LCA, Environmental, and Sustainability Aspects of Emerging Biomass Conversion Technologies

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Outline:

- Biofuels and policy context for decarbonizing transportation
  - Global consequences of biofuels: land use change (LUC)
- Life Cycle Assessment (LCA) of lignocellulosic biofuel conversion technologies
  - Model development for bio-ethanol (E100) fuels; uncertainty
  - Focus: GHG environmental impacts
- Better biomass and biofuels and analytics:
  - Feedstock: perennial grasses, ag. residues, winter crops,
  - Fuel conversion: pyrolysis bio-oil, higher alcohols → upgrade to infrastructure compatible fuels and value-added co-products
  - Temporally and spatially explicit accounting procedures

Introduction and Background

- A 2004 paper outlined a strategy for reducing GHG emissions from different economic sectors by 1 gigaton each, a "wedge analysis"
  Pacala and Socolow, *Science*, 2004. 305: 968-972
- Biofuels are one avenue for achieving this "wedge" in the transportation sector
- Gigaton-scale bioenergy production will demand
  - Large land and water inputs
  - Will transform rural communities (social-economic-environmental implications)
    - Agricultural landscape

Policy Context:

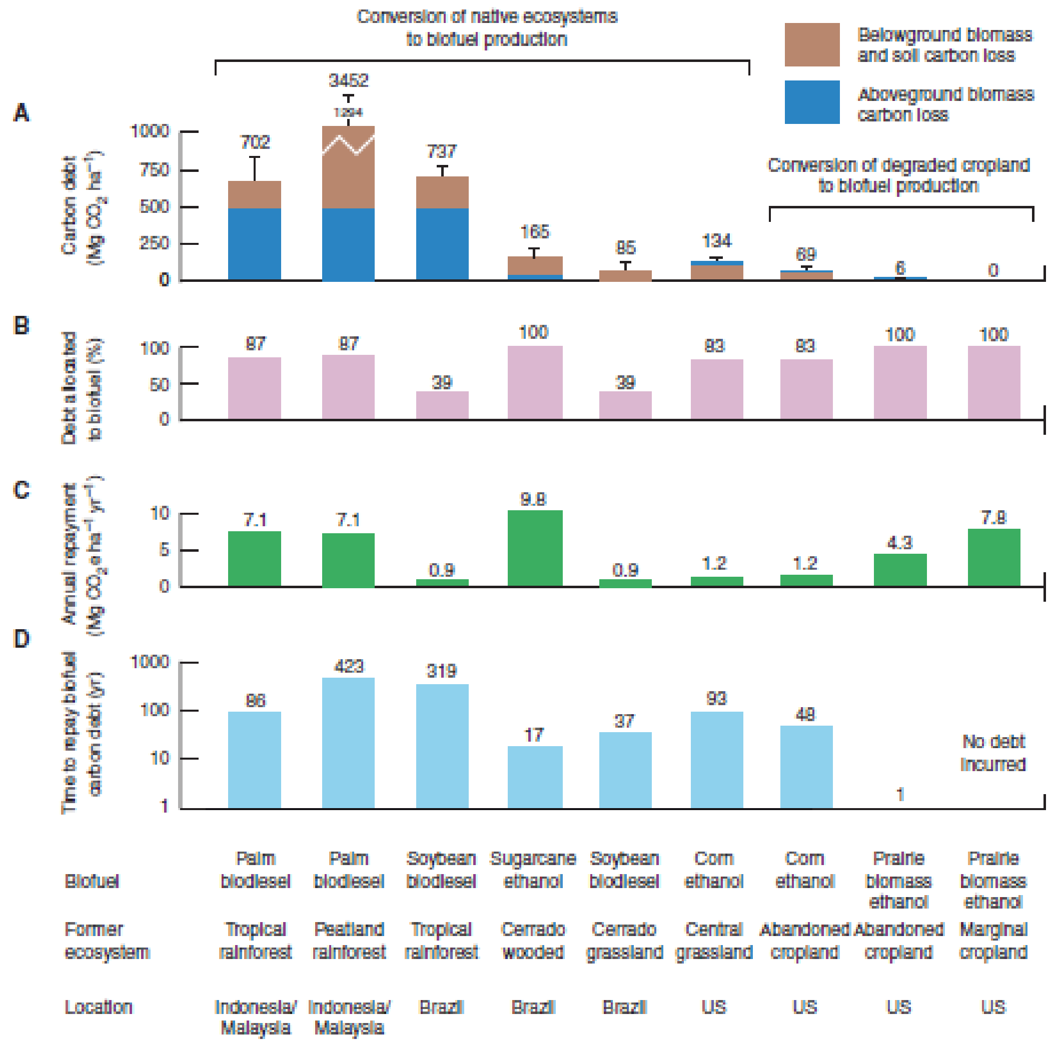
- Since 2004, low carbon and renewable fuel policies in development around the world
  - LCFS (California, North-east states, Canada), RFS (US), Europe (EC)
  - Reduce GHGs relative to baseline gasoline ~93 gCO_2e/MJ
- Biofuels compatible, attractive strategy for reducing transportation’s carbon intensity
  - Feedstocks today: corn (ethanol), soybean (diesel)
    - Mingles energy with food markets
- Recent research on adverse “land-based” impacts of biofuels:
  - – Direct and indirect CO_2 from land use change (LUC)
  - – Other sustainability risks: water, biodiversity, food security
- Need a robust life cycle assessment tool to estimate complete fuel cycle GHG emissions + consequences

Carbon debt from direct LUC

Carbon debt →

Annual repayment →

Payback time→



Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. 2008, Science.

Indirect land use change (LUC) may cause large GHG emissions

U.S. corn/soybean farmers sell land to developers, land is now developed

U.S. soybean exports go down and world soybean prices rise

Additional land in Brazil (for instance) is put into soy production

Soy farmers everywhere use more inputs to increase yields

Unobservable variables!

Indirect LUC emissions

Indirect process emissions

Direct process emissions: Change in CO2 flux on land

Potentially large global land carbon debt!

From M. O'Hare, UC Berkeley; Searchinger et al., 2008, 10.1126/science.1151861

Sustainability issues:

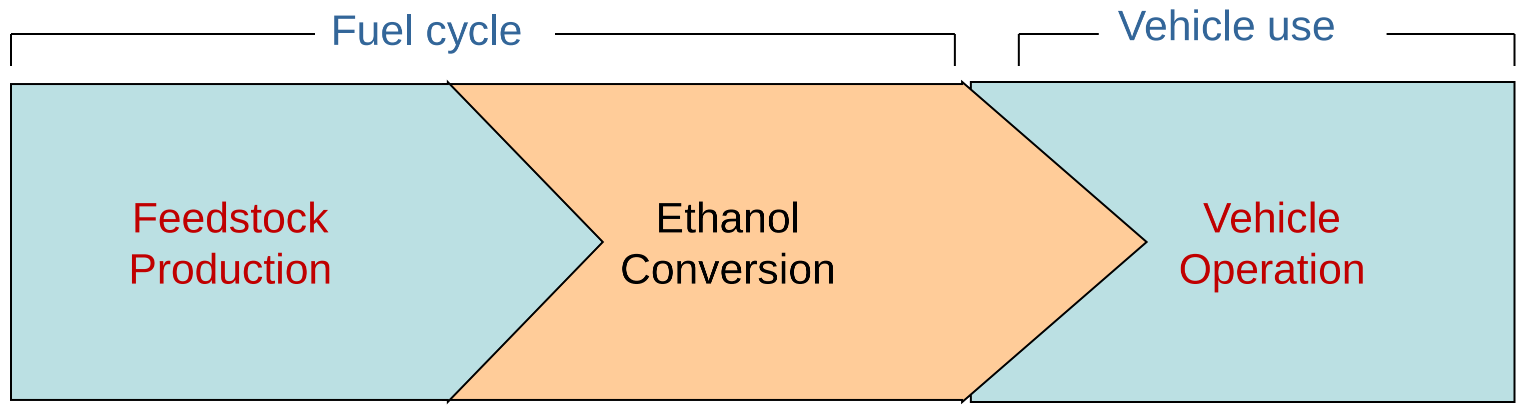
Sustainability criteria[1]	
Ecological	**Socio-economic**
Water use	Food and energy security
Water pollution	Land tenure
Organic pollutants	Net Employment
Agro-chemicals	Income distribution
Biodiversity	Wages
Soil erosion	Working conditions
Fertilizer use	Child labor
GMOs	Social responsibility
GHGs/energy input	Competitiveness
Harvesting practices	Culture - Traditional way of life

[1]Direct + Indirect

Scale: Regional, national, global

Spatari, O'Hare et al. 2008

LCFS/RFS: Fuel Cycle Model



- Fertilizer
- Herbicides
- Harvesting operations
-CO2/N2O flux

Feedstocks:
- corn

- Chemicals, Enzymes,
-Nutrients
-Co-products: CO2, protein meal, hulls (energy recovery)
-Denaturant (2% gasoline)

Technologies:
-Dry grind process
-Sugar generation
-Fermentation
-co-product crediting

- Blending with gasoline
- Vehicle operation

Vehicle:
-Ethanol-fueled vehicle (E92)

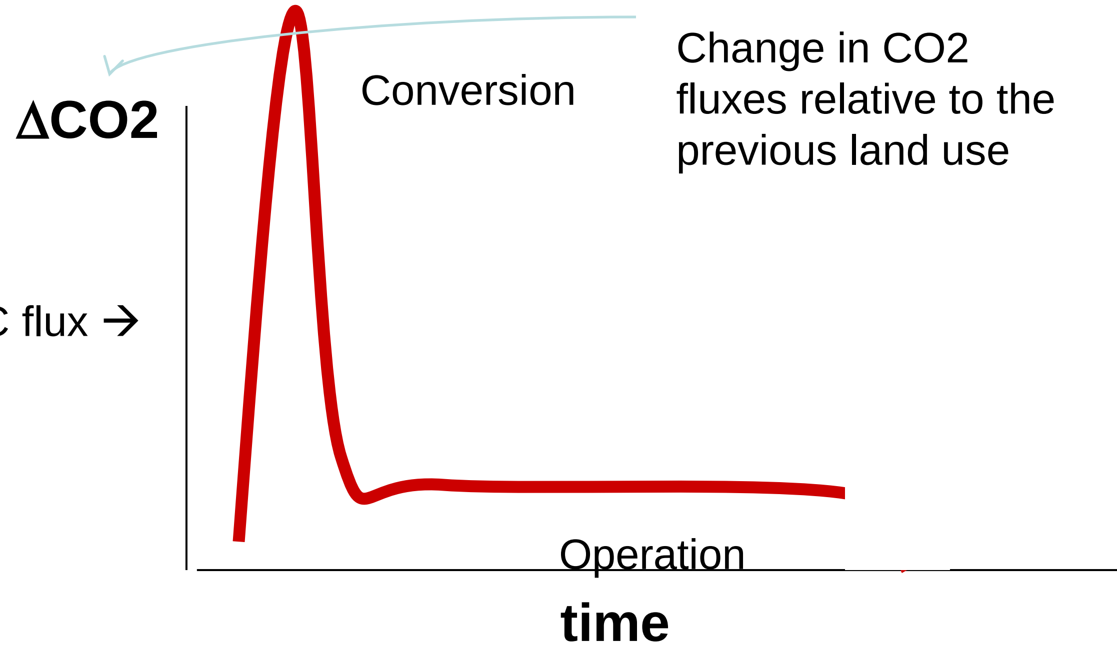
-Compare with baseline
-gasoline vehicle
(96 g CO2e/MJ)

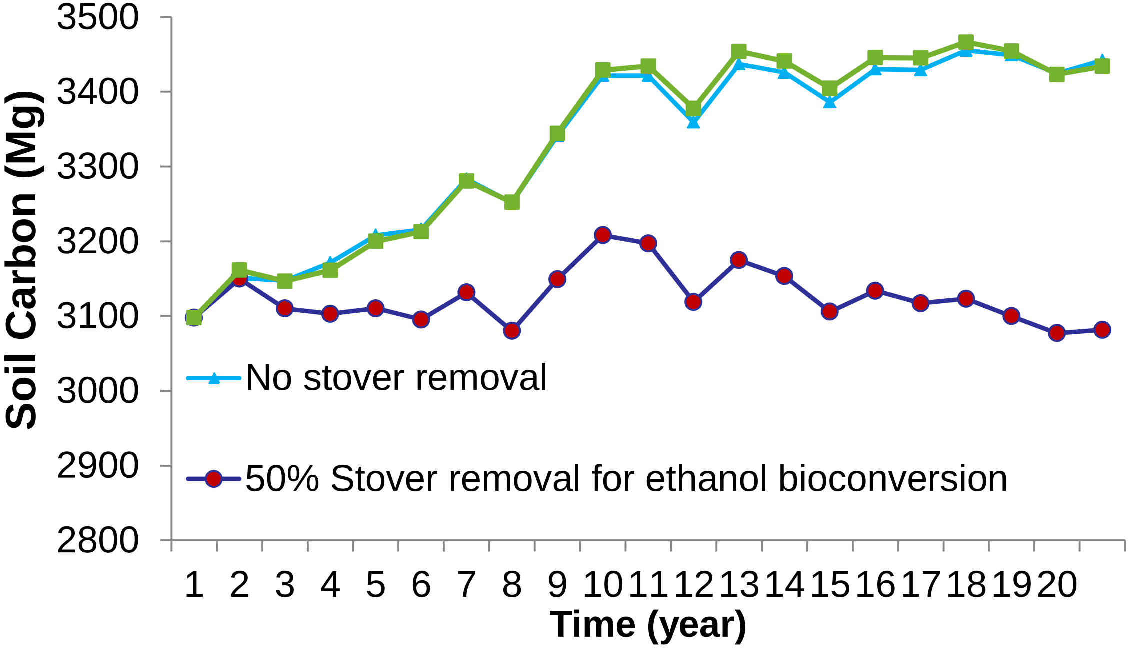
+ Indirect consequences

Time Effects

Change in CO_2 fluxes relative to the previous land use

Indirect change to soil C flux →



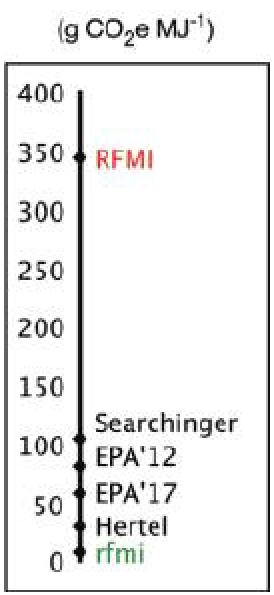


← Direct change to soil C flux

Ethanol: Energy and Environment

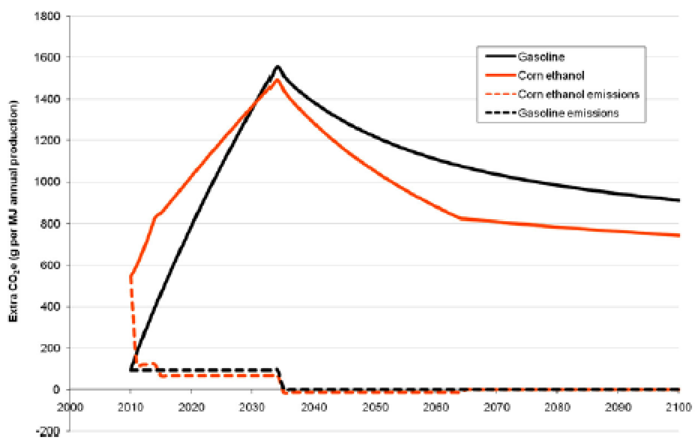
- Energy security: compared to gasoline, corn ethanol:
  - Significantly reduces petroleum use (~95%), moderately lowers (13%) fossil energy use (Farrell et al. 2006);
- *M*any increased risks related to land use change (LUC)

iLUC



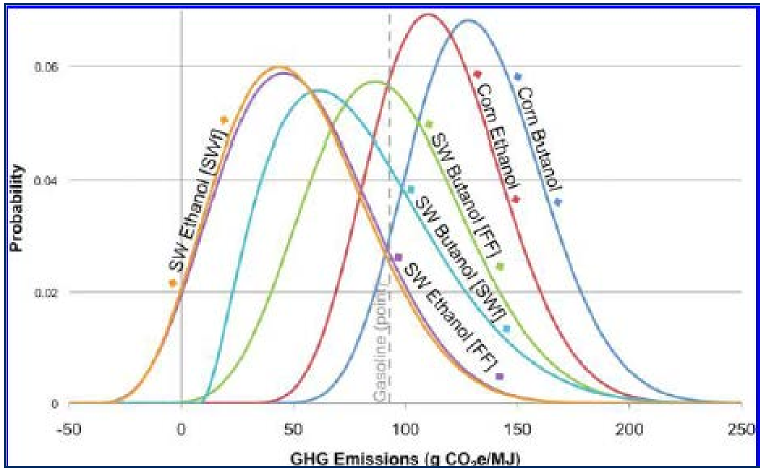
Plevin et al 2010

Time Effects



O'Hare et al 2009

Uncertainty



Mullins et al 2010

Direct LUC-GHG Emissions – biofuels versus conventional & unconventional oil

energy source	energy yield (PJ/ha)	GHG emissions per disturbed area (t CO_2e/ha)	GHG emissions per energy output (g CO_2e/MJ)
Fossil Fuel			
California oil	0.79 (0.48−2.6)	73 (59−117)	0.09 (0.02−0.25)
	0.55 (0.33−1.8)		0.13 (0.03−0.35)
Alberta oil	0.33 (0.16−0.69)	157 (74−313)	0.47 (0.12−1.98)
	0.20 (0.092−0.40)		0.78 (0.20−3.39)
oil sands - surface mining	0.92 (0.61−1.2)	3596 (953−6201)	3.9 (0.83−10.24)
oil sands - in situ	3.3 (2.2−5.1)	205 (23−495)	0.04 (0.0−0.23)
Biofuel			
palm biodiesel (Indonesia/Malaysia)[a]	0.0062	702 ± 183	113 ± 30
palm biodiesel (Indonesia/Malaysia)[a]	0.0062	3452 ± 1294	557 ± 209
soybean biodiesel (Brazil)[a]	0.0009	737 ± 75	819 ± 83
sugar cane (Brazil)[a]	0.0059	165 ± 58	28 ± 10
soybean biodiesel (Brazil)[a]	0.0009	85 ± 42	94 ± 47
corn ethanol (US)[a]	0.0038	134 ± 33	35 ± 9
corn ethanol (US)[a]	0.0038	69 ± 24	18 ± 6

→ Peatland conversion

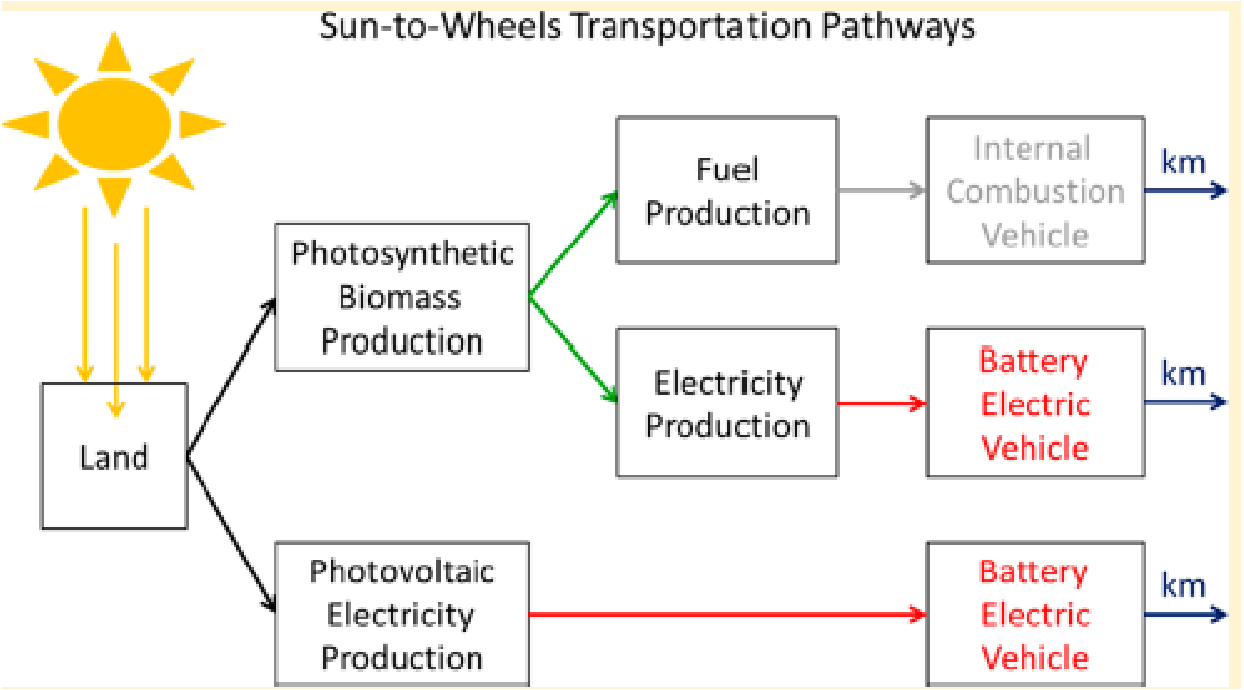
Yeh et al. 2010, Environ. Sci. Tech. 44: 8766-8772

The Nonsense of Biofuels!

Michel, H., 2012*

Low overall conversion of sunlight to terrestrial biomass <1%

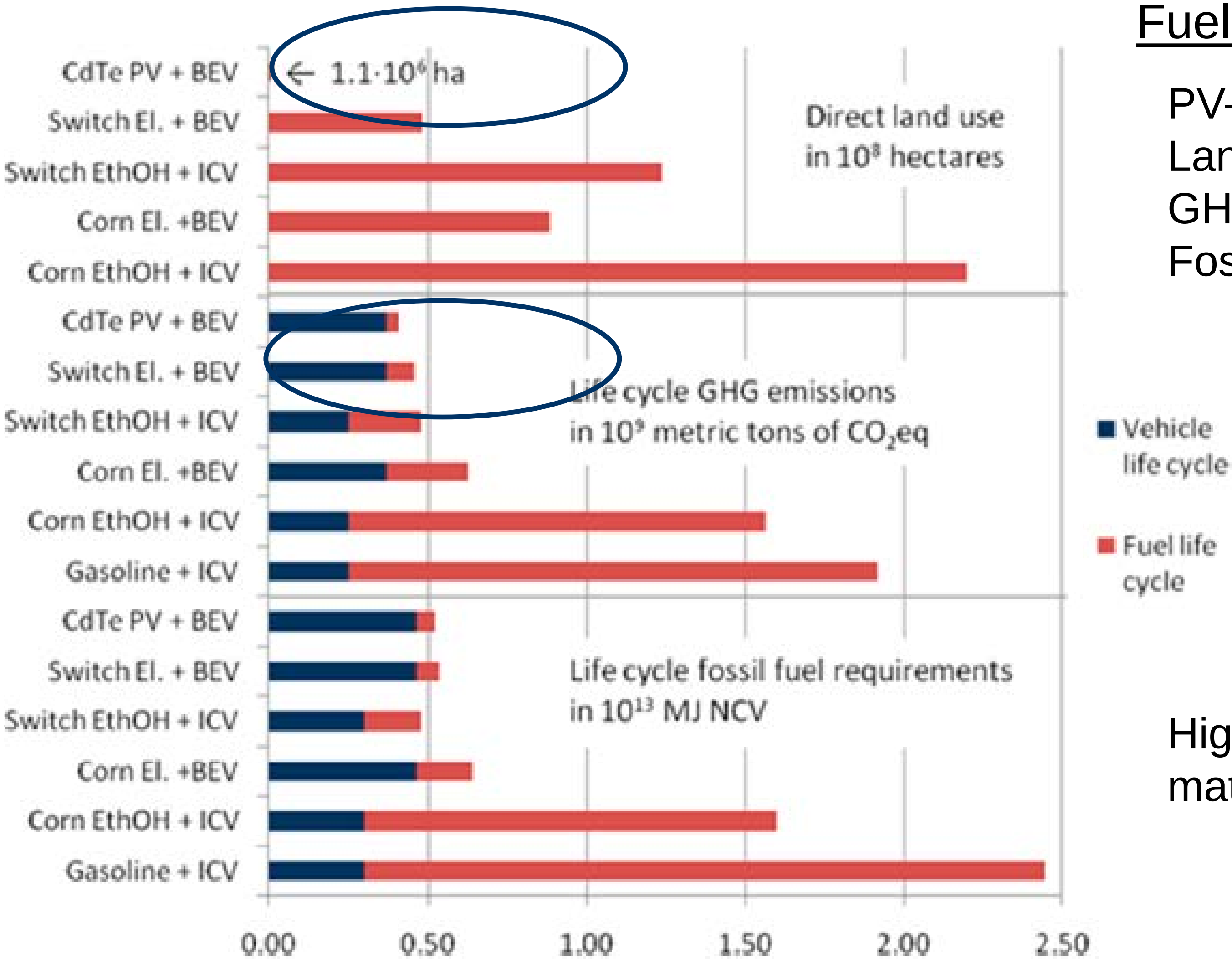
Higher land use efficiency with PV technology →



Geyer et al. 2013

* Angew. Chem. Int. Ed. 51, 2516 – 2518

Comparing sun-to-wheels pathways



<u>Fuel + vehicle cycle</u>

PV-powered BEV low:
Land
GHG
Fossil energy

Higher fraction of vehicle material intensity

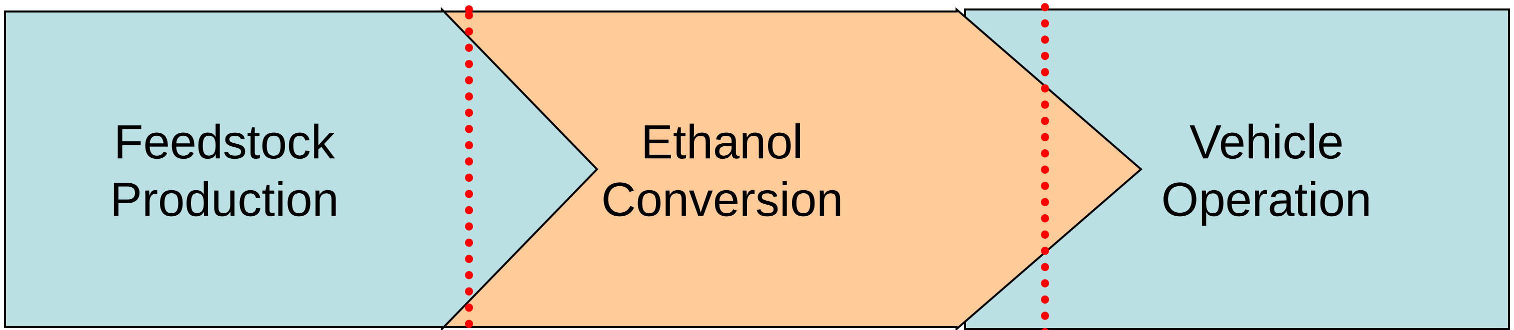
Basis: 17.8E12 MJ NCV to gasoline

Geyer et al. 2013

Better Biomass & Biofuels

- Need for robust life cycle assessment tools to estimate the complete fuel cycle GHG emissions + consequences with accounting of uncertainty
  - Biomass feedstocks that do not compete for arable land
- Minimize iLUC effects by selecting lignocellulosic feedstocks that do not compete for arable land and use “sustainable” fractions:
  - Ag. Residue, MSW, forest/mill waste, novel technologies (e.g., algae)

Biomass to Ethanol: Life Cycle Model



- Fertilizer
- Herbicides
- Harvesting operations

- Pretreatment chemicals
- Enzymes
- Nutrients

- Blending with gasoline
- Vehicle operation

Technologies:

- Dilute acid (NREL)
- Ammonia fibre explosion (AFEX)
- Steam explosion (SE)
- Organosolv (OS)
-Enzymatic Hydrolysis
-Fermentation

Feedstocks:

- Corn stover (CS)

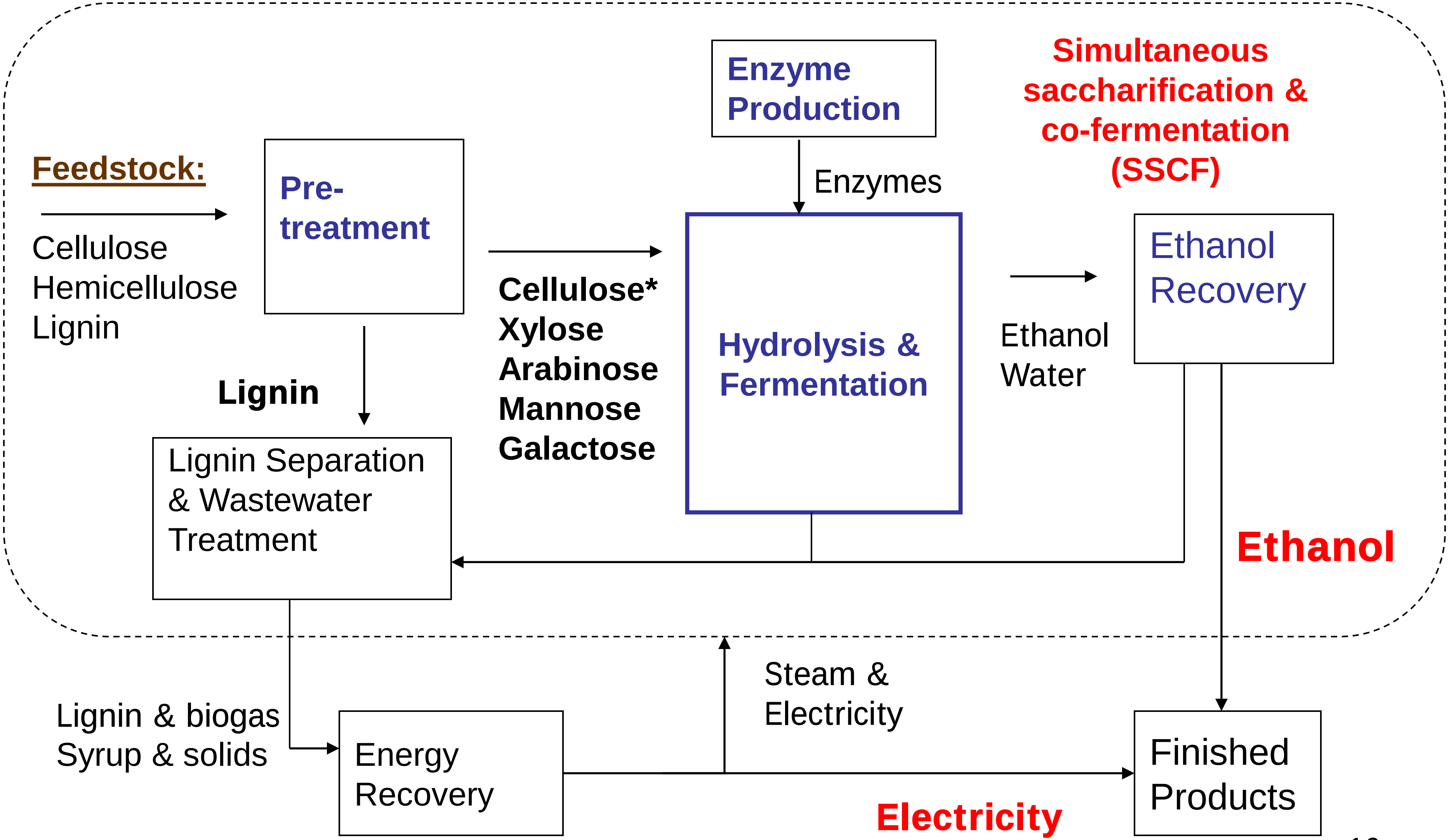
- Switchgrass (SG)

- Douglas fir (Df)

Vehicles:

- Ethanol-fueled vehicle (E85)
- Reformulate gasoline-fueled vehicle (RFG)

Ethanol Conversion Model: Near-term



* Pre-treated cellulose

State of Technology: Chemicals and Enzymes

- Chemical/enzyme inputs: 30-35% WTG GHG emissions
  - Alternative pretreatment: steam explosion, oganosolv, autohydrolysis
- Cellulase cocktails (endoglucanases, exoglucanases, β-glucosidases) still specialty products, only a few decades old, high production costs
- Use of xylanases to improve sugar recovery
- Challenges in enzyme development:
  - Improving specific activity (70 versus 450-600 FPU/g)
  - On-site (in-situ) production can reduce GHG emissions;
  - Reducing global warming intensity (GWI) - C-source
- Trade-off between chemical and enzyme dose

MacLean, H. L.; Spatari, S., (2009)

Enzymes, Cellulose recalcitrance

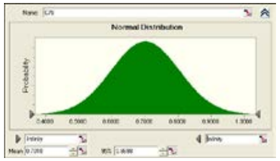
- Specific technological challenges
- Key challenges for R&D:
  - Overcoming the "recalcitrance" of the cellulosic feedstock (Stephanopolous, 2007)
  - Improving enzyme performance
    - Improving enzyme specific activity (FPU/g cellulase)
  - Reducing enzyme costs
  - Reducing pretreatment chemical costs (Himmel et al, 2007)
- Result in improved yields, better cost performance

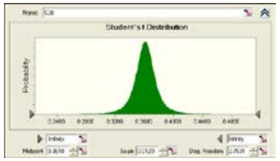
Stephanopolous, 2007, Science. 315:801-804; Himmel et al., 2008, Science. 315:804-807

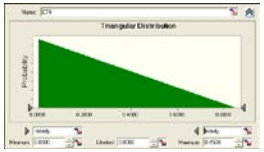
Research Methods – Uncertainty diagnostics

1. Process/pathway selection (technologies, feedstocks)
2. Temporal and spatial boundary definition
3. LCA model construction and data collection
   - Performance metrics identified
4. Hypothesis development
5. Sensitivity analysis: LCA model variables
   - Factorial design
6. Uncertainty analysis on LCA models
   - Applying Monte Carlo simulation
   - Testing resource/environmental performance hypotheses
7. Analysis of model results
   - Expert elicitation – assess the state of technology

Model Equations and Variables: Life Cycle







x_1 x_2 x_3…

Ethanol (Y_i) = f(x_1, x_2, x_3;y_1,y_2…)

Electricity (E_b) = g(x_1, x_2, x_3; y_1 …)

$$E_i = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{e_{i,j}}{\dot{M}_F \frac{\alpha}{\rho_{EtOH}} \times \sum_{i=1}^{5} Y_i}$$

Sample model results

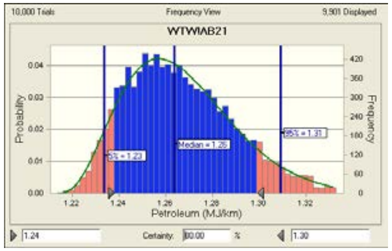
- Fossil energy (MJ/L and /km)
- Petroleum (MJ/L and/km)
- GHG emissions (g CO_2 eq./L and /km)

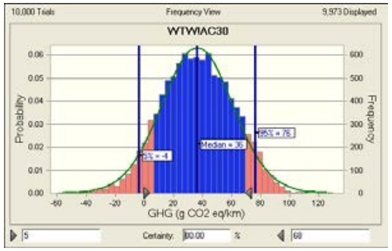
<u>9 ethanol conversion variables:</u>

Feedstock	(2)
Pre-treatment	(1)
Hydrolysis	(1)
Fermentation	(5)

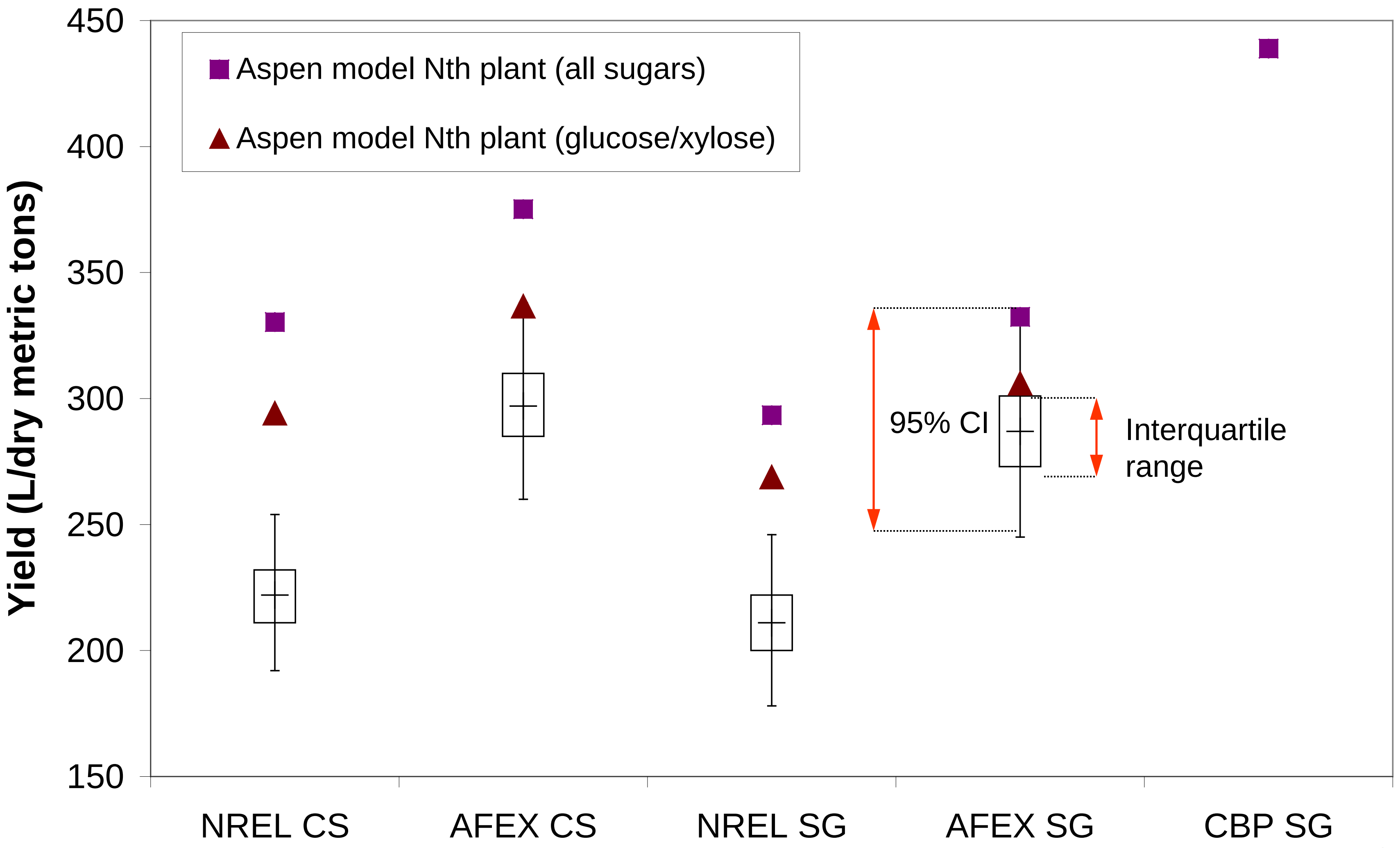
<u>4 feedstock production variables:</u>

CO_2 sequestration, N-fertilizer use; N_2O emission, Farm energy

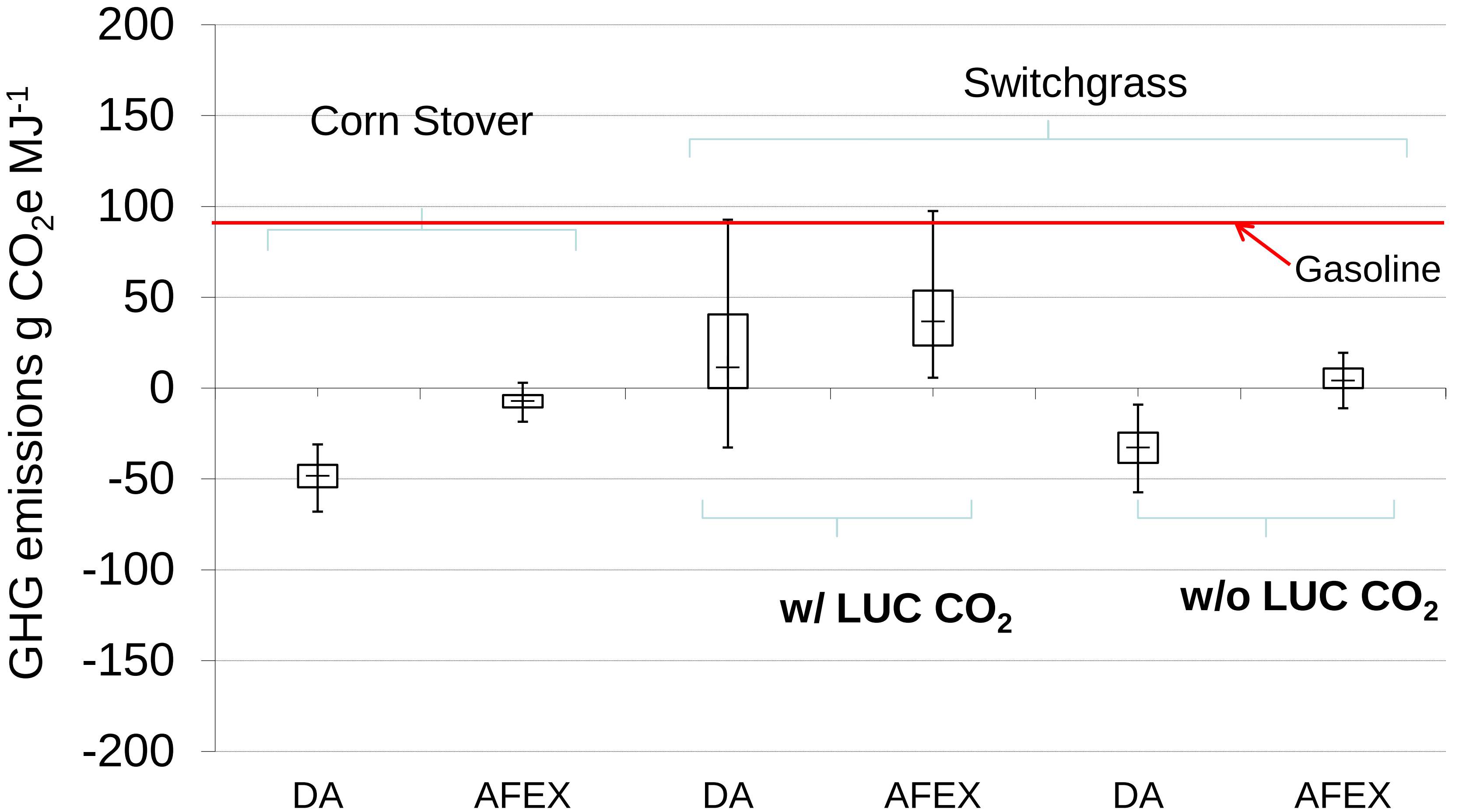




Performance: Ethanol Yield



Uncertainty in LC GHG emissions (with LUC vs. without LUC)



DA = dilute acid pretreatment followed by simultaneous saccharification and cofermentation (SSCF)
AFEX = ammonia fiber explosion pretreatment followed by SSCF

Spatari and MacLean (2010), Environ. Sci. Technol. 44: 8773-8780

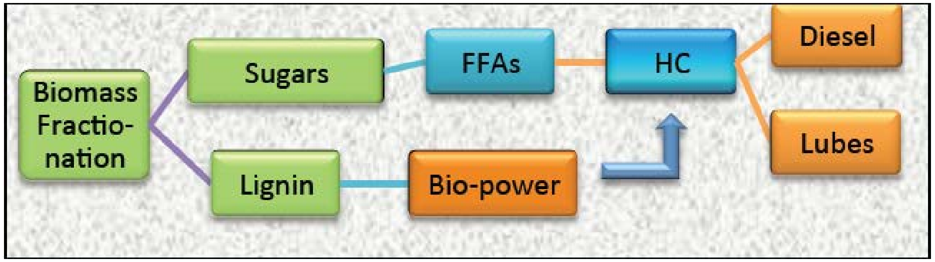
Better Biofuels? Lignocellulosic biomass

- LCA models show reduction in GHG intensity of ag. residue and energy crops on marginal lands
  Spatari et al., 2010. *Bioresource Technology*, doi:10.1016/j.biortech.2009.08.067
- Lignocellulosic ethanol is still under development!
  - No competitive technologies at commerical-scale
  - Key technological challenge for R&D is enhancing individual processes AND overall **integration**
  - Demonstration scale projects
- Development of other infrastructure compatible fuels show promise but need further research
  - Upgraded pyrolysis bio-oil + biochar
  - Higher alcohols

Life Cycle & Techno-Economic Analysis

Model development through synergistic tools:

- Aspen Plus, Simapro, DayCent, Risk-uncertainty analysis:
  - Feedstock production, collection, densification, transport
  - Material/energy balance basis (feedstock conversion);
  - Spatially-explicit feedstock environmental analysis (GHGs) and risk/uncertainty
- Integration with experimental research:
  - Fuel conversion pathway at commercial scale
    - Pretreatment/hydrolysis
    - Free fatty acid synthesis
    - Electrochemical deoxygenation to diesel and bio-lubricants



Research in collaboration with Ceramatec

Catalytic Pyrolysis Pathway LCA & TEA

Life cycle model development:

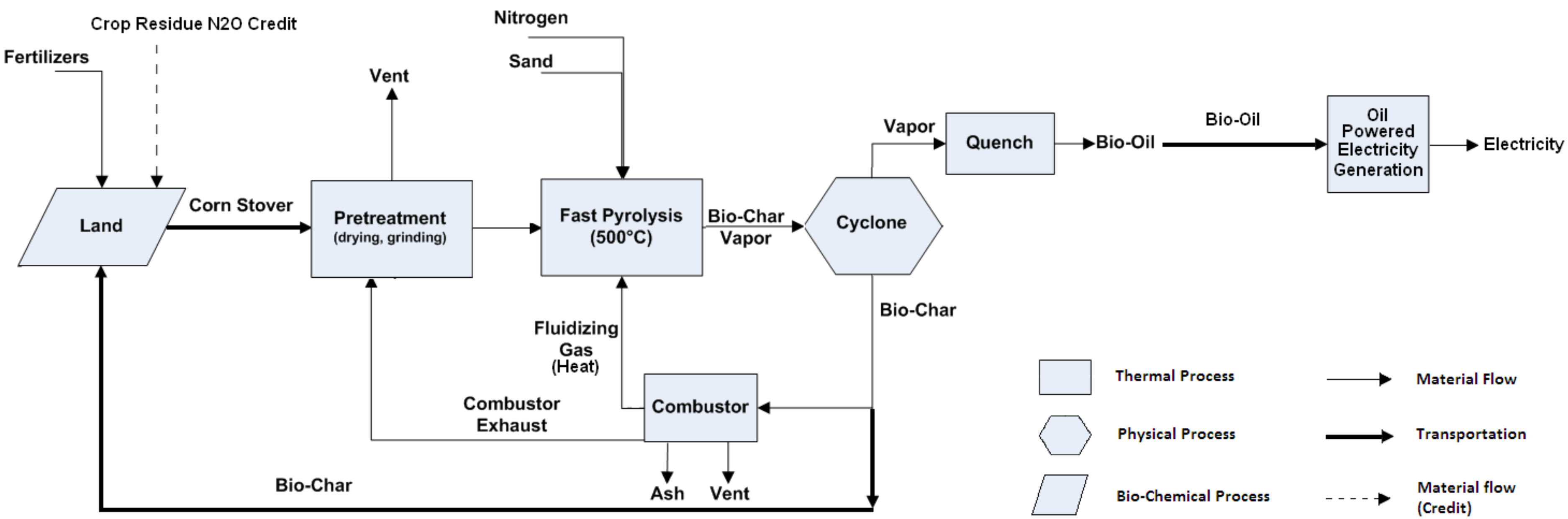
- Aspen Plus, Simapro and GIS modeling:
  - Feedstock production, collection, transport
  - Material/energy balance basis (feedstock conversion);
- Integration with experimental research:
  - Pyrolysis bio-oil blendstock development
    - In-situ catalytic pyrolysis products
    - Ex-situ catalytic pyrolysis products
  - Combustion experiments for
    - Non-catalytic pyrolysis products
    - Catalytic pyrolysis products

NIFA

Research in collaboration with AA Boateng et al.

Pyrolysis Bio-oil Production

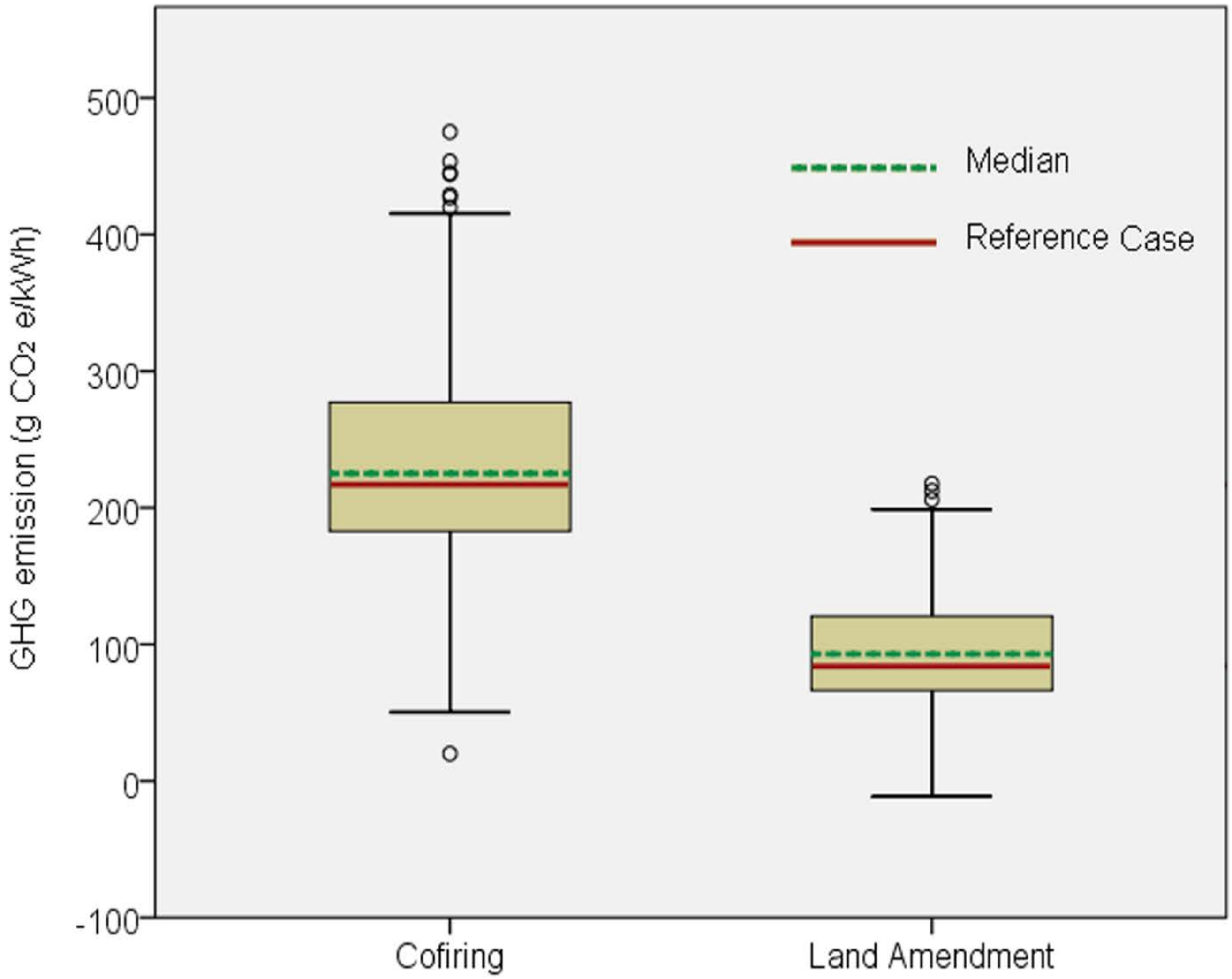
Bio-oil replaces fuel oil for electricity generation
Bio-char co-product used as soil nutrient replacement



Bio-char coproduct used for process energy and land amendment

Pourhashem et al. 2013 *Energy & Fuels*

Pyrolysis Bio-oil-to-Electricity



Pourhashem et al. 2013 *Energy & Fuels*

Pyrolysis Bio-oil Production (200 TPD) Economics

Capital Costs (million $U.S.)

Feedstock handling preparation	$1.91
Feedstock drying	$0.74
Pyrolysis process	$5.78
Utility	$0.99
Product/Co-product storage	$0.43
Total Equipment Purchase Costs	**$9.85**
Total Installed Costs	**$24.6**

Operating Costs (million $U.S.)/yr

Feedstock	$4.28
Utility	$0.77
Labor, Supplies and Overhead	$2.03
Depreciation	$2.46
Co-product Credit	-$0.18
Total Production cost	**$9.36**

Bio-oil energy: 44.6 MJ/gal

Bio-oil production cost: $12.4/GJ

Pourhashem et al. 2013 *Energy & Fuels*

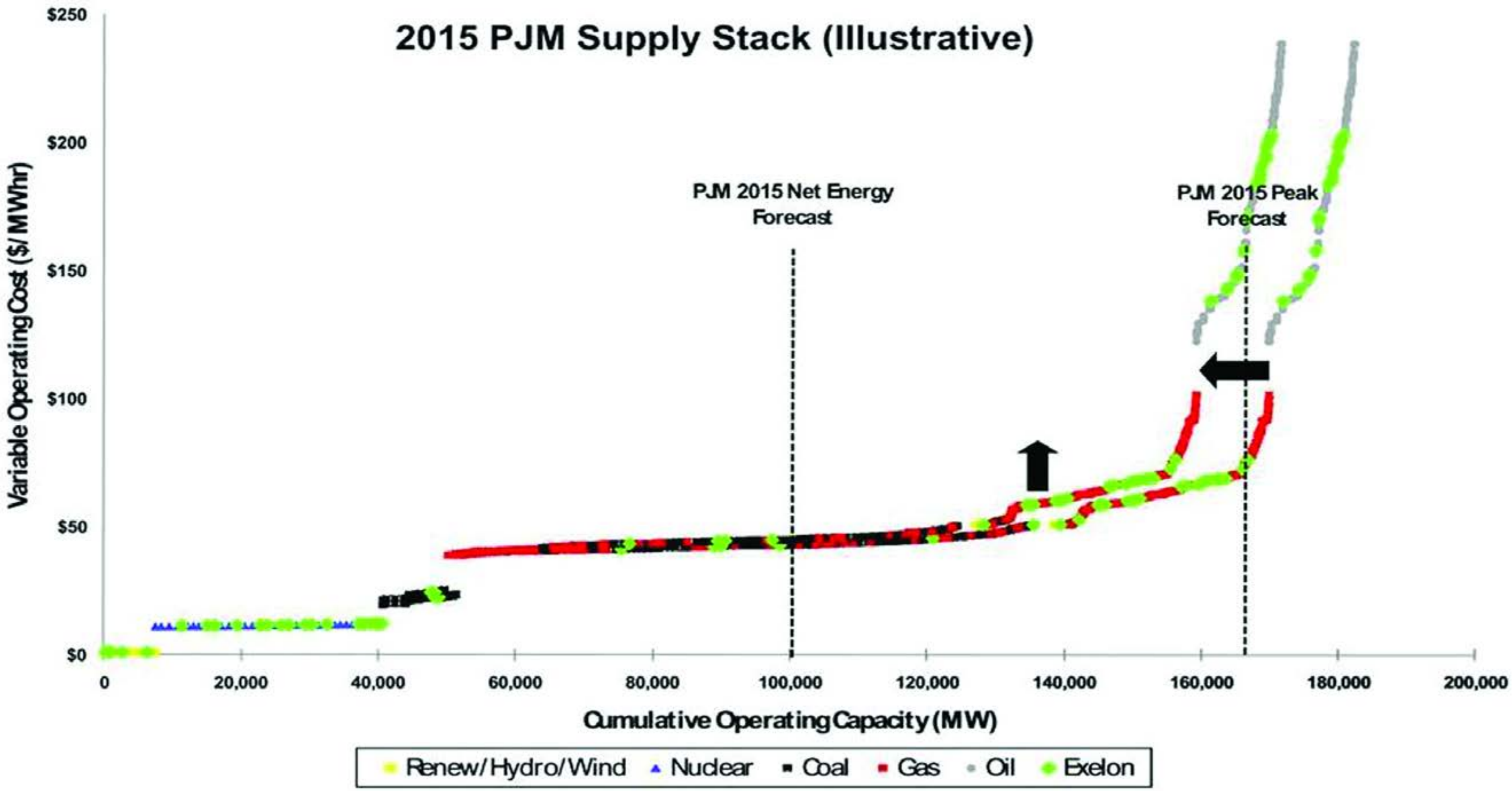
Electricity markets – RPS commitments

Variable Operating Cost (VOC)

Fuel Cost + Fixed operating cost + Emission cost

Bio-oil electricity: $93/MWh

Bio-char electricity: $18/MWh



Summary: LCA of Emerging Technology

- Systems analysis methods critical to informing the development of low-C energy technology
  - Understanding and estimating uncertainties in environmental performance
- Moving towards spatio-temporal analysis within LCA research
  - Inclusion of CO_2 growth/decay in time
  - Use of spatial statistics to describe location-specific GHG profiles for regulated biorefinery products
- Multiple sustainability metrics for “greening” engineered systems

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- P.R. Adler, K.B. Hicks, A.J. McAloon, A.A. Boateng, C.A. Mullen, M. Karanjikar, P. Gurian, N. Macken, H.L. MacLean, R. Mallinson, K. Marcellus, J.G. Mitchell, G. Pourhashem, K.Y. San, T. Selfa, P. Vadlani, Y. Zhang

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