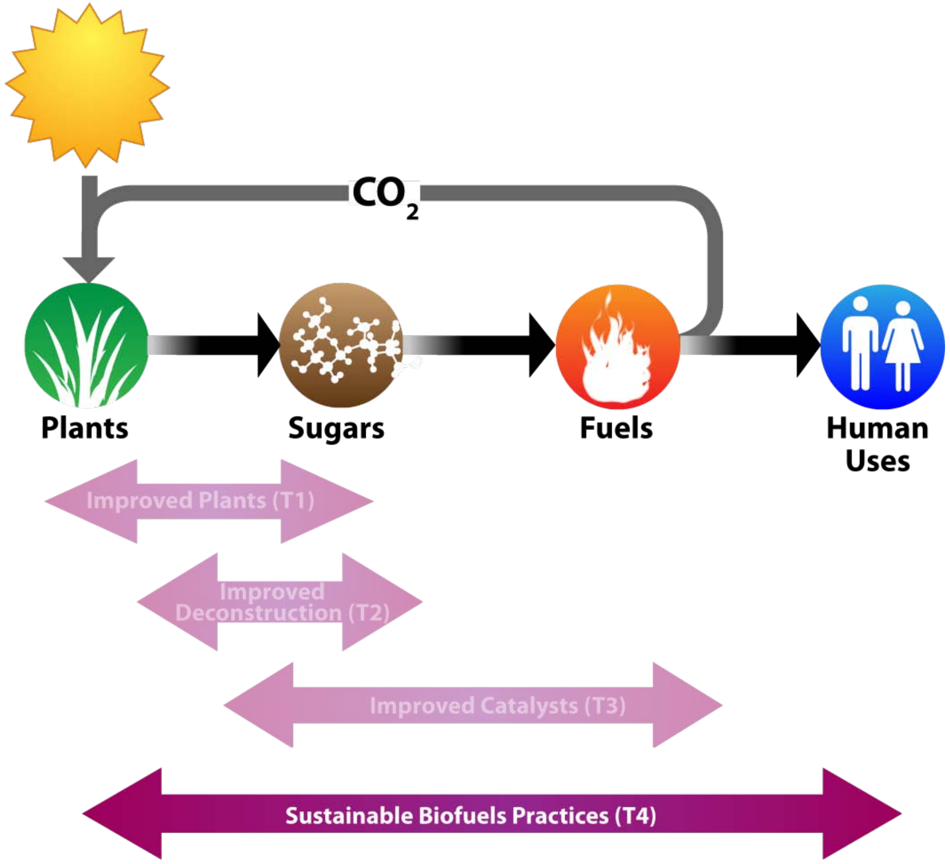
Bioenergy and Sustainability

A Biogeochemical Perspective



Phil Robertson
W.K. Kellogg Biological Station
and Great Lakes Bioenergy
Research Center
Michigan State University

robertson@kbs.msu.edu

MICHIGAN STATE UNIVERSITY
U.S. DEPARTMENT OF ENERGY
DOE Bioenergy Research Centers
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Legislated Biofuel Goals

- U.S. Energy Independence and Security Act of 2007 (EISA) 22% of transportation fuel mix in 2022
  - 36 billion gallons ethanol
    - 15 billion gallons of grain-based ethanol
    - 21 billion gallons of advanced ethanol (>16 cellulosic…)
- European Union
  - 20% renewable energy by 2020
  - 10% of transport fuels by 2020

Current U.S. Ethanol Production Status

	Existing Plants	Capacity bgal yr	New Plants	Production bgal yr	Capacity bgal yr
2007	110	5.5	76	4.8	11.1
2008	139	7.9	61	6.4	13.4
2009	170	10.6	24	9.0[1]	14.6
2015+				15*	

Source: USDA 2009; DOE 2009; RFA 2010

[1] World total 17.3 (Brazil 6.4) * US EISA 2007

Legislated Biofuel Goals

- U.S. Energy Policy Act of 2007
  22% of transportation fuel mix in 2022
  - 36 billion gallons ethanol
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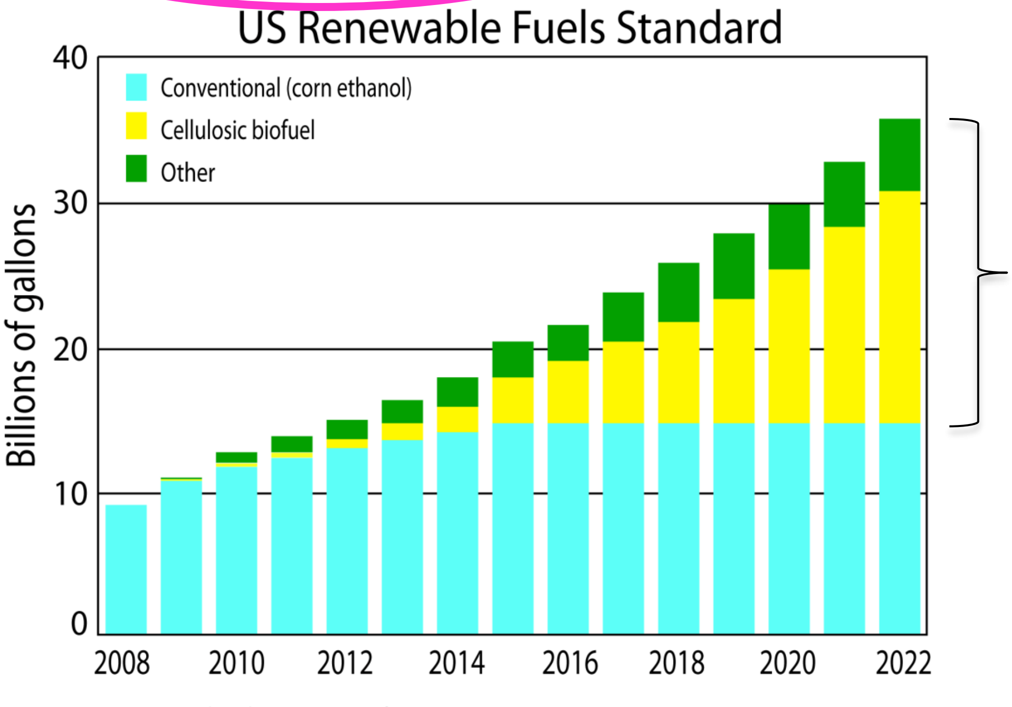
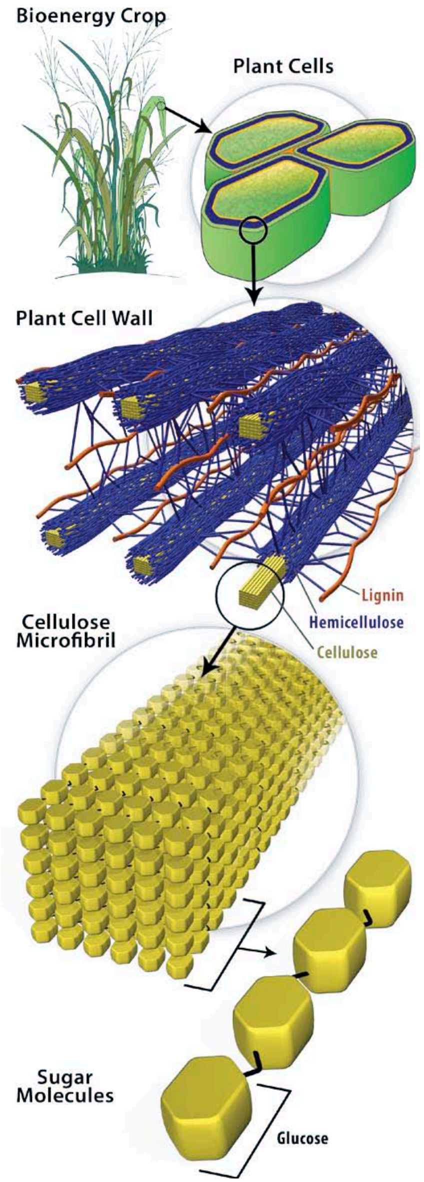
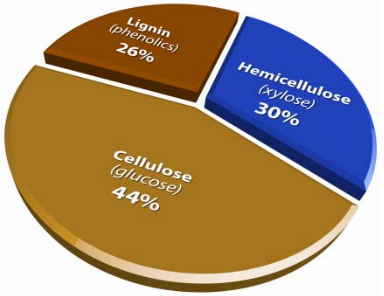
    - 21 billion gallons of advanced biofuels (>16 cellulosic)



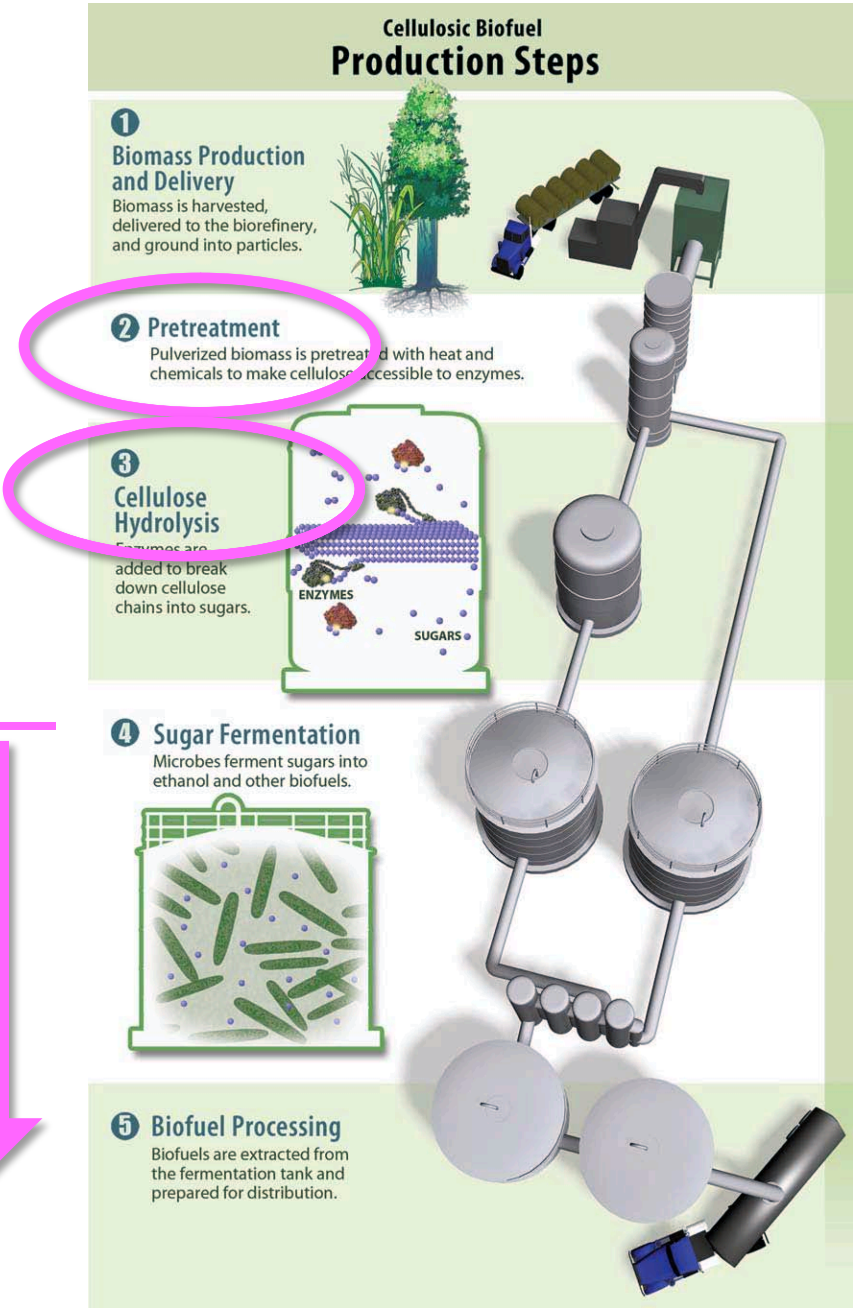
Source: Energy Independence & Security Act of 2007

Cellulosic Ethanol Production





same as grain



Cellulosic Biofuel Production Steps

❶ **Biomass Production and Delivery**
Biomass is harvested, delivered to the biorefinery, and ground into particles.

❷ **Pretreatment**
Pulverized biomass is pretreated with heat and chemicals to make cellulose accessible to enzymes.

❸ **Cellulose Hydrolysis**
Enzymes are added to break down cellulose chains into sugars.

❹ **Sugar Fermentation**
Microbes ferment sugars into ethanol and other biofuels.

❺ **Biofuel Processing**
Biofuels are extracted from the fermentation tank and prepared for distribution.

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DOE; http://genomics.energy.gov

Agnostic enzymes…..

High Diversity

Restored prairie

Early successional

Poplar trees

Native grasses

Switchgrass

Miscanthus

Corn-Soybean-Canola

Corn

Low Diversity

Environmental Performance?

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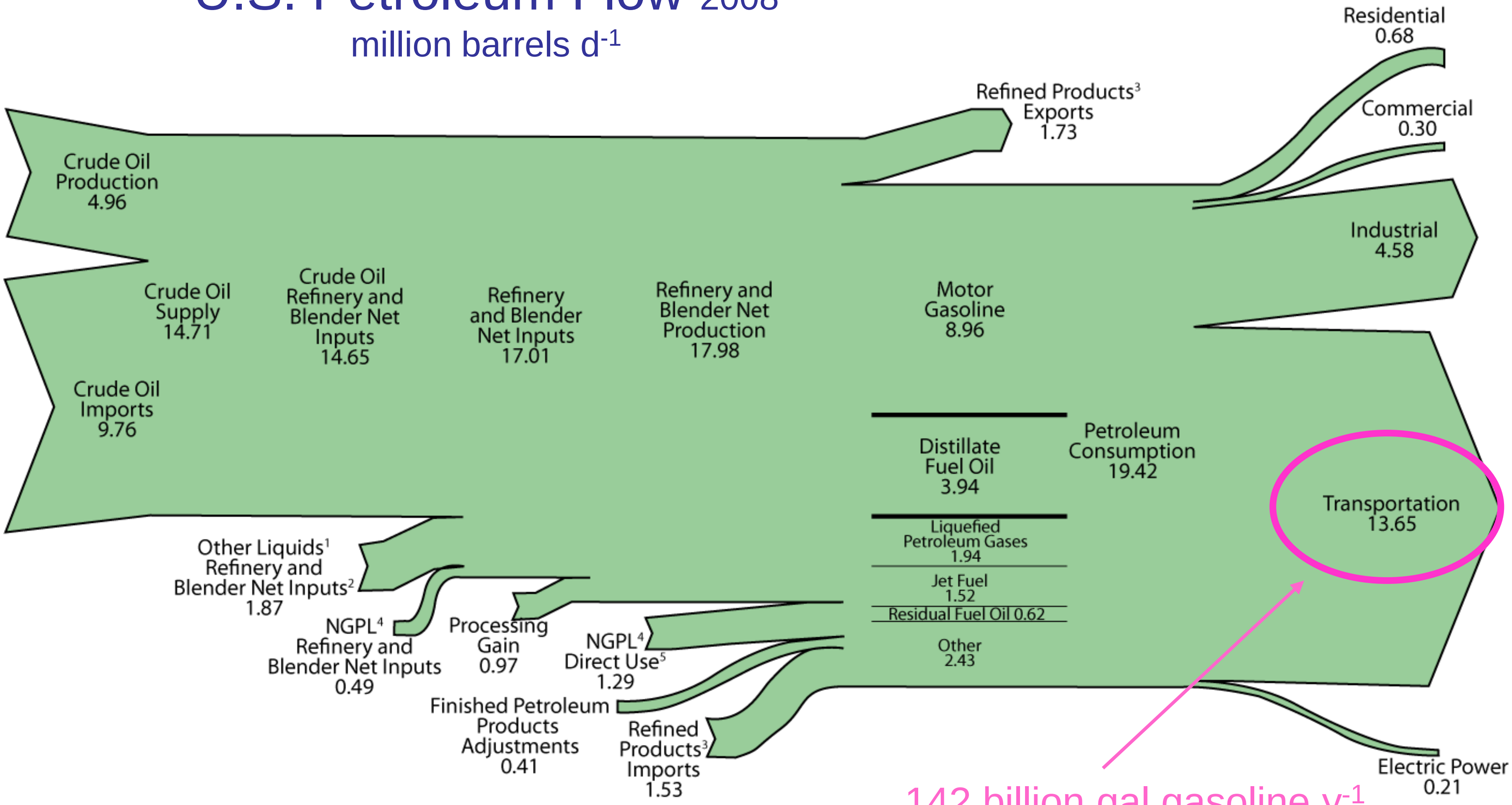
How much ethanol do we need?

U.S. Petroleum Flow 2008

million barrels d^{-1}



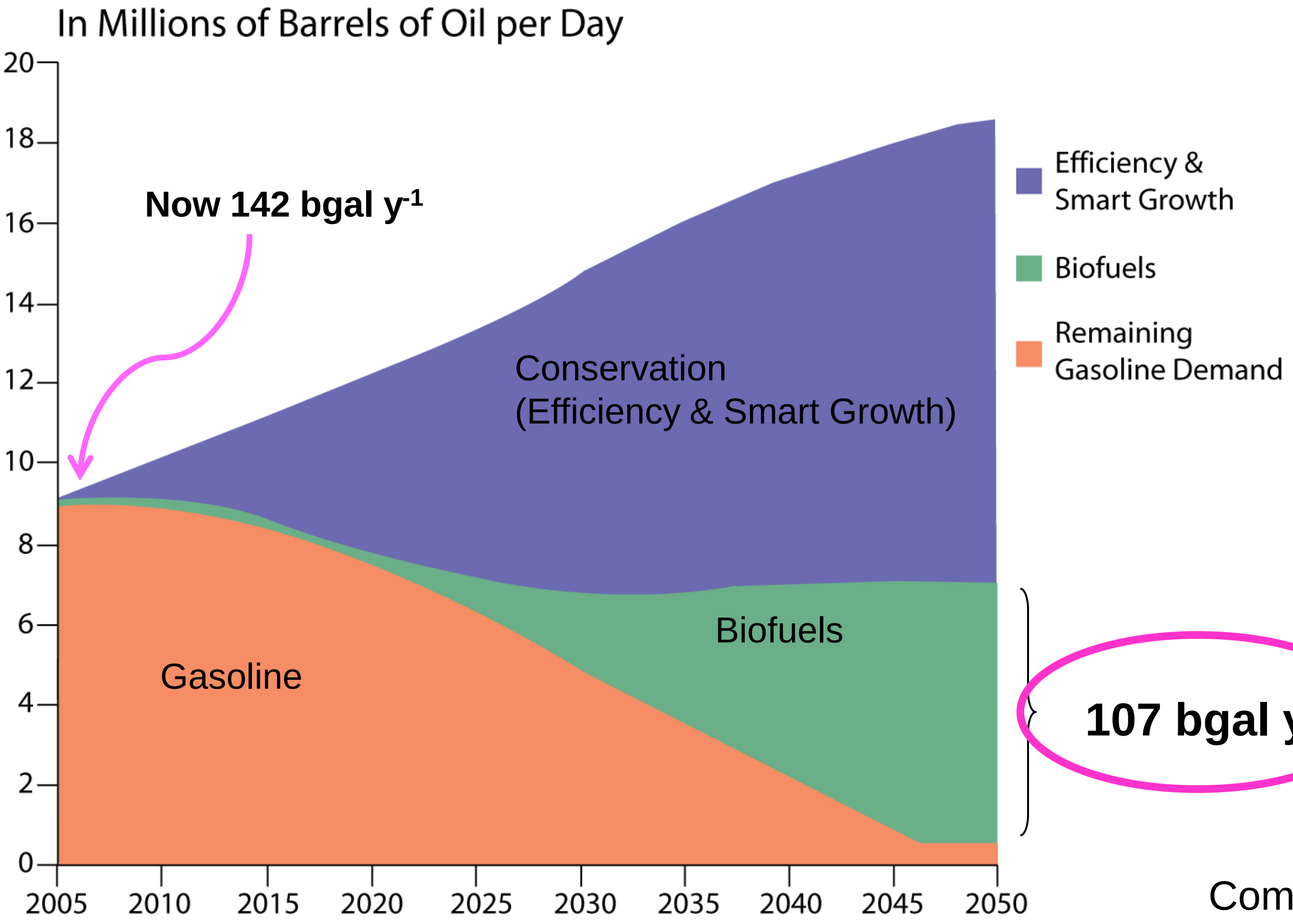
142 billion gal gasoline y^{-1}

Source: DOE 2009; www.eia.doe.gov/emeu/aer/

How much ethanol do we need?

EPA & Natural Resources Defense Council (NRDC) 2050 Projection

Reduced Gasoline Demand through Biofuels, Efficiency, and Smart Growth



Now 142 bgal y^{-1}

107 bgal y^{-1}

Compare to 36 bgal y^{-1} legislative target for 2022

Source: NRDC 2007 (http://www.nrdc.org/air/transportation/biofuels.asp)

How much biomass is needed?

Feedstock	Conversion Factor	To make 1 gal ethanol
Corn grain	0.39 L / kg grain	9.6 kg corn
Cellulosic biomass (expected)	0.4 L / kg biomass	9.8 kg straw

Grain:

Time period	EtOH	Grain required
Today's needs (2009)	9.0 bgal	3.5 b bushels
Tomorrow's needs (2015)*	15 bgal*	5.8 b bushels
Future needs (2050)	107 bgal	42 b bushels

** EISA 2007 mandate*

Compare to 13 x10^9 bu total US corn crop in 2007

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How much cellulosic biomass is needed?

Time period	EtOH	Biomass required
Today's needs (2007)	0 bgal	-
Tomorrow's needs (2022)*	21 bgal*	205 MMT
Future needs (2050)	92 bgal	902 MMT

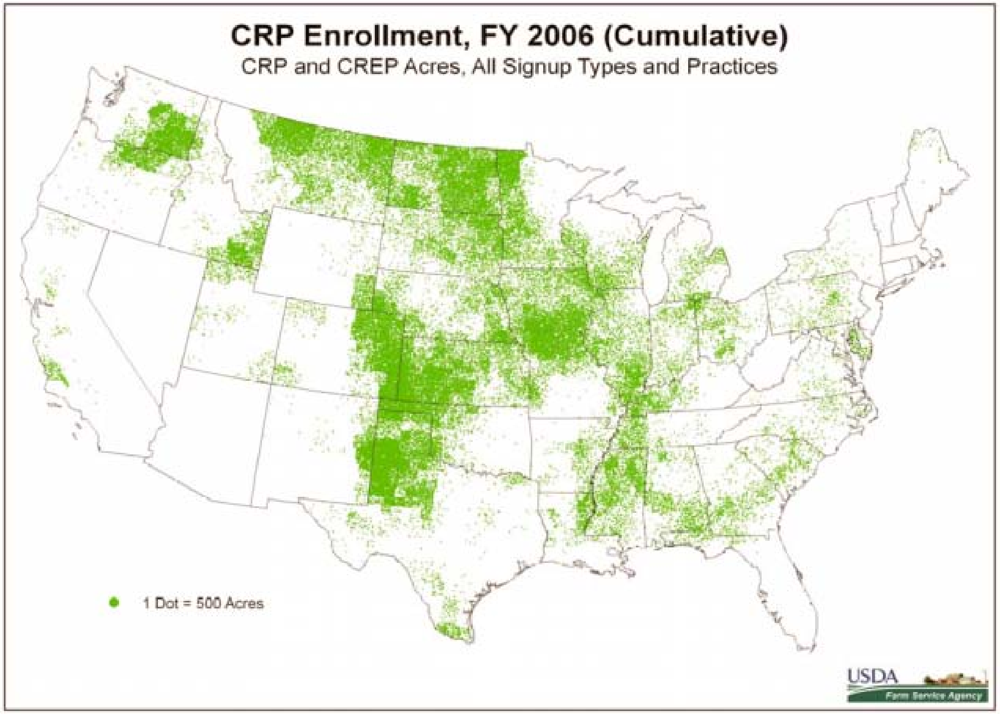
** EISA mandate*

Existing Amount	Source[1]	
109 MMT	Forest Products 41 MMT Logging residues (50-65%) 60 MMT Forest thinnings (15-20%) 8 MMT mill residues (5%)	
90 MMT	Municipal Solid Waste (64%)	
55 MMT	Corn Stover 110 MMT (55%; no till; erosion protection; Graham et al. 2007) 76 MMT (39%; no till; some C protection; NRC 2009) 25 MMT (13%; no till; C protection; Wilhelm et al. 2007)	
254 MMT	Total - Leaving ~650 MMT to be grown	

[1] Perlack et al. 2005; NRC 2009

How much land?

- Land Requirements for 650 x 10^6 MT biomass
    - Switchgrass today[1] at 7.5 (6-9) MT/ha = 86 x 10^6 ha
- Compare to
    - 178 x 10^6 ha cropland
    - 240 x 10^6 ha range, grasslands
    - 15 x 10^6 ha CRP



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[1] Schmer et al. 2008 *PNAS* 105:464-468

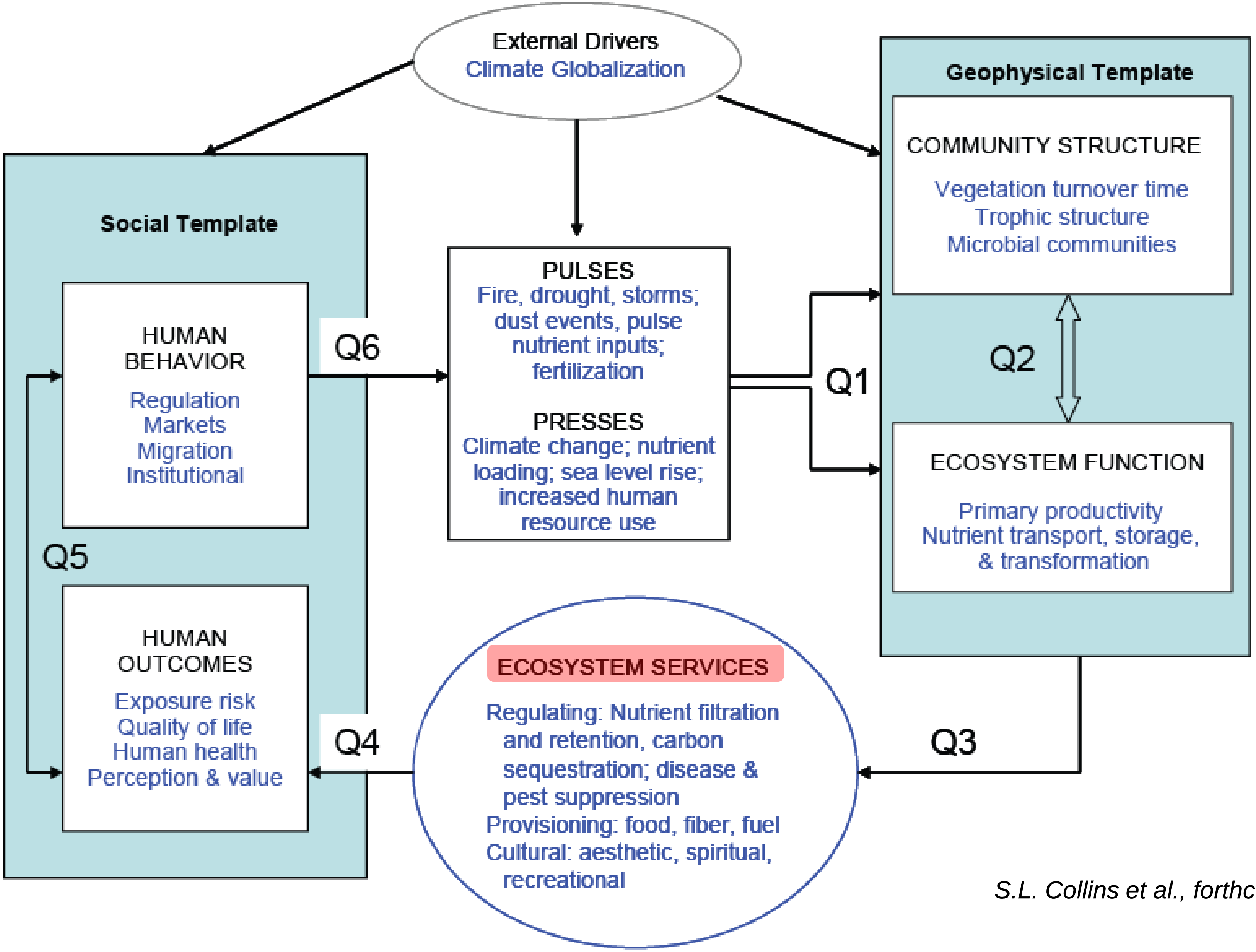
Major Elements of Biofuel Sustainability

- Economic
  - ✓Profitable

- Environmental
  - ✓Carbon negative (climate stabilizing)
  - ✓Nutrient, water conservative
  - ✓Biodiversity benefits

- Social
  - ✓Food, energy security
  - ✓Rural community health

A Coupled Human-Natural Systems Framework



External Drivers
Climate Globalization

Social Template

HUMAN BEHAVIOR
Regulation
Markets
Migration
Institutional

Q5

HUMAN OUTCOMES
Exposure risk
Quality of life
Human health
Perception & value

Q6

PULSES
Fire, drought, storms; dust events, pulse nutrient inputs; fertilization

PRESSES
Climate change; nutrient loading; sea level rise; increased human resource use

Q1

Geophysical Template

COMMUNITY STRUCTURE
Vegetation turnover time
Trophic structure
Microbial communities

Q2

ECOSYSTEM FUNCTION
Primary productivity
Nutrient transport, storage, & transformation

Q3

ECOSYSTEM SERVICES
Regulating: Nutrient filtration and retention, carbon sequestration; disease & pest suppression
Provisioning: food, fiber, fuel
Cultural: aesthetic, spiritual, recreational

Q4

S.L. Collins et al., forthcoming

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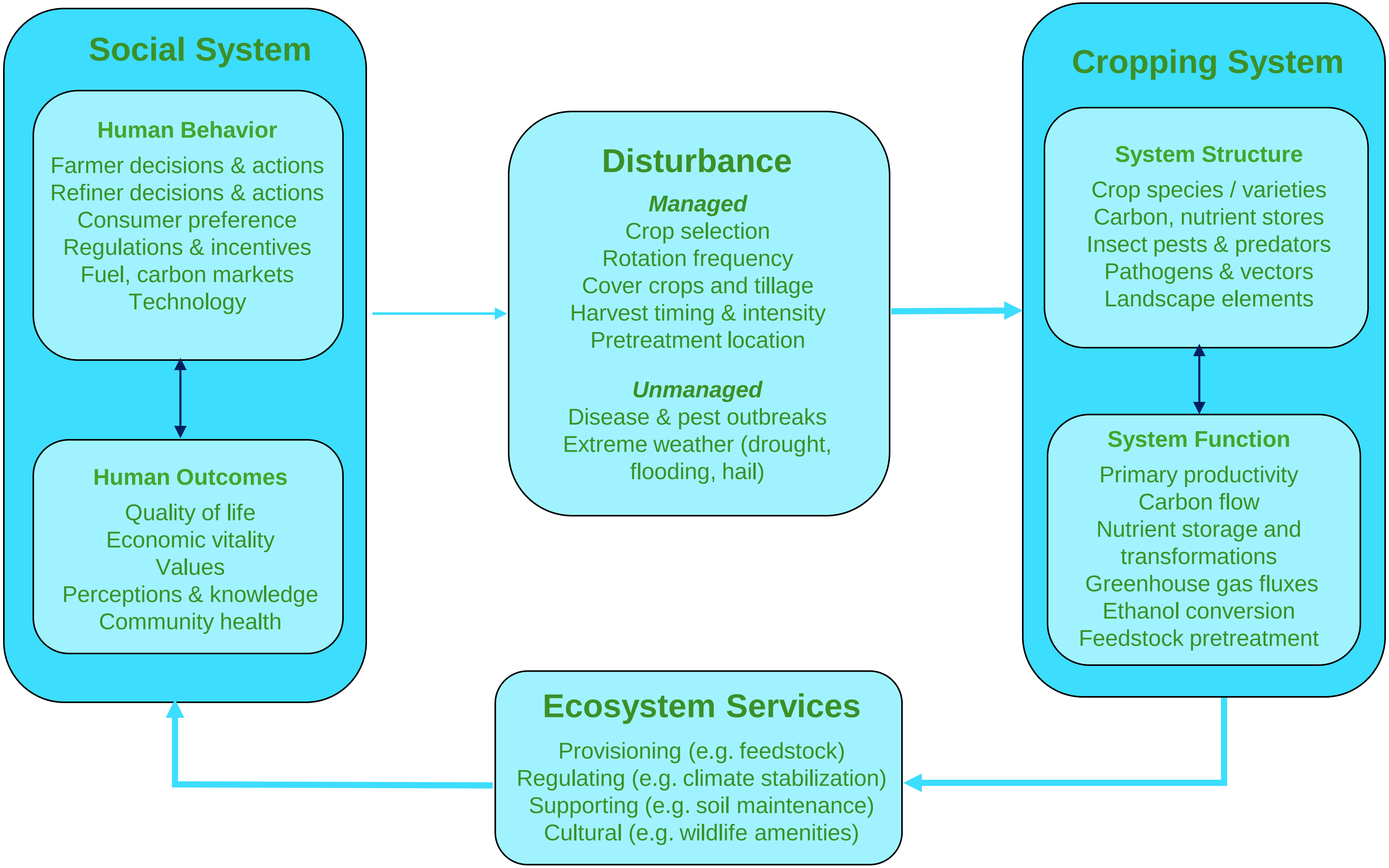
A Socio-Ecological Framework for Biofuel Systems



Social System

Human Behavior

Farmer decisions & actions
Refiner decisions & actions
Consumer preference
Regulations & incentives
Fuel, carbon markets
Technology

Human Outcomes

Quality of life
Economic vitality
Values
Perceptions & knowledge
Community health

Disturbance

Managed

Crop selection
Rotation frequency
Cover crops and tillage
Harvest timing & intensity
Pretreatment location

Unmanaged

Disease & pest outbreaks
Extreme weather (drought, flooding, hail)

Cropping System

System Structure

Crop species / varieties
Carbon, nutrient stores
Insect pests & predators
Pathogens & vectors
Landscape elements

System Function

Primary productivity
Carbon flow
Nutrient storage and transformations
Greenhouse gas fluxes
Ethanol conversion
Feedstock pretreatment

Ecosystem Services

Provisioning (e.g. feedstock)
Regulating (e.g. climate stabilization)
Supporting (e.g. soil maintenance)
Cultural (e.g. wildlife amenities)

Robertson et al., in prep; After S. Collins et al. 2007

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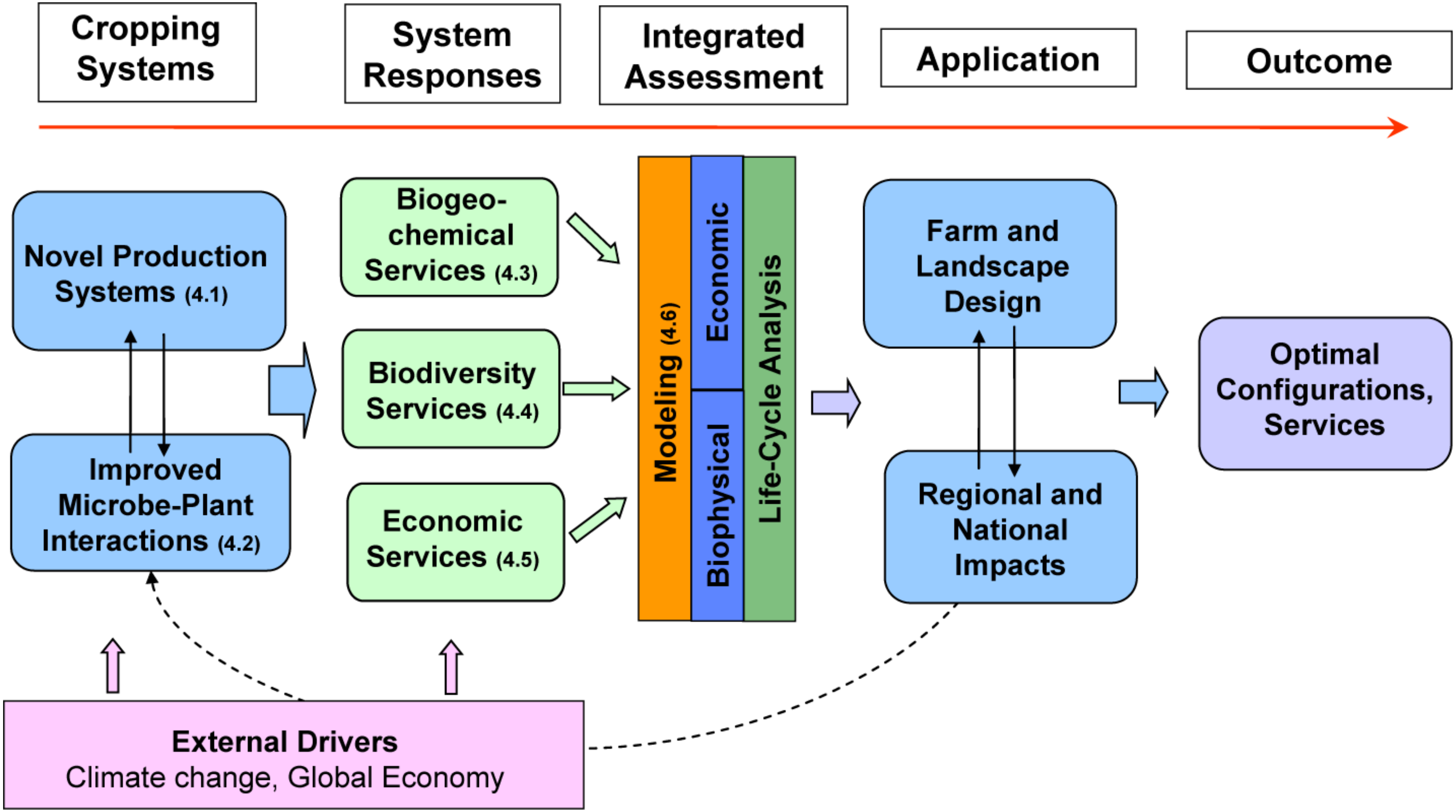
A Sustainability Research Roadmap



Cropping Systems

System Responses

Integrated Assessment

Application

Outcome

Novel Production Systems (4.1)

Improved Microbe-Plant Interactions (4.2)

Biogeo-chemical Services (4.3)

Biodiversity Services (4.4)

Economic Services (4.5)

Modeling (4.6)

Economic

Biophysical

Life-Cycle Analysis

Farm and Landscape Design

Regional and National Impacts

Optimal Configurations, Services

External Drivers
Climate change, Global Economy

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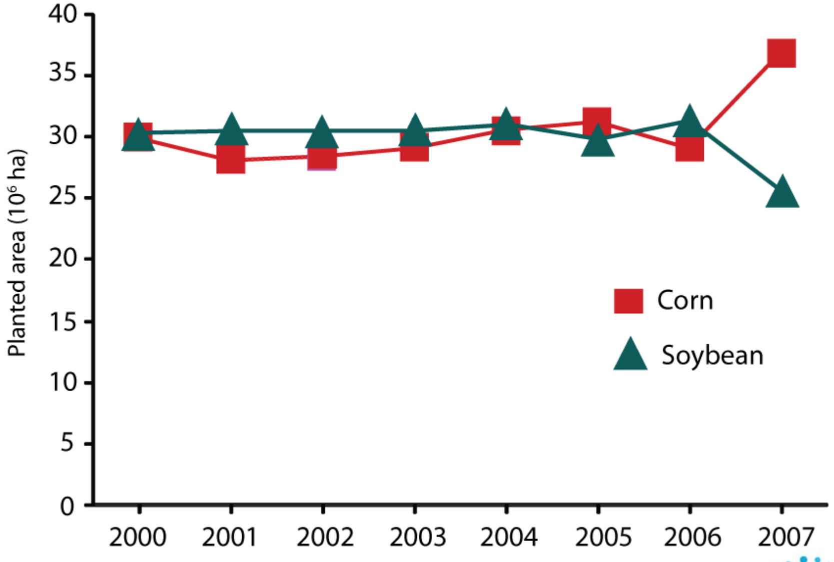
What we know now about biofuels sustainability

1. Grain-based fuel comes with environmental costs not different from conventional food crops:
    a. Not much effect on climate stabilization
    b. Greater intensification of existing farmscapes with associated
        a. erosion
        b. nitrate, phosphorus loss
        c. pesticide loading
        d. biodiversity loss

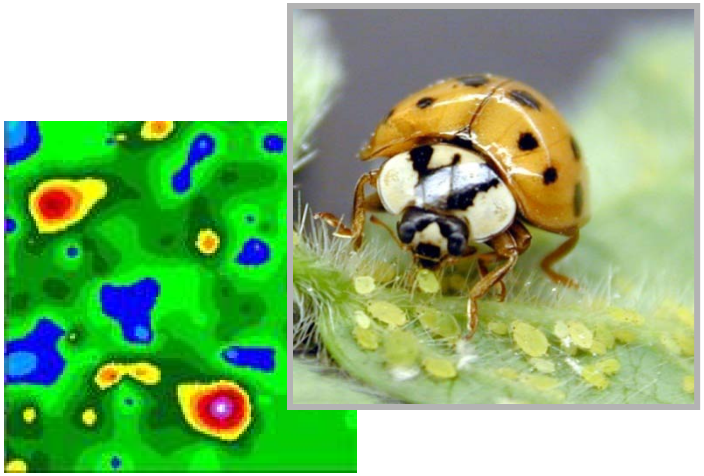
Business as usual writ larger…..

US Corn & Soybean Acreage



What we know now about biofuels sustainability (2)…..

2. Best-performance practices can mitigate many effects:
   a. More complex rotations provide landscape diversity
   b. Cover crops
   c. Conservation tillage
   d. Better fertilizer technology
   e. Biocontrol practices



But require incentives not now sufficient…..

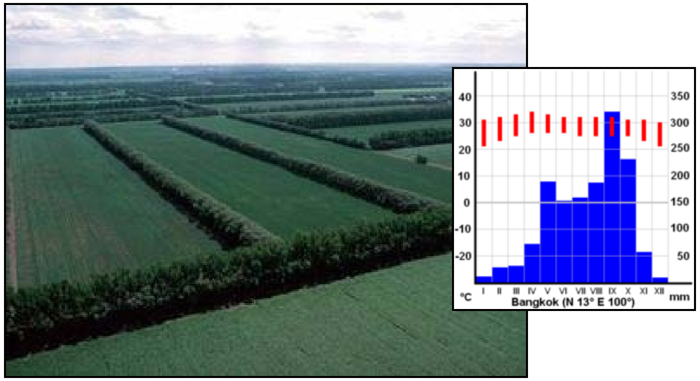
What we know about biofuels sustainability (3)…..

3. Cellulosic crops could provide major contrast:
    a. Perennial herbaceous and woody crops
    b. Landscape diversity (feedstock diversity)
    c. No carbon debt (if grown right places)
    d. Ecosystem Services
        - Biodiversity
        - Biogeochemical

- Pollination & Biocontrol

- Clean water

- Climate stabilization



- Wildlife

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Biogeochemical Responses

Carbon Impacts - Life Cycle Analysis

Considers the greenhouse gas cost of producing biofuels

Agronomic CO_2 Costs

- Equipment fuel use
- Fertilizer, pesticide production
- Soil carbon change
- Other greenhouse gases (N_2O)

Biorefinery CO_2 Costs

- Fuel for transporting grain
- Energy to heat dryers & boilers

Land-use Conversion Costs

- Conversion of natural ecosystems releases carbon in soil, trees to atmosphere as CO_2
- Other greenhouse gases (N_2O)

RFS2- Lifecycle GHG Thresholds Specified in EISA

Feedstock	Percent Reduction from 2005 Baseline for Gasoline/Diesel	
Renewable Fuel	20%	
Advanced Biofuel	50%	
Biomass-based Diesel	50%	
Cellulosic Biofuel	60%	

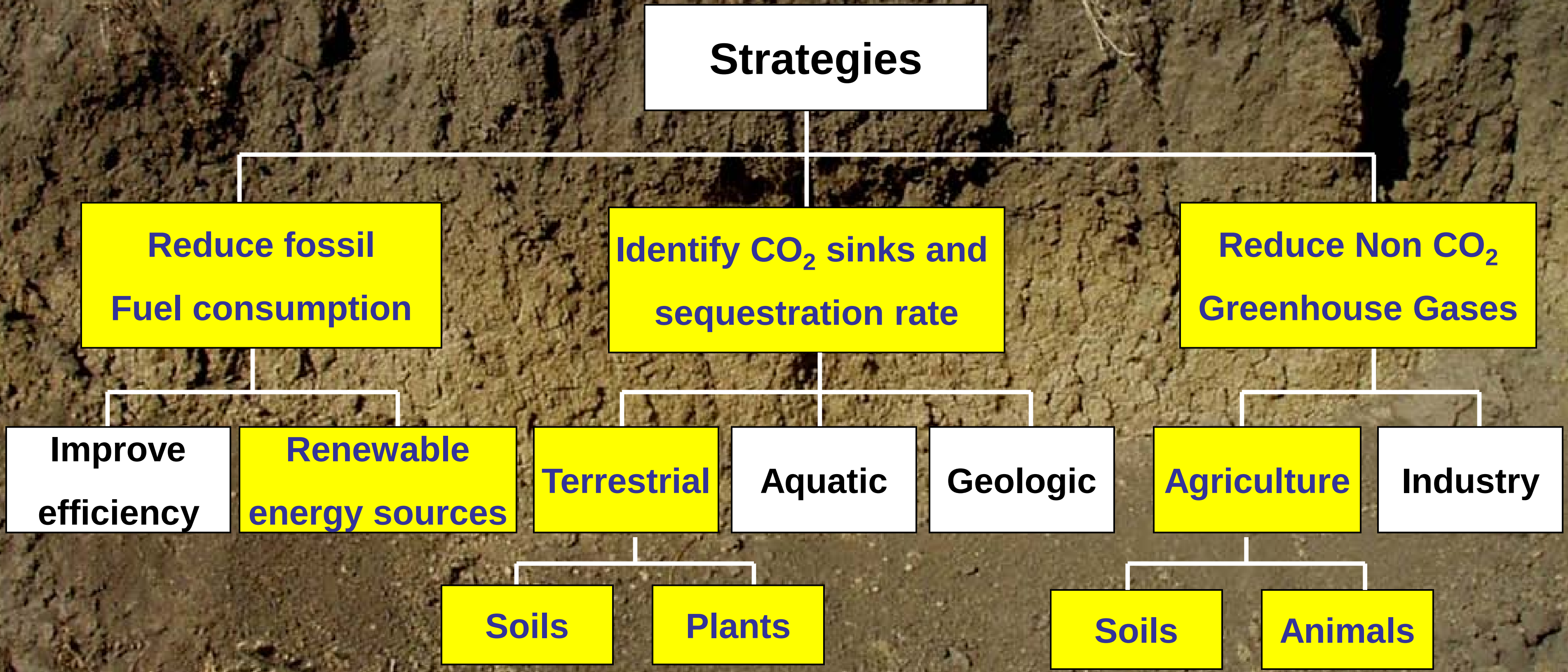
Indirect Land Use Effects

Displaced food production creates carbon debt

www.nature.org

Strategies to Stabilize Atmospheric CO_2

Agriculture's Role



- **Strategies**
  - Reduce fossil Fuel consumption
    - Improve efficiency
    - Renewable energy sources
  - Identify CO_2 sinks and sequestration rate
    - Terrestrial
      - Soils
      - Plants
    - Aquatic
    - Geologic
  - Reduce Non CO_2 Greenhouse Gases
    - Agriculture
      - Soils
      - Animals
    - Industry

Adapted from C. Rice

Contemporary Global CO_2 Budget

Source/Sink (Pg C / y)	1990-1999	2000-2006
	Pg C y^{-1}	
<u>Sources</u>		
Emissions from fossil fuels	6.3	7.6
Emissions from deforestation	<u>1.6</u>	<u>1.5</u>
Total Sources	7.9	9.1
Sinks		
Atmospheric increase	3.3	4.1
Oceanic uptake	2.3	2.2
Terrestrial Uptake	<u>2.3</u>	<u>2.8</u>
Total Sinks	7.9	9.1

Pg C = 10^{15} g C = GT C = 1000 MMT C

Source IPCC (2002); Canadell et al. 2007 *PNAS*

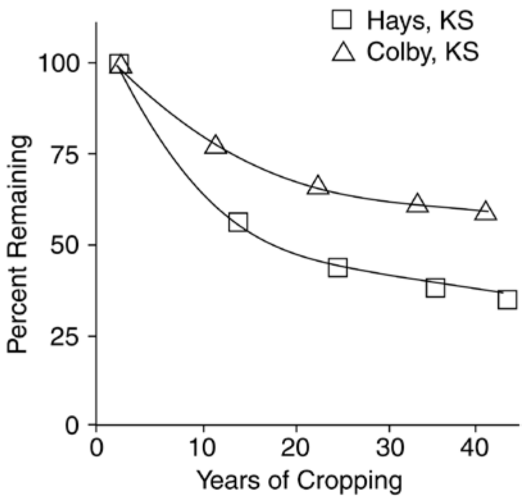
A Portfolio of Potential CO_2 Stabilization Options

	Rapidly Deployable	Not Rapidly Deployable
Minor Contributors <0.2 PgC/y	• Biomass co-fire electric generation • Cogeneration (small scale) • Hydropower • Natural Gas Combined cycle • Niche options (geothermal, small scale solar)	• Integrated photovoltaics • Forest management (fire suppression) • Ocean fertilization
Major Contributors >0.2 PgC/y	• Carbon sequestration in agricultural soils • Improved appliance efficiency • Improved buildings • Improved vehicle efficiency • Non-CO_2 gas abatement from industry • Non-CO_2 gas abatement from agriculture • Reforestation • Stratospheric sulfates	• Biomass to hydrogen • Biomass to fuel • Cessation of deforestation • Energy-efficient urban and transportation systems • Fossil-fuel C separation with geologic or ocean storage • High efficiency coal technology • Large-scale solar • Next generation nuclear fission • Wind with H2 storage • Speculative technologies (space solar, nuclear fusion, etc.)

Caldeira, Morgan, Baldocchi, Brewer, Chen, Nabuurs, Nakicenovic, & Robertson. 2004. A portfolio of carbon management options, p. 103-130, *In* C. B. Field and M. R. Raupach, eds. The Global Carbon Cycle. Island Press, Washington, DC.

Historical Soil Carbon Loss from Cropping Systems

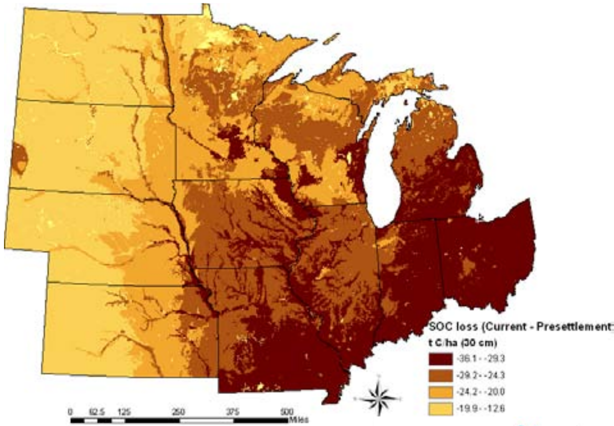
- locally 40-60% of original C lost after 40-60 years of cultivation in North America



Haas et al. 1957

- globally 54 Pg C from an original 222 Pg C (about 25%)

- potential for recovering 0.3 – 0.5 Pg C y^{-1}
  - Increasing C inputs (crop residues, cover crops)
  - Slowing decomposition (no-till)



Source: Lal 1999, Smith 2004, IPCC 2002, Grace et al. 2006

How to Restore Soil Carbon?

1. Increase C inputs to soil

   - Cover crops
   - Rotations
   - Residue quantity

2. Decrease C loss from soil (slow decomposition)

   - Tillage reduction
   - Residue quality

KBS Long-Term Ecological Research (LTER) Site

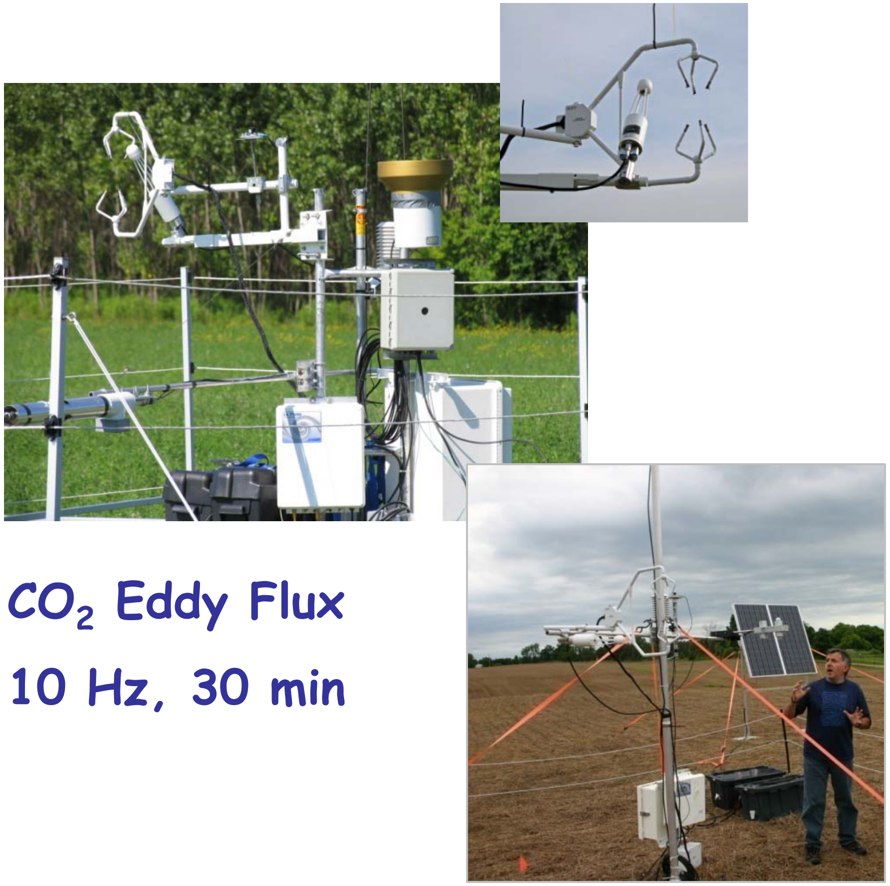
Ecosystem Type	**Management Intensity**
Annual Grain Crops (Corn - Soybean - Wheat)	
Conventional tillage	High
No-till	
Low-input with legume cover	
Organic with legume cover	
Perennial Biomass Crops	
Alfalfa	
Poplar trees	
Unmanaged Communities	
Early successional old field	
Mid successional old field	
Late successional forest	Low

Soil Carbon Change in 10 Years of Cropping

KBS System	Carbon		
	%C	kg/m^2	g/m^2/y*
Annual Grain Crops (c-s-w)			
Conventional Tillage	1.00	.94	0
No-Till	1.24	1.24	30
Organic with cover	1.09	1.02	8
Perennial Biomass Crops			
Alfalfa	1.30	1.38	44
Poplar	1.40	1.26	32
Successional (Unmanaged) Communities (CRP)			
Early Successional (<10y)	1.63	1.54	60
Mid-Successional (50 y)	1.61	1.37	<11
Late Successional	2.93	2.29	0

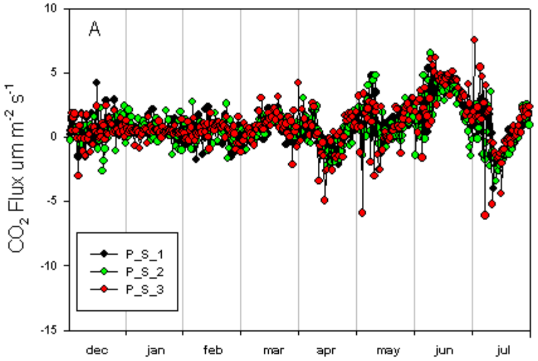
* Initial C = 1.0%

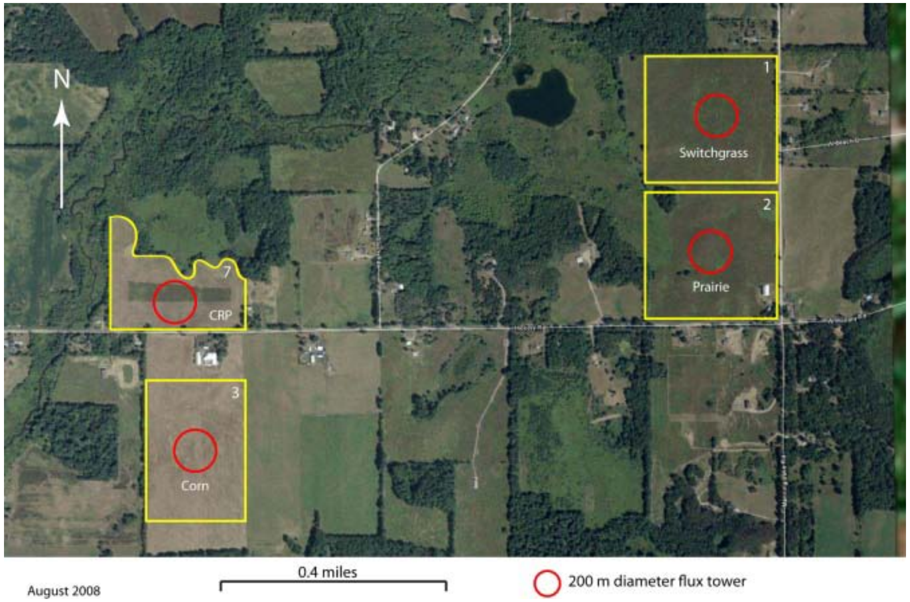
CO_2 Flux Measurements (Net Ecosystem Productivity)



CO_2 Eddy Flux

10 Hz, 30 min





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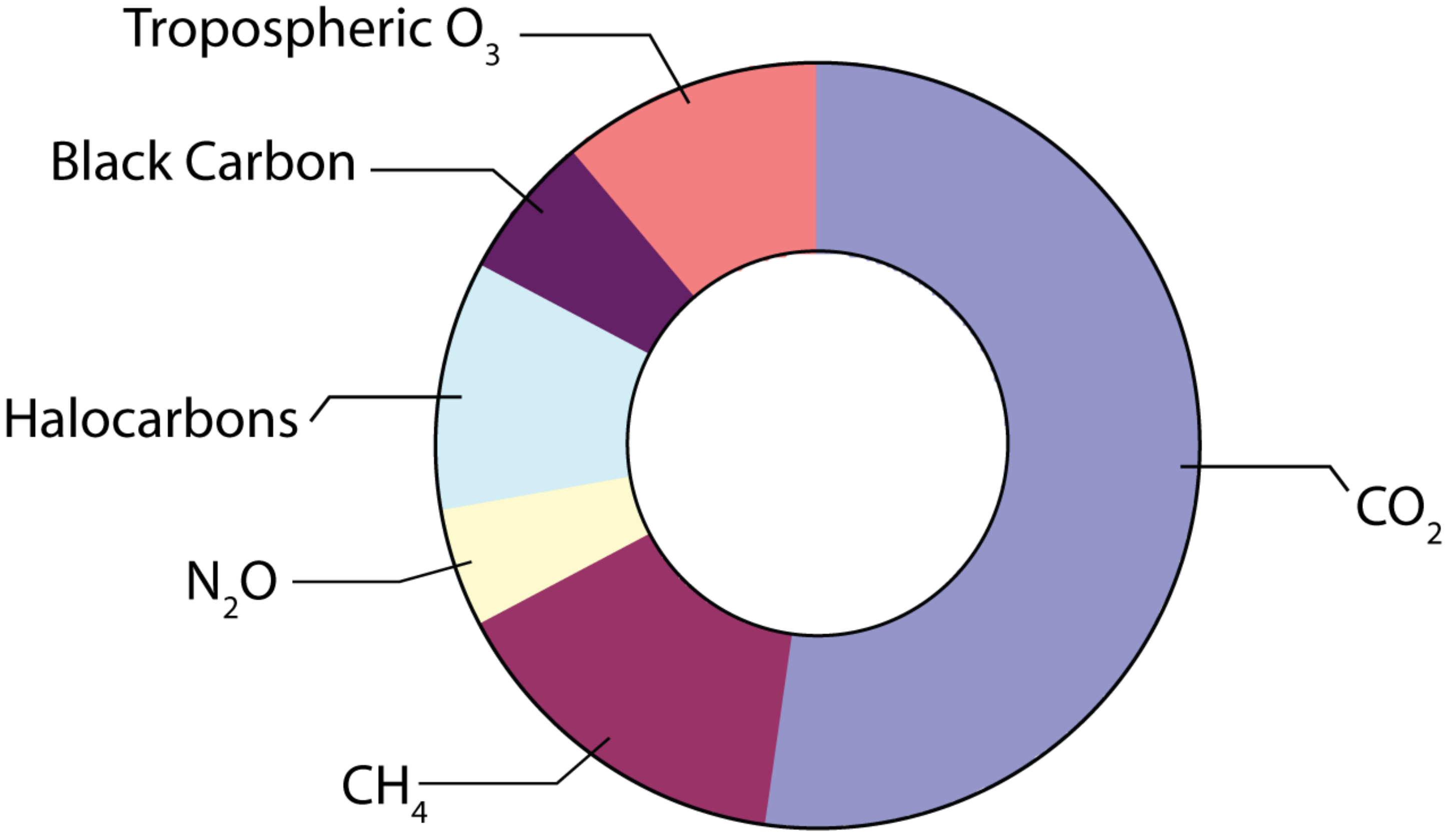
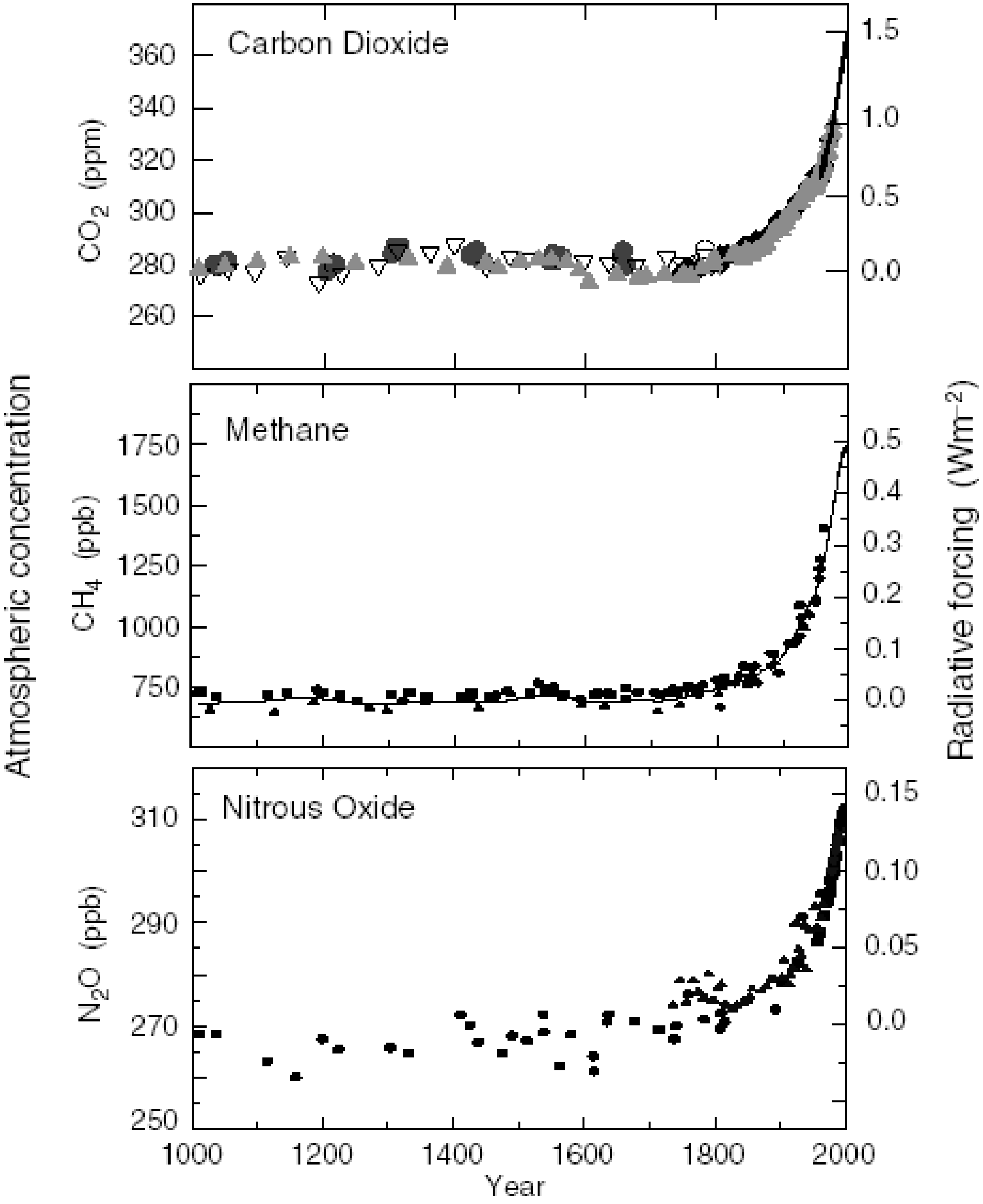
Global Sources of Atmospheric Radiative Forcing 1750 - 2006



Source: IPCC (2007)

Biogeochemical Pieces – N_2O, CH_4



Atmospheric concentrations of the biogenic greenhouse gases (CO_2, methane, and nitrous oxide) from 1000 A.D.

From IPCC (2001)

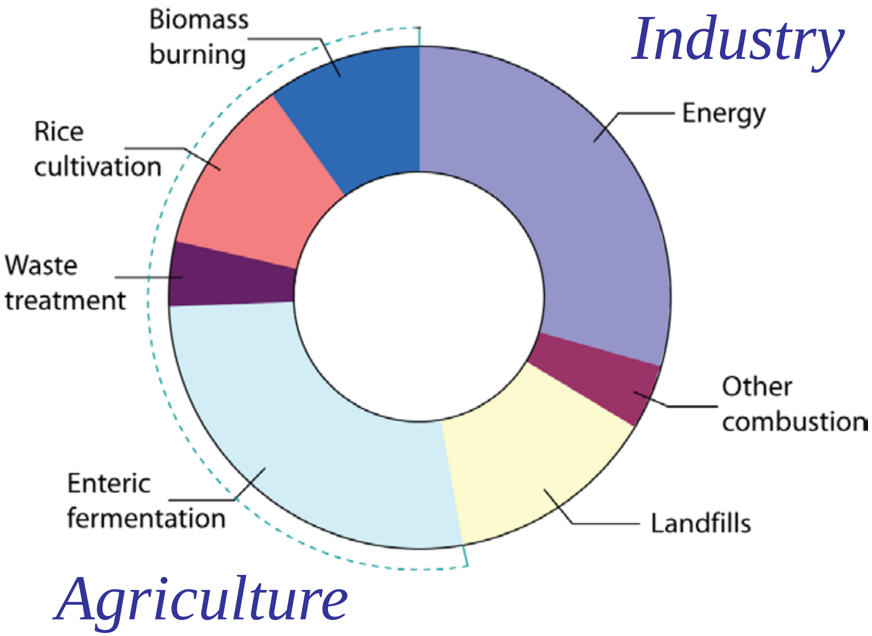
Global Warming Potential (GWP)
Biogenic Gases

	Lifetime yr	Global Warming Potential 20 yr	Global Warming Potential 100 yr	Global Warming Potential 500 yr
CO_2	variable	1	1	1
CH_4	12	62	23	7
N_2O	114	275	296	156

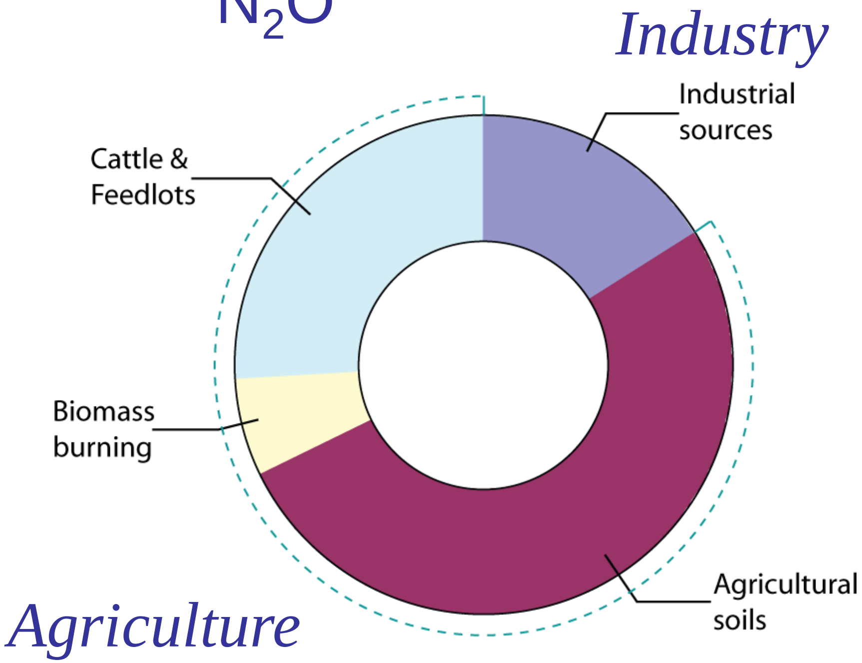
Source: IPCC 2002; 2007

Anthropic Sources of Methane and Nitrous Oxide Globally

CH_4



N_2O



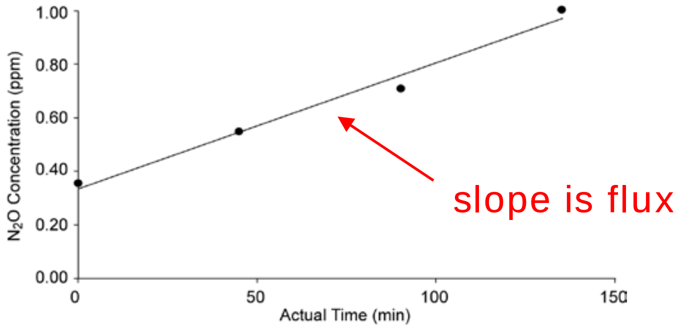
Total Impact	2.0 Pg C_{equiv}	1.2 Pg C_{equiv}

(compare to fossil fuel CO_2 loading = 4.1 PgC per year)

Source IPCC 2001, 2007; Prinn 2004; Robertson 2004

Measuring Nitrous Oxide Production and Methane Oxidation in the Field

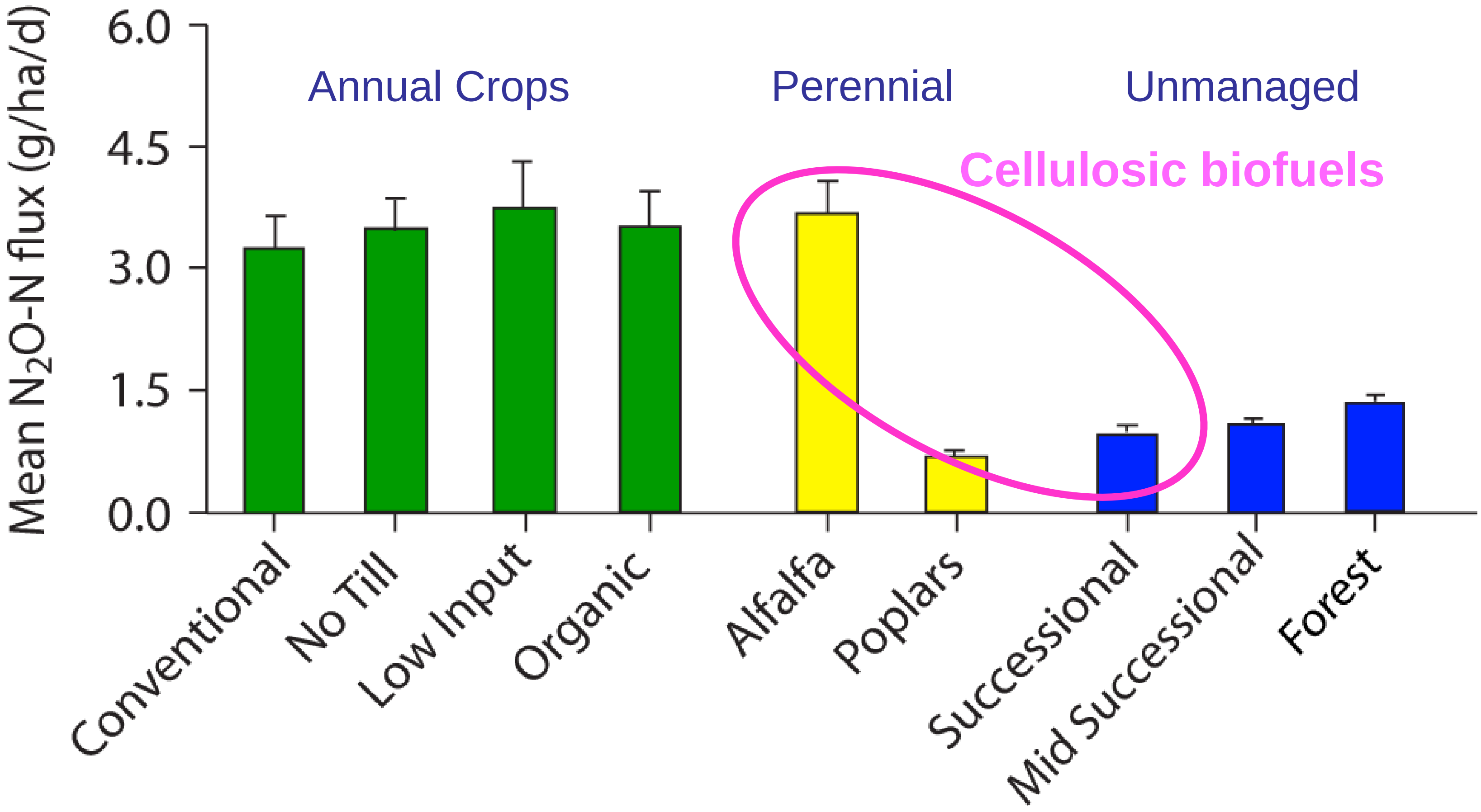
1. Chamber covers soil surface
2. Headspace samples removed over 1-2 hour period
3. Flux = Rate of accumulation or disappearance



slope is flux

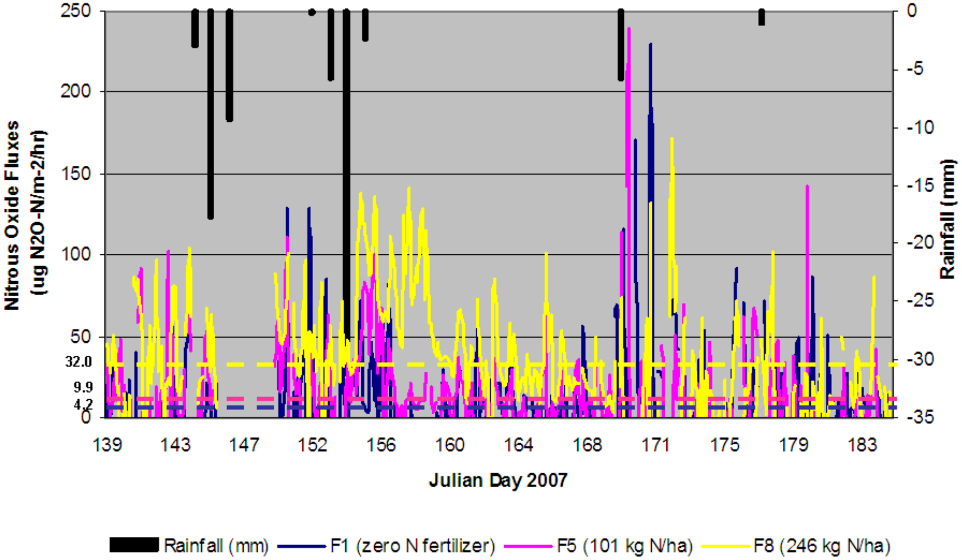
4. Eddy correlation not possible

Nitrous Oxide Fluxes at KBS (1992-2007)



Robertson et al. 2000; Grandy et al. 2006 *JEQ; and Parr et al. in prep.*

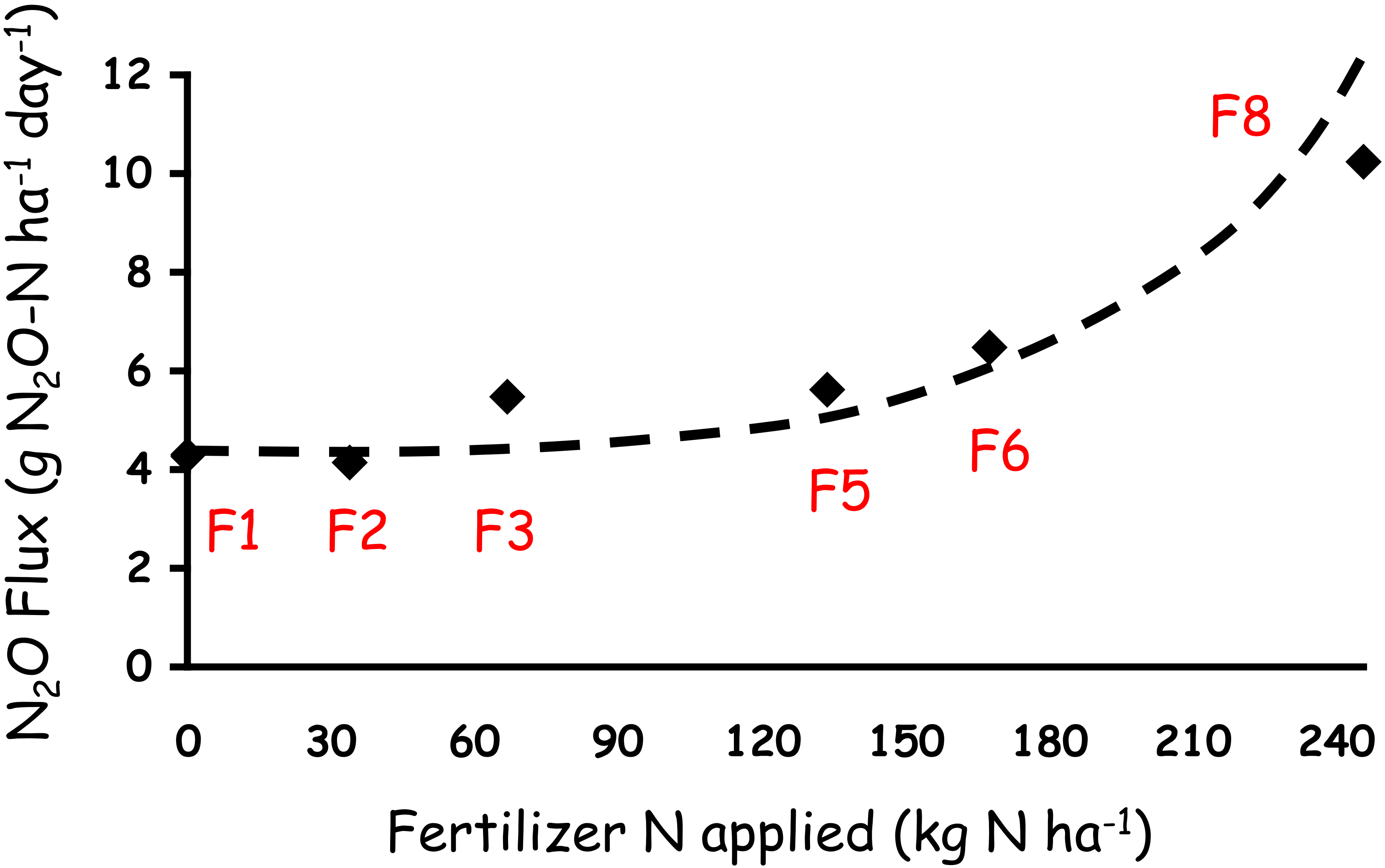
Automated chambers provide needed resolution to test models



Source: Millar et al. in review

Best N_2O flux predictor = Soil N availability

- both among and within systems:



Source: Millar et al. unpub.

What about Methane?

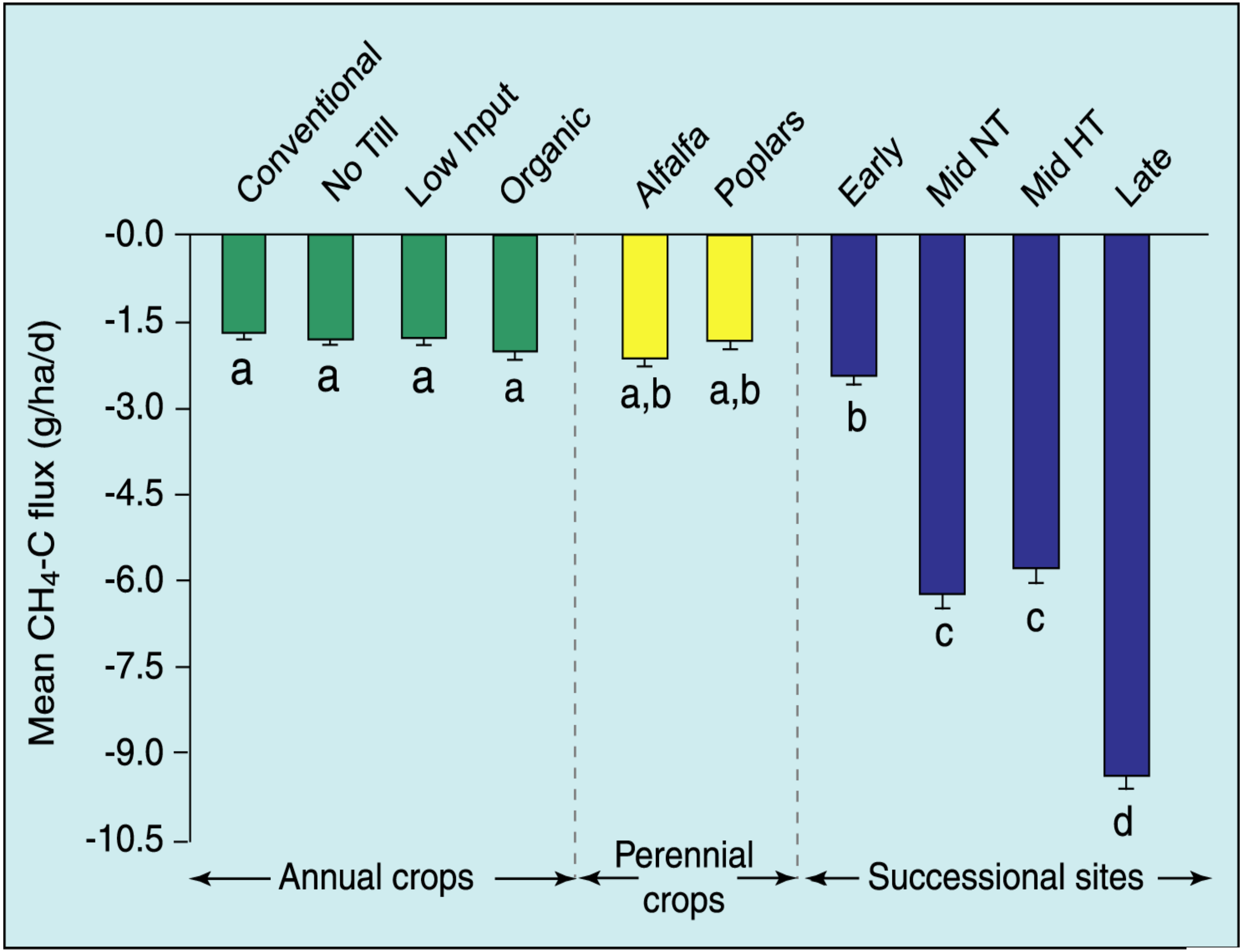
Global CH_4 Budget

Sinks	Tg CH_4/y
Troposphere	490
Stratosphere	40
Upland Soils	30
Atmospheric Increase	37
	597

Sources	
Natural	160
Anthropogenic	375
	535

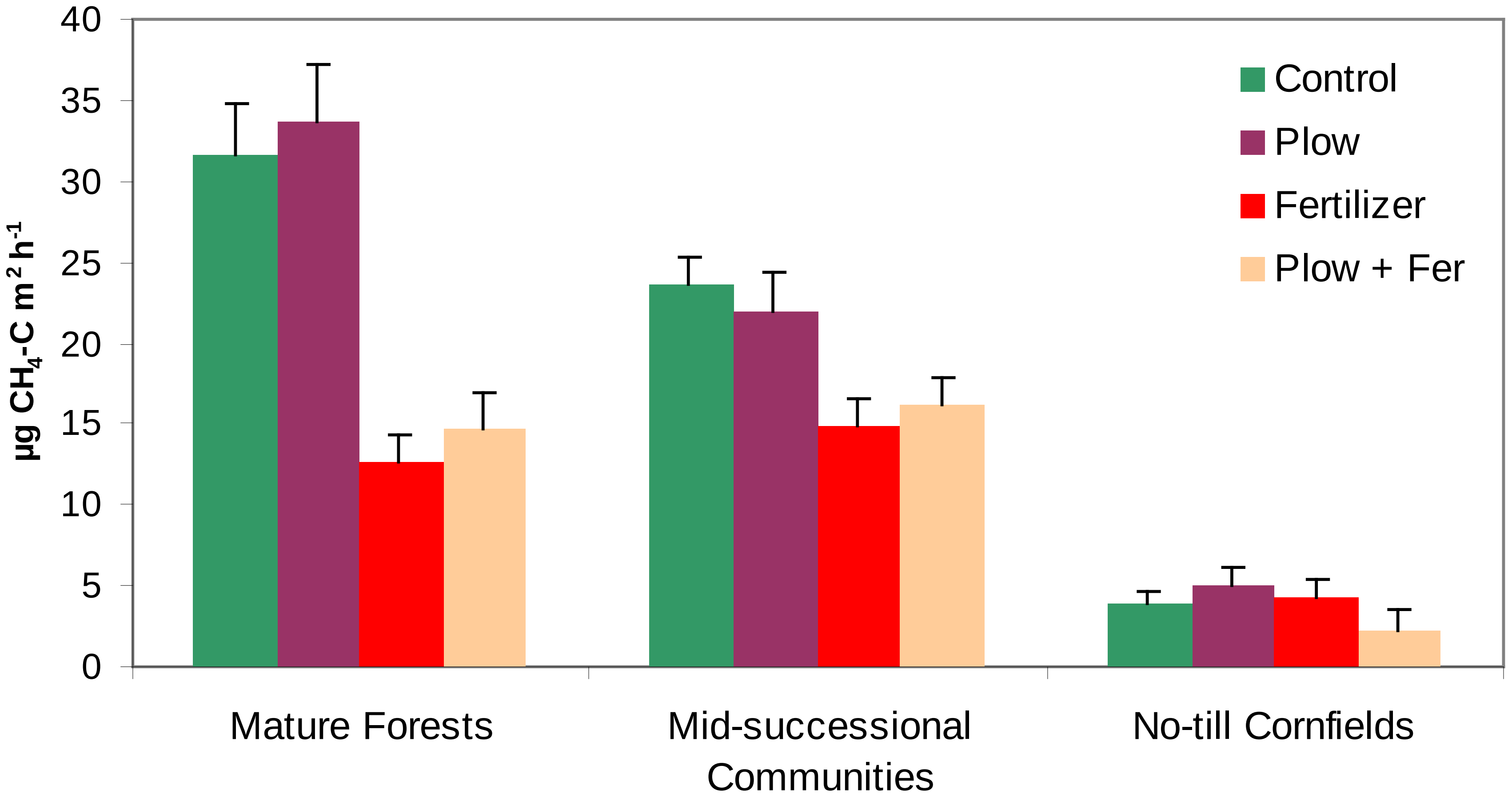
Source IPCC 1997

CH_4 Flux (Oxidation) at KBS (from 1992)



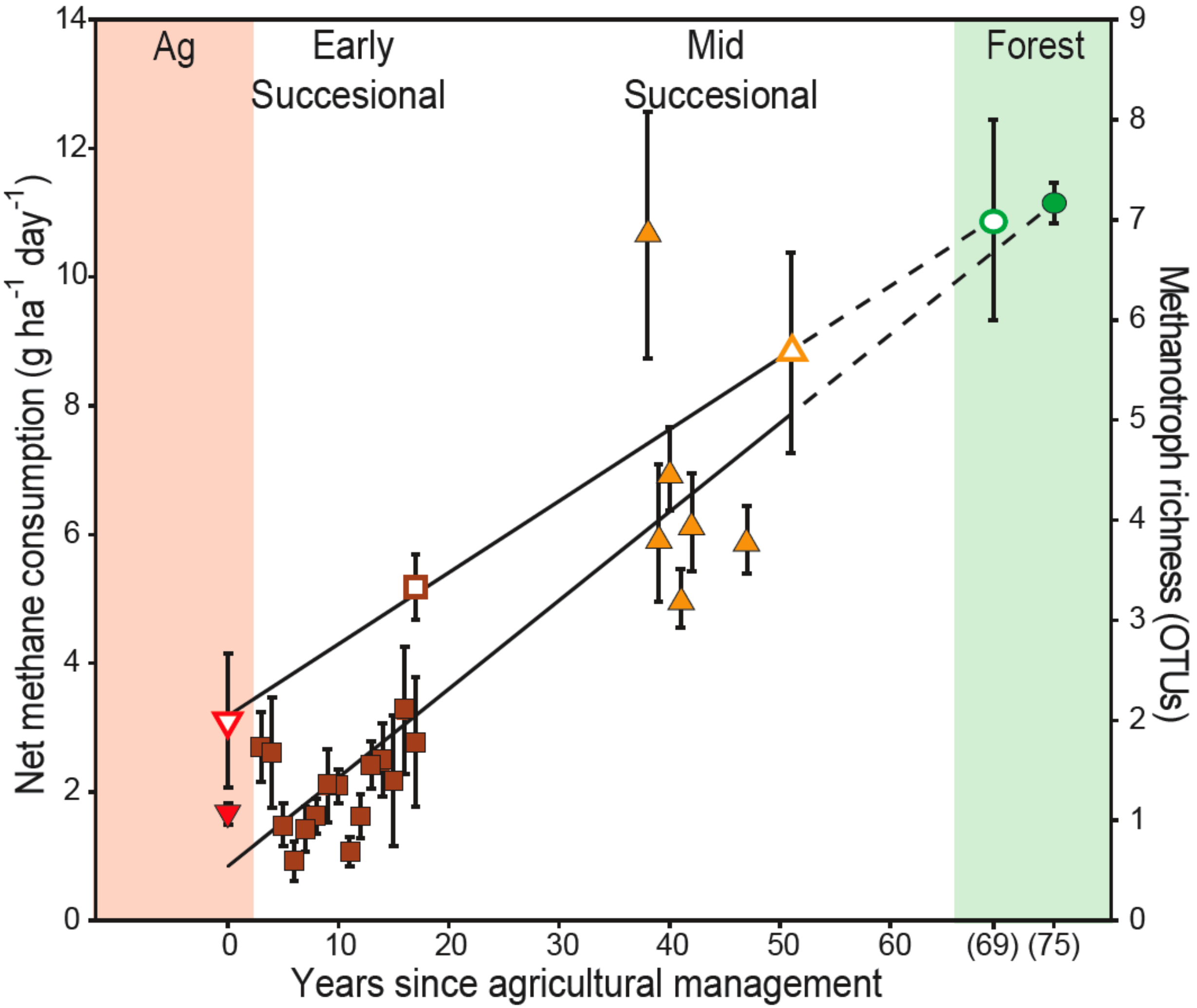
Robertson et al. 2000 *Science*; Grandy et al. 2006 *JEQ*

Net CH_4 Oxidation: Effects of N and Soil Disturbance



Suwanawaree & Robertson (2005)

Methanotroph Diversity and Oxidation Rate



U. Levine, T. Schmidt, et al. in review

Major Potential Sources of Global Warming Impact (CO_2e) in Biofuel Cropping Systems

- Farm Operations
  - Fuel use
  - Fertilizer, pesticides
  - Lime ($CaCO_3$)
- Soil carbon change
- N_2O flux
- CH_4 oxidation
- Post-harvest transport
- Fuel Production (CO_2 offset)

GWP Impact for Field Crop Activities

	Farming	N_2O	CH_4	Soil C Δ	Fuel Offset (farm gate)	Trans-port	Net
Conventional grain/stover	46	56	-1.5	0	-641	13	-527

N_2O is largest source of CO_2e

Soil carbon is at equilibrium (no annual change)

Includes 50% of corn stover

All values = g CO_2 m^{-2} y^{-1} for 1992-2007

GWP Impact for Field Crop Activities

	Farming	N_2O	CH_4	Soil C Δ	Fuel Offset (farm gate)	Transport	Net
Conventional grain/stover	46	56	-1.5	0	-641	13	-527
No-till grain/stover	45	60	-1.8	-66	-606	12	-557

No change in N_2O

Soil carbon gain; offsets N_2O

Greater overall mitigation

All values = g CO_2 m^{-2} y^{-1} for 1992-2007

GWP Impact for Field Crop Activities

	Farming	N_2O	CH_4	Soil C Δ	Fuel Offset (farm gate)	Trans-port	Net
Conventional grain/stover	46	56	-1.5	0	-641	13	-527
No-till grain/stover	45	60	-1.8	-66	-606	12	-557
Alfalfa	31	56	-2.2	-186	-539	11	-618

Lower farming cost (no fertilizer)

Greater soil C gain

All values = g CO_2 m^{-2} y^{-1} for 1992-2007

GWP Impact for Field Crop Activities

	Farming	N_2O	CH_4	Soil C Δ	Fuel Offset (farm gate)	Trans-port	Net
Conventional grain/stover	46	56	-1.5	0	-641	13	-527
No-till grain/stover	45	60	-1.8	-66	-606	12	-557
Alfalfa	31	56	-2.2	-186	-539	11	-618
Early succession	3	22	-2.2	-339	-300	6	-610

Little farming cost (harvest only)

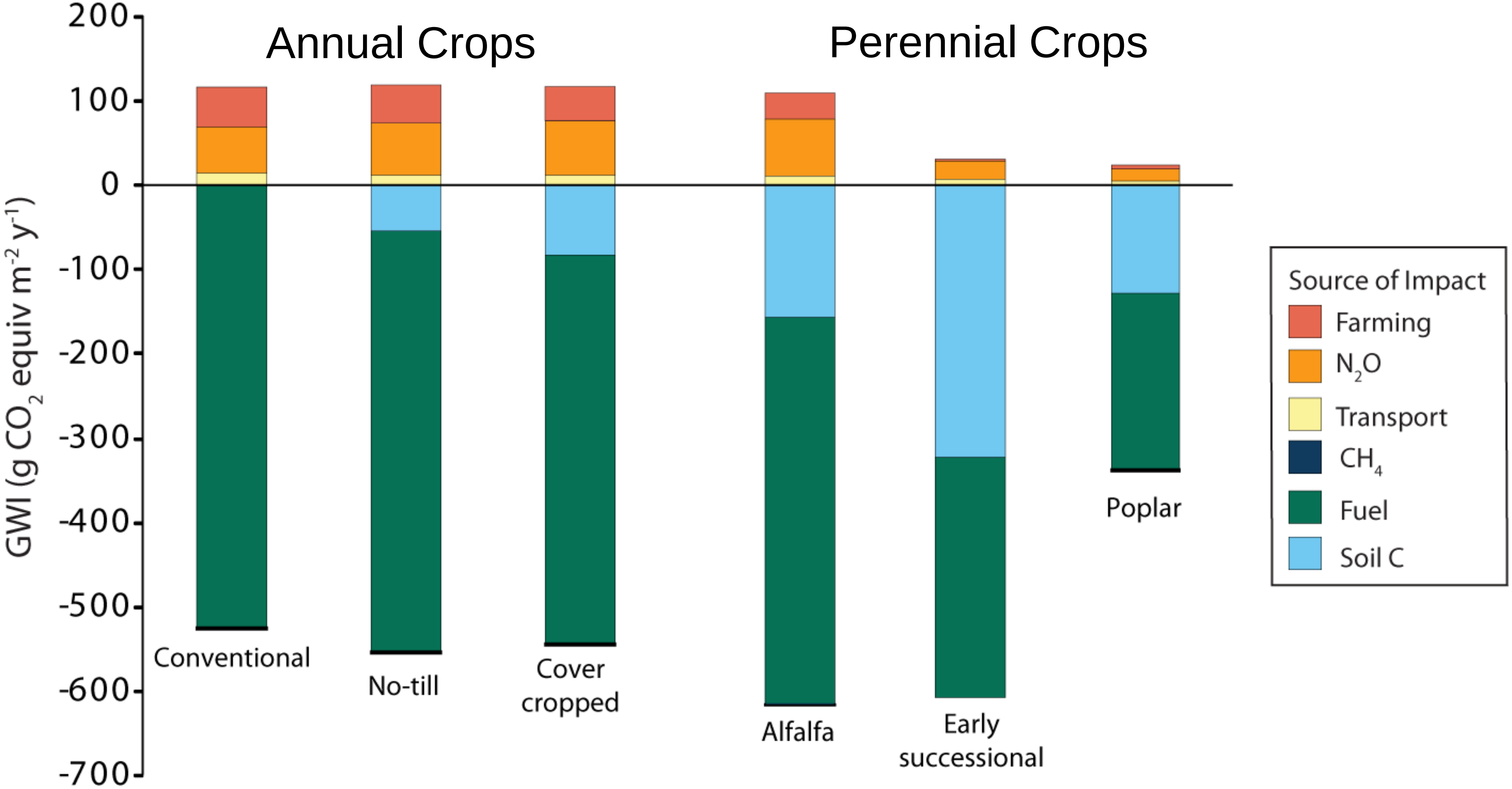
Large N_2O drop

Large SOC gain

Less biomass

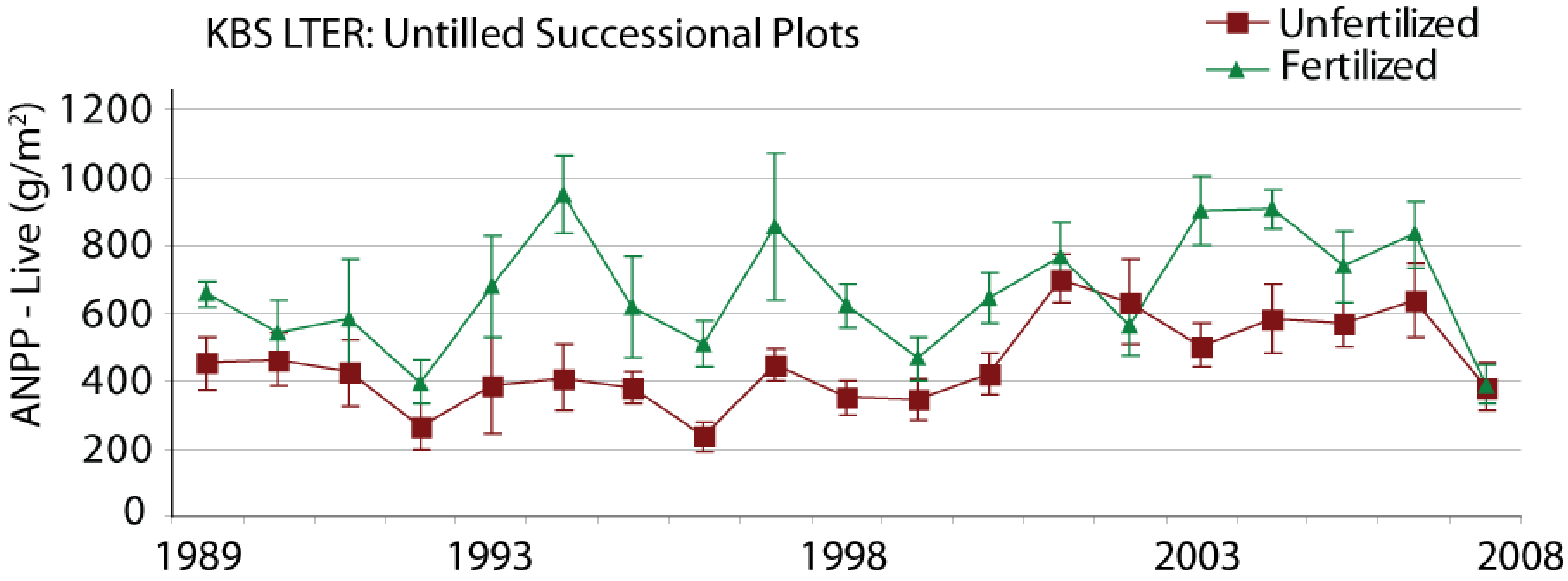
Same net

Global Warming Impact – KBS Field Crops



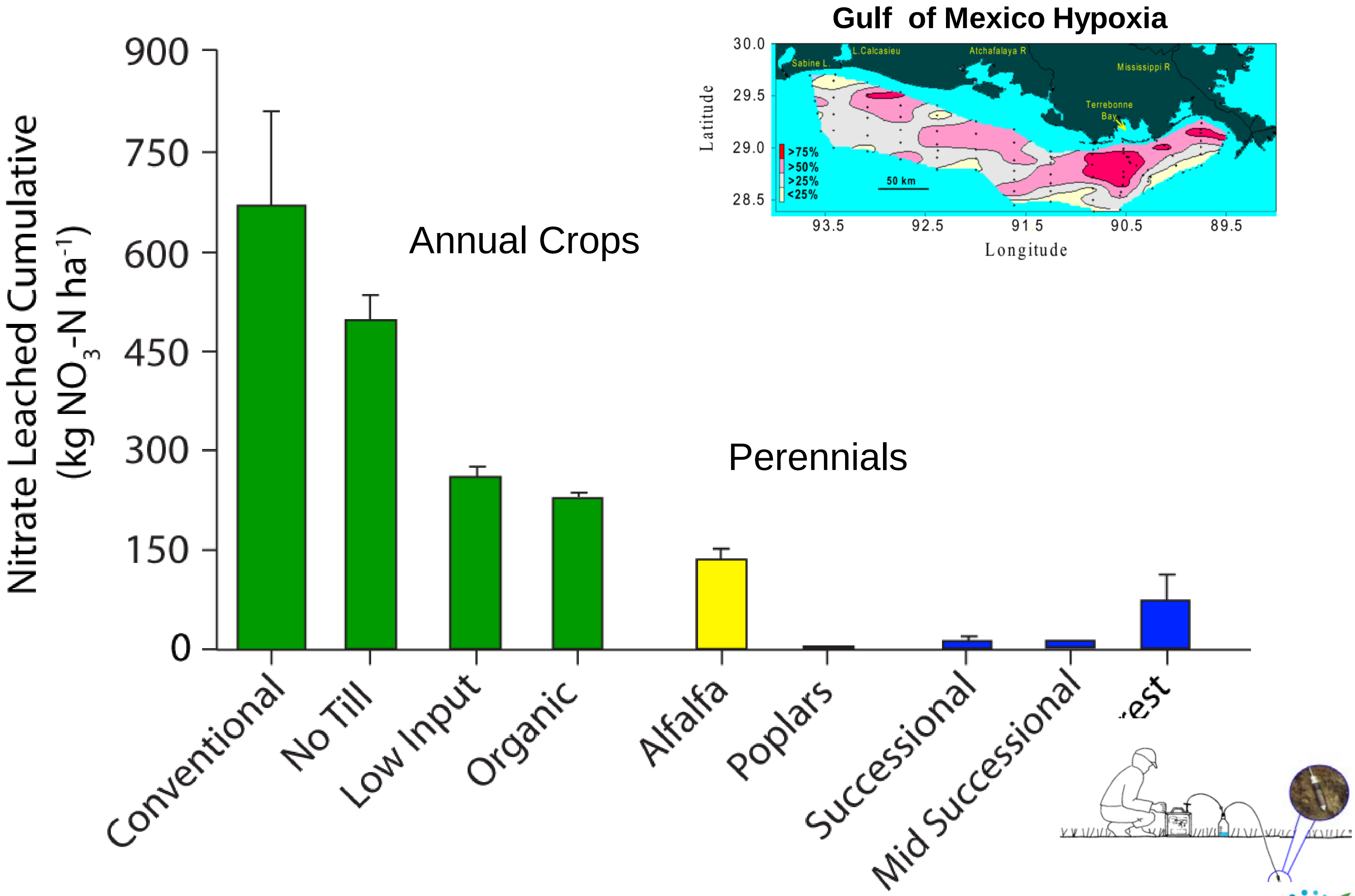
Missing: Indirect Land Use Costs

Fertilized successional yields are similar to on-farm switchgrass yields



K.L. Gross et al., in prep.

Nitrate Loss 1996-2007



Source: Syswerda, et al. in prep.

Conclusions: What do we know?

1. Land requirements are substantial (ca. 80-100 M ha US)
2. Outcomes that provide multiple benefits (ecosystem services) are possible
3. Best biogeochemical outcomes will depend on
    - Choice of crops (e.g. annual vs. perennial)
    - Management practices (residue return, fertilization rate, harvest intensity and timing, irrigation…)
    - Location – prior crop history
4. We know what's needed
    - Comprehensive science understanding at systems level, using a framework that includes human interactions
    - Willingness to incentivize environmental performance

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