NOVEMBER 7, 2022 | GREET TRAINING WORKSHOP

Argonne NATIONAL LABORATORY GREET LIFE-CYCLE MODEL

GREET Life Cycle Analysis of Bioenergy Technologies

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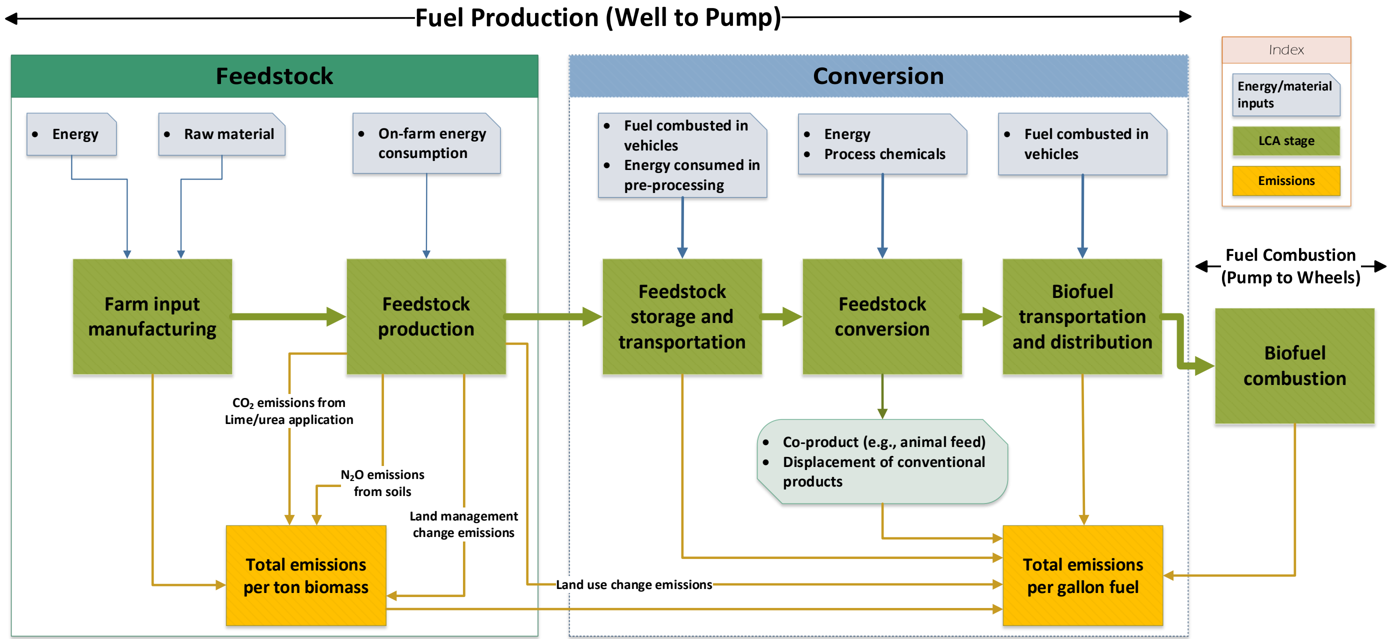
Key Sponsors

Providing long-term support for GREET development

- **Bioenergy Technologies Office (BETO)**
  - Data, Modeling, and Analysis
  - Strategic Development and Integration
  - Conversion Technologies
  - Feedstock Technologies
  - Advanced Algal Systems
- **Advanced Research Projects Agency-Energy (ARPA-E)**
  - Decarbonizing agriculture and biofuel feedstocks
  - Green ammonia
  - Macroalgae Cultivation and Products
- **U.S. Dept. of Agriculture**
  - Bioenergy, low carbon agricultural products

Comprehensive Scope

Detailed modeling of feedstocks and conversion



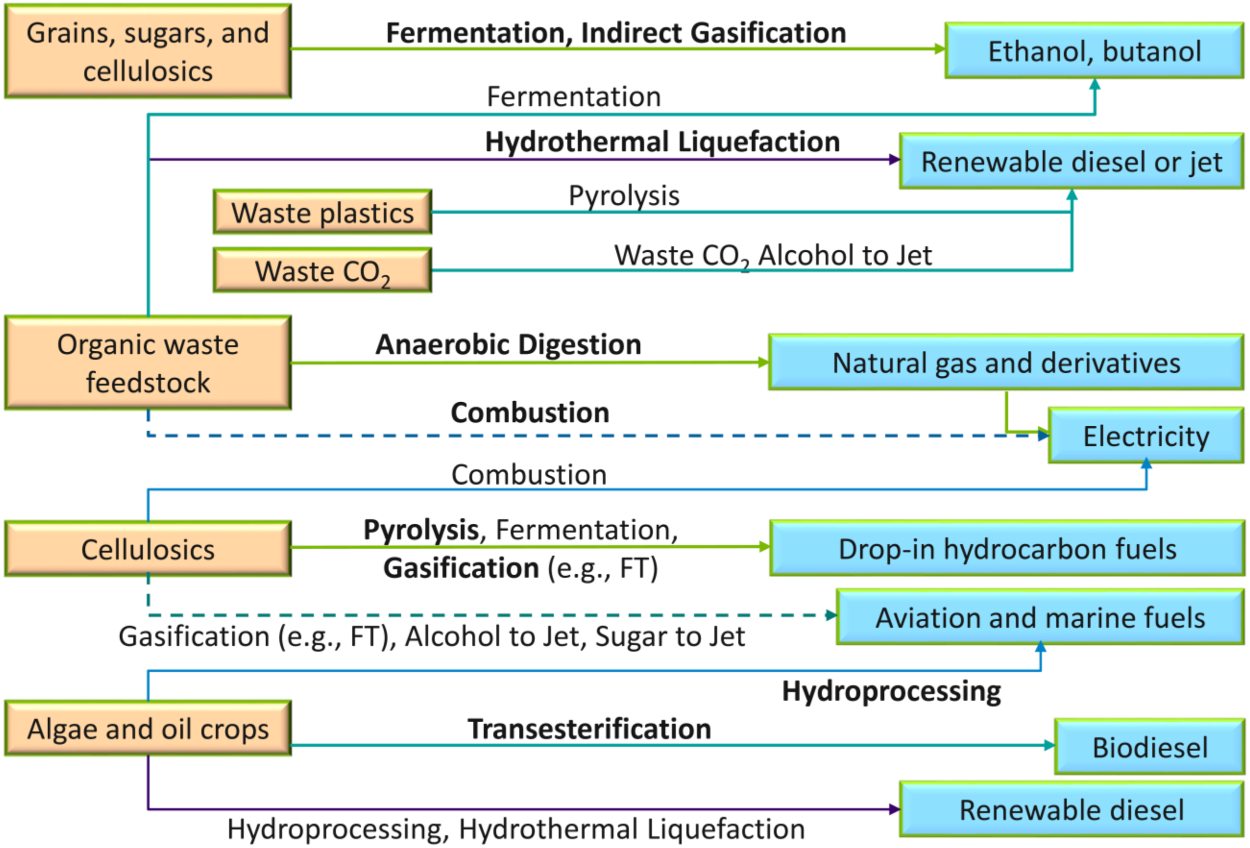
Land Use Change

- Carbon Calculator for Land Use Change from Biofuels Production (CCLUB)
- Feedstock average soil C and soil nitrous oxide (N_2O)

Land Management Practices

Comprehensive Scope

Feedstocks, conversion, and end use fuels, energy, chemicals



Focus Areas and Related Models

LCA, location-specific, water stress, water quality, decarbonization

- **Biofuels and Bioenergy**
  - Biofuels / low-carbon liquid fuels
  - Renewable natural gas
  - Refinery coprocessing
  - Biopower
  - Biogenic CO_2 utilization

- **Bioproducts**
  - Bioplastics and biochemicals
  - Circular economy
  - Agricultural products/animal feed

Models

- **GREET** - Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
- **CCLUB** - Carbon Calculator for Land Use Change from Biofuels Production
- **FDCIC** - Feedstock Carbon Intensity Calculator
- **AWARE US** - Available Water Remaining U.S.
- **Bioeconomy AGE** - Bioeconomy Air, Greenhouse Gases, and Energy Use
- **Decarbonization Scenario Analysis Model**
- **RP-LCA** - Refinery Products LCA and RP-VOC - Refinery Products VOC Calculator
- **WATER** - Water Analysis Tool for Energy Resources
- **DAYCENT / CENTURY**
- **SWAT** - Soil and Water Assessment Tool [external]

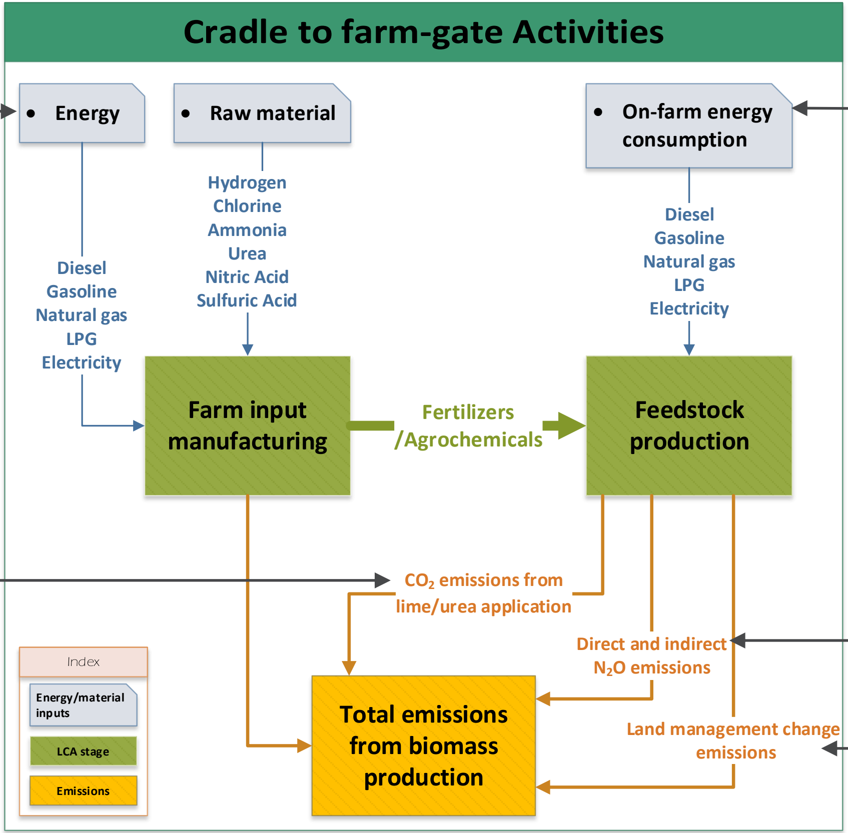
LCA of Feedstock Production

Consistent and Inclusive Feedstock LCA Framework

Detailed considerations for corn and soy cultivation

- Upstream emissions of producing energy source and raw material
- Emissions from energy and material consumption to manufacture farm inputs (e.g., fertilizers/agrochemicals)

- CO_2 emissions from lime/urea application
  - ✓ 0.216 $gCO_2/g\ CaCO_3$ (EPA)
  - ✓ 0.733 $gCO_2/g\ CH_4N_2O$



- Upstream emission of producing energy source
- Emissions from energy consumption to operate farm machinery

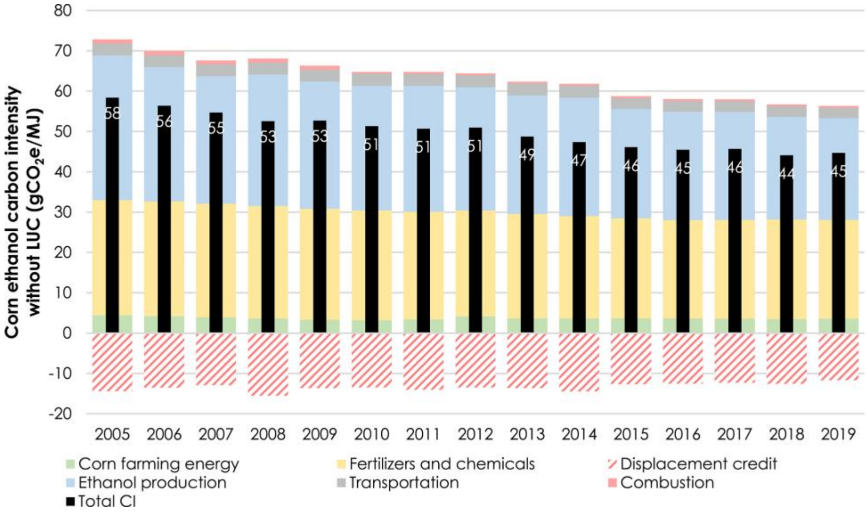
- Direct and indirect N_2O emissions from
  - ✓ Corn residue left in soils (1% + 0.225% of 141.6 g N per bushel)
  - ✓ N fertilizer application (1% + 0.325%)
  - ✓ Animal manure (1% + 0.425%)

- Modeled soil organic C (SOC) sequestration potentials associated with diverse farming practices by using a process-based simulation model

Actively Updating GREET for Changing Practices

Ongoing research to address current and future biomass production

- Tracking and updating key parameters
  - Yield, farming inputs, energy consumption (corn, soybean, and sorghum)
  - N2O emissions from crop residues of bio-oil feedstocks
  - Land use change emissions for biodiesel and renewable diesel
- Near-term GHG reduction opportunities
  - Mitigation measures for corn farms
  - Decarbonizing agriculture
  - Low carbon biofuel feedstocks
- What if low-carbon fuel standards recognized improved farming practices?
  - Significant potential for SOC, but concerns around additionality and permanence



Reference:
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CCLUB Provides GREET Land Use Change Modeling Capability

Carbon Calculator for Land Use Change from Biofuels Production

Biofuel scenarios

- 5 scenarios for ethanol from corn grain, stover, Miscanthus, switchgrass
- 4 scenarios for soy biodiesel

GTAP-Bio CGE model

- Estimates land conversion associated with scenarios.
- Domestic and international
- Forest, grassland, cropland pasture, feedstock land

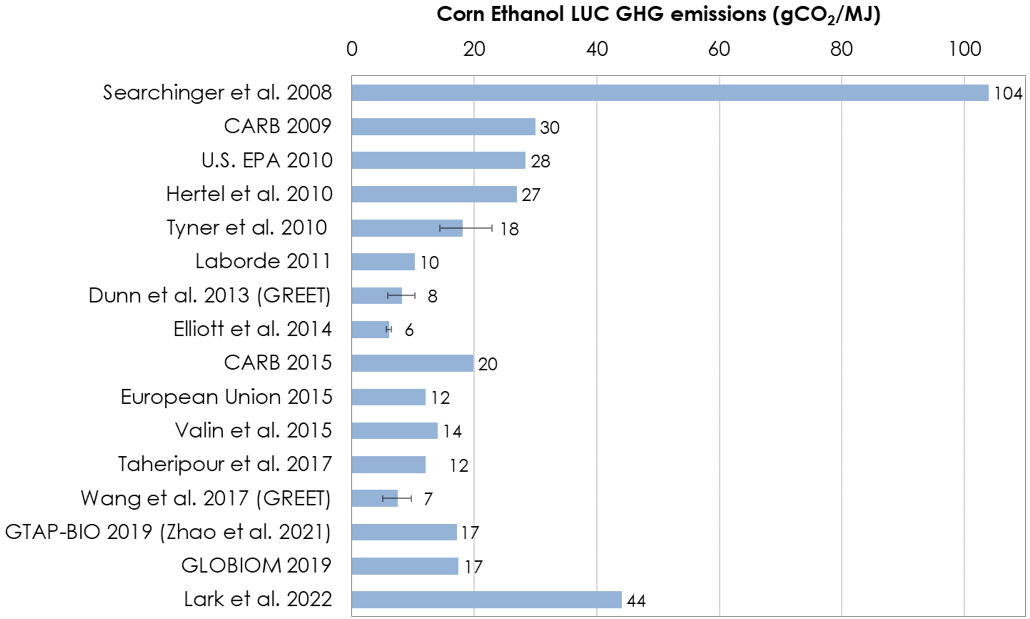
Soil C and N_2O emission factors related to LUC

- Domestic EFs modeled using U.S. county-level soil C simulations.
- International EFs derived from Winrock and Woods Hole datasets

GREET CCLUB: Macroeconomic and Process-Based Modeling

Understanding of LUC GHG emissions has been evolving since 2008

- Down trends in LUC estimates due to improved and better calibrated models incorporating newer data
- GREET combines GTAP LUC and detailed process modeling of soil carbon changes
- Critical factors for LUC GHG
  - Intensification vs. extensification
    - Yields: existing vs. new cropland
    - Double cropping
    - Extension to new land types
  - Price elasticities
    - Crop yield response to price
    - Food demand response to price
  - SOC change from land conversion and mgt practices

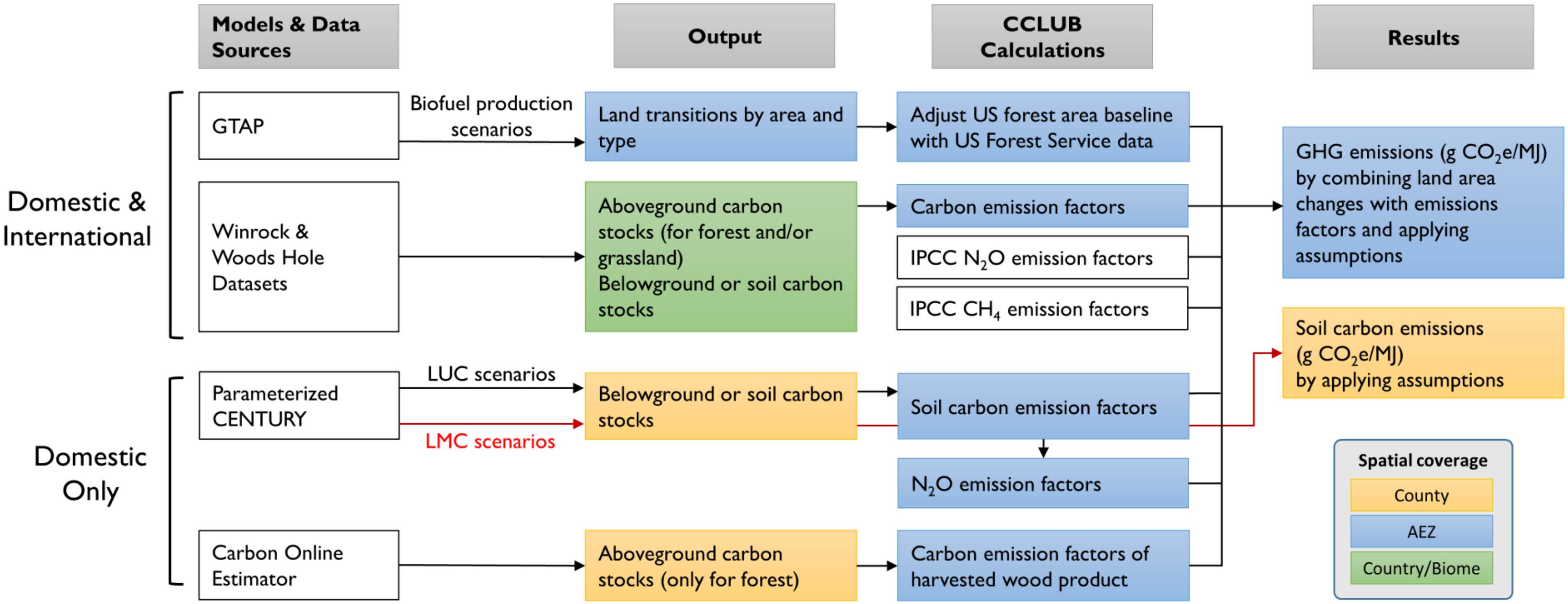


Lee et al 2021 Retrospective analysis of the U.S. corn ethanol industry for 2005–2019

Visit https://greet.es.anl.gov/publications for modeling methods, results, and responses to related efforts.

Rigorous Estimates of GHG Emissions from LUC

Harmonized, peer-reviewed, and transparent framework for reliable and repeatable results

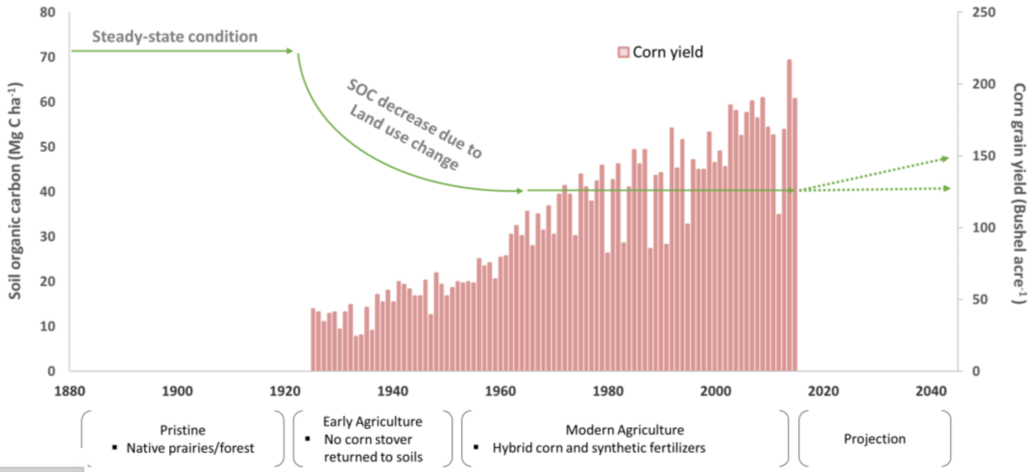


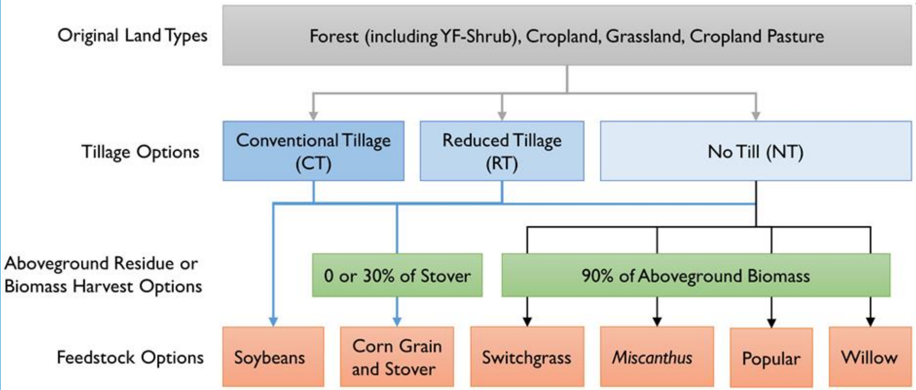
Kwon et al 2021 CCLUB users' manual and technical documentation

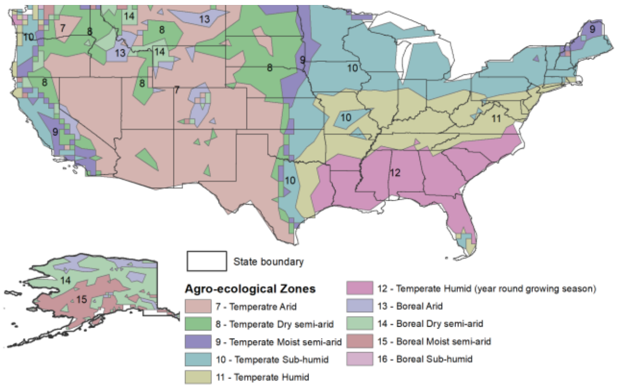
Customized CENTURY Model Provides LUC GHG Emissions

SOC estimates over 30 years at the U.S. county-level aggregated to AEZ

- Long-term land use history
- Tillage and harvest practices
- Constant or increasing yield
- Consistent with USDA and EPA GHG accounting
- Broad applicability across soil, climate and management conditions







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CCLUB SOC and N_2O Estimates Informed by Meta-Analysis

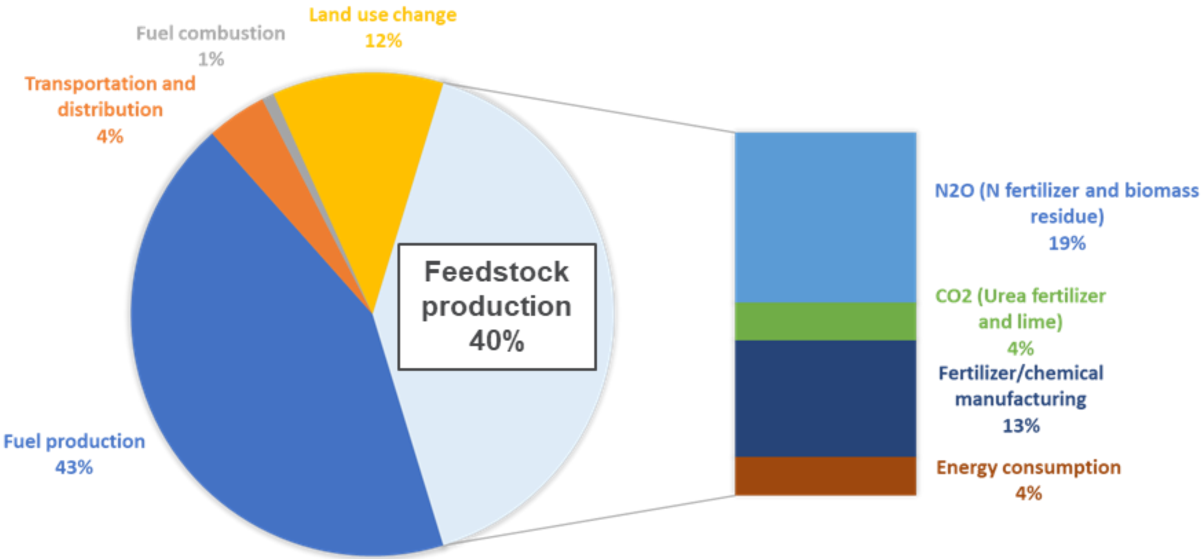
Synthesizing information from measured data and recent literature

- Forest harvesting and biomass removal (James et al 2021)
  - Measured data from the North American Long-Term Soil Productivity study and recent publications
- Corn stover removal (Xu et al 2019)
  - Effect of removal rate, tillage, soil texture, and soil sampling depth
- Indirect peatland loss (Qin and Kwon, 2018)
  - Updates for Southeast Asian palm plantations
- Corn and cellulosic ethanol and soy biodiesel (Qin et al 2016)
  - Cropland, grassland, and forest land to production of corn, switchgrass, Miscanthus, poplar, and willow

Feedstock Carbon Intensity Calculator (FD-CIC)

Cradle to farm-gate GHG emissions for feedstocks

- New tool for field-specific feedstock LCA
- Considers alternate farming practices
- Harmonized framework based on GREET
- Feedstocks significant in LCA of corn ethanol and other biofuels



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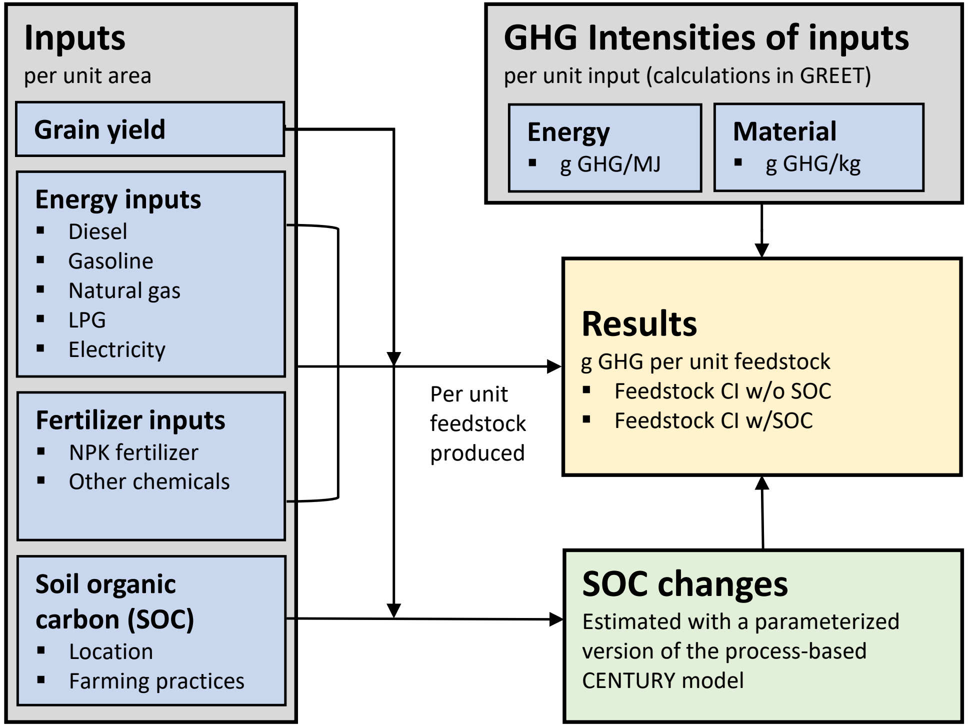


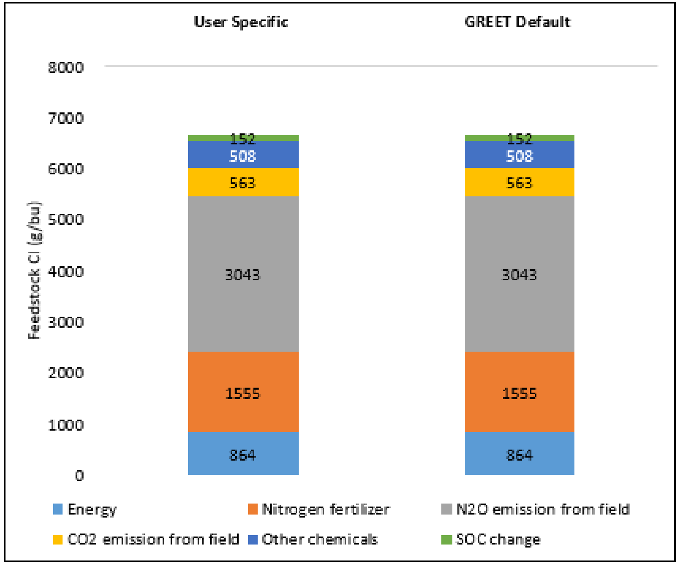
- Key parameters:
  - Crop yield
  - Energy consumption
  - Fertilizer/soil amendment use
  - Pesticide use
- Input supply chains from GREET

Feedstock Carbon Intensity Calculator (FD-CIC)

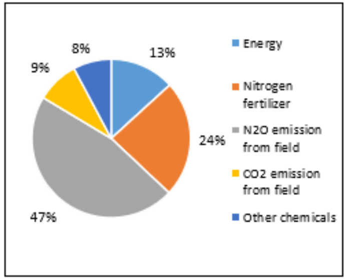
Cradle to farm-gate GHG emissions for feedstocks

1.2) Energy	User Specific GHG	GREET Default GHG	Unit
1.2.1) Diesel	491	491	g GHG/bu
1.2.2) Gasoline	77	77	g GHG/bu
1.2.3) Natural gas	39	39	g GHG/bu
1.2.4) Liquefied petroleum gas	86	86	g GHG/bu
1.2.5) Electricity	171	171	g GHG/bu
1.3) Nitrogen Fertilizer	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.3.1) Ammonia	394	394	g GHG/bu
1.3.2) Urea	239	239	g GHG/bu
1.3.3) Ammonium Nitrate	54	54	g GHG/bu
1.3.4) Ammonium Sulfate	28	28	g GHG/bu
1.3.5) Urea-ammonium nitrate solution	651	651	g GHG/bu
1.3.6) Monoammonium Phosphate as N fert	70	70	g GHG/bu
1.3.7) Diammonium Phosphate as N fert	119	119	g GHG/bu
N2O emission due to nitrogen fertilizer and bi	3043	3043	g GHG/bu
CO2 emission due to urea use	248	248	g GHG/bu
1.4) Phosphorus Fertilizer	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.4.1) Monoammonium Phosphate as P fert	166	166	g GHG/bu
1.4.2) Diammonium Phosphate as P fert	137	137	g GHG/bu
1.5) Potash Fertilizer	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.5.1) K2O	82	82	g GHG/bu
1.6) Lime	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.6.1) CaCO3	14	14	g GHG/bu
CO2 emission due to CaCO3 use	315	315	g GHG/bu
1.7) Herbicide	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.7.1) Herbicide	109	109	g GHG/bu
1.8) Insecticide	**User Specific GHG**	**GREET Default GHG**	**Unit**
1.8.1) Insecticide	0.27	0.27	g GHG/bu

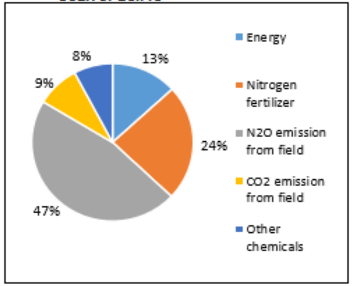
GHG, Conventional ammonia



GREET DEFAULT



USER SPECIFIC



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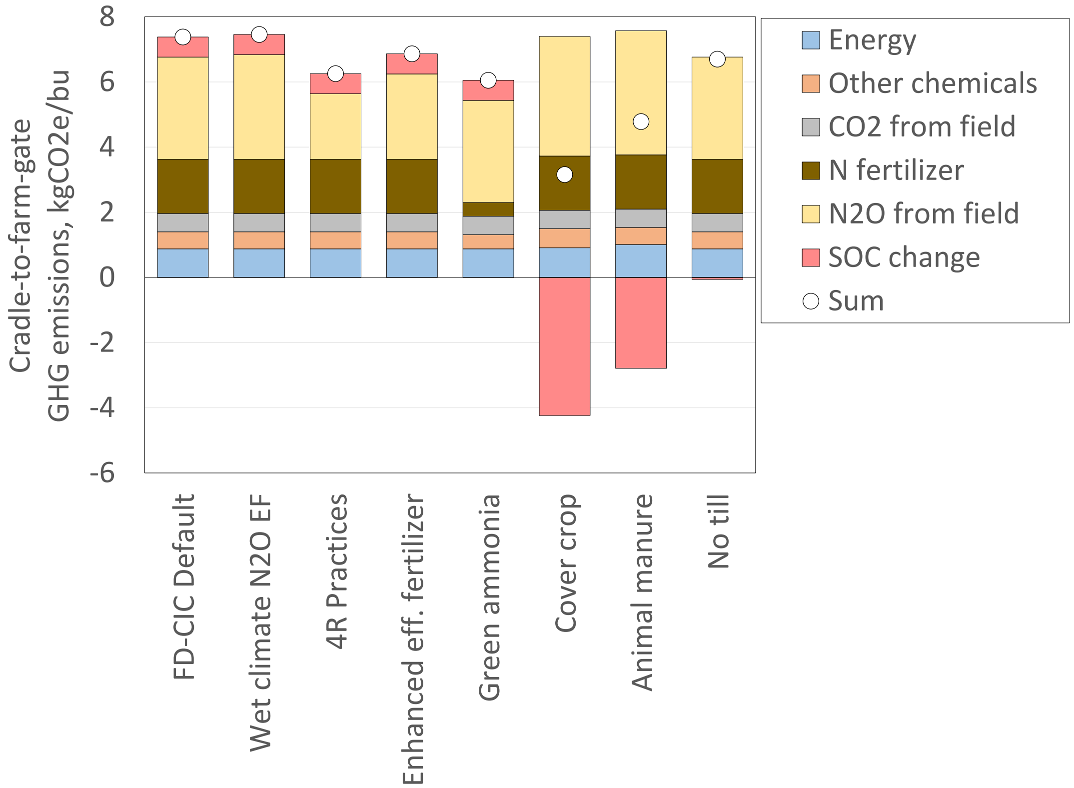
Feedstock Carbon Intensity Calculator (FD-CIC)

Farming practices significantly affect feedstock carbon intensities

- Soil carbon, N_2O, and inputs supply chains are all significant
- No-till, cover crops, and manure application can achieve low GHG biofuel feedstocks



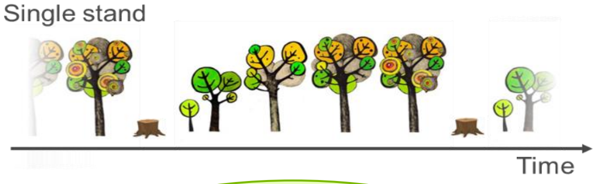
Expanding FD-CIC for Key Feedstocks & Management Options

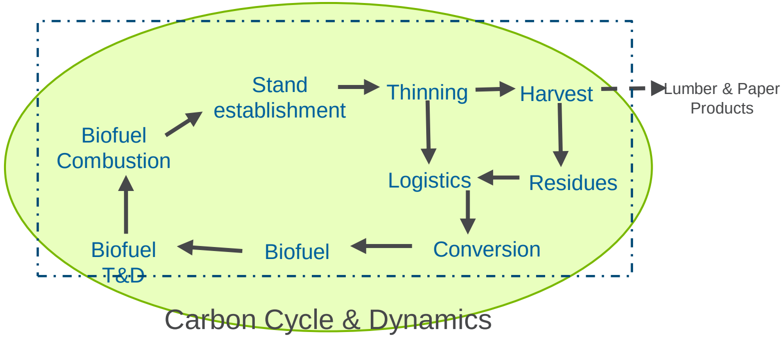
- Feedstocks
  - Domestic: corn, soybean, grain sorghum, rice
  - International: Brazilian sugarcane, Canadian corn
- Corn farm management practices
  - N_2O EFs for different climate zones
  - Nitrogen management: right time, right place, right form, right rate (4R’s) and enhanced efficiency fertilizer
  - Fertilizer production: conventional (fossil NG), green ammonia via electrolysis with renewable electricity
  - Cover cropping
  - Manure application
  - Tillage: conventional tillage, reduced tillage, and no tillage
- Rice farm management practices
  - Water management
  - Straw management

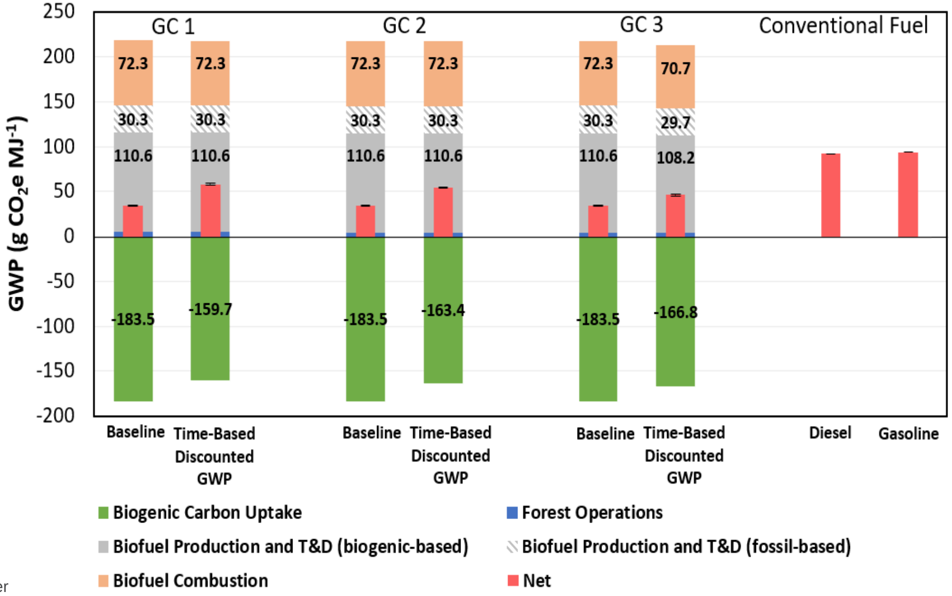
Wood Feedstock Production

Various species, temporal effects, whole tree and residuals

- GREET wood feedstocks include Pine, Douglas-Fir, Spruce/Fir, Eucalyptus, Poplar, Willow.
- Calculations based on growth cycles address temporal effects on C balance.







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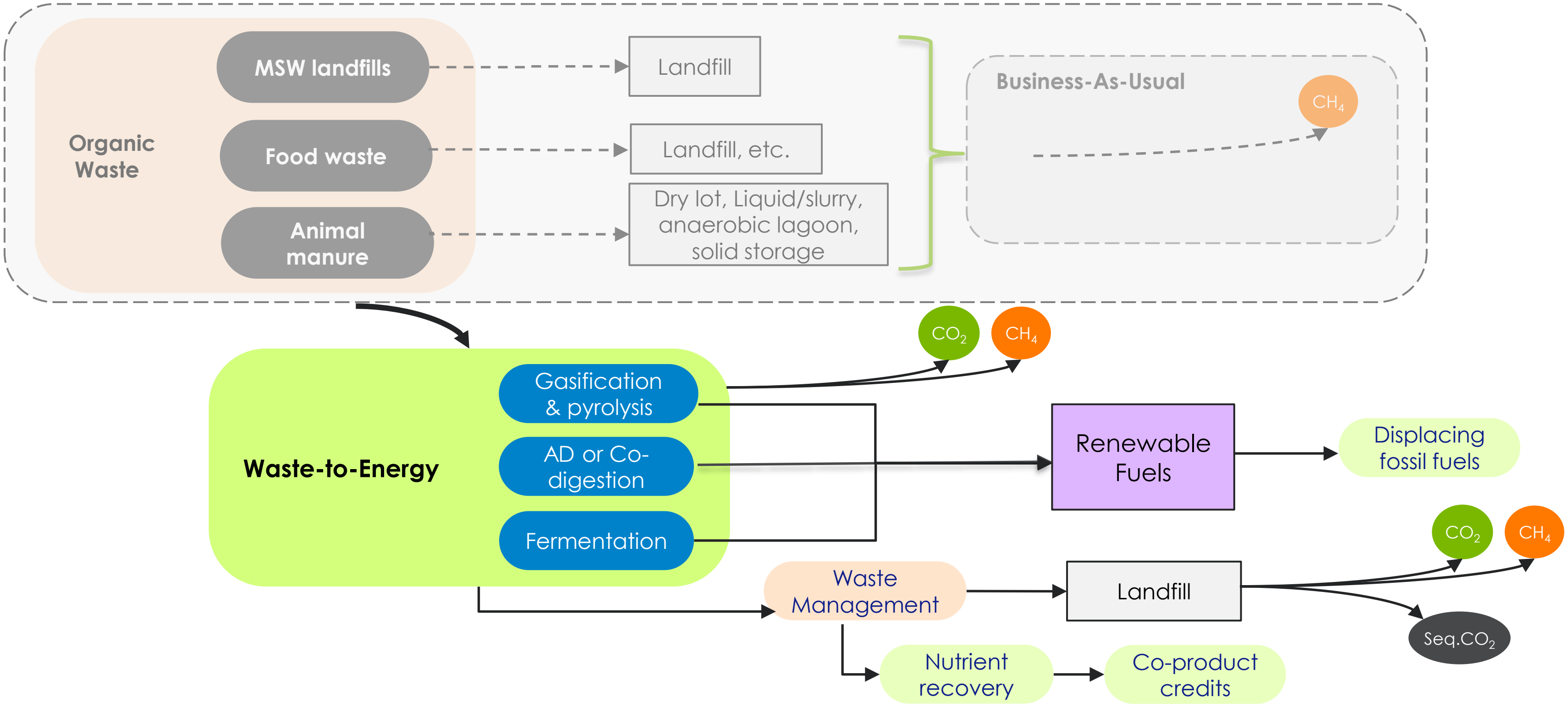
Avoided Emissions and Carbon Balance for Wastes

Quantifying the effect of diverting wastes from conventional mgt.



Seq. CO_2: Avoided CO_2 emissions from sequestered carbon; AD: Anaerobic digestion;

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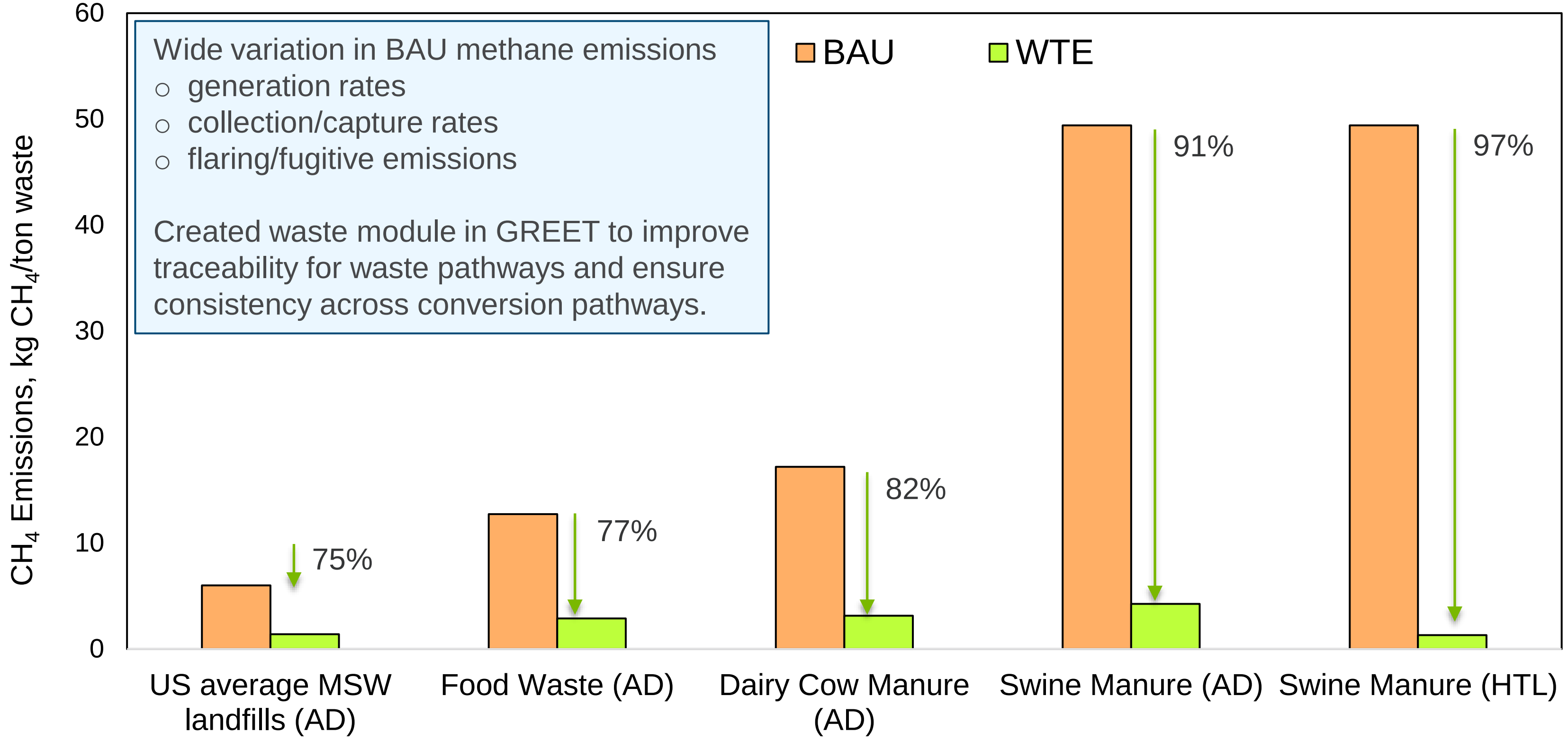
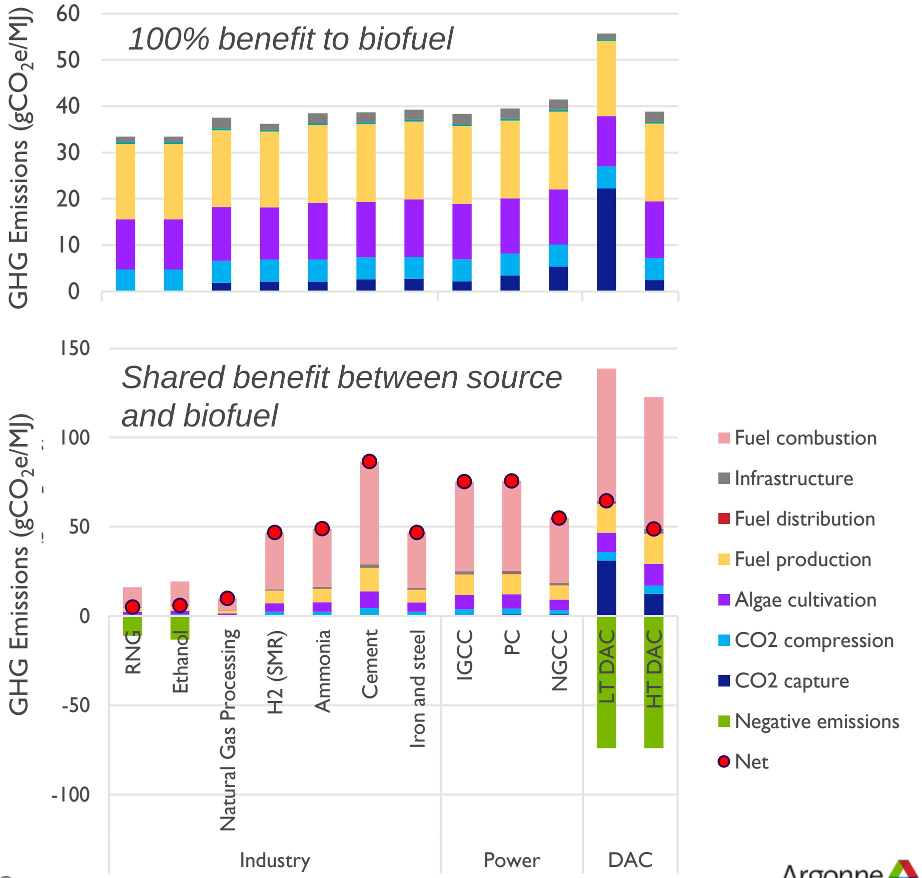


Microalgae Cultivation

Open Raceway and Photobioreactor

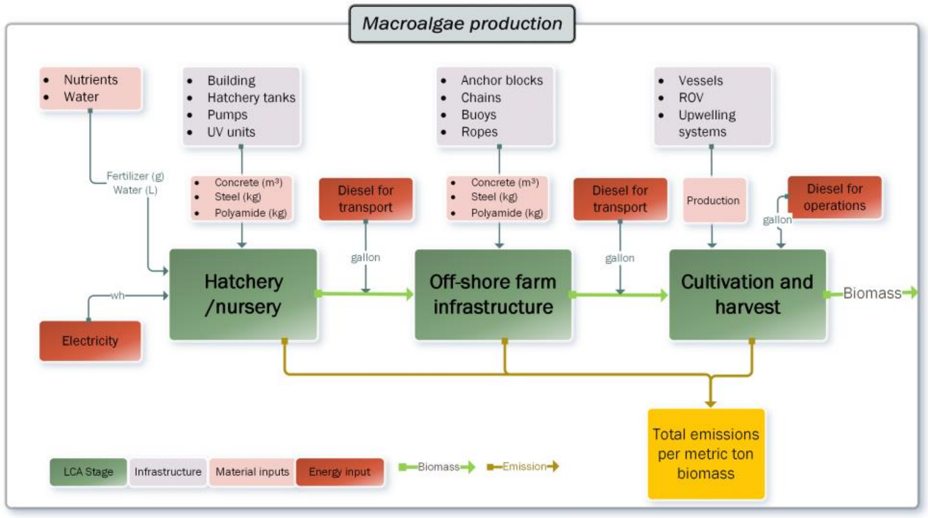
- Recent updates focusing on water stress, CO_2 source, and recycling of nutrients and carbon.
- Algae is often a CCUS pathway.
- Developed consistent projections across CO2 sources.
  - CO_2: biogenic, fossil, and direct air capture
  - Source CO_2 purity affects capture reqs.
  - Allocating CO_2 credit distinguishes sources
    - Biogenic CO_2: low carbon intensity
    - Fossil CO_2: higher carbon intensity
    - Direct air capture CO_2: potential for future



GREET Macroalgae Module

New – Released with GREET 2022

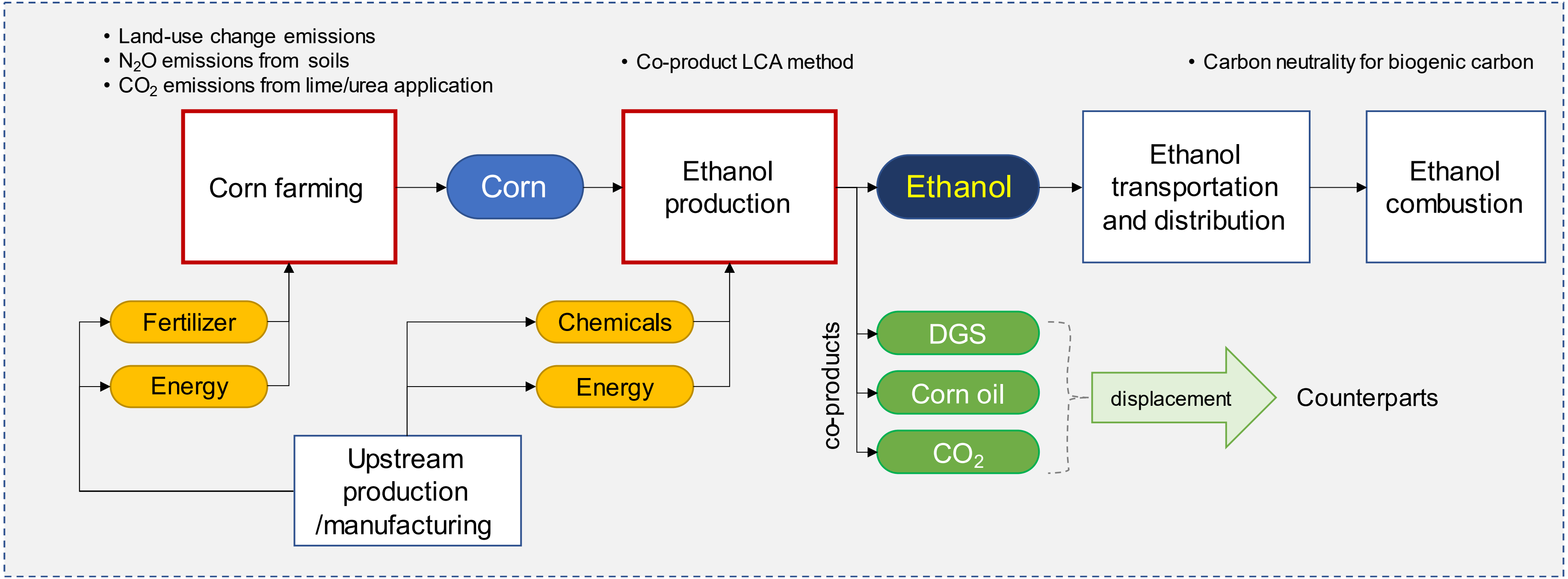
- **Support from ARPA-E MARINER**
- **Data collected from MARINER teams.**
- **Includes full life cycle for macroalgae production system**
  - Hatchery/nursery
  - Offshore farm infrastructure
  - Installation and maintenance
  - Cultivation and harvest
  - Also includes fuel production via hydrothermal liquefaction to provide a fuel functional unit
- Ready to parameterize with case-specific results
- Publication forthcoming



LCA of Biofuel Production

Corn Ethanol

Updated based on industry survey, GHG reduction potential, CO_2 capture



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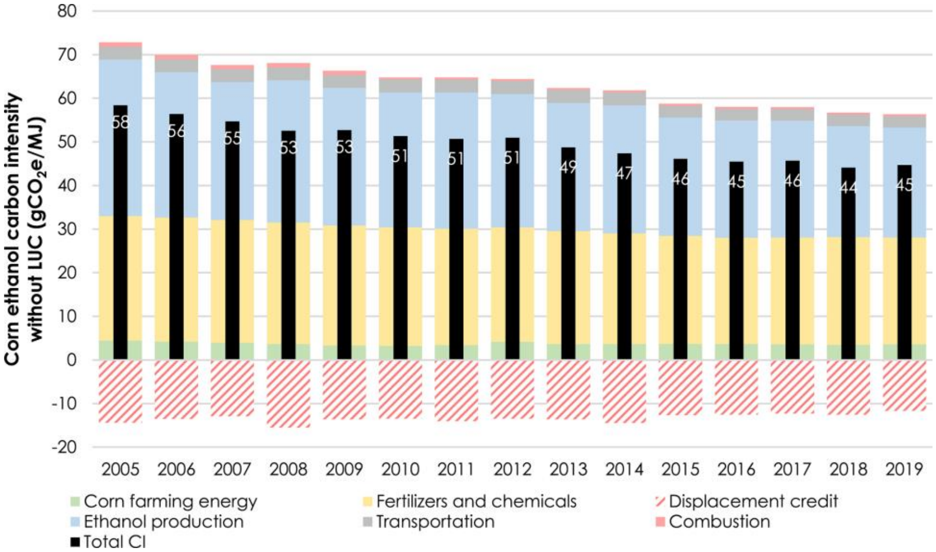
- Decrease in corn ethanol CI from 58 to 45 gCO2e/MJ over 2005-2019
  - Retrospective analysis based on industry survey
  - Increase in corn yield, 6.5% increase in ethanol yield/bushel, 24% reduction in ethanol plant energy use.
- Evaluated options for decarbonizing corn ethanol production.
- Evaluated use of high-purity fermentation CO_2 for producing additional ethanol via gas fermentation and electrochemical reduction.



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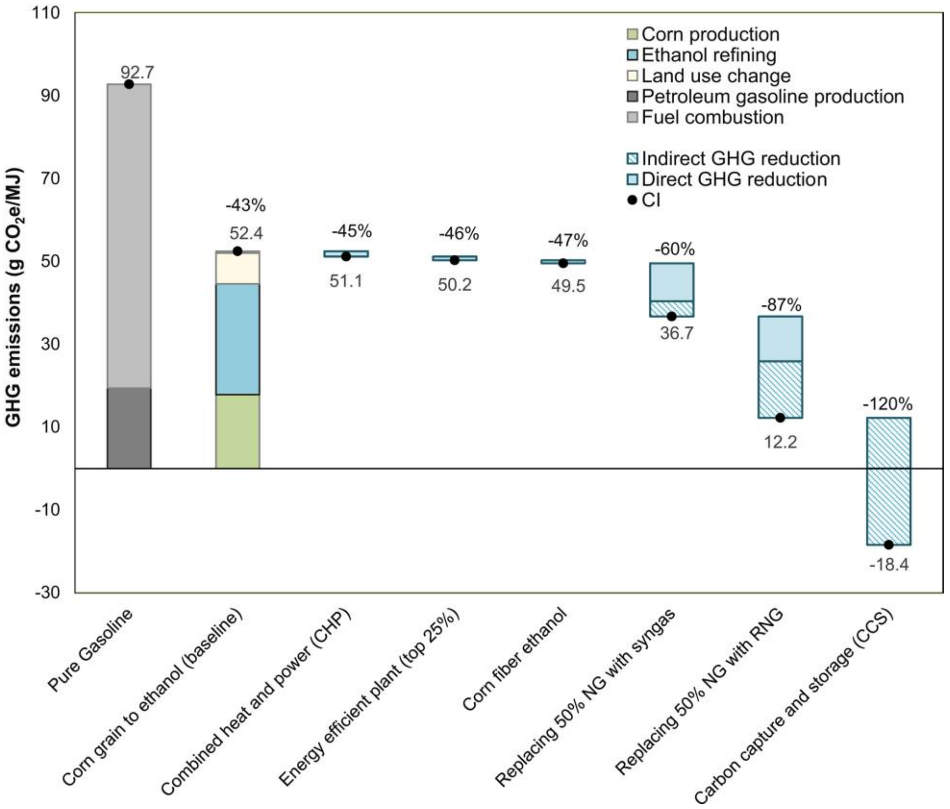

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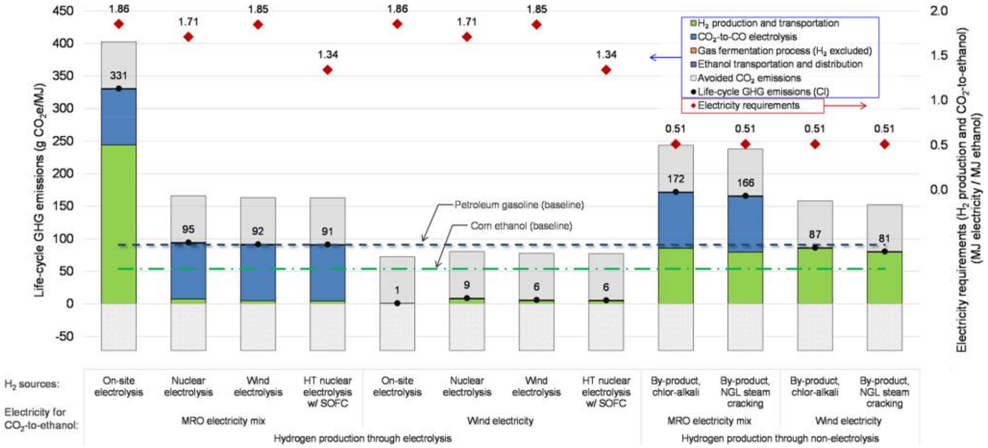
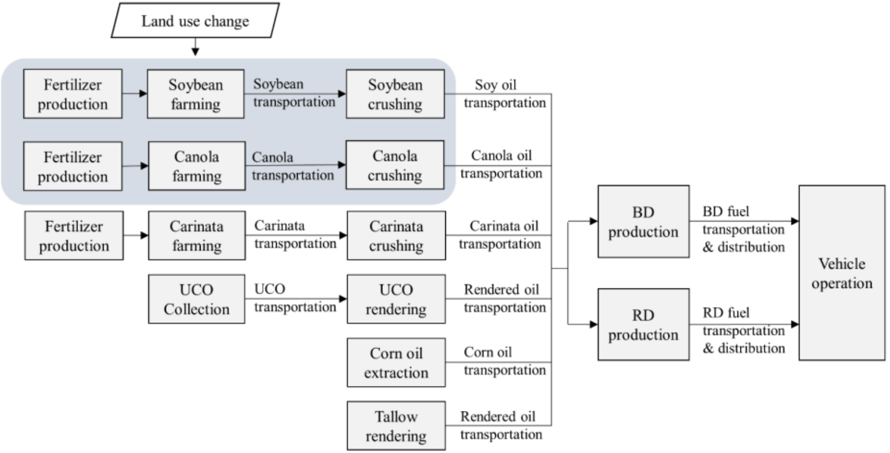
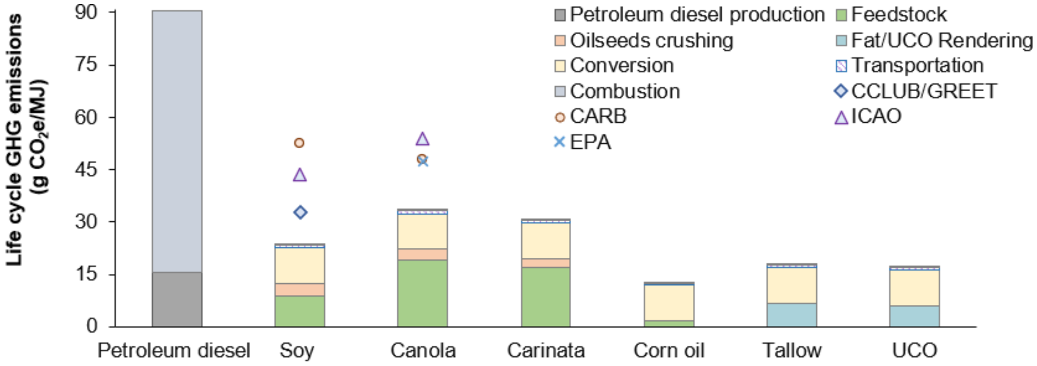


Biodiesel and Renewable Diesel

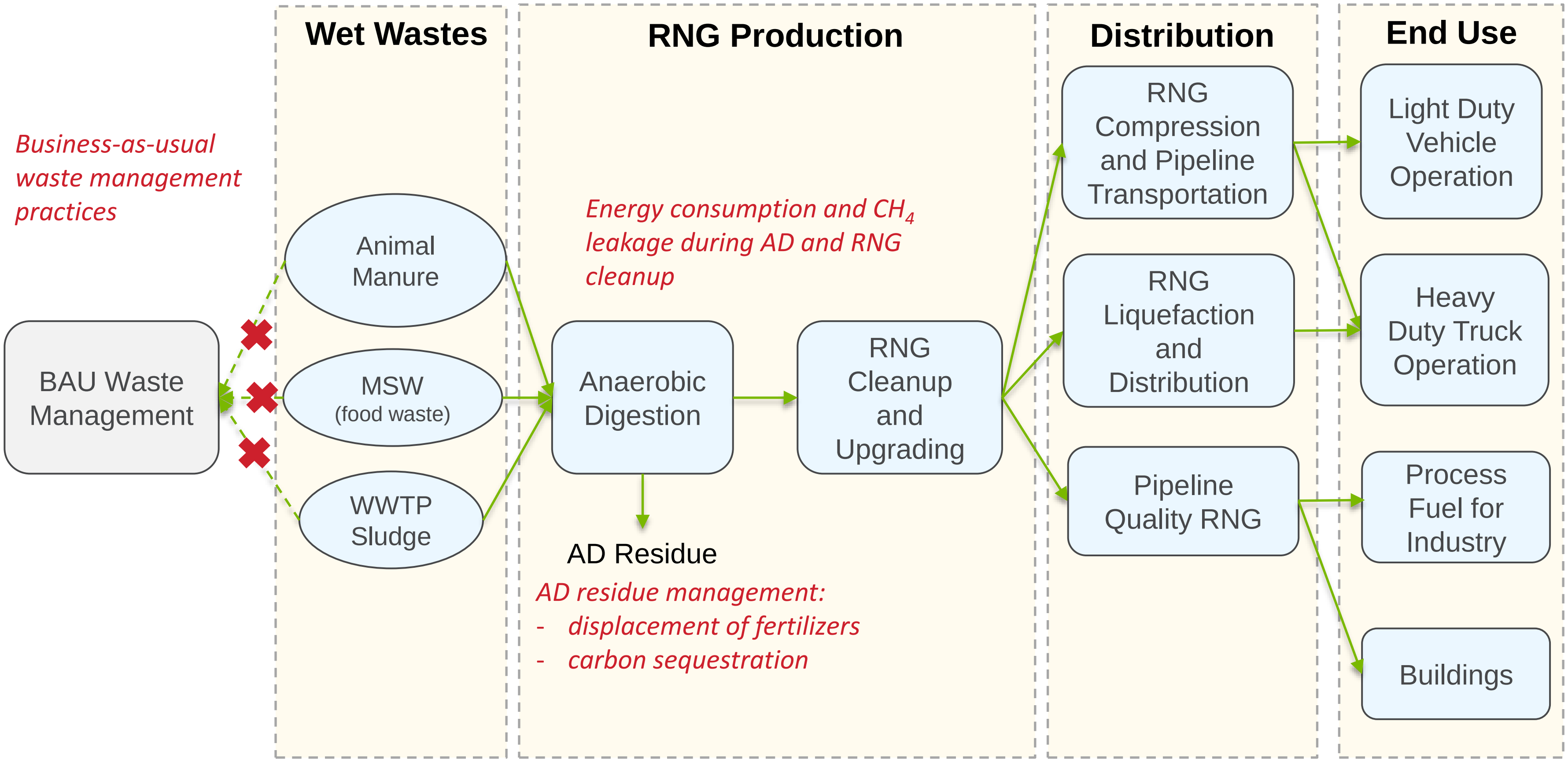
Updated in GREET 2022 based on industry survey data

- Updated using surveys of producers and renderers of animal fat and used cooking oil
- System boundary includes farming, conversion, use, and land-use change (when applicable)
- Carbon intensities for soy pathways can be 64-67% lower than petroleum diesel using the GREET LUC value
- Carbon intensities for waste pathways reach 79 to 86% reductions



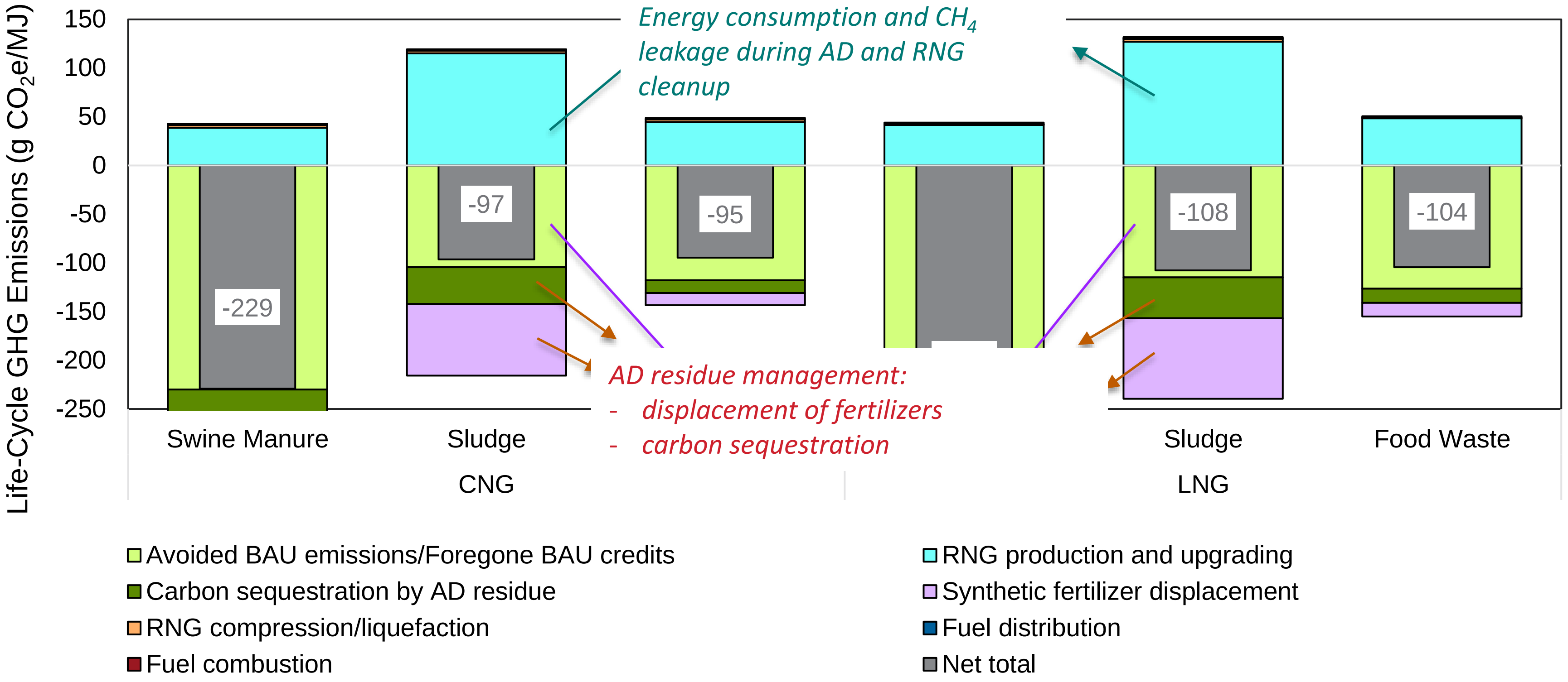


Renewable Natural Gas



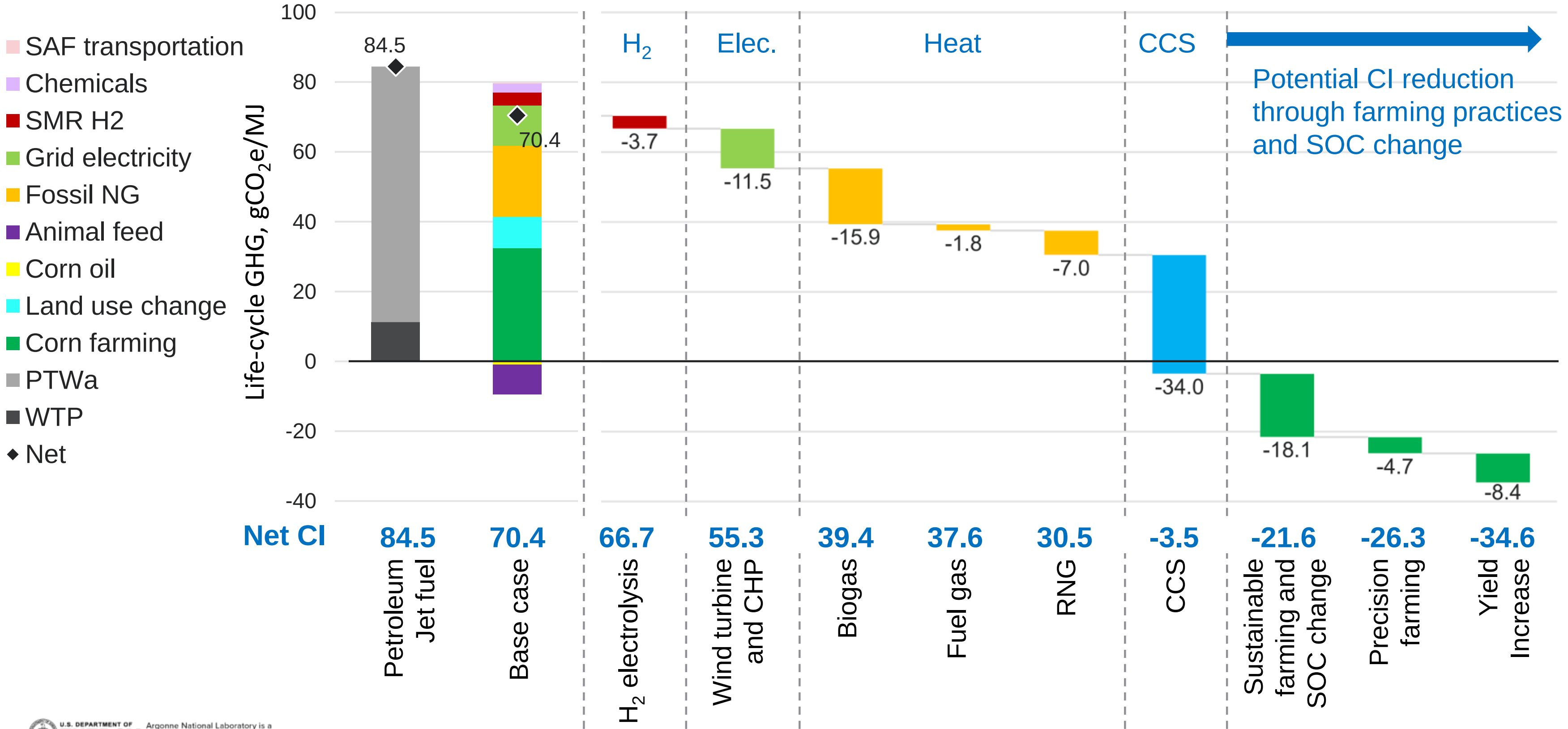
Renewable Natural Gas

Avoided emissions and displacement credits can be signficant



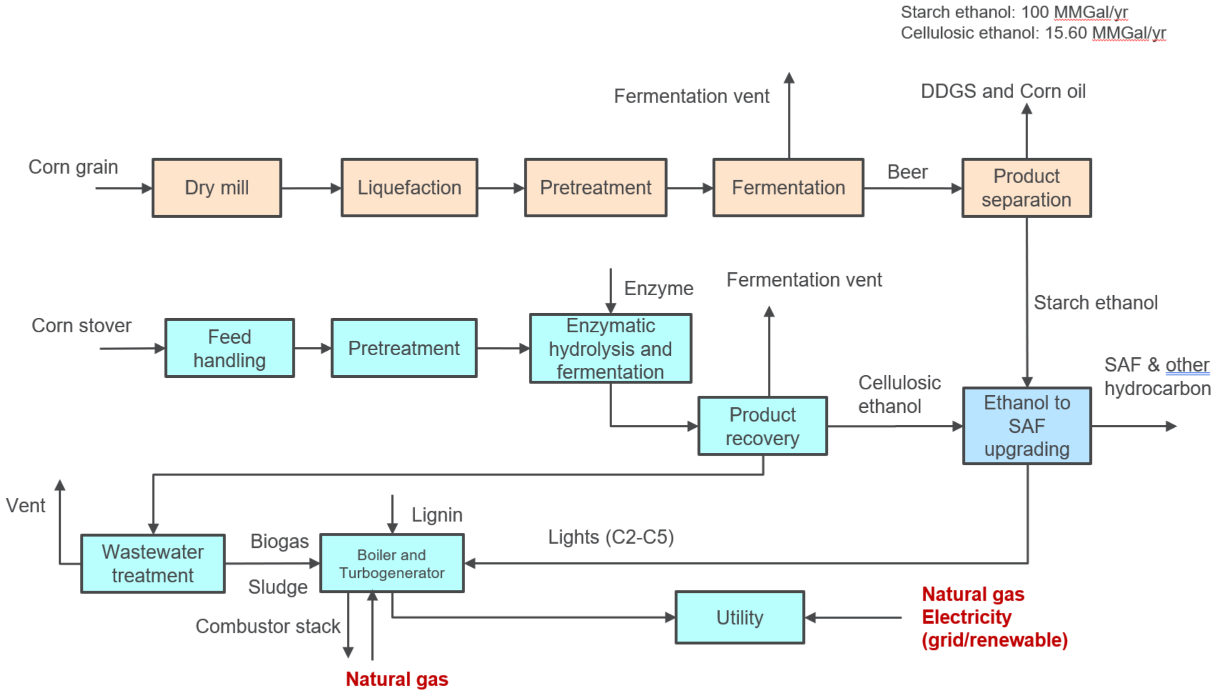
Sustainable Aviation Fuels

Adding Pathways and Identifying Opportunities to Reduce Emissions



Ethanol-to-Jet
From first- and second-generation ethanol

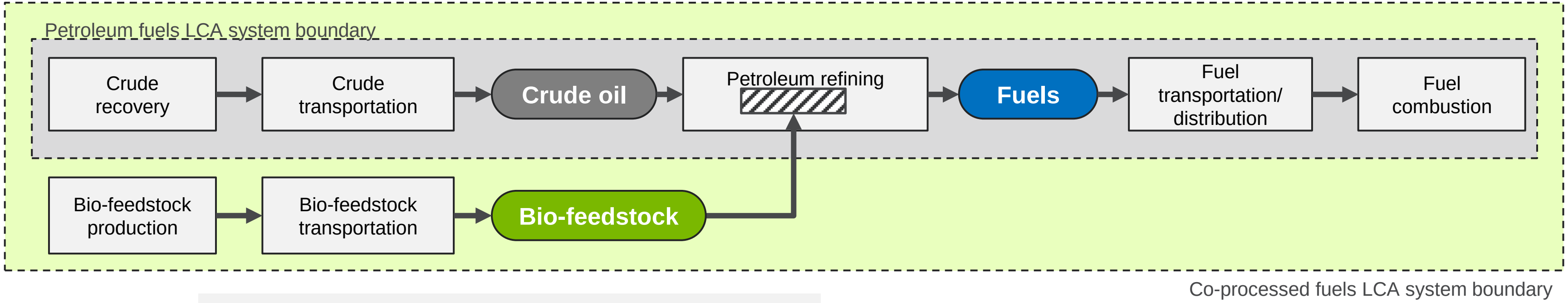
- Ongoing, completion spring 2023
- Corn grain and corn stover ethanol-to-jet pathways
- Comparing stand-alone and integrated (corn grain + corn stover) system designs
- Evaluating measures for deep decarbonization of the ethanol-to-jet pathway.
  - NG to biomass/RNG
  - Renewable electricity
  - Low carbon farming

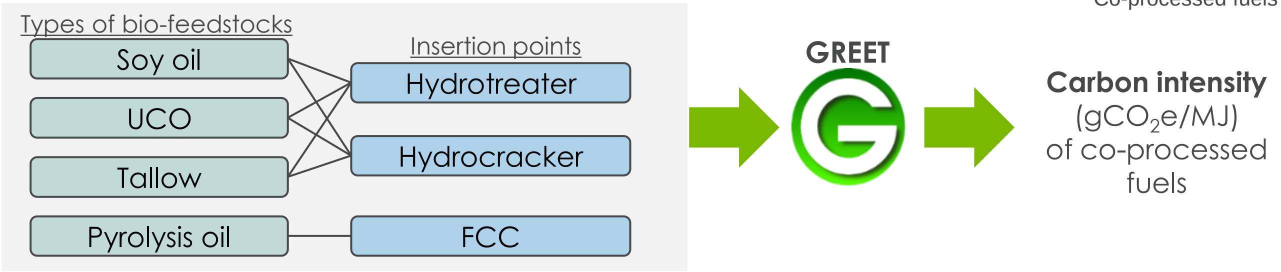


Refinery Biomass Co-Processing

New GREET module based on collaboration with ExxonMobil

Soy oil, used cooking oil, tallow, and pyrolysis oil inserted into hydrotreater, hydrocracker, and fluid catalytic cracker

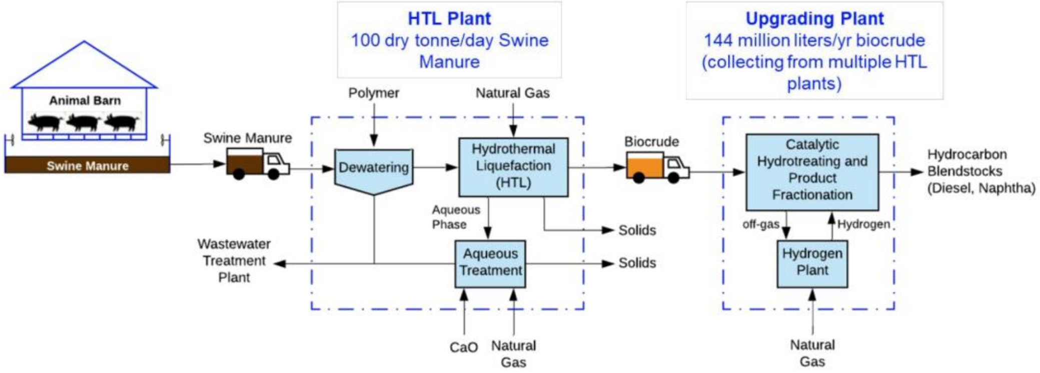


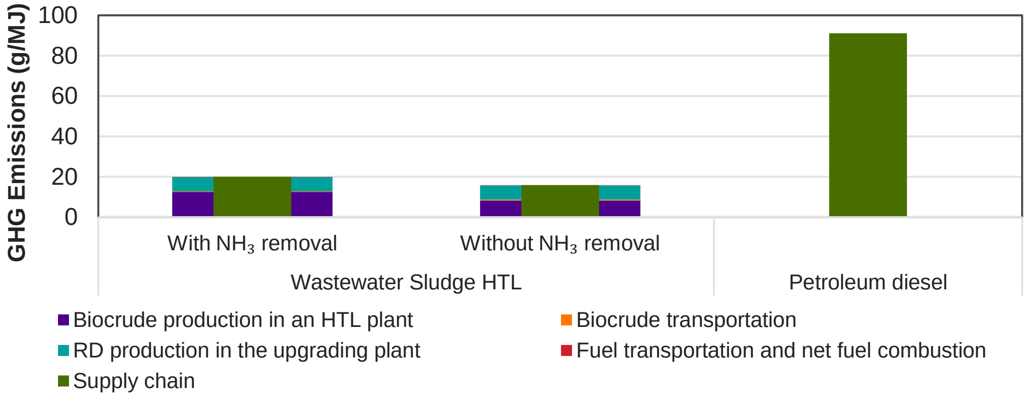


Hydrothermal Liquefaction

High temperature, high pressure conversion of wet feedstocks to biocrude

- HTL biocrude is hydroprocessed to produce hydrocarbon fuels.
- Various feedstocks:
  - Algae (*Algae* tab)
  - Wastewater sludge (*RNG* tab)
  - Animal manure (*RNG* tab)





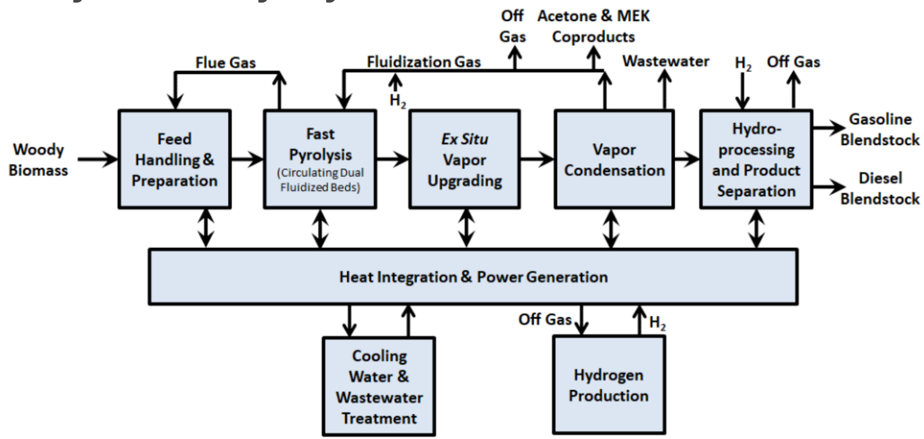
Pyrolysis and Fischer-Tropsch Synthesis Pathways

Conversion of woody and herbaceous feedstocks

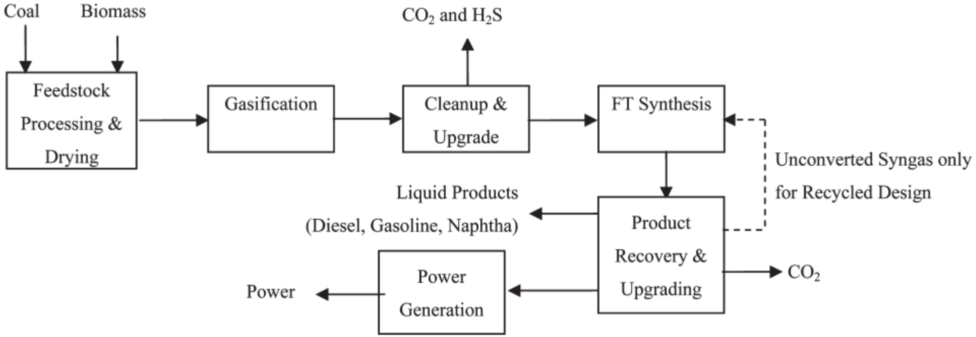
- **Pyrolysis**
  - GREET includes conventional, fast, and catalytic fast pyrolysis.
  - Pyrolysis pathways using a variety of wood and herbaceous biomass.
  - Pyrolysis oil is hydroprocessed to produce hydrocarbon fuels.

- **Fischer-Tropsch Synthesis**
  - Hydrocarbon fuels via gasification to Fischer-Tropsch synthesis.
  - FT pathways using various biomass as well as natural gas, coal, or blends.
  - FT pathways with CO_2 capture and sequestration.

Catalytic Fast Pyrolysis



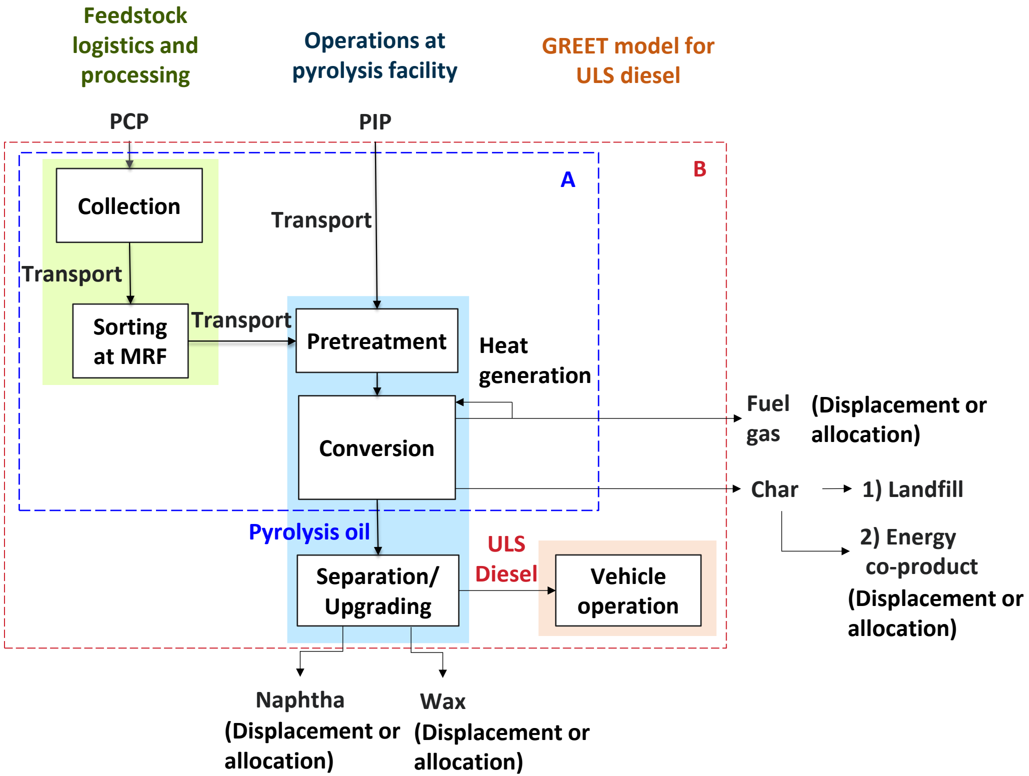
Fischer-Tropsch Synthesis



Pyrolysis Pathways

Conversion of post-use non-recycled plastics to fuel

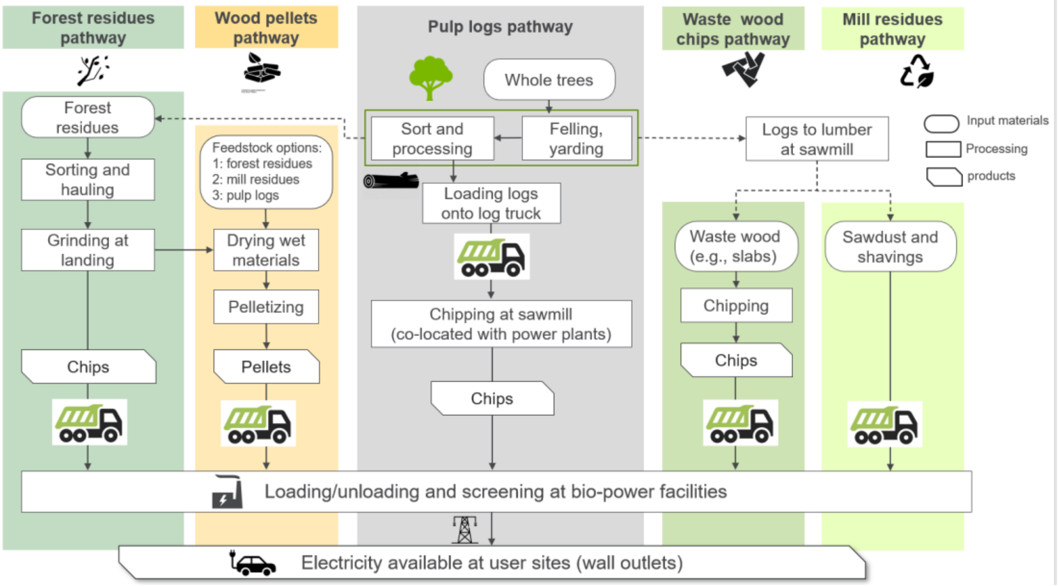
- Recently updated post-use non-recycled plastic-to-fuel pathway via pyrolysis
- Collected industry data through partnership with the American Chemistry Council
- Production of pyrolysis oil intermediate and ultra-low sulfur diesel fuel

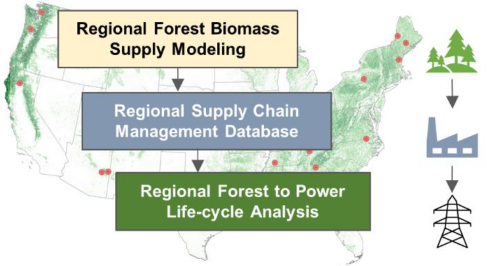


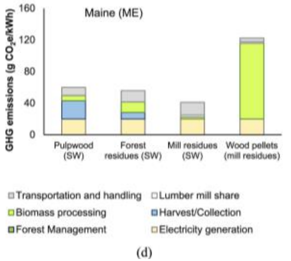
Bio-Electricity

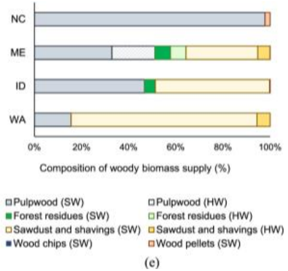
New bio-electricity module added from GREET 2021

- Bio-electricity from forest residues
- Results for 11 U.S. states
- Feedstock quantities, types, and composition by state based on economic modeling considering multi-sector interactions









Summary

- The GREET Model includes the full life cycle of many bioenergy feedstocks, conversion technologies, and end use fuels.
- Bioenergy and bioproduct pathways in GREET are regularly updated and expanded with support from our long-term sponsors BETO, ARPA-E, and USDA.
- Recent updates include corn ethanol, soy biodiesel, soy renewable diesel, and renewable natural gas, as well as new advanced pathways (waste feedstocks, cellulosic feedstocks, CCS/CCUS, non-recycled plastic)
- Publications, documentation, and models available at https://greet.es.anl.gov/

Thank you!

U.S. DEPARTMENT OF ENERGY

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CHANGING WHAT'S POSSIBLE

USDA

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