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\textsubscript{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 (Lawrence 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)
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 km², 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!

### Table: Nitrogen Inputs onto Land

<table>
<thead>
<tr>
<th>Years</th>
<th>2002</th>
<th>2007</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Inputs onto Land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural N Fixation</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Agricultural fertilizer</td>
<td>9.8</td>
<td>11.2</td>
<td>11.9</td>
</tr>
<tr>
<td>Urban Fertilizer</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>N-fixing Crop Cultivation</td>
<td>5.8</td>
<td>6.0</td>
<td>5.8</td>
</tr>
<tr>
<td>Livestock N Recovered*</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Human N Waste</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Total N Deposition</td>
<td>6.9</td>
<td>6.1</td>
<td>5.5</td>
</tr>
<tr>
<td>Livestock Waste</td>
<td>6.0</td>
<td>6.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Grand Total of Nitrogen Inputs onto Land</td>
<td>34.9</td>
<td>36.2</td>
<td>34.8</td>
</tr>
</tbody>
</table>
Equivalency in N inputs not universal
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
Terrestrial Nitrogen Surplus declined 1.5 Tg
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\textsubscript{X} emission control programs (total N deposition)
  - 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
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

Year
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
Develop a simple watershed empirical loading model for total nitrogen

• Model proposed by Caraco and Cole (1999)

\[ E_{w,t} = (PS_{w,t} + I_{w,t} \times WS_{w,t}) \times S_w \]

1. Catchment TN export \((E_{w,t}, \text{ kg N yr}^{-1})\) in a given year is a function of some fraction of the summed point source \((PS_{w,t}, \text{ kg N yr}^{-1})\) and non-point source inputs \((I_{w,t}, \text{ kg N yr}^{-1})\) reaching the watershed outlet.

2. Both \(WS_{w,t}\) and \(S_w\) are both unitless export coefficients
   
   - \(WS_{w,t}\) is a non-linear function of discharge
   
   \[ WS_{w,t} = B_w R_{w,t} C_w \]
   
   - \(R_{w,t}\) (annual discharge)
   
   - \(B_w (\text{yr m}^{-1})\) and \(C_w\) (unitless) are both constants.
$E_{w,t} = (PS_{w,t} + I_{a,t} \times WS_{a,t} + I_{u,t} \times WS_{u,t} + I_{f,t} \times WS_{f,t}) \times S_w$
Parametrization and Optimization

- $WS_{a,t} = B_a R_{w,t}^{ca}$
- $WS_{u,t} = B_u R_{w,t}^{cu}$
- $WS_{f,t} = B_f R_{w,t}^{cf}$

- **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**
Watershed Export (kg N yr\(^{-1}\))

- **LLUS-N Model**
- **LLUS-N with zero discharge effect**
- **Observed WRTDS Export Values**

<table>
<thead>
<tr>
<th>Year</th>
<th>Watershed Export (kg N yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>0</td>
</tr>
<tr>
<td>1990</td>
<td>5e+5</td>
</tr>
<tr>
<td>1995</td>
<td>1e+6</td>
</tr>
<tr>
<td>2000</td>
<td>2e+6</td>
</tr>
<tr>
<td>2005</td>
<td>2e+6</td>
</tr>
<tr>
<td>2010</td>
<td>3e+6</td>
</tr>
</tbody>
</table>
The graphs depict the mean annual flow-weighted concentrations of nitrogen in the NFSR over the years 1985 to 2010. The concentrations are categorized into different sources:

- **Agricultural Land**
- **Point Source**
- **Forests**
- **Urban**
- **Catchment**

The left graph shows the trend for all categories combined, while the right graph separates the data for Urban, Forests, and Catchment. The data points indicate a significant increase in agricultural land concentrations before a sharp decline, possibly due to policies or management practices. The other categories show more fluctuating patterns with varying peaks and troughs.
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

<table>
<thead>
<tr>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural $\text{N}_2\text{O}$</td>
</tr>
<tr>
<td>Agricultural Denitrification ($\text{N}_2$)</td>
</tr>
<tr>
<td>Agricultural $\text{NH}_y$</td>
</tr>
<tr>
<td>Forest Fire</td>
</tr>
<tr>
<td>Other Emission Sources</td>
</tr>
<tr>
<td>Livestock N Content*</td>
</tr>
<tr>
<td>Harvested Crop N Content</td>
</tr>
</tbody>
</table>

**Total non-Hydrologic N Losses from Land**

29
## Nitrogen Inputs onto Land

<table>
<thead>
<tr>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural N Fixation</td>
</tr>
<tr>
<td>Agricultural Fertilizer</td>
</tr>
<tr>
<td>Urban Fertilizer</td>
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<tr>
<td>Livestock Waste, Livestock N Recovered*</td>
</tr>
<tr>
<td>Human N Waste</td>
</tr>
<tr>
<td>Total N Deposition</td>
</tr>
</tbody>
</table>

**Total Nitrogen Inputs onto Land**
### Emissions from Fossil Combustion and Lightning

<table>
<thead>
<tr>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning</td>
</tr>
<tr>
<td>Fossil Fuel Combustion: Transportation</td>
</tr>
<tr>
<td>Fossil Fuel Combustion: Utility and Industry</td>
</tr>
</tbody>
</table>

### 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