GREET® DEVELOPMENT AND BIOFUEL PATHWAY RESEARCH AND ANALYSIS

Analysis and Sustainability Session
2019 BETO Peer Review, March 5, 2019

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Acronyms

A&S	Analysis and Sustainability Program of DOE BETO
AA	Adipic acid
ABF	Agile bio foundry
AEO	Annual Energy Outlook
AGE	Air and Greenhouse Gas Emissions
AFTF	Alternative Fuel Task Force
ARS	Agricultural Research Service of USDA
AWARE US	Available Water Remaining Model for the United States
BAU	Business as usual
BAT	Biomass Assessment Tool
BGY	Billion Gallons per Year
BGYe	Billion Gallons per Year Equivalent
CAP	Combined algae processing
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use Change from Biofuel Production
CF	Characterization Factor
CFP	Catalytic fast pyrolysis
CI	Carbon intensity
CNG/LNG	Compressed/liquefied natural gas
CO	Carbon monoxide
CORRIM	Consortium for Research on Renewable Industrial Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DGS	Distillers' grain with solubles
DOD	U.S. Department of Defense
DOT	Department of Transportation
EC	European Commission
EG	Ethylene glycol
EIA	Energy Information Administration
EO	Ethylene oxide
ERS	Economic Research Service of USDA
EtOH	Ethanol
FAA	Federal Aviation Administration
FCIC	Feedstock Conversion Interface Consortium
FQD	Fuel Quality Directive
FRA	Federal Rail Administration of DOT
FT	Fischer-Tropsch
FWG	Fuels Working Group of US DRIVE
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GJ	Gigajoule
GREET	GHGs, Regulated Emissions, and Energy use in Transportation
GTAP	Global Trade Analysis Project
GWP	Global warming potential
HFO	Heavy fuel oil
HTL	Hydrothermal liquefaction
IBR	Integrated biorefinery
ICAO	International Civil Aviation Organization of UN
IDL	Indirect liquefaction
iLUC	Indirect land use change
IMO	International Marine Organization of UN
INL	Idaho National Laboratory
JRC	Joint Research Center of the EC
KDF	Knowledge Discovery Framework
LCA	Life cycle assessment
LCFS	Low Carbon Fuel Standard
LUC	Land Use Change
MARAD	Maritime Administration
MIT	Massachusetts Institute of Technology
MJ	Megajoule
MOVES	Motor Vehicle Emission Simulator
MPGGE	Miles per gasoline gallon equivalent
MSW	Municipal Solid Waste
MYPP	Multi-Year Program Plan
NASS	National Agricultural Statistics Service
NEI	National Emissions Inventory
NG	Natural gas
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
openLCA	The Open Source Life Cycle Assessment Software
PBR	Photobioreactor, for algae production
PET	Polyethylene terephthalate
PM	Particulate matter
PTW	Pump-to-wheel
QA/QC	Quality assurance/quality control
R&D	Research & development
RA	Resource assessment
RD	Renewable diesel
RFS2	Second Renewable Fuels Standard
SCSA	Supply chain sustainability analysis
SOC	Soil organic carbon
SOT	State of technology
SOx	Sulfur oxides
T&D	Transportation & distribution
TEA	Techno-economic analysis
TPA	Terephthalic acid
UN	United Nations
US DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VOC	Volatile organic compound
WATER	Water Analysis Tool for Energy Resources
WSI	Water stress index
WTE	Waste-to-energy
WTP	Well-to-pump
WTW	Well-to-wheels

Goal Statement

- *Goal:* **Quantify the life-cycle energy and environmental impacts of biofuels**
  - Energy diversification; greenhouse gas & other air pollutant emissions; water consumption
- *Outcome:* ***A*ccurate information about the system-wide energy and environmental implications of biofuel systems to help R&D and business decisions**
  - Consistent model with transparency; LCA results for biofuels with peer-reviewed studies and benchmarked against other analyses/studies; rigorous, reliable, and timely responses to key questions from BETO and the bioenergy community.
- *Relevance:* **Interact with and conduct outreach to biofuel stakeholders**
  - Provide LCA results to agencies, technology developers, other stakeholders for R&D directions; interact with researchers and industries to examine critical issues affecting biofuel LCA results; provide LCA tool to biofuel and LCA community

Quad Chart Overview

Timeline

- Original GREET LCA efforts began in 1994 supported by multiple DOE programs including BETO
- Project start date: FY17
- Project end date: FY19
- Percent complete: 70%

Barriers addressed

- At-B: analytical tools and capabilities for system-level analysis
- At-A: analysis to inform strategic direction
- At-E: quantification of economic, environmental, & other benefits & costs

Funding

	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$1.46M	$1.05M	$1.41M*

*FY19 also includes contributions from the BETO Conversion Program and Algae Program.

Objective

- Identify and quantify the life-cycle energy and environmental impacts of biofuels with analytical tools

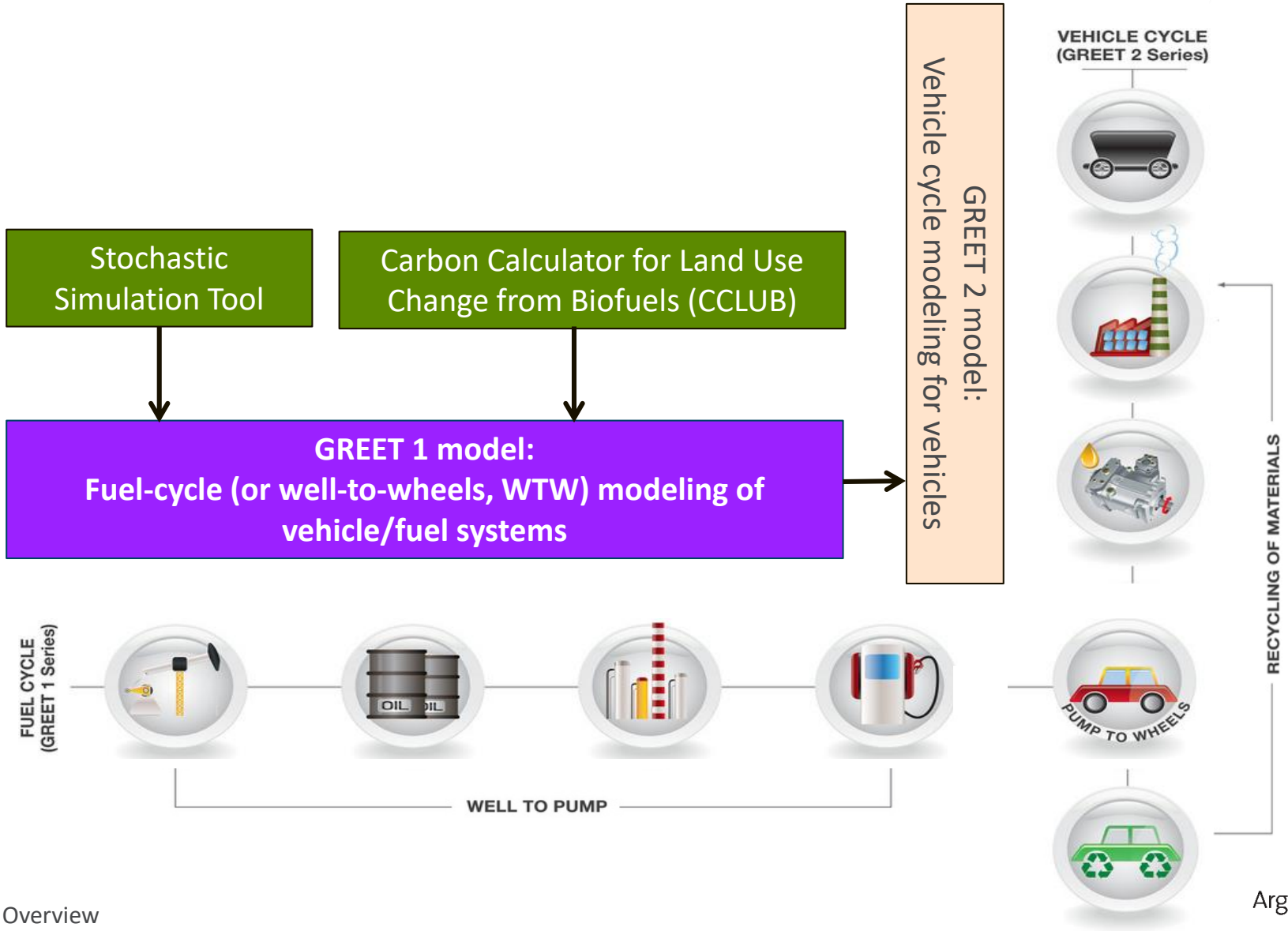
End of Project Goal

- GREET model with all BETO-relevant biofuel pathways; publications of LCA results for the energy and environmental implications of biofuels and their conventional counterparts.

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 conventional 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_2 utilization of industry waste streams) to GREET
  - Address emerging LCA issues (e.g., 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

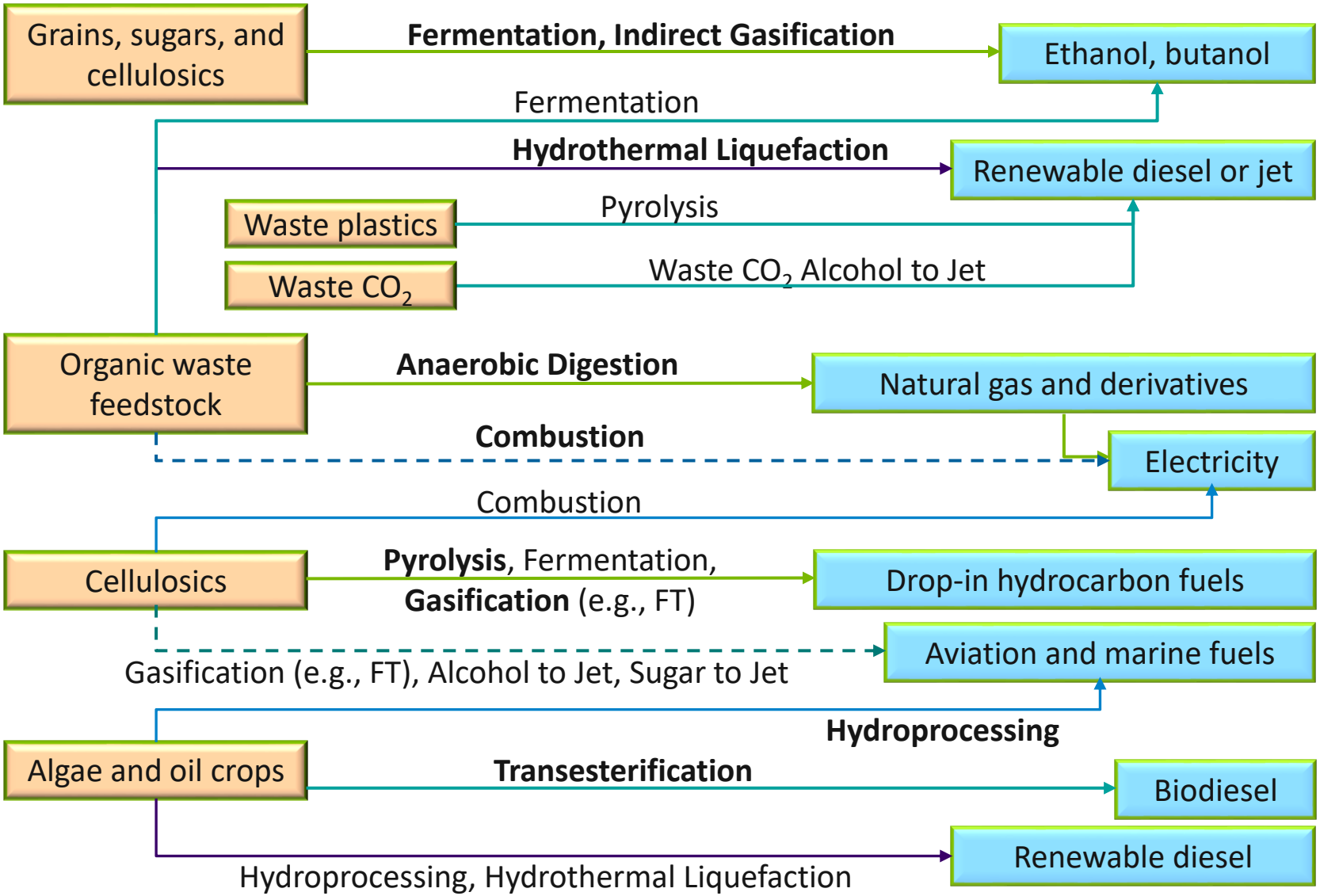
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model Framework



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



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GREET Includes All Transportation Subsectors

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

Road transportation

Air transportation

- Globally, a fast growing sector with GHG reduction pressure
- GREET includes
  - ✓ Passenger and freight transportation
  - ✓ Various renewable jet fuels blended with petroleum jet fuels

Rail transportation

- Freight transportation
- GREET includes
  - ✓ Diesel
  - ✓ Electricity
  - ✓ CNG/LNG

Marine transportation

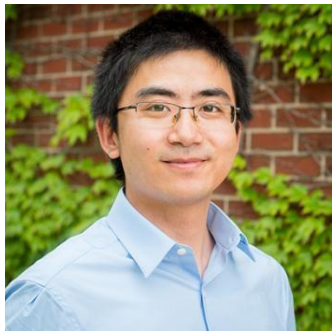
- The sector is under pressure to reduce air emissions and GHG emissions
- GREET includes
  - ✓ Ocean and inland water transportation
  - ✓ Baseline HFO and alternative/renewable marine fuels

BETO GREET Project Team

❑ **The key to the success of the GREET project is the strength of the team.**

Michael Wang

Thathiana Benavides



Hao Cai

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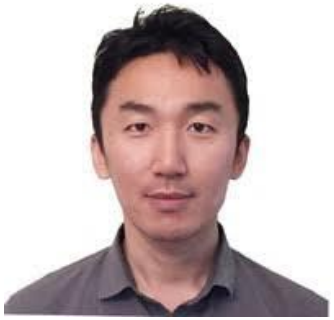
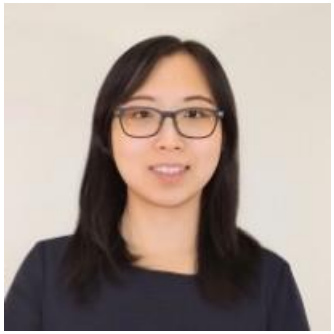
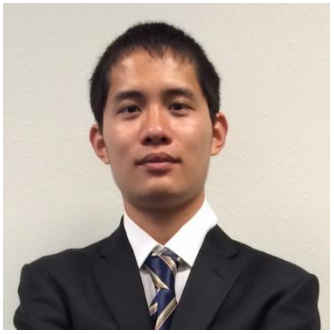


Uisung Lee



Xinyu Liu



Longwen Ou

Hui Xu

Technical Approach & 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 Positions Well in the Landscape of Bioenergy Modeling

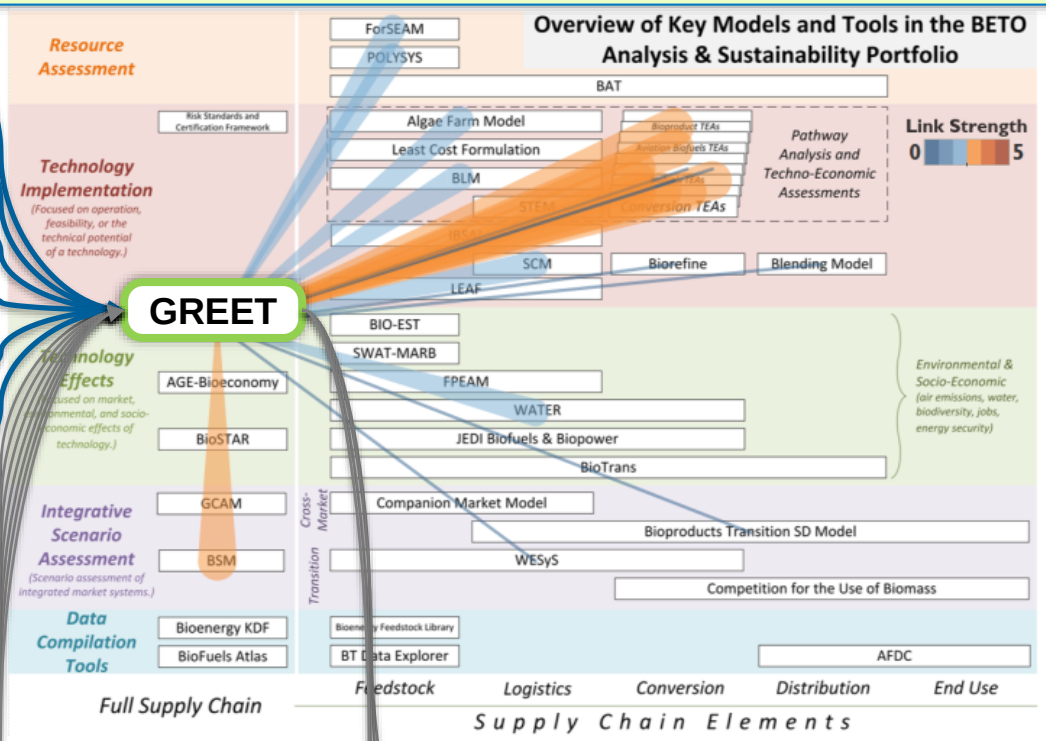
GREET Inputs from BETO-Sponsored Models

- BETO TEA Models
- Algae Farm Model
- Biomass Logistics Model
- WATER
- Biomass Scenario Model
- PNNL BAT Model

GREET Inputs from Other Models & Databases

- EIA AEO/Statistics
- USDA NASS
- GTAP
- CENTURY
- EPA eGRID
- USGS Water Use
- EPA MOVES

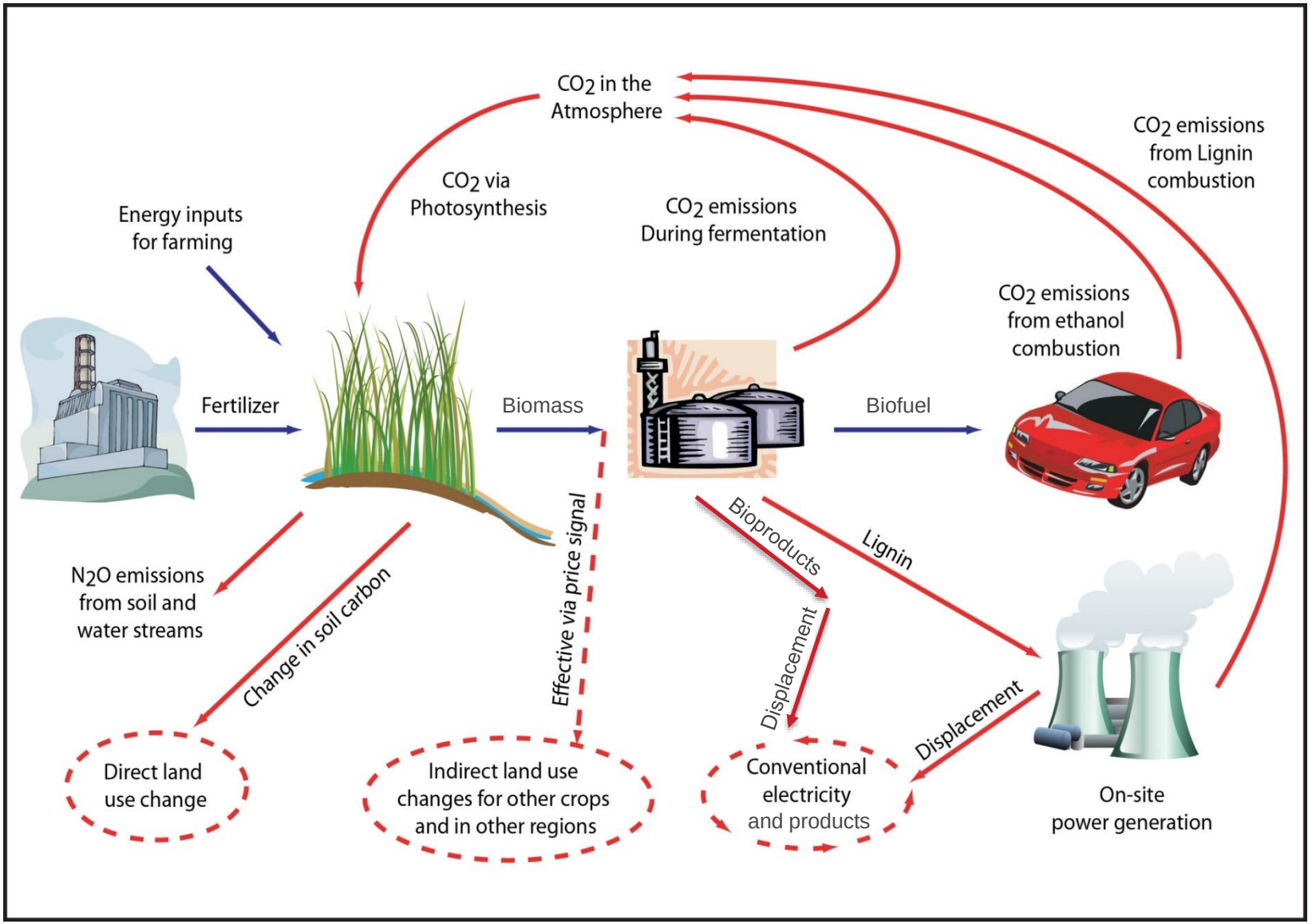
GREET Interactions with Other BETO-Sponsored Models



Examples of GREET Supporting Other Efforts

- DOT MARAD
- ICAO CORSIA
- CA-GREET for LCFS
- EPA RFS

Technical Approach: Direct Activities and Indirect Effects Are Included in GREET's System Boundary



Approach: Project Management

- Regular interactions with BETO staff
  - Maintain focus on programmatic priorities, align approach with state-of-the-art, & coordinate GREET project with related DOE efforts
  - Project tracking through monthly and quarterly written reports to BETO, quarterly briefings with BETO sponsor to track milestone completion
- Regular conference calls with other national laboratories and collaborators (e.g. 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 bioeconomy community for data availability & reliability
- Other interactions and communications
  - Interact with researchers, biofuel producers, and technology developers to address key issues, exchange data, and share LCA results
  - Communicate via peer-reviewed publications, presentations, and outreach

Technical Approach: Critical Success Factors Identified for GREET Development and Applications

- Critical LCA issues need to be addressed with science and rigor
  - 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 2017

GREET model development

- Added biofuel & bioproduct pathways and updated baseline pathways
- Conducted LCA of jet fuel pathways for ICAO
- Water stress impacts of LCA water consumption of biofuel pathways
- Supply Chain Sustainability Analysis of BETO-selected pathways

Emerging LCA issues

- Systematically addressed biorefinery co-products in LCA
- Holistically evaluated benefits of bioeconomy by including bioproducts alongside fuels
- Analyzed bio-plastics vs. fossil plastics

Feedstock analysis

- SOC changes of feedstock harvest/production
- Woody feedstock carbon dynamics over time (using outputs of CORRIM project)
- Algal biofuel resource potential with considering regional water stress
- Enhanced SOC modeling of land management/use change

Conversion analysis

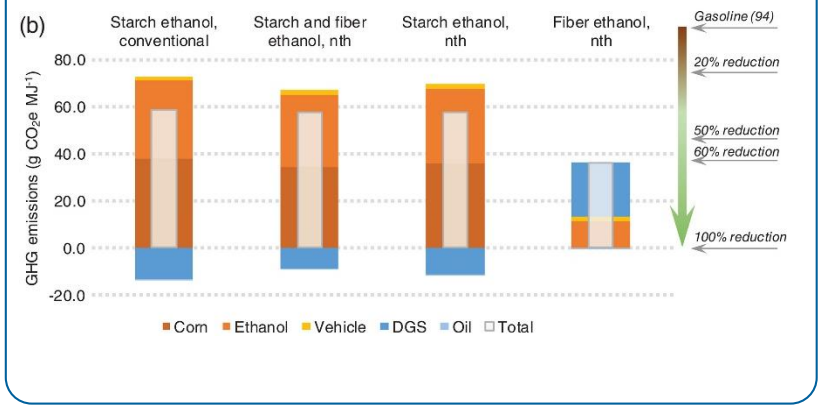
- Added LCA of WTE pathways
- Conducted LCA of industrial waste CO_2 to bioenergy

GREET Model Development

Implemented Biofuel/Bioproduct Pathways and Updated Baseline Fuels in GREET 2018 (and 2017)

- Implemented new biofuel and bioproduct pathways and updated major parameters of existing biofuel pathways
  - Major inclusion and updates: corn kernel fiber ethanol, biomass-derived high-octane gasoline, soybean and tallow biodiesel, waste-to-energy, and algae-derived biodiesel
- Updated the Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) for land use change and land management change for GHG emission modeling
- Major updates for baseline fuels and electricity
  - Methane leakage of natural gas supply chain, transportation and distribution energy intensity, crude oil mix for US refineries, electricity generation mix, and others

Corn kernel fiber ethanol



(Qin et al., 2018)

Research → **GREET Model** → **Applications**

GREET Model

GREET Excel

GREET.Net

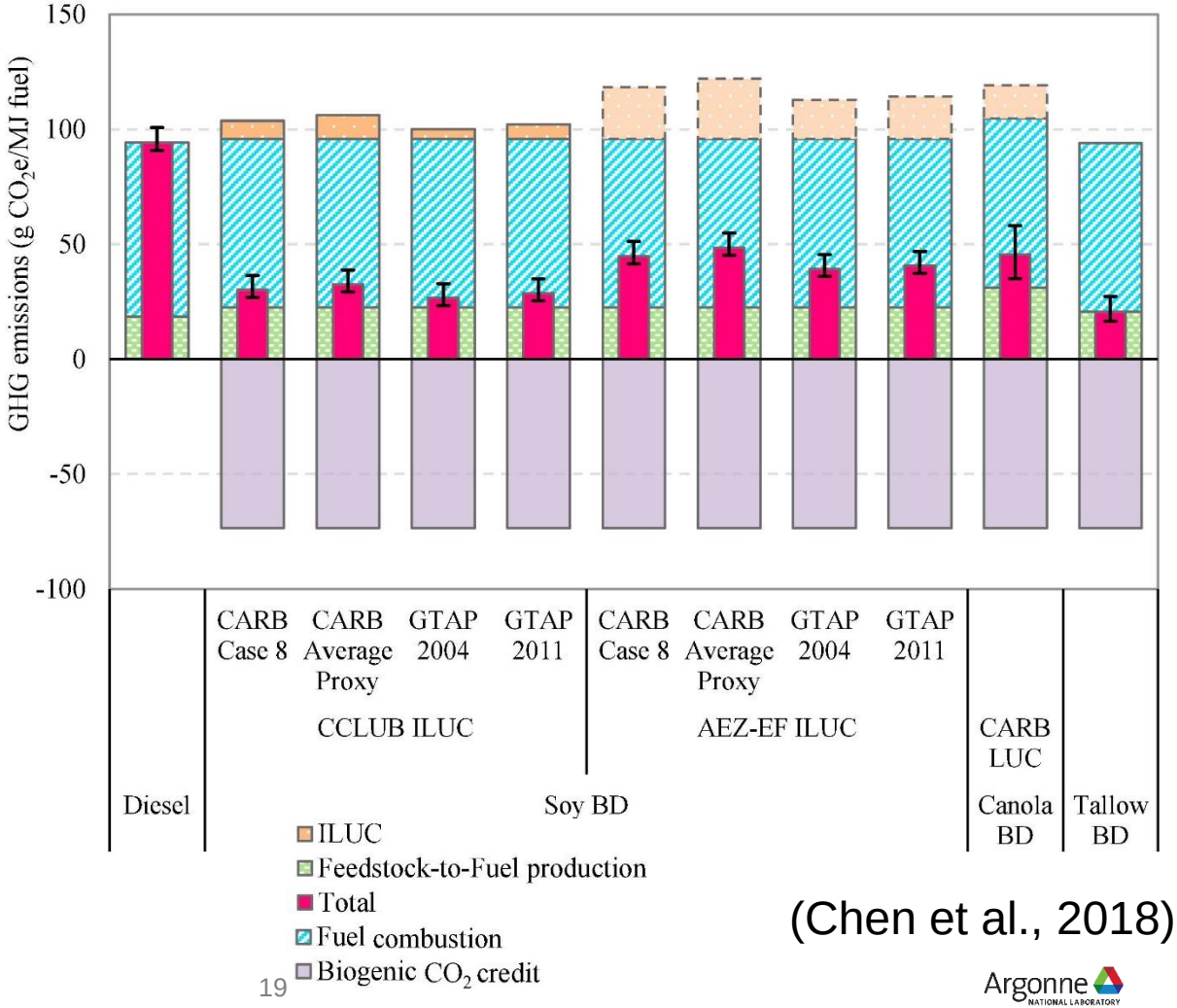
Applications

- DOE BETO Programs
- LCFS by CARB
- CORSIA by ICAO
- RFS by EPA
- ⋮

Evaluated WTW GHG Emissions of Soybean Biodiesel Including Induced Land Use Change Emissions

- New LCA results for energy use and GHGs of biodiesel from soy, canola, tallow-based)

- Addressed iLUC of soy biodiesel
- Examined discrepancy on the estimation of ILUC emissions related to peatland loss
- Soy biodiesel achieves 66–72% reductions in GHG emissions when ILUC is considered

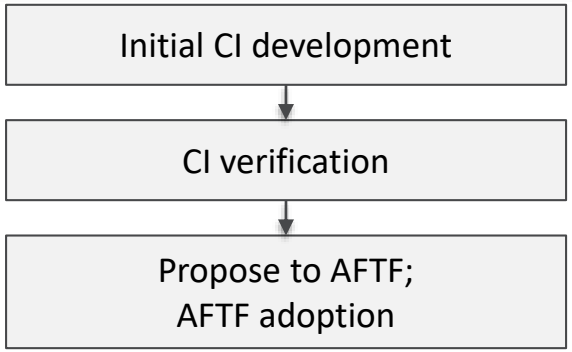


(Chen et al., 2018)

Supported ICAO to Evaluate Life-Cycle GHG Emissions of Various Jet Fuel Production Pathways

- ANL is a member of the ICAO Alternative Fuels Task Force tasked with modeling carbon intensities for the Carbon Offsetting & Reduction Scheme for International Aviation (CORSIA).
- ANL is part of AFTF's core LCA group with MIT, EC JRC, & U of Toronto
  1. developing core LCA values for alternative jet fuels
  2. writing the guidance document for LCA data submission

Core LCA Group Working Approach



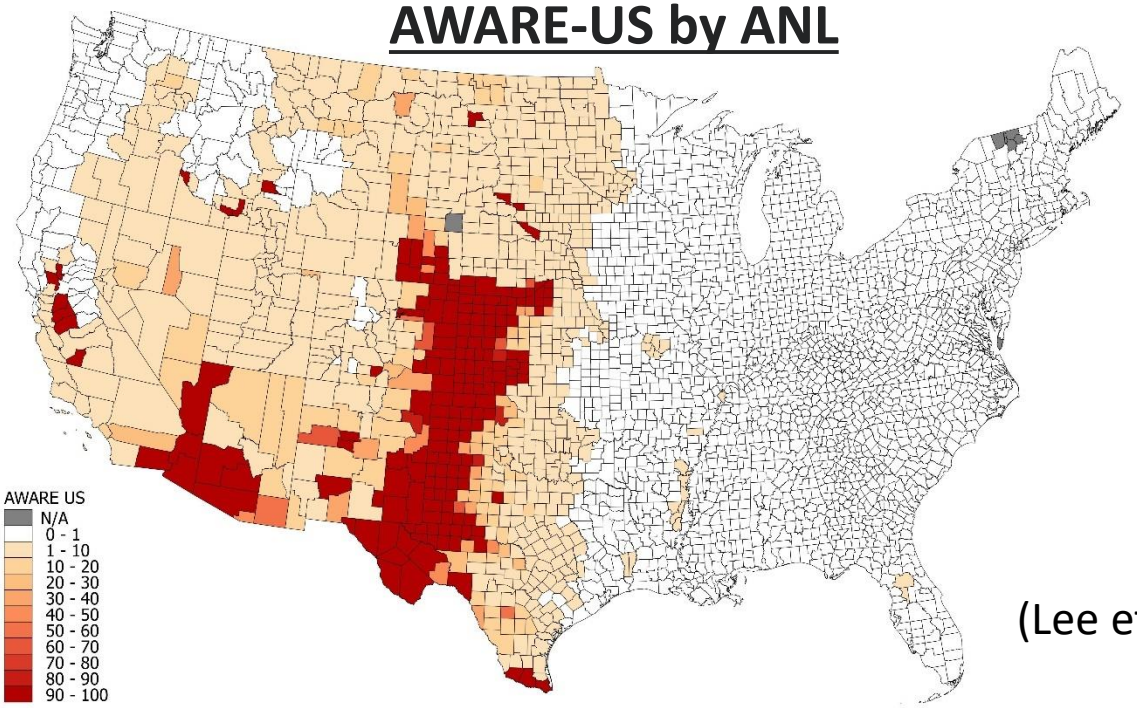
	Feedstock	Core LCA value [gCO_2e/MJ]
Fischer-Tropsch	Agricultural residues	7.7
	Forestry residues	8.3
	MSW, 0% NBC	5.2
	MSW, NBC as % of total C	NBC*170.5 + 5.2
	Short-rotation woody crops	12.2
	Herbaceous energy crops	10.4
Hydro-processed Esthers & Fatty Acids (HEFA)	Tallow	22.5
	Used cooking oil	13.9
	Palm fatty acid distillate	20.7
	Corn oil	17.2
	Soybean	40.4
	Rapeseed/canola	47.4
	Camelina	42
	Palm oil - closed pond	37.4
	Palm oil - open pond	60.0
	Brassica carinata	34.4
SIP	Sugarcane	36.6
	Sugarbeet	32.4
Isobutanol to Jet	Sugarcane	27.8
	Agricultural residues	29.3
	Forestry residues	23.8
	Corn grain	55.8
	Herbaceous energy crops	43.4
	Molasses	27.0
EtOH to Jet	Sugarcane	24.1
	Corn grain	65.7

Note: NBC – Non-biogenic carbon

Development of AWARE-US for the Regional Water Impact Analysis of Energy Systems

- Water consumption in different regions has different meaning (water stress level).
- ANL developed a high-fidelity database (AWARE-US) that enables water stress impact analysis for new energy systems deployment.
- AWARE-US by incorporating latest human water consumption data and groundwater recharge data from USGS.

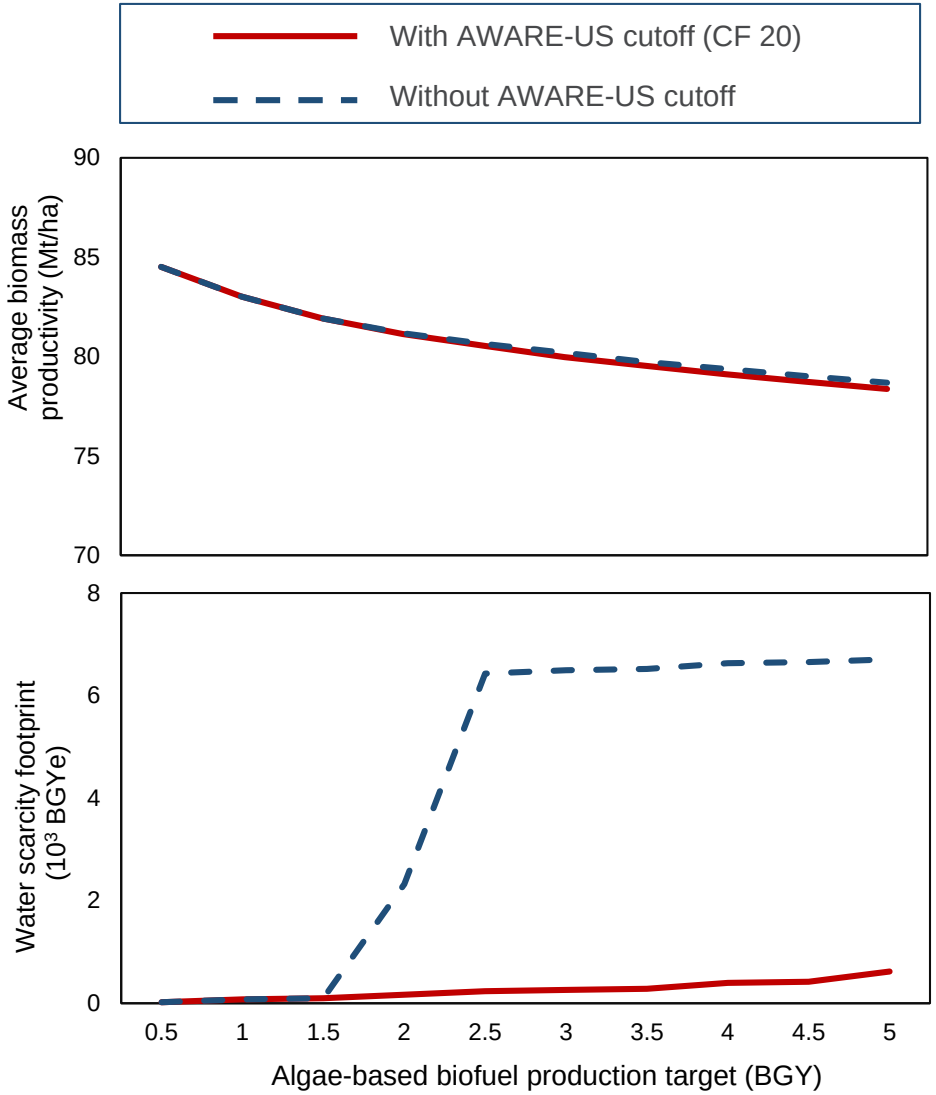
AWARE-US by ANL



(Lee et al., 2019)

Incorporating AWARE-US into Algae Biofuel Siting Can Reduce Water Stress Impact Significantly

- Assessed water stress impacts of alternative algae pond locations.
- Scaling up algae biofuel production requires significant water resources; considering regional water stress is important.
- **Water stress was reduced by 96% w/o lowering average biomass yield (<1%) when AWARE-US was used as an additional constraint** for 5 billion gal/yr renewable diesel target.
- These findings support the BETO Algae Program's focus on saltwater strains and use of waste or surplus water.



(Xu et al., 2019)

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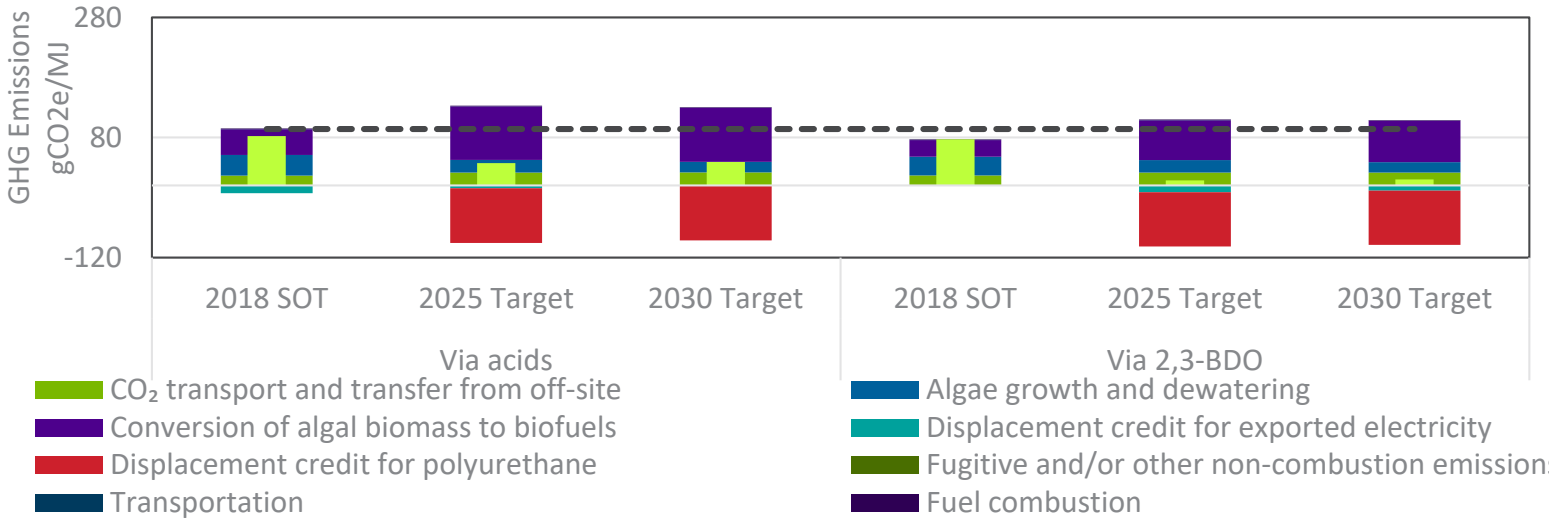
SCSA Tracks Progress & Identify Opportunities to Improve Performance of Biofuel Technologies

- **Three dry feedstock pathways** to produce renewable gasoline and renewable diesel with woody feedstock via IDL and ex-situ CFP, and with herbaceous feedstock via biochemical conversion
- **Three wet feedstock pathways** to produce renewable diesel with algae via HTL and CAP, and with wastewater plant wet sludge via HTL
- Regular and rigorous coordination among labs for data and information exchange
- Continuous improvement in 2018 SOT cases and projection cases driven by improvement in conversion yields and energy efficiency in feedstock logistics
- Co-product designs in the biochemical conversion and algae CAP pathways have significant impacts on SCSA results



Algae CAP pathway

(Cai et al., 2018)

Emerging LCA Issues

Biorefinery-Level Analysis Is Needed to Fully Account for Energy and Emission Impacts of Biorefineries with Significant Co-Product Outputs

Biofpr Biofuels Bioproducts & Biorefining

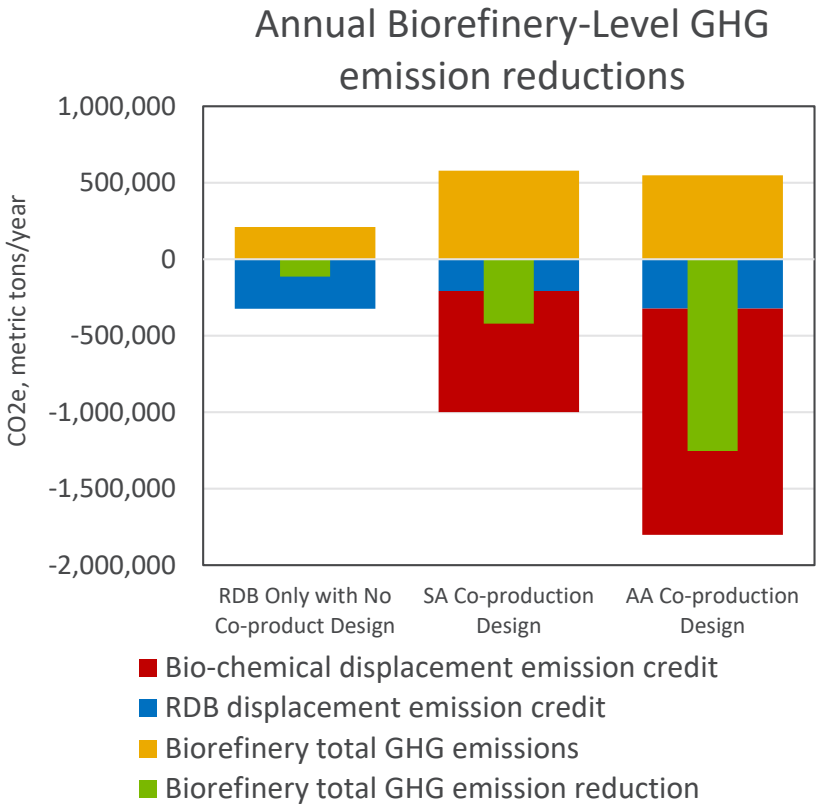
Modeling and Analysis | Full Access

Life-cycle analysis of integrated biorefineries with co-production of biofuels and bio-based chemicals: co-product handling methods and implications

Hao Cai, Jeongwoo Han, Michael Wang, Ryan Davis, Mary Biddy, Eric Tan

First published: 12 June 2018 | https://doi.org/10.1002/bbb.1893

Read the full text >



The system expansion method is the only way to fully account for life cycle emissions of both fuel and non-fuel products in existing fuel-focused carbon regulations.

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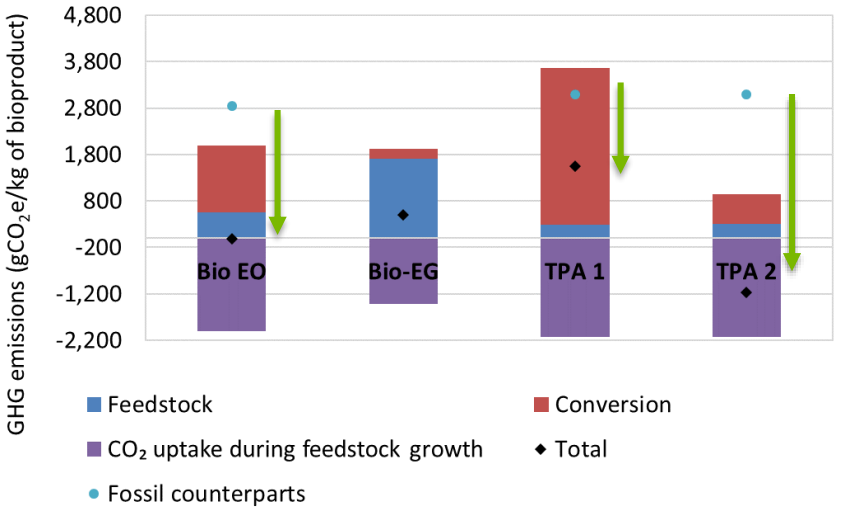
Bioproducts Play an Integral Role in the Bioeconomy

- A growing market for products from renewable resources
- Help to meet the nation's need for chemicals and plastics
- Support the production of biomass-derived hydrocarbon fuels at MFSP of $3/gasoline gallon equivalent or lower as high value-added co-products
- Potential to reduce a product's environmental footprint

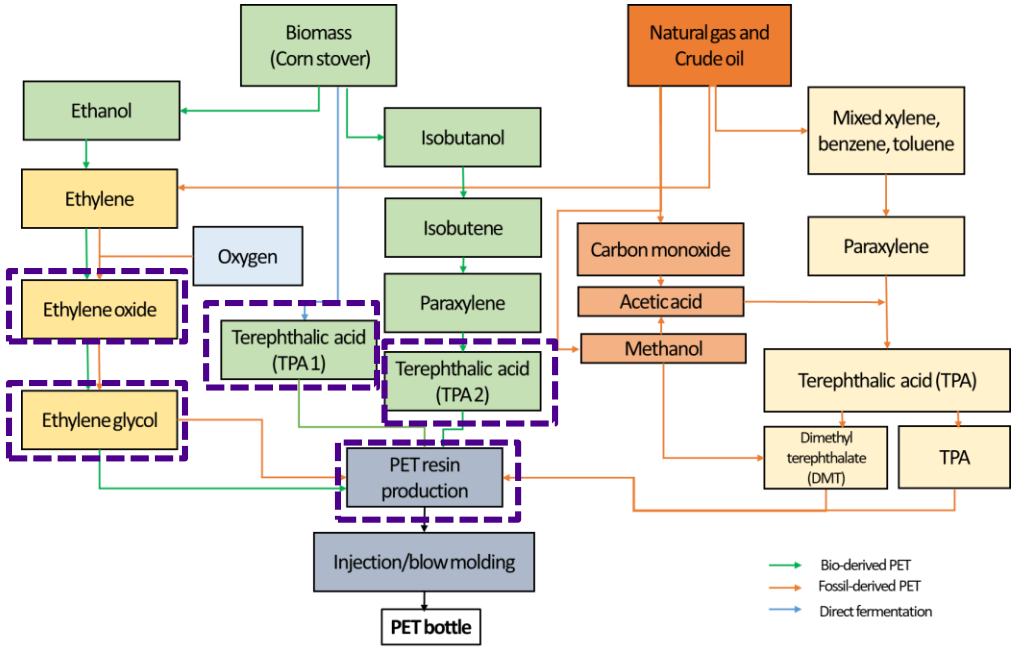
Collaborative efforts within BETO's consortia

The GREET model has a expanded bio-product module to include new pathways commonly used in the sustainable production of plastics such as polyethylene terephthalate (PET)



Cradle-to-gate GHG emissions of bio-ethylene oxide (EO), bio-ethylene glycol (EG) & bio-terephthalic acid (TPA) via direct fermentation & via isobutanol intermediate

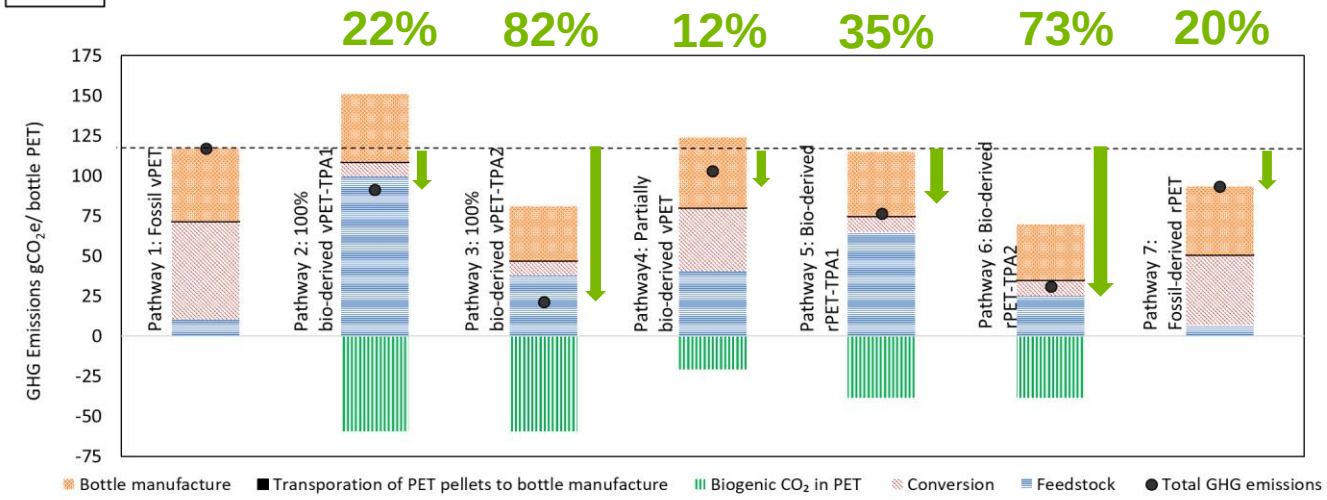
With Bioproducts LCA, We Have Addressed Environmental Impacts of Plastic Production Like PET



Bio and recycled PET bottles could offer significant GHG reductions

Major driver of GHG reductions is the biogenic carbon in the biomass-derived portion of the PET bottles.

The precursors of bio-based PET (TPA and EG) are the major contributors to the GHG emissions

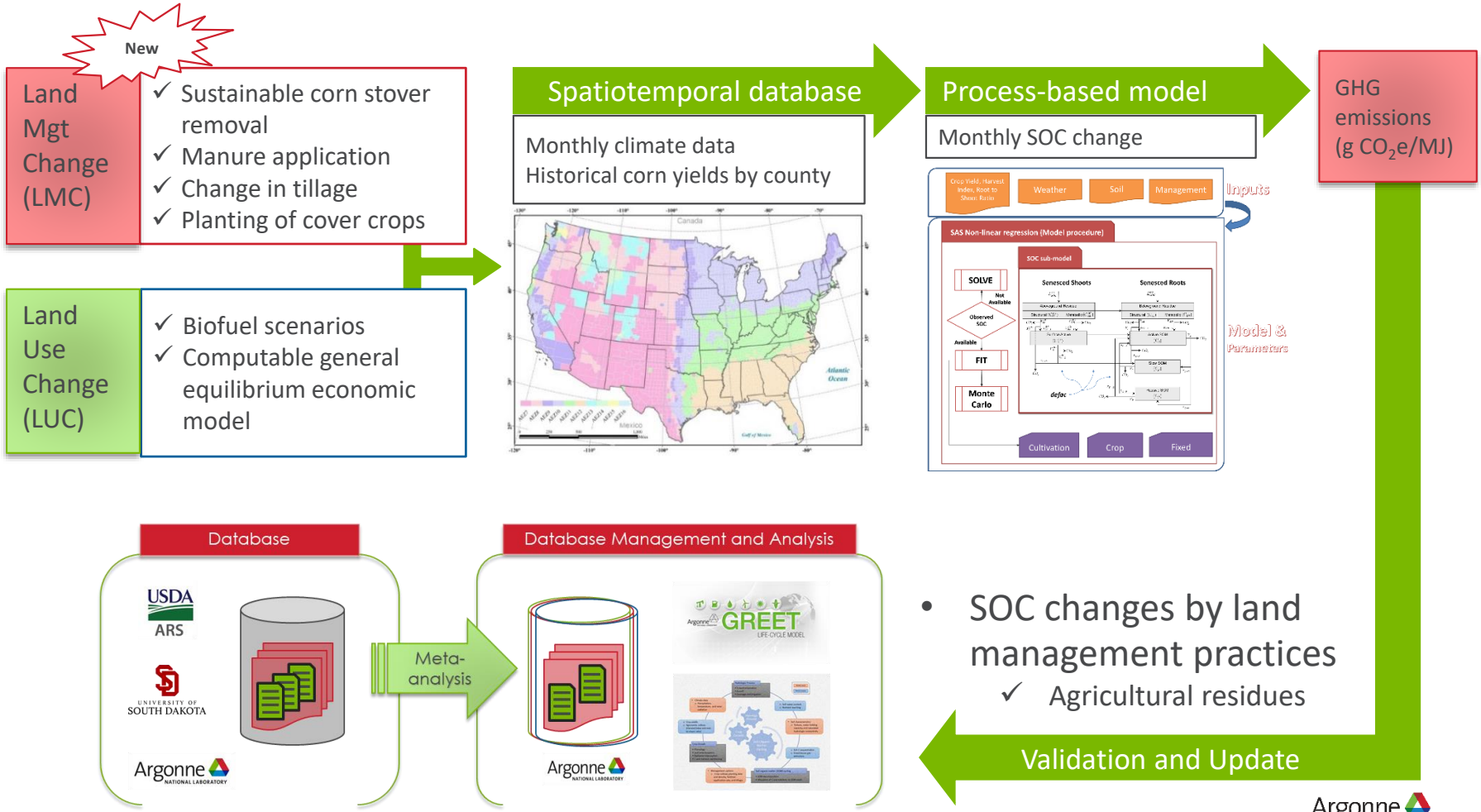


(Benavides P.T et al., 2018)

Feedstock Analysis

Development of New Soil Organic Carbon (SOC) Modeling Capacities and Database

- Created modules to enable SOC change evaluation related to alternative land management practices for corn stover and now working on other feedstocks
- Collaborated with multiple agencies on developing relevant SOC database



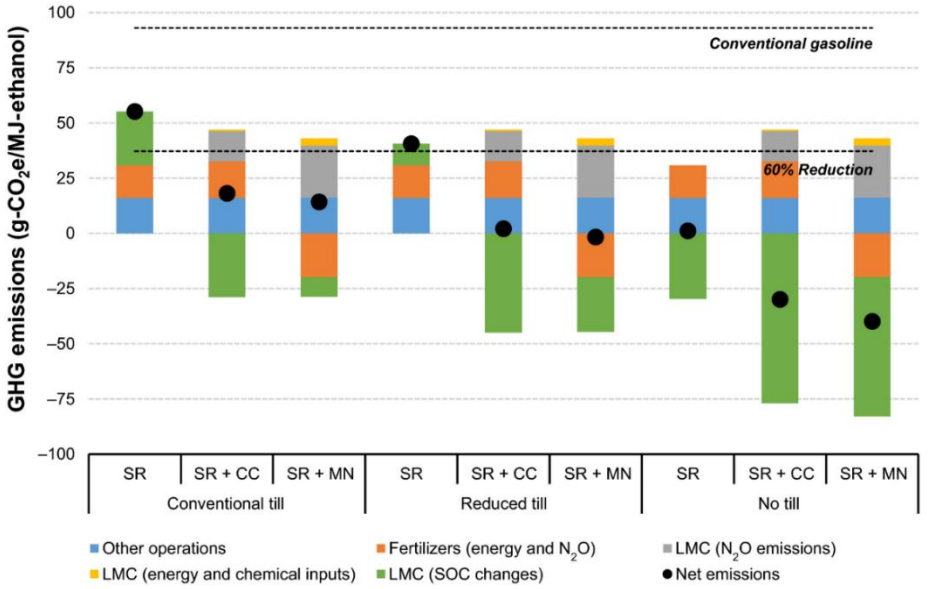
Assessment of SOC Change Driven by Land Management and Land Use Changes

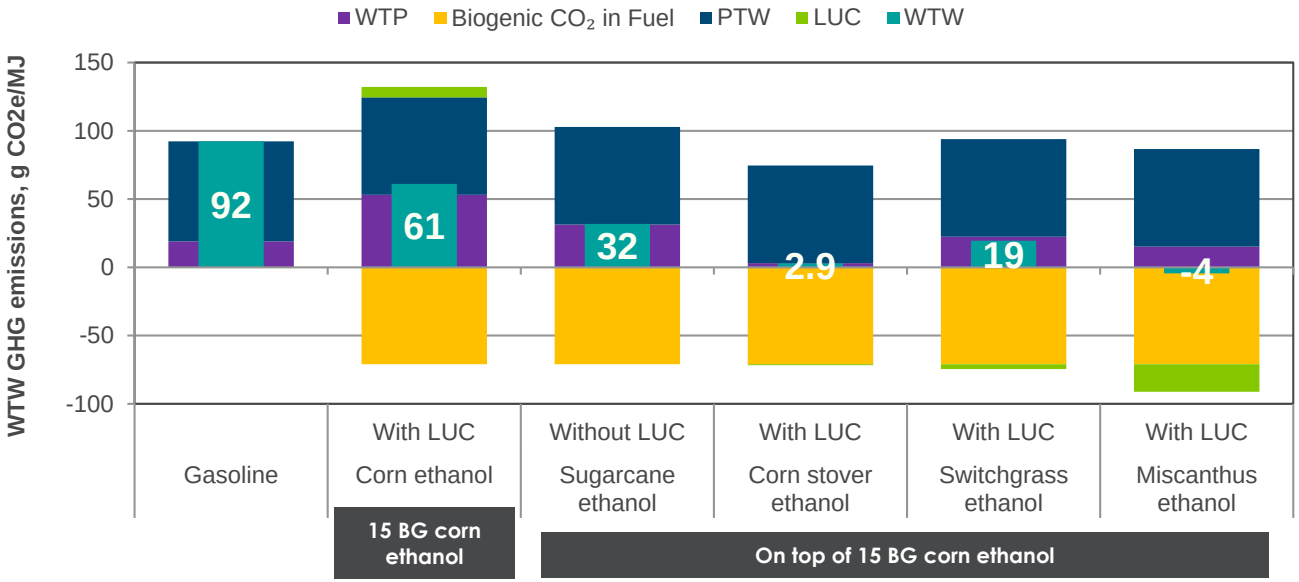
- SOC change upon LMC may dramatically affect corn stover ethanol GREET LCA GHG results

Soil C impacts

SR: Stover removal
MN: manure
CC: cover crop

(Qin et al., 2018)





- GREET LCA GHG results of selected biofuels for LUC associated with a biofuel scenario
- Feedstock is a main driver

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Conversion Analysis

Performed LCA of WTE Pathways that Provide Significant WTW GHG Reductions

- LCA of waste-to-energy (WTE) pathways needs to evaluate emissions associated with business-as-usual (BAU) case of waste management in order to account for avoided emissions.

BAU → GHG emissions (A gCO_2e)

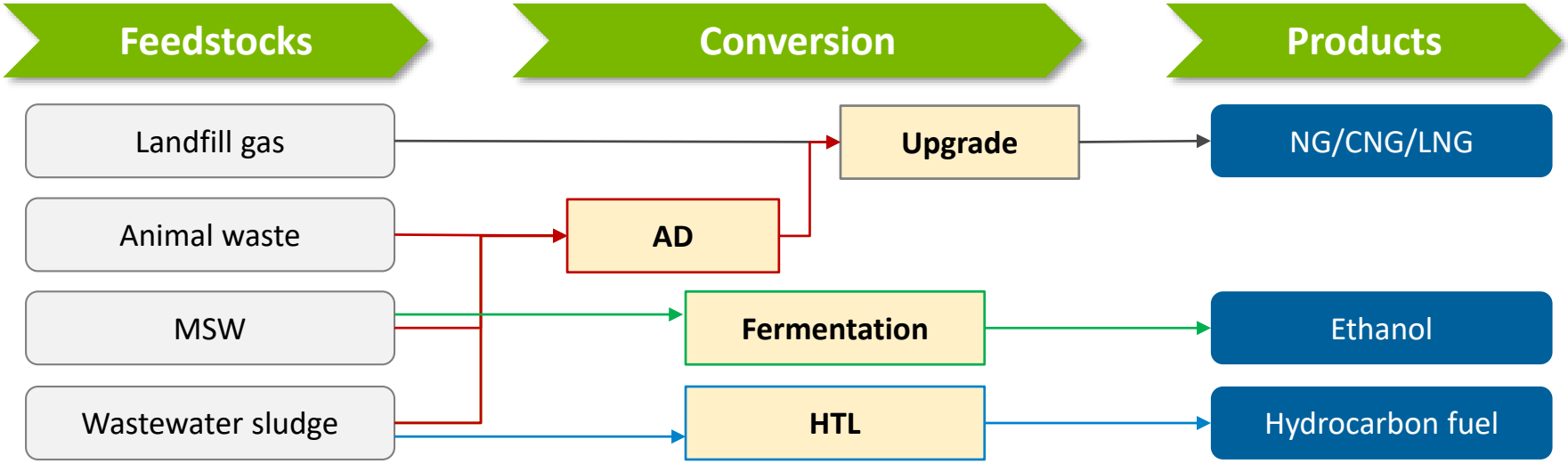
Avoidance (Negative)

WTE → GHG emissions (B gCO_2e)

Positive

Fuel (MJ)

Pathways in GREET



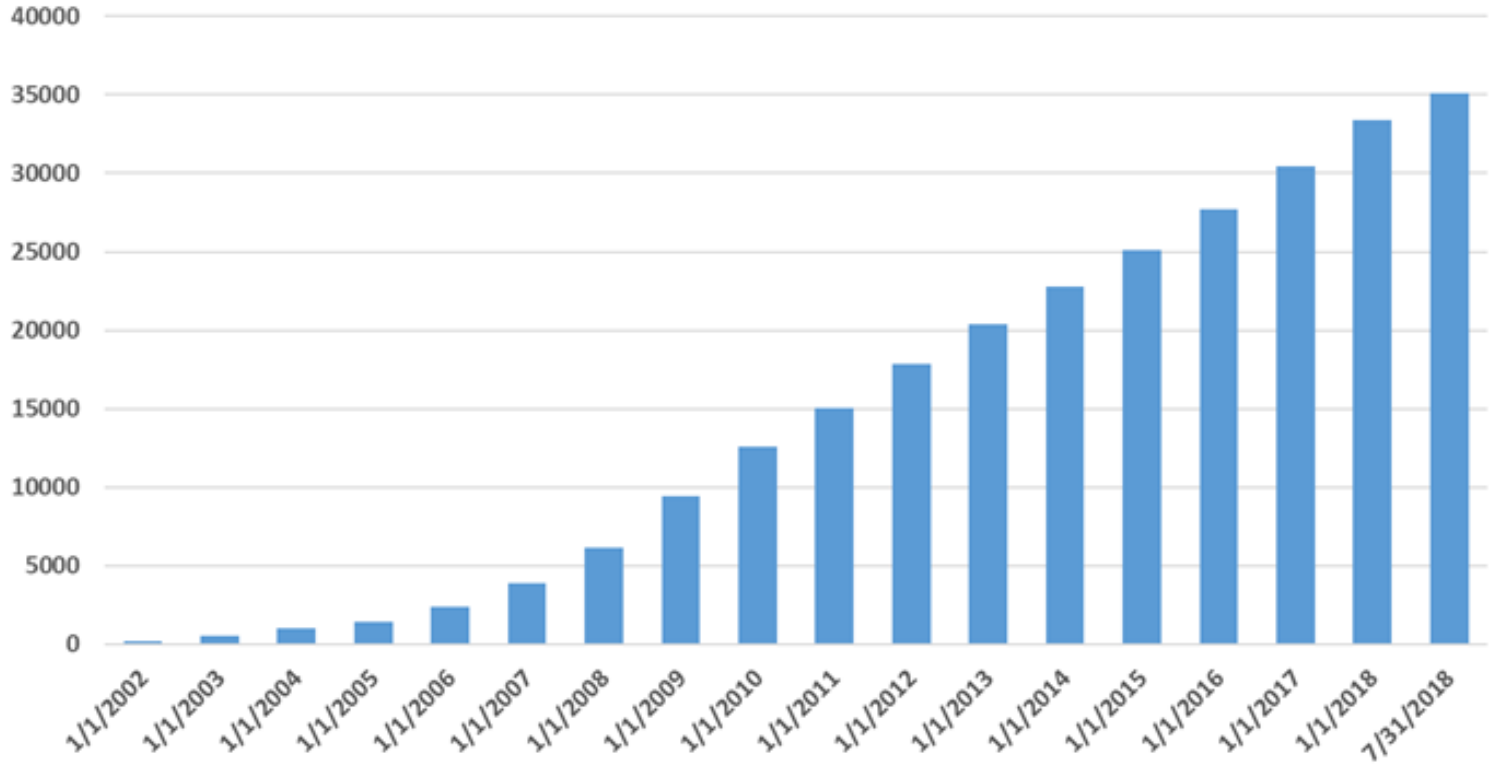
Relevance of GREET Development and Applications (1)

- The goal of this project is to develop an LCA model that supports BETO A&S Team by identifying and quantifying energy and environmental impacts of biofuels
- 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
- Sustainability criteria are critical for BETO and bioenergy community in R&D evaluation
  - GREET LCA quantifies and clarifies the energy diversification, 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)

- Sustaining 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
- 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
- The bioeconomy community benefits from the availability of this free platform which they use to inform R&D direction
- GREET is a helpful tool that provides guidance for regulations/ requirements such as CARB LCFS, EPA RFS2, and ICAO CORSIA.

There Are 35,000 Registered GREET Users Globally



- Geographically, 71% in North America, 14% in Europe, 9% in Asia
- 57% in academia and research, 33 % in industries, 8% in governments

Relevance: Key GREET Application Examples

- CA-GREET3.0 built based on and uses data from ANL GREET
- EPA RFS2 used GREET and other sources for LCA of fuel pathways
- FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways
- GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report
- Extensive support to other BETO consortia
  - Co-Optima, Agile BioFoundry (ABF), Feedstock Conversion Interface Consortium (FCIC), Separation Consortium
- LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD
- US Dept of Agriculture
  - ARS modeling the carbon intensity of corn production and providing a database for SOC change associated with land management practices
  - ERS water stress of food & diet change supporting 2020 Dietary Guidelines
  - Office of the Chief Economist – biofuel & bioproduct LCA

Future Work: Improve Accuracy of LCA Methods

Develop methods to address issues material to bioenergy systems.

- Complete landscape-based analyses of bioenergy systems to address local issues potentially obscured by end-use, product-based analysis
- Define criteria for product classification to allow for appropriate allocation, i.e. main products, co-products, and by-products
- Address regional differences, ex. criteria air pollutants, soil organic carbon, water stress, resource availability
- Address seasonal differences, ex. water consumption/stress in various energy systems including biofuels, electricity, and food/diets
- Explore GREET pathways in openLCA to increase exposure to larger LCA community
- **New methods are incorporated in annual GREET releases and widely distributed to improve LCA studies in general**

Future Work: High-Priority Emerging Issues

Perform LCA studies to address high-priority emerging issues.

- Examine the sustainability of waste-to-energy pathways
  - CO_2 utilization of industrial waste gas streams for fuel/chemical production
  - Continue to evaluate technologies to divert waste from current waste management practices to WTE
  - Expand the evaluation of waste plastics to bioenergy/bioproducts
- Address BETO priority biofuel pathways and emerging issues with supply chain sustainability analyses
  - Reduce uncertainties by incorporating location-specific supply chain criteria air pollutant emissions in collaboration with NREL
- Address biorefinery waste streams and issues associated with carbon and nitrogen releases
- Address key issues for biochemical pathways
  - enzyme and yeast production and loading
- Add BETO priority bioproduct pathways
- Collaboration with and support to other agencies and DOE labs
  - CARB, FAA, MARAD, USDA, ICAO, EPA OTAQ

Summary

- GREET is a widely-accepted LCA tool that evaluates the energy and environmental effects of biofuels
  - **System-level analysis** capacity
  - **Provides access to 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 the community can **build consensus** on pursuing clean, efficient biofuel systems
- Outcomes of GREET LCAs
  - Agencies use GREET results to **develop policies** that promote biofuel development and use
  - BETO uses GREET results to **select biofuel technologies** for R&D
  - Biofuel producers and tech developers use GREET results to **improve process energy efficiencies**, improving profitability and minimizing carbon footprint
  - Biofuel LCAs with GREET have **advanced understanding** of critical LCA issues
- Future work
  - Addresses **critical issues** in biofuel sustainability analysis
  - Supports BETO and its community in assessment of technology options for sustainable bioenergy and bioproduct systems from farm to consumer

Additional slides

Responses to Selected Comments in 2017 Peer Review

Reviewer Comment #1	*ANL Response*
While, taken as a whole, GREET represents a tremendous achievement, in its current state it also raises some important concerns for the management of the BETO portfolio. Something in excess of $7 million has been spent to date in the development of GREET and it appears to have been money well spent. As the final roughly $1.5 million allocated to the project is committed, however, it begs some questions: After spending as much as has been, what remains to be done? If the answer to the previous question is "a lot," were earlier priorities chosen wisely? If it's the case that earlier spending priorities were appropriate but a lot still remains to be done, what is the comparative advantage of doing the work under the auspices of the GREET platform, as opposed to by others, after which results might be integrated into GREET? It is not entirely clear to me, however, how important the work now being taken up for GREET is (albedo?). Some scrutiny should be applied to ongoing expenditures. Related to this, several other projects refer to the use of their results in GREET. This testifies to the usefulness of GREET as a platform, but complicates the task of the reviewer. How should credit be assigned between the creators and maintainers of the GREET platform itself and the teams contributing to its extensions?	Thanks for bringing up the resource commitment vs. accomplishments/deliverables of this AOP. This AOP is based on BETO's decision (and the transportation energy community's desire) that energy and environmental sustainability of bioenergy needs to be addressed with the LCA approach. This single AOP comprises 4 tasks – GREET development, feedstock sustainability, conversion sustainability, and algae LCA. In fact, the latter three tasks are integral parts of BETO R&D portfolios in the sense that R&D advances are evaluated for their sustainability. They provide critical inputs to GREET development. As shown in the accomplishments of the 2017 Peer Review and this year's Peer Review, ANL's research efforts are to address critical LCA and sustainability issues for bioenergy. As new feedstocks, conversion technologies, and energy and chemical products continue to be developed, their sustainability implications need to be addressed, which has been an on-going effort in sync with BETO R&D portfolios. In addition, bioenergy sustainability has been often challenged because of the emerging LCA and sustainability issues. Such issues include water stress, carbon neutrality, SOC changes under different farming management practices, carbon dynamics of forest feedstocks, etc. Argonne has undertaken major efforts to address these issues and has contributed significantly to our understanding of the energy and environmental outcomes associated with biotechnologies and the bioeconomy as well as helping build consensus amongst stakeholders. In summary, LCA research is key focus of this AOP. GREET development and release are a natural product of the research so that the entire bioenergy community can benefit. In fact, it is analytical topics and issues that determine ANL research priorities.

Responses to Selected Comments in 2017 Peer Review

Reviewer Comment #2	*ANL Response*
This project is of central relevance to BETO's goals by providing a consistent comparison platform to assess sustainability across multiple dimensions. Moreover, given the wide recognition and use of GREET, it is important to ensure ongoing improvement to reflect the best available science and the project should be commended for striving to do so. Particular high priorities in this respect are the identified next steps of assessing the temporal dynamics of forest feedstocks under alternative assumptions, and comprehensively evaluating the issues of carbon neutrality and additionality. The inability to address these issues left notable gaps in BT16 volume 2 report, and it will be important to able to continue developing capacities to be able to address them within the BETO portfolio. To ensure the best available information, it is also essential that the project draw on the best evidence from the other parts of BETO portfolio. A key consideration is how best to characterize and report uncertainties and spatial (and temporal) heterogeneity of results to provide a more detailed picture of life cycle impacts appropriate for different policy objectives.	Thank you for your comment. Many of our research efforts in FY18 and FY19 reflect the identified issues and gaps. For example, we addressed carbon dynamics of forest feedstocks in collaboration with CORRIM. We will address counter-factual scenarios of forest growth and management in FY19. ANL has benefited tremendously from BETO R&D portfolios by obtaining data generated from other BETO efforts such as the TEA efforts in NREL, PNNL, and INL. LCA at ANL is an integral part of the BETO analysis efforts with close interactions among these labs with coordination of the BETO A&S Team. Characterizing and reporting of uncertainties and spatial/temporal heterogeneity of LCA results are indeed included in GREET. Stochastic modeling features are built to address uncertainties of key parameters. Temporal variations are built in GREET with time-series variations for key parameters. While certain regionality is built in GREET (such as transportation logistics and electricity generation), further regionality is needed for bioenergy pathways since feedstock production is regional and certain environmental attributes (such as critical air pollutant emissions and water consumption) are regional, which is our desire to address.

Responses to Selected Comments in 2017 Peer Review

Reviewer Comment #3	*ANL Response*
BETO has long supported the development of the GREET model, a LCA tool used to quantify the energy and environmental impacts of biofuels. Today, GREET provides a well validated and rigorous tool to advance the understanding of biofuel sustainability. It is used broadly by the LCA community with nearly 30,000 users and serves as an enabler for policies such as the RFS and the Low Carbon Fuel Standard program. It provides a consistent and comprehensive format to assess the benefits of various biofuels pathways. The project displays a high level of collaboration and integration. Much has been accomplished since the last review. GREET has undergone additional model development including the modeling of LUC and soil organic compound change for biofuel feedstocks. GREET also served as a major contributor to the BT16 volume 2 sustainability report. Life cycle water consumption and additional co-feedstocks and co-products were added to the model. Of particular interest was the LCA expansion for various production scenarios for algae. This integrates nicely with the efforts BETO is making in the algae space. GREET provides a platform to integrate the LCA of biofuel pathways to address their overall energy and environmental benefits which is critical for BETO and the rest of the bioenergy community. Future work includes continuing to address farming management practices and their impacts on soil organic compound for biofuel feedstocks, continuing to expand key GREET modules and GREET functionalities, and continuing to monitor and expand emerging biofuel conversion technologies. An effort will be made to regionalize the GREET well-to-wheels analyses of criteria pollutants and water stress assessment as well as extend LCA for different algal cultivation and fuel processing pathways to provide R&D guidance to BETO and the biofuels community. It will be important to remain focused on the most critical issues. I do feel, however, that adding biobased chemical and biobased products to the model would be useful as these materials are enablers of the bioeconomy with many early examples already in commercial production.	Thank you for the comment. In the past two years, we have indeed worked to address most of the priorities. For example, we addressed SOC changes of farming management practices. We expanded GREET with bio-based chemicals and products by interacting with other labs such as NREL and PNNL. Regionality of key environmental attributes such as criteria air pollutants remains to be an outstanding issue for us to address, while water consumption regionality has been addressed with a newly developed water stress system (AWARE-US). In FY18, we spent a considerable amount of effort to update and expand bio-based chemicals and products. We will continue the effort in FY19.

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- Lee U, Xu H, Daystar J, Elgowainy A, Wang M. **2019**. "AWARE-US: Quantifying water stress impacts of energy systems in the United States" *Science of the Total Environment*. 15 (648): 1313-22.
- Xu H, Lee U, Coleman AM, Wigmosta MS, Wang M. **2019**. "Assessment of algal biofuel resource potential in the United States with consideration of regional water stress" *Algal Research*. 1 (37): 30-9.
- Benavides PT, Dunn J, Han J, Biddy M, Markham J. **2018** "Exploring Comparative Energy and Environmental Benefits of Virgin, Recycled and Bio-derived PET Bottles. ACS Sustainable Chem. Eng 6 (8), 9725–9733.
- Chen R, Qin Z, Han J, Wang M, Taheripour F, Tyner W, O'Connor D, Duffield J. **2018**. "Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts" *Bioresource technology*. 1 (251): 249-58
- Lee U, Han J, Elgowainy A, Wang M. **2018**. "Regional water consumption for hydro and thermal electricity generation in the United States" *Applied Energy*. 15 (210):661-72.
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- Lee U, Han J, Wang M. **2017**. "Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways" *Journal of Cleaner Production*. 10 (166):335-42.
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- Qin Z, Canter CE, Cai H. **2017**. Toward Life Cycle Analysis on Land Use Change and Climate Impacts from Bioenergy Production: A Review. Bioenergy and Land Use Change, 231, 65.
- Tan EC, Zhang YM, Cai H. **2017**. Relative Sustainability of Natural Gas Assisted High-Octane Gasoline Blendstock Production from Biomass (No. NREL/PR-5100-70425). National Renewable Energy Lab.(NREL), Golden, CO (United States).
- Qin Z, Li Q, Wang M, Han J, Dunn JB. **2018**. "Life-cycle greenhouse gas emissions of corn kernel fiber ethanol" *Biofuels, Bioproducts and Biorefining*.

Publications: Selected Technical Reports

- Wang M, Elgowainy A, Benavides PT, Burnham A, Cai H, Dai Q, Hawkins TR, Kelly JC, Kwon H, Lee DY, Lee U. **2018**. "Summary of Expansions and Updates in GREET® 2018" Argonne National Lab.(ANL), Argonne, IL (United States). ANL-18/38.
- Cai H, Benavides PT, Lee U, Wang M, Tan E, Davis R, Dutta A, Biddy M, Clippinger J, Grundl N, Tao L, Hartley D, Mohammad R, Thompson D, Snowden-Swan L, Zhu Y, Jones S. **2018**. Supply chain sustainability analysis of renewable hydrocarbon fuels via indirect liquefaction, ex situ catalytic fast pyrolysis, hydrothermal liquefaction, combined algal processing, and biochemical conversion: update of the 2018 state-of-technology cases and design cases, Argonne Technical Report, ANL/ESD-18/13.
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- Dutta A, Tan EC, Ruddy D, Nash CP, Dupuis DP, Hartley D, Cai H. **2018**. High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2018 State of Technology and Future Research (No. NREL/TP-5100-71957). National Renewable Energy Lab.(NREL), Golden, CO (United States).
- Qin Z, Kwon H. **2018.** Estimating emissions related to indirect peatland loss in Southeast Asia due to biofuel production. Technical Memorandum. Argonne National Laboratory. Lemont, IL.
- Han J, Canter C, Cai H, Wang M, Qin Z, Dunn J. **2018.** Carbon dynamics for biofuels produced from woody feedstocks. Argonne National Laboratory. Lemont, IL.
- Ou L, Cai H. **2018.** Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET1_2018 Model
- Qin Z, Kwon H, Dunn J, Mueller S, Wander M, Wang M. **2018.** Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) Manual. Argonne National Laboratory, Lemont, IL. ANL/ESD/12-5 Rev. 6.
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- Chen R, Qin Z, Canter C, Cai H, Han J, Wang M. **2017.** Updates on the Energy Consumption of the Beef Tallow Rendering Process and the Ratio of Synthetic Fertilizer Nitrogen Supplementing Removed Crop Residue Nitrogen in GREET. Argonne National Laboratory. Lemont, IL.

Selected Presentations and Awards

Selected Presentations

- Benavides, P. T.et al. **2018**. “Life-cycle analysis (LCA) of bio-derived chemicals in the GREET model”. International Congress on Sustainability Science and Engineering (ICOSSE), Cincinnati, OH
- Benavides, P. T. et al. **2017**. “Life-cycle analysis (LCA) of bio-derived terephtalic acid (TPA) and bio-derived-hexamethylenediamine (HMDA)”. American Institute of Chemical Engineers (AIChE) Annual meeting, Minneapolis, MN
- Lee U, Wang M. **2018**. “Marginal Approach for Estimating Life-cycle Emissions of Waste-Derived Fuels by Considering Avoided Landfill Gas Emissions” LCA XVIII, Fort Collins, CO, Sep. 25-28. 2018.
- Lee U, Benavides P, Han J. **2018**. “Life-cycle Analysis of Renewable Fuels Derived from Municipal Solid Waste and Evaluation of Avoided Landfill Gas Emissions” The Air & Waste Management Association’s 111th Annual Conference & Exhibition, Hartford, CT, June 25-28.
- Lee U, Daystar J, Xu H, Han J, Canter C, Elgowainy A, Wang M. **2017**. “The Regional Impact Analysis of Water Consumption for Algal Biofuel Production in the United States” LCA XVII, Portsmouth, NH, Oct 3-5. 2017.
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