Biofuel Sustainability Ten Years On

An Ecological Perspective on Cellulosic Bioenergy

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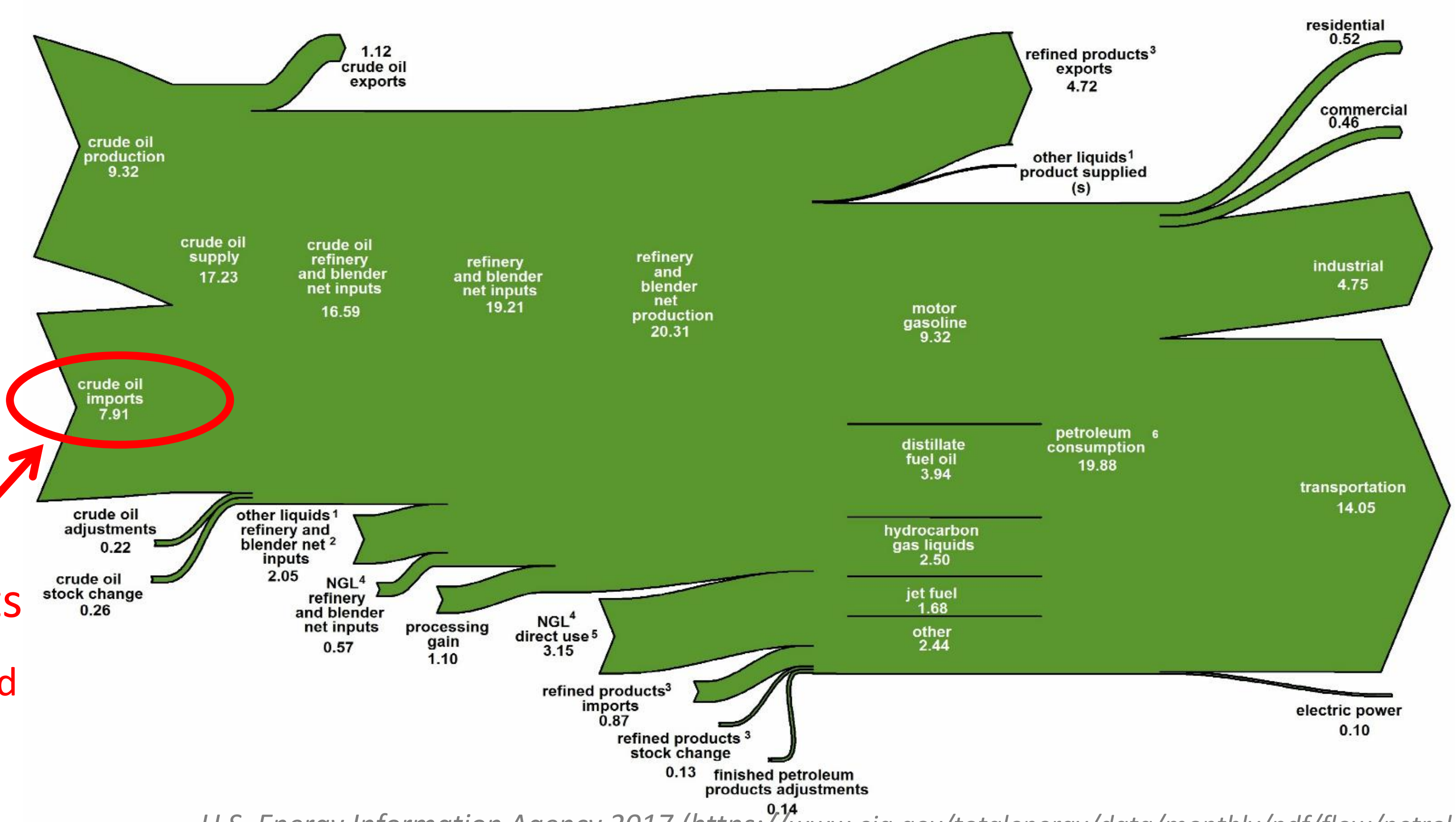
Lignocellulose for bioenergy: The promise

1. Energy independence (EISA 2007)

US Petroleum Flow 2016

million barrels per day



Imports

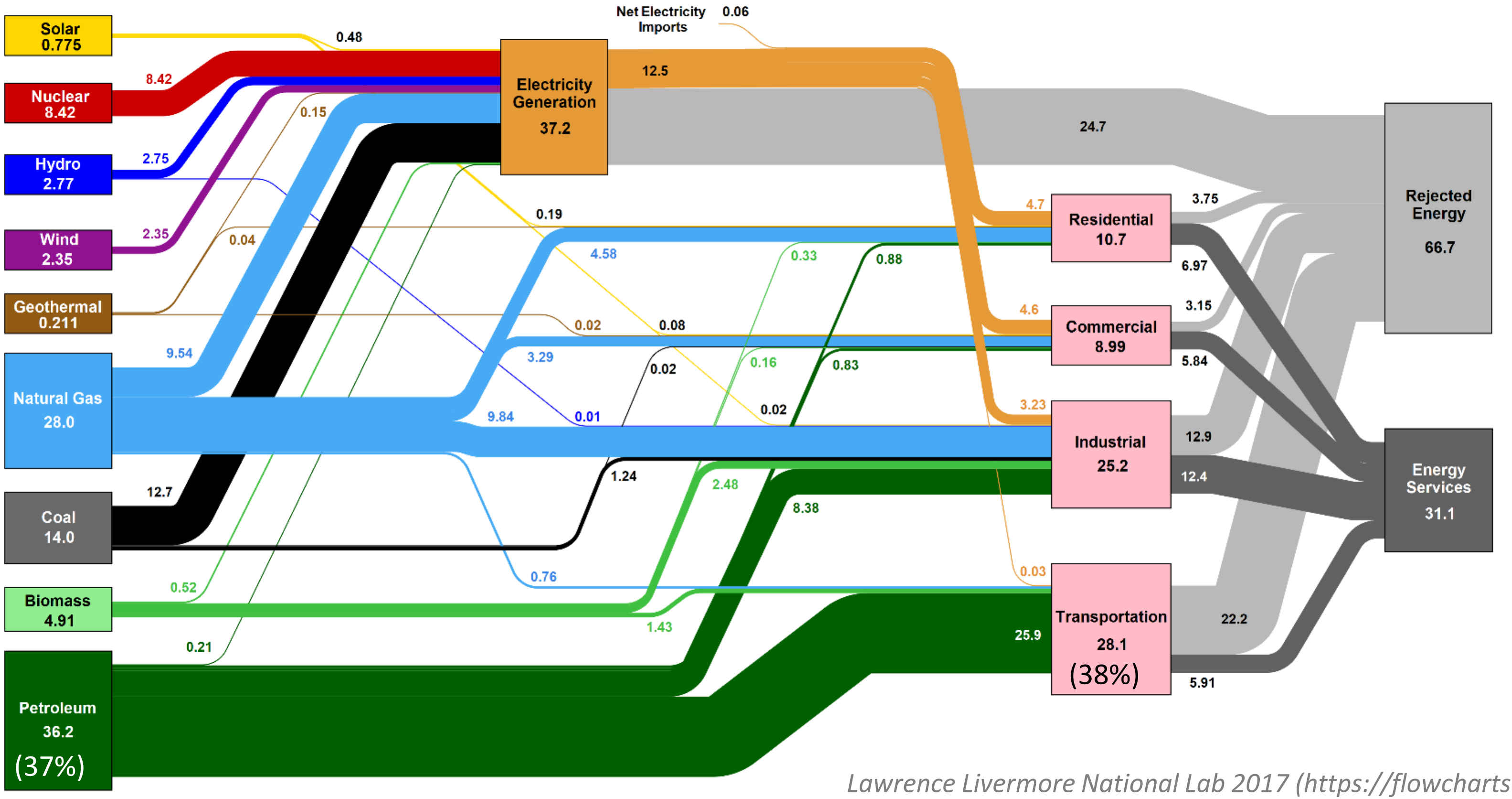
~$0.5B/d

U.S. Energy Information Agency 2017 (https://www.eia.gov/totalenergy/data/monthly/pdf/flow/petroleum.pdf)

Lignocellulose for bioenergy: The promise

1. Energy independence

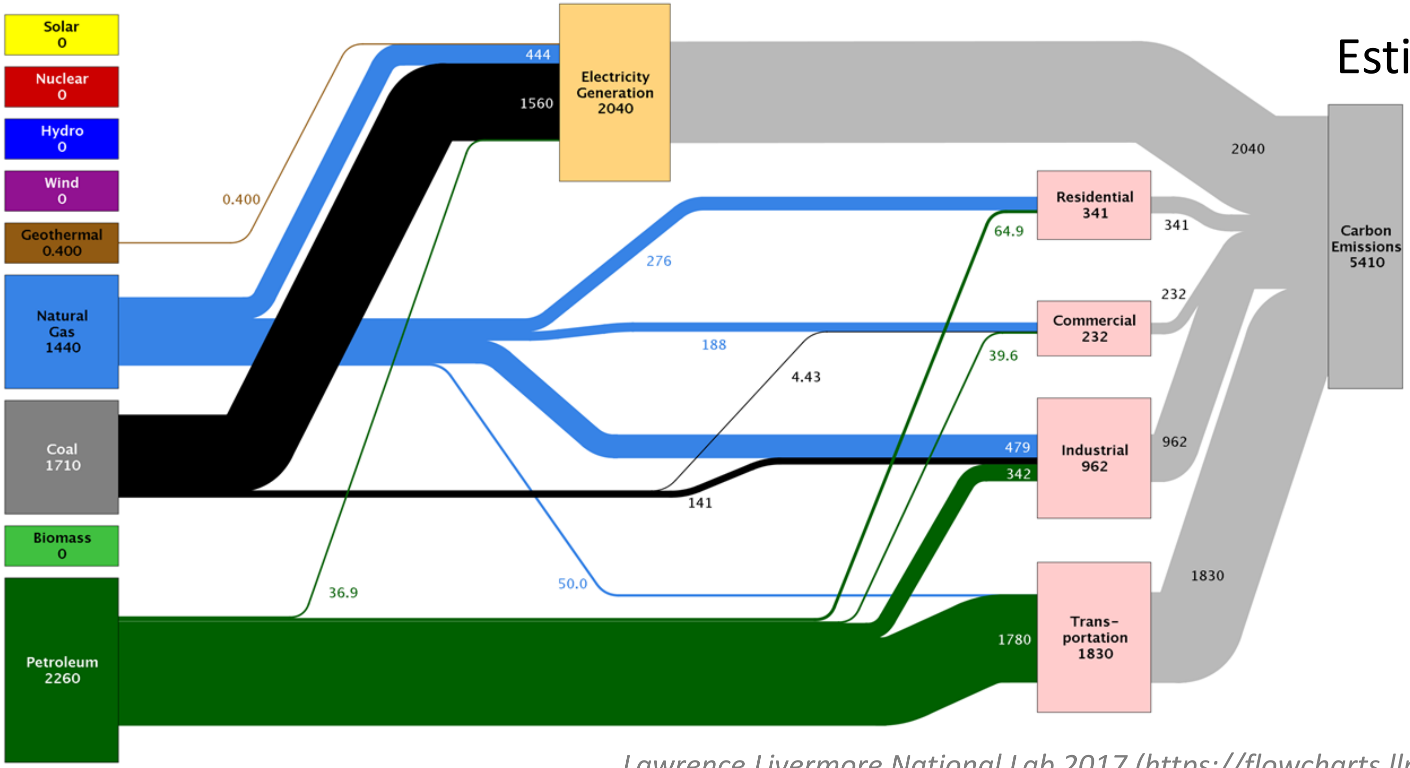
Estimated U.S. Energy Generation and Consumption in 2017 (99 Quads)



Lawrence Livermore National Lab 2017 (https://flowcharts.llnl.gov/)

Lignocellulose for bioenergy: The promise

1. Energy independence (EISA)
2. Climate mitigation
    - Avoided CO_2 emissions – substitute for petroleum



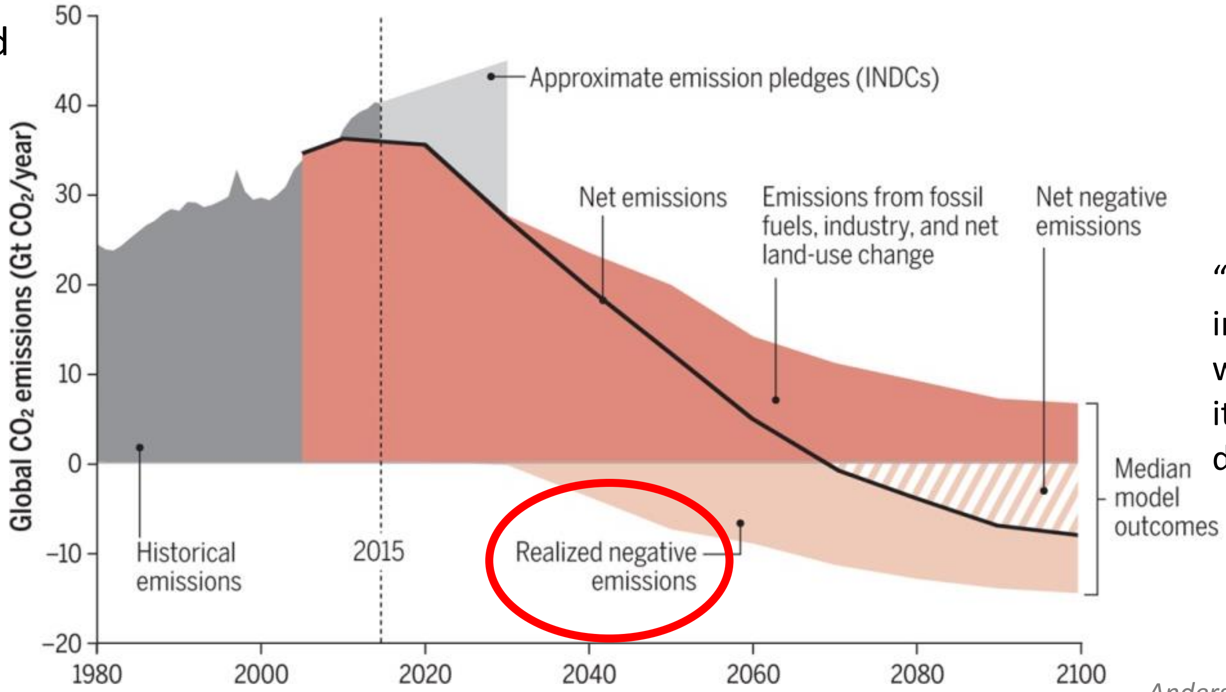
Estimated U.S. Carbon Emissions in 2014 (5.4 Gt CO_2)

Lawrence Livermore National Lab 2017 (https://flowcharts.llnl.gov/commodities/carbon)

Lignocellulose for bioenergy: The promise

1. Energy independence
2. Climate mitigation
    - Avoided CO_2 emissions – substitute for petroleum
    - Negative emissions – Bioenergy Carbon Capture and Storage

Paris Accord
CO_2 Impact



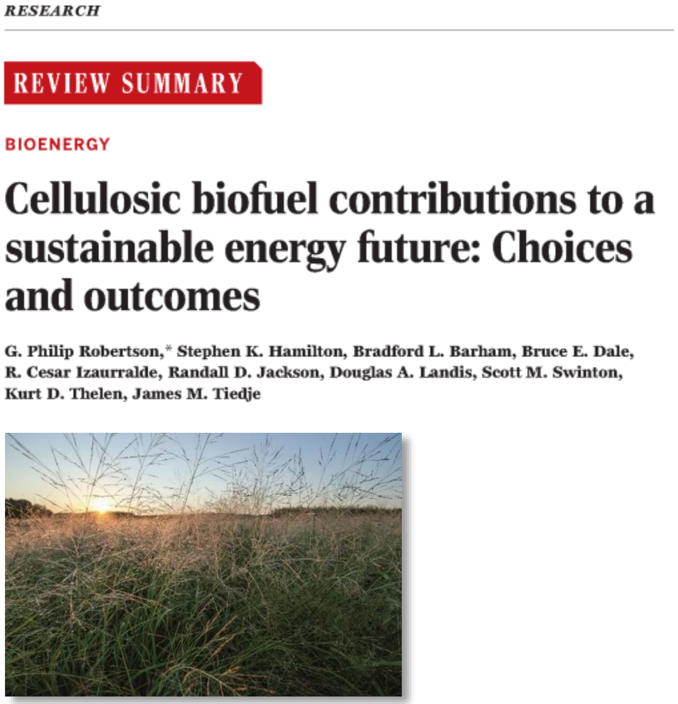
Anderson and Peters 2016 Science

"Bioenergy use is substantial in 1.5°C-consistent pathways with or without BECCS due to its multiple roles in decarbonizing energy use."

-IPCC 2018 1.5°C report

Lignocellulose for bioenergy: The promise of sustainability

1. Sustainability writ large:
    - Reaping benefits today without future harm
2. Key bioenergy considerations:
    - Prior land use
    - Crop choice
    - Biodiversity impacts
    - Reactive N loss
    - Water use
    - Land availability
    - Landowner incentives
3. Remaining knowledge gaps



RESEARCH

REVIEW SUMMARY

BIOENERGY

Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes

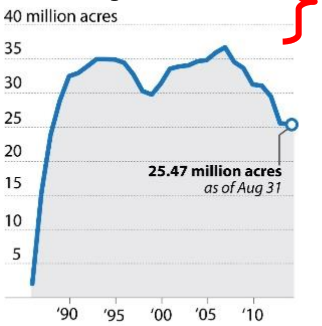
G. Philip Robertson,* Stephen K. Hamilton, Bradford L. Barham, Bruce E. Dale, R. Cesar Izaurralde, Randall D. Jackson, Douglas A. Landis, Scott M. Swinton, Kurt D. Thelen, James M. Tiedje

Robertson et al. 2017. Science 356:eaal2324.

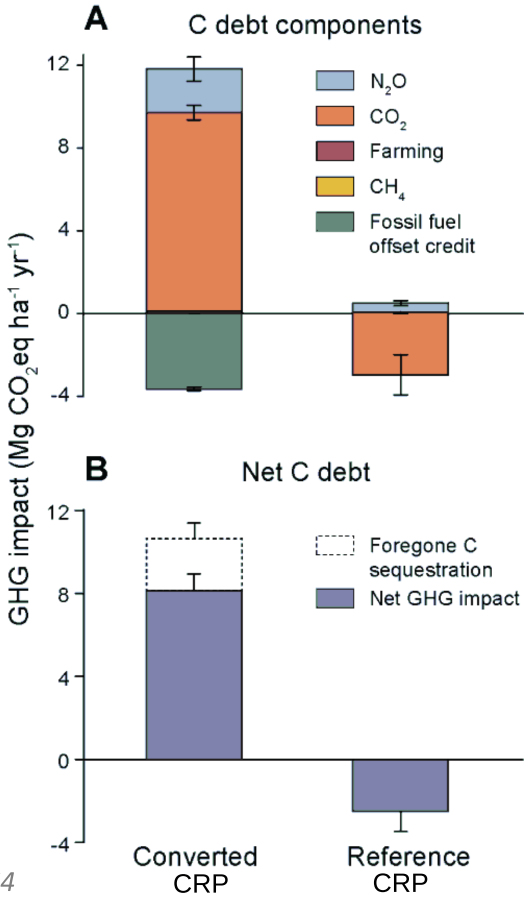
Lignocellulose Bioenergy Sustainability: 1. Land use

- Climate benefits are contingent first on <u>prior</u> land use
  - Prior land use defines short-term and much of the mid-term benefit – due to potential C debt
  - Carbon debt can be huge if prior C stores huge
  - For Conservation Reserve Program grasslands, smaller than modeled (for perennial crops)
  - For forests & wetlands, debilitating
  - Net climate benefit also depends on foregone (pre-existing) sequestration - often ignored
- Use of existing cropland is risky
  - Indirect Land Use Change (ILUC) effect is real even if hard to quantify & turns out to be minor
  - Likely to intensify as global food demand grows – as will food-fuel conflicts
  - Avoidable, depending on energy goals

CRP Acreage



CRP Conversion to Bioenergy

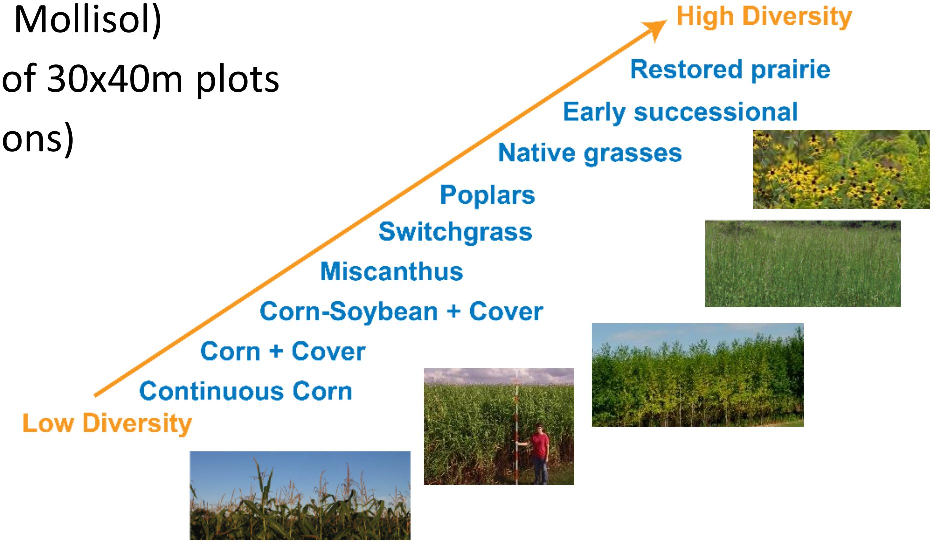


Gelfand et al. 2011 PNAS 108:13864

Lignocellulose Bioenergy Sustainability: 2. Crop choice

- GLBRC Bioenergy Cropping System Experiment (BCSE)
  - 2 locations (Michigan Alfisol, Wisconsin Mollisol)
  - 9 cropping systems x 5 replicate blocks of 30x40m plots
  - Established 2008 (now 10 growing seasons)

K. Stepnitz

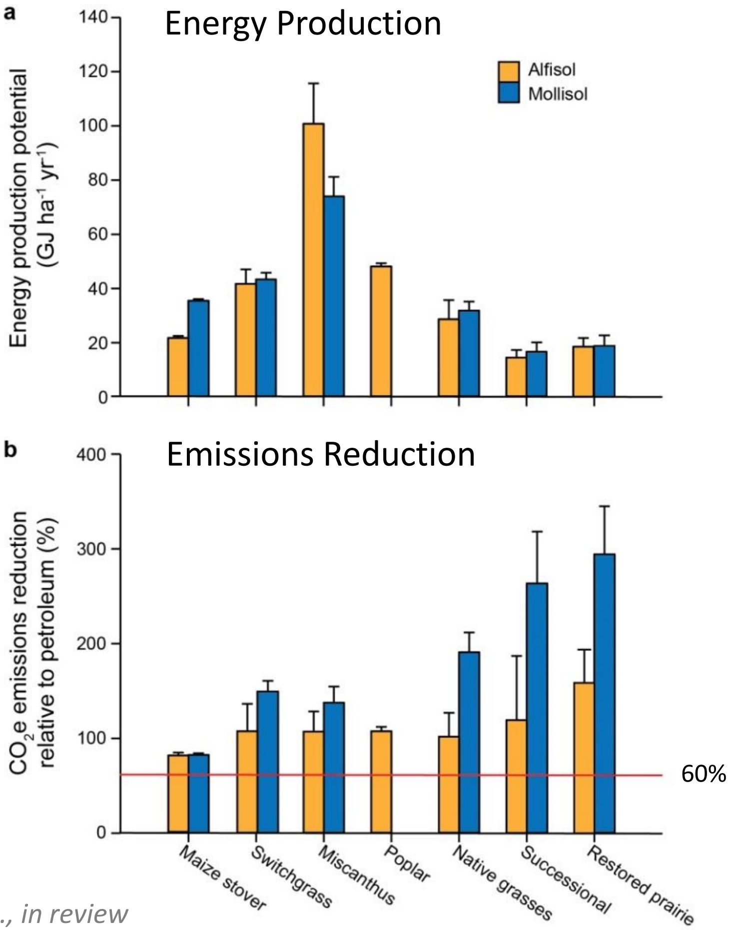


High Diversity
Restored prairie
Early successional
Native grasses
Poplars
Switchgrass
Miscanthus
Corn-Soybean + Cover
Corn + Cover
Continuous Corn
Low Diversity

- Major differences in
  - Net primary productivity
  - Water and nitrogen use efficiencies
  - GHG emissions, Global warming impacts
  - Microbiomes

Lignocellulose Bioenergy Sustainability: 2. Crop choice

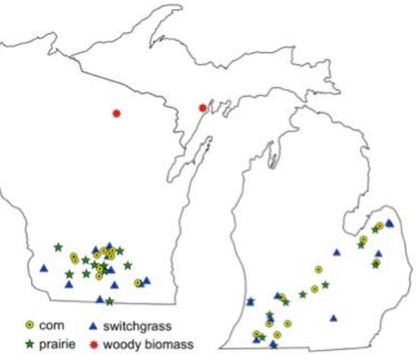
- Choice of crops is key consideration
- Perenniality is best predictor of unambiguous benefit
  - with exception of crop residues and cover crops
- Mixed species may or may not provide a productivity benefit
- Native species can provide biodiversity conservation benefits

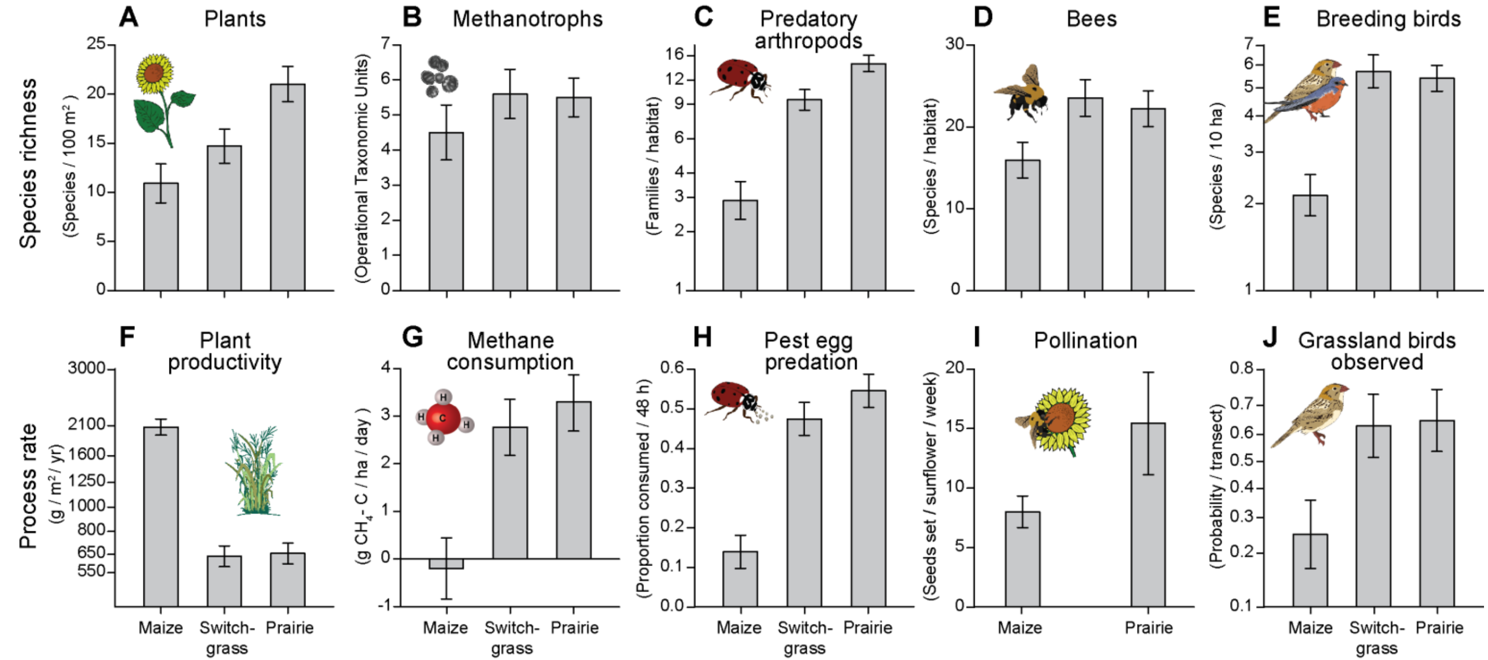


Gelfand et al., in review

Lignocellulose Bioenergy Sustainability: 3. Biodiversity

- Will cellulosic bioenergy enhance or diminish biodiversity conservation? – an important sleeper issue
- A modest amount of plant diversity may go a long way





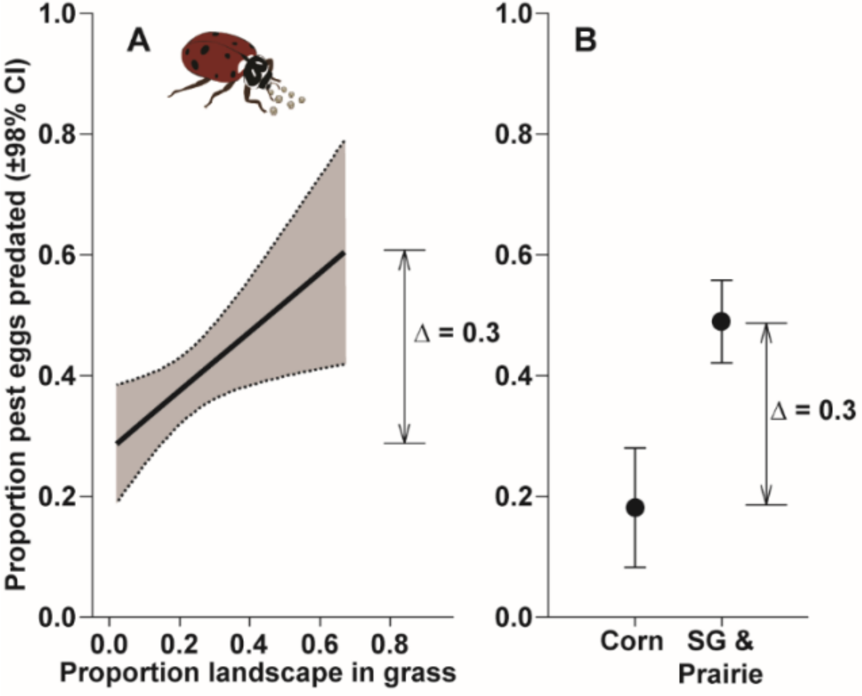
Taxa

Function

Werling et al. 2014 PNAS 111:1652

Lignocellulose Bioenergy Sustainability: 3. Biodiversity, cont.

- Benefits extend to other portions of the landscape
- Local landscape context (placement) is important
  - (A) Predation of pest eggs in annual crops enhanced 3x with greater proportion of landscape in perennial grasses
  - (B) Planted grassland provides same degree of benefit at field scale



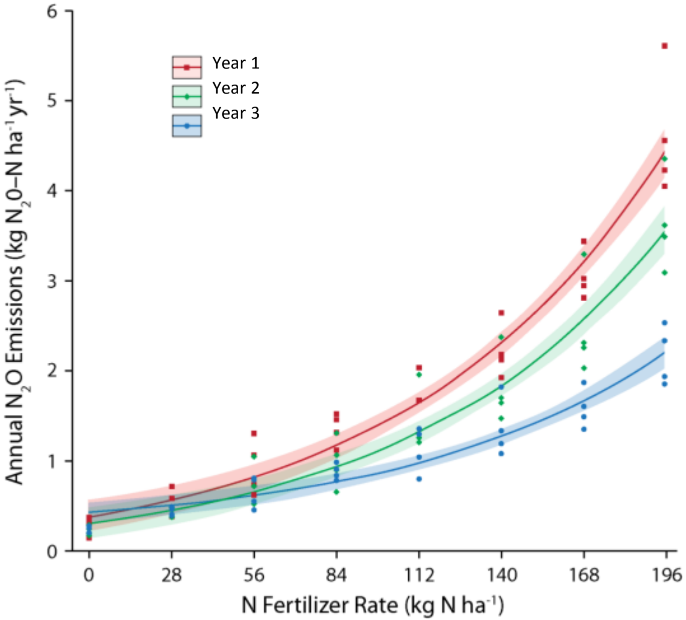
Werling et al. 2014 PNAS 111:1652

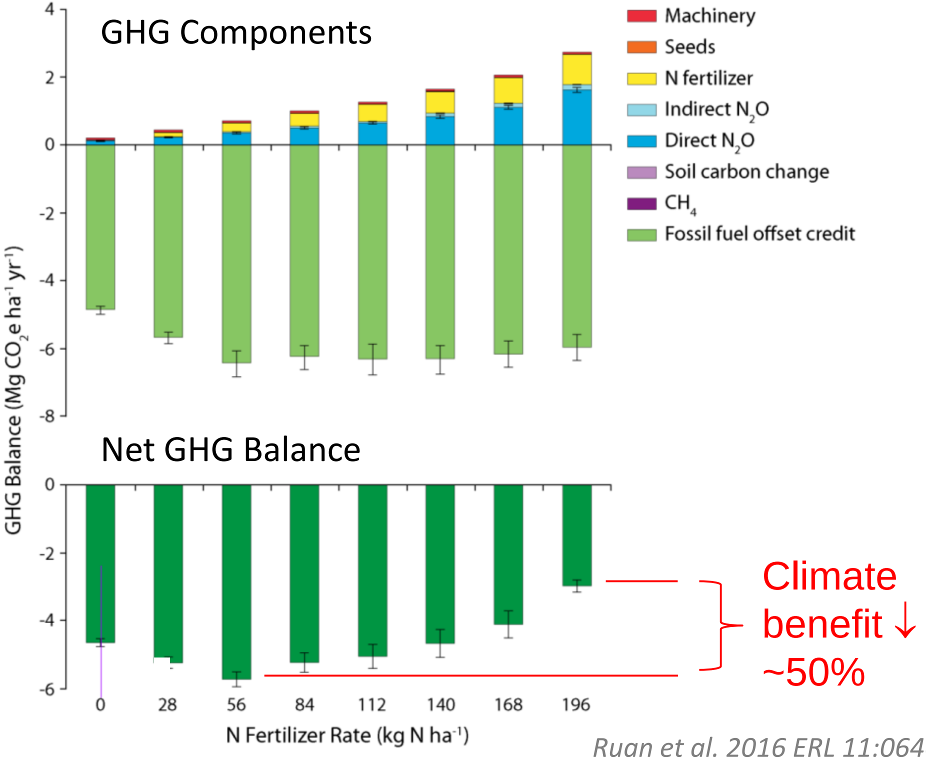
Lignocellulose Bioenergy Sustainability: 4. Reactive N loss

Will cellulosic bioenergy production increase environmental N loading?

- Fertilization in excess of crop need forces disproportionate N loss
- Careful fertilizer use is crucial: many crops may need less N than harvest removal
- Also diminishes climate benefit

Switchgrass N_2O Emissions by N Fertilizer Rate



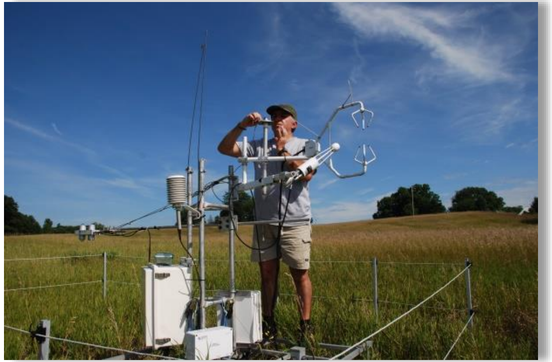


Climate benefit ↓ ~50%

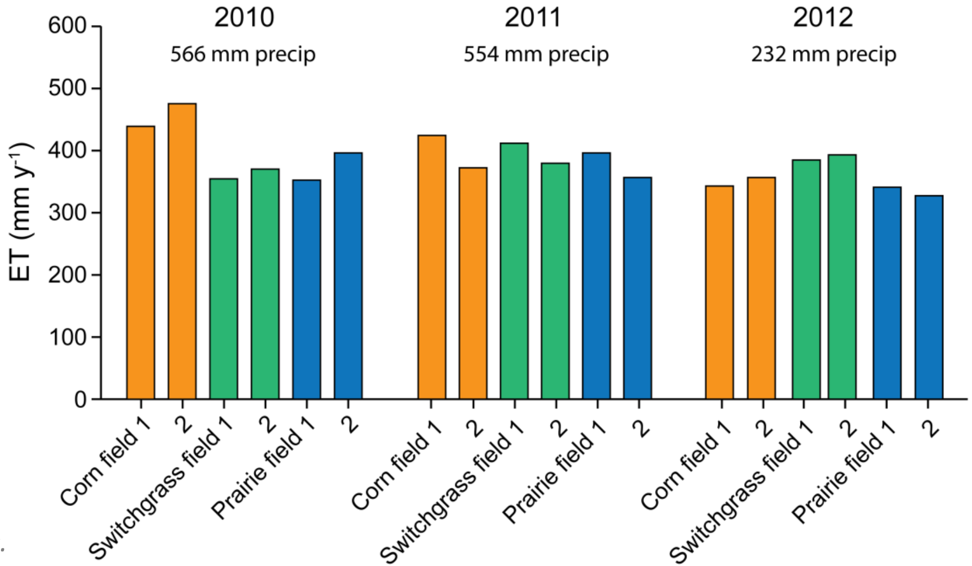
Ruan et al. 2016 ERL 11:064007

Lignocellulose Bioenergy Sustainability: 5. Water use

- Will cellulosic bioenergy systems deplete groundwater recharge?
  - Regional modeling suggested potential aquifer, surface water depletion
  - Field measurements in mesic climate (precip > ET) show large WUE differences but minimal differences in growing season ET – whether TDR, Eddy Covariance (EC), or watershed based
  - All crops use most stored water plus growing season rainfall



ET by Eddy Covariance (7-20 ha fields)

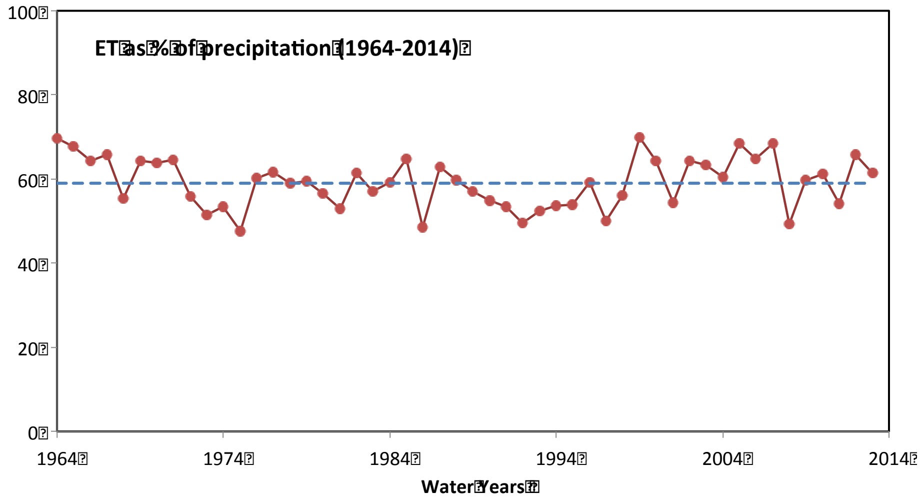


Abraha et al. 2015 GCB-B 7:1344;
Hamilton et al. 2015 ERL 10:064015 and 2018 Hydrol Proc.

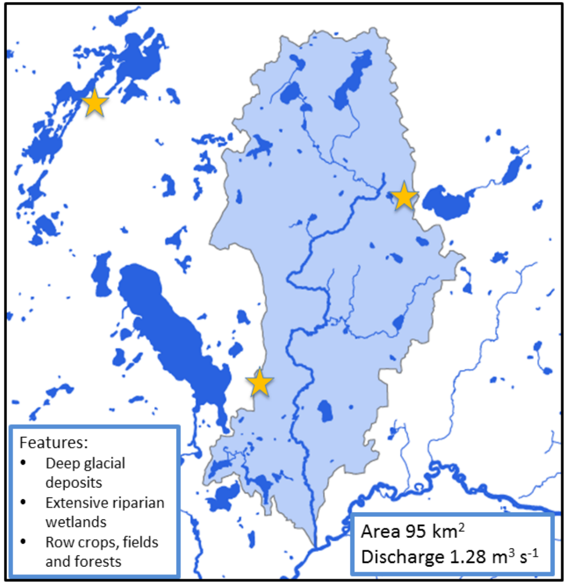
Lignocellulose Bioenergy Sustainability: 5. Water use

Watershed water balance

- 50 years of stream flow and precipitation records for KBS area watershed
- Upland water balance yields ET by difference



Augusta Creek Watershed



Features:

- Deep glacial deposits
- Extensive riparian wetlands
- Row crops, fields and forests

Area 95 km^2
Discharge 1.28 m^3 s^{-1}

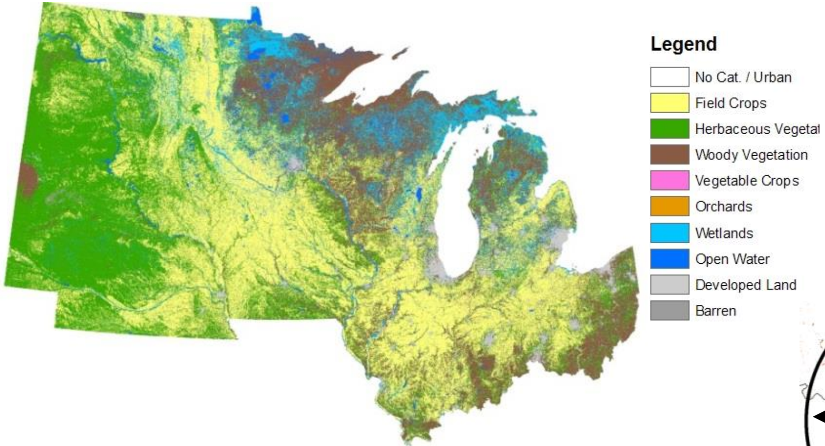
- Watershed ET: 59 ± 6% of annual precipitation
- TDR-estimated ET: 52-62% (seasonal)
- EC-estimated ET: 60% (annual)

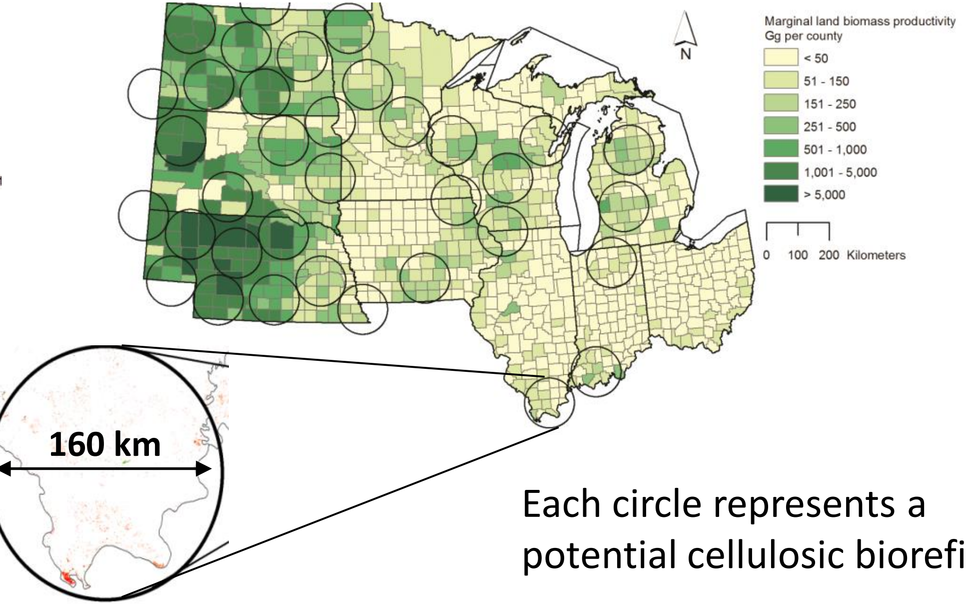
- No temporal trend in spite of substantial cropland abandonment (50%) and reversion to grassland and forest

Hamilton et al. 2018 Hydrol Proc. 32:655

Lignocellulose Bioenergy Sustainability: 6. Land use

- Land use availability will ultimately limit potential climate benefit
- Marginal lands have the most unambiguous benefit:
  - Non-farmed, non-grazed, non-forested, non-wetland, non-urban, privately held
  - Models for Midwest suggest that 35 locations could provide enough biomass within 50 miles to supply a 30 million gallon refinery
  - About half of available marginal land in 10 states could meet ~25% of the legislated fuel mandate for 2022



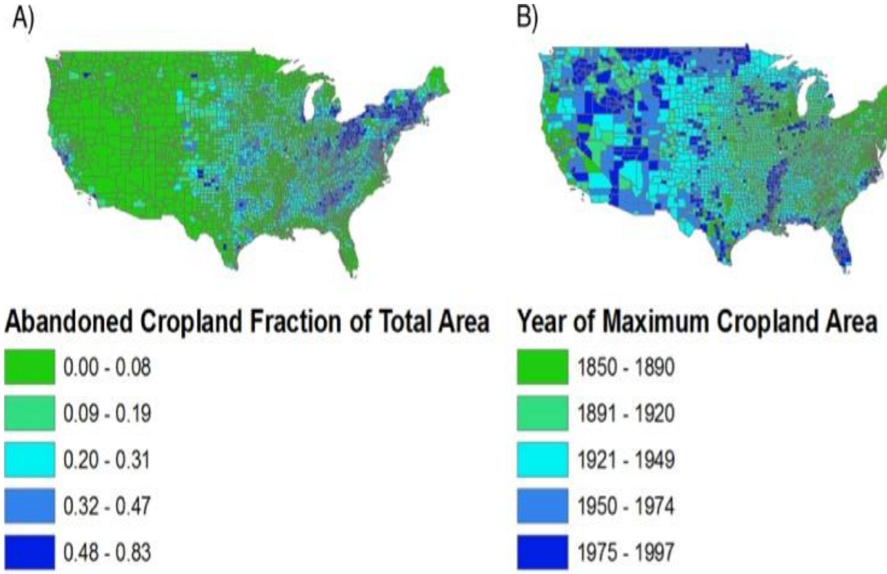


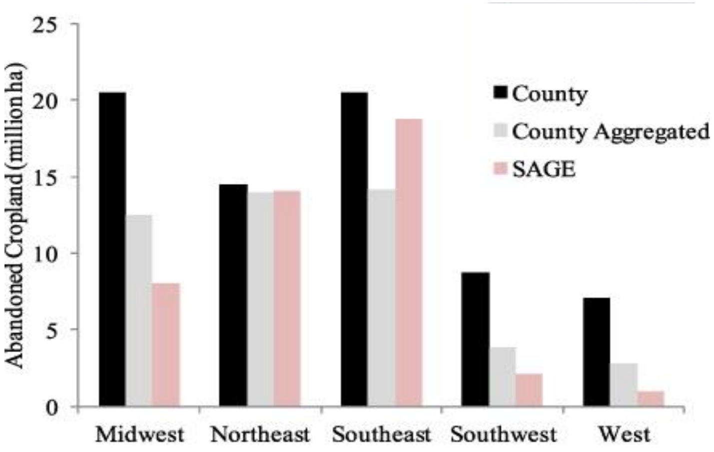
Each circle represents a potential cellulosic biorefinery

Gelfand et al. 2013. Nature

Lignocellulose Bioenergy Sustainability: 6. Land use, cont.

- Land use availability will ultimately limit potential climate benefit
  - The US target of 10^9 Mg total biomass will require 33-40 Mha of productive land or ~55 Mha of marginal land for dedicated bioenergy crops
  - 30% of US cropland abandoned since 1900
  - In US, 70-100 Mha currently available as marginal land (non-forested, non-wetland, non-urban, non-public) based on satellite (70 Mha) and county land use history maps (100 Mha)





Campbell et al. 2013. ERL 8: 035012; Bandaru et al. 2015; Robertson et al. 2017

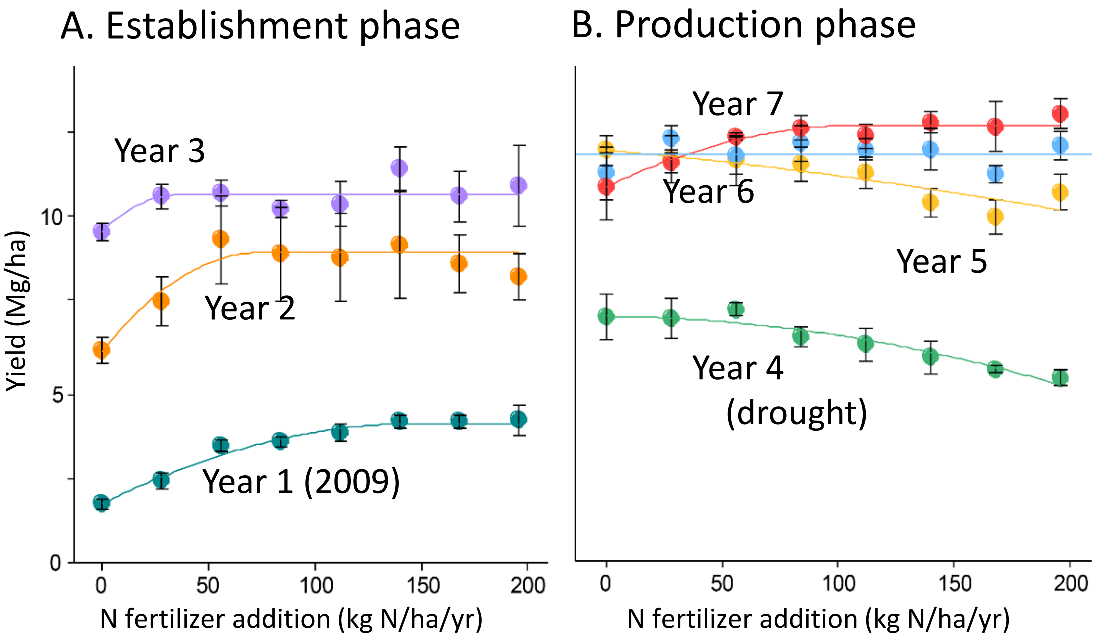
Lignocellulose Bioenergy Sustainability: Key remaining knowledge gaps

1. How to best integrate cropping systems into agricultural landscapes to deliver multiple ecosystem services: **predicting tradeoffs at landscape scales**
2. Understanding the **microbiome to alleviate plant stress** in challenging soils
3. Enhancing **soil C accrual** by better understanding mechanisms contributing to soil C persistence
4. The **biodiversity services** provided by combinations of cropping system traits
5. The **integration of the field-to-product pipeline** to design optimal value chains
6. How to **incentivize optimal systems**: climate benefits + co-benefits

A. Associative Nitrogen Fixation in Switchgrass

Evidence for unknown N source

- Switchgrass is often non-responsive to N fertilizer (~50%)
- At KBS, mass balance suggests >35 kg N yr^{-1} of unaccounted N inputs (58 kg N yr^{-1} during production phase)



7-year mass balance for N (0 N fert)

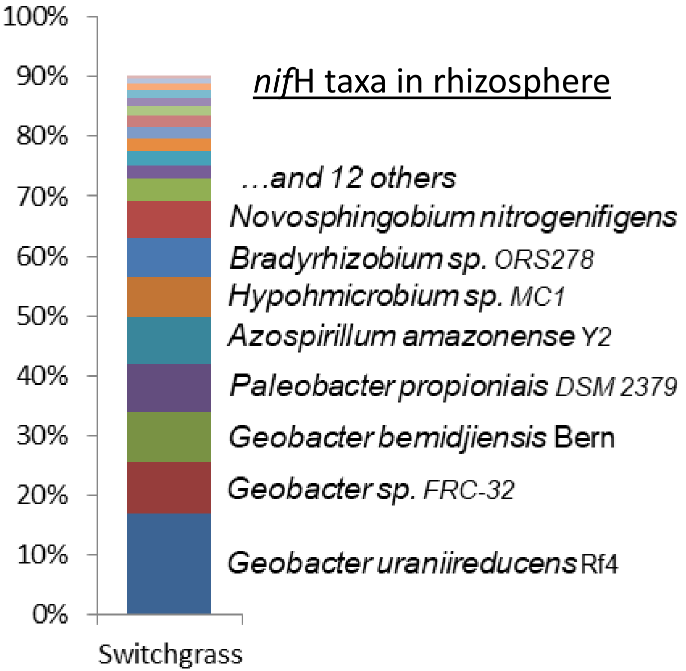
Inputs (kg N ha^{-1} yr^{-1})	
Precipitation	6
N mineralization	0
Outputs (kg N ha^{-1} yr^{-1})	
Harvest	41
Leaching	>0
Denitrification	>0
N immobilization	>0
Balance	-35 kg N yr^{-1}

Ruan et al. 2016 ERL; Roley et al. 2018 PLoS One

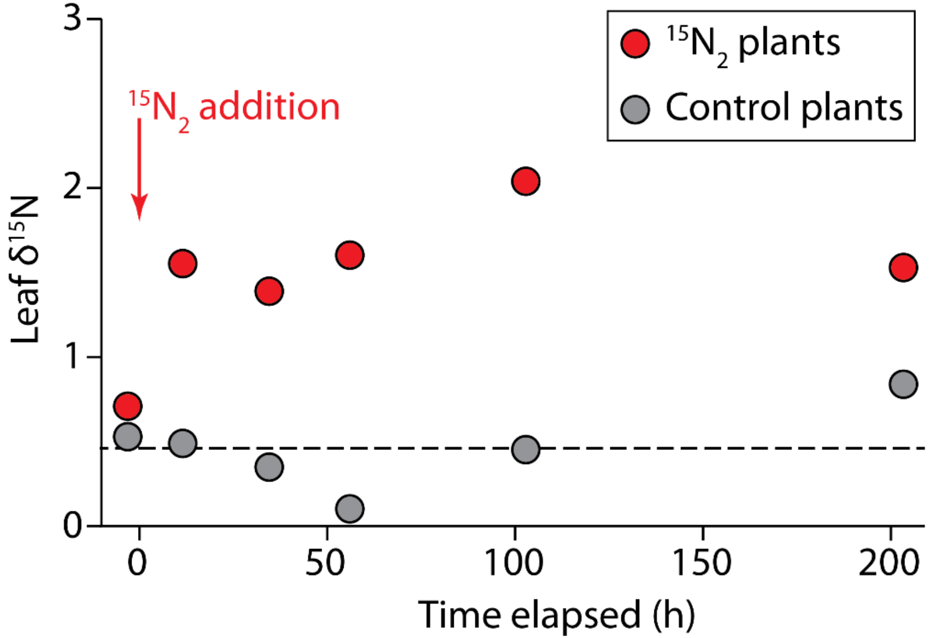
A. Associative Nitrogen Fixation in Switchgrass

Evidence for biological source

- Rhizosphere hosts a rich *nifH* community
- $^{15}N_2$ added to rhizosphere *in situ* is incorporated into plant tissue



*nif*H taxa in rhizosphere



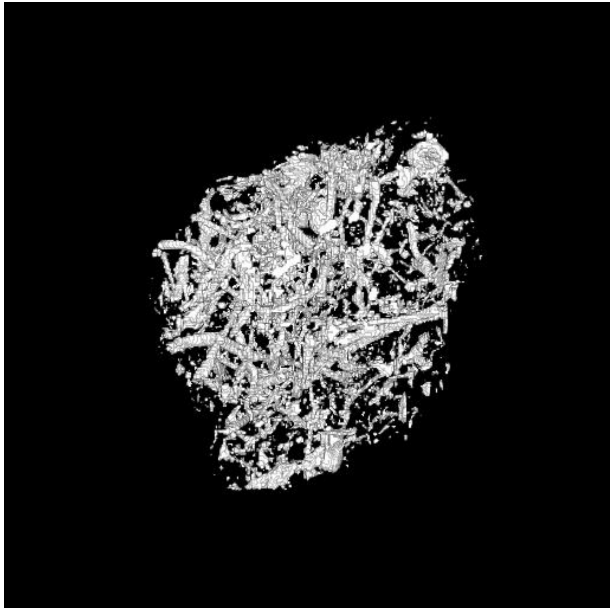
Guo et al., in review; Roley et al. 2018 SBB (in press)

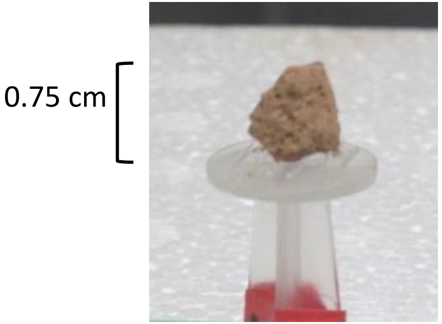
B. Soil Carbon Stabilization

- Soil carbon gain is crucial for climate benefit
  - *fn*(physical, chemical, biological attributes)
  - Importance of soil pores largely unrecognized

Annual cropping system

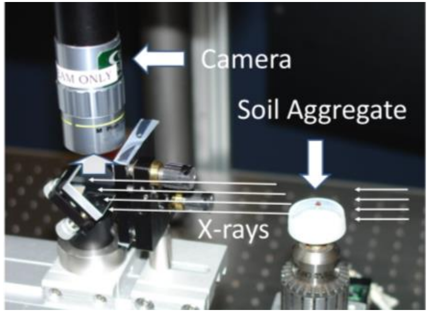
Perennial mixed species





J. Frey

Argonne



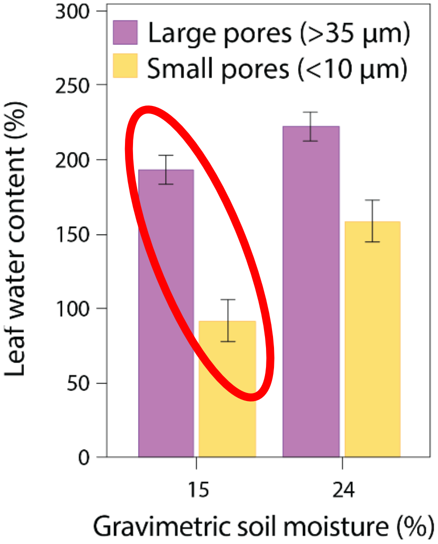
AJMS Smucker

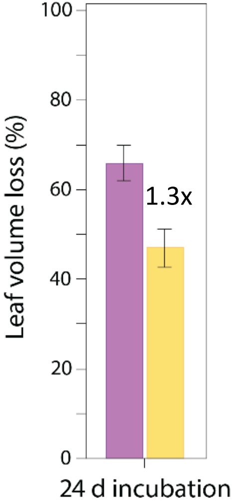
Kravchenko et al. 2017 Nature Geosci; Quigley et al. 2018

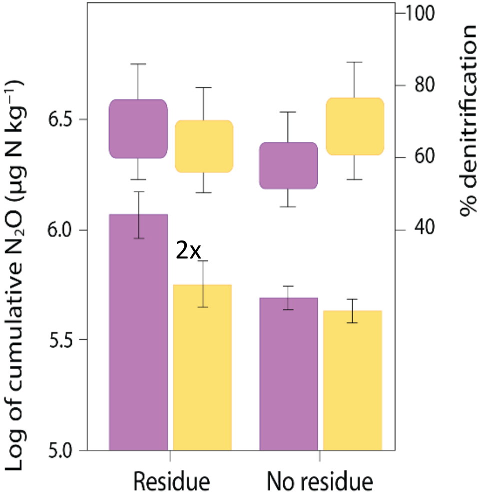
B. Soil Carbon Stabilization

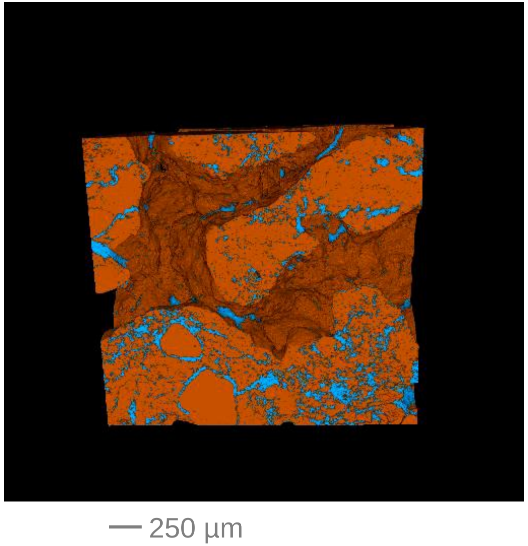
Porosity (pore size distributions) matter

- Large pores (>35 µm) allow residue (particulate organic matter) to accumulate water
- With consequences for CO_2 and N_2O emissions


Leaf residue water content


Decomposition


N_2O Emissions



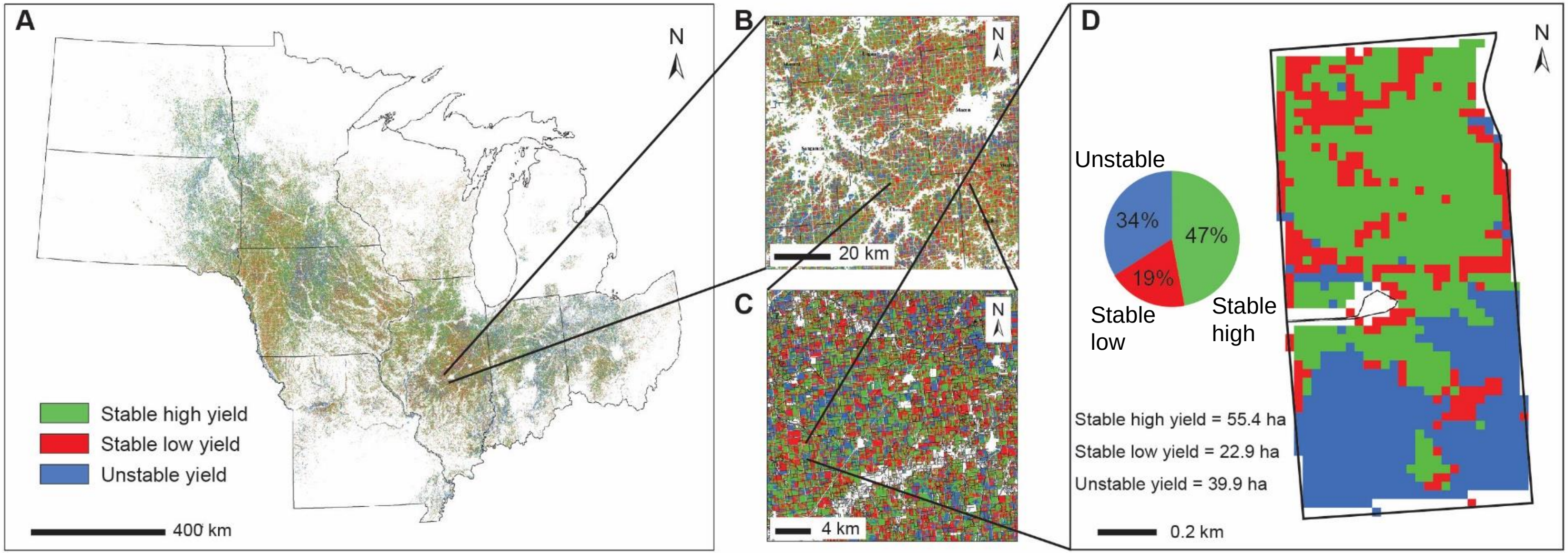
Water in intra-aggregate and inter-aggregate soil pores

Kravchenko et al. 2017 Nature Geo

C. An expanded view of marginal lands

Using low yielding cropland for bioenergy

- Crop yield stability maps for 10 U.S. states (2010-2017): 10^8 fields, 30 Mha
    - Based on remotely sensed NDVI differences at peak biomass
- Subfield areas of stable low productivity comprise 26% of region
- Responsible for most fertilizer nitrogen loss



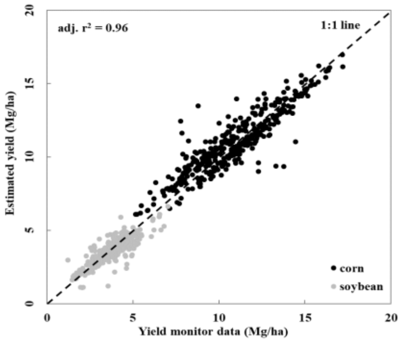
Basso et al., in review

C. An expanded view of marginal lands

- Using low yielding cropland for bioenergy
  - In 2017, 37% of total corn crop was used for ethanol
  - Converting this 37% of corn cropland (17 Mha) to perennial cellulosic bioenergy would provide similar level of biofuel with
    - ↑ climate mitigation
    - ↑ biodiversity benefits
    - ↑ nitrogen conservation

State	**Fertilizer Rate (kg N ha^{-1} y^{-1})**	**Fertilizer loss (kg N ha^{-1} y^{-1})**		
		Stable High	**Stable Low**	**Unstable**
IL	183 – 191	0	45 – 53	5 – 13
IN	175 – 209	0 – 23	50 – 84	11 – 45
IA	158 – 173	0	12 – 27	0
MI	151 – 165	0	30 – 44	0 – 5
MN	160 – 177	0	14 – 31	0 – 0
MO	197 – 217	34 – 54	89 – 109	55 – 75
ND	143 – 158	0 – 5	37 – 52	6 – 21
OH	174 – 195	0 – 7	47 – 68	9 – 30
SD	138 – 152	0	25 – 39	0 – 5
WI	117 – 129	0	0 – 2	0
Average loss		3 – 9	35 – 51	9 – 19

Total N loss 0.33-0.48 Tg N yr^{-1}



NDVI vs. Combine yield monitor estimates of yield

Basso et al., in review

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1. How to best integrate cropping systems into agricultural landscapes to deliver multiple ecosystem services: **predicting tradeoffs at landscape scales**
2. Understanding the **microbiome to alleviate plant stress** in challenging soils
3. Enhancing **soil C accrual** by better understanding mechanisms contributing to soil C persistence
4. The **biodiversity services** provided by combinations of cropping system traits
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