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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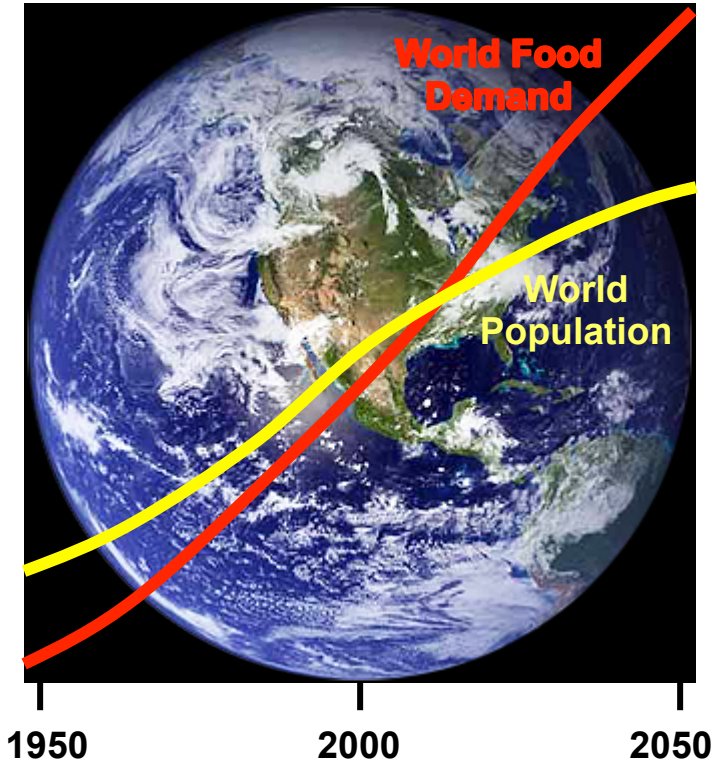
Grand Challenges Facing Agriculture in the 21st Century



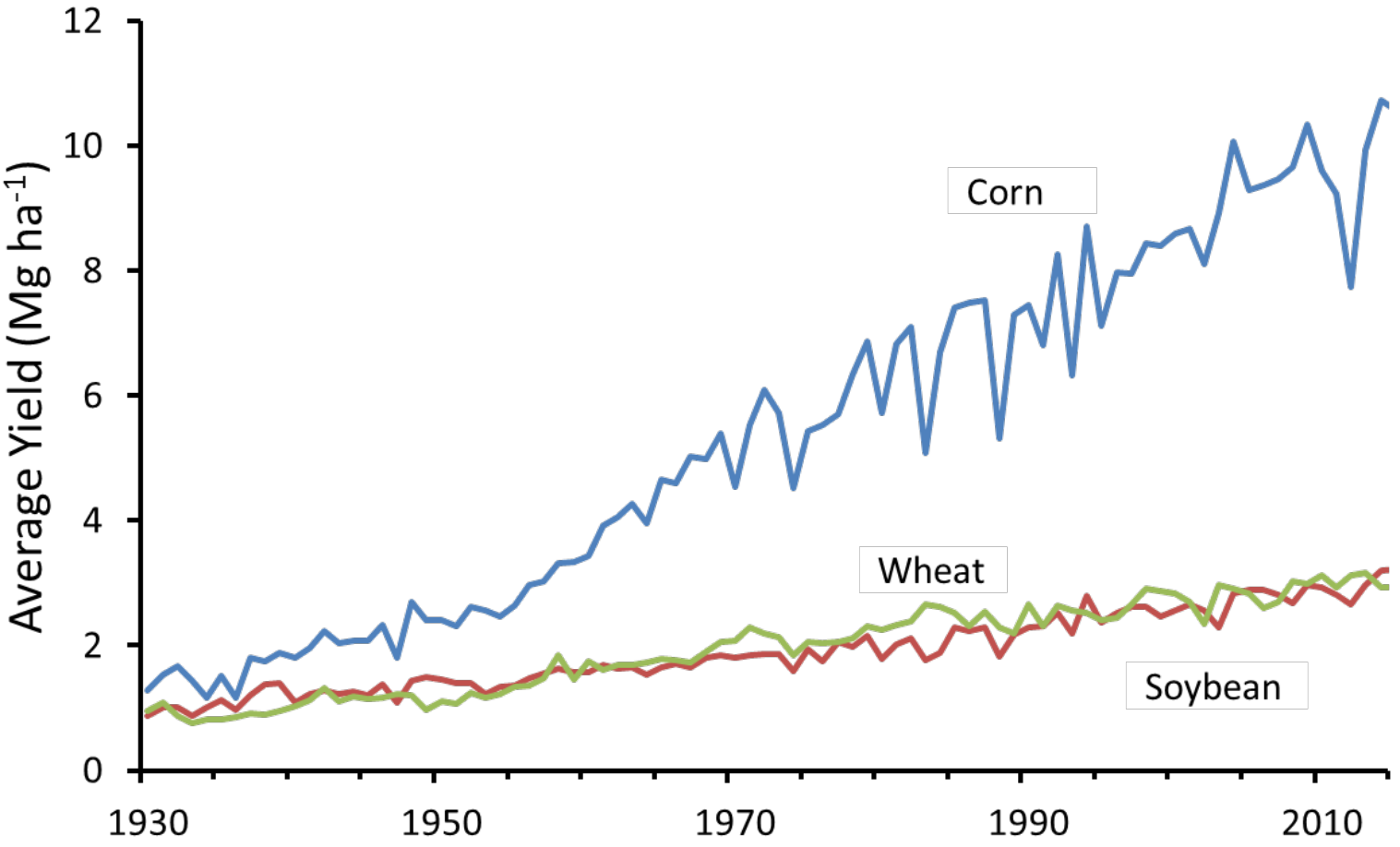
By 2050, agriculture will need to:

- 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).**

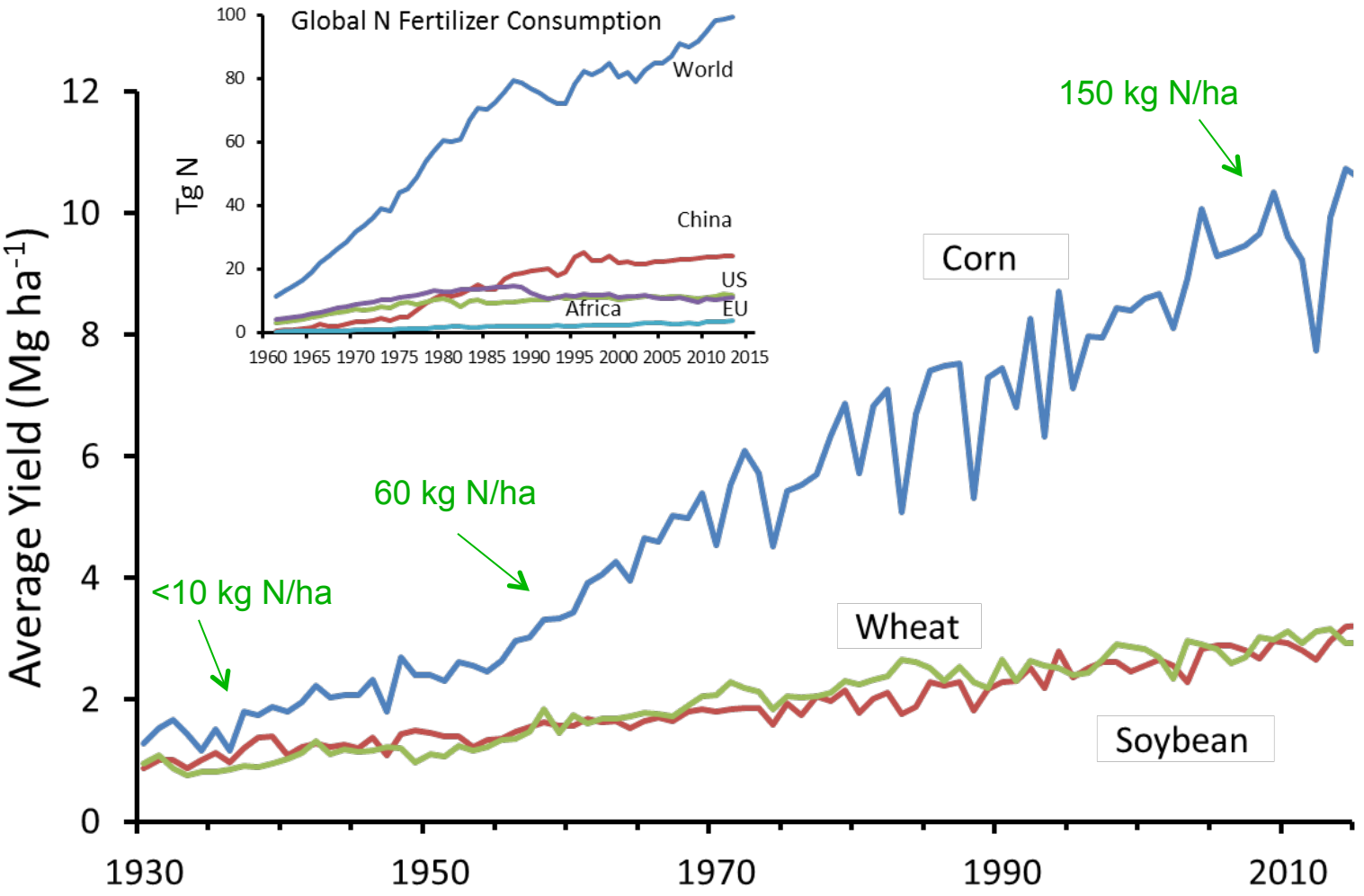
After M. Walbridge, pers. comm.; World Bank 2014

U.S. Average Yields for Major Grain Crops from 1930



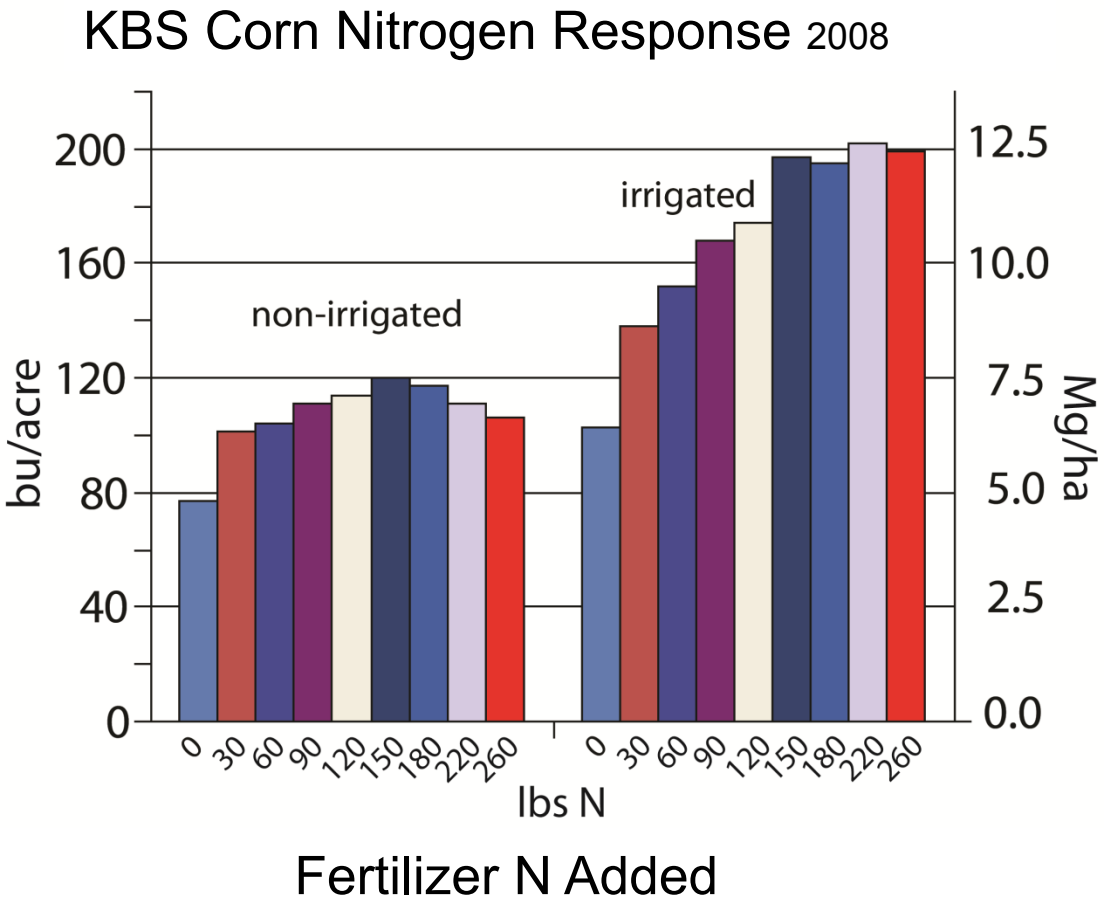
Source: USDA NASS 2015

U.S. Average Yields for Major Grain Crops from 1930



Source: USDA NASS 2015; FAO 2014; Robertson & Vitousek 2009 Ann .Rev.

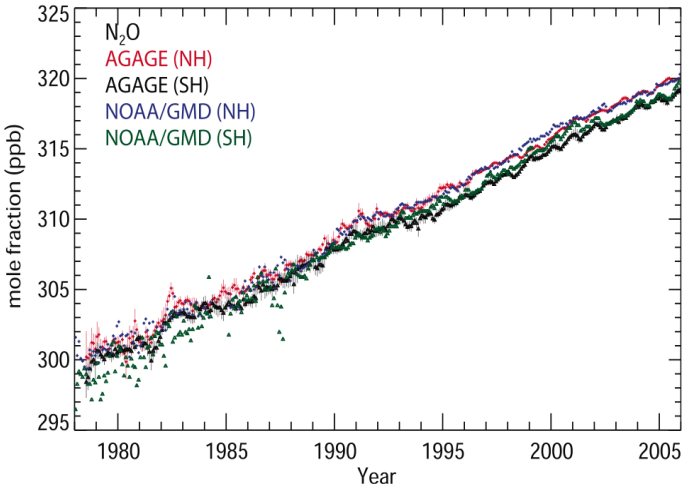
How important is nitrogen?



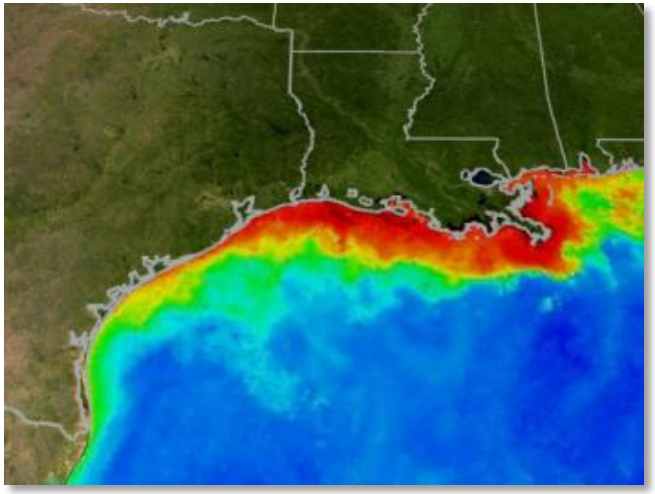
The response of corn to nitrogen fertilizer is typical for most crops, grasslands, and forests.

Environmental Signals of Agricultural Intensification

Inland Phosphorus



Atmospheric N_2O

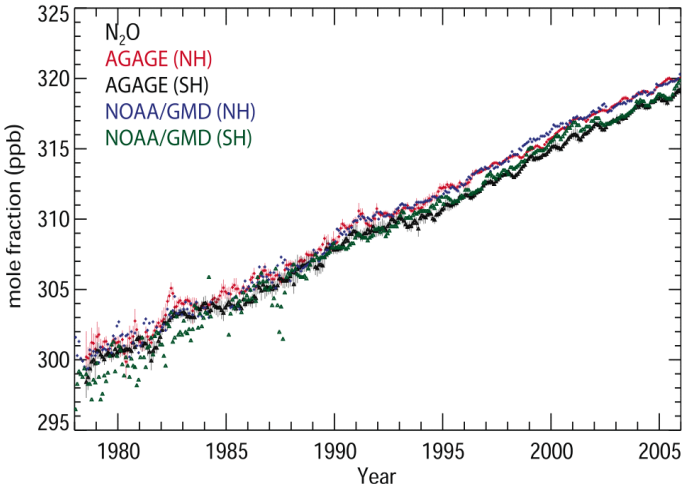


Coastal Nitrate

Habitat / Biodiversity loss

Environmental Signals of Agricultural Intensification

Inland Phosphorus



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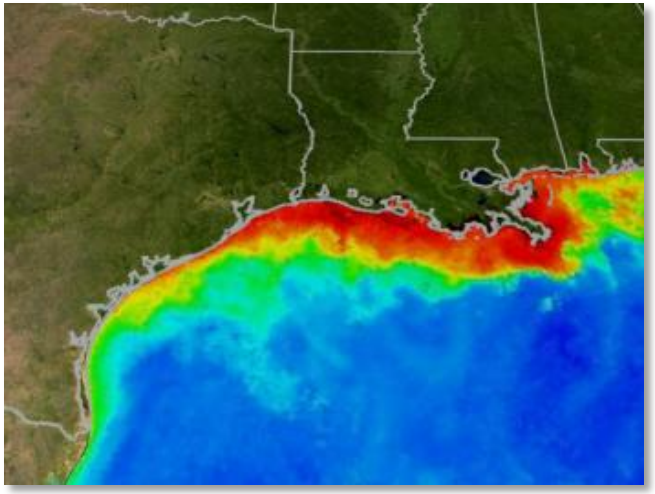
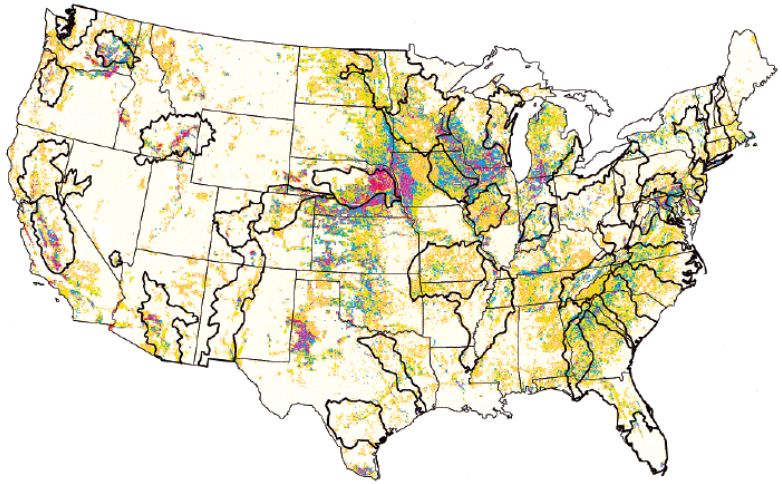
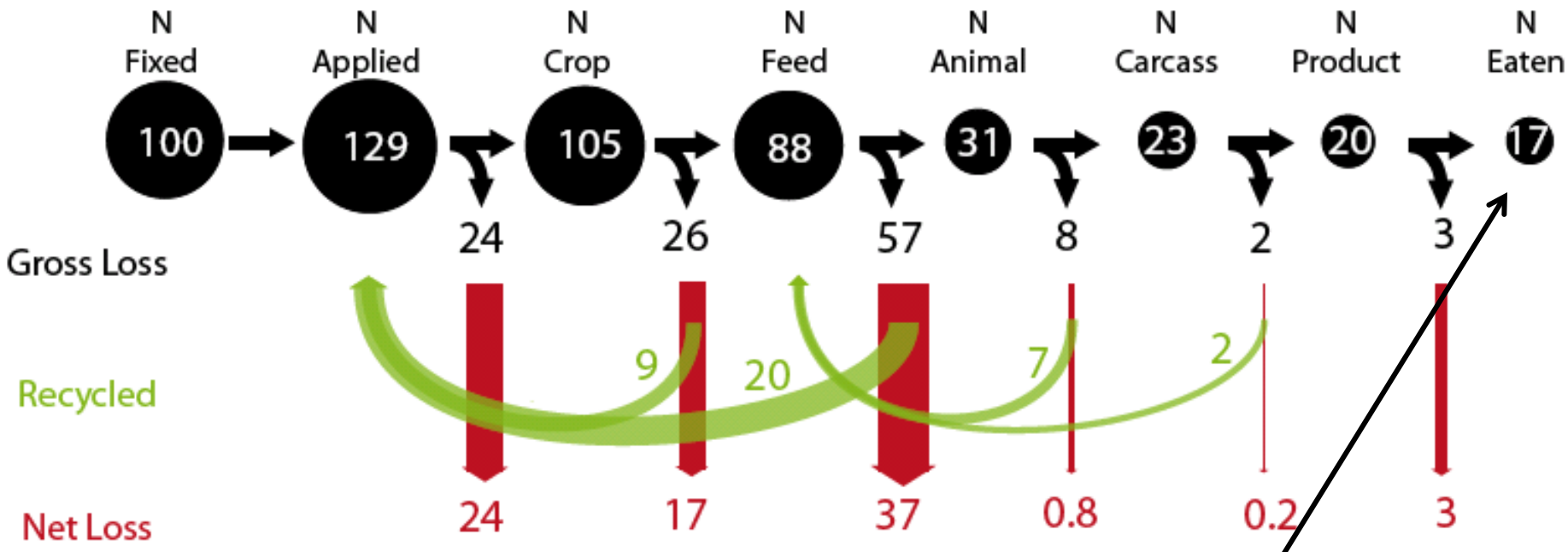


Coastal Nitrate



Groundwater Nitrate

Fate of fertilizer N added to a typical farm field



Units are kg N / ha

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

Source: UNEP 2007

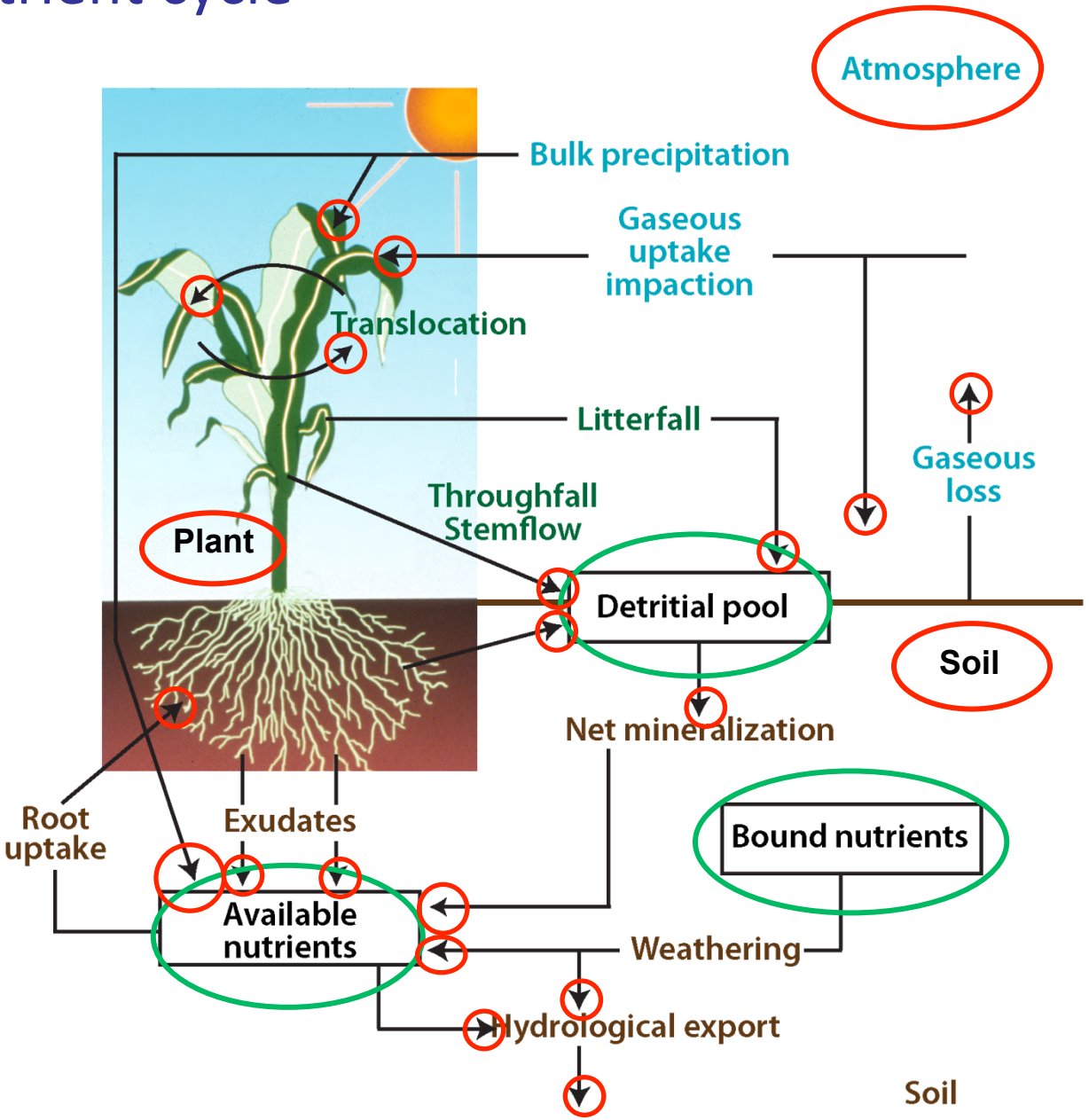
Today's talk

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

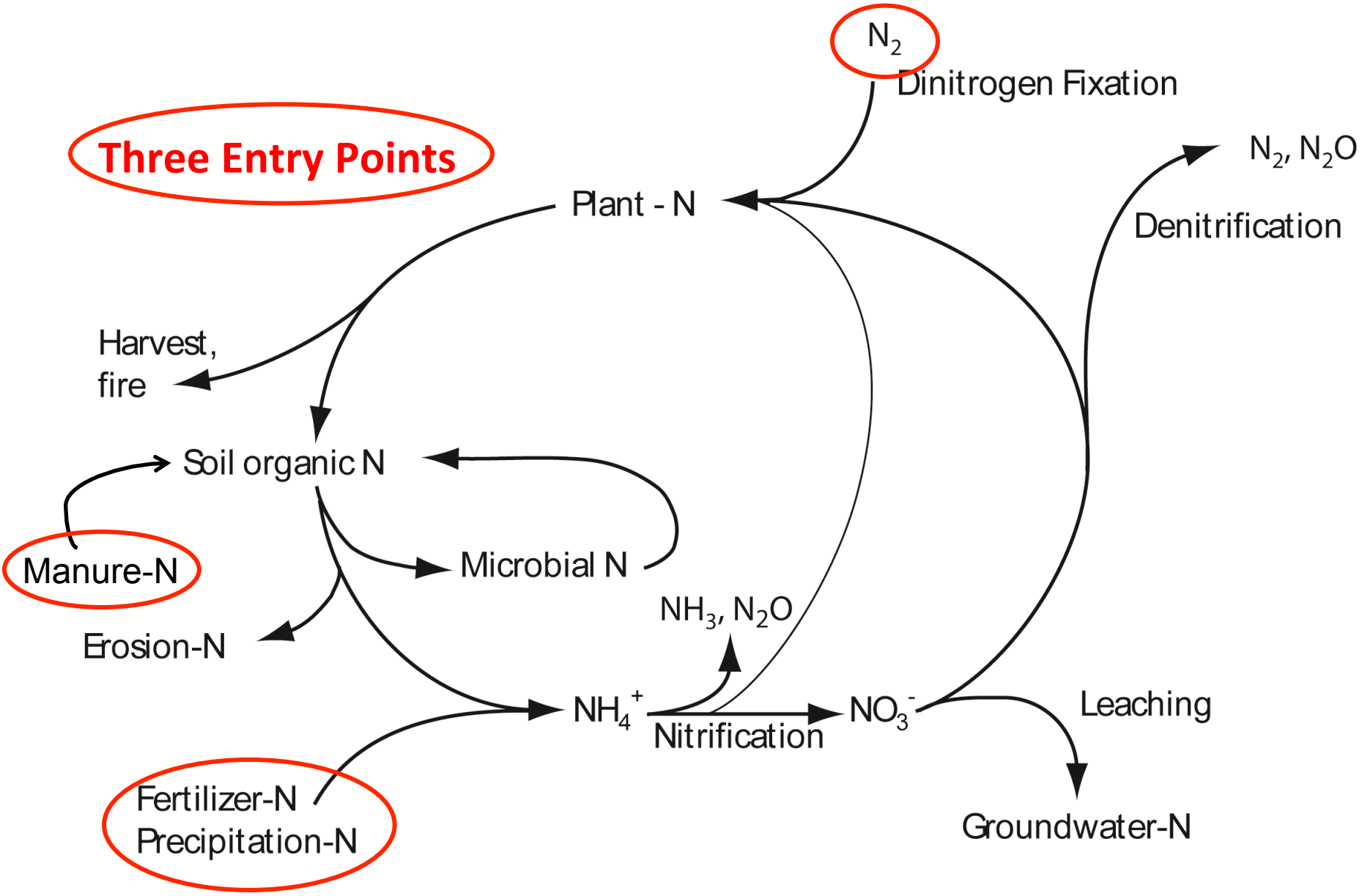
Pools

Fluxes



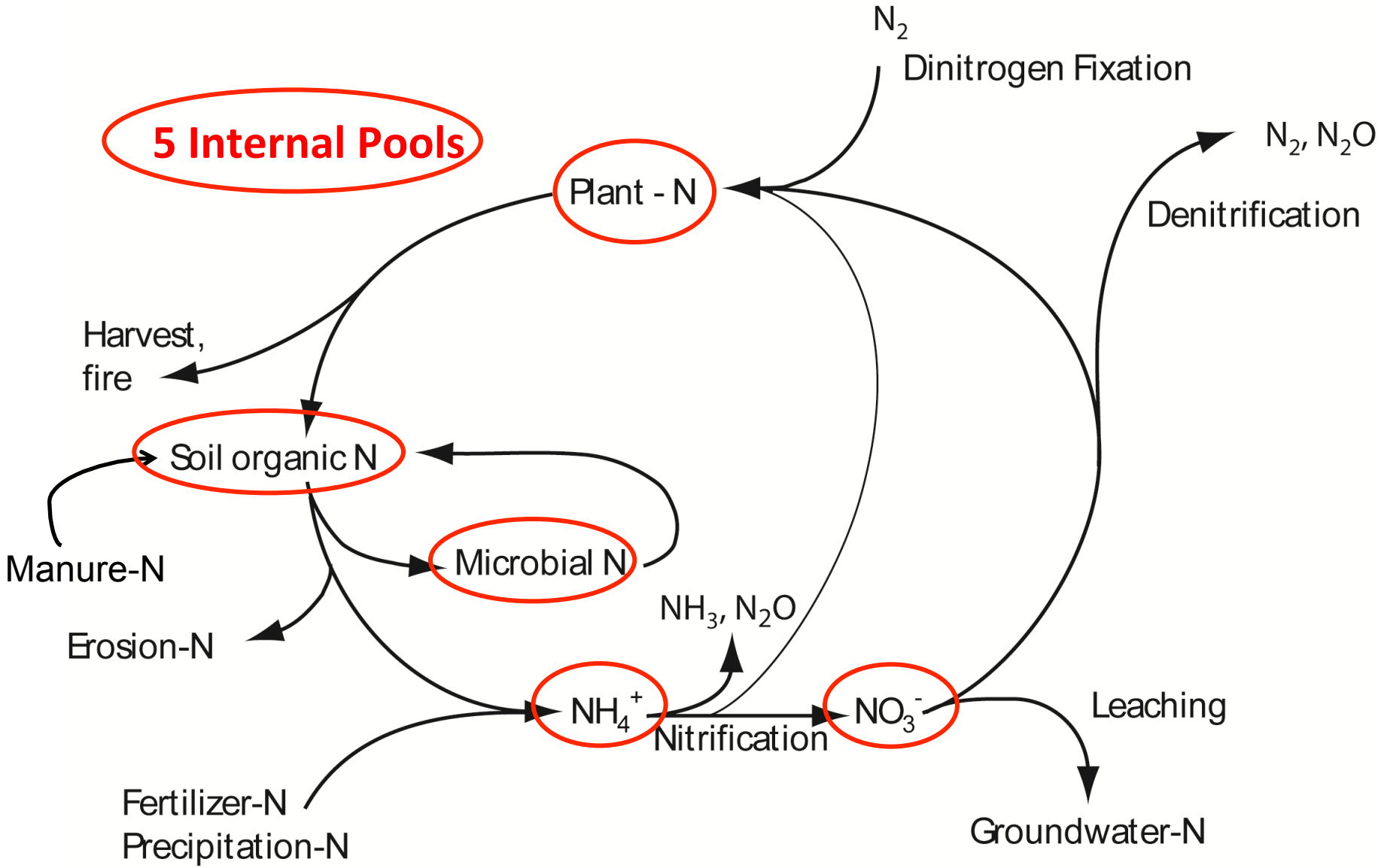
Source: After Charley and Richards 1983

The Generalized Nitrogen Cycle



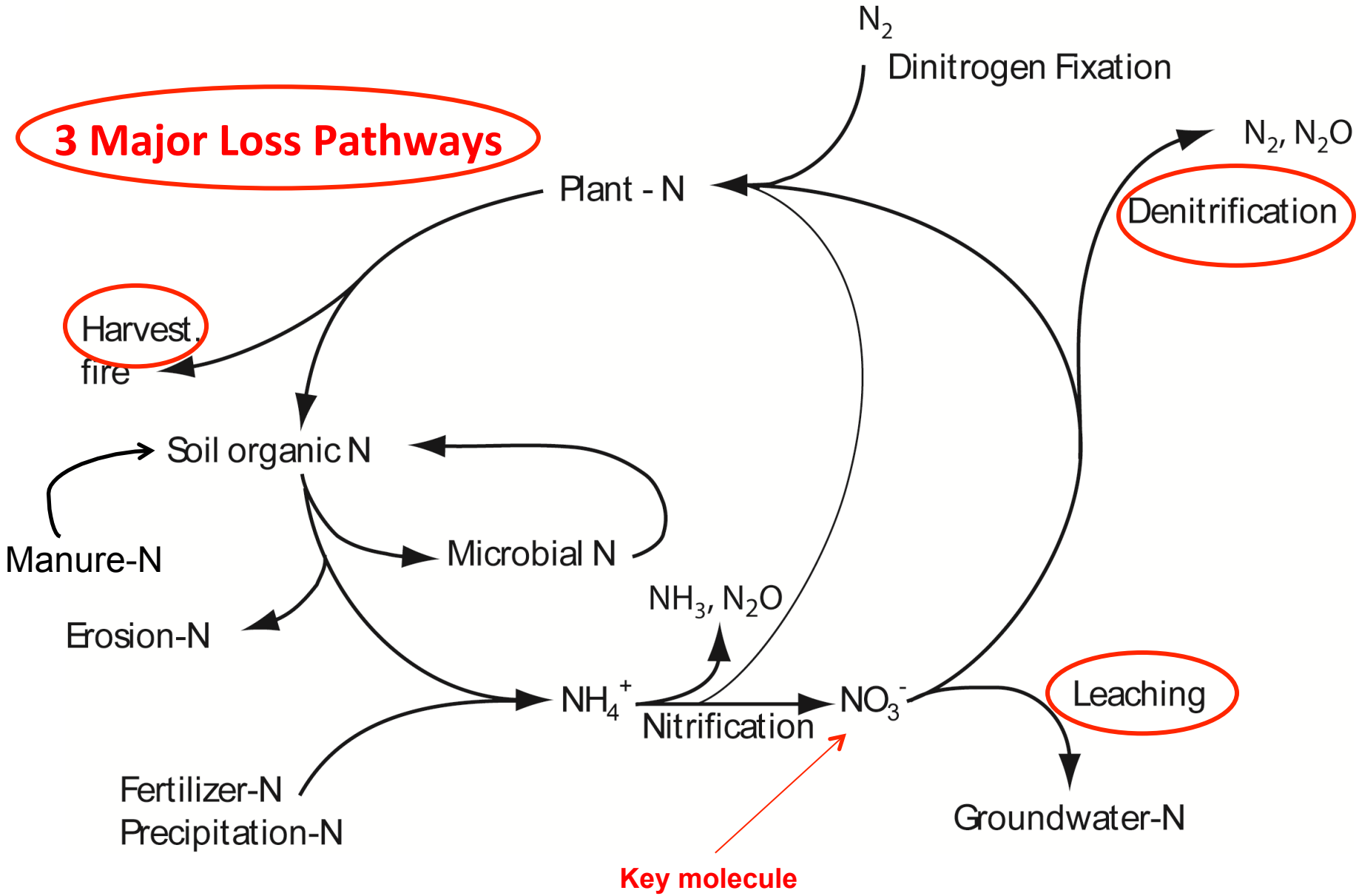
Source: Robertson & Groffman 2015

The Generalized Nitrogen Cycle



Source: Robertson & Groffman 2015

The Generalized Nitrogen Cycle



Source: Robertson & Groffman 2015

Fast Facts

1. Field crops remove a lot of nitrogen in harvest

	Grain	Stover	Total Uptake
	kg N ha $^{-1}$ y^{-1}		
Corn	84	22	106
Wheat	61	9	70

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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   - Nitrous oxide emissions

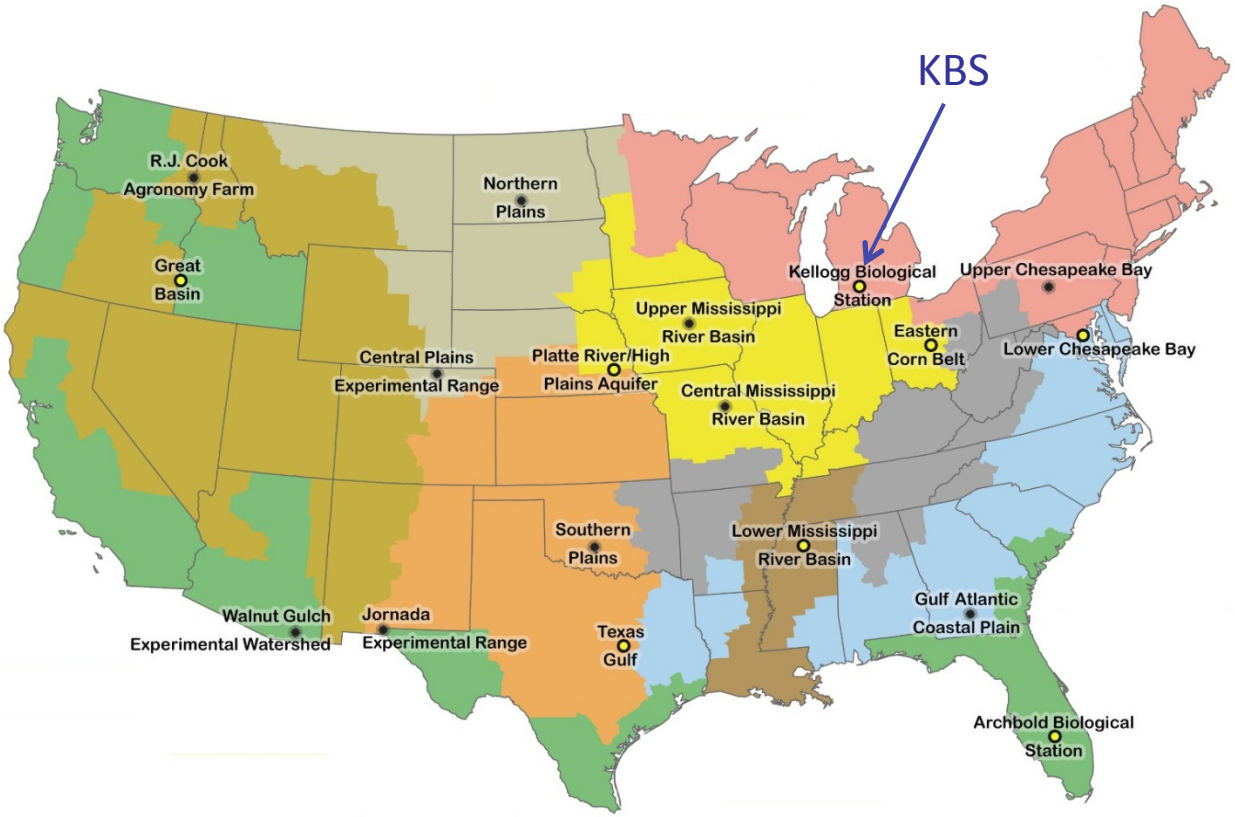
   } Examples from KBS
3. Looking forward
   - Climate impacts on agricultural N
   - Agricultural N as a climate mitigation strategy

KBS Long-Term Ecological Research (LTER) Site

Ecosystem Type	Management Intensity
Annual Grain Crops (Corn - Soybean - Wheat)	
Conventional tillage	High
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	
	Low

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

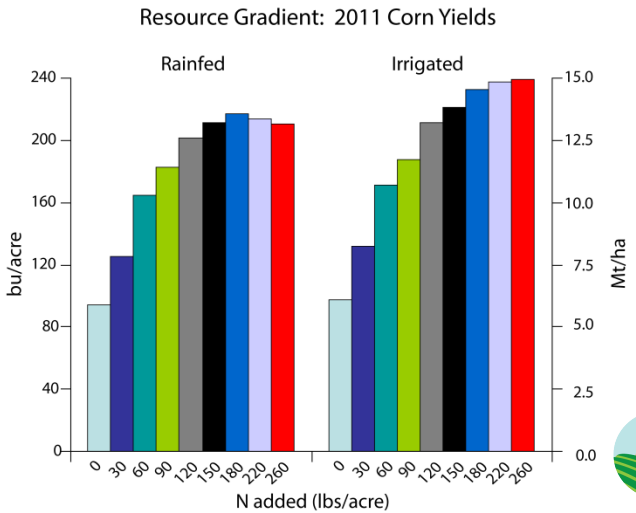
Annual Cropping Systems

- 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



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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

Annual Cropping Systems, cont.

Biologically Based System

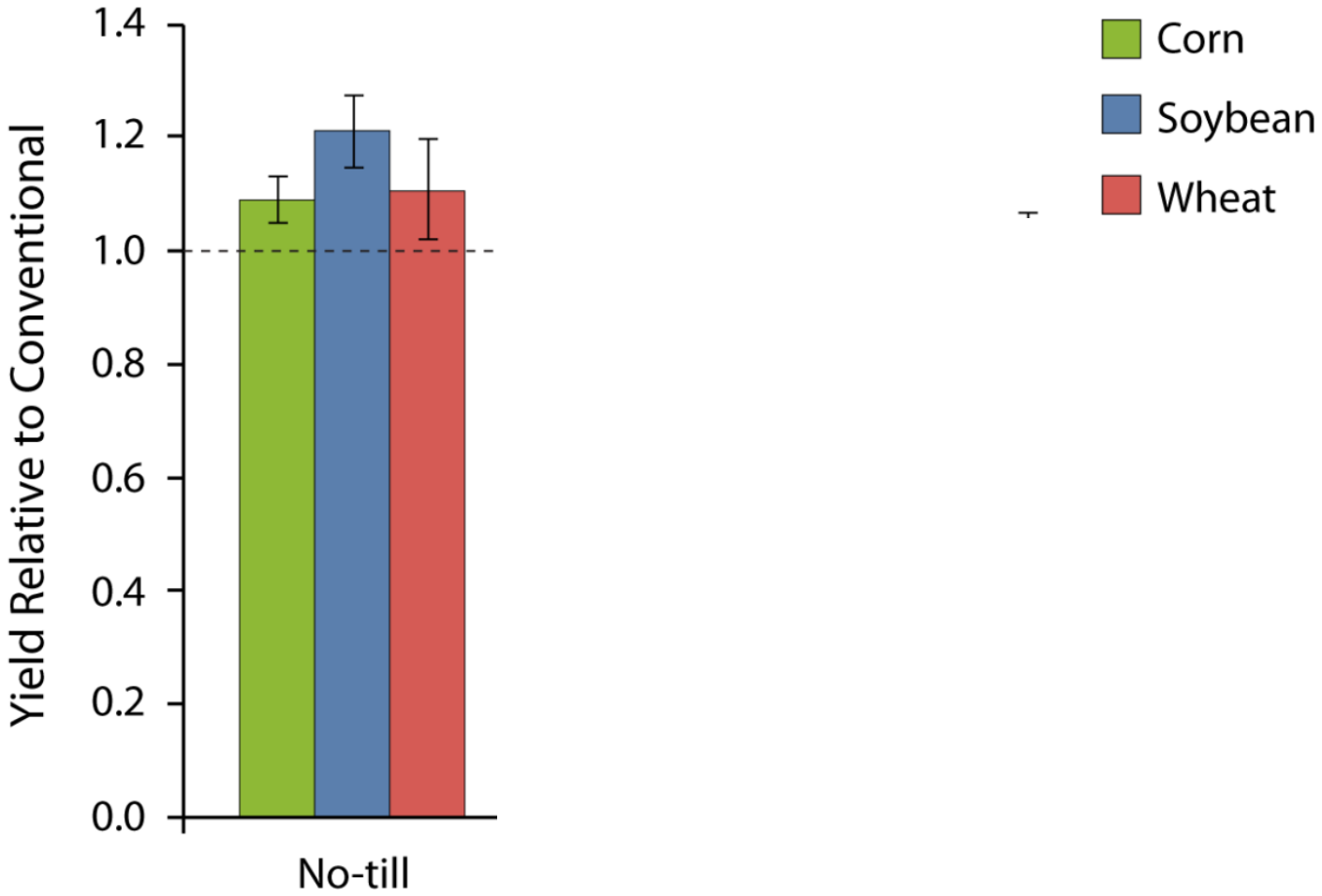
Same as Conventional System but no synthetic chemicals

- 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

Cultivating soybeans

Incorporating cover crop

KBS LTER Relative Yields (1989–2012)



KBS vs. National Yields

Corn: KBS ≈ U.S.

Soybean: KBS ≥ U.S.

Wheat (soft red): KBS > U.S.

Source: Robertson et al. 2014 BioScience

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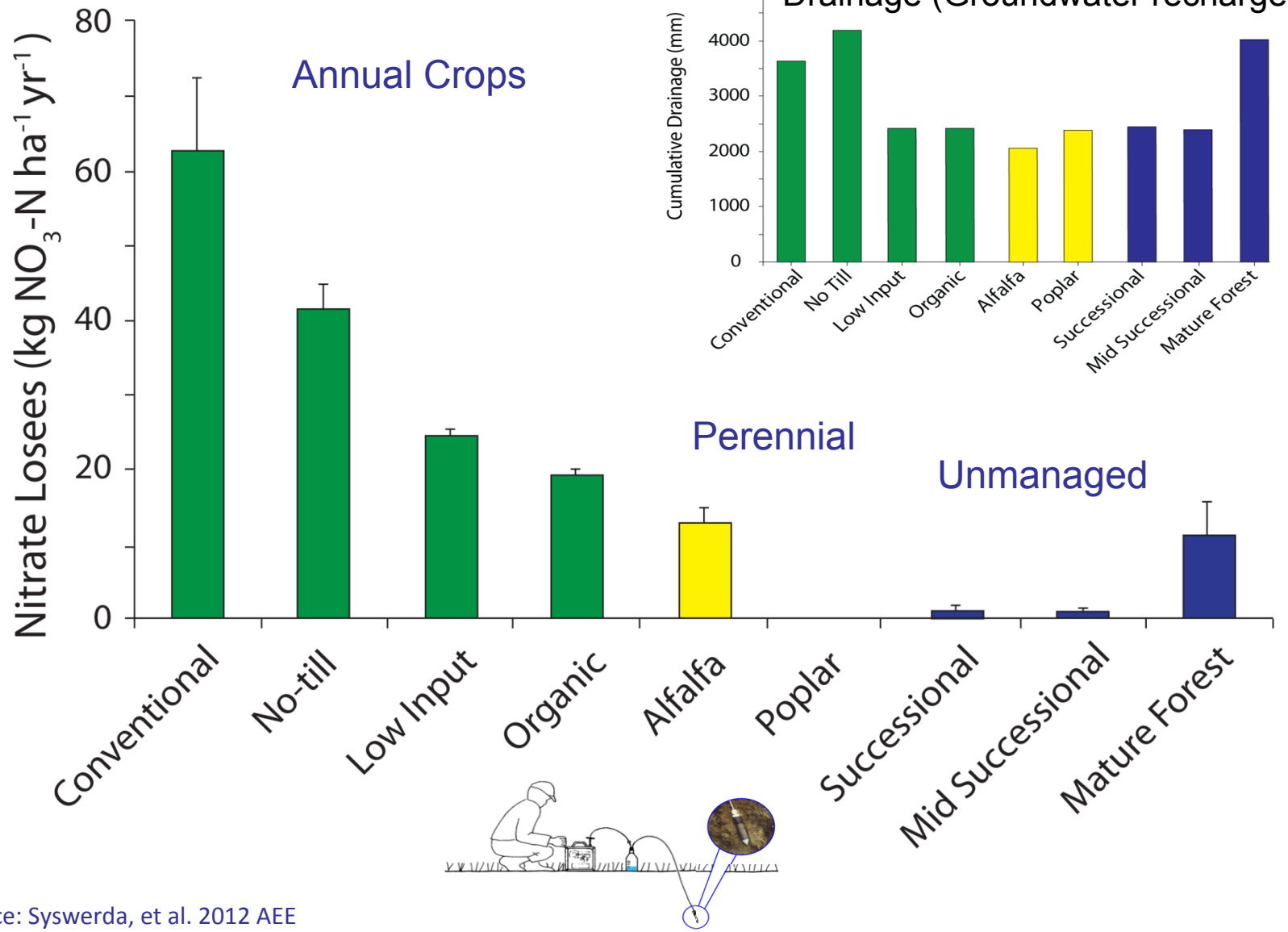
Nitrate Loss from KBS Cropping Systems 1996-2007



Source: Syswerda, et al. 2012 AEE

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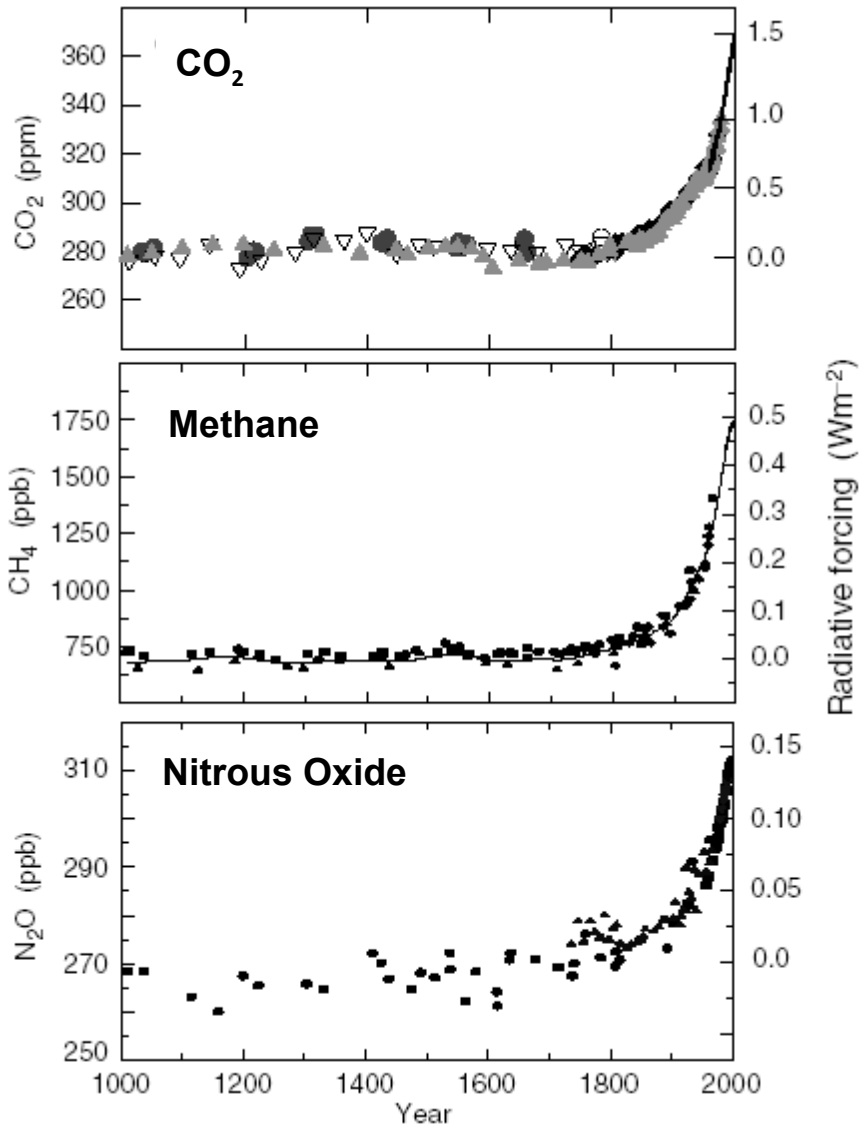
All 3 of the major biogenic greenhouse gases are affected by agriculture (~13% of total global GHG load)

Atmospheric Concentrations from 1000 C.E.



Source: IPCC (2001, 2007)

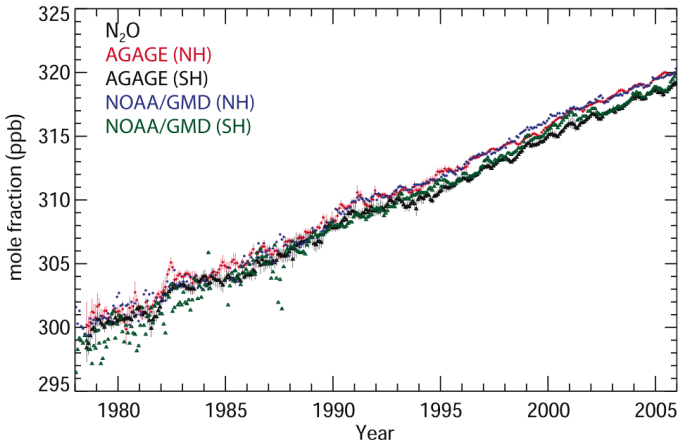
CO_2 GWP = 1

GWP = Global Warming Potential for 100 y time horizon

CH_4 GWP = 23

N_2O GWP = 296

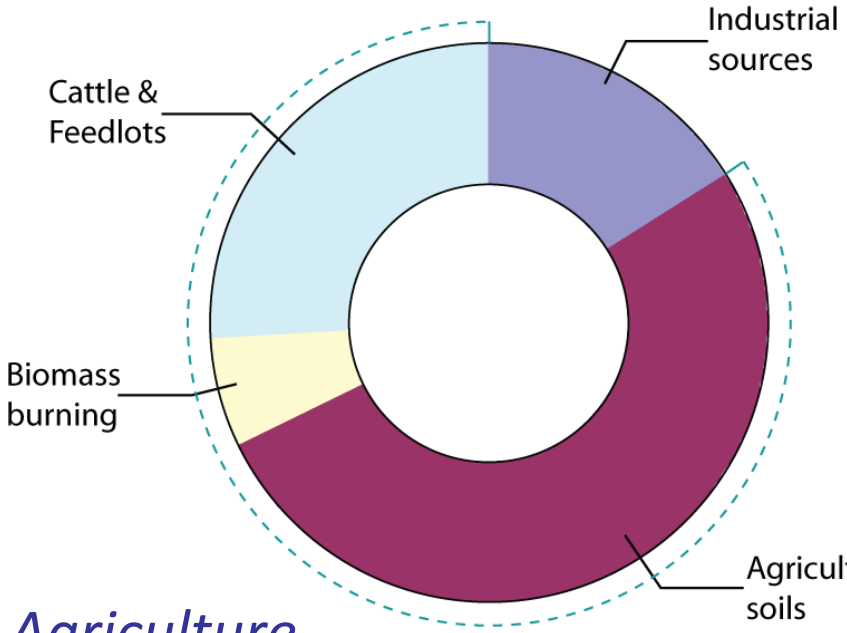
Atmospheric N_2O from 1976



The contemporary N_2O increase is largely due to agricultural intensification

- with a total annual impact ~ 1.2 Pg C_{equiv}

(compare to atmospheric CO_2 loading = 4.3 Pg C y^{-1})

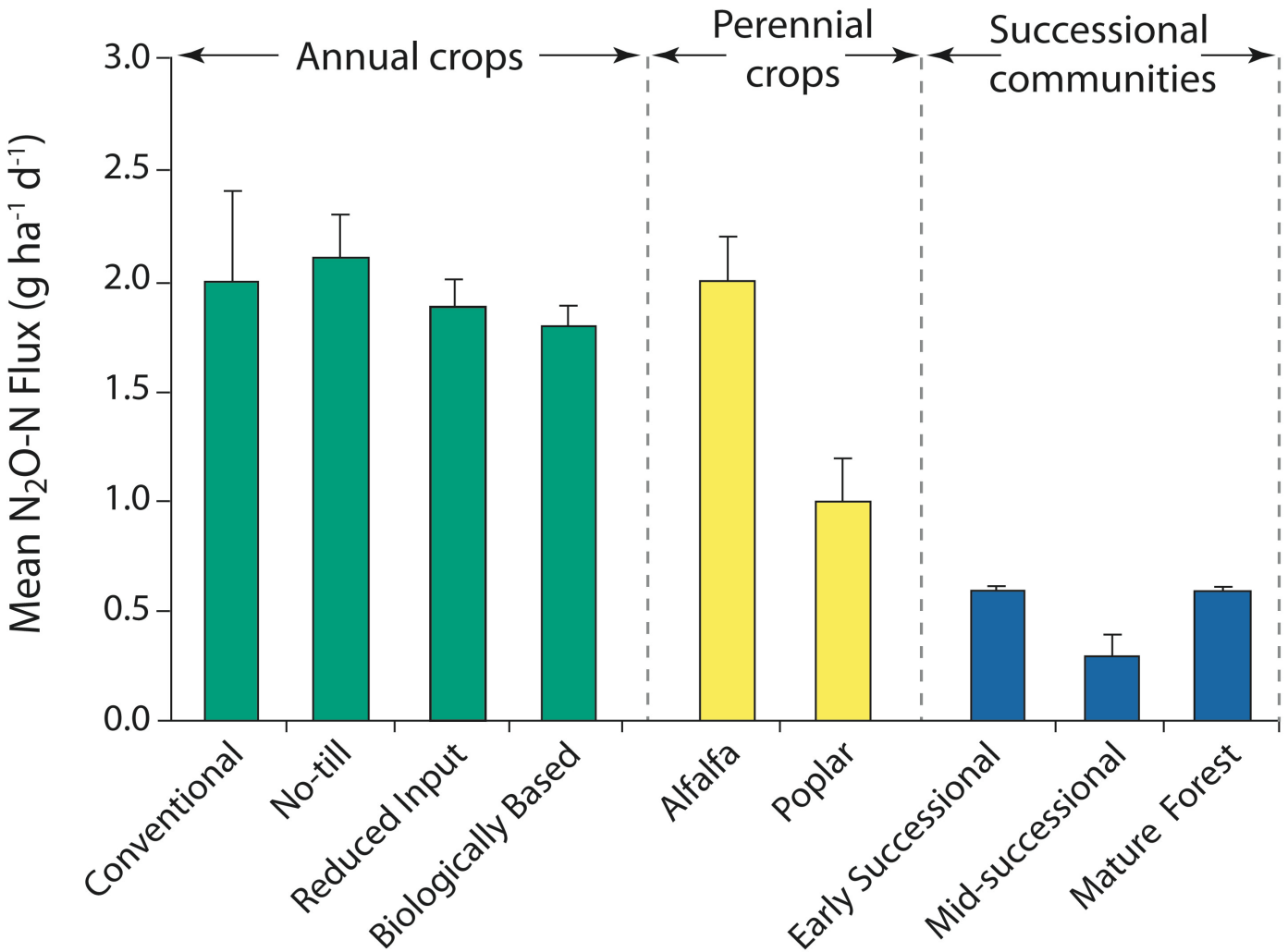


Agriculture

- Industry is responsible for ~16% of the anthropogenic source
  - Agriculture for the remainder
- with most of the agricultural increase (~60%) from cropped soils

Source: IPCC 2001, 2007; Prinn 2004; Robertson 2004; Tian et al. 2016 Nature

Nitrous Oxide Fluxes at KBS (1992-2010)



Source: Robertson et al. 2000 Science; Gelfand and Robertson 2015

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Today's talk

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    - overall cycle and pressure points
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    - Nitrous oxide emissions
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Sources of Global Warming Impact (GWI) in Field Crop Ecosystems

- Soil carbon change
- Fuel use
- Nitrogen fertilizer
- Lime (carbonate) inputs
- Pesticides, seeds, other inputs
- N_2O emission
- CH_4 consumption & emission

Global Warming Impact of Field Crop Activities

	Soil-C	N-Fert	Fuel	Other Inputs	N_2O	CH_4	Net
	g CO_2-equiv / m^2/ y						
Annual Crops (c-s-w)							
Conventional	0	33	13	19	37	-1	101

NB

a. Soil C is at equilibrium (no annual change)

b. N_2O 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

	Soil-C	N-Fert	Fuel	Other Inputs	N_2O	CH_4	Net
	g CO_2-equiv / m^2 / y						
Annual Crops (c-s-w)							
Conventional	0	33	13	19	37	-1	101
No-till	-122	33	9	28	39	-1	-14

NB No-till

a. No-till C gain provides substantial mitigation

b. Other sources (including N_2O) similar

c. Net impact is negative - mitigation

Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015

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Global Warming Impact of Field Crop Activities

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Annual Crops (c-s-w)							
Conventional	0	33	13	19	37	-1	101
No-till	-122	33	9	28	39	-1	-14
Biologically Based	-183	0	20	8	32	-1	-124

NB Biologically Based

a. C gain even with more cultivation

b. Gains from no inputs, but no N_2O 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

	Soil-C	N-Fert	Fuel	Other Inputs	N_2O	CH_4	Net
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Biologically Based	-183	0	20	8	32	-1	-124
Successional Communities (Unmanaged)							
Early Successional	-397	0	0	0	11	-1	-387
Mid-successional	-214	0	0	0	16	-3	-201
Deciduous Forest	0	0	0	0	12	-5	7

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

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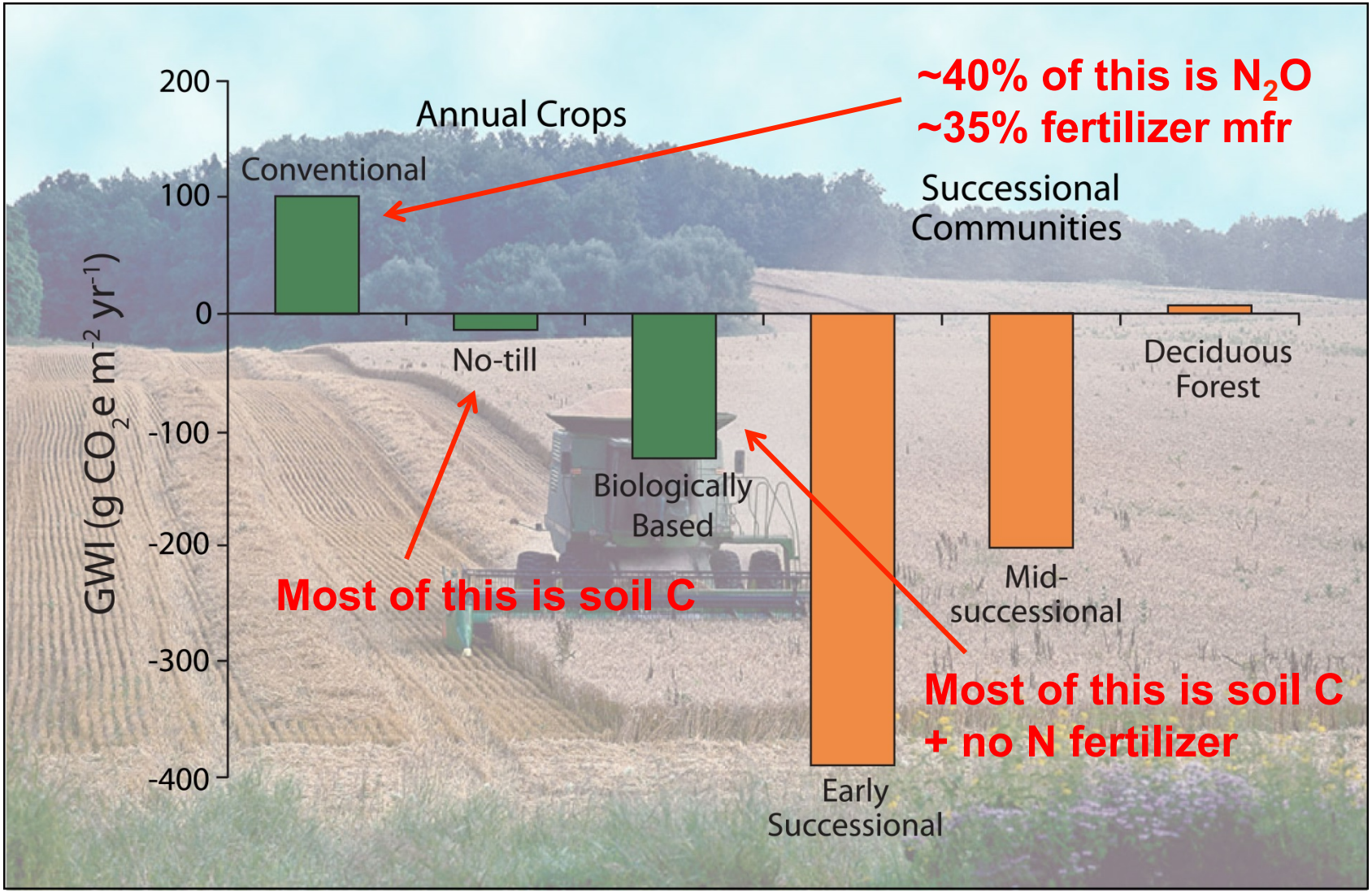
Net Global Warming Impact of Cropped and Successional Ecosystems at KBS



Source: Gelfand et al. 2013 Nature; Gelfand and Robertson 2015

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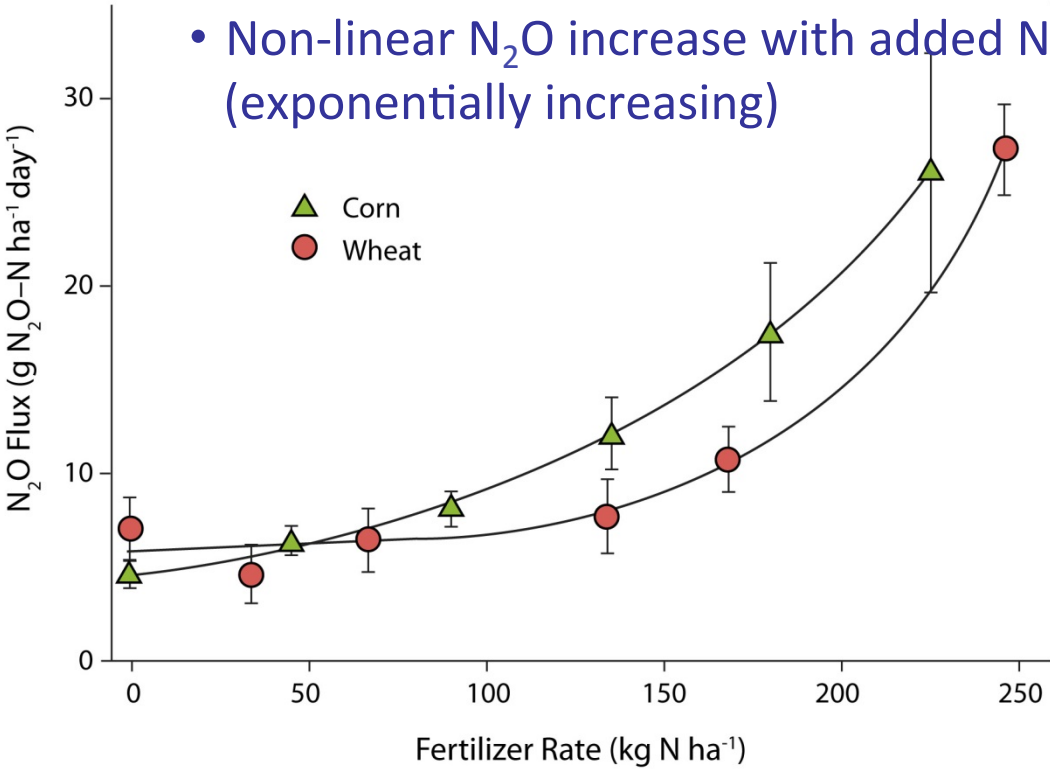
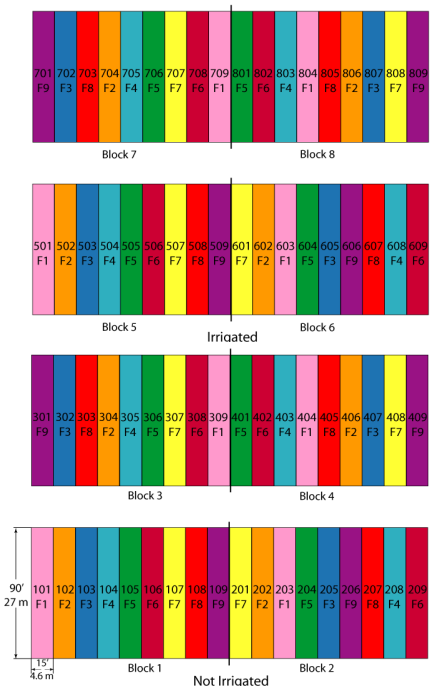
N_2O fluxes are strongly affected by nitrogen fertilizer inputs

- Non-linear N_2O increase with added N (exponentially increasing)





Millar and Robertson 2015

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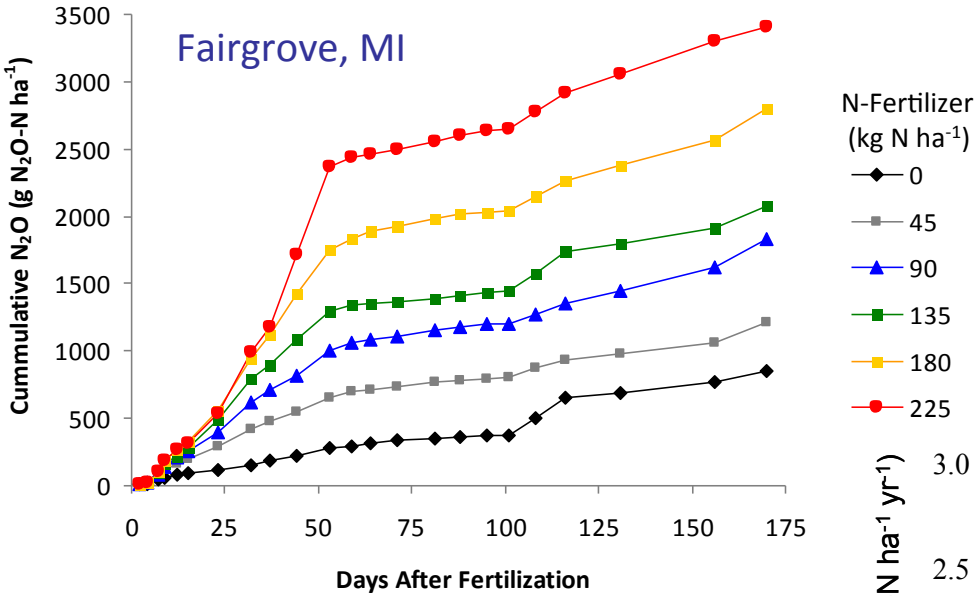
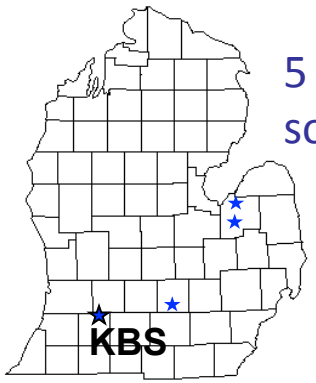
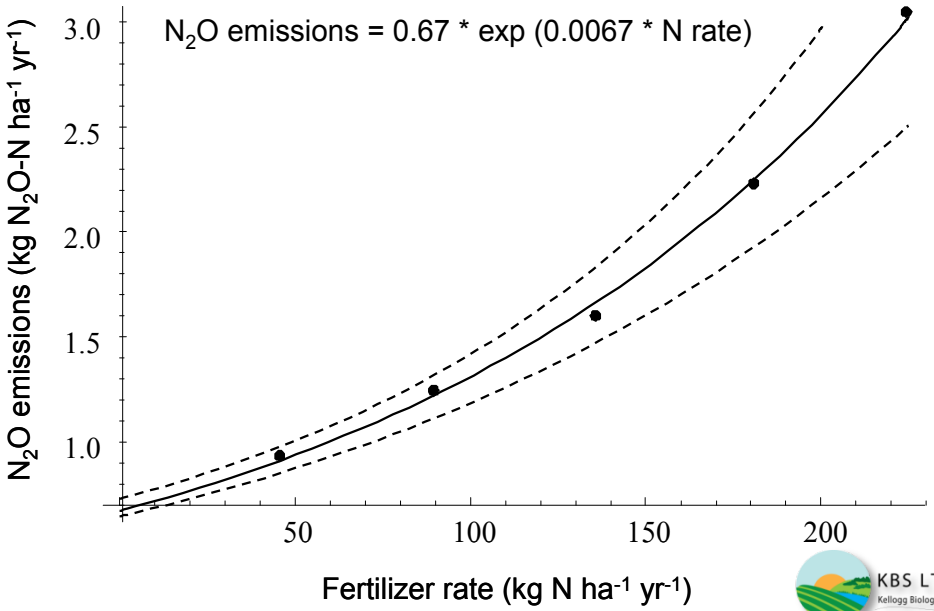
Cross-state test of non-linear N_2O response to N-fertilizer





5 commercial corn-soybean farms



Hoben et al., 2011, GCB

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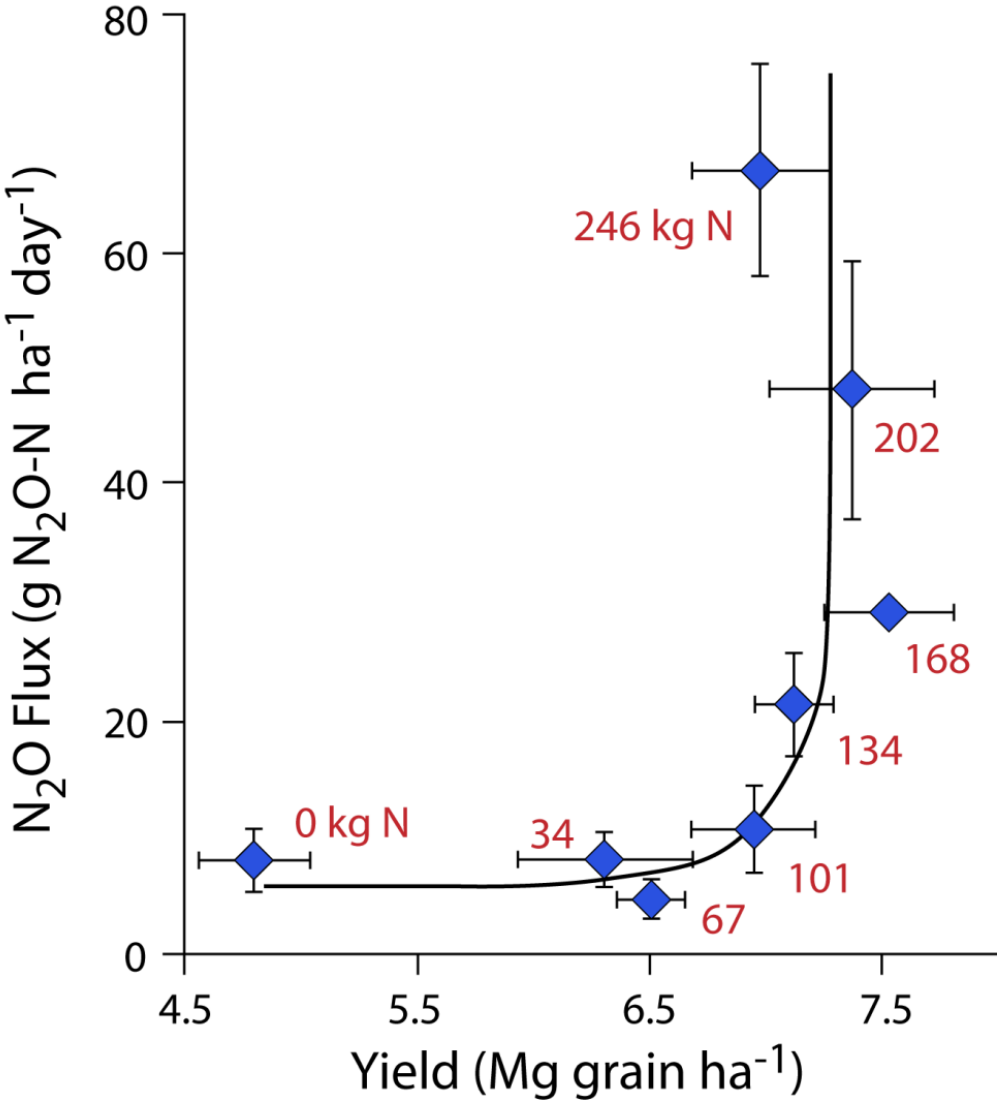
Over-fertilizing matters a lot

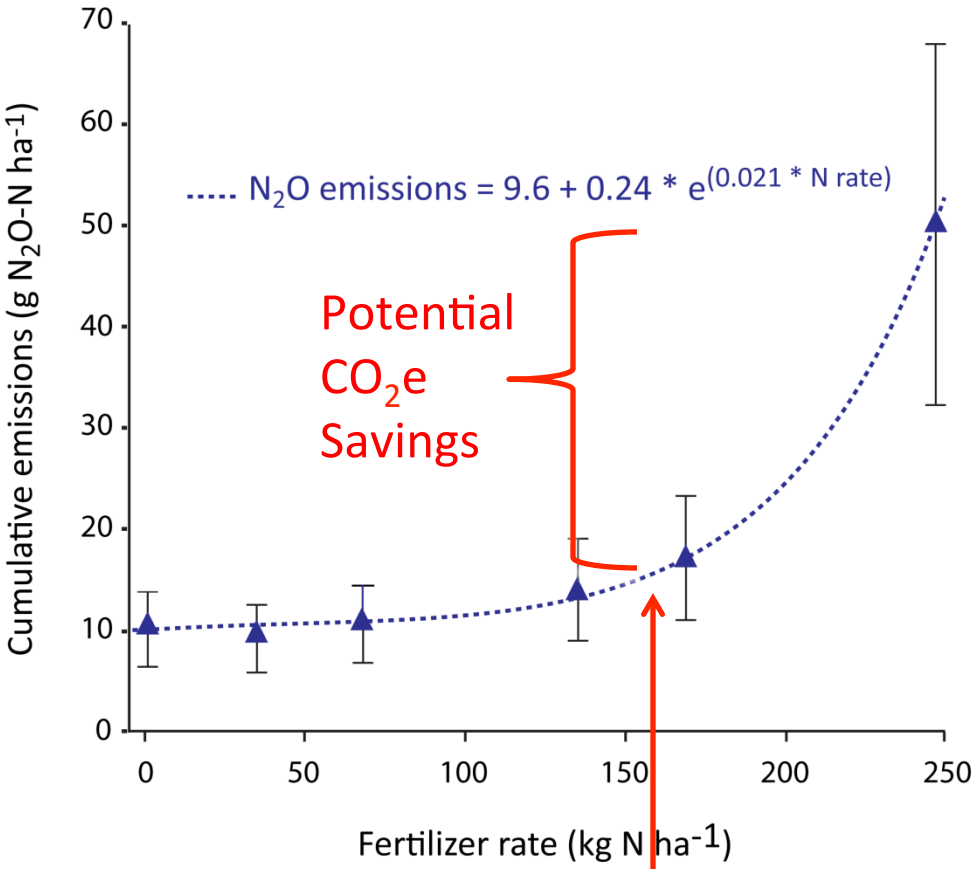


N_2O Flux × Crop Yield

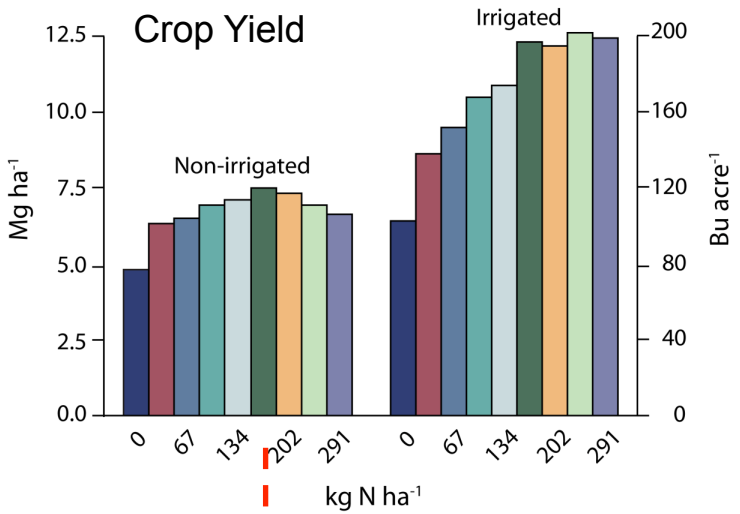
- N_2O fluxes accelerate at N-fertilizer rates greater than yield response
- Implication – N_2O savings can be substantial where fertilizer rate exceeds crop needs

Source: McSwiney & Robertson 2005

At any given site, significant potential GHG mitigation



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



Optimum N Fertilizer Rate

Millar et al., in review

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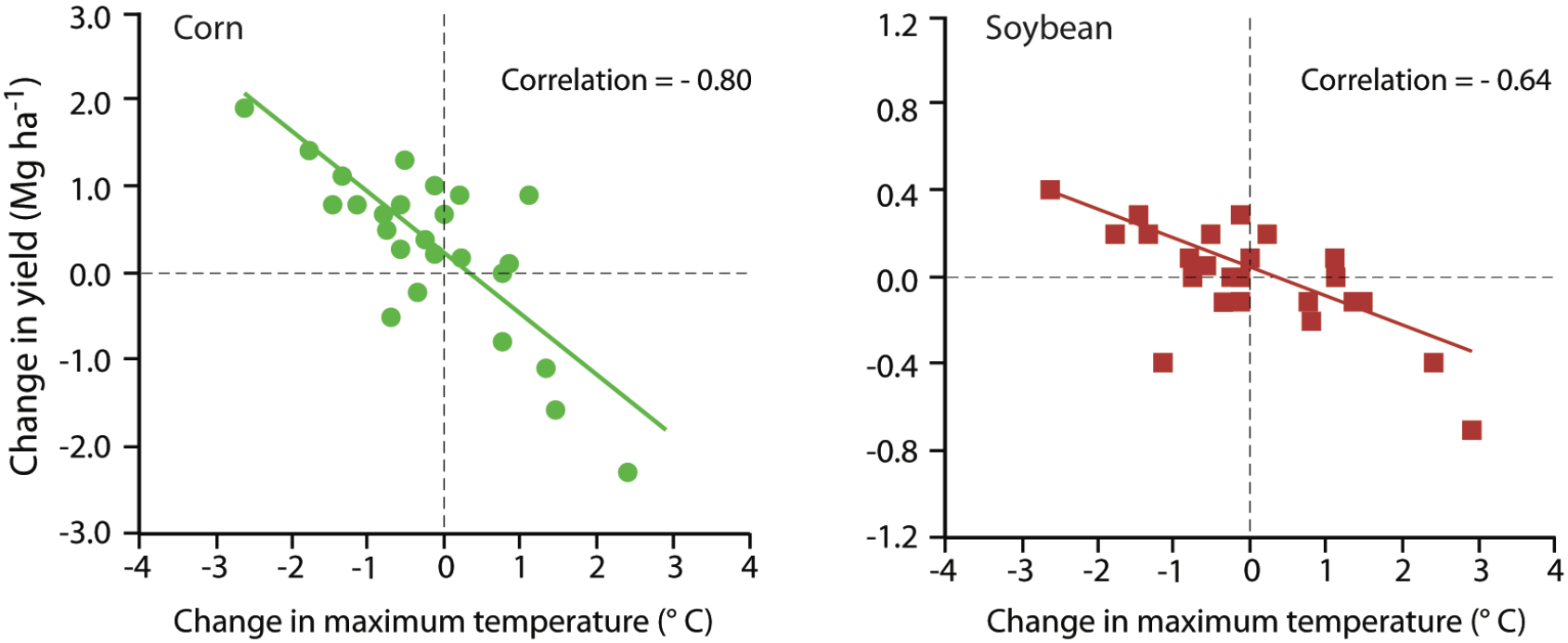
3. Looking forward
    - Agricultural N (N_2O) and climate mitigation
    - Climate change impacts on agricultural N

Climate change is likely to release more reactive N to the environment

1) As growing season temperature extremes depress yields

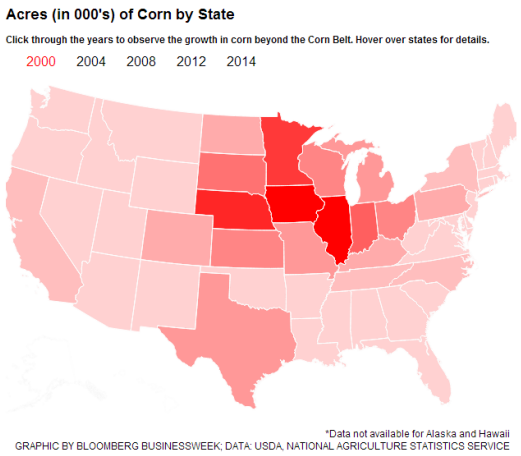
E.G. maximum temperature effects on corn and soybean during grain filling (1980-2007 IL and IN):



Mishra and Cherkauer, 2010, AFM; NCA 2014

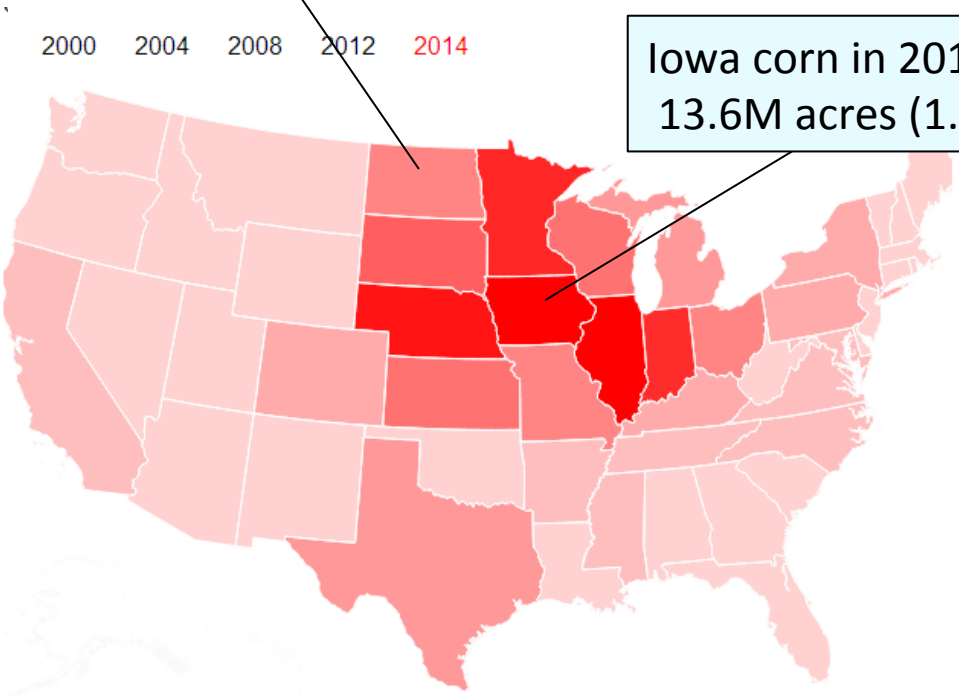
Climate change is likely to release more reactive N to the environment

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



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

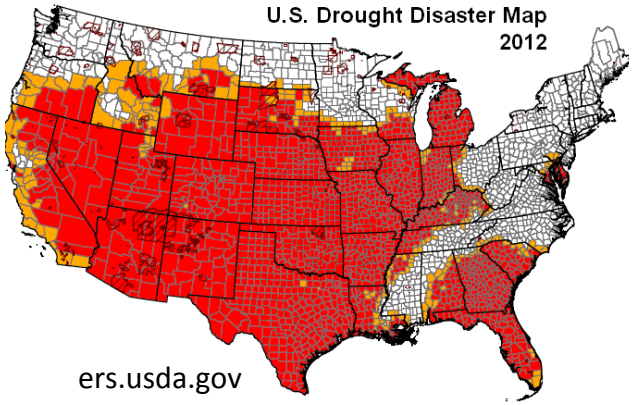
Iowa corn in 2014
13.6M acres (1.1x from 2000)



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

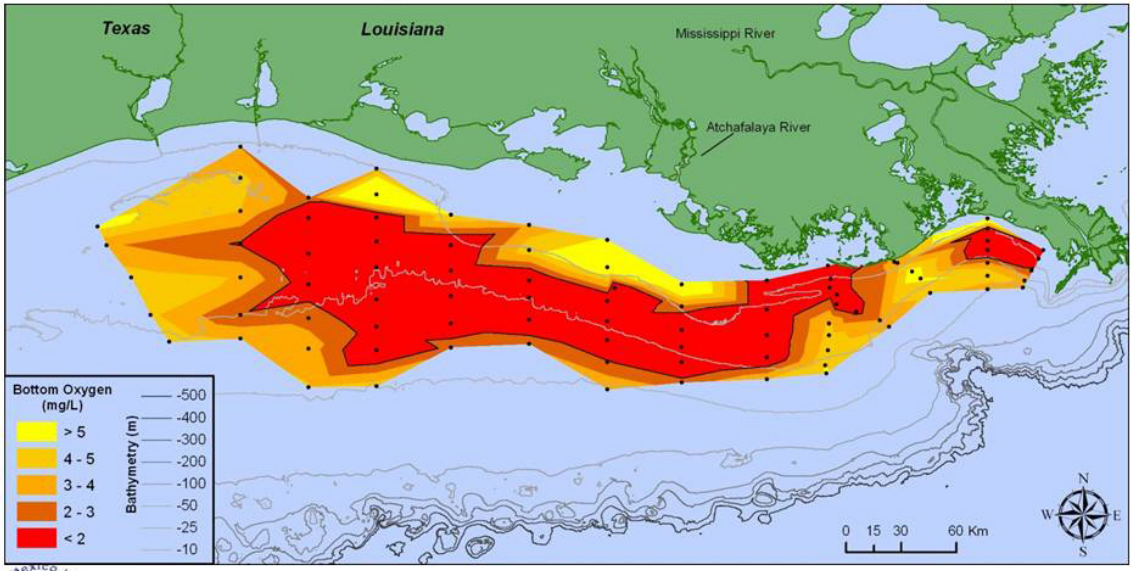
3) As extreme events such as drought depress the crop N sink



ers.usda.gov

npr.org

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



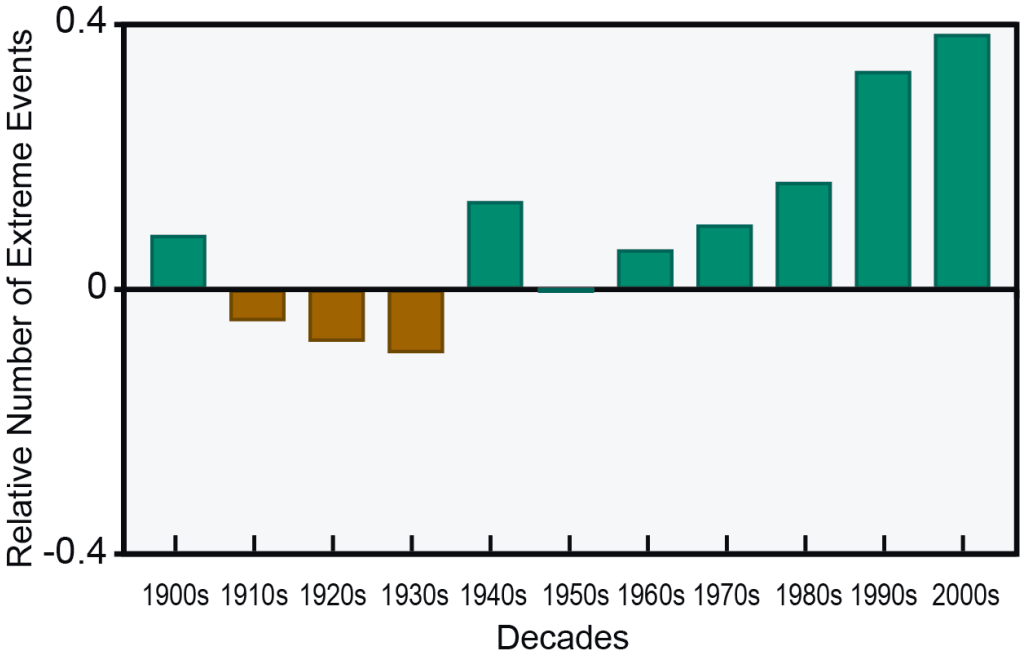
Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, R.E. Turner, Louisiana State University
Funded by: NOAA, Center for Sponsored Coastal Ocean Research

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

Observed U.S. Trends in Extreme Precipitation



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

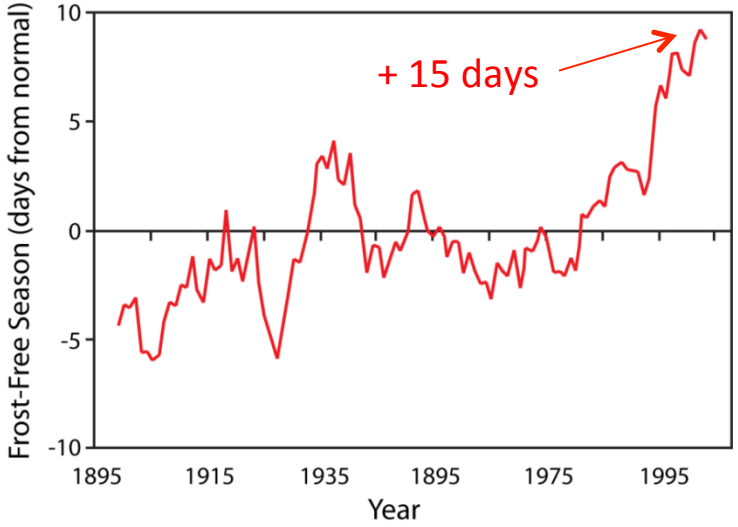
NRCS

Kunkel et al. 2012; NCA 2014

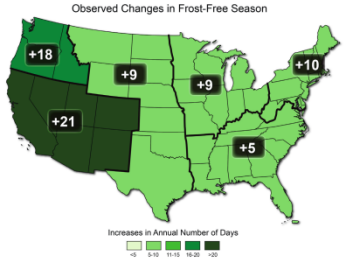
Climate change is likely to release more reactive N to the environment

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

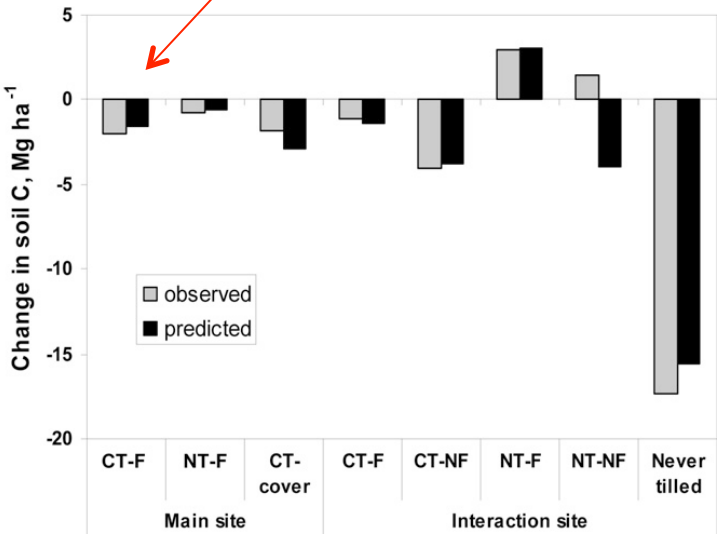
Growing season length (Michigan)



Part of a national trend



Soil C loss under long-term conventional tillage in MI



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

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