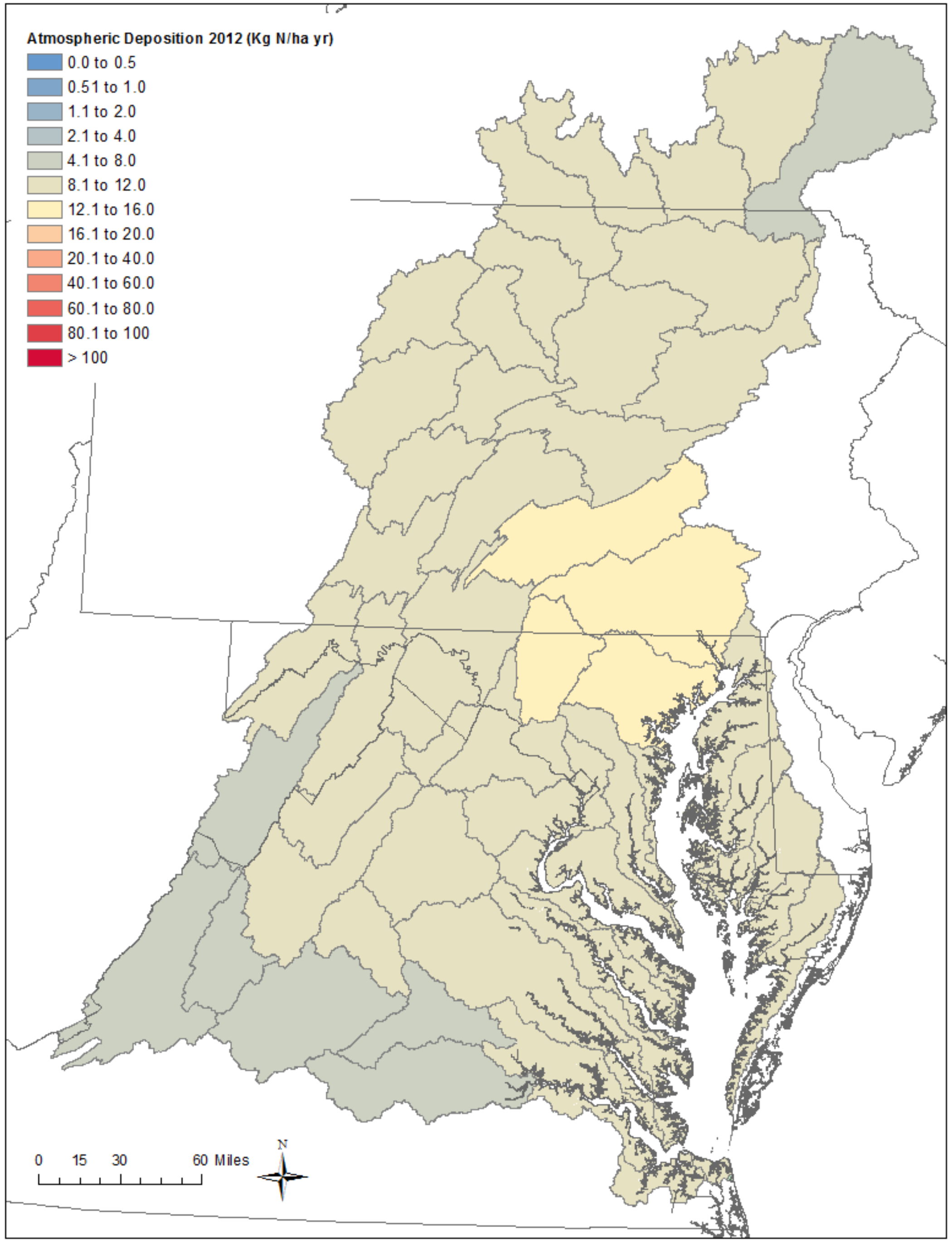
- Agricultural fertilizer application increased ~2 Tg N yr^{-1}
  - Total increase offset by decreased total N deposition of 1.4 Tg N yr^{-1}
- Natural N fixation only accounts ~16% of nitrogen inputs onto land
  - Consistent with Houlton *et al.*, 2013
- Lots of intriguing questions are inspired by this simple table!

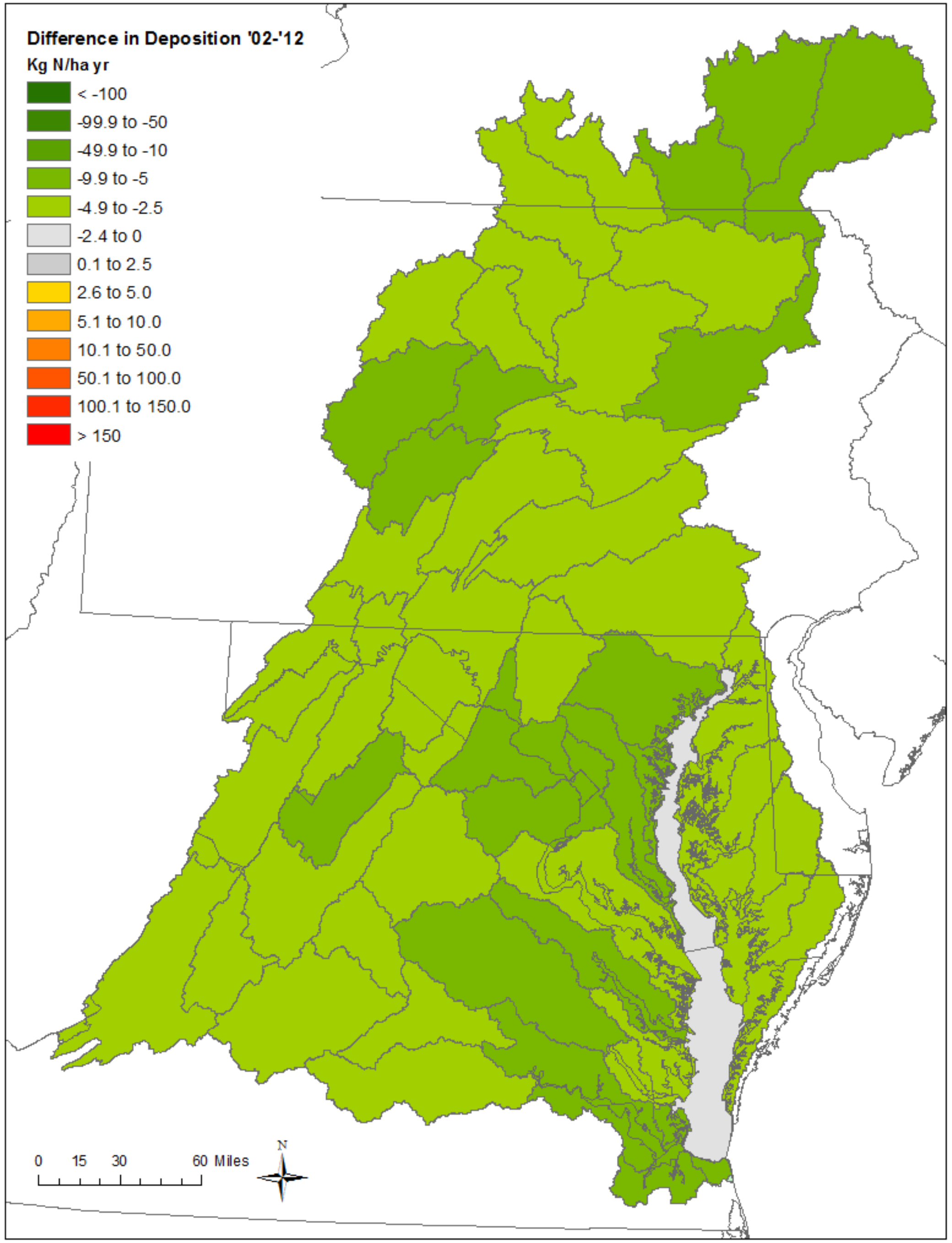
Years	2002	2007	2012
Nitrogen Inputs onto Land			
Natural N Fixation	4.8	4.8	4.8
Agricultural fertilizer	9.8	11.2	11.9
Urban Fertilizer	0.3	0.4	0.2
N-fixing Crop Cultivation	5.8	6.0	5.8
Livestock N Recovered*	1.2	1.2	1.0
Human N Waste	1.3	1.4	1.4
Total N Deposition	6.9	6.1	5.5
Livestock Waste	6.0	6.2	5.1
Grand Total of Nitrogen Inputs onto Land	34.9	36.2	34.8

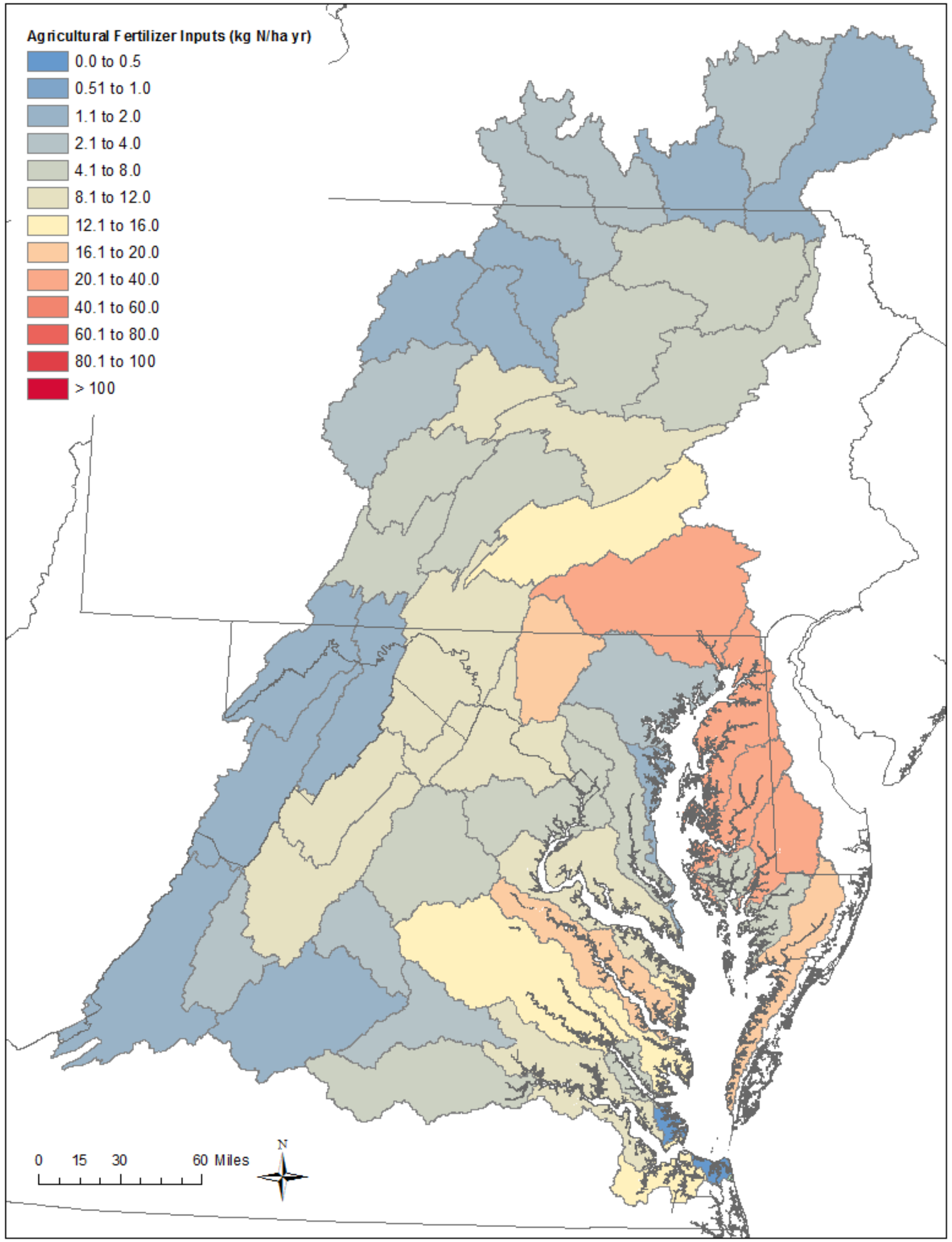


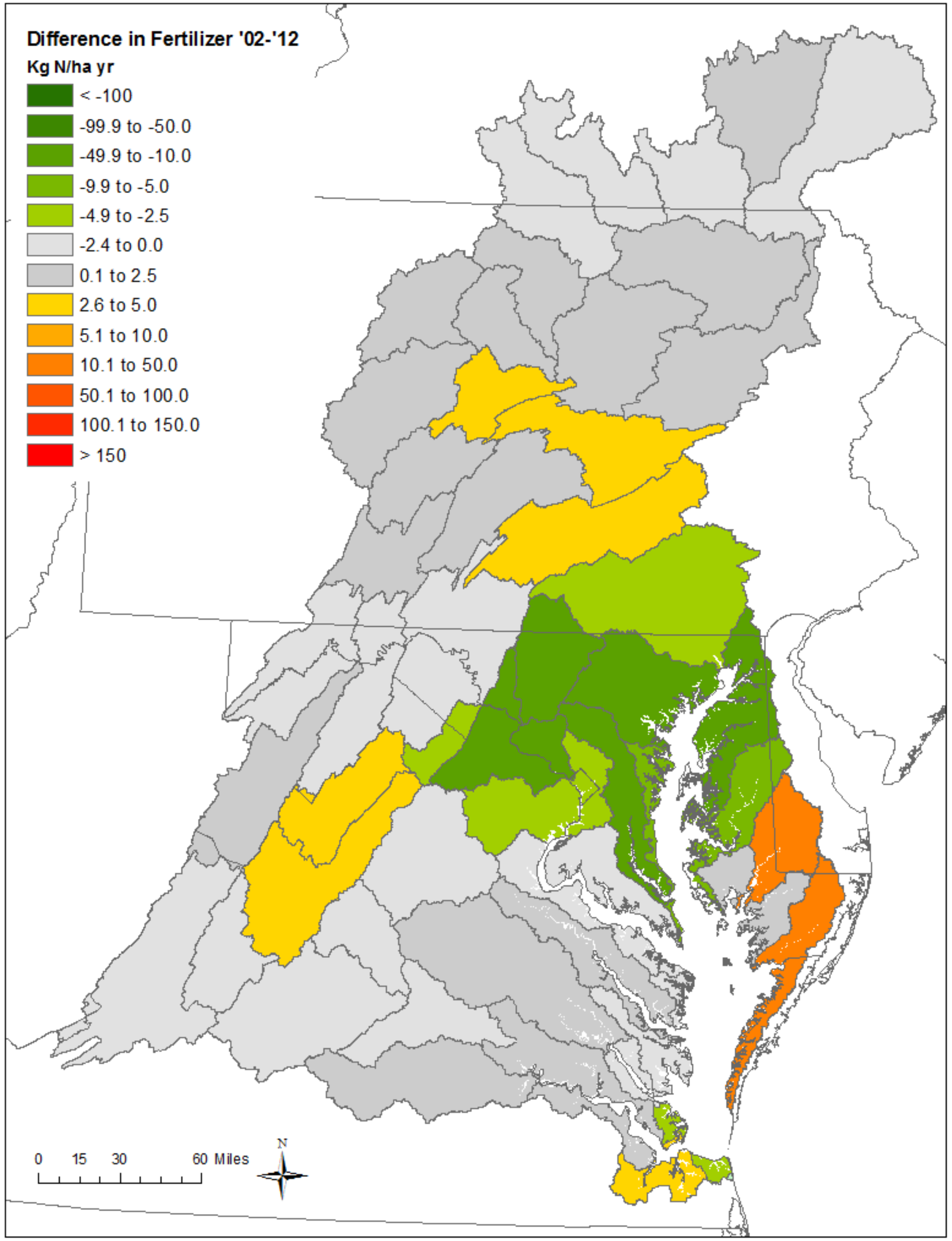


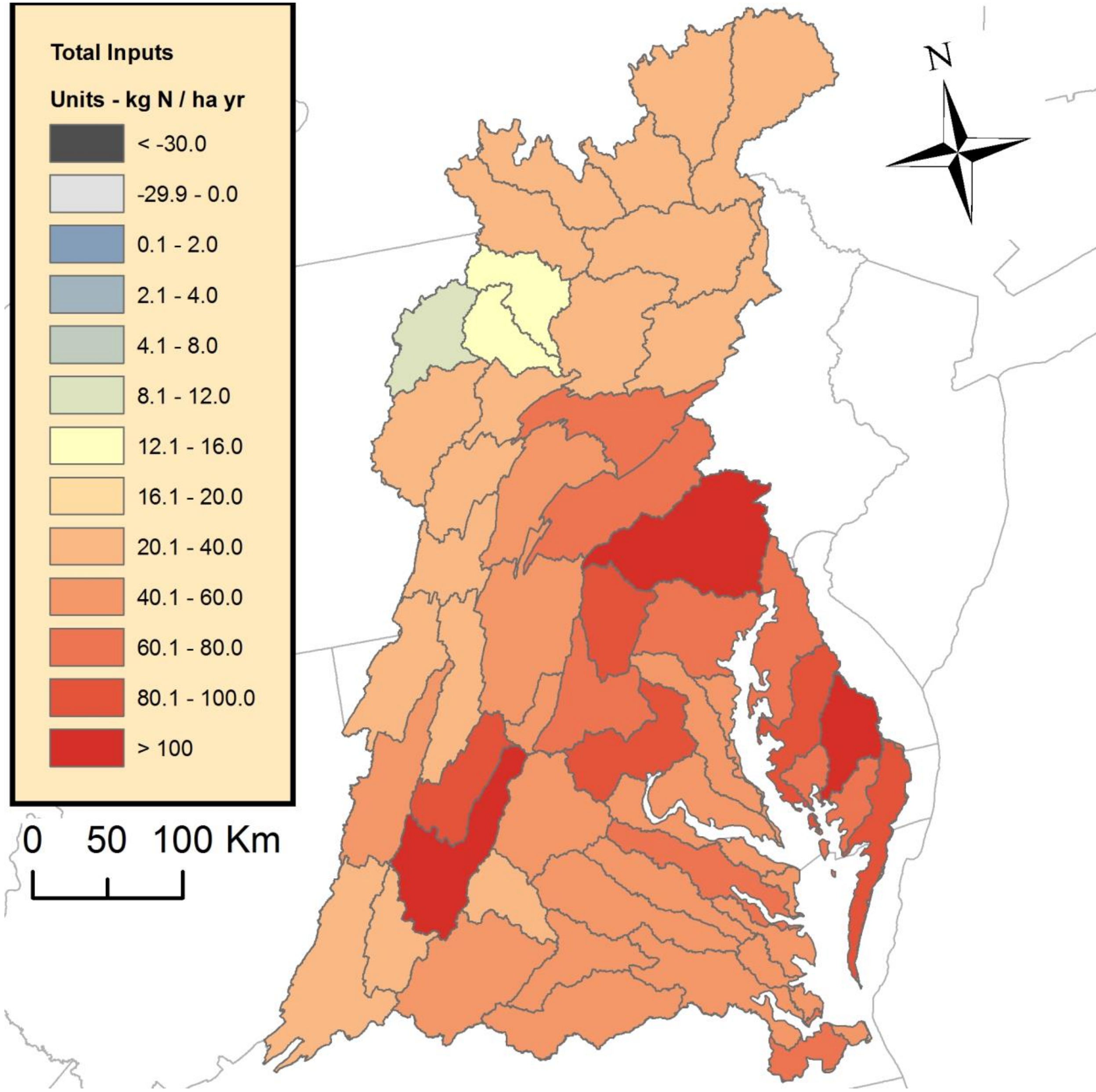
Equivalency in N inputs not universal

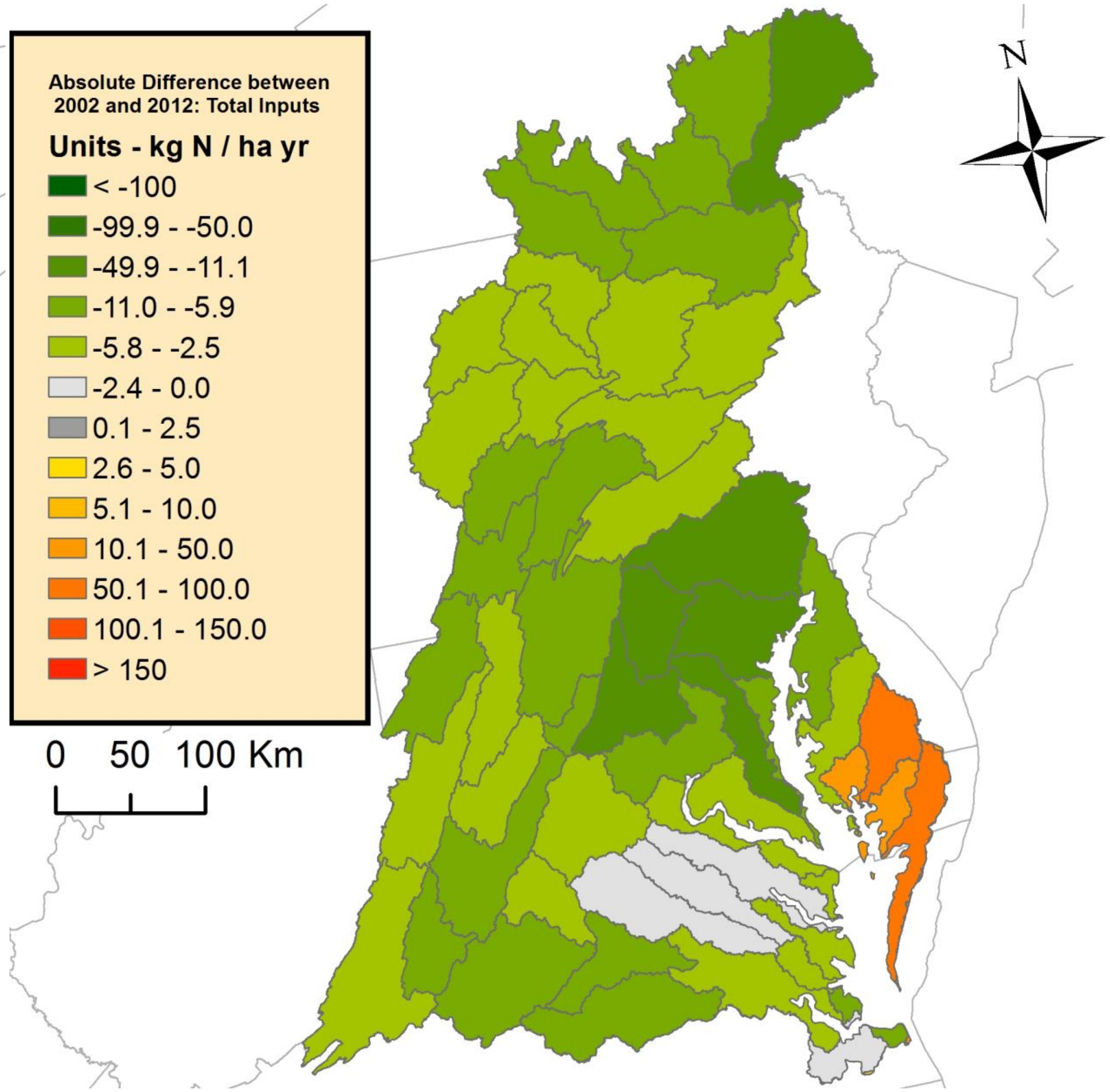

Atmospheric Deposition 2012 (Kg N/ha yr)
0.0 to 0.5
0.51 to 1.0
1.1 to 2.0
2.1 to 4.0
4.1 to 8.0
8.1 to 12.0
12.1 to 16.0
16.1 to 20.0
20.1 to 40.0
40.1 to 60.0
60.1 to 80.0
80.1 to 100
> 100
0 15 30 60 Miles
N


Difference in Deposition '02-'12
Kg N/ha yr
< -100
-99.9 to -50
-49.9 to -10
-9.9 to -5
-4.9 to -2.5
-2.4 to 0
0.1 to 2.5
2.6 to 5.0
5.1 to 10.0
10.1 to 50.0
50.1 to 100.0
100.1 to 150.0
> 150
0 15 30 60 Miles
N

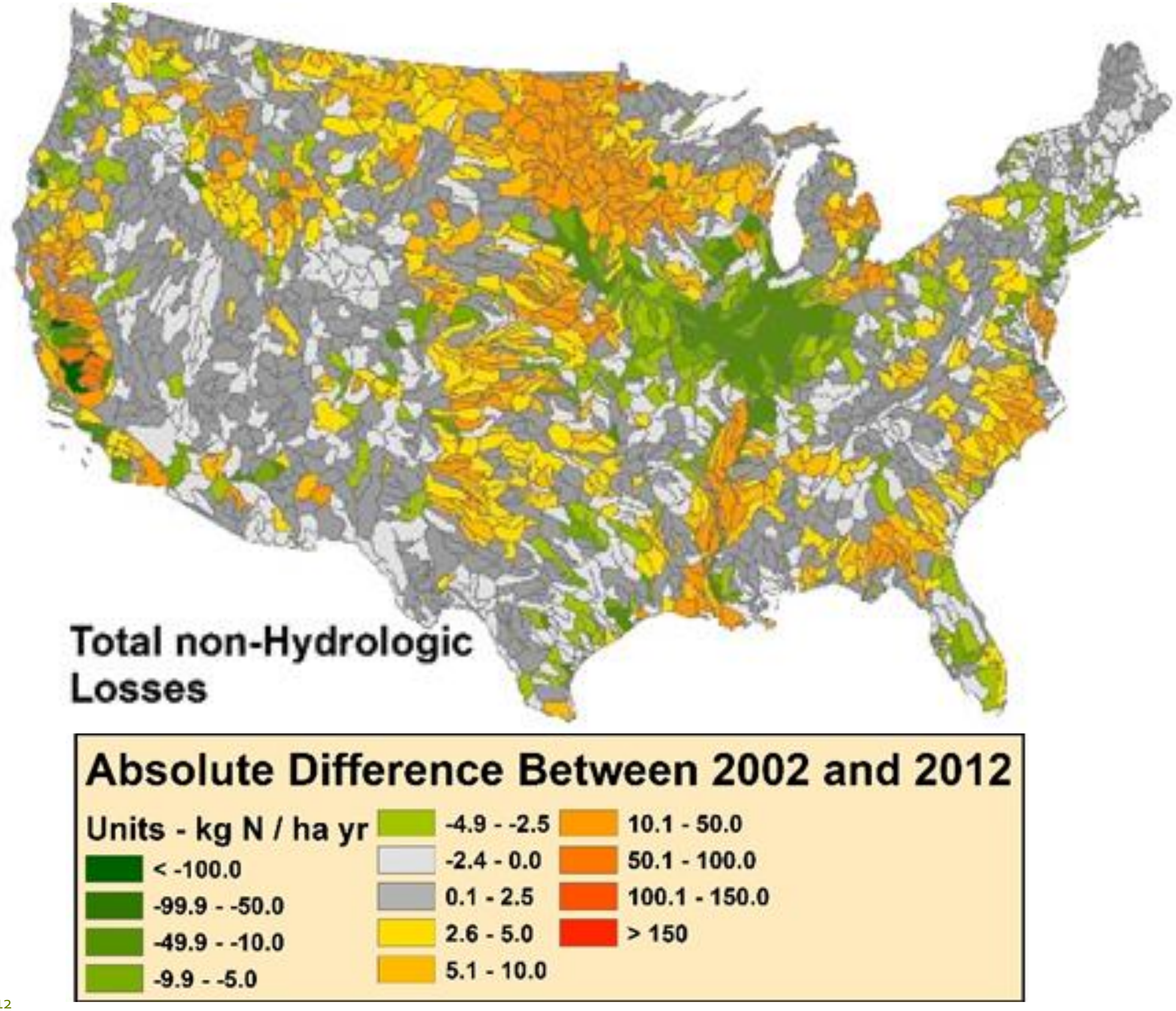

Agricultural Fertilizer Inputs (kg N/ha yr)
0.0 to 0.5
0.51 to 1.0
1.1 to 2.0
2.1 to 4.0
4.1 to 8.0
8.1 to 12.0
12.1 to 16.0
16.1 to 20.0
20.1 to 40.0
40.1 to 60.0
60.1 to 80.0
80.1 to 100
> 100
0 15 30 60 Miles
N


Difference in Fertilizer '02-'12
Kg N/ha yr
< -100
-99.9 to -50.0
-49.9 to -10.0
-9.9 to -5.0
-4.9 to -2.5
-2.4 to 0.0
0.1 to 2.5
2.6 to 5.0
5.1 to 10.0
10.1 to 50.0
50.1 to 100.0
100.1 to 150.0
> 150
0 15 30 60 Miles
N

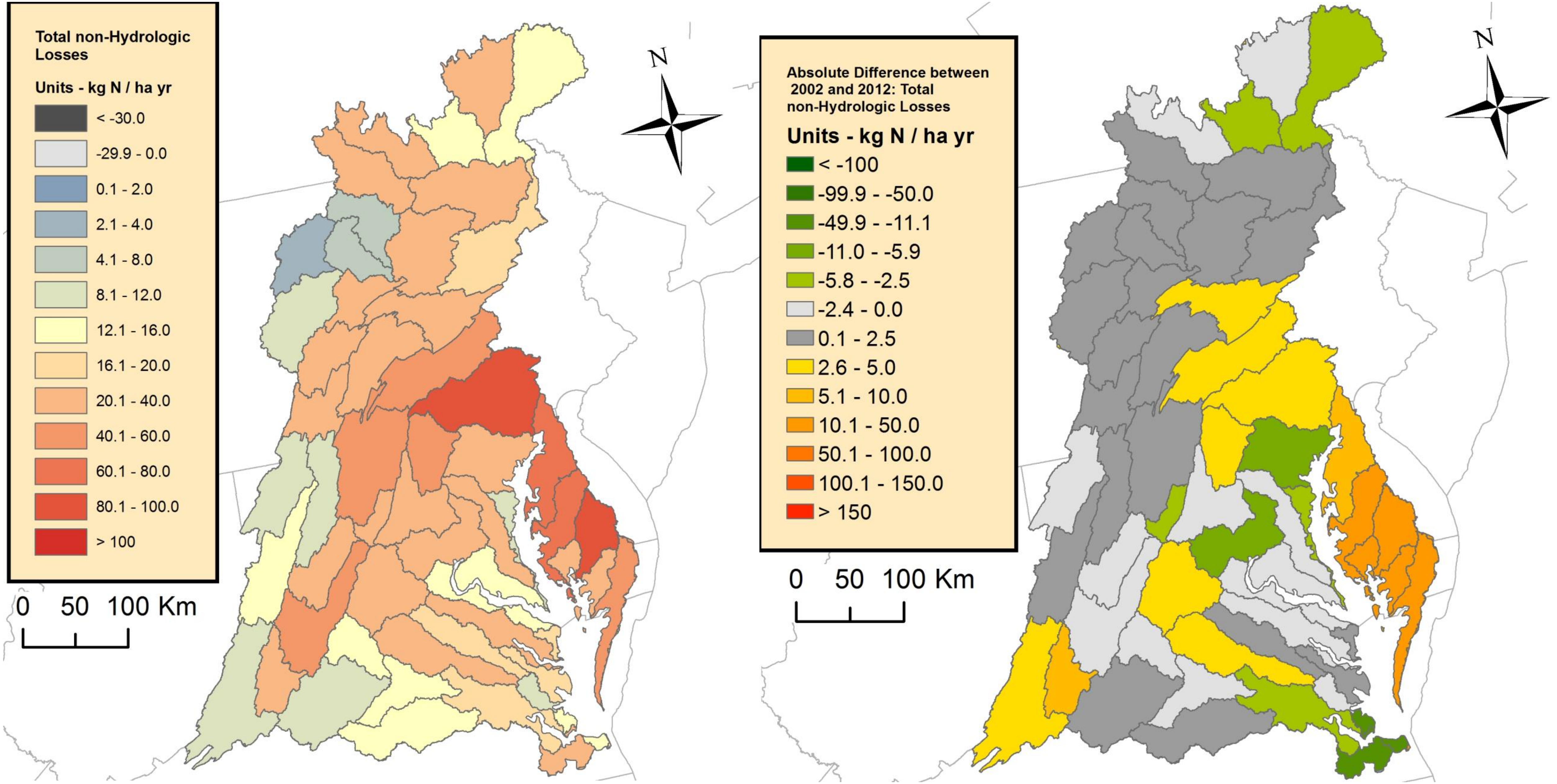

Total Inputs
Units - kg N / ha yr
< -30.0
-29.9 - 0.0
0.1 - 2.0
2.1 - 4.0
4.1 - 8.0
8.1 - 12.0
12.1 - 16.0
16.1 - 20.0
20.1 - 40.0
40.1 - 60.0
60.1 - 80.0
80.1 - 100.0
> 100
0 50 100 Km
N


Absolute Difference between 2002 and 2012: Total Inputs
Units - kg N / ha yr
< -100
-99.9 - -50.0
-49.9 - -11.1
-11.0 - -5.9
-5.8 - -2.5
-2.4 - 0.0
0.1 - 2.5
2.6 - 5.0
5.1 - 10.0
10.1 - 50.0
50.1 - 100.0
100.1 - 150.0
> 150
0 50 100 Km
N

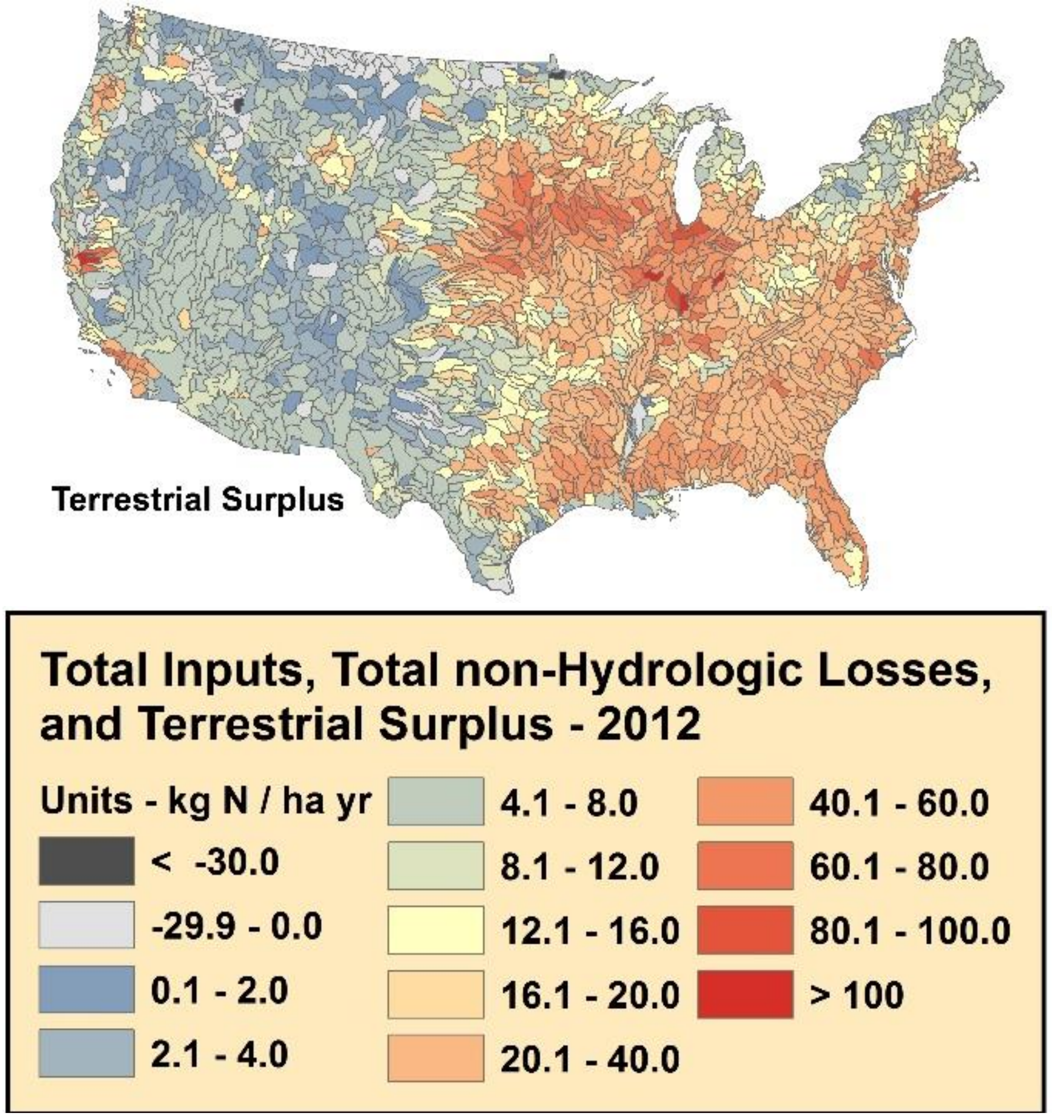
National increases in non-hydrologic N losses for the CONUS, regional changes in losses were even more pronounced

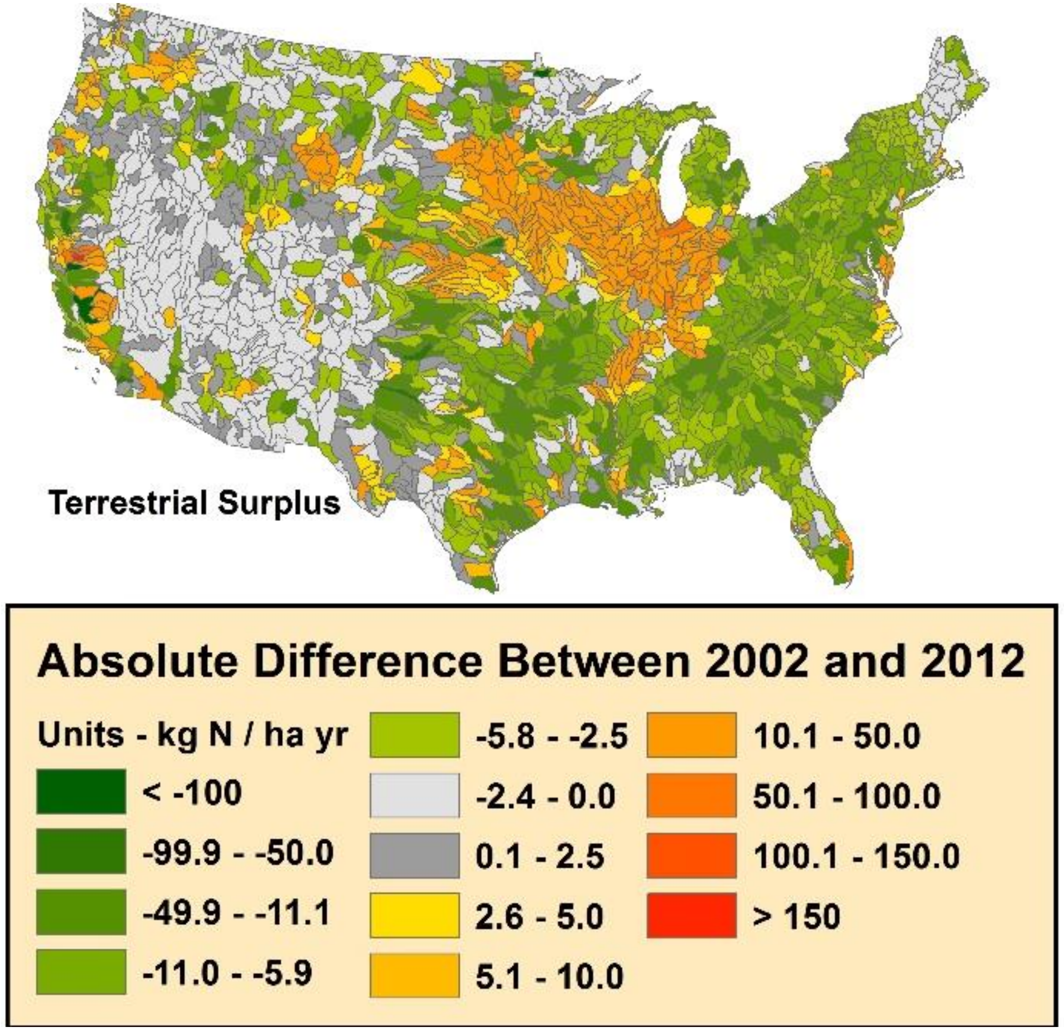


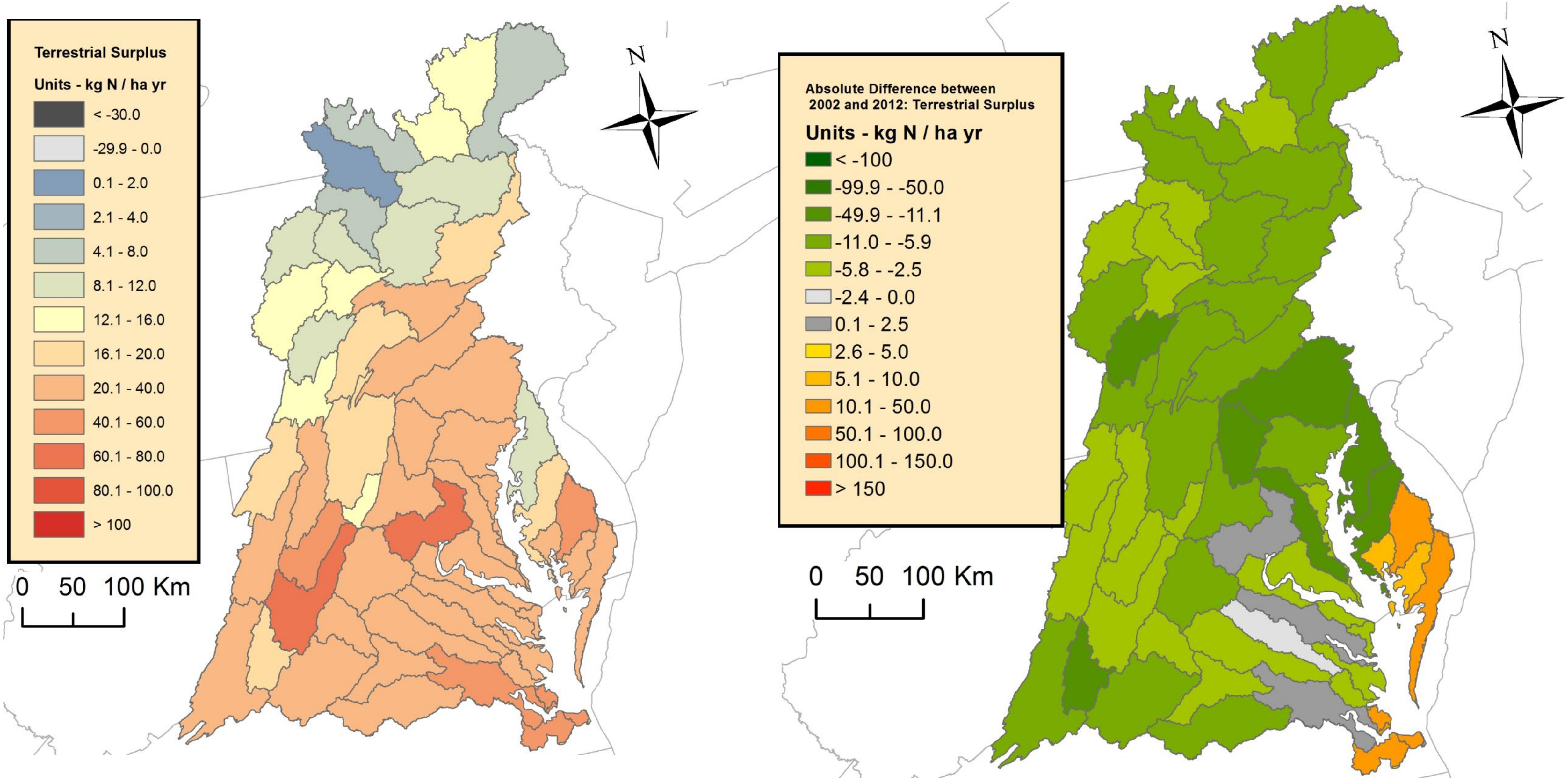
- Regional drought in the Midwest depressed crop yields 10-50 kg N ha^{-1} yr^{-1}
  - Somewhat anomalous
  - High fertilizer input and high crop yield strategies may sometimes result in greatly increased terrestrial N surpluses
- Areas outside of the drought in the great plains showed increased losses due high yields and increased cultivation


Total non-Hydrologic Losses
Units - kg N / ha yr
< -30.0
-29.9 - 0.0
0.1 - 2.0
2.1 - 4.0
4.1 - 8.0
8.1 - 12.0
12.1 - 16.0
16.1 - 20.0
20.1 - 40.0
40.1 - 60.0
60.1 - 80.0
80.1 - 100.0
> 100
0 50 100 Km
N
Absolute Difference between 2002 and 2012: Total non-Hydrologic Losses
Units - kg N / ha yr
< -100
-99.9 - -50.0
-49.9 - -11.1
-11.0 - -5.9
-5.8 - -2.5
-2.4 - 0.0
0.1 - 2.5
2.6 - 5.0
5.1 - 10.0
10.1 - 50.0
50.1 - 100.0
100.1 - 150.0
> 150
0 50 100 Km
N

Terrestrial Nitrogen Surplus declined 1.5 Tg





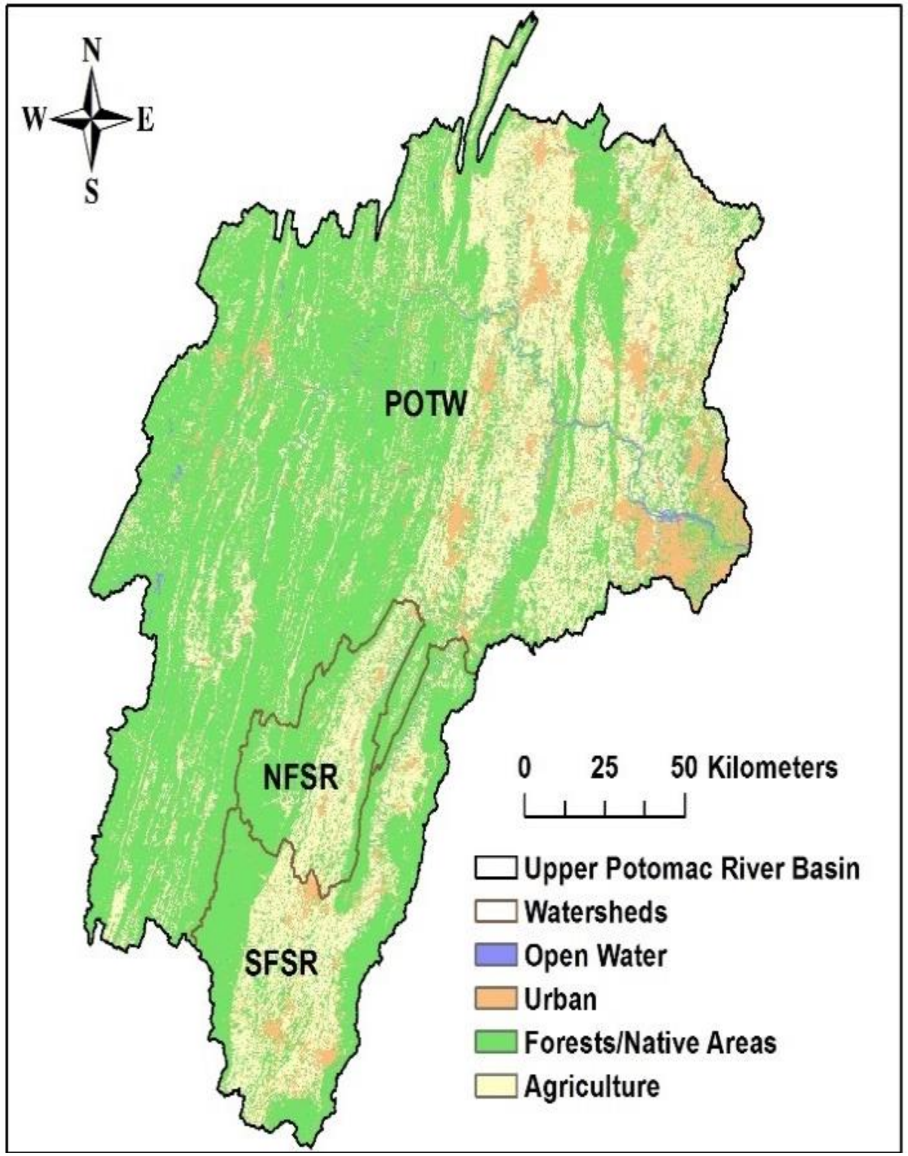


Terrestrial Surplus
Units - kg N / ha yr
< -30.0
-29.9 - 0.0
0.1 - 2.0
2.1 - 4.0
4.1 - 8.0
8.1 - 12.0
12.1 - 16.0
16.1 - 20.0
20.1 - 40.0
40.1 - 60.0
60.1 - 80.0
80.1 - 100.0
> 100
0 50 100 Km
N
Absolute Difference between
2002 and 2012: Terrestrial Surplus
Units - kg N / ha yr
< -100
-99.9 - -50.0
-49.9 - -11.1
-11.0 - -5.9
-5.8 - -2.5
-2.4 - 0.0
0.1 - 2.5
2.6 - 5.0
5.1 - 10.0
10.1 - 50.0
50.1 - 100.0
100.1 - 150.0
> 150
0 50 100 Km
N

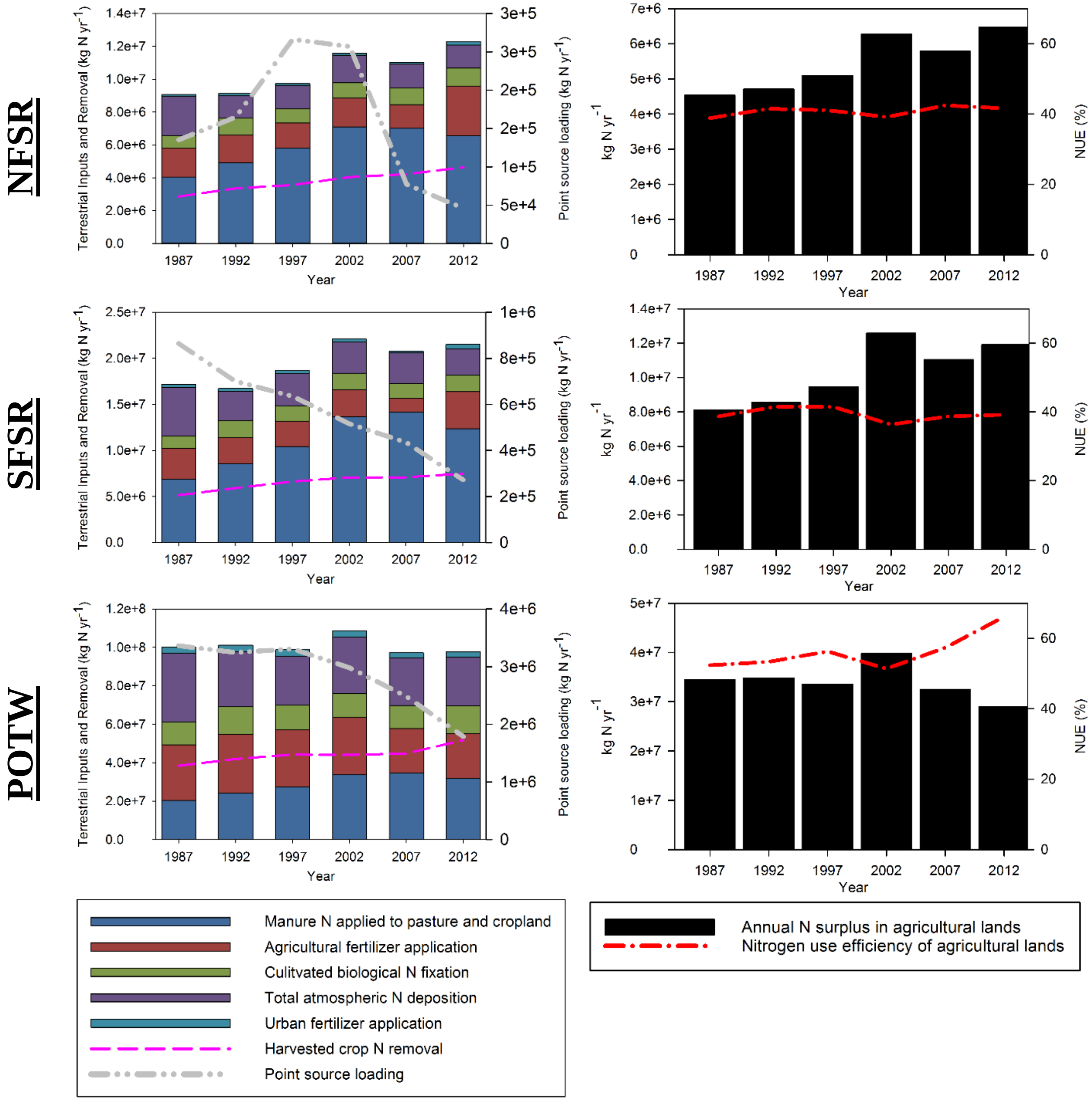
Conclusions

- Regulatory, technological, economic, and policy actions have drastically altered the magnitude of regional N inputs and losses in CONUS
  - Clean Air Act Amendments of 1990 along with NO_X emission control programs (total N deposition)
  - Energy Independence and Security Act of 2007 and the associated Renewable Fuel Standard of 2010 (agricultural fertilizer inputs)
  - Shifting dietary habits (changes in livestock protein consumption and production?)
- Less nitrogen is being inputted into the Chesapeake Bay, fueling declines in surpluses
  - Decreased fertilizer use in MD and PA Piedmont
  - Decreased atmospheric deposition
  - Increased crop removal

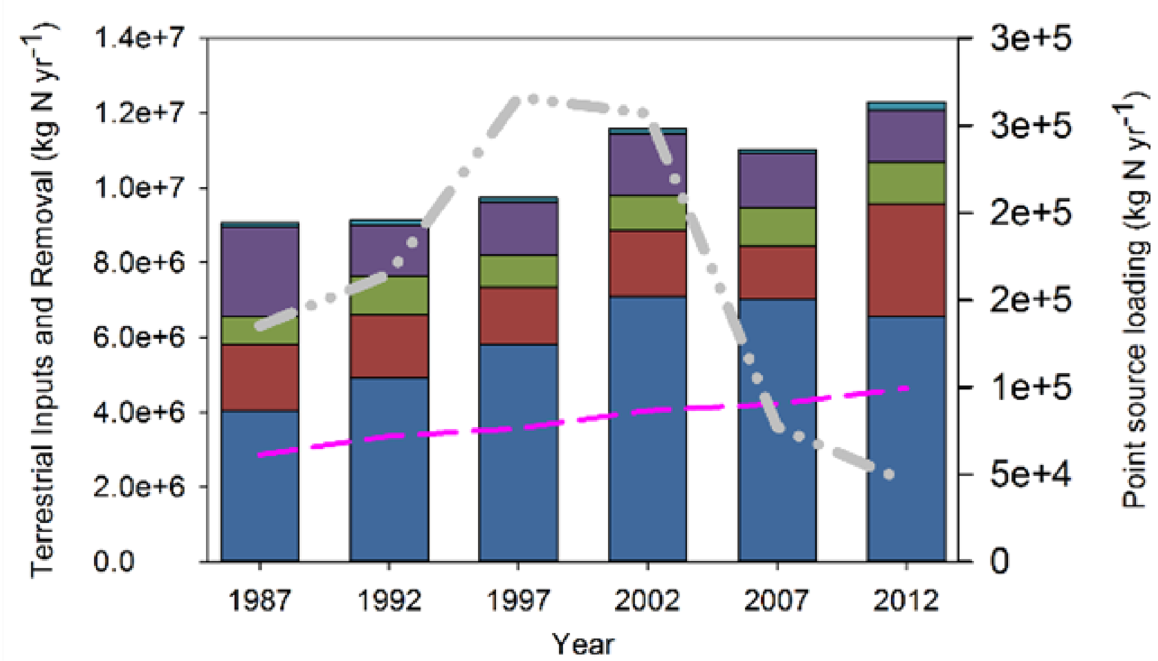
Can we make this nutrient inventory more locally relevant?

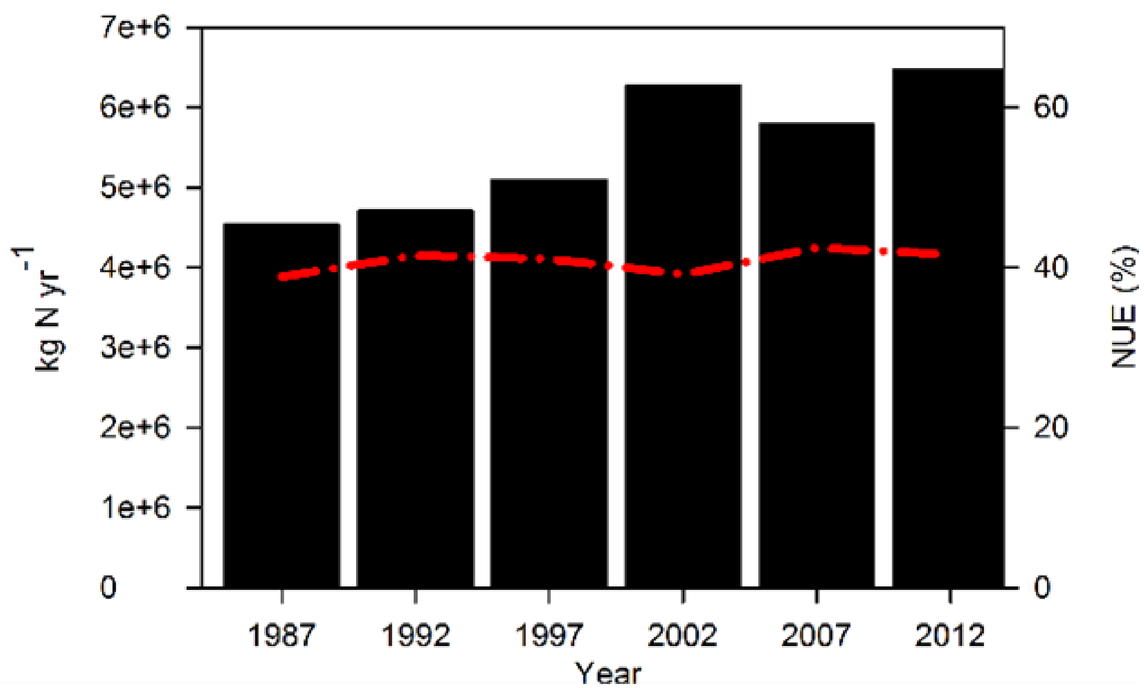


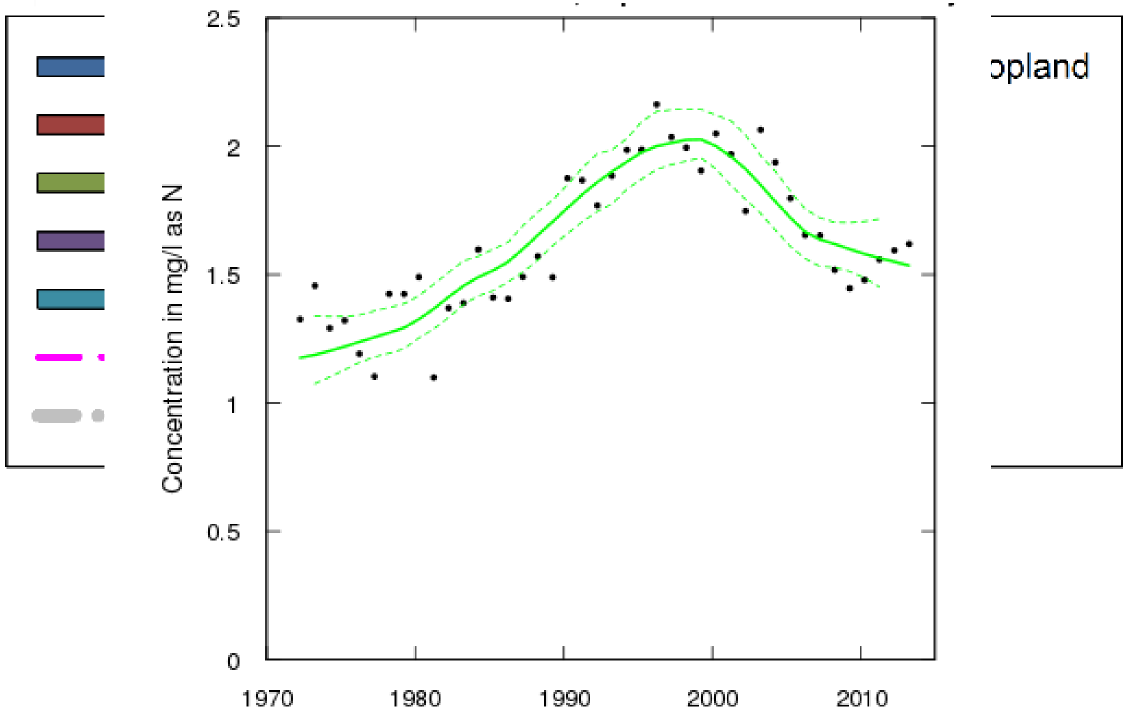
POTW = Potomac River at Chain Bridge
NFSR = North Fork Shenandoah River near Strasburg, VA
SFSR = South Fork Shenandoah River at Front Royal, VA

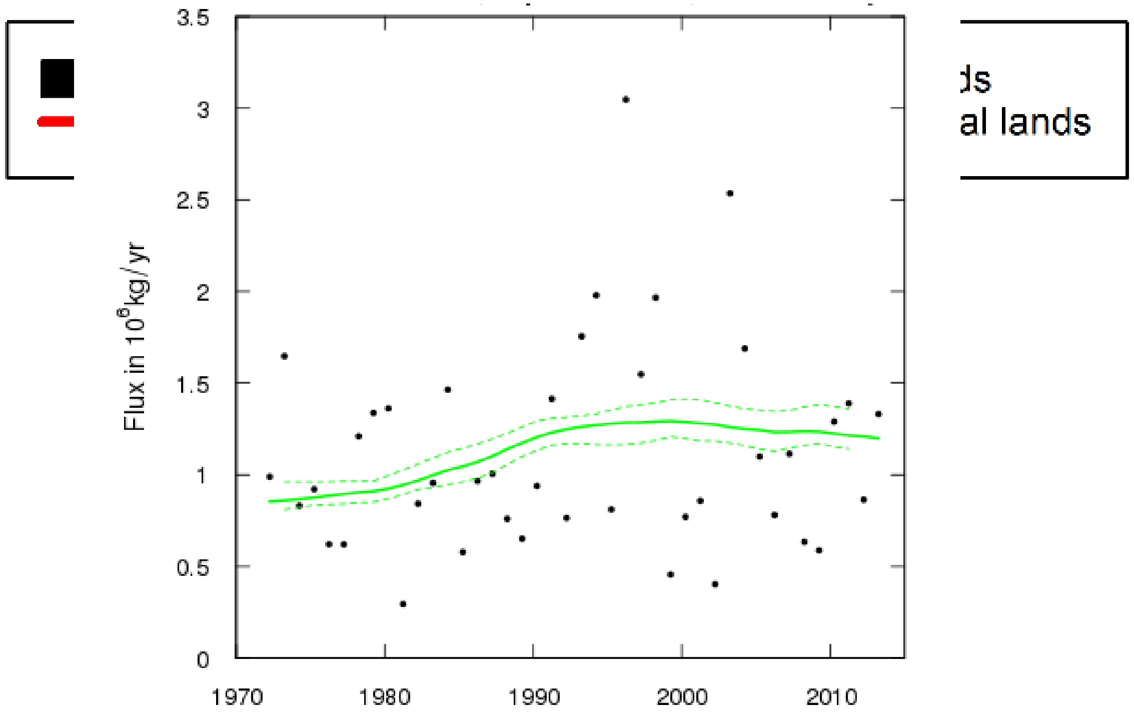


NFSR

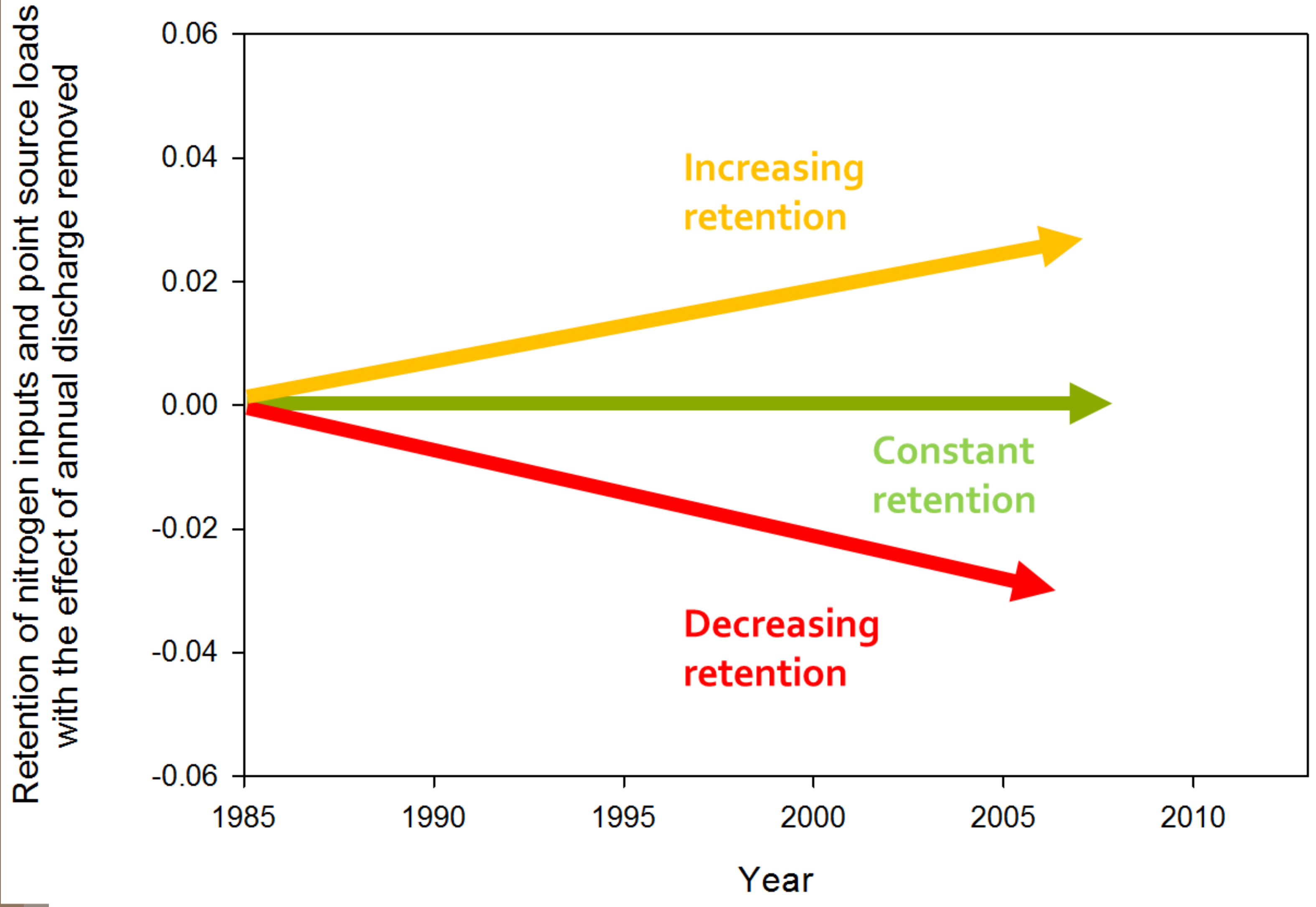

Terrestrial Inputs and Removal (kg N yr-1)
Point source loading (kg N yr-1)
0.0
2.0e+6
4.0e+6
6.0e+6
8.0e+6
1.0e+7
1.2e+7
1.4e+7
0
5e+4
1e+5
2e+5
2e+5
3e+5
3e+5
1987
1992
1997
2002
2007
2012
Year

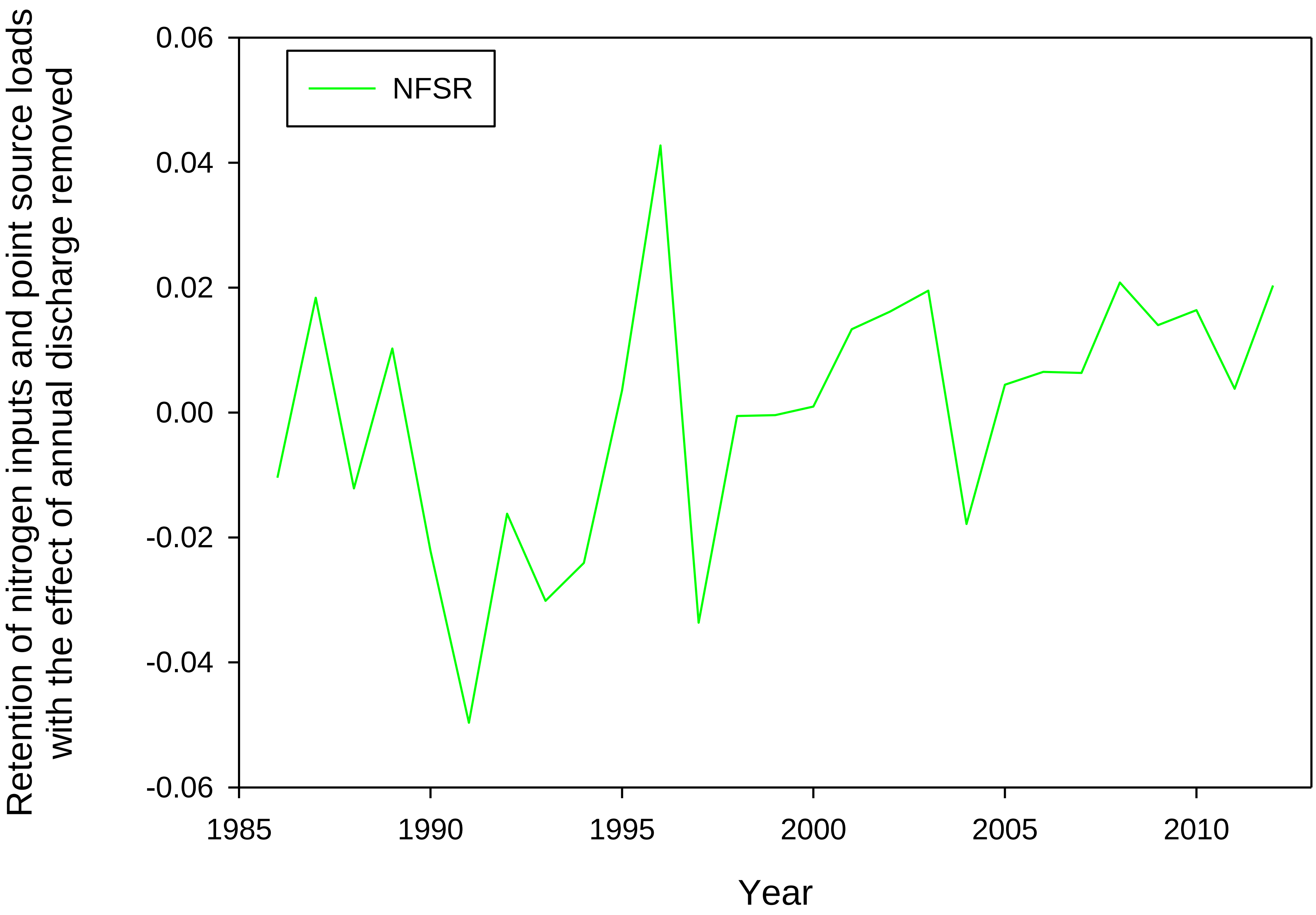

kg N yr-1
NUE (%)
0
1e+6
2e+6
3e+6
4e+6
5e+6
6e+6
7e+6
0
20
40
60
1987
1992
1997
2002
2007
2012
Year


opland
Concentration in mg/l as N
0
0.5
1
1.5
2
2.5
1970
1980
1990
2000
2010


ds
al lands
Flux in 10^6kg/yr
0
0.5
1
1.5
2
2.5
3
3.5
1970
1980
1990
2000
2010

First question, has the retentiveness of NFSR changed through time?





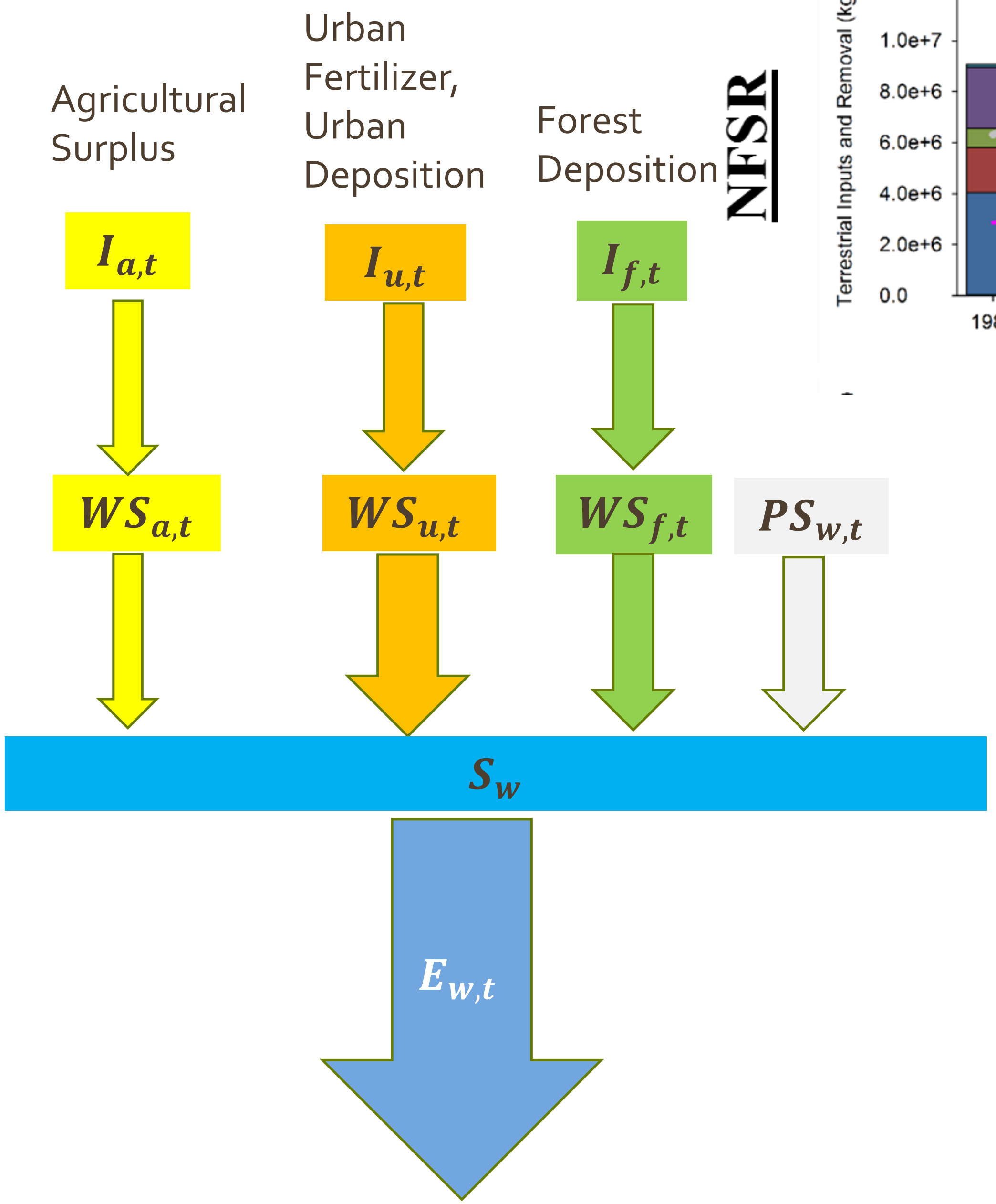
Retention of nitrogen inputs and point source loads with the effect of annual discharge removed
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
NFSR
1985
1990
1995
2000
2005
2010
Year

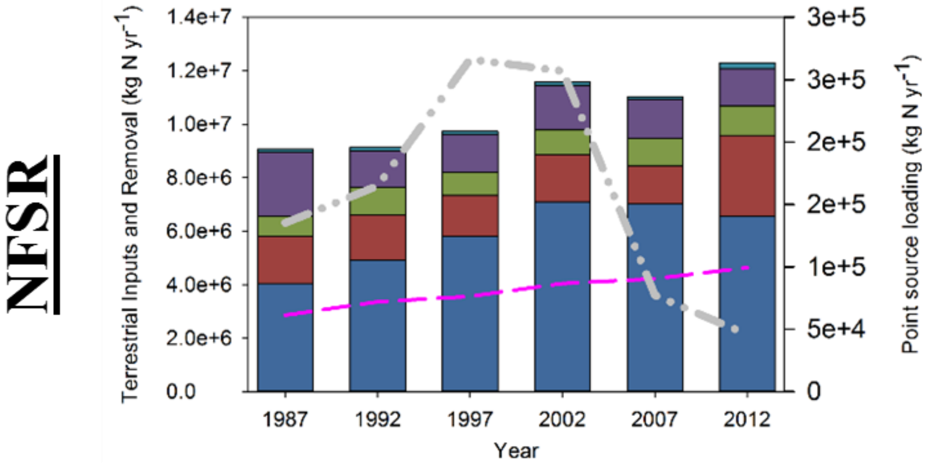
Develop a simple watershed empirical loading model for total nitrogen

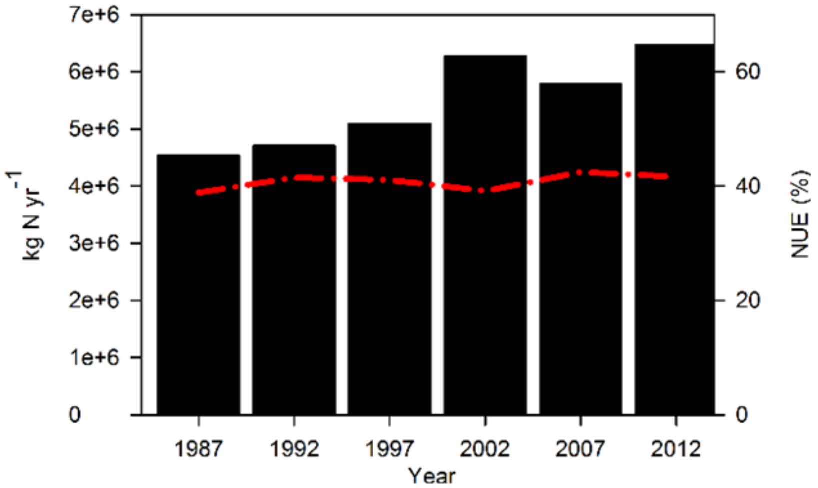
- Model proposed by Caraco and Cole (1999)

- $$\boldsymbol{E_{w,t} = \left(PS_{w,t} + I_{w,t} \times WS_{w,t}\right) \times S_w}$$

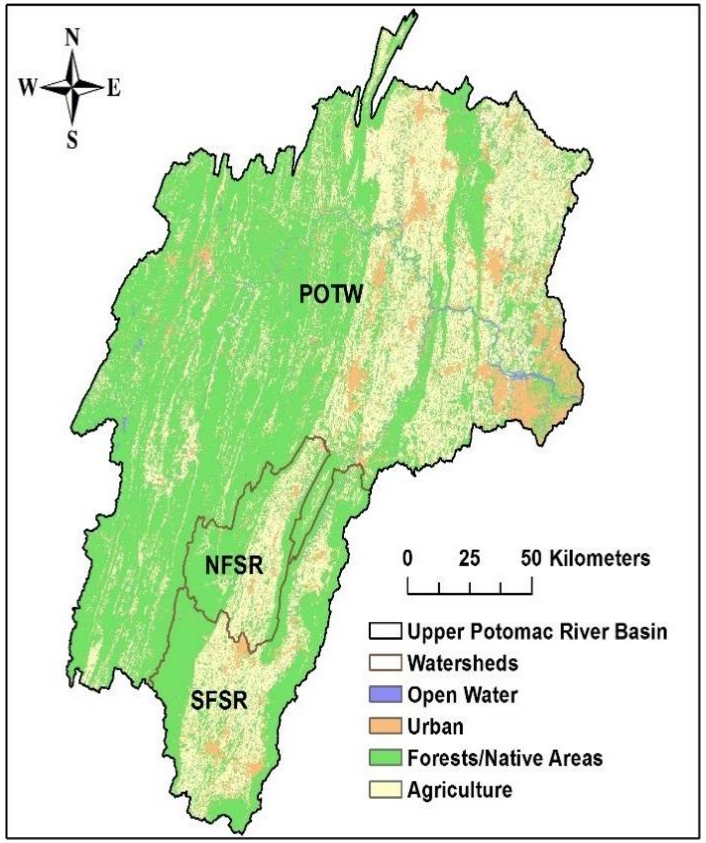
1. Catchment TN export ($\boldsymbol{E_{w,t}}$, **kg N yr^{-1}) in a given year** is a function of some fraction of the summed point source ($\boldsymbol{PS_{w,t}}$, **kg N yr^{-1}**) and non-point source inputs ($\boldsymbol{I_{w,t}}$, **kg N yr^{-1}**) reaching the watershed outlet.
2. Both $\boldsymbol{WS_{w,t}}$ and $\boldsymbol{S_w}$ are both unitless export coefficients
   - ❑ $\boldsymbol{WS_{w,t}}$ is a non-linear function of discharge
     - ❑ $\boldsymbol{WS_{w,t} = B_w {R_{w,t}}^{C_w}}$
       - ❑ $\boldsymbol{R_{w,t}}$ **(annual discharge)**
       - ❑ B_w (yr m^{-1}) and C_W (unitless) are both constants.





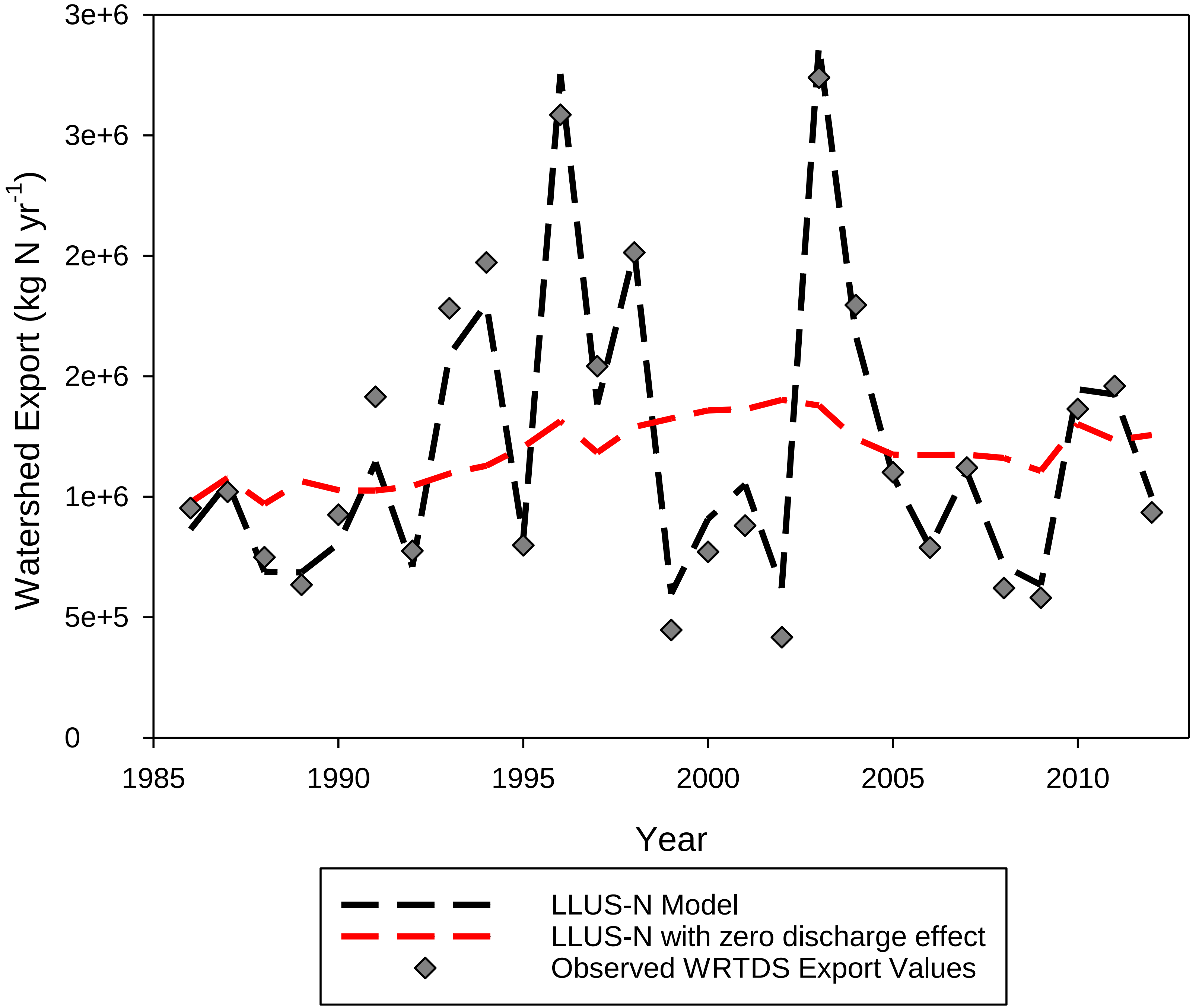


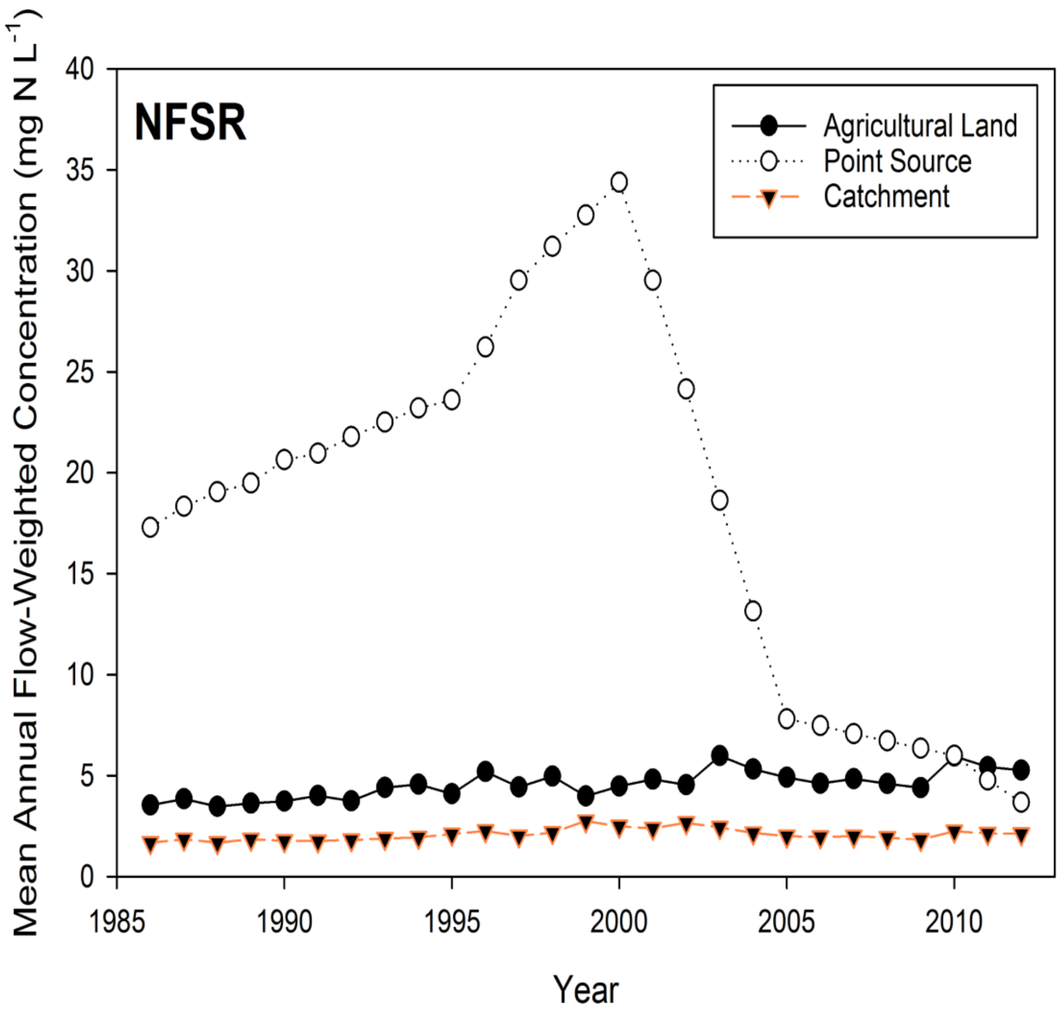
$$E_{w,t} = \left(PS_{w,t} + I_{a,t} \times WS_{a,t} + I_{u,t} \times WS_{u,t} + I_{f,t} \times WS_{f,t}\right) \times S_w$$

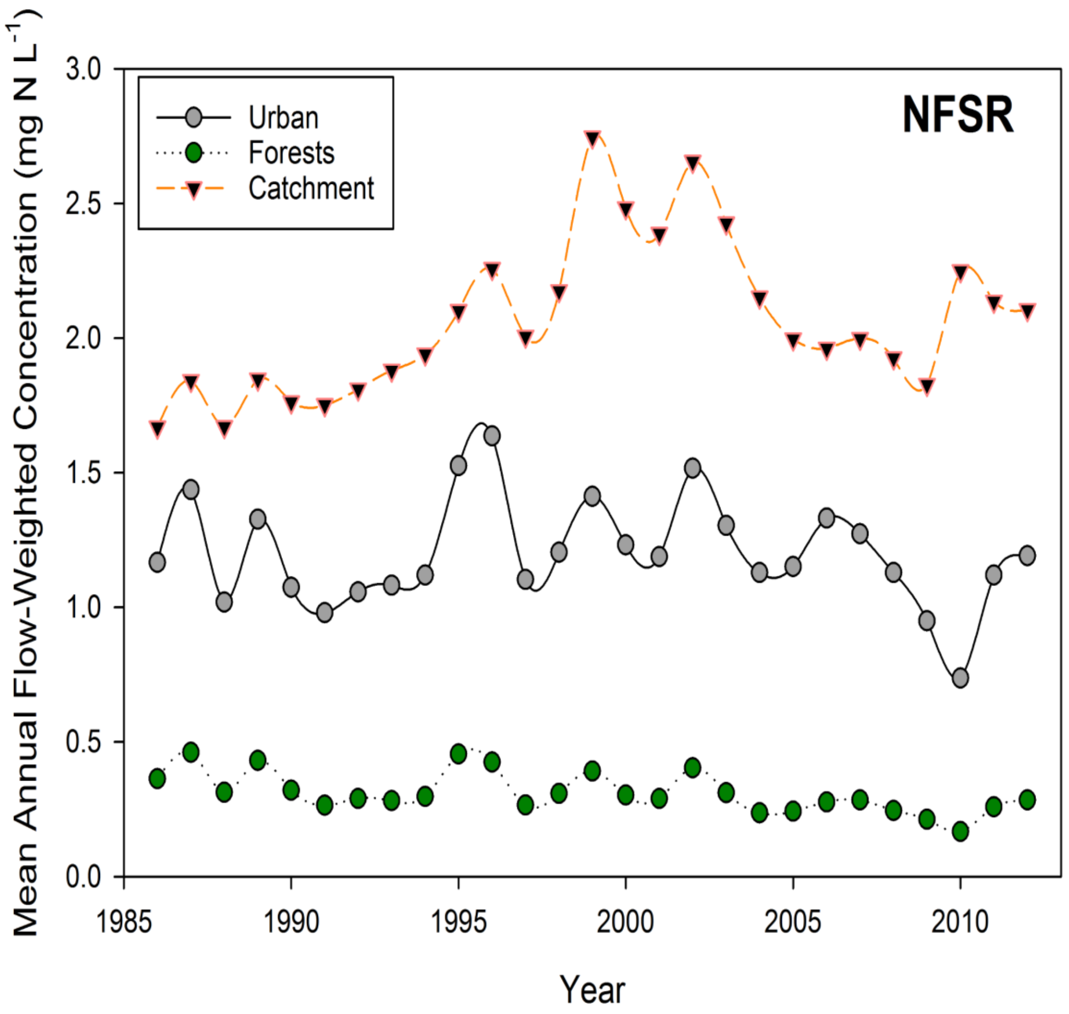


Parametrization and Optimization

- ❑ $WS_{a,t} = B_a {R_{w,t}}^{C_a}$
- ❑ $WS_{u,t} = B_u {R_{w,t}}^{C_u}$
- ❑ $WS_{f,t} = B_f {R_{w,t}}^{C_f}$
- **Lots of unknown parameters (n=6), issue of equifinality**
  - Apply multiple scenarios and constraints defined by the literature, optimize goodness of fit with GRG algorithm.
    - Forest must retain 89% of atmospherically deposited nitrogen, urban areas must retain 20% of fertilizer and atmospherically deposited nitrogen. Agricultural retention is then essentially solved by difference since point source loads are accounted for.
    - Leverage sensitivity analysis to identify most influential variables (i.e., vary retention for forests and urban areas while holding the parameters constant during recalibration)
    - Apply a Monte-Carlo analysis to constrain constants, *B* and *C*
- ***Nash-Sutcliffe > 0.94***

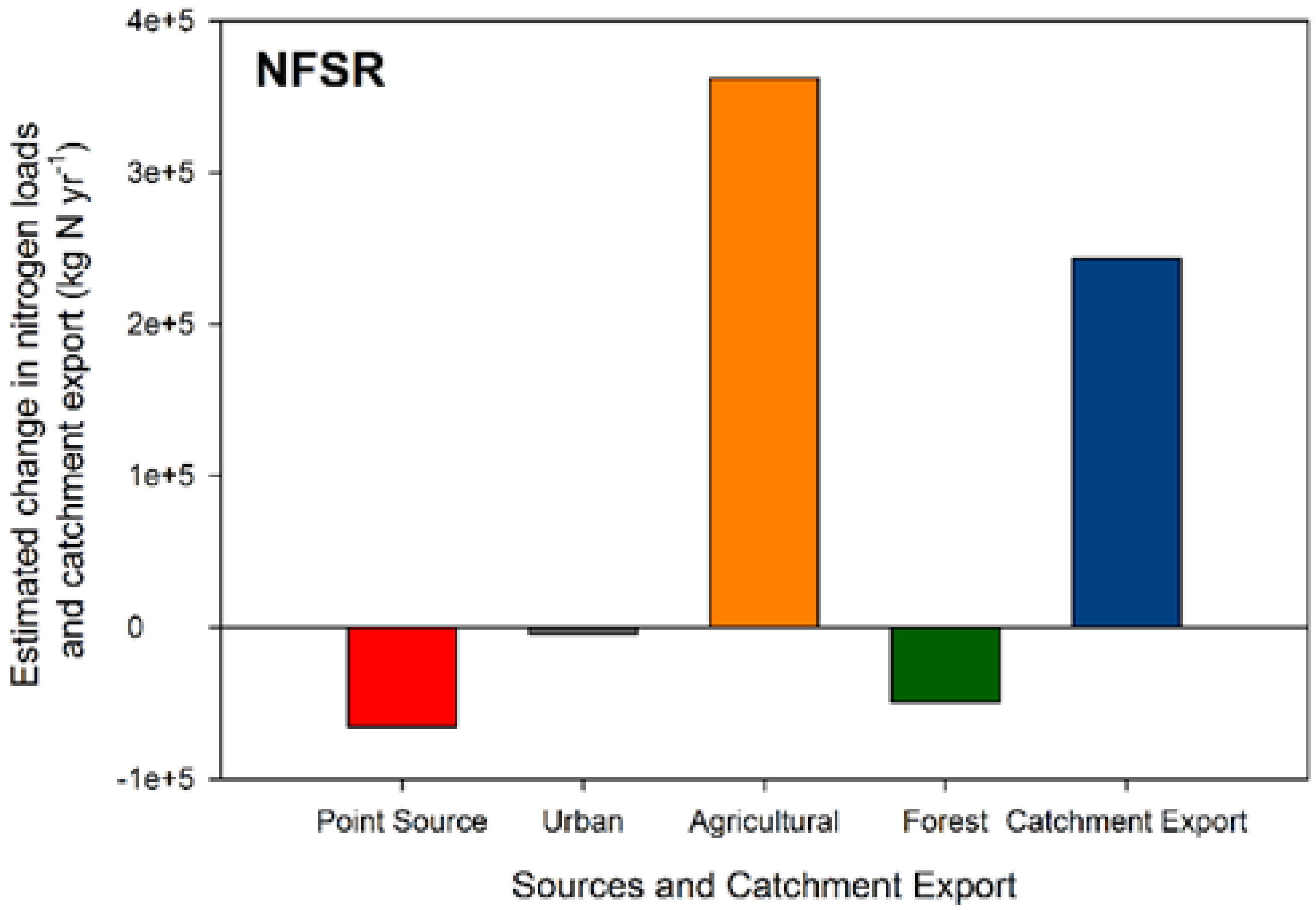

3e+6
3e+6
2e+6
2e+6
1e+6
5e+5
0
Watershed Export (kg N yr-1)
1985
1990
1995
2000
2005
2010
Year
LLUS-N Model
LLUS-N with zero discharge effect
Observed WRTDS Export Values


NFSR
Agricultural Land
Point Source
Catchment
Mean Annual Flow-Weighted Concentration (mg N L-1)
Year
0
5
10
15
20
25
30
35
40
1985
1990
1995
2000
2005
2010


NFSR
Urban
Forests
Catchment
Mean Annual Flow-Weighted Concentration (mg N L-1)
Year
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1985
1990
1995
2000
2005
2010

Countervailing changes in point and non-point source nutrient loads

- Decreased atmospheric N deposition reduced non-point source loads across the catchment
  - Decreased atmospheric deposition offset increased agricultural loads by 10%
- Decreased point source loads and non-point source loads from urban areas and forests offset increased agricultural loads by 32%



Inventories can be used to describe local changes in the N cycle and attribute changes in catchment nitrogen export

- North Fork Shenandoah analysis suggested that increased manure inputs from bourgeoning poultry production is increasing agricultural surpluses
  - Point source loads were increasing until the late 90s.
- It retains roughly 80% of non-point source inputs and point source loads!
  - No apparent change in the retentiveness in the catchment was detected
- Changes in non-point source inputs and point source loads along with annual catchment discharge can explain the inter-annual variation in catchment TN export
  - Changes in non-point source inputs and point source loads can only explain the trend, however!
- These narratives and simple empirical models can be developed for any catchment of interest using GIS software and Microsoft excel.

Non-Hydrologic Nitrogen Losses from Land

Agricultural N_2O

Agricultural Denitrification (N_2)

Agricultural NH_y

Forest Fire

Other Emission Sources

Livestock N Content*

Harvested Crop N Content

Total non-Hydrologic N Losses from Land




Nitrogen Inputs onto Land

Natural N Fixation

Agricultural Fertilizer

Urban Fertilizer

N-fixing Crop Cultivation

Livestock Waste, Livestock N Recovered*

Human N Waste

Total N Deposition

Total Nitrogen Inputs onto Land

Emissions from Fossil Combustion and Lightning
Lightning
Fossil Fuel Combustion: Transportation
Fossil Fuel Combustion: Utility and Industry
Subtotal of Fossil Fuel Combustion
Total Fossil Fuel and Lightning Emissions
Human and Livestock N Demand
Livestock Food Demand
Human Food Demand
Total N Demand