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Issues Related to Uncertainty and Variability in LCA Modeling

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Motivation

- Variability, although inherent in LCA, is often not explicitly considered
- Results are typically reported as a point value
  - These approaches cannot develop new data sets to target the sensitivity of specific factors, which could help understand best practices for reducing LC-GHG emissions
- A new methodological approach was developed using screening level LCAs to understand how variability impacts LC-GHG inventories of transportation fuels
- Screening level analyses provide preliminary assessments of technology alternatives with the intent of informing research funding and decision makers
  - Identify pivotal factors defining the LC-GHG emission profiles of fuel production for each LC step and each feedstock

Drop-In Fuel Life Cycle GHG Emissions

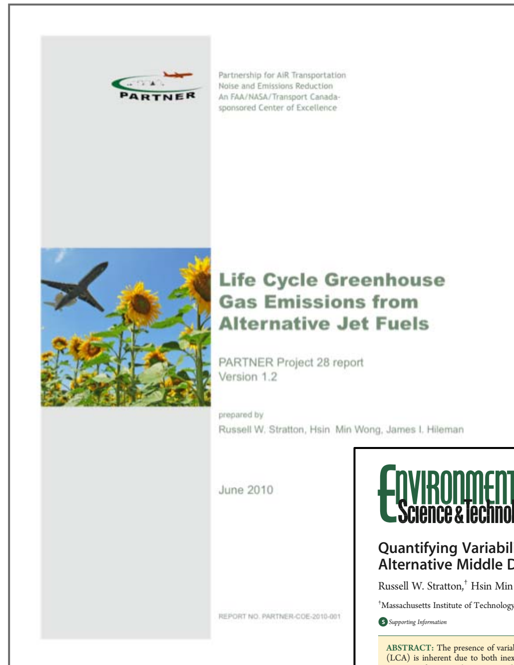
PARTNER Project 28 Report and ES&T Article

- PARTNER <u>Jet Fuel</u> Study
  - Screening level study of next generation alternative jet fuels
  - Examine low, baseline, and high emissions scenarios
  - Emphasize influential aspects of fuel production on GHG emissions

- Results are a range of possible LC-GHG inventories intended to demonstrate variability in fuel production processes.

- Other issues considered: land, water, invasiveness

- Developed analysis into a <u>diesel fuel</u> article for ES&T



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Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels

PARTNER Project 28 report
Version 1.2

prepared by
Russell W. Stratton, Hsin Min Wong, James I. Hileman

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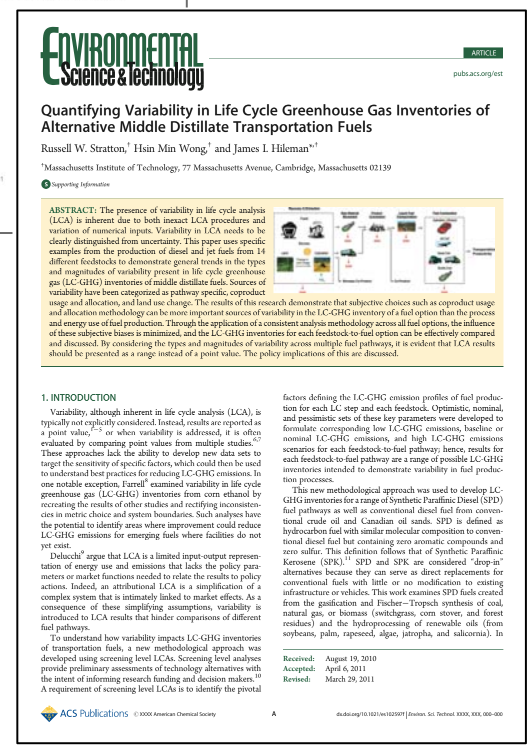

ARTICLE

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Quantifying Variability in Life Cycle Greenhouse Gas Inventories of Alternative Middle Distillate Transportation Fuels

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Supporting Information

ABSTRACT: The presence of variability in life cycle analysis (LCA) is inherent due to both inexact LCA procedures and variation of numerical inputs. Variability in LCA needs to be clearly distinguished from uncertainty. This paper uses specific examples from the production of diesel and jet fuels from 14 different feedstocks to demonstrate general trends in the types and magnitudes of variability present in life cycle greenhouse gas (LC-GHG) inventories of middle distillate fuels. Sources of variability have been categorized as pathway specific, coproduct usage and allocation, and land use change. The results of this research demonstrate that subjective choices such as coproduct usage and allocation methodology can be more important sources of variability in the LC-GHG inventory of a fuel option than the process and energy use of fuel production. Through the application of a consistent analysis methodology across all fuel options, the influence of these subjective biases is minimized, and the LC-GHG inventories for each feedstock-to-fuel option can be effectively compared and discussed. By considering the types and magnitudes of variability across multiple fuel pathways, it is evident that LCA results should be presented as a range instead of a point value. The policy implications of this are discussed.

1. INTRODUCTION

Variability, although inherent in life cycle analysis (LCA), is typically not explicitly considered. Instead, results are reported as a point value,[1−5] or when variability is addressed, it is often evaluated by comparing point values from multiple studies.[6,7] These approaches lack the ability to develop new data sets to target the sensitivity of specific factors, which could then be used to understand best practices for reducing LC-GHG emissions. In one notable exception, Farrell[8] examined variability in life cycle greenhouse gas (LC-GHG) inventories from corn ethanol by recreating the results of other studies and rectifying inconsistencies in metric choice and system boundaries. Such analyses have the potential to identify areas where improvement could reduce LC-GHG emissions for emerging fuels where facilities do not yet exist.

Delucchi[9] argue that LCA is a limited input-output representation of energy use and emissions that lacks the policy parameters or market functions needed to relate the results to policy actions. Indeed, an attributional LCA is a simplification of a complex system that is intimately linked to market effects. As a consequence of these simplifying assumptions, variability is introduced to LCA results that hinder comparisons of different fuel pathways.

To understand how variability impacts LC-GHG inventories of transportation fuels, a new methodological approach was developed using screening level LCAs. Screening level analyses provide preliminary assessments of technology alternatives with the intent of informing research funding and decision makers.[10] A requirement of screening level LCAs is to identify the pivotal factors defining the LC-GHG emission profiles of fuel production for each LC step and each feedstock. Optimistic, nominal, and pessimistic sets of these key parameters were developed to formulate corresponding low LC-GHG emissions, baseline or nominal LC-GHG emissions, and high LC-GHG emissions scenarios for each feedstock-to-fuel pathway; hence, results for each feedstock-to-fuel pathway are a range of possible LC-GHG inventories intended to demonstrate variability in fuel production processes.

This new methodological approach was used to develop LC-GHG inventories for a range of Synthetic Paraffinic Diesel (SPD) fuel pathways as well as conventional diesel fuel from conventional crude oil and Canadian oil sands. SPD is defined as hydrocarbon fuel with similar molecular composition to conventional diesel fuel but containing zero aromatic compounds and zero sulfur. This definition follows that of Synthetic Paraffinic Kerosene (SPK).[11] SPD and SPK are considered "drop-in" alternatives because they can serve as direct replacements for conventional fuels with little or no modification to existing infrastructure or vehicles. This work examines SPD fuels created from the gasification and Fischer−Tropsch synthesis of coal, natural gas, or biomass (switchgrass, corn stover, and forest residues) and the hydroprocessing of renewable oils (from soybeans, palm, rapeseed, algae, jatropha, and salicornia). In

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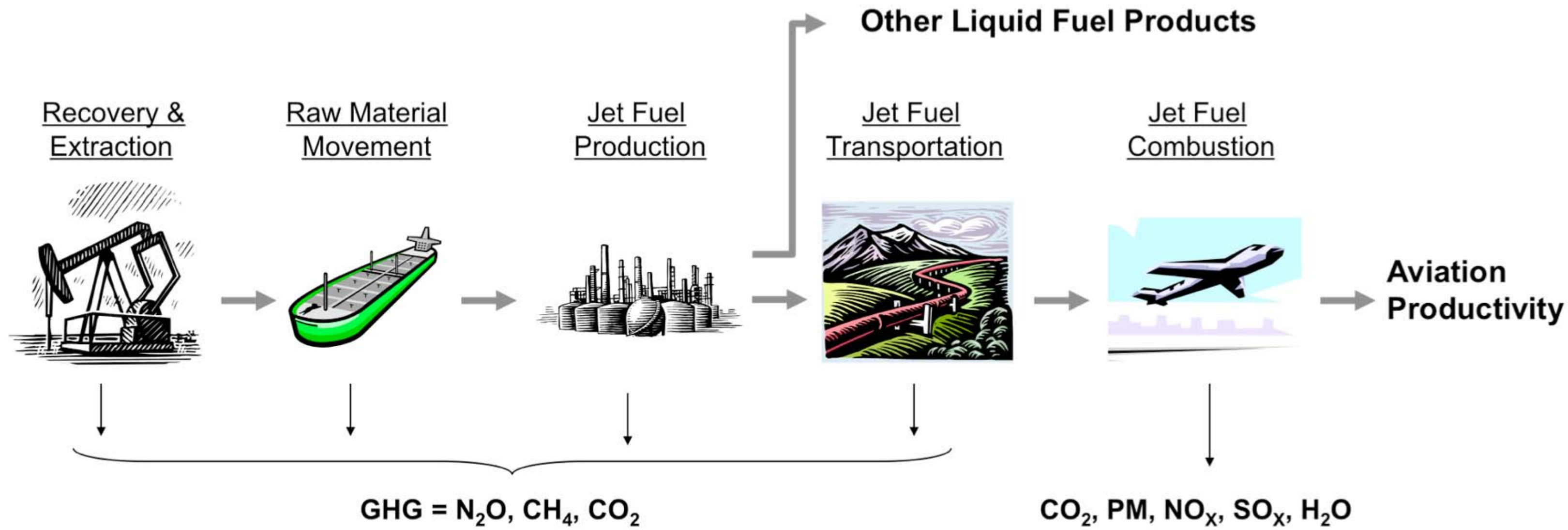
http://web.mit.edu/aeroastro/partner/projects/project28.html

Well-to-Wake GHG Emissions
Fossil-based Jet Fuels



Key Issues in Life Cycle Analysis:

- System Boundary Definition
- Allocating Emissions among Co-Products
- Data Quality and Uncertainty

Analysis based on GREET 1.8 – some of these results have subsequently been incorporated into GREET.1.2011*

* GREET Website: http://www.transportation.anl.gov/modeling_simulation/GREET/

Fuel Pathways Examined for LC GHG

All result in a product slate of diesel, jet, and naphtha

Source	Feedstock	Recovery	Processing	Final Product
Petroleum	Conventional crude	Crude extraction	Crude refining	Jet A / Diesel
	Conventional crude	Crude extraction	Crude refining	ULSJ/D
	Canadian oil sands	Bitumen mining/ extraction and upgrading	Syncrude refining	Jet A / Diesel
	Oil shale	In-situ conversion	Shale oil refining	Jet A / Diesel
Natural gas	Natural gas	Natural gas extraction and processing	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (F-T)
Coal	Coal	Coal mining	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (F-T)
Coal and Biomass	Coal and Biomass	Coal mining and biomass cultivation	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (F-T)
Biomass	Biomass – switchgrass – corn stover – forest waste	Biomass cultivation	Gasification, F-T reaction and upgrading	SPK Jet / Diesel Fuel (F-T)
	Renewable oil – soybeans – palm – algae – jatropha – rapeseed – salicornia	Biomass cultivation and extraction of plant oils	Hydroprocessing	SPK Jet / Diesel Fuel (HRJ/HRD)

Variability in LC GHG Inventories

- LCA is a technique to simplify a complex system that is intimately linked to market effects. Result is a system of input-output representations of energy use and emissions.
- Necessity for simplifying assumptions introduces variability into LCA results that hinder comparisons of different fuel pathways.

Types of variability:

Pathway Specific • Co-product Usage and Allocation • Land Use Change

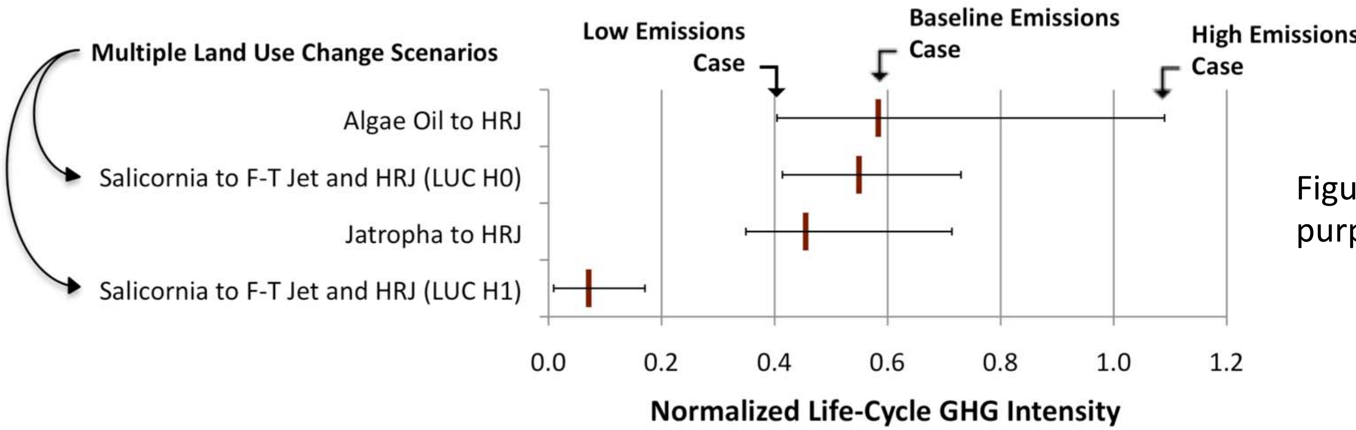
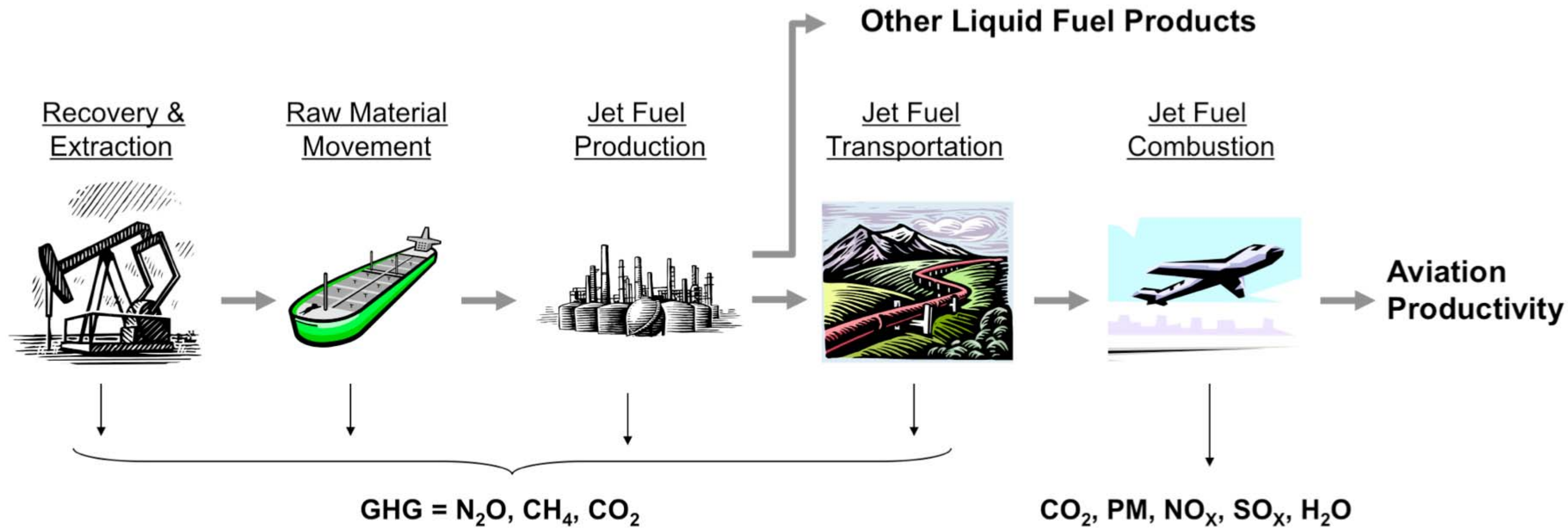


Figure for illustrative purposes only

Variability considered using scenarios with consistent assumption sets

Pathway Specific Variability



Screening level analyses include all key processes, but only parameters with considerable influence on results examined in detail.

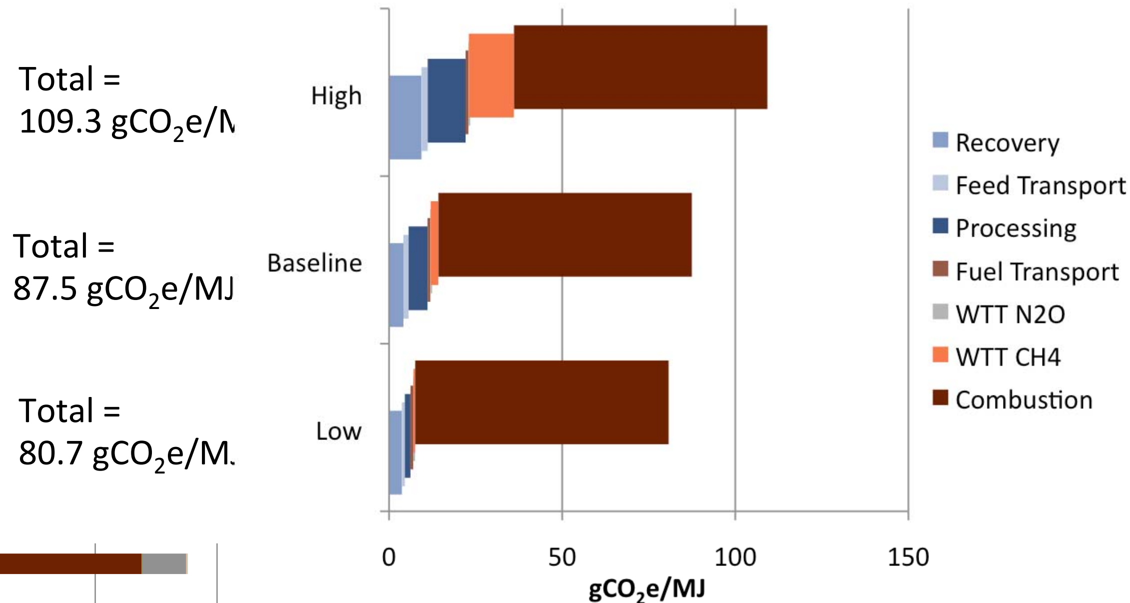
Such key parameters can be examined to ascertain pathway-specific variability that is present in all fuel options.

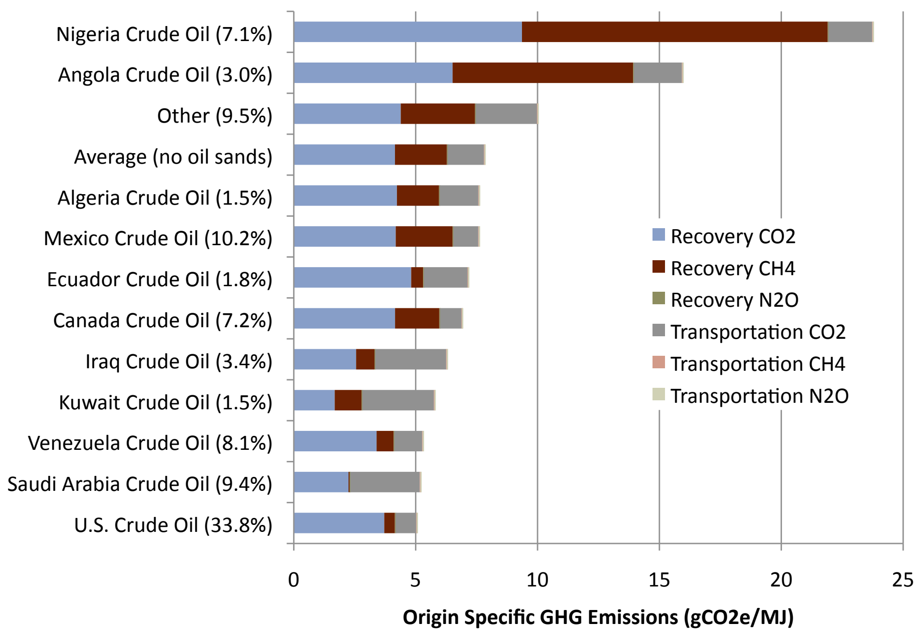
Two examples:

- Petroleum extraction for conventional fuel production
- Fischer-Tropsch diesel fuel production from a combination of coal and biomass

Pathway Specific Variability
Conventional Jet Fuel

- Life cycle analysis is fundamentally a comparative tool
- Fuel from conventional crude is benchmark for alternative fuels





Consistency between analysis methodologies is essential for comparisons and for setting a baseline

Anlaysis of Stratton et al. (2010) based on country profiles from Skone and Gerdes (2008)

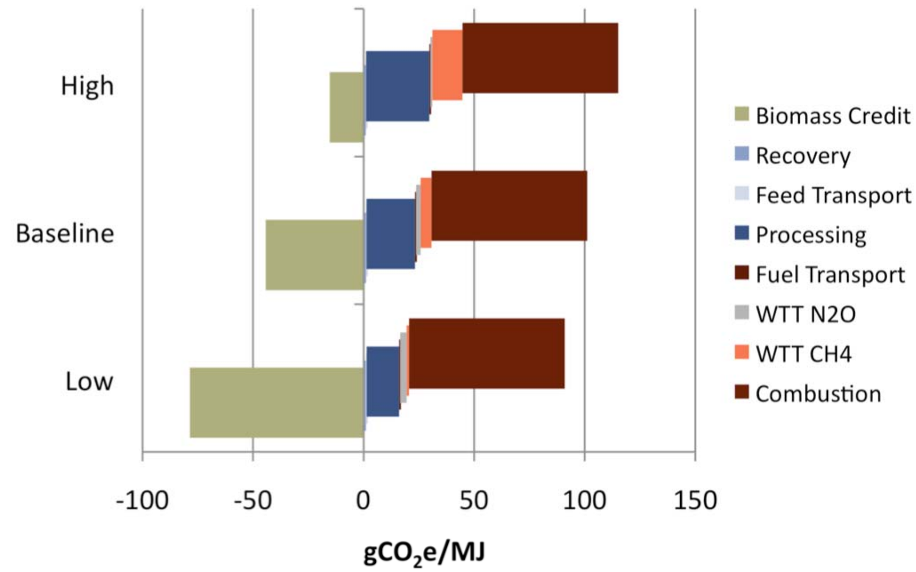
Pathway Specific Variability
F-T Fuel from Coal and Switchgrass w/ CCS

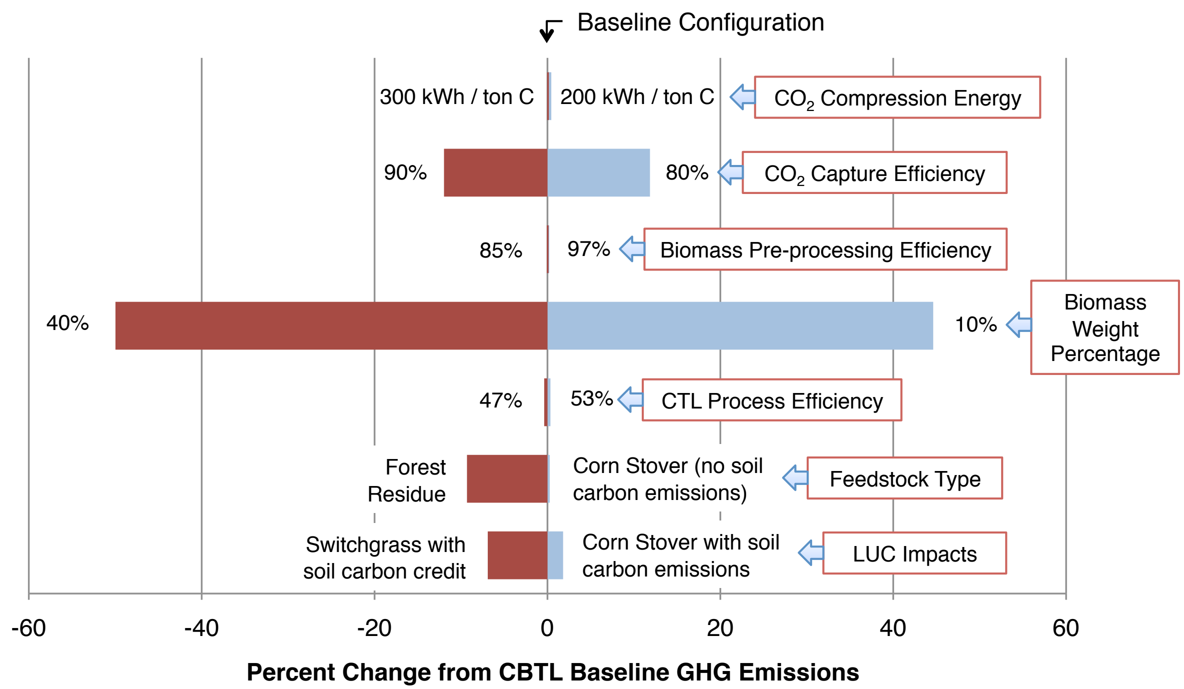
Majority of disparity between cases comes from biomass weight percent and CCS efficiency

Total = 99.8 gCO_2e/MJ

Total = 56.9 gCO_2e/MJ

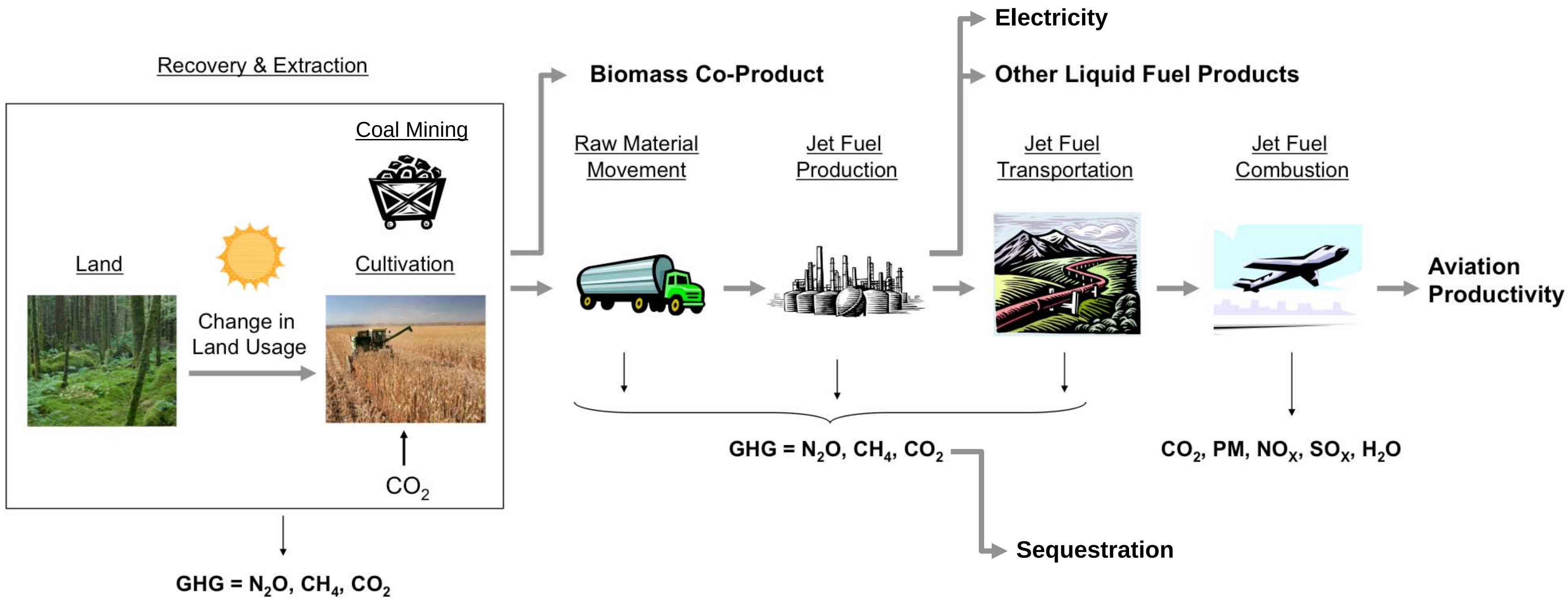
Total = 12.4 gCO_2e/MJ





- Feedstock type, biomass weight percent and CCS efficiency → **Very Important for GHG**
- Process Efficiency and energy inputs → **Less important for GHG**

Allocating GHG among Co-Products

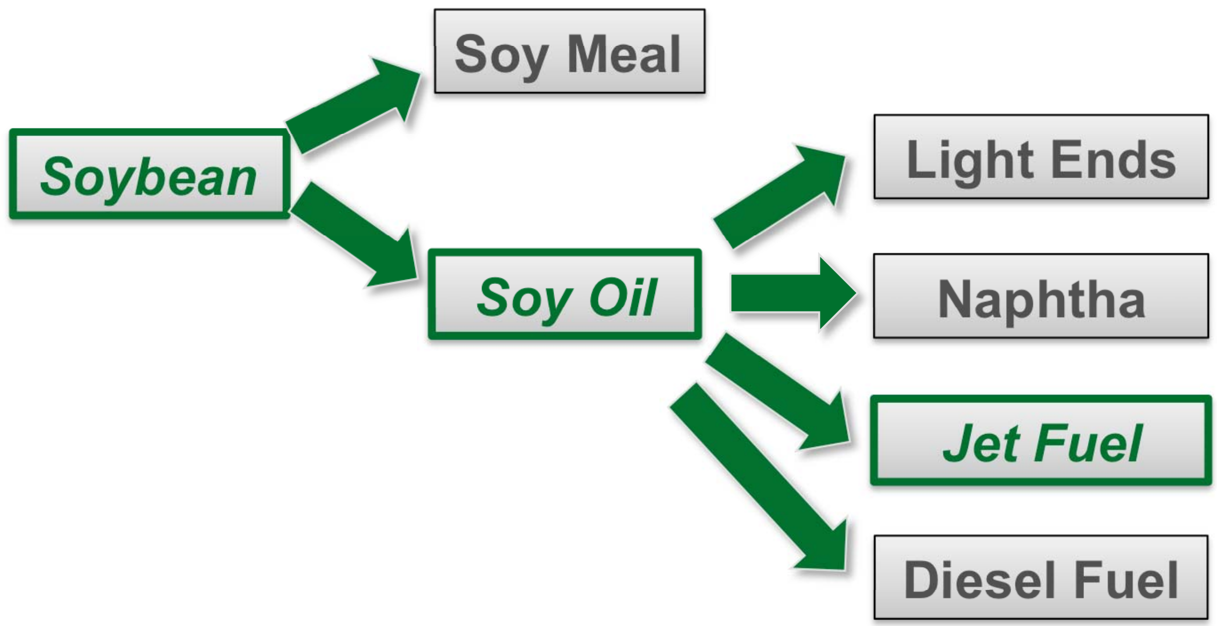


Examples:

- Soybean and jatropha to hydroprocessed fuels (HRx)
- Fischer-Tropsch fuel production

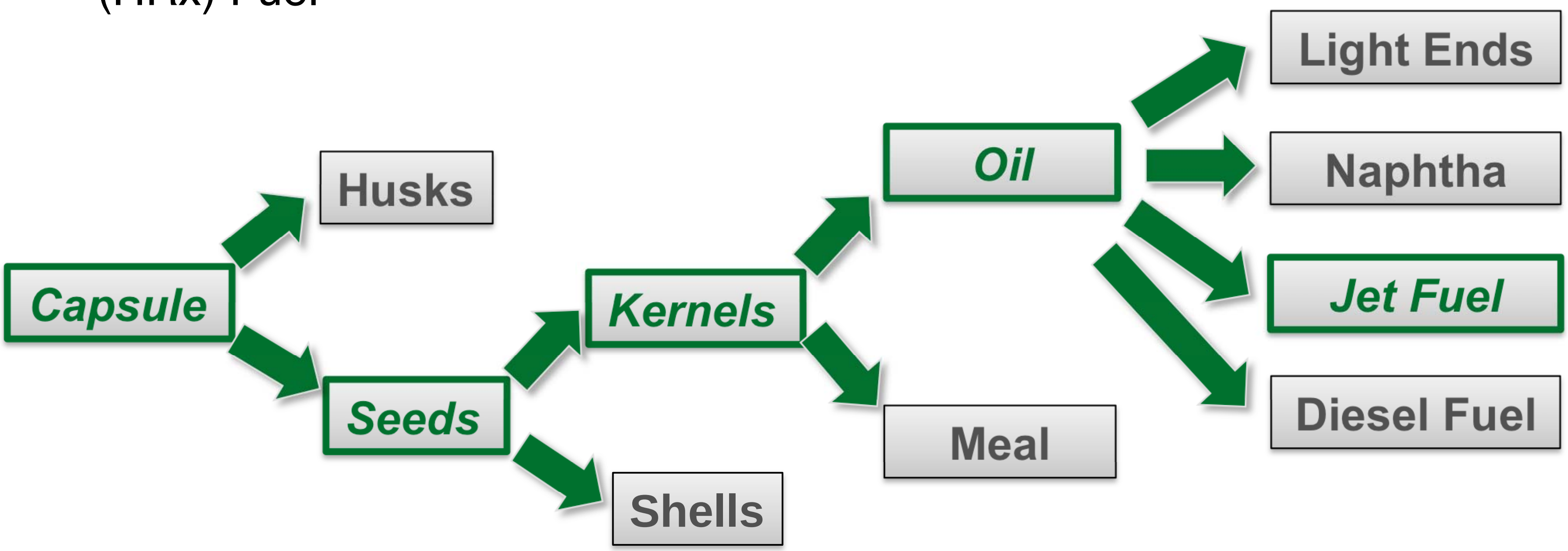
Co-product Usage and Allocation
Soybean to HRx

- For well established pathways, need an allocation methodology that **reflects the established co-product usage**
- Example: Soybean to Hydroprocessed Renewable Diesel/Jet/Naptha (HRx) Fuel



Co-product Usage and Allocation
Jatropha to HRx (1)

- For emerging pathways, need to **examine the range of possible co-product uses** and allocation methodology
- Example: Jatropha to Hydroprocessed Renewable Diesel/Jet/Naptha (HRx) Fuel



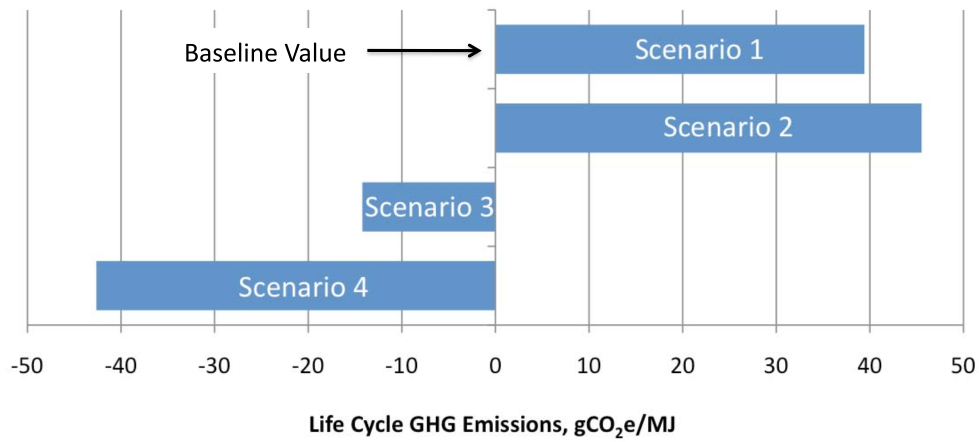
Trade studies were conducted to examine the impacts of different co-product usage assumptions and allocation methodologies

Co-product Usage and Allocation
Jatropha to HRJ (2)

Co-product usage should be linked to the allocation method:

- Mass
- Economic value
- Energy
- Displacement (system expansion)

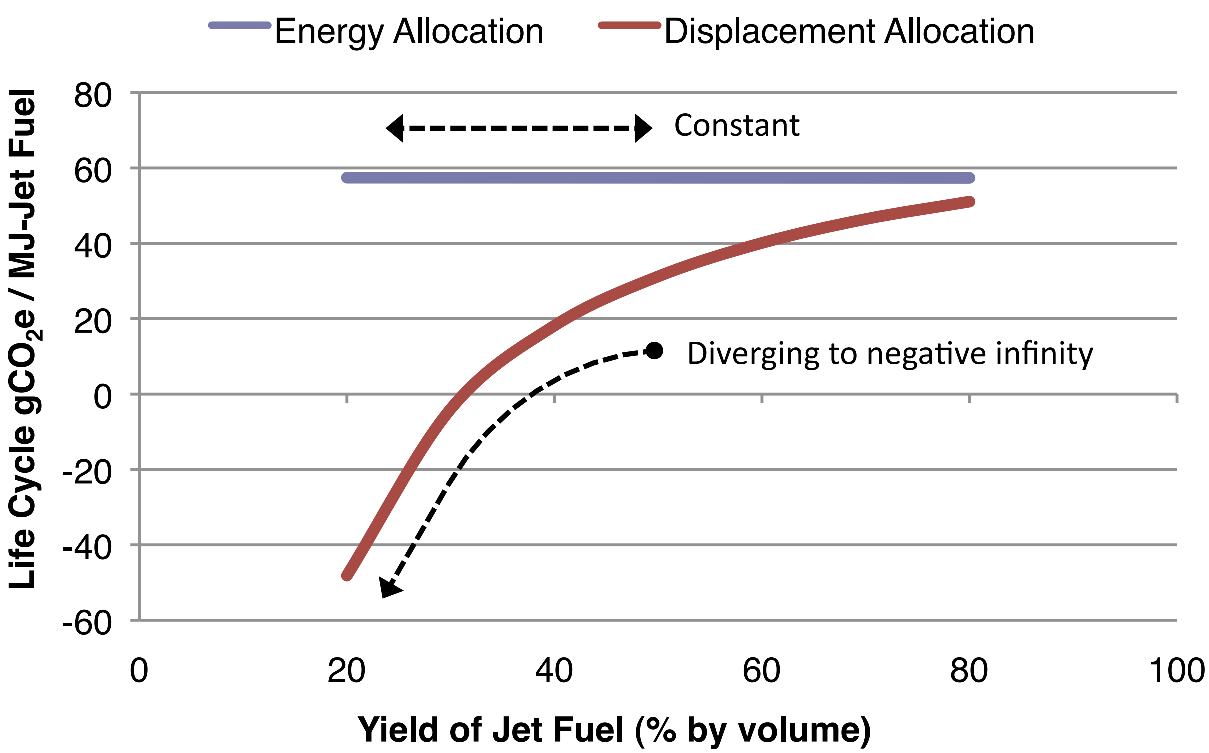
1	**Co-product use:**	Electricity
	Allocation:	Energy
2	**Co-product use:**	Fertilizer
	Allocation:	Displacement
3	**Co-product use:**	Animal feed, Electricity
	Allocation:	Economic value, Displacement
4	**Co-product use:**	Electricity
	Allocation:	Displacement



Subjective allocation and co-product usage choices can be more significant than numerical inputs

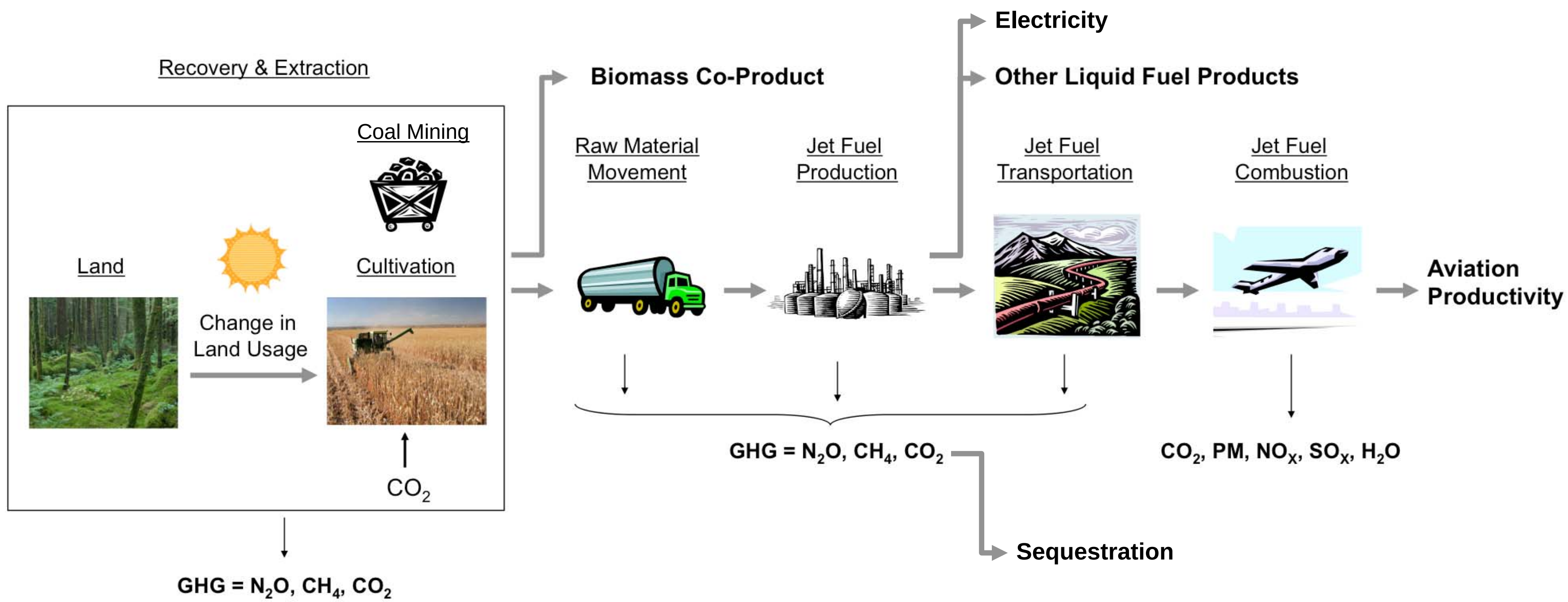
Co-product Usage and Allocation
Coal and Biomass F-T Fuel

- F-T facility operator has some control over the product slate of diesel, jet, and naphtha
- Displacement allocation makes LC-GHG inventory of F-T jet fuel VERY sensitive to product slate distribution



Important when product of interest is NOT the primary product, (e.g., jet fuel)

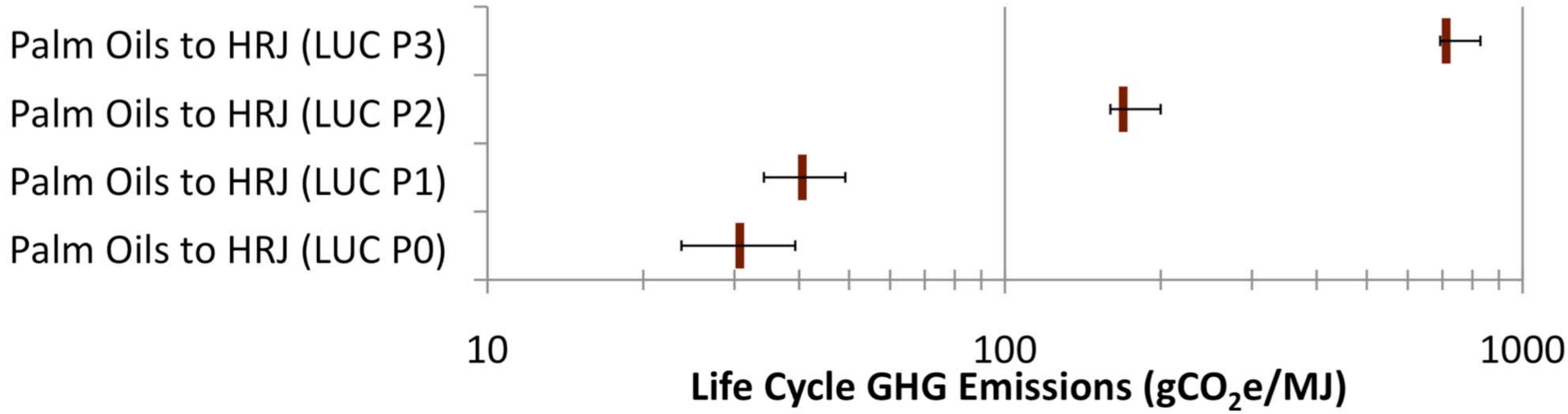
Land Use Change (LUC)



- Can be either positive or negative depending on land involved
- Magnitude depends primarily on the type of land being converted to cropland and the type of crops being grown
- LUC can be direct (due to land conversion) or indirect (consequence of a price signal in agricultural products)

Impact of LUC on Palm HRJ Emissions

LUC P0: No land use change
LUC P1: Conversion of logged over forest
LUC P2: Conversion of tropical rainforest
LUC P3: Conversion of peat land rainforest

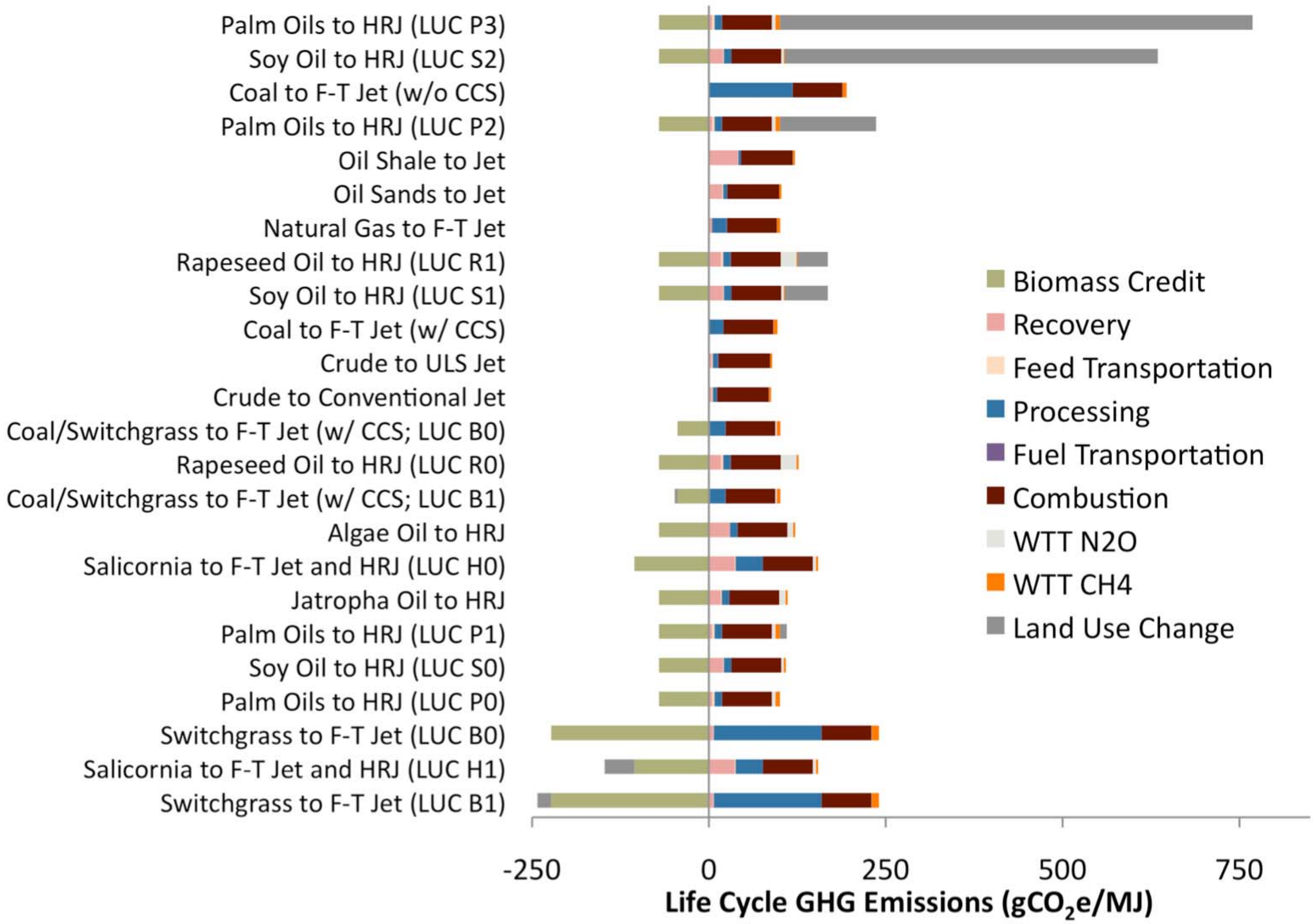


- GHG emissions from LUC can dominate a LC-GHG inventory
- Any given feedstock could be subject to different types of LUC
- Independent sets of results under select LUC scenarios used to account for the variability of if and when a fuel pathway may be subject to a particular type of LUC

LUC Scenarios Considered

Land use change	LUC Scenario 1	LUC Scenario 2	LUC Scenario 3
Switchgrass (B0, B1)	Carbon depleted soils converted to switchgrass cultivation	n/a	n/a
Soy oil (S0, S1, S2)	Grassland converted to soybean cultivation	Tropical rainforest converted to soybean cultivation	n/a
Palm oil (P0, P1, P2, P3)	Prev. logged over forest converted to palm plantation	Tropical rainforest converted to palm plantation	Peat land rainforest converted to palm plantation
Rapeseed oil (R0, R1)	Set-aside land converted to rapeseed cultivation	n/a	n/a
Salicornia (H0, H1)	Desert land converted to salicornia cultivation	n/a	n/a
Note: In all cases, LUC scenario 0 denotes no land use change			

Comparison of LC GHG Inventories
Broken Out by Process



Soy HRJ Pathway Scenarios	
LUC-S0	No land use change
LUC-S1	Grassland conversion to soybean field
LUC-S2	Tropical rainforest conversion to soybean field
Palm HRJ Pathway Scenarios	
LUC-P0	No land use change
LUC-P1	Logged over forest conversion to palm plantation
LUC-P2	Tropical rainforest conversion to palm plantation
LUC-P3	Peatland rainforest conversion to palm plantation
Rapeseed SPK Pathway Scenarios	
LUC-R0	No land use change
LUC-R1	Set-aside land converted to cultivation
Salicornia SPK Pathway Scenarios	
LUC-H0	No land use change
LUC-H1	Desert converted to salicornia cultivation
Switchgrass to BTL and CBTL	
LUC-B0	No land use change
LUC-B1	Carbon depleted converted to switchgrass cultivation

To reduce GHG emissions, need biofuels created from waste products or from crops that do not incur positive land use changes.

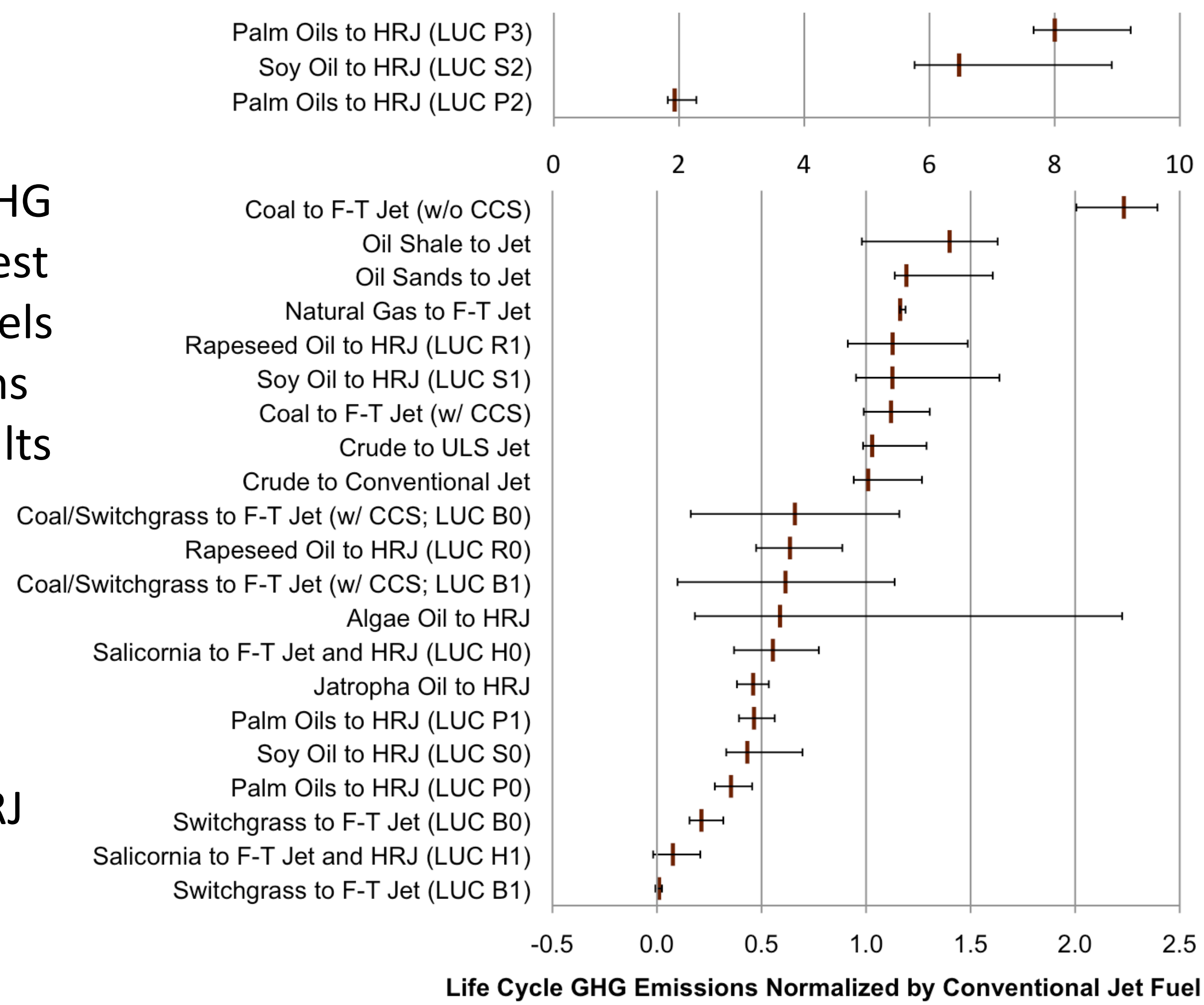
Comparison of LC GHG Inventories

Key Points:

- Screening level study
- Large variability
- Few biofuels have zero GHG
- Conv. petroleum has lowest emissions among fossil fuels
- Land use change emissions have large impact on results
- Continuing analysis

Next to be considered:

- “Sugars” to Jet Fuel
- Pyrolysis oils to Jet Fuel
- Improvement to Algae HRJ



Does not include non-CO2 combustion impacts

Challenges in Conducting LCA
Multiple Metrics

Life cycle GHG emissions are one of many considerations that must be examined when evaluating feasibility and sustainability:

- *Technical feasibility*
- *Environmental impacts on global climate change*
- *Environmental impacts on surface air quality*
- *Efficient usage of fresh water and land resources*
- *Species invasiveness*
- *Economic cost of fuel production*

This research demonstrated challenges of assessing and comparing fuel options using a single attribute.

Challenges in Conducting LCA
Key Conclusions

Three key conclusions derive from influence of variability from co-product usage and allocation and LUC assumptions

1. Minimizing variability across LCA results by maximizing methodological consistency is essential to making useful comparisons between fuel options.

2. Absolute results from an attributional LCA may have a diluted physical meaning and are therefore most effective as a comparative tool, given the above condition.

3. To make adequate comparisons, decision makers and general public need to be presented LC-GHG inventories as a range.

Approach emphasizes importance of understanding key aspects that determine LC-GHG emissions.

Thank you

All results discussed herein are presented in more detail in:

- Stratton, R.W.; Wong, H.M.; Hileman, J.I.; "Quantifying Variability in Life Cycle GHG Inventories of Alternative Middle Distillate Transportation Fuels," *Environ. Sci. Technol.* **2011**, 45 (10), 4637-4644.
- Stratton, R.W.; Wong, H.M.; Hileman, J.I.; "Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels," Partnership for Air Transportation Noise and Emissions Reduction, Massachusetts Institute of Technology: Cambridge, MA, 2010.

PARTNER Alt Fuels Research: *http://partner.aero - search for Project 28 to get links to ES&T article and PARTNER Report.*

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  - MIT Joint Program on Global Change
  - Argonne National Labs (GREET)
  - U.S. Department of Transportation Volpe Transportation Center
  - Woods Hole Marine Biological Lab
  - Environmental Law Institute
- Cost share partners:
  - DLR, U. of Cambridge, Boeing, Pratt & Whitney, and Shell