Finding Solutions for Sustainable Nitrogen Use in Midwest Cropping Systems

An Overview of the Agricultural Nitrogen Cycle

The Nitrogen Roundtable
June 1, 2016

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Grand Challenges Facing Agriculture in the 21st Century

By 2050, agriculture will need to:

• Supply enough agricultural products to support 9.7 billion people;
• Without substantially depleting natural resources or further degrading the environment;
• Against a background of significant climate change.
• Even in the absence of climate change, this would be a significant challenge.

• More than ¾ of the 70% increase in global food production needed by 2050 will have to come from the ‘sustainable intensification’ of existing agricultural lands (FAO 2011).

After M. Walbridge, pers. comm.; World Bank 2014
U.S. Average Yields for Major Grain Crops from 1930

Source: USDA NASS 2015
U.S. Average Yields for Major Grain Crops from 1930

The response of corn to nitrogen fertilizer is typical for most crops, grasslands, and forests.
Environmental Signals of Agricultural Intensification

- Inland Phosphorus
- Coastal Nitrate
- Atmospheric N<sub>2</sub>O
- Habitat / Biodiversity loss
Environmental Signals of Agricultural Intensification

Inland Phosphorus

Atmospheric $N_2O$

Coastal Nitrate

Groundwater Nitrate
Fate of fertilizer N added to a typical farm field

Less than 17% of the N added as fertilizer is consumed as protein by humans

Source: UNEP 2007
Today’s talk

1. N-cycle basics
   - What you need to know to be conversant about N-cycle problems and solutions
   - Overall N-cycle and pressure points

2. Pathways of loss that matter most
   - Nitrate leaching
   - Nitrous oxide emissions

3. Looking forward
   - Climate impacts on agricultural N
   - Agricultural N as a climate mitigation strategy
A generalized nutrient cycle

Source: After Charley and Richards 1983
The Generalized Nitrogen Cycle

**Three Entry Points**

- Manure-N
- Erosion-N
- Fertilizer-N / Precipitation-N

**Processes**

- Dinitrogen Fixation
- Denitrification
- N$_2$, N$_2$O
- NH$_3$, N$_2$O
- Nitrification
- Leaching
- Groundwater-N

**Source:** Robertson & Groffman 2015
The Generalized Nitrogen Cycle

Source: Robertson & Groffman 2015
The Generalized Nitrogen Cycle

3 Major Loss Pathways

Source: Robertson & Groffman 2015
Fast Facts

1. Field crops remove a lot of nitrogen in harvest

<table>
<thead>
<tr>
<th></th>
<th>Grain</th>
<th>Stover</th>
<th>Total Uptake</th>
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<tbody>
<tr>
<td>Corn</td>
<td>84</td>
<td>22</td>
<td>106</td>
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<tr>
<td>Wheat</td>
<td>61</td>
<td>9</td>
<td>70</td>
</tr>
</tbody>
</table>

*Based on KBS conventional yields, ~national average*

2. Nitrogen use efficiency is low

- About 50% of N fertilizer added to corn is lost
- Maximizing yields requires the addition of much more N than the crop can take up

*Source: Millar and Robertson 2015*
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   - Climate impacts on agricultural N
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Examples from KBS
## KBS Long-Term Ecological Research (LTER) Site

<table>
<thead>
<tr>
<th>Ecosystem Type</th>
<th>Management Intensity</th>
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<tbody>
<tr>
<td><strong>Annual Grain Crops (Corn - Soybean - Wheat)</strong></td>
<td></td>
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<tr>
<td>Conventional tillage</td>
<td>High</td>
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<tr>
<td>No-till</td>
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<tr>
<td>Low-input with legume cover</td>
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<td>Biologically-based with legume cover</td>
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<td><strong>Perennial Biomass Crops</strong></td>
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<td>Alfalfa</td>
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<td>Hybrid poplars</td>
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<td><strong>Unmanaged Communities</strong></td>
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<td>Early successional old field</td>
<td>Low</td>
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<td>Mid successional old field</td>
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<tr>
<td>Late successional forest</td>
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### Diagram:
- **Left Column:**
  - *Annual Grain Crops (Corn - Soybean - Wheat)*
  - Conventional tillage
  - No-till
  - Low-input with legume cover
  - Biologically-based with legume cover
  - *Perennial Biomass Crops*
    - Alfalfa
    - Hybrid poplars
  - *Unmanaged Communities*
    - Early successional old field
    - Mid successional old field
    - Late successional forest

- **Right Column:**
  - Photos of different ecosystems and management practices.
USDA Long-term Agricultural Research Network

- 18 long-term research sites in nascent network
- ARS, university, and institute-based
- National coverage - USDA (ERS) Farm Resource Regions

Source: ars.usda.gov/research/programs/programs.htm?np_code=211&docid=22480
Annual Cropping Systems

- Maize – Soybean – Wheat Rotations
- Rainfed, 1 primary crop per year (May-October growing season, 600mm)
- Four management treatments (full factorial design, 6 replicate 1-ha plots)

Conventional System

*Current farmer practice using synthetic inputs*

- Chisel plow + secondary tillage
- Herbicides, insecticides applied based on Integrated Pest Management (scouting plus very targeted pesticide applications)
- Varieties chosen from regional trials (GMO maize, soybean)
- Fertilizer based on university-based (Extension) recommendations and fertilizer-response trials
- No manure
- No cover crops

> Leaching and N$_2$O loss

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Resource Gradient: 2011 Corn Yields

- Rainfed
- Irrigated
Annual Cropping Systems, cont.

**No-till System**

*Same as Conventional System but no-till management*

- Permanent no-till since 1989
- Additional herbicides as needed
- Pesticides, varieties, fertilizer rates same as Conventional
- No manure, no cover crops

**Reduced Input System**

*Same as Conventional System but using fewer synthetic inputs, more biology*

- One-third herbicides (band within rows, no broadcast)
- Mechanical weed control between rows
- One-third N fertilizer (N from cover crops)
- Winter cover crops provide nitrogen
  - Annual rye grass after maize
  - Clover after wheat before maize

Cultivating maize

Clover in wheat

Leaching and $N_2O$ loss
Annual Cropping Systems, cont.

**Biologically Based System**

Same as Conventional System but no synthetic chemicals

- Mechanical weed control same as Reduced Input System
- No fertilizers, herbicides, insecticides
- No GMOs
- Cover crops same as Reduced Input System
  - Annual rye grass after corn before soybeans
  - Clover after wheat before corn

Incorporating cover crop

Cultivating soybeans

Leaching and $N_2O$ loss
KBS vs. National Yields
Corn: KBS ≈ U.S.
Soybean: KBS ≥ U.S.
Wheat (soft red): KBS > U.S.

Source: Robertson et al. 2014 BioScience
Nitrate Loss from KBS Cropping Systems 1996-2007

Source: Syswerda, et al. 2012 AEE
All 3 of the major biogenic greenhouse gases are affected by agriculture (~13% of total global GHG load)

Atmospheric Concentrations from 1000 C.E.

- **CO₂ GWP = 1**
- **CH₄ GWP = 23**
- **N₂O GWP = 296**

The contemporary N₂O increase is largely due to agricultural intensification

- with a total annual impact \(~1.2\) Pg C_{equiv} 
  (compare to atmospheric CO₂ loading = 4.3 Pg C y⁻¹)

- Industry is responsible for \(~16\)% of the anthropogenic source

- Agriculture for the remainder

- with most of the agricultural increase (\(~60\)% from cropped soils)

Nitrous Oxide Fluxes at KBS (1992-2010)

Source: Robertson et al. 2000 Science; Gelfand and Robertson 2015
Today’s talk

1. N-cycle basics
   - what you need to know to be conversant about problems and solutions
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2. Pathways of loss that matter most
   - Nitrate leaching
   - Nitrous oxide emissions

3. Looking forward
   - Agricultural N (N$_2$O) and climate mitigation
   - Climate impacts on agricultural N
Sources of Global Warming Impact (GWI) in Field Crop Ecosystems

- Soil carbon change
- Fuel use
- Nitrogen fertilizer
- Lime (carbonate) inputs
- Pesticides, seeds, other inputs
- $\text{N}_2\text{O}$ emission
- $\text{CH}_4$ consumption & emission
## Global Warming Impact of Field Crop Activities

<table>
<thead>
<tr>
<th></th>
<th>Soil-C</th>
<th>N-Fert</th>
<th>Fuel</th>
<th>Other Inputs</th>
<th>N$_2$O</th>
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</tbody>
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### NB

a. Soil C is at equilibrium (no annual change)
b. N$_2$O is single largest source of GWP
c. Net impact >100 g CO$_2$-equiv / m$^2$/y

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015
# Global Warming Impact of Field Crop Activities

Agricultural N (N$_2$O) and climate mitigation

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**NB No-till**

a. No-till C gain provides substantial mitigation

b. Other sources (including N$_2$O) similar

c. Net impact is negative - mitigation

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015
Global Warming Impact of Field Crop Activities

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<td>8</td>
<td>32</td>
<td>-1</td>
<td>-124</td>
</tr>
</tbody>
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**NB Biologically Based**

a. C gain even with more cultivation

b. Gains from no inputs, but no N$_2$O benefit

c. Net impact is very negative – net mitigation

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015
### Global Warming Impact of Field Crop Activities

**Table: Agricultural N ($N_2O$) and climate mitigation**

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<td>Successional Communities (Unmanaged)</td>
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<tr>
<td>Early Successional</td>
<td>-397</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>-1</td>
<td>-387</td>
</tr>
<tr>
<td>Mid-successional</td>
<td>-214</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>-3</td>
<td>-201</td>
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<tr>
<td>Deciduous Forest</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>-5</td>
<td>7</td>
</tr>
</tbody>
</table>

**NB Successional**

* a. Huge soil C gain early in succession (only)
* b. $N_2O$ fluxes low throughout (low nitrate availability)
* c. Net impact high early, neutral late

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015
Net Global Warming Impact of Cropped and Successional Ecosystems at KBS

Agricultural N (N\textsubscript{2}O) and climate mitigation

~40% of this is N\textsubscript{2}O
~35% fertilizer mfr

Most of this is soil C

Most of this is soil C + no N fertilizer

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015
N$_2$O fluxes are strongly affected by nitrogen fertilizer inputs

- Non-linear N$_2$O increase with added N (exponentially increasing)
Cross-state test of non-linear $\text{N}_2\text{O}$ response to N-fertilizer

$\text{N}_2\text{O}$ emissions = $0.67 \times \exp(0.0067 \times \text{N rate})$

Hoben et al., 2011, GCB
Over-fertilizing matters a lot

- $N_2O$ fluxes accelerate at N-fertilizer rates greater than yield response
- Implication – $N_2O$ savings can be substantial where fertilizer rate exceeds crop needs

Source: McSwiney & Robertson 2005
At any given site, significant potential GHG mitigation

- Emissions factors vary with N-rate – especially above crop optimum

\[ \text{N}_2\text{O emissions} = 9.6 + 0.24 \times e^{(0.021 \times \text{N rate})} \]

Potential CO\textsubscript{2}e Savings

Optimum N Fertilizer Rate

Millar et al., in review
Today’s talk

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   - Agricultural N ($N_2O$) and climate mitigation
   - Climate change impacts on agricultural N
Climate change is likely to release more reactive N to the environment

1) As growing season temperature extremes depress yields

E.G. maximum temperature effects on corn and soybean during grain filling (1980-2007 IL and IN):

Mishra and Cherkauer, 2010, AFM; NCA 2014
Climate change is likely to release more reactive N to the environment

2) As N-intensive crops move northward, increasing N use and loss

North Dakota corn in 2014
3.05M acres (2.8x from 2000)

Iowa corn in 2014
13.6M acres (1.1x from 2000)

USDA; www.businessweek.com/articles/2014-08-18/corn-fuels-a-farmland-boom-in-the-northern-plains
Climate change is likely to release more reactive N to the environment

3) As extreme events such as drought depress the crop N sink

Climate change impacts on agricultural N

U.S. Drought Disaster Map 2012
ers.usda.gov

Bottom-water dissolved oxygen across the Louisiana shelf from July 22-28, 2013
npr.org

Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, R.E. Turner, Louisiana State University
Funded by: NOAA, Center for Sponsored Coastal Ocean Research
noaanews.noaa.gov/stories2013/2013029_deadzone
Climate change is likely to release more reactive N to the environment

4) As changing rainfall intensities affect N runoff, erosion

Number of once-in-five-year >2-inch precipitation events (compared to 1901-1960)

Kunkel et al. 2012; NCA 2014
Climate change is likely to release more reactive N to the environment.

5) As longer growing seasons and warmer winters mineralize more soil organic matter.

Part of a national trend

Andresen 2014, NCA 2014, Senthilkumar et al. 2009 SSSAJ
Climate change is likely to release more reactive N to the environment:

1) as growing season temperature extremes depress yields, leaving more N available for loss;

2) as N-intensive crops move northward, increasing regional N use and losses;

3) as extreme events such as drought depress crop N sinks;

4) as changing rainfall intensities affect N runoff and erosion; and

5) as warming winters and longer growing seasons mineralize more soil organic matter.

So: without intervention, even more reactive N circulating
Conclusions

1. The agricultural N cycle is complex but dominated by a limited number of inputs, internal pools, and loss pathways.

2. Management options abound for keeping N within the system:
   - Improving plant N use efficiency is attractive but elusive solution.
   - More important will be management changes that target specific transformations and loss pathways.

3. Nitrogen management has a role to play in climate mitigation.

4. Climate change, coupled with sustainable intensification, will make keeping N within the system all the harder in the future.