GREET® DEVELOPMENT AND BIOFUEL PATHWAY RESEARCH AND ANALYSIS

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ANALYSIS AND SUSTAINABILITY SESSION
2017 BETO PEER REVIEW

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Acronyms List

AFTF	Alternative Fuel Task Force
AGWP	Absolute Global Warming Potential
ANL	Argonne National Laboratory
AWARE	Available WAter REmaining
BETO	Bioenergy Energy Technology Office
BT16	2016 Billion-Ton
BTL	Biomass-to-Liquid
CARB	California Air Resources Board
CB20TL	Coal and Biomass to Liquid (20% biomass feed share by mass)
CCLUB	Carbon Calculator for Land Use Change from Biofuel Production
CCS	Carbon Capture and Sequestration
CHP	Combined Heat and Power
CNG/LNG	Compressed/Liquefied Natural Gas
CORRIM	Consortium for Research on Renewable Industrial Materials
DGS	Distillers' Grain Solubles
DOD	Department of Defense
DOE	Deaprtment of Energy
E10/E25/E40	10%, 25% and 40% Ethanol Blended Gasoline (by volume)
EERE	Energy Efficiency and Renewable Energy Office of DOE
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERG	Eastern Research Group
ETJ	Ethanol-to-Jet
EtOH	Ethanol
EU	European Union
FAA	Federal Aviation Administration
FQD	Fuel Quality Directive
FRA	Federal Rail Administration of DOT
FT	Fischer Tropsch
FWG	Fuels Working Group of US DRIVE
FY	Fiscal Year
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GJ	Giga-Joules
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	Global Warming Potential
HPH	High Pressure Homogenization
HRJ	Hydroprocessed Renewable Jet

ICAO	International Civil Aviation Organization of UN
IMO	International Marine Organization of UN
INL	Idaho National Laboratory
LCA	Life Cycle Analysis
LCFS	Low Carbon Fuel Standard
LUC	Land Use Change
MIT	Massachusetts Institute of Technology
MJ	Mega-Joules
MOVES	MOtor Vehicle Emission Simulator
MPGGE	Miles Per Gasoline Gallon Equivalent
MYPP	Multi-Year Program Plan
NG	Natural Gas
NGO	Non-Governmental Organization
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PBR	Photobioreactor (for algae)
PM	Particulate Matter
PNNL	Pacific Northwest National Laboratory
PTW	Pump to Wheels
QC/QA	Quality Control/Quality Assurance
R&D	Research & Development
RA	Resource Assessment
RFS2	Renewable Fuel Standard 2
SCSA	Supply Chain Sustainability Analysis
SOC	Soil Organic Carbon
SOT	State of Technology
STJ	Sugar-to-Jet
T&D	Transportation & Distribution
TEA	Techno-Economic Analysis
UC	University of California
UIC	University of IL at Chicago
UIUC	University of IL at Urbana-Champaign
US DRIVE	US Driving Research and Innovation for Vehicle efficiency and Energy sustainability
USDA	US Department of Agriculture
VOC	Volatile Organic Compound
WSI	Water Stress Index
WTP	Well to Pump
WTW	Well to Wheels

Goal Statement

- Develop a life-cycle analysis (LCA) model that supports BETO and bioenergy community by quantifying energy and environmental impacts of biofuels
  - Energy security
  - Greenhouse gas (GHG) emissions
  - Air pollutant emissions
  - Water consumption
- Produce consistent, comprehensive LCA results for biofuels with peer-reviewed studies and comparing with other analyses/studies
- Interact with and conduct outreach to biofuel stakeholders
  - Provide LCA results to agencies, technology developers, other stakeholders for R&D and policy decision making
  - Interact with researchers and industries to examine critical issues affecting biofuel LCA results
  - Provide LCA tool training to biofuel and LCA community

Quad Chart Overview

Timeline

- Original GREET LCA efforts began in 1994 supported by multi-DOE programs including BETO
- Project start date: FY2015
- Project end date: FY17
- Percent complete: 80%

Budget

	Total Costs FY 12 –FY 14	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	$4.40 M	$ 1.20 M	$ 1.46 M	$ 1.46 M

Barriers addressed

- At-B: analytical tools and capabilities for system-level analysis
- At-A: transparent, and reproducible analyses
- St-F: systems approach to bioenergy sustainability
- Mm-A: lack of understanding of environmental/energy tradeoffs

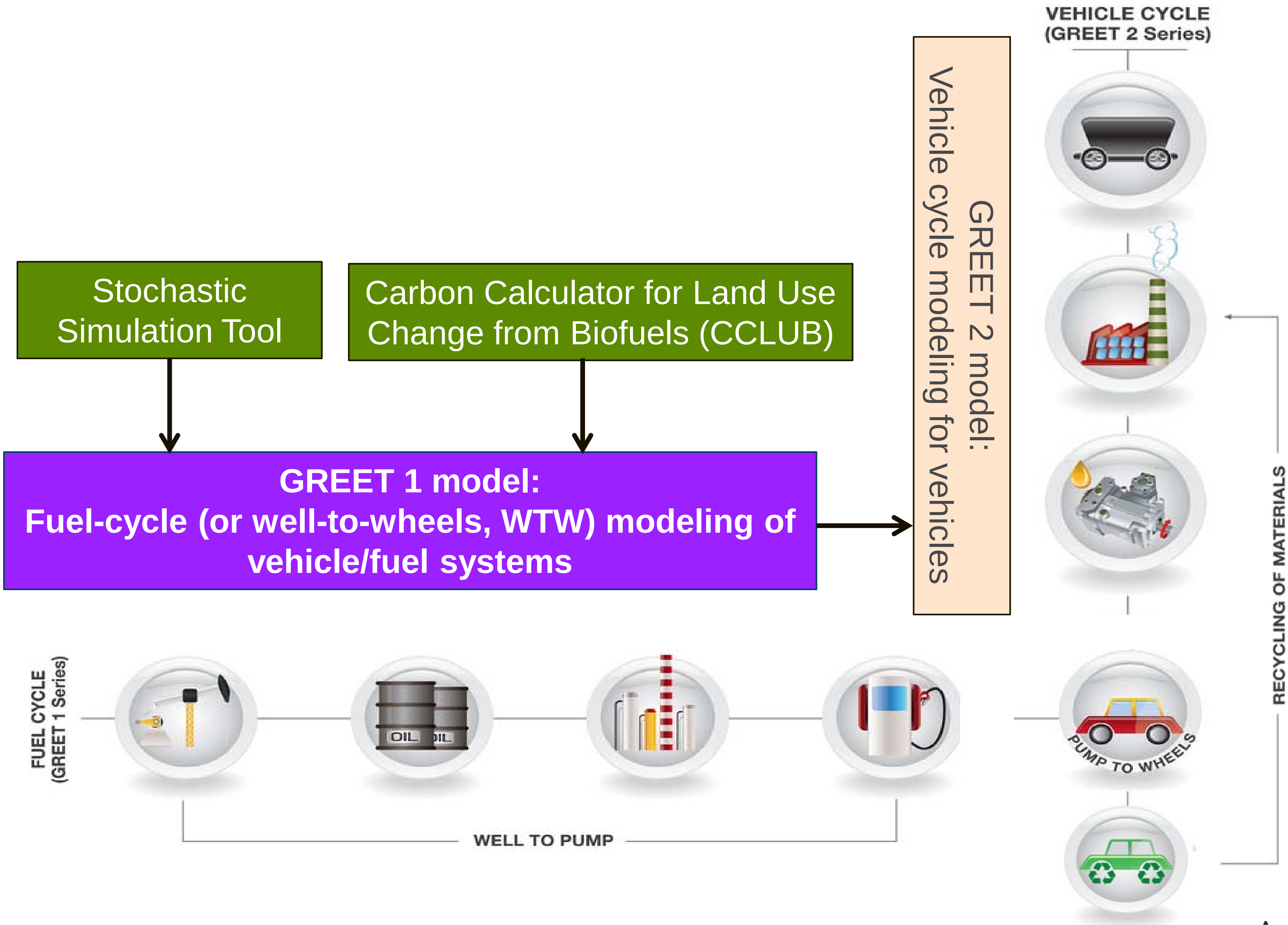
Partners

- In-kind
  - NREL, ORNL, PNNL, INL, MIT, CORRIM
  - Other agencies: USDA, FAA, EPA, CARB, FRA
  - Industry stakeholders: energy companies, biofuel producers/tech developers, auto companies
  - Research institutions and NGOs
- Supported
  - UIC, UIUC, Stanford U, UC Davis, Duke U
  - Jacobs, ERG, Great Plains Institute

Project Overview

- Develop GREET® LCA model to address energy and environmental impacts of biofuels and conventional fuels
  - Develop LCA methodologies especially to deal with technology advancements, LCA system boundary, co-products, indirect effects, etc.
  - Develop extensive, reliable data for LCAs of biofuel and petroleum fuel pathways
  - Maintain model openness and transparency
- Conduct LCAs of biofuel production pathways
  - Update existing biofuel pathways in GREET
  - Examine and add emerging biofuel pathways (e.g., co-processing of bio-crude in petroleum refineries) to GREET
  - Address emerging LCA issues (e.g., albedo, biomass additionality, carbon neutrality, land management change, and water stress assessment)
  - Publish biofuel LCA studies and review/evaluate relevant studies
- Interact with stakeholders (researchers, agencies, industries) to improve understanding and use of LCA results with a consistent modeling platform

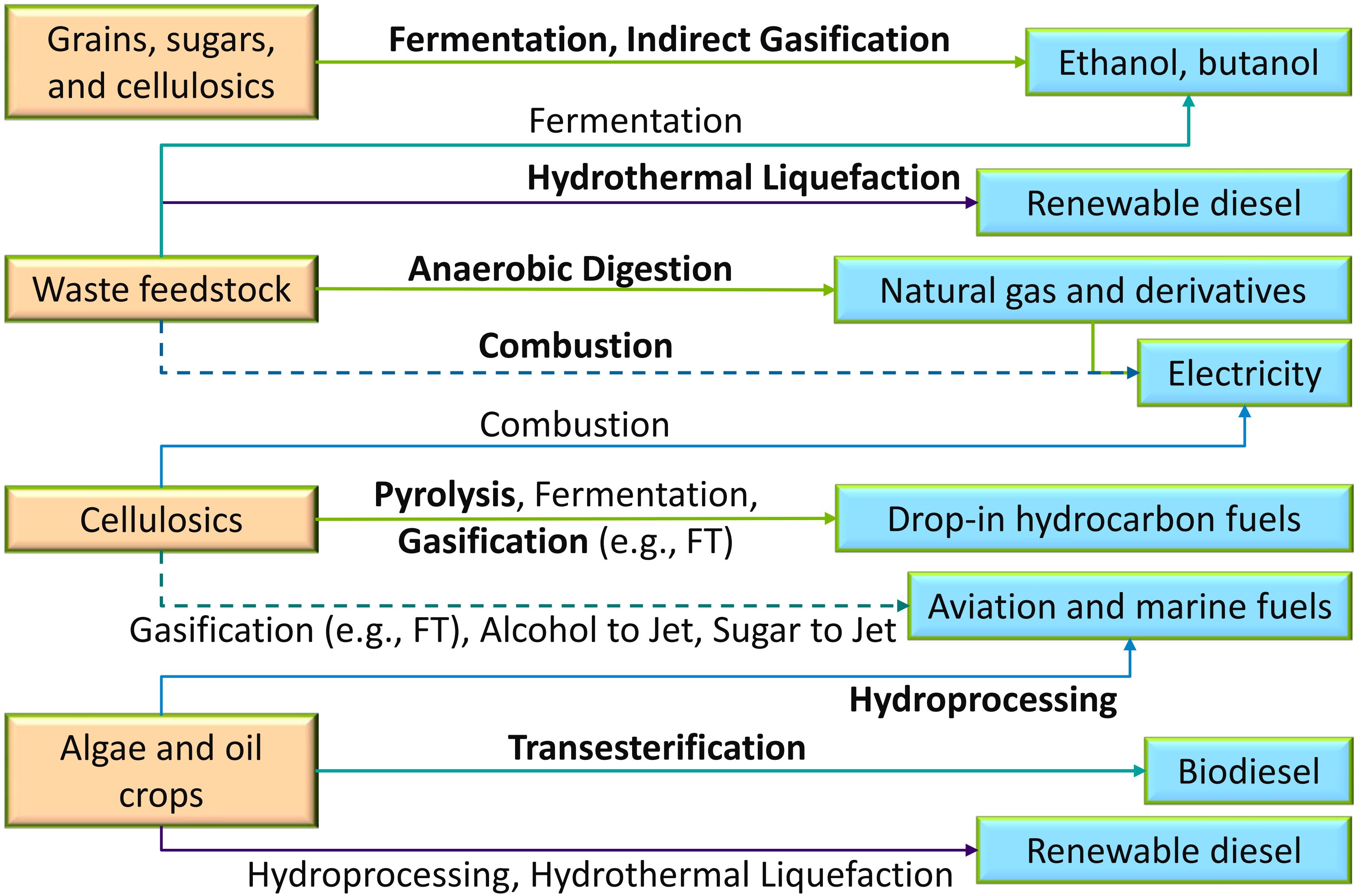
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model Framework



GREET at a Glance

- A publicly available LCA tool for consistently examining life-cycle energy and environmental effects of vehicle/fuel systems
  – Available for free download at greet.es.anl.gov
  – Contains over 100 vehicle/fuel systems
  – Fuel types include gasoline, diesel, hydrogen, NG-based fuels, electricity, and many **biofuel types**
- GREET produces results for
  – Greenhouse gas emissions (CO_2e of CO_2, CH_4, N_2O, black carbon, albedo)
  – Criteria pollutant emissions (VOC, CO, NO_x, SO_x, $PM_{2.5}$, and PM_{10}); separated into total and urban emissions
  – Water consumption
  – Energy use by total energy, fossil energy, petroleum energy
- Biofuels have been an important fuel group in GREET development and applications

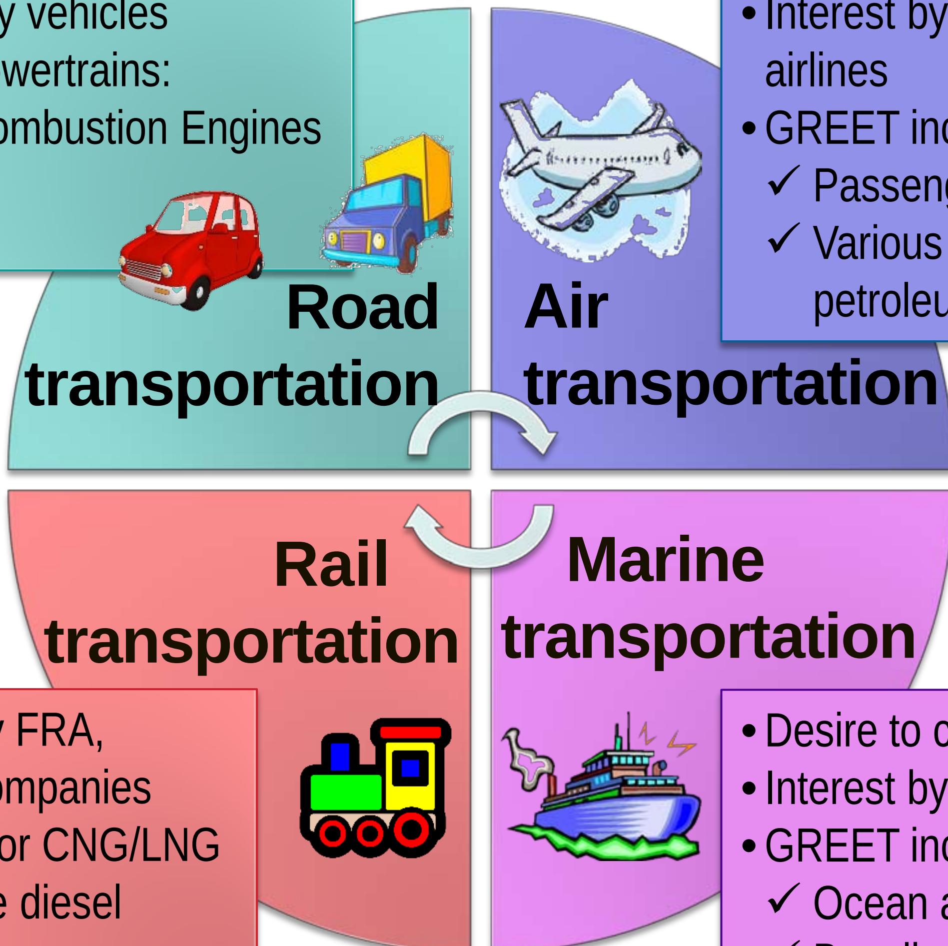
GREET Includes Various Biomass Feedstocks, Conversion Technologies, and Fuels



GREET Includes All Transportation Subsectors

- Light-duty vehicles
- Medium-duty vehicles
- Heavy-duty vehicles
- Various powertrains:
  Internal Combustion Engines
  Electrics
  Fuel cells

- Globally, a fast growing sector with GHG reduction pressure
- Interest by DOD, ICAO, FAA, and commercial airlines
- GREET includes
  - ✓ Passenger and freight transportation
  - ✓ Various alternative fuels blended with petroleum jet fuels



- Interest by FRA, railroad companies
- Potential for CNG/LNG to displace diesel

- Desire to control air pollution in ports globally
- Interest by EPA, local governments, IMO
- GREET includes
  - ✓ Ocean and inland water transportation
  - ✓ Baseline diesel and alternative marine fuels

GREET Approach and Data Sources

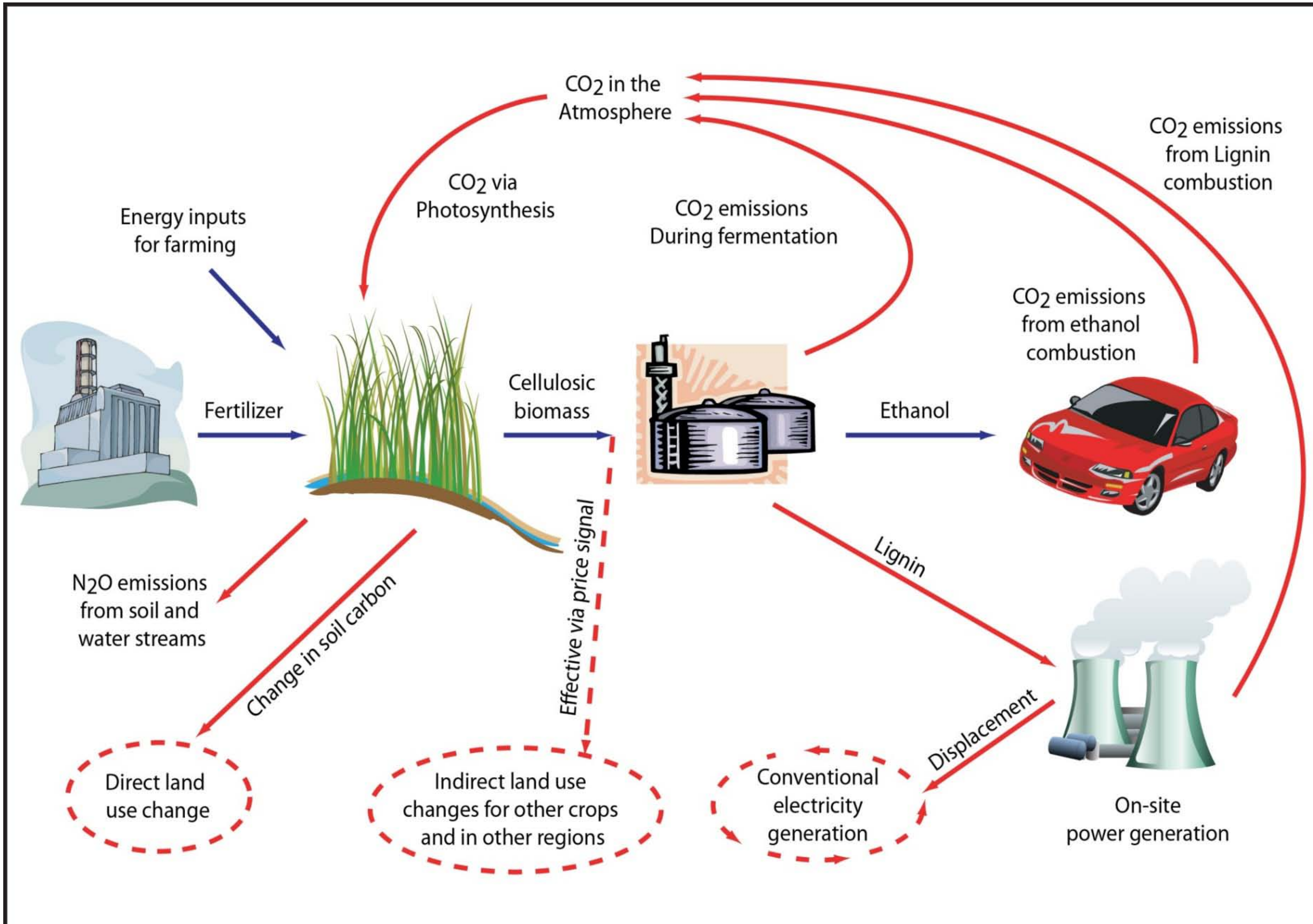
Approach

- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Maintain openness and transparency of LCAs by making GREET publicly available
- Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

Data sources

- Open literature and results from other researchers
- DOE and other agencies R&D results
- Fuel producers and technology developers for fuels and automakers for vehicles
- Simulations with models such as ASPEN Plus for fuel production and ANL Autonomie and EPA MOVES for vehicle operations
- Baseline technologies and energy systems: EIA Annual Energy Outlook (AEO) projections, EPA eGrid for electric systems, etc.
- Consideration of effects of regulations already adopted by agencies

GREET System Boundary for Biofuel LCA: Direct Activities and Indirect Effects Are Included



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Approach: Project Management

- Project tracking through monthly and quarterly written reports to BETO, quarterly conference calls with BETO sponsor to track milestone completion
- Monthly conference calls with other national laboratories and CORRIM on coordinated projects
- Biweekly internal team meetings to review technical progress and gain feedback
- Internal QC/QA procedures implemented for analyses and GREET development
- Engage community for data availability and reliability
- Interactions and communications
  - Interact with researchers, biofuel producers, and tech developers to address key issues, exchange data, and share LCA results
  - Communicate via peer-reviewed publications, presentations, and public outreach

Project Management: Critical Success Factors Identified for GREET Development and Applications

- Critical LCA issues need to be addressed with science and thoroughness
  - LCA system boundary needs to be complete and consistent among fuel pathways
  - Co-products of biofuels need to be handled with reliable and transparent methods
  - LCA output attributes should be relevant to energy and environmental concerns

- GREET (and LCA models) should address technology advancements and technical variability and uncertainties
  - LCA simulations should be dynamic to consider technology advancements over time
  - Technical variability of pathway parameters is addressed with stochastic simulations in GREET
  - Technical uncertainties are addressed with scenario analysis and a variety of technology paths for a given supply chain with GREET

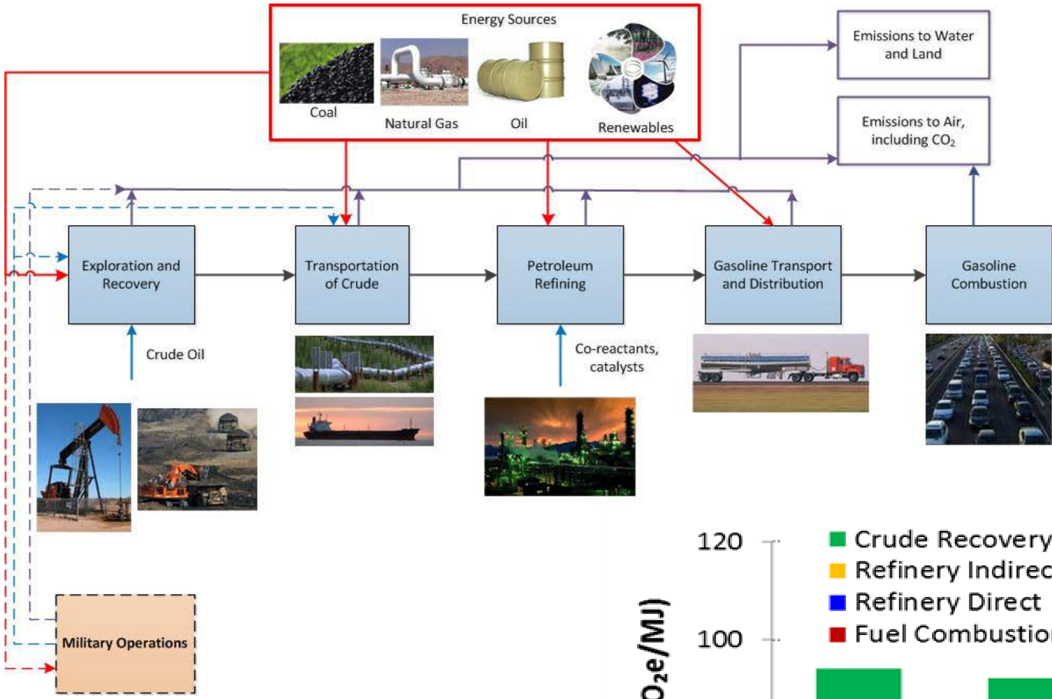
- Reliable data and transparent models and analyses
  - Engage agencies and stakeholders for data sharing and verification
  - Make GREET and data open and transparent
  - Produce high-quality, consistent, and peer-reviewed analyses/publications
  - GREET enables users to input data from their practices/experiments

Key Technical Accomplishments Since March 2015

1. GREET model development
2. Emerging LCA issues: albedo
3. Modeling of LUC and SOC change for biofuel feedstocks
4. BETO Supply Chain Sustainability Analysis (SCSA) with other labs
5. Contribution to BT16 Vol. 2 sustainability report
6. GREET life-cycle water consumption results
7. Co-feedstocks and co-products in biofuel LCA: corn grain/stover for EtOH; corn starch/corn oil for EtOH/biodiesel
8. Modeling of woody feedstock growth and carbon dynamics for GREET LCA (collaboration with CORRIM)
9. Expanded algae LCA for various production scenarios

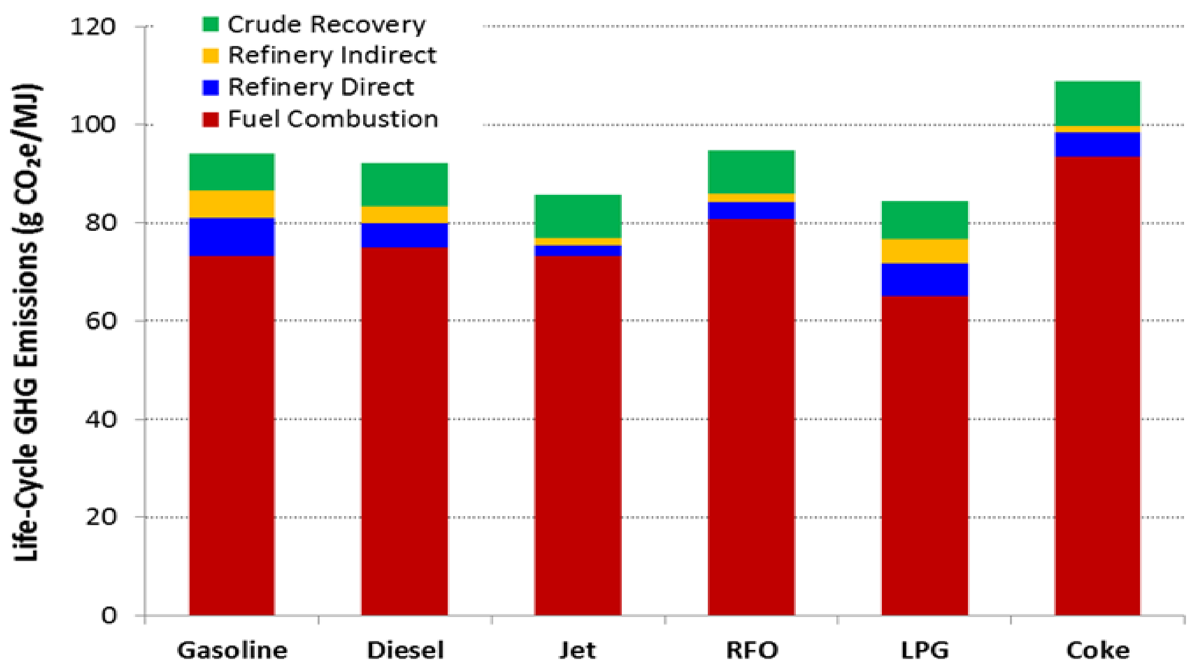
3.1: GREET Model Development

GREET WTW Analysis of Petroleum Baseline Fuels



Key activities

- Updated Canadian oil sands in GREET
- Added shale oil into GREET
- Thorough Linear Programming (LP) modeling of petroleum refining



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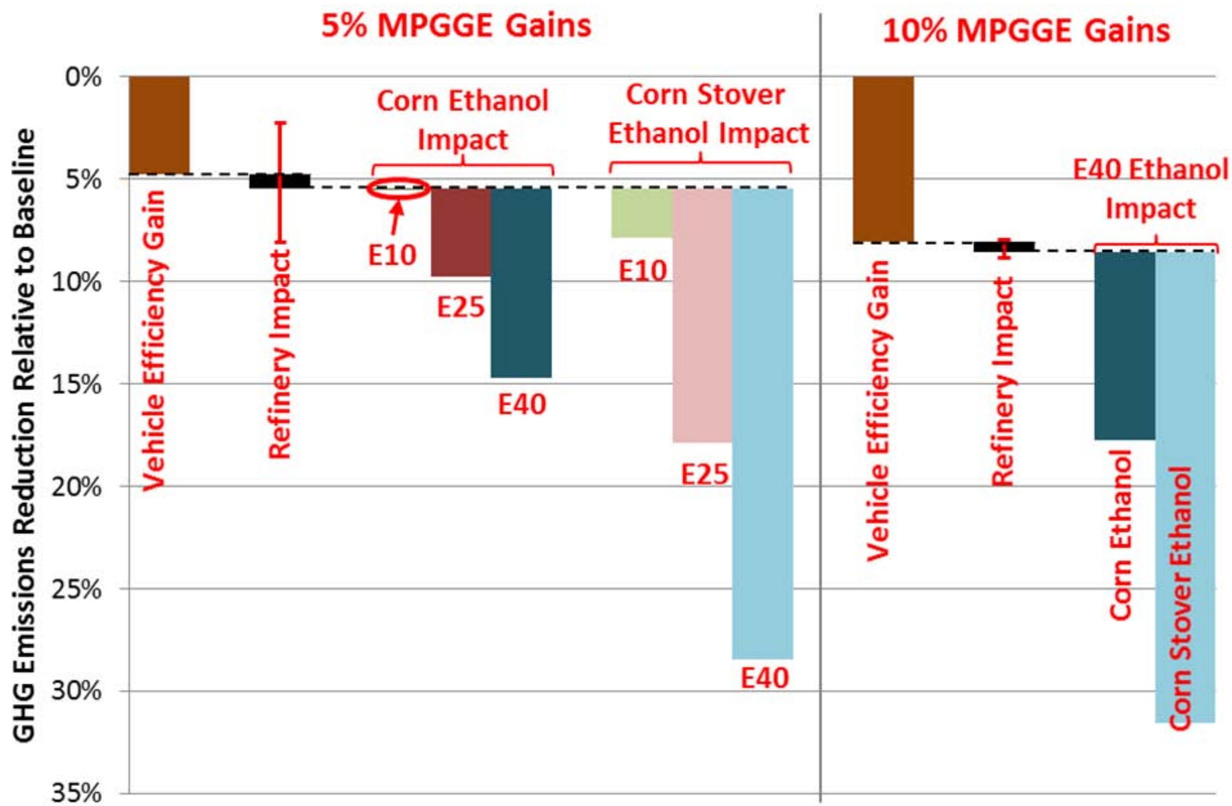
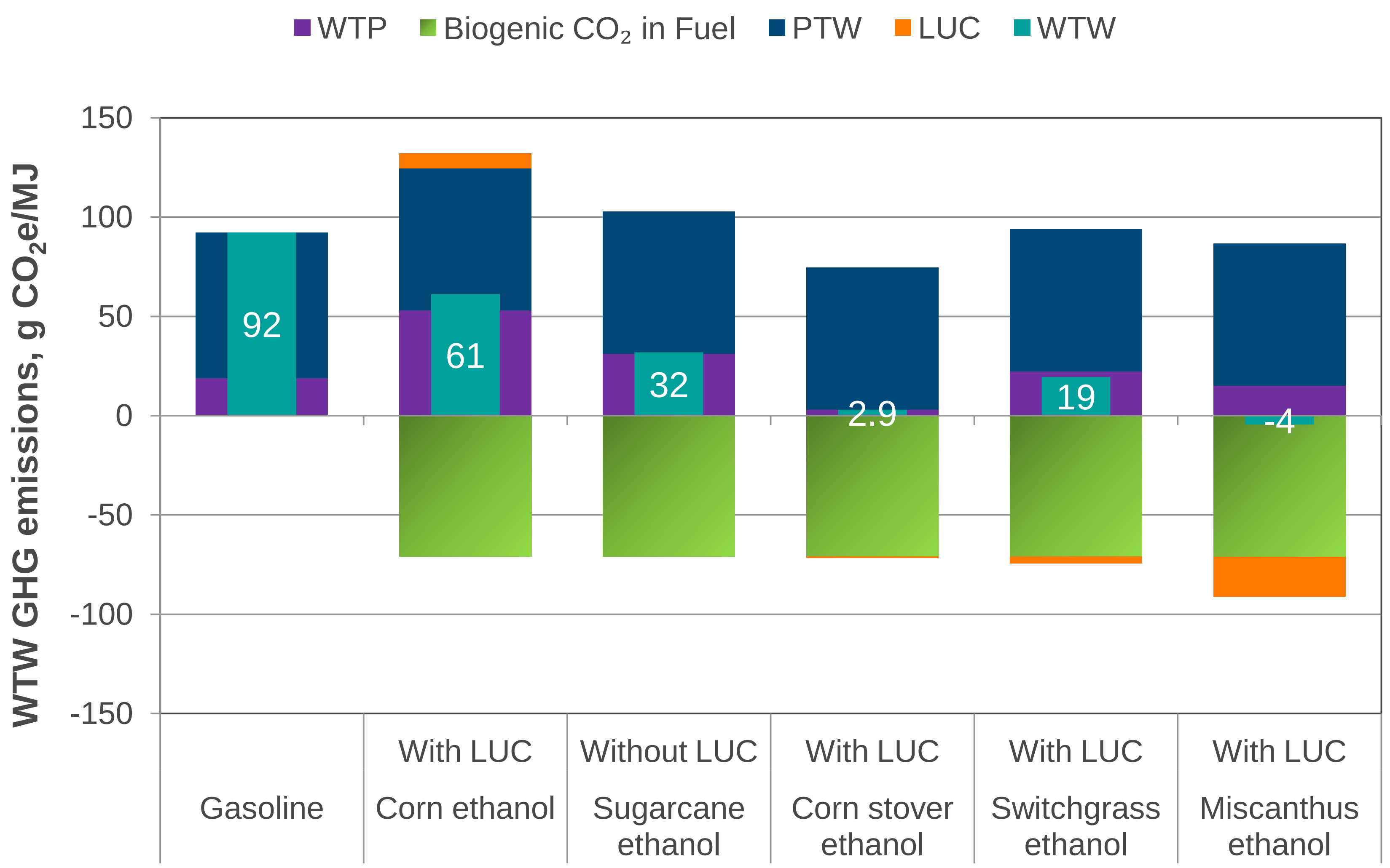
As An Enabler for High Octane Fuel, Blending of Ethanol Provides Additional GHG Benefits from Vehicle Efficiency

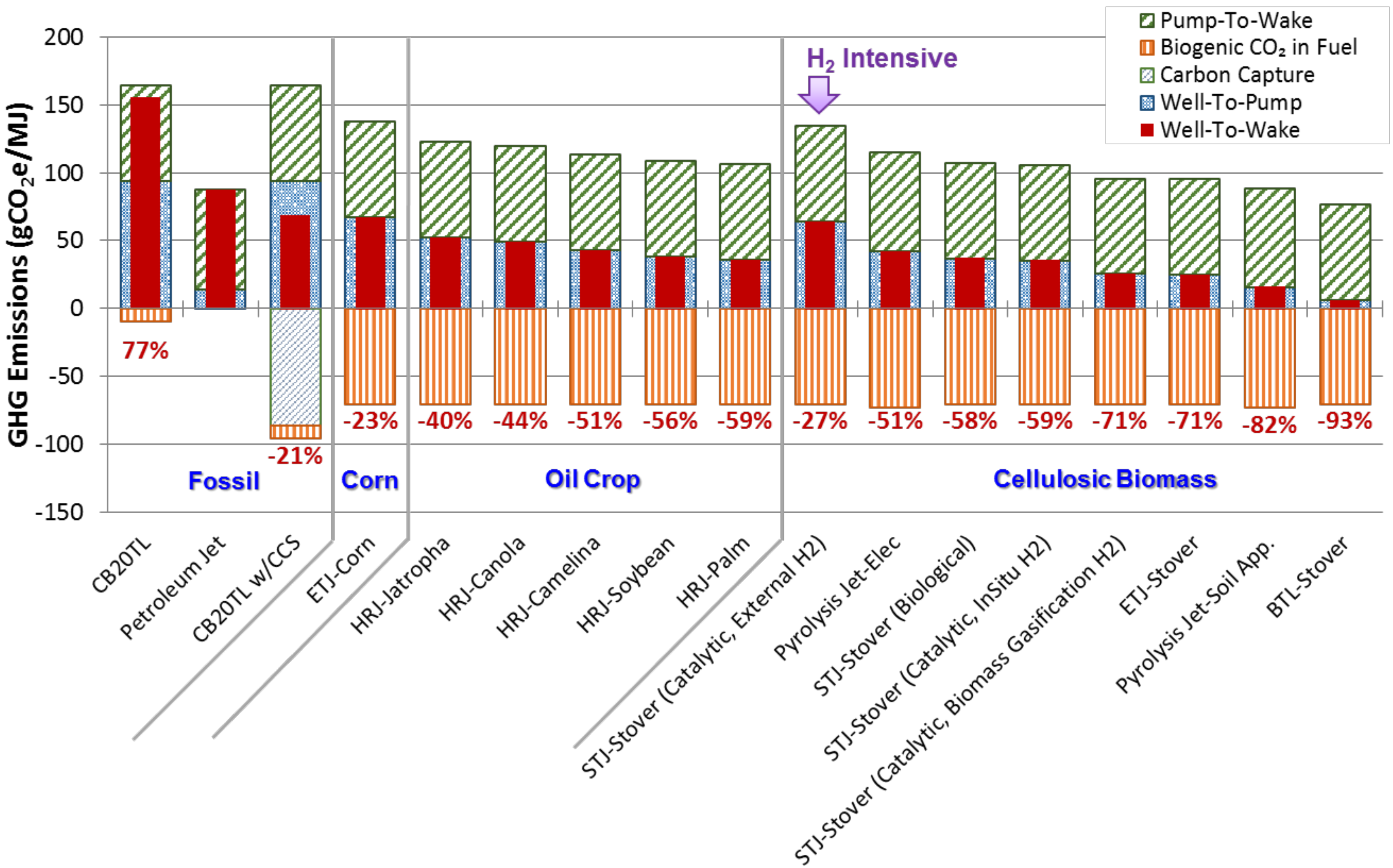


- GHG reduction w/ vehicle efficiency gain: 4% with 5% MPGGE gain, 8% with 10% MPGGE gain
- Refinery GHG Impact on Blendstock for Oxygenate Blending (BOB) : <1%
- Ethanol Blending additional GHG benefits
  - ✓ <u>Corn Ethanol: </u>0% for E10, 5% for E25, 10% for E40
  - ✓ <u>Corn Stover Ethanol</u>: 3% for E10, 12% for E25, 24% for E40

GREET Life-Cycle GHG Emissions of Selected Biofuels: Feedstock Is the Main Driver



GREET Bio-Jet Fuel GHGs: Feedstock and Conversion Are Key Drivers



Based on GREET2016. Emissions from land use change is not included.

GREET.net: *Modular User Interface and Structured Database*

- Embeds the GREET methodology in the programming code to avoid accidental errors in Excel
- Provides an efficient and a standard LCA modeling interface

GREET 1 (Fuel Cycle)

GREET 2 (Materials)

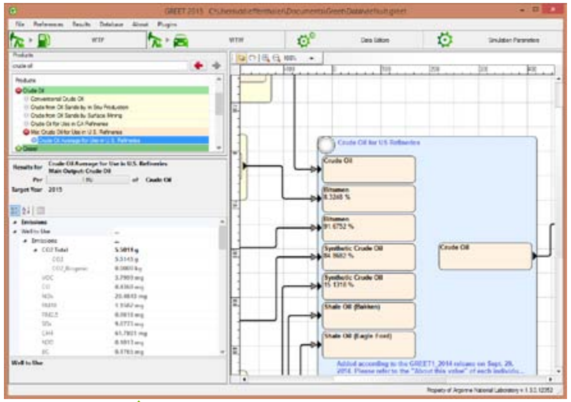
Stochastic

CCLUB

GREET.Net integrates all databases in Excel Models

GREET.Net

Local GREET Application Only implement methodology



As of Jan. 2017

General Statistics	
Number of pathways	925
Number of processes	1442
Number of stationary processes	1146
Number of transportation processes	296
Number of modes	11
Number of gases	27
Numbrer of resources	466
Number of technologies	328
Number of parameters	64927
Number of mixes	106

Local greet file Only store data sets

GREET.Net seperates datasets and methodology

GREET Data Service

Regular Updates

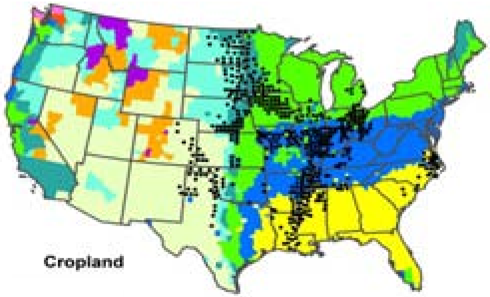
GREET Software Server

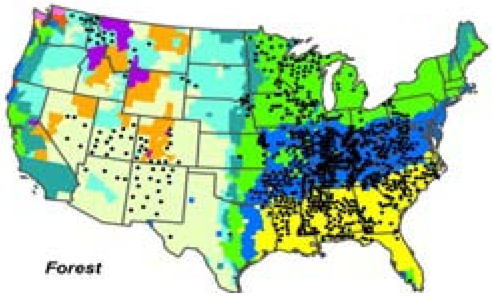
Regular Updates

3.2: Emerging LCA Issues: Albedo

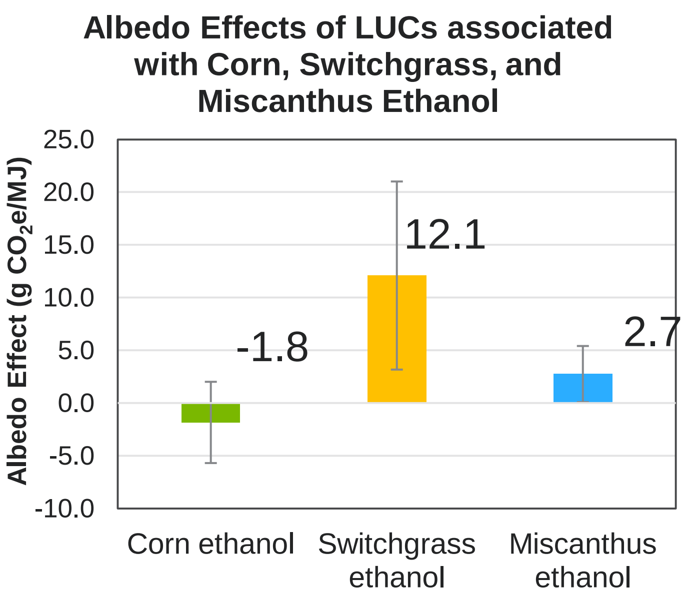
Quantification and Integration of Albedo Effects into GREET Biofuel GHG Modeling

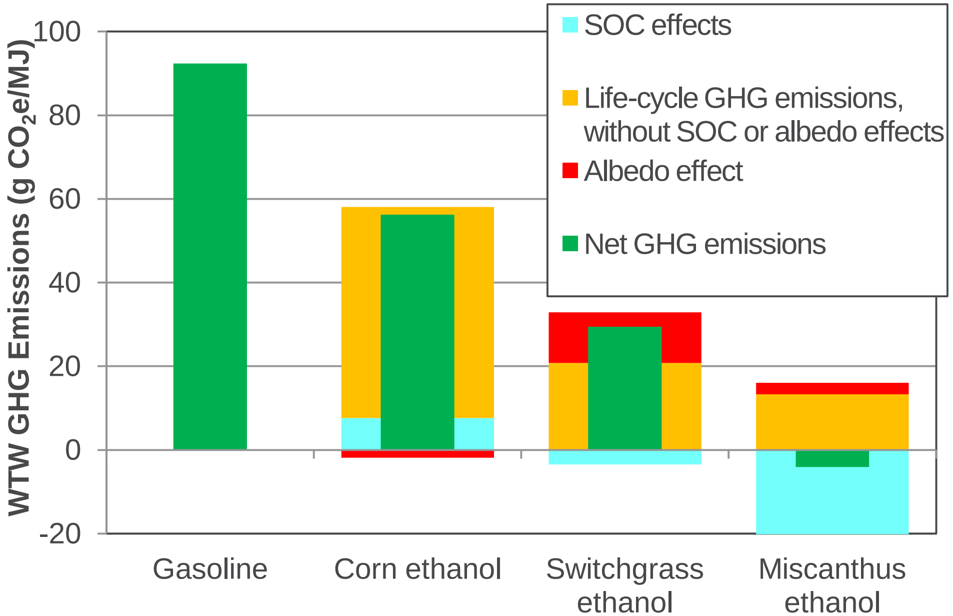
✓ LUC-induced albedo effects were quantified with >one million biomass growth sites and were aggregated to Agro-Ecological Zone (AEZ) level





✓ Temporal albedo variations were addressed with daily solar radiation data for each site

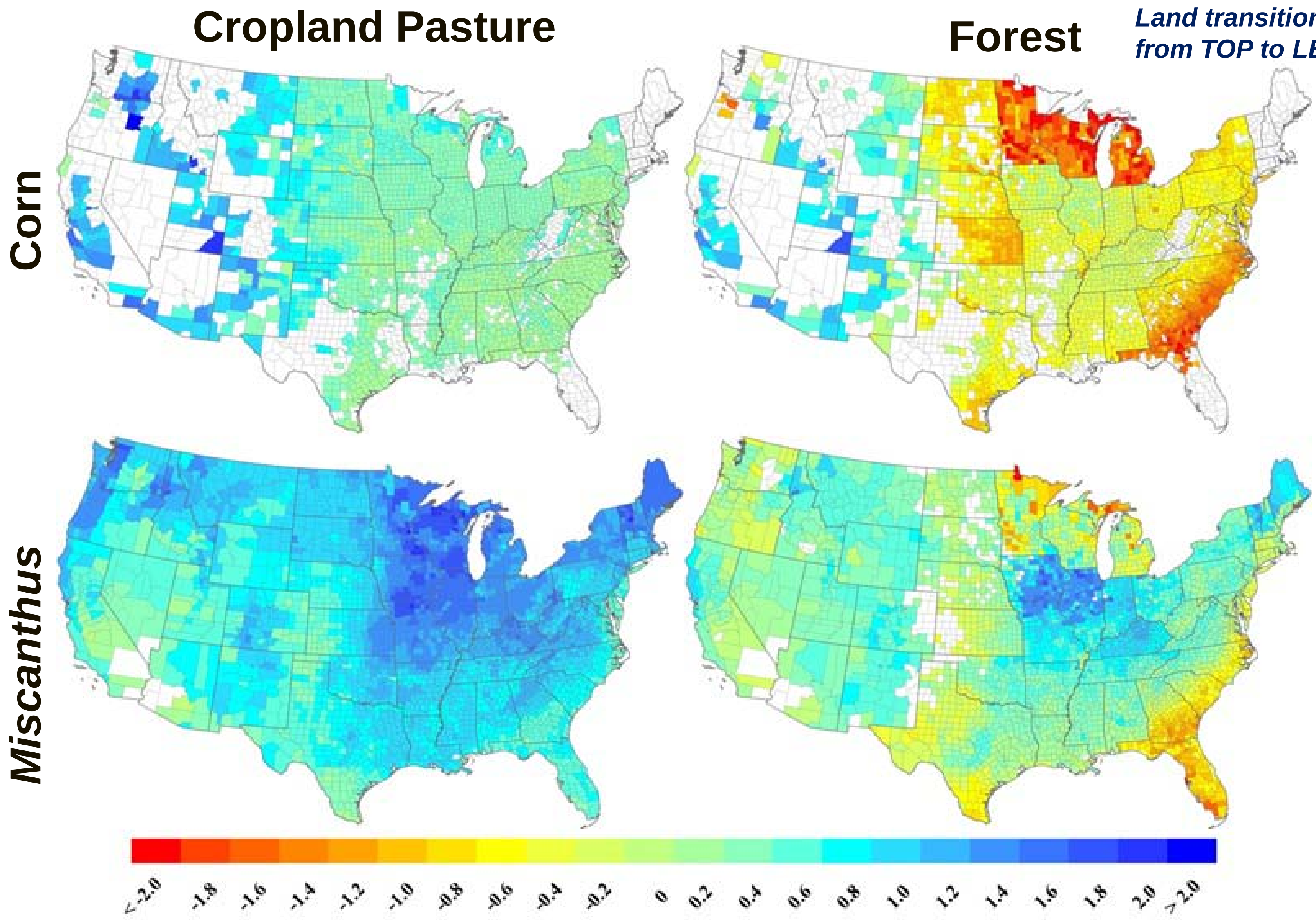




3.3: Modeling of Land Use Change and Soil Organic Carbon Change for Biofuel Feedstocks

SOC Changes Upon Land Transition Are Highly Spatial and Feedstock-Dependent

Land transition notation: from TOP to LEFT



SOC rate t ha^{-1} yr^{-1}

LUC-Related GHG Emissions Vary Significantly Among Biofuel Feedstocks

For cellulosic feedstocks, conversion of cropland and grassland to energy grass fields (e.g., *Miscanthus* farms) could increase or maintain SOC

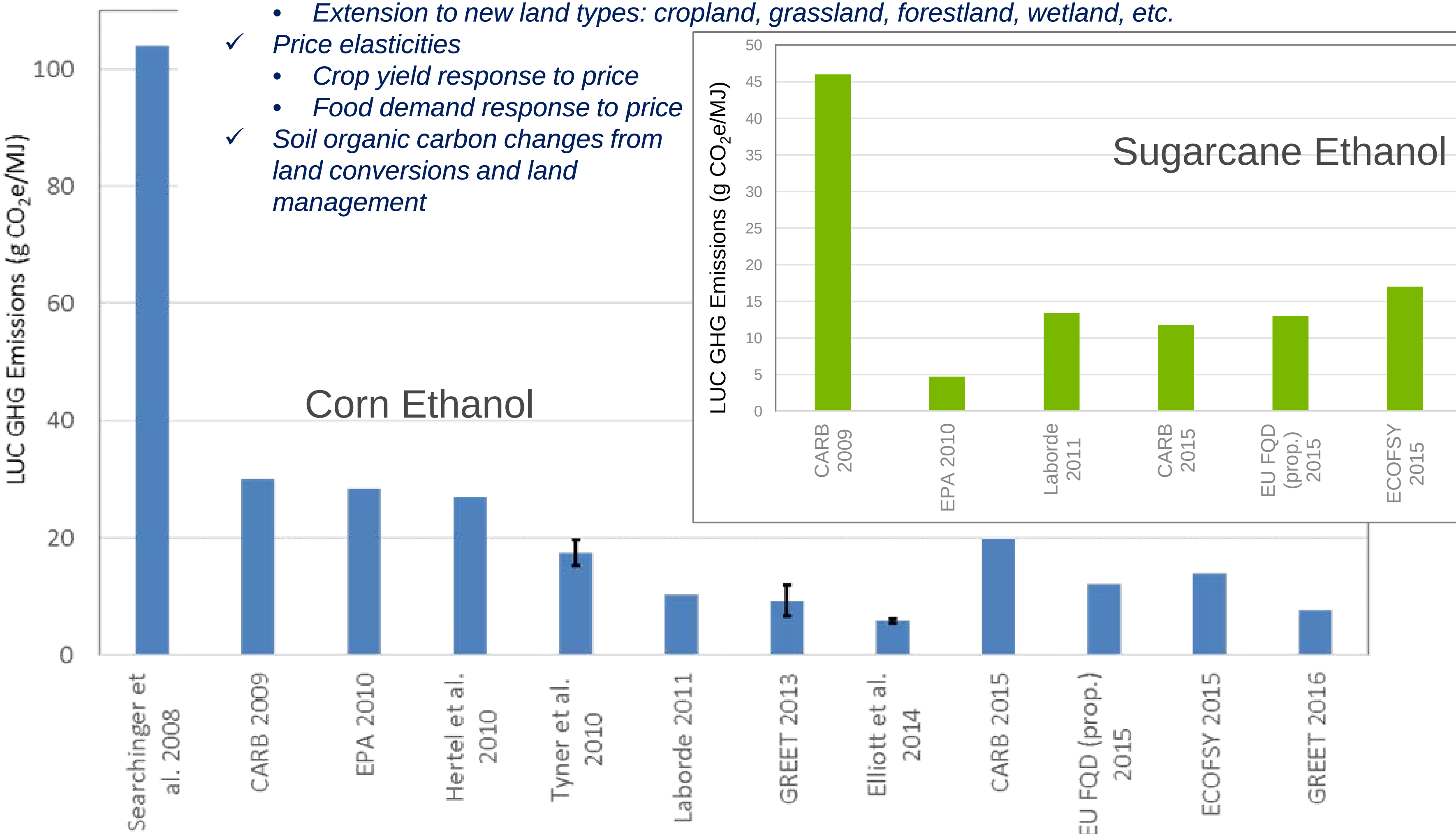
	LUC GHG emissions ($g\ CO_2eq\ MJ^{-1}$)			WTW GHG w/o LUC ($g\ CO_2e\ MJ^{-1}$)	WTW GHG w/ LUC ($g\ CO_2e\ MJ^{-1}$)
	Domestic	International	Total		
Corn	1.4 – 4.3	5.0	6.4 – 9.3	57.1	63.5 – 66.4
Miscanthus	-22.3 – -16.3	2.2	-20.1 – -14.1	13.5	-6.7 – -0.6

Note: 1) LUC GHG emissions are based on 100cm soil depth; variations reflect types of land impacted and land management practices.
2) Conversion of cropland to cornfield with sustainable stover removal could result in increased SOC; conversion of grassland or forest to cornfield could result in decreased SOC

Trend of Estimated LUC GHG Emissions for Corn and Sugarcane Ethanol

Critical factors for LUC GHG emissions:

- ✓ *Land intensification vs. extensification*
  - *Crop yields: existing cropland vs. new cropland; global yield differences and potentials*
  - *Double cropping on existing land*
  - *Extension to new land types: cropland, grassland, forestland, wetland, etc.*
- ✓ *Price elasticities*
  - *Crop yield response to price*
  - *Food demand response to price*
- ✓ *Soil organic carbon changes from land conversions and land management*



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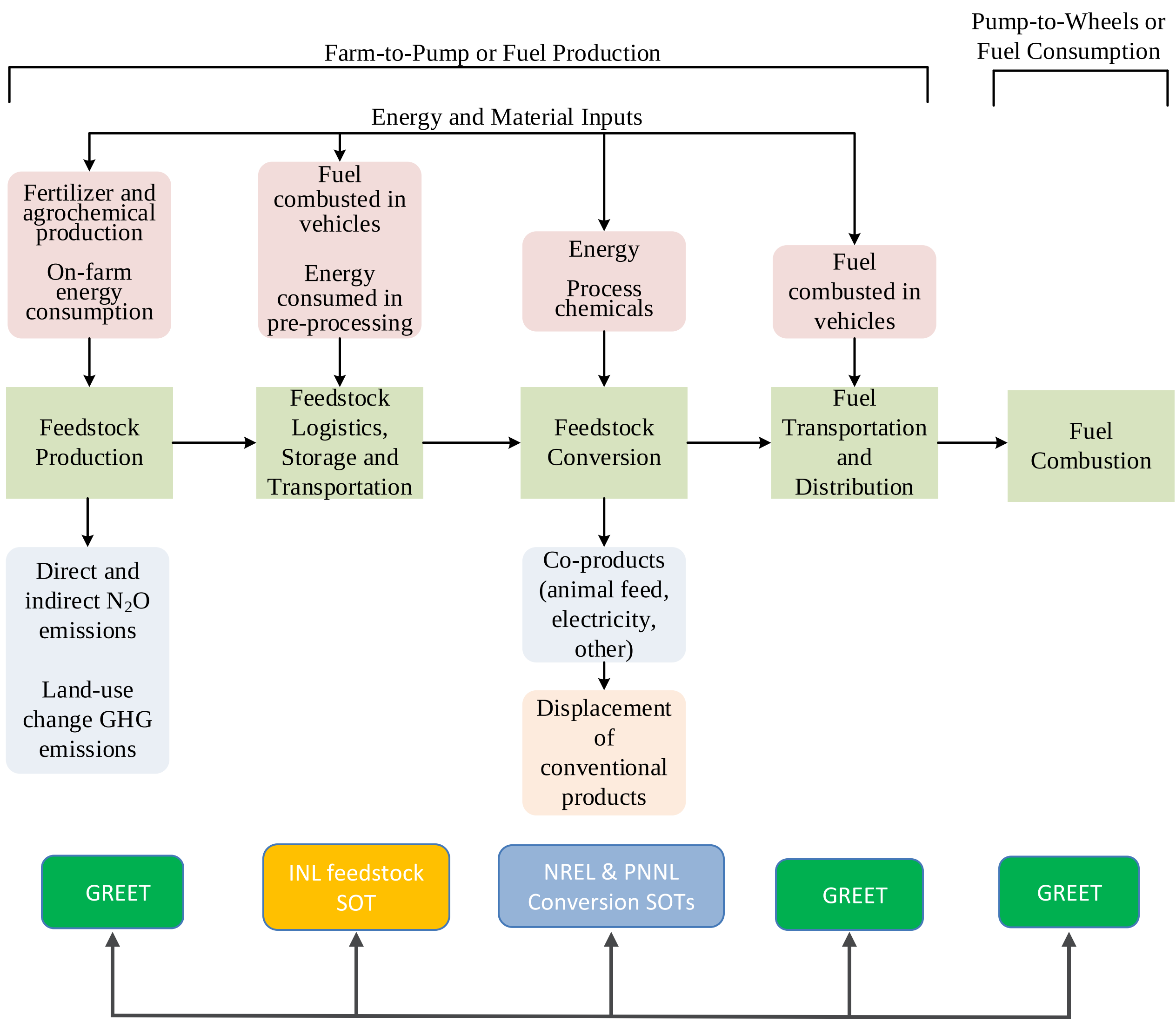
3.4: BETO Supply Chain Sustainability Analysis (SCSA) with Other Labs

SCSA of Priority Fuel Pathways Was Conducted Using GREET in Collaboration with Other Labs

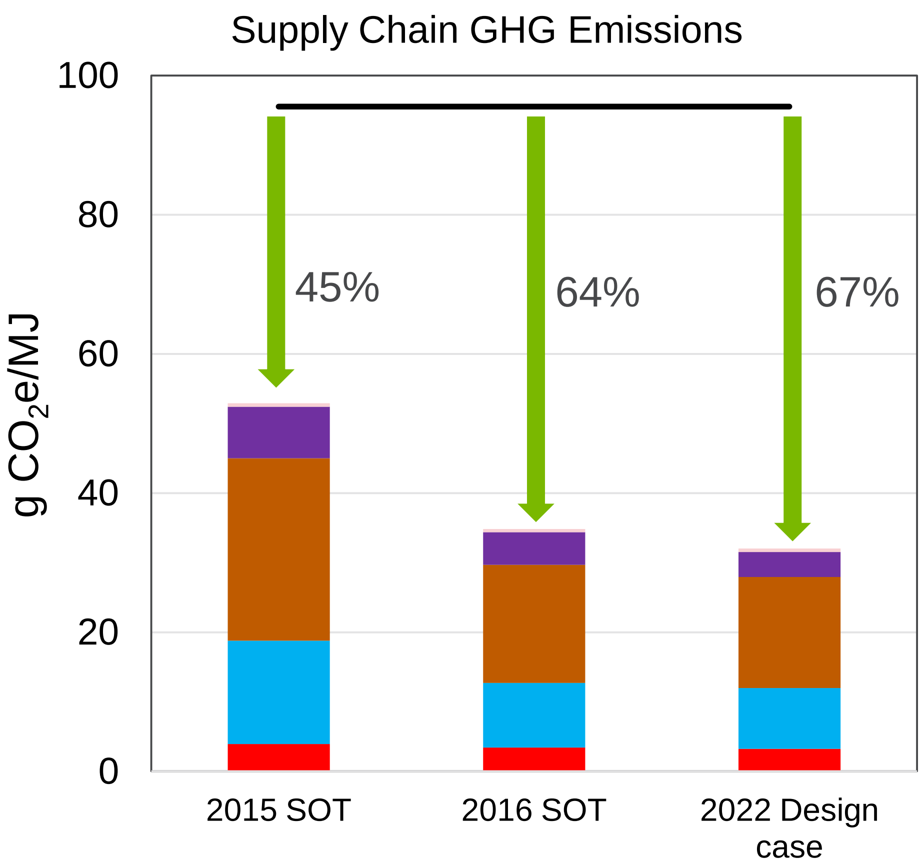


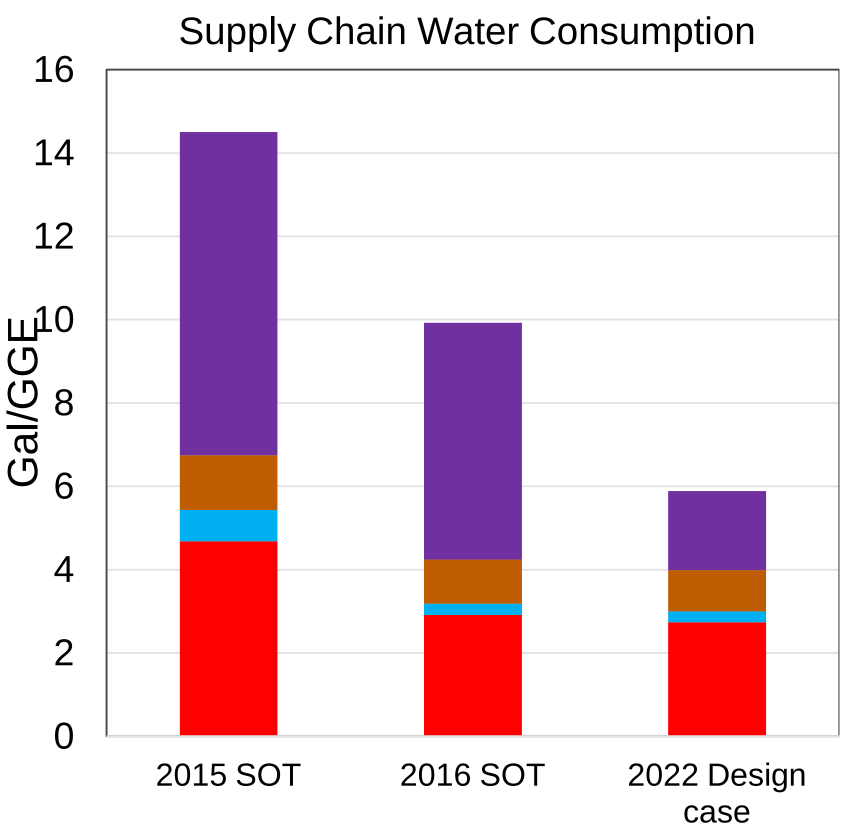
FY16 SCSA includes:

- Gasoline via indirect liquefaction
- Renewable gasoline from fast pyrolysis
- Renewable diesel from algae hydrothermal liquefaction (HTL)
- Renewable diesel from biological conversion of sugars

SCSA of New SOT Cases Informs Environmental Effects of Technology Progress

Gasoline via Indirect Liquefaction





- Feedstock Production
- Feedstock Landing Preprocessing and Handling
- Feedstock Preprocessing
- Fuel Production and Transportation
- Net Fuel Combustion
- Petroleum Gasoline

3.5: Contribution to BT16 Volume 2 Sustainability Report

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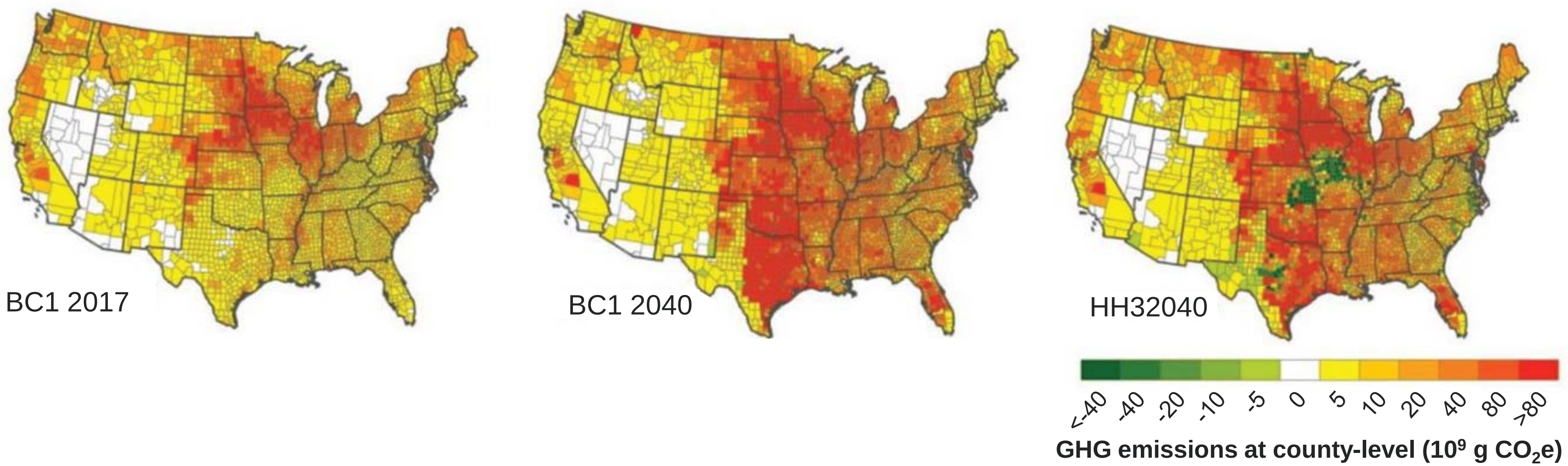
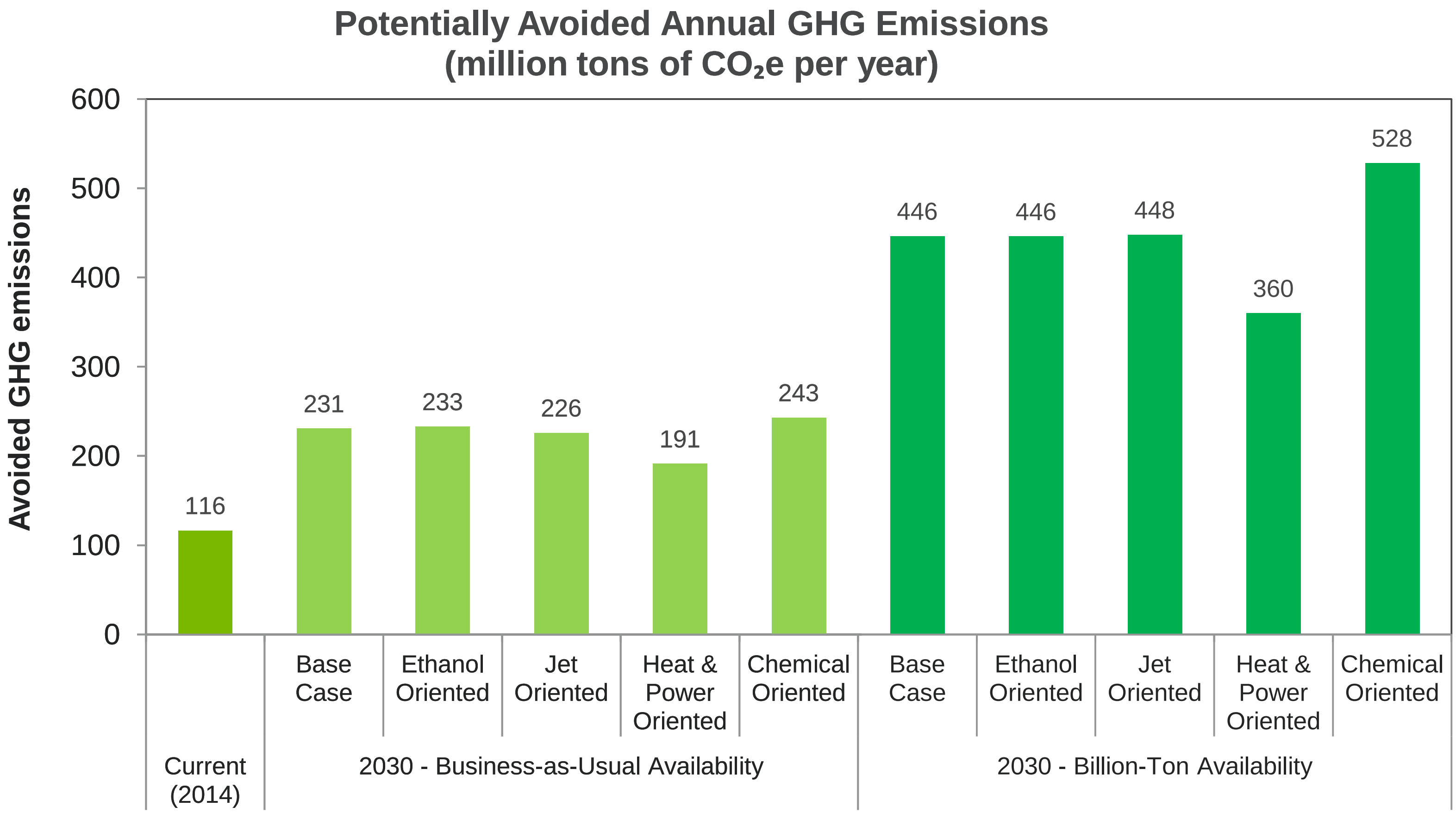
County-Level GHGs Are Driven by the Amount of Biomass Produced and Resulted SOC Change



- As expected, increased biomass farming activities results in feedstock GHG emissions
- But, some locations can be net carbon sinks due to land conversions to energy crops (predominately *Miscanthus*)
- Moreover, replacement of conventional fuels and chemicals by those from the biomass feedstocks will result in large, net GHG reductions

Billion-Ton Bioeconomy Could Offer Up to 530 Million Tons of GHG Reduction, 9% of Total US GHGs

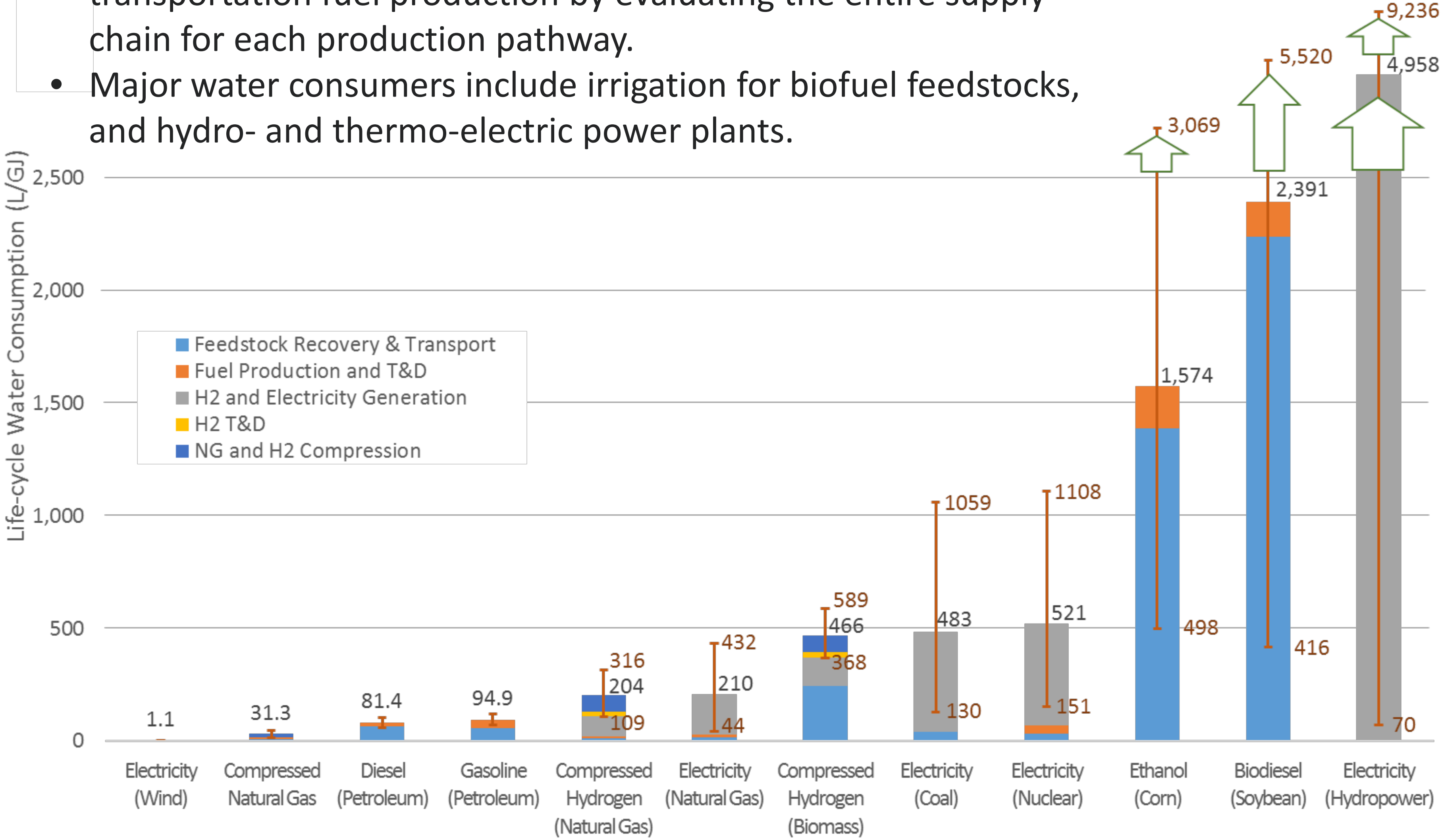
Benefits analysis was conducted with Bioeconomy AGE (Air emissions, Greenhouse gas emissions, and Energy consumption), a GREET derivative



3.6: GREET Life-Cycle Water Consumption Results

GREET LCA Water Consumption Results (L/GJ): Irrigation for Biofuel Feedstocks Can Increase Water Use

- Water LCA accounts for life-cycle freshwater consumption of transportation fuel production by evaluating the entire supply chain for each production pathway.
- Major water consumers include irrigation for biofuel feedstocks, and hydro- and thermo-electric power plants.



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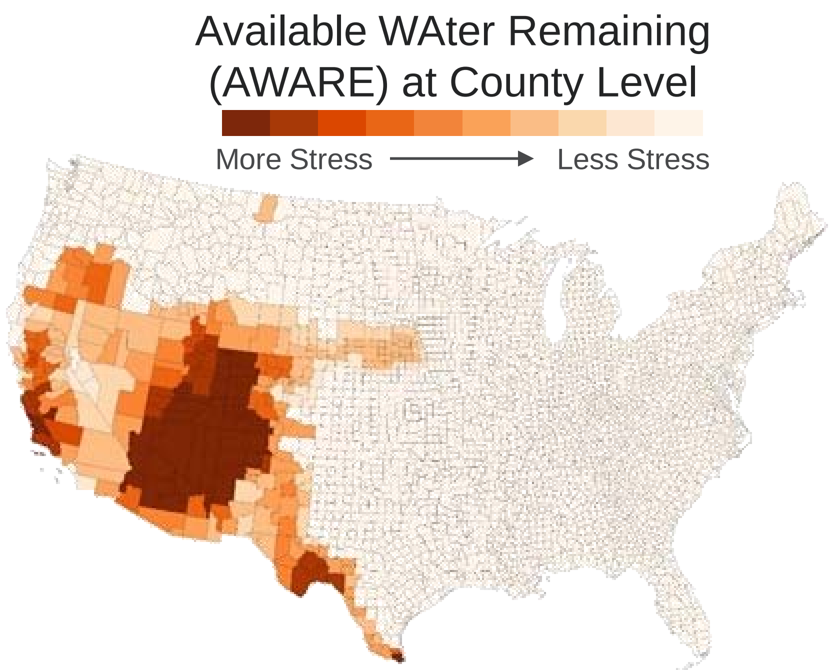
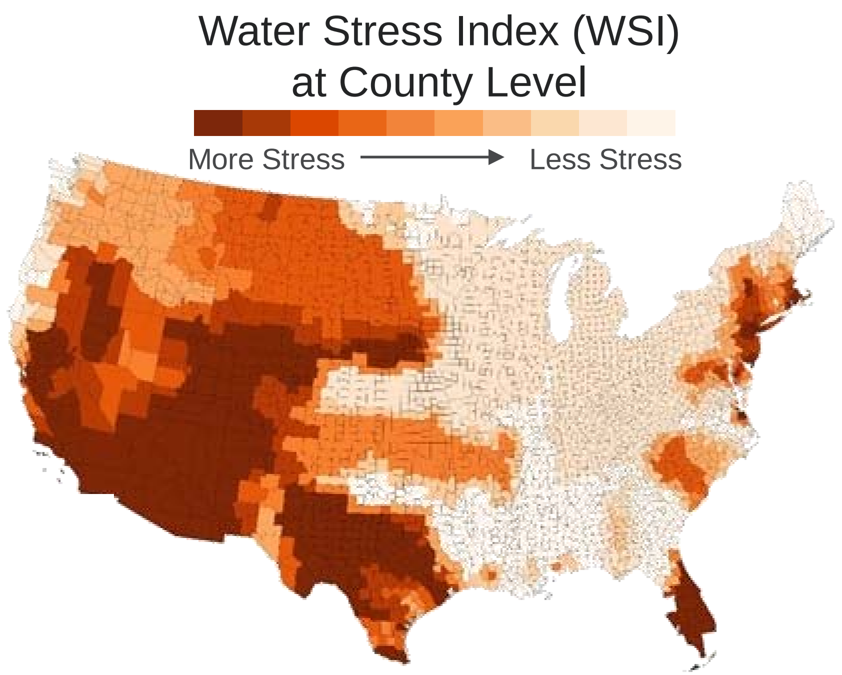
Regional Impact Analysis of Water Consumption Using Water-Stress Index

- The impact of water consumption varies by region due to significant differences in water availability by region
- Water footprint is addressed by ANL in a separate effort
- Regional water stress analysis:
  - Address regional relative impacts
  - Is based on GREET water LCA and ANL water footprint

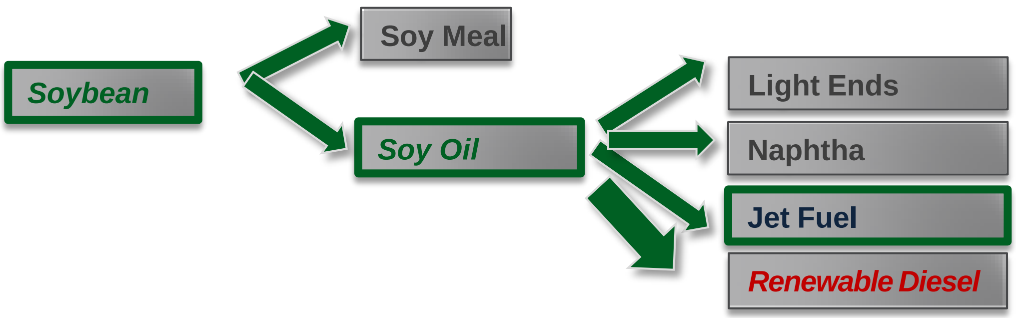




3.7: Co-Feedstocks and Co-Product Situations for Biofuel LCA:

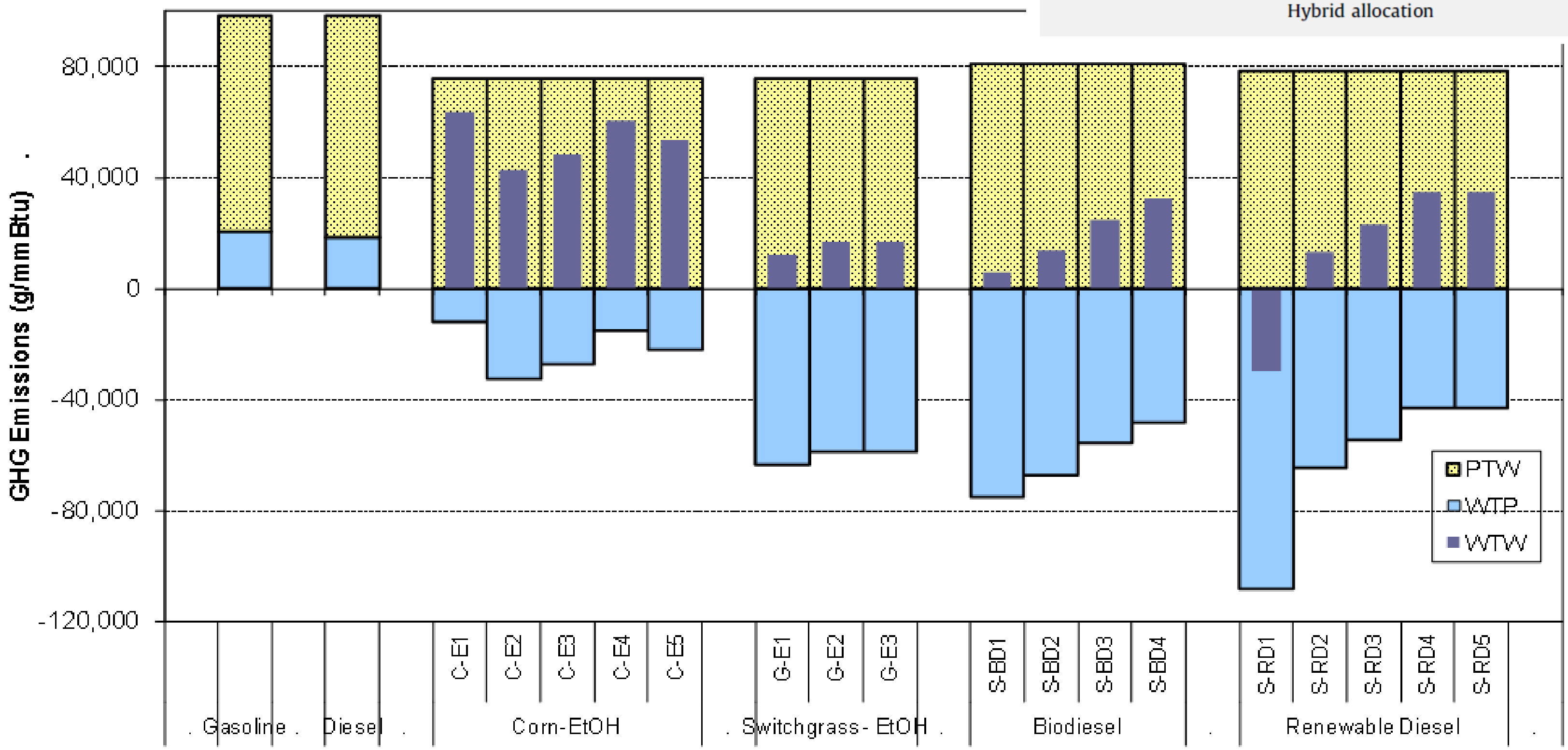
Corn Grain/Stover for EtOH; Corn Starch/Corn oil for EtOH/Biodiesel

Choice of Co-Product Methods Can Have Significant LCA Effects



Biofuel production pathways and co-product methods included in this Study.

Biofuel Pathway	Method of Dealing with Multiple Products	Case Number
Corn to ethanol	Displacement	C-E1
	Mass	C-E2
	Energy content	C-E3
	Market value	C-E4
	Process purpose	C-E5
Switchgrass to ethanol	Displacement	G-E1
	Energy content	G-E2
	Market value	G-E3
Soybeans to biodiesel	Displacement	S-BD1
	Mass	S-BD2
	Energy content	S-BD3
	Market value	S-BD4
Soybeans to renewable diesel	Displacement	S-RD1
	Mass	S-RD2
	Energy content	S-RD3
	Market value	S-RD4
	Hybrid allocation	S-RD5



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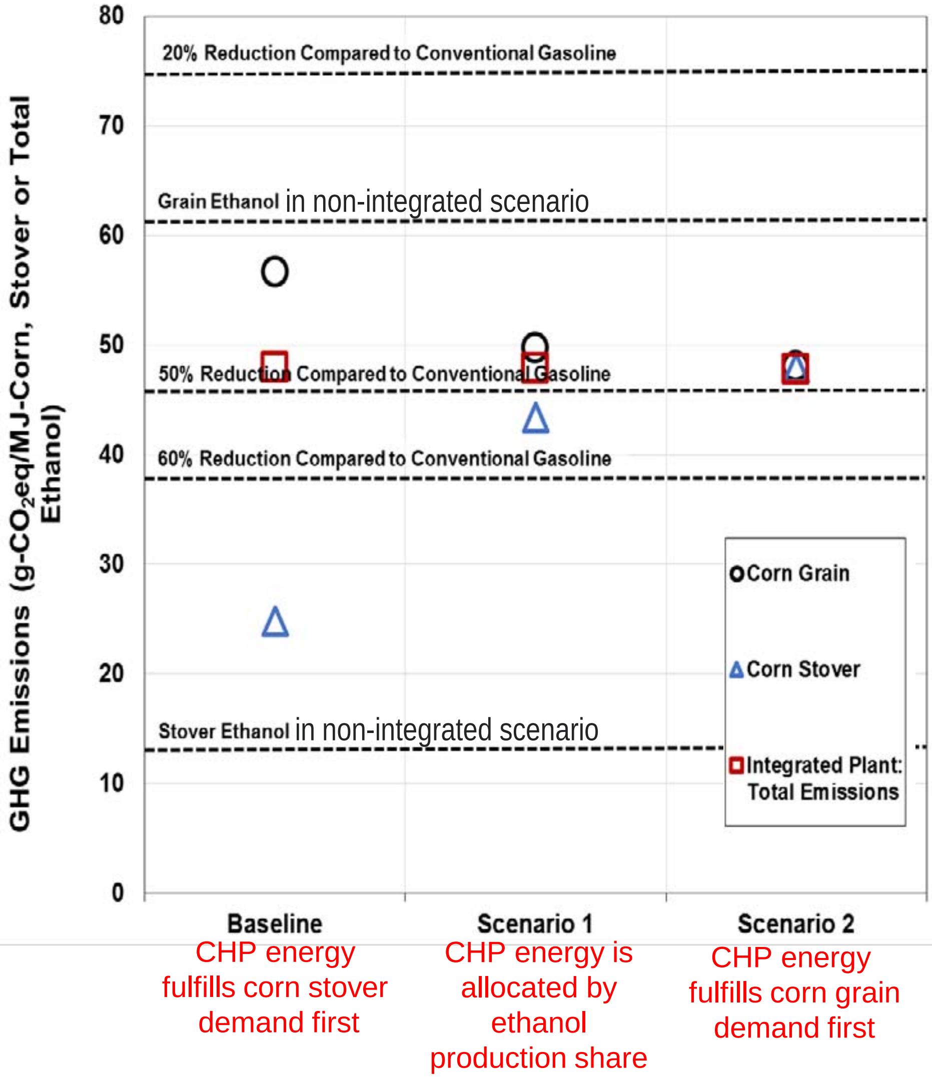
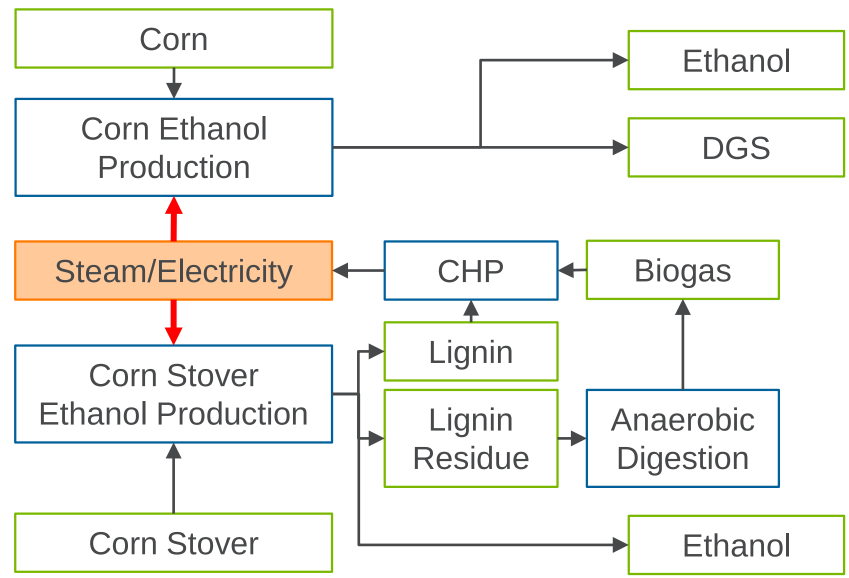
Integrated Production of Ethanol from Corn Grain and Stover Can Further Reduce GHG Emissions

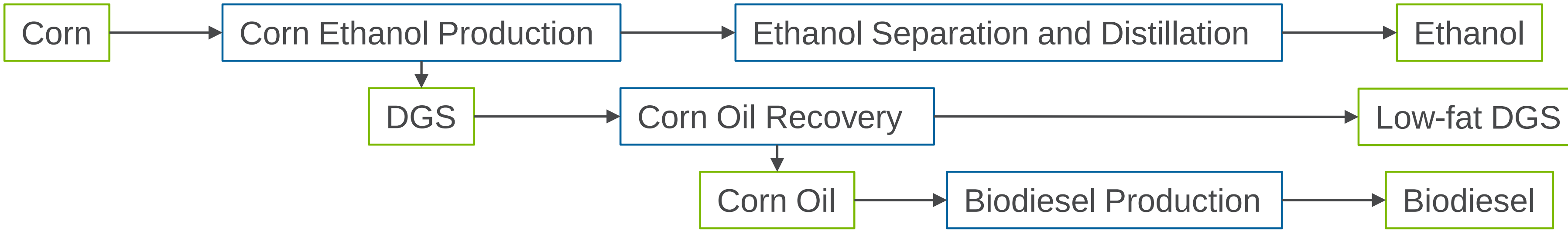
Net GHG emissions for corn grain and stover ethanol for baseline and two alternative CHP usage scenarios

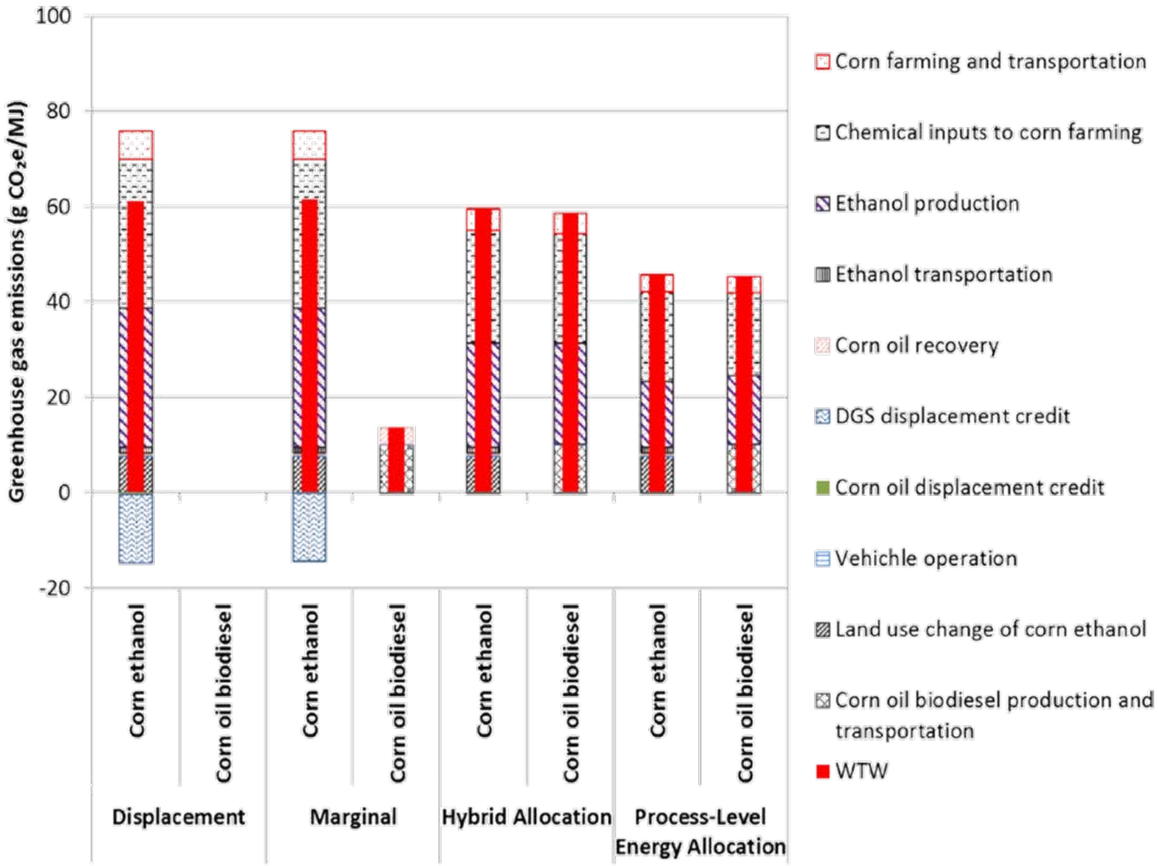




- GHG results of the integrated grain/stover ethanol have near 50% reduction
- If corn ethanol and stover ethanol are evaluated separately, treatment of allocation between the two types strongly affects results

GREET Was Expanded to Consider Co-Production of Ethanol and Biodiesel from Corn Grain





Four GREET Scenarios

- **Displacement**: corn oil-based biodiesel displaces soy biodiesel
- **Marginal**: only energy consumed for corn oil recovery is allocated to corn oil biodiesel
- **Hybrid Allocation**: market value allocation between DGS and ethanol+corn oil; energy allocation between ethanol and biodiesel
- **Process-Level Energy Allocation**: corn oil shares energy burden of corn ethanol production with ethanol and DGS

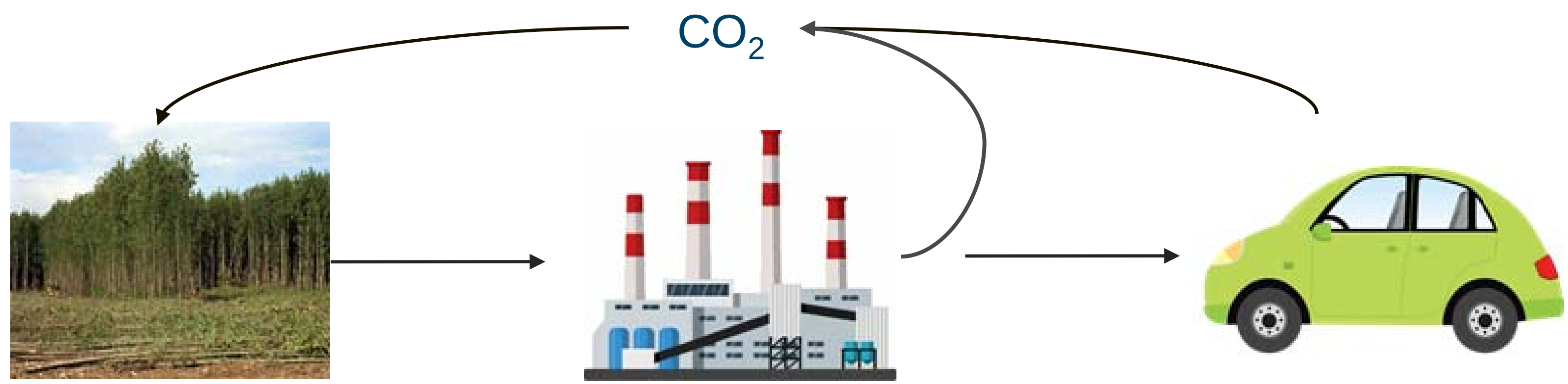
The co-product treatment method has a large effect on the GHGs of corn ethanol and corn oil biodiesel

3.8: Modeling of Woody Feedstock Growth and Carbon Dynamics for GREET LCA – a collaboration with CORRIM

GREET LCA for woody feedstocks is benefited from CORRIM

- ***Deep expertise in forest growth and management***
- ***Detailed analysis of composition of different woody feedstocks***
- ***Process modeling efforts for woody feedstocks to biofuels***

Long Time Between Planting and Harvest Results in Slower Carbon Uptake Compared with Annual Crops

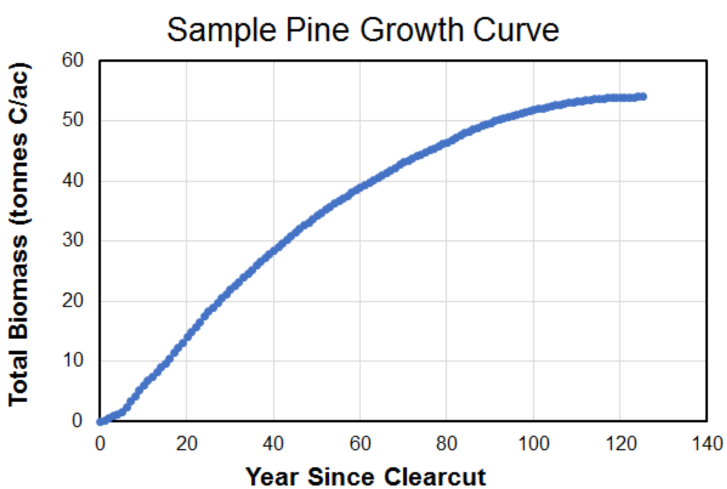


Trees uptake and store atmospheric carbon

Carbon cycle is slower than annual crops

Woody feedstock converted to a transportation fuel

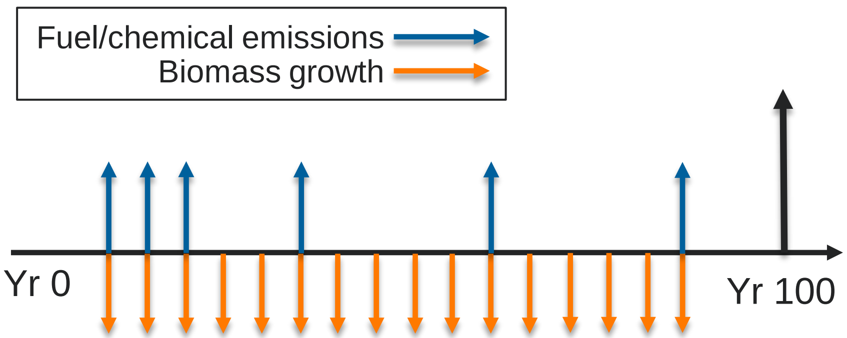
Vehicles combust fuel and emit CO_2

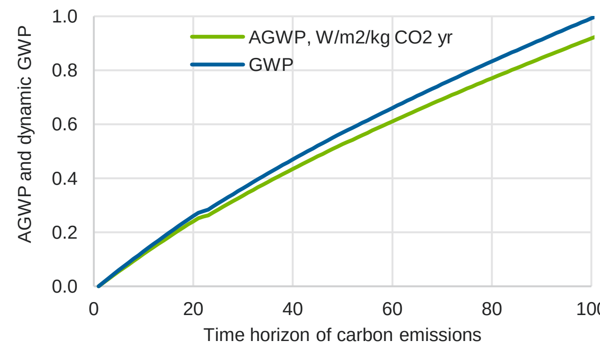


- The growth curve highlights how long it can take to reach pre-harvest carbon levels.
- Specific growth curves are dependent on tree species, growth management regime, and other local conditions (climate, soil, etc.).

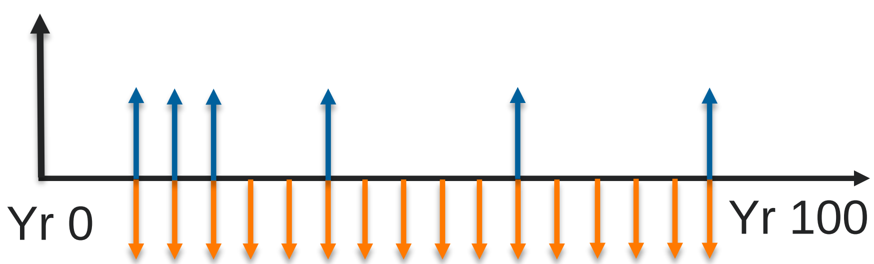
Two Carbon Accounting Methods Were Considered to Address the Temporal Carbon Dynamics

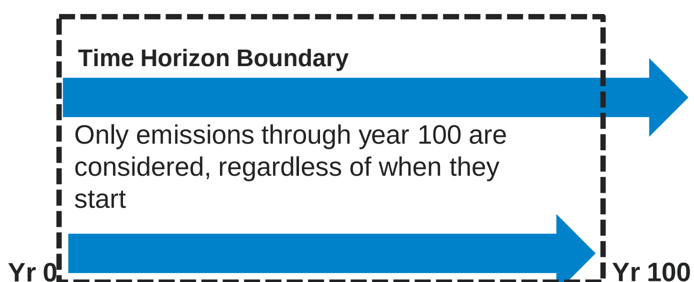
Accounting Method 1 – Cumulative effects of CO_2 over the growth/harvest Cycle (e.g., 100 yrs) using the time dependent GWP to address warming effect at Yr 100)





Accounting Method 2 – "Net present emissions" over the growth/harvest cycle (e.g., 100 yrs) by discounting emissions with 2% rate based on annual atmospheric decay rate of CO_2





Both methods have shortfalls:

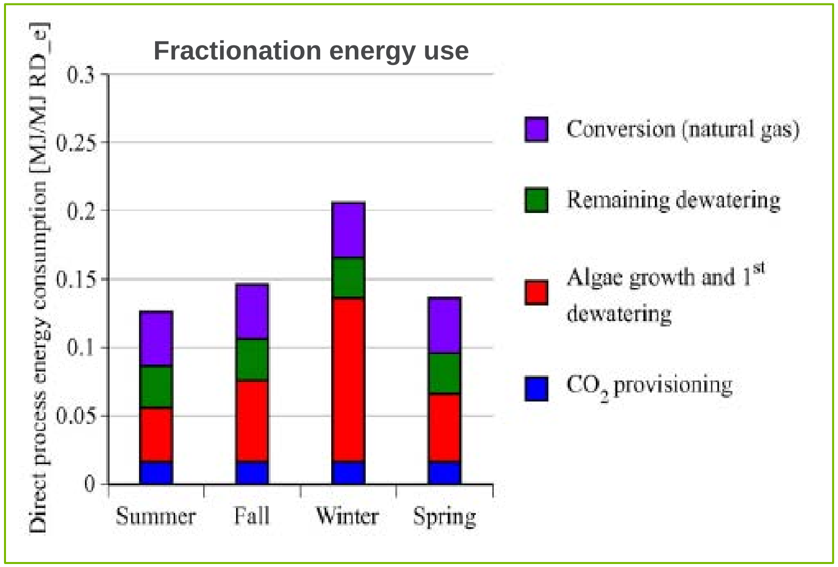
- Even though warming effects continues over long time, Method 1 stops the effect arbitrarily at Yr 100 of the growth/harvest cycle
- Discounting of emissions in Method 2 has no relation to warming effects

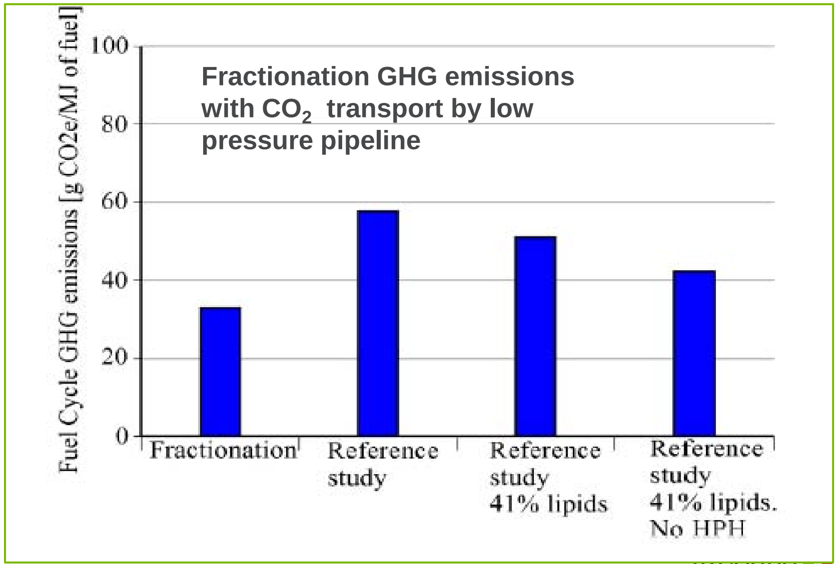
3.9: Expanded Algae LCA for Various Production Scenarios

Algal Fuel Pathway LCA Was an Integral Part of BETO Algae Analysis (1)

Objectives
- Quantify energy use, water consumption and GHG emissions
- Provide sustainability constraint indication for economic and resource assessment
- Provide R&D guidance to BETO

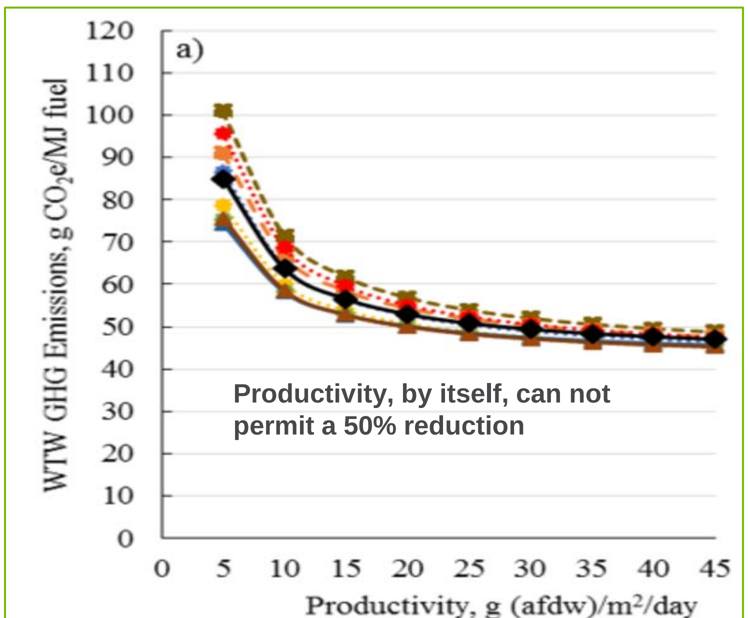
Activities (FY15)	Outcomes
Algal fractionation process	Fractionation increases fuel yield while achieving lower GHG and energy performance than reference study with CO_2 transported by low pressure pipeline.
LCA of an expanded ensemble of sites	* Algal sites utilized forest and land may not be "marginal" * Need for direct land use change evaluation * Need to update resource assessment selection criteria
Material transport during algae growth and processing	Well-planned algae site layout and material conveyance system are necessary for sustainable algal biofuel production
PBR systems	LCA guided project prioritization and experimental work plan

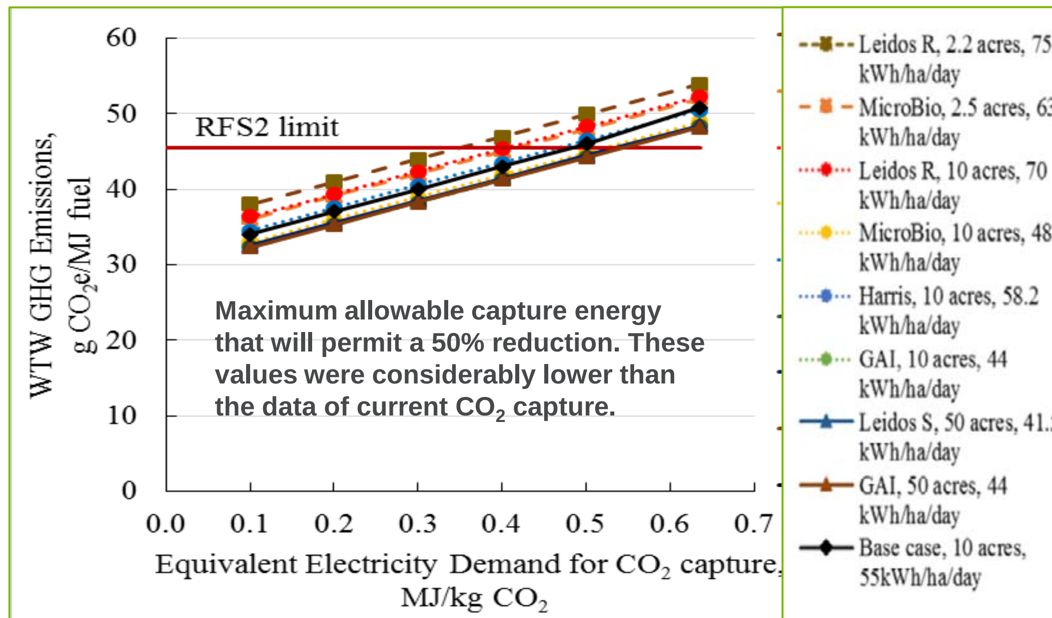




Algal Fuel Pathway LCA Was an Integral Part of BETO Algae Analysis (2)

Activities (FY16)	Outcomes
Algal biofuel with coproducts	Identified large co-product method uncertainties because fuel is not dominant product. Need to identify market capacity for coproducts
Energy, GHGs, and water in 2016 MYPP algal biofuel scenarios	Burdens from CO_2 capture are problematic. Second generation CO_2 capture systems may still be so
LCA of algal biomass production – “farm report”	Biomass productivity, mixing energy, and CO_2 supply need to be improved
PBR algae production; LCA/RA/TEA harmonization	Ongoing





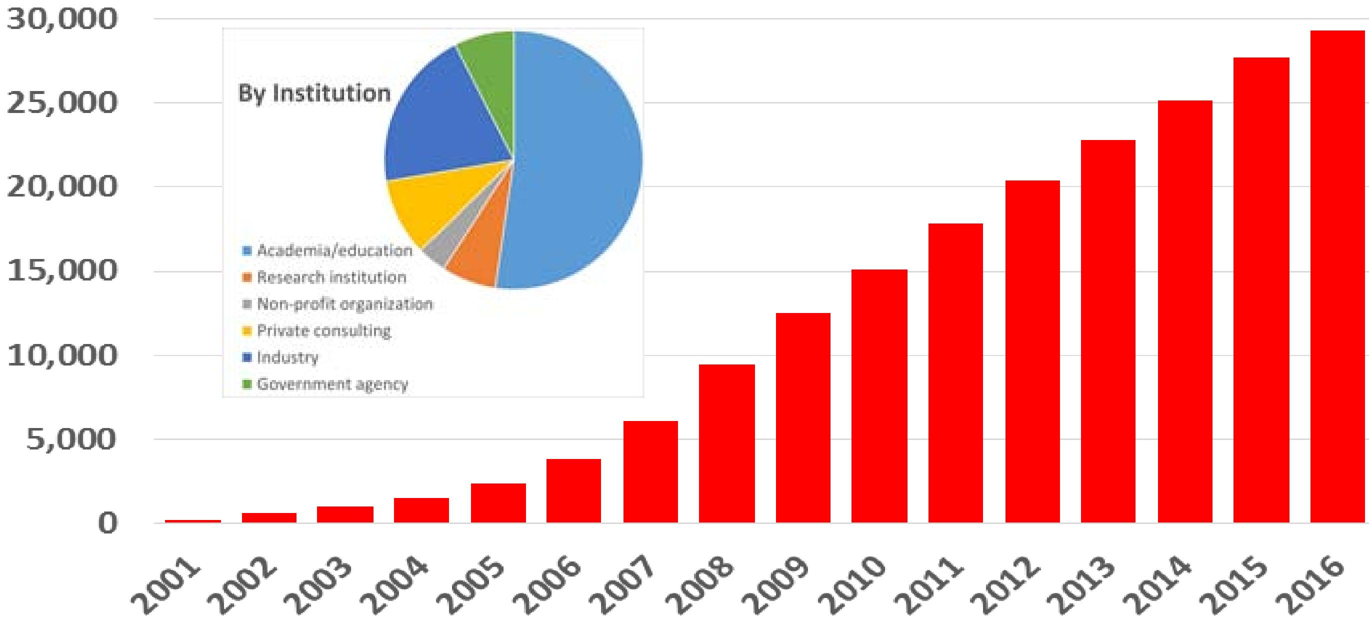
Relevance of GREET Development and Applications (1)

- The goal of this project is to develop an LCA model that supports BETO Analysis and Sustainability by quantifying energy and environmental impacts of biofuels
- To cover the supply chain from feedstock to fuel use to inform BETO and bioenergy community R&D
  - GREET provides a platform to integrate life cycle stages of biofuel pathways to address their overall energy and environmental benefits
- Sustainability criteria are critical for BETO and bioenergy community in R&D evaluation
  - GREET LCA quantifies and clarifies the energy security, GHG, air pollutant, and water consumption effects of biofuels and conventional fuels
  - Inclusion of the complete supply chain by GREET helps identify adverse environmental hot spots and develop mitigation measures

Relevance of GREET Development and Applications (2)

- GREET is an integral part of BETO mission
  - Develop a consistent model to advance understanding of biofuel sustainability
  - Produce high-quality, consistent, peer-reviewed analyses/publications
  - Outreach and engage agencies and stakeholders with LCA results to promote clean, efficient biofuels and biofuel production
- Sustaining program funding to GREET by BETO (and other EERE programs) results in an open, transparent LCA tool for consistent comparisons among biofuel options and with other non-biofuel options
- The biofuel community benefits from the availability of this free platform which they use to help their R&D as well as to assess carbon intensity scores of their products under regulations such as CARB LCFS and EPA RFS2.

Relevance: There Are Nearly 30,000 Registered GREET Users Globally



- ***GREET2015 and GREET2016 release in Oct. of each year***
- ***GREET user workshop conducted in Oct. 2015***

Relevance: Key GREET Application Examples

- CA-GREET2.0 from ANL GREET
- RFS2 relied partially on GREET
- FAA and ICAO AFTF
- Recent USDA ethanol report on retrospective GHG emissions effects of RFS2
- US DRIVE Cradle-to-Grave (C2G) report (June 2016)
- On-going US DRIVE FWG project
- National Petroleum Council study
- National Research Council study
- EERE Program Records

Future Work: GREET Model Development

- Address biomass additionality and carbon neutrality in biofuel LCA GHG analysis
- Thoroughly analyze biomass growth and carbon dynamics of forest feedstocks for bioenergy and counterfactual scenarios
- Continue to address farming management practices and their impacts on SOC for biofuel feedstocks
- Continue to expand key GREET modules and GREET functionalities
- Continue to monitor and expand emerging biofuel conversion technologies
- Regionalization of GREET WTW analyses:
  - Criteria pollutants
  - Water stress assessment (e.g., algae biofuel production)

Future Work: GREET LCA Applications

- Continue to carry out SCSA for BETO priority SOT pathways
- LCA of co-feeding of bio-crude in conventional refineries
- LCA of competing scenarios of resource utilization for fuel, power, and biochemicals production
- Continue to extend LCA for different algal cultivation and fuel processing pathways to provide R&D guidance to BETO and community
- LCA of biomass systems designed to reduce agriculture nutrient runoff
- Harmonize co-product methodologies between LCA and TEA with other labs
- Develop a tool with NREL to guide biofuel process catalyst design by considering cost and environmental impacts
- Interact with other agencies
  - Core LCA values for selected bio-jet pathways for ICAO AFTF
  - Work with FAA and Commercial Aviation Alternative Fuels Initiative (CAAFI) to address aviation fuel GHG intensities
  - Interact with CARB for LCFS3.0 GREET version
  - USDRIVE Integrated Systems Analysis Tech Team (ISATT) and FWG WTW analyses

Summary

- GREET is a widely-accepted LCA tool that evaluates the energy and environmental effects of biofuels
  - System-level analysis capacity
  - A resource with accessible critical data for biofuel analysis
- GREET-based LCAs of biofuels help
  - Overcome lack of comparable, transparent, and reproducible analysis
  - Address energy and environmental benefits of biofuels systematically so that community can approach consensus on pursuing clean, efficient biofuels and biofuel production
- Outcomes of GREET LCAs
  - Agencies use GREET results to develop policies that promote biofuel technologies and their deployment
  - BETO uses GREET results to select biofuel technology options in R&D decisions
  - Biofuel producers and tech developers used GREET results to improve process energy efficiencies to achieve low carbon footprint for biofuels
  - Biofuel LCAs with GREET have helped advance understanding of critical LCA issues
- Future work aims to address the most critical issues in biofuel sustainability analysis and to continue to assist BETO and community in assessment of technology options for sustainable biofuel production from farm to wheels

Additional slides

Responses to Previous Reviewers' Comments

Reviewer Comment	ANL Response
A threat to the project is scope creep as more and more metrics and pathways are added to the model. This requires the researchers to be able to prioritize and focus on the most critical issues.	The reviewers raised concerns that as the GREET model grows in scope and complexity, transparency may be compromised and the model could become unwieldy. We have had the same concern over the past five years and thank the reviewers for these comments to remind us the importance of transparency. As Argonne's LCA research efforts continue to expand its research scope, we have taken several steps to maintain transparency and ease of use for the GREET LCA model. First, data sources, methodology, and assumptions that underpin the data within GREET are documented in technical reports and journal articles that are peer reviewed and maintained on the GREET website. In the GREET.net platform, as pathways are added to GREET, the model is annotated with the report or article URL such that it is easily located. Second, the availability of the Excel platform enables users to see deep into the model and access the raw data and formulae. Third, complex LCA issues such as land use change (LUC) are addressed in a standalone module in GREET so that users can readily follow the analytic steps to address LUCs and deeply dive into critical issues affecting LUCs. Fourth, we periodically conduct GREET user workshops to demonstrate new GREET features and to seek user input. Additionally, we maintain communication channels with users and stakeholders on their priorities and their issues of understanding our LCA results and using the GREET model to refining our research approach and GREET design.
Because the model has grown in scope and complexity, there is a constant struggle between adding extra functionality and keeping it readily available to all users. I urge the team as they move to the GREET.net platform to continue to get feedback from users on how to improve it. Finally, I see the integrated use of biogas and bioproducts as key enablers of the biofuels space and applaud efforts to include these pathways.	The reviewers' encouragement to acquire user feedback and use it to adjust our approach to developing GREET.net is well taken. Besides emails directed to greet.@anl.gov, we use a web-based platform to receive feedbacks from users and to address users questions. Further, users can send emails to greet@anl.gov (our email hotline to address GREET questions and issues) requesting assistance providing feedbacks. In fact, GREET user feedbacks have been critical in our design of GREET new features and functionalities. We had a GREET user workshop in Oct. 2015 (as we had had in the past) to demonstrate GREET features and seek user inputs. Overall, we thank the reviewers for their acknowledgement of the project's progress since the last review and their support of our plans for future work.
GREET serves as a foundation of numerous projects and analyses. Its acceptance and use by the LCA community at large shows the relevance and impact the tool has had. It currently serves as an enabler of policies such as the Renewable Fuel Standard and Low Carbon Fuel Standard where assessing the greenhouse gas benefits of the various new fuel pathways is critical to the mandates. Great progress has been made since the last review. The expansion of GREET to include water consumption, black carbon emissions, and algal pathways was critical. Also, adding the ability to look at co-products and biochemicals/bioproducts will be important as we move to a more integrated biorefinery approach in the future. Data is the key and a rigorous attention to detail has made the model the success it has become. Efforts should be taken to ensure that the model's continued growth in scope and complexity does not come at the expense of transparency and utility. Another key to the success and impact of GREET is that it is open for public use.	The reviewers raised these important concerns multiple times in their comments. We share these concerns that the GREET model grows in scope and complexity, transparency may be compromised and the model could become unwieldy. As we responded in Section 2 (Project Approach), we take several steps to maintain transparency. First, data sources, methodology, and assumptions that underpin the data within GREET are documented in technical reports and journal articles that are peer reviewed and maintained on the GREET website. In the GREET.net platform, as pathways are added to GREET, the model is annotated with the report or article URL such that it is easily located. Second, the availability of the Excel platform enables users to see deep into the model and access the raw data and formulae. Third, complex LCA issues such as land use change (LUC) are addressed in a standalone module in GREET so that users can readily follow the analytic steps to address LUCs and deeply dive into critical issues affecting LUCs. Fourth, we periodically conduct GREET user workshops to demonstrate new GREET features and to seek user input. Additionally, we maintain communication channels with users and stakeholders on their priorities and their issues of understanding our LCA results and using the GREET model to refining our research approach and GREET design. Reviewers raised a concern that not all aspects of biofuel LCA could or should be analyzed in GREET. While we understand this concern, we have approached tis somewhat differently. As the biofuel community has observed, some researchers have raised and analyzed some additional issues that the biofuel community did not. These have changed biofuel sustainability debate considerably. From these experiences, we decided to address some emerging LCA issues proactively. In some cases, our LCA research shows that certain issues are not important and some issues are too uncertain to determine biofuel sustainability. We often get into detailed issues in order to shed light of their impacts on LCA results. For example, in the context of analyzing soil organic carbon, we collaborate with subject matter experts at the University of Illinois at Champaign Urbana. Further, to maintain its LCA focus, we keep some elements of our analysis outside GREET, such as the economy-level analysis which is conducted in a new tool called Bioeconomy AGE that uses GREET and other data sources. Also, we maintain open lines of communication with BETO to identify gaps in the field of biofuel LCA and the role the GREET project team should have in addressing that gap versus other researchers internal or external to the BETO portfolio. We will stay mindful of excessive scope expansion and will target high-impact areas for research. Finally, reviewers encouraged increased stakeholder engagement and peer review with federal agencies (EPA, USDA, DOD, DOT, etc.) and state agencies. We will strive to maintain and increase these interactions with the aim of receiving feedback on existing analyses and input as to future direction in model development and research. As we stated above, we will have a GREET user workshop in the summer of 2015 to demonstrate new GREET features and seek user inputs.

Publications: Selected Peer Reviewed Journal Articles

- Benavides, PT, D Cronauer, F Adom, Z Wang, and JB Dunn. **2017**. "The Influence of Catalysts on Biofuel Life Cycle Analysis (LCA)." *Sustainable Materials and Technologies*, Accepted.
- Yeh, S, A Ghandi, BR Scanlon, AR Brandt, H Cai, MQ Wang, K Vafi, and RC Reedy. **2017**. "Energy Intensity and Greenhouse Gas Emissions from Oil Production in the Eagle Ford Shale." *Energy & Fuels*, Available Online.
- Dunn, J, D Merz, KL Copenhaver, and S Mueller. **2017**. "Measured Extent of Agricultural Expansion Depends on Analysis Technique." *Biofuels, Bioproducts, and Biorefining*, Available Online.
- Emery, I, S Mueller, Z Qin, and JB Dunn. **2017**. "Evaluating the Potential of Marginal Land for Cellulosic Feedstock Production and Carbon Sequestration in the United States." *Environmental Science & Technology* 51 (1): 733–41.
- Han, J, L Tao, and M Wang. **2017**. "Well-to-Wake Analysis of Ethanol-to-Jet and Sugar-to-Jet Pathways." *Biotechnology for Biofuels* 10: 21.
- Rogers, JN, B Stokes, J Dunn, H Cai, M Wu, Z Haq, and H Baumes. **2017**. "An Assessment of the Potential Products and Economic and Environmental Impacts Resulting from a Billion Ton Bioeconomy." *Biofuels, Bioproducts and Biorefining* 11 (1): 110–28.
- Adom, F, and JB Dunn. **2016**. "Life Cycle Analysis of Corn-Stover-Derived Polymer-Grade L-Lactic Acid and Ethyl Lactate: Greenhouse Gas Emissions and Fossil Energy Consumption." *Biofuels, Bioproducts and Biorefining*.
- Brandt, AR, T Yeskoo, MS McNally, K Vafi, S Yeh, H Cai, and MQ Wang. **2016**. "Energy Intensity and Greenhouse Gas Emissions from Tight Oil Production in the Bakken Formation." *Energy & Fuels* 30 (11): 9613–21.
- Cai, H, J Wang, Y Feng, M Wang, Z Qin, and JB Dunn. **2016**. "Consideration of Land Use Change-Induced Surface Albedo Effects in Life-Cycle Analysis of Biofuels." *Energy & Environmental Science* 9 (9): 2855–67.
- Lampert, D, H Cai, and A Elgowainy. **2016**. "Wells to Wheels: Water Consumption for Transportation Fuels in the United States." *Energy & Environmental Science* 9 (3): 787–802.
- Pegallapati, AK, and ED Frank. **2016**. "Energy Use and Greenhouse Gas Emissions from an Algae Fractionation Process for Producing Renewable Diesel." Algal Research 18 (September): 235–40.
- Qin, Z, JB Dunn, H Kwon, S Mueller, and M Wander. **2016**. "Soil Carbon Sequestration and Land Use Change Associated with Biofuel Production: Empirical Evidence." *GCB Bioenergy* 8 (1): 66–80.
- Qin, Z, JB Dunn, H Kwon, S Mueller, and M Wander. **2016**. "Influence of Spatially Dependent, Modeled Soil Carbon Emission Factors on Life-Cycle Greenhouse Gas Emissions of Corn and Cellulosic Ethanol." *GCB Bioenergy* 8: 1136–1149.
- Cai, H, AR Brandt, S Yeh, JG Englander, J Han, A Elgowainy, and MQ Wang. **2015**. "Well-to-Wheels Greenhouse Gas Emissions of Canadian Oil Sands Products: Implications for U.S. Petroleum Fuels." Environmental Science & Technology 49 (13): 8219–8227.
- Canter, CE, JB Dunn, J Han, Z Wang, and M Wang. **2015**. "Policy Implications of Allocation Methods in the Life Cycle Analysis of Integrated Corn and Corn Stover Ethanol Production." *BioEnergy Research* 9 (1): 77–87.
- Han, J, GS Forman, A Elgowainy, H Cai, M Wang, and VB DiVita. **2015**. "A Comparative Assessment of Resource Efficiency in Petroleum Refining." *Fuel* 157: 292–98.
- Cai, H, and MQ Wang. **2014**. "Consideration of Black Carbon and Primary Organic Carbon Emissions in Life-Cycle Analysis of Greenhouse Gas Emissions of Vehicle Systems and Fuels." *Environmental Science & Technology* 48 (20): 12445–53.

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Publications: Selected Technical Reports

- Canter CE, Z Qin, H Cai, JB Dunn, M Wang, DA Scott. **2017**. "04-Fossil Energy Consumption and Greenhouse Gas Emissions, Including Soil Carbon Effects, of Producing Agriculture and Forestry Feedstocks." Chapter In "2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1." RA Efroymson, MH Langholtz, KE Johnson, and BJ Stokes (Eds.), ORNL/TM-2016/727
- Adom, F, H Cai, JB Dunn, DS Hartley, EM Searcy, E Tan, S Jones, and LJ Snowden-Swan. **2016**. "Supply Chain Sustainability Analysis of Fast Pyrolysis and Hydrotreating Bio-Oil to Produce Hydrocarbon Fuels." ANL/ESD-15/2 Rev. 1.
- Cai, H, CE Canter, JB Dunn, E Tan, MJ Biddy, M Talmadge, DS Hartley, and LJ Snowden-Swan. **2016**. "Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline." ANL/ESD-15/24 Rev.1.
- Dunn, J, Z Qin, S Mueller, H Kwon, M Wander, and M Wang. **2016**. "Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) - Users' Manual and Technical Documentation." ANL/ESD/12-5. Rev.3.
- Elgowainy, A, J Han, J Ward, F Joseck, D Gohlke, A Lindauer, T Ramsden, et al. **2016**. "Cradle-to-Grave Lifecycle Analysis of U.S. Light Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies." ANL/ESD-16/7.
- Frank, E, AK Pegallapati, RE Davis, J Markham, A Coleman, SB Jones, M Wigmosta, and Y Zhu. **2016**. "Life-Cycle Analysis of Energy Use, Greenhouse Gas Emissions, and Water Consumption in the 2016 MYPP Algal Biofuel Scenarios." ANL/ESD-16/11.
- Han, J, M Wang, A Elgowainy, and V DiVita. **2016**. "Well-to-Wheels Greenhouse Gas Emission Analysis of High-Octane Fuels with Ethanol Blending: Phase II Analysis with Refinery Investment Options." ANL/ESD--16/9.
- Lee, U, J Han, M Urgun-Demirtas, M Wang, and L Tao. **2016**. "Lifecycle Analysis of Renewable Natural Gas and Hydrocarbon Fuels from Wastewater Treatment Plant's Sludge." ANL/ESD-16/19.
- Lee, U, J Han, and M Wang. **2016**. "Well-to-Wheels Analysis of Compressed Natural Gas and Ethanol from Municipal Solid Waste." ANL/ESD-16/20.
- Theiss, TJ, T Alleman, A Brooker, A Elgowainy, G Fioroni, J Han, SP Huff, et al. **2016**. "Summary of High-Octane Mid-Level Ethanol Blends Study." ORNL/TM--2016/42. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States); National Renewable Energy Lab. (NREL), Golden, CO (United States); Argonne National Lab. (ANL), Argonne, IL (United States).
- Dunn, J, F Adom, N Sather, J Han, and S Snyder. **2015**. "Life-Cycle Analysis of Bioproducts and Their Conventional Counterparts in GREET." ANL/ESD-14/9 Rev.
- Han, J, A Elgowainy, MQ Wang, and VB DiVita. **2015**. "Well-To-Wheels Analysis of High Octane Fuels with Various Market Shares and Ethanol Blending Levels." ANL/ESD-15/10.
- Pegallapati, AK, JB Dunn, ED Frank, S Jones, Y Zhu, LJ Snowden-Swan, RS Davis, and C Kinchin. **2015**. "Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading." ANL/ESD-15/8.
- Qin, Z, CE Canter, JB Dunn, S Mueller, H Kwon, J Han, M Michelle, and M Wang. **2015**. "Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production." ANL/ESD-15/26.
- Wang, Z, PT Benavides, J Dunn, and D Cronauer. **2015**. "Development of the GREET Catalyst Module." ANL/ESD-14/12 Rev.

Selected Presentations and Awards

Selected Presentations

- Cai H, F Adom, JB Dunn. **2016**. Supply Chain Sustainability Analysis of Biomass-to-Fuel Pathways via Fast Pyrolysis and Indirect Liquefaction Technologies. LCA XVI, Charleston, SC, Sep. 26-29, 2016.
- Dunn J, Z Qin, M Wang. **2016**. Estimating land-use change greenhouse gas emissions with the GREET model and its CCLUB module. Sustainability & ILUC Workshop. St. Louis, MO. Sept. 21, 2016.
- Wang M. **2016**. Alternative Jet Fuel LCA with the Greet® Model. Alternative Aviation Fuel Workshop, Macon, GA. Sep. 14-15, 2016.
- Han J. **2016**. Well-To-Wake Analysis of Ethanol-To-Jet and Sugar-To-Jet Pathways. Alternative Aviation Fuel Workshop, Macon, GA. Sep. 14-15, 2016.
- Dunn JB. **2016**. Capturing Innovation in Biofuel Life Cycle Analysis. Bioenergy 2016, Washington, D.C. Jul. 2016.
- Efroymson R, M Langholtz, K Johnson, B Stokes, Z Qin. **2016**. Investigating sustainability issues in bioenergy resource assessments: The example of the US 2016 Billion Ton Report. US-IALE 2016 Annual Meeting. Asheville, NC. Apr. 3-7, 2016
- Benavides T, D Cronauer, JB Dunn. **2016**. The Influence of Catalysts on Biofuel LCA. AIChE Midwest Conference. Chicago, IL. Mar. 3 -6, 2016
- Qin Z, J Dunn, H Kwon, S Mueller, M Wander. **2015**. Estimating soil carbon change and biofuel life-cycle greenhouse gas emissions with economic, ecosystem and life-cycle models. AGU Fall Meeting 2015. San Francisco, CA. Dec. 14-18, 2015.
- Mueller S, JB Dunn. **2015**. Soil Carbon Sequestration and Land Use Change Associated with Biofuels Production. CRC Workshop on Life Cycle Analysis of Transportation Fuels. Argonne, IL. Oct. 28, 2015.
- Qin Z. **2015**. Land use change and biofuel life cycle analysis. 2015 National Science Foundation (NSF) Food Energy Water Nexus (FEW) Workshop. Rapid City, SD. Oct. 19-20, 2015.
- Canter CE, JB Dunn, M Wang. **2015**. Key Assumptions in Life Cycle Analysis of Woody Bioenergy Feedstocks. LCA XV, Vancouver, Canada, Oct. 7, 2015.
- Han J. **2015**. Life-Cycle Analysis of Ethanol. 28th Annual American Coalition for Ethanol Conference, Omaha, NE. Aug. 21, 2015
- Dunn JB. **2015.** Biofuel Feedstock Production Influence on Soil Organic Carbon. American Society of Agricultural and Biological Engineers Annual Conference, New Orleans LA. Jul. 26-29, 2015.
- Dunn JB. **2015**. Quantitative Analysis of Biofuel Sustainability, Including Land Use Change GHG Emissions. Bioenergy 2015, Washington, D.C. Jun. 24, 2015.
- Han J. **2015**. Life-Cycle Analysis of Aviation Fuels with the GREET Model. National Research Council Low Carbon Aviation Committee Meeting, Washington, D.C. Jun 3, 2015.
- Qin Z, J Dunn, H Kwon, S Mueller, M Wander. **2015**. Sharing land with food: How will corn stover biofuel development impact soil carbon balance and imply life cycle greenhouse gas emissions? AAG Annual Meeting. Chicago, IL. Apr. 21-25, 2015.

Awards

- Han J. 2016 Joint DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Special Recognition Award (U.S. Department of Energy)