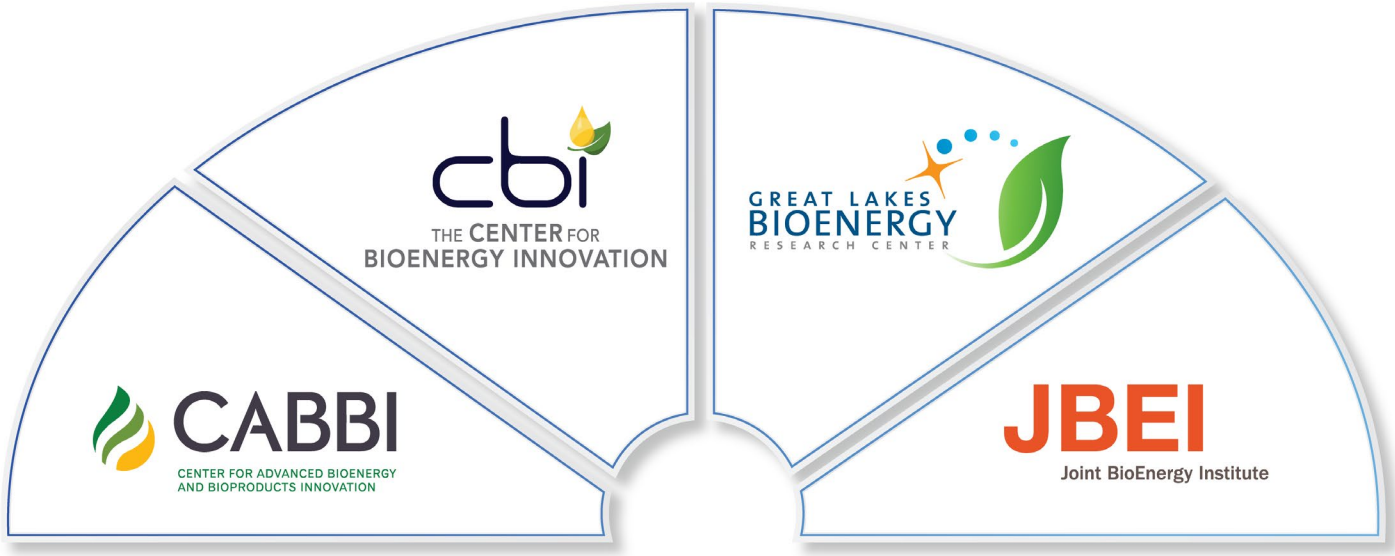
Bioenergy Research Centers: Paths to Sustainable Aviation Fuels

Brian Davison
CSO, Center for Bioenergy Innovation
August 15, 2023

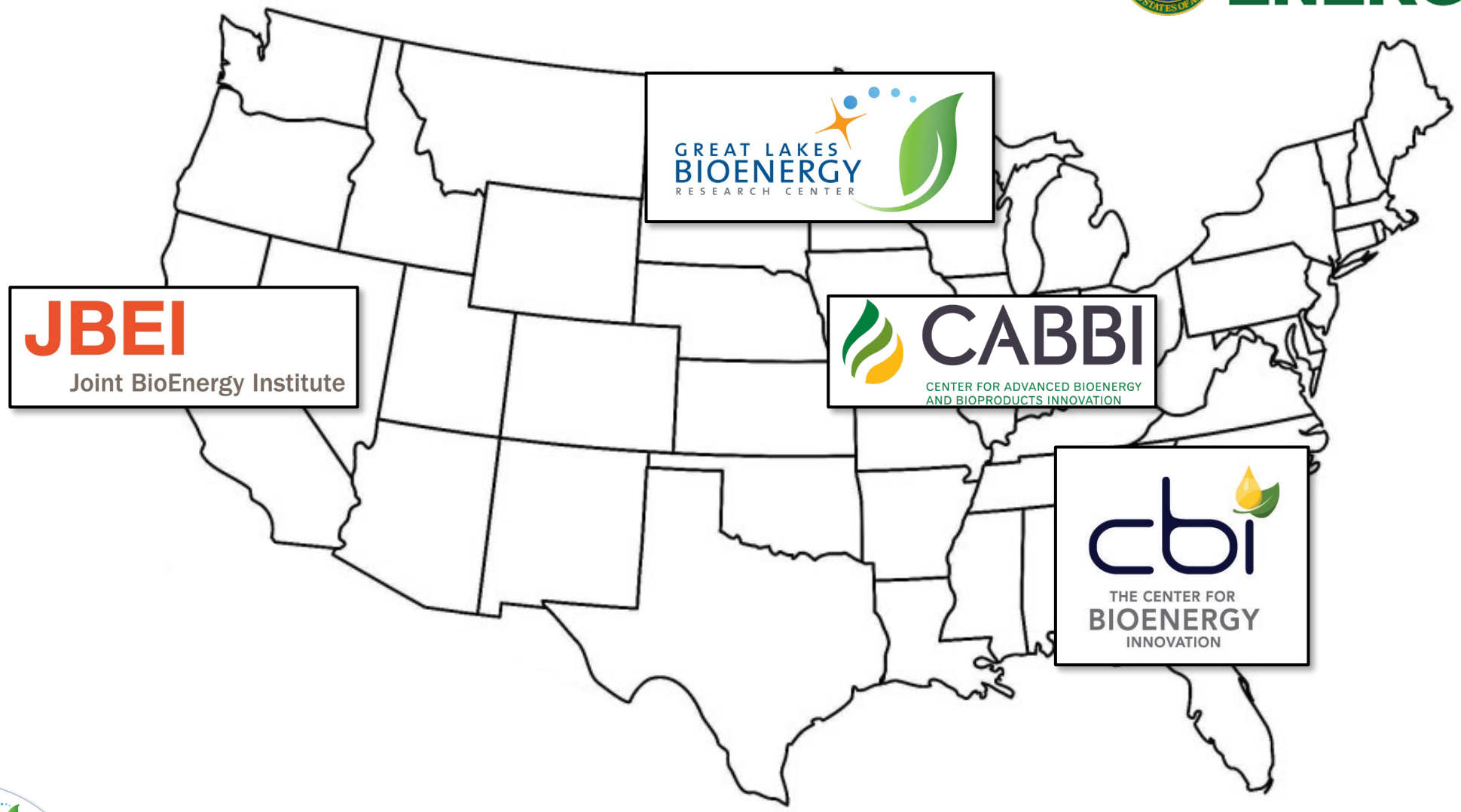
THE CENTER FOR BIOENERGY INNOVATION



Bioenergy Research Centers sponsored by the U.S. Department of Energy Office of Science Biological and Environmental Research Program

DOE funds four Bioenergy Research Centers (BRCs)

U.S. DEPARTMENT OF ENERGY | Office of Science



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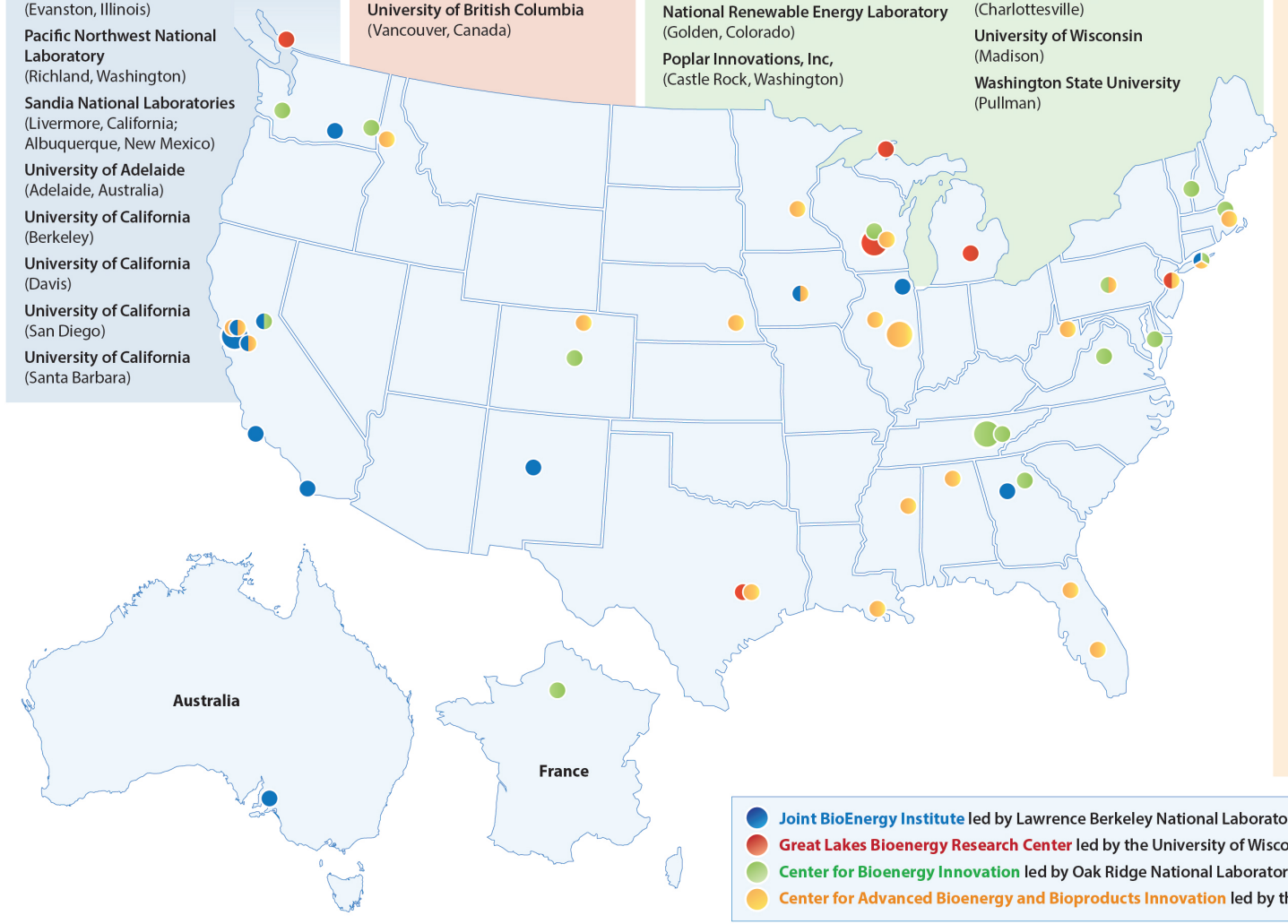
BRC research spans the country



Joint BioEnergy Institute

Lawrence Berkeley National Laboratory (Berkeley, California)
Brookhaven National Laboratory (Upton, New York)
Georgia Institute of Technology (Atlanta)
Iowa State University (Ames)
Lawrence Livermore National Laboratory (Livermore, California)
Northwestern University (Evanston, Illinois)
Pacific Northwest National Laboratory (Richland, Washington)
Sandia National Laboratories (Livermore, California; Albuquerque, New Mexico)
University of Adelaide (Adelaide, Australia)
University of California (Berkeley)
University of California (Davis)
University of California (San Diego)
University of California (Santa Barbara)

Great Lakes Bioenergy Research Center

University of Wisconsin (Madison)
Michigan State University (East Lansing)
Michigan Technological University (Houghton)
Princeton University (Princeton, New Jersey)
Texas A&M University (College Station)
University of British Columbia (Vancouver, Canada)

Center for Bioenergy Innovation

Oak Ridge National Laboratory (Oak Ridge, Tennessee)
Brookhaven National Laboratory (Upton, New York)
Dartmouth College (Hanover, New Hampshire)
Institut National de la Recherche Agronomique (INRAE) (Paris, France
Massachusetts Institute of Technology (Cambridge)
National Renewable Energy Laboratory (Golden, Colorado)
Poplar Innovations, Inc, (Castle Rock, Washington)
The Pennsylvania State University (State College)
University of California (Davis)
University of Georgia (Athens)
University of Maryland Eastern Shore (Princess Anne)
University of Tennessee (Knoxville)
University of Virginia (Charlottesville)
University of Wisconsin (Madison)
Washington State University (Pullman)

Center for Advanced Bioenergy and Bioproducts Innovation

University of Illinois Urbana-Champaign (Champaign, Illinois)
Archbold Biological Station (Venus, Florida)
Boston University (Boston, Massachusetts)
Brookhaven National Laboratory (Upton, New York)
Colorado State University (Fort Collins)
HudsonAlpha Institute for Biotechnology (Huntsville, Alabama)
Iowa State University (Ames)
Lawrence Berkeley National Laboratory (Berkeley, California)
Lawrence Livermore National Laboratory (Livermore, California)
Mississippi State University (Starkville)
Princeton University (Princeton, New Jersey)
Texas A&M AgriLife Research (College Station)
The Pennsylvania State University (State College)
University of California (Berkeley)
University of Florida (Gainesville)
University of Idaho (Moscow)
University of Minnesota–Twin Cities (Minneapolis)
University of Nebraska (Lincoln)
University of Wisconsin (Madison)
U.S. Department of Agriculture Agricultural Research Service (Houma, Louisiana; Peoria and Urbana, Illinois)
West Virginia University (Morgantown)

- **Joint BioEnergy Institute** led by Lawrence Berkeley National Laboratory
- **Great Lakes Bioenergy Research Center** led by the University of Wisconsin–Madison
- **Center for Bioenergy Innovation** led by Oak Ridge National Laboratory
- **Center for Advanced Bioenergy and Bioproducts Innovation** led by the University of Illinois Urbana-Champaign

CABBI JBEI

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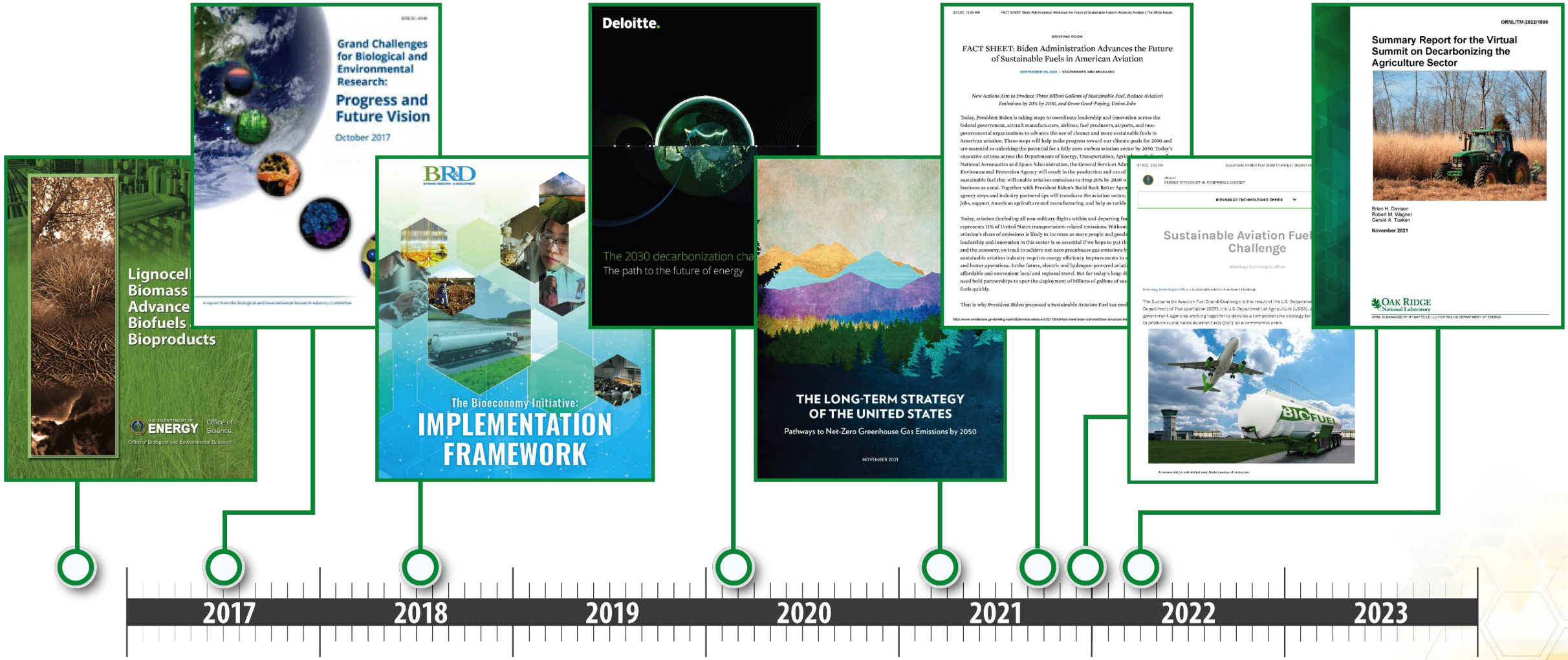
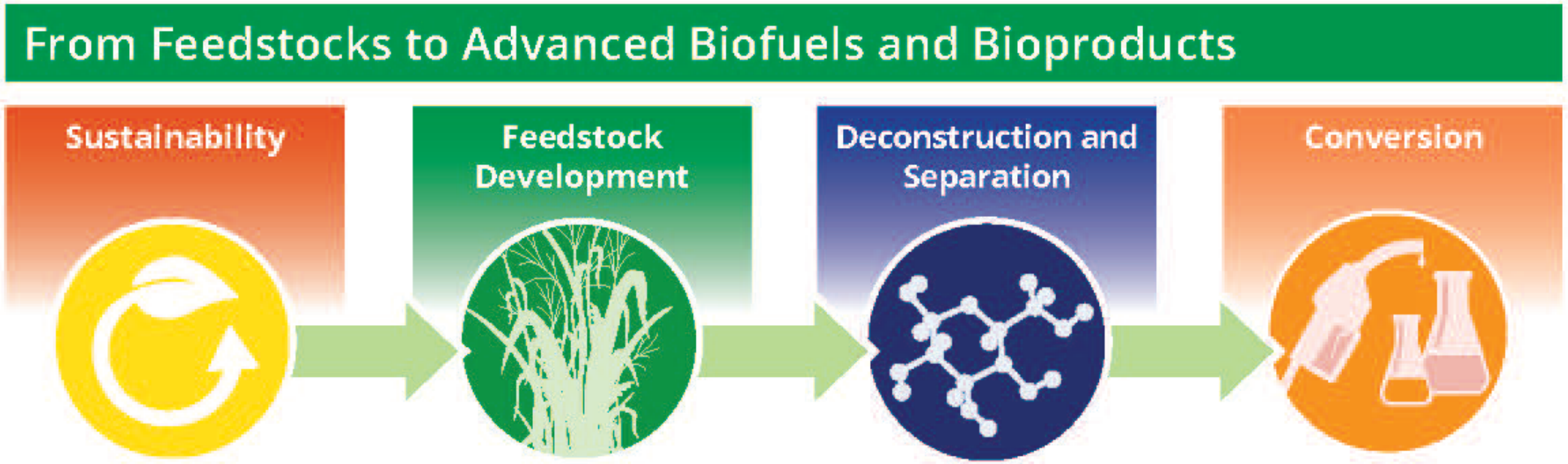
Historical Context



The BRCs perform fundamental science for DOE missions



Sustainability

Produce feedstocks for biofuels and bio-products with minimal to positive impacts on the environment.

Improved Plant Feedstocks

Develop crops with cell walls optimized for deconstruction and conversion to biofuels and bioproducts.

Feedstock Breakdown

Improve enzymes and microbes that break down feedstocks into sugars and lignin.

Biofuel and Bioproduct Synthesis

Engineer metabolic pathways in microbes to produce biofuels and bioproducts.

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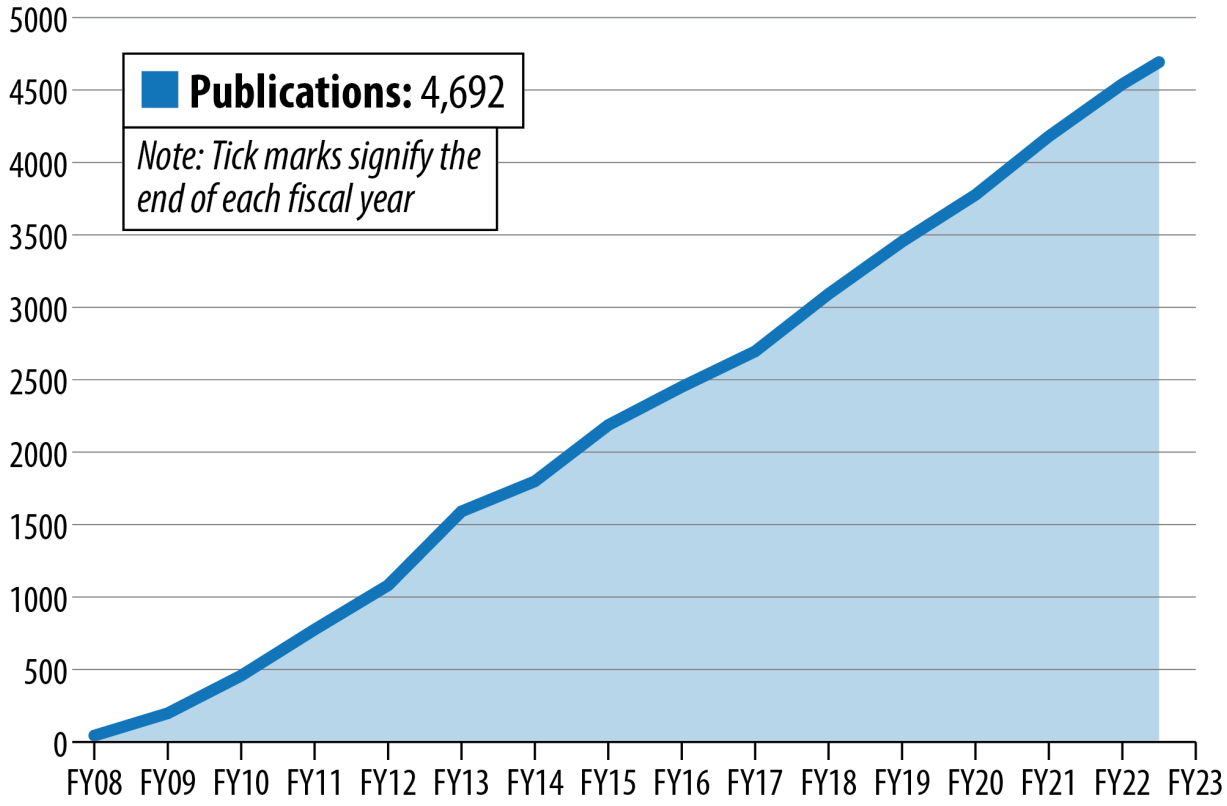
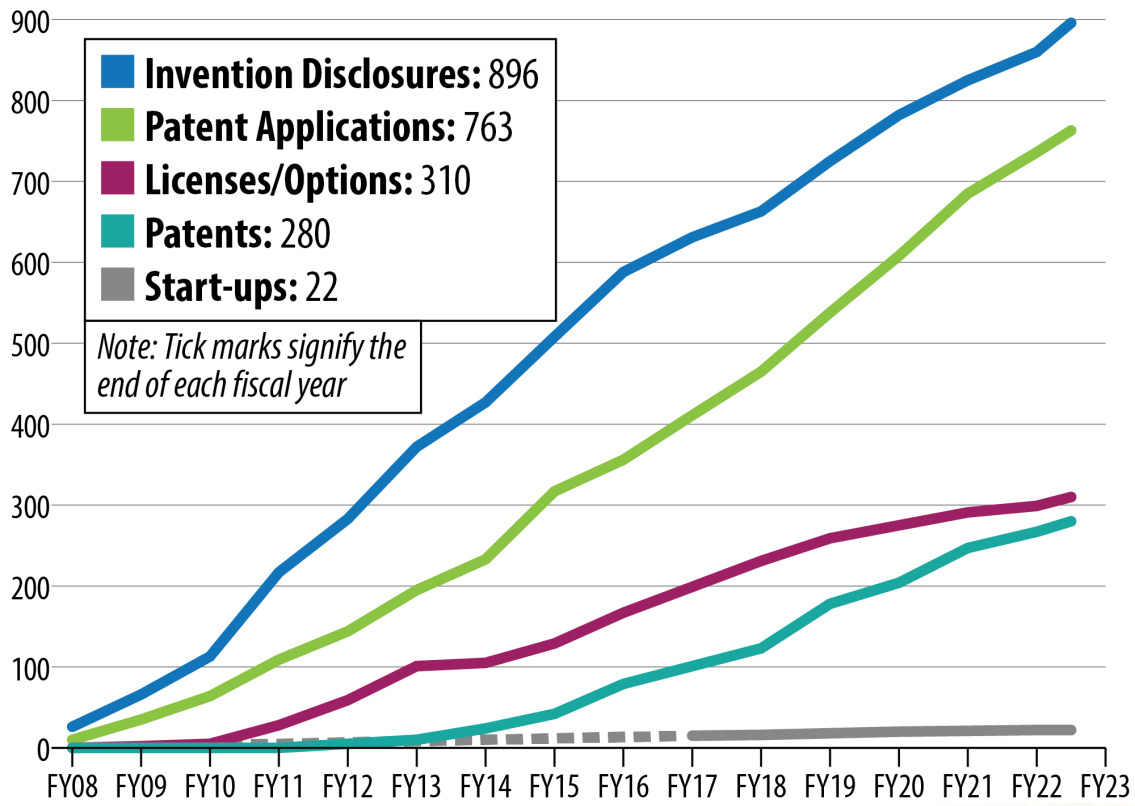
U.S. DEPARTMENT OF ENERGY | Office of Science

BRC Impact Metrics:
Accelerating Deployment of Science & Commercialization





(as of March 2023)

BRCs are learning where to fit into your SAF Drivers

Drivers in the SAF grand challenge

Aviation Fuel Consumption
- 200 million ton/year in 2012
- Predicted 852 million ton/yr by 2050

Industry-Wide Emissions Reduction
- 50% of 2005 levels by 2050

Four Ways to 2050 Goals
- Better engines (20%)
- Better ATC (10%)
- Better operations (10%)
- **SAF (50%)**

Fundamental Proof-of-Concept Goals: Demonstrate that the various BRC feedstocks-to-fuels processes will support various blendstocks for SAF.

BRCs are collaborating with WSU Heyne lab to orm the Tier Tier α/Tier β SAF tests

WASHINGTON STATE UNIVERSITY TRI-CITIES

How much renewable carbon do we need?

- 35 B gallons of SAF = 800 M tons of biomass
- 9 B gallons of marine fuel = 150 M tons of biomass
- 5 B gallons of biodiesel = 80 M tons of biomass
- 100 M tons of chemicals (50% of today's market) = 400 M of biomass

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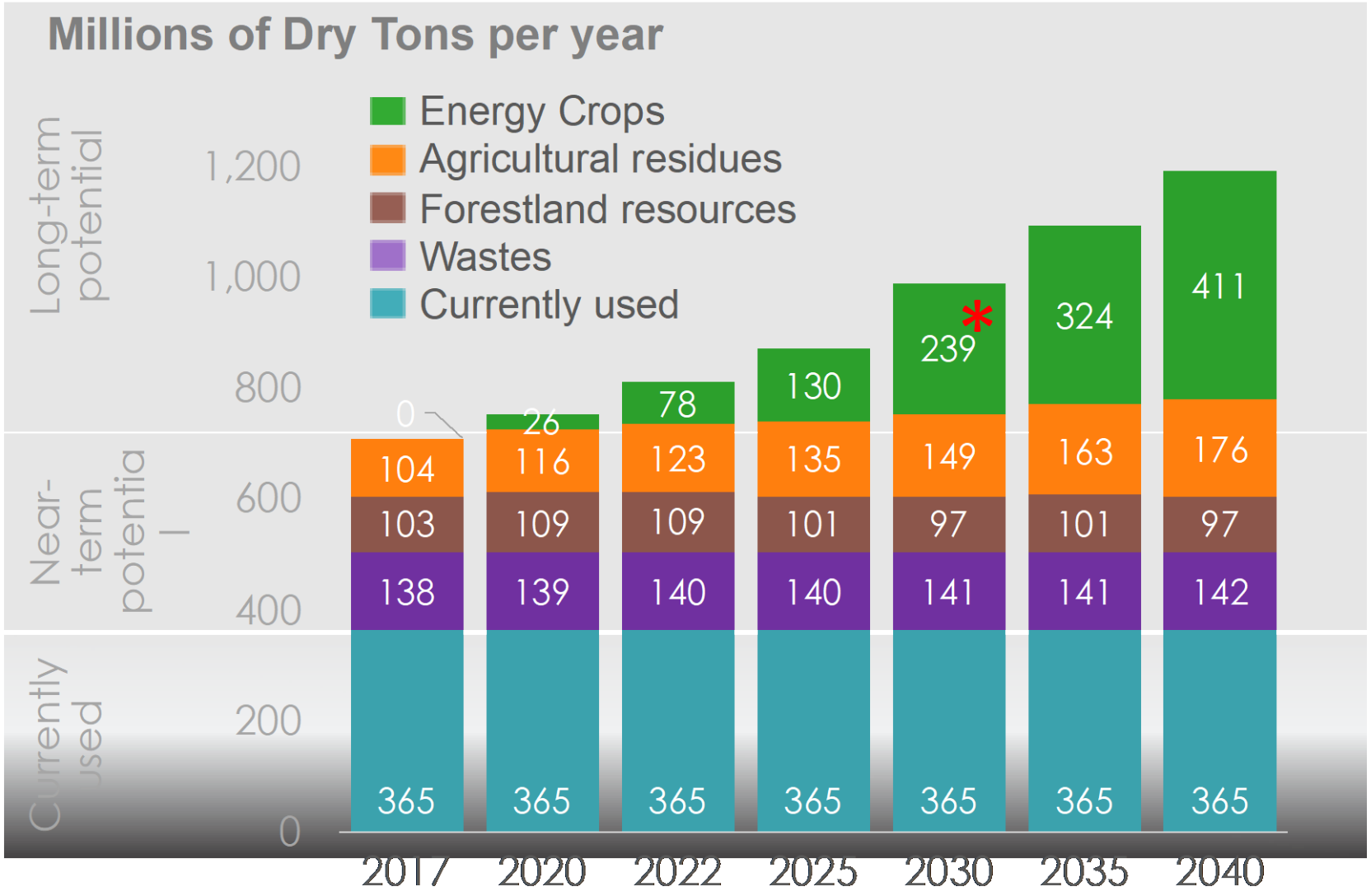
- TOTAL = 1.5 B tons of biomass (very conservative)

Where will the biomass come from?



*

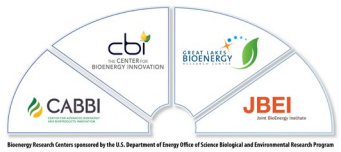
represents approximately 27 million acres

ca. 0.8 billion tons of new potential

U.S. Department of Energy. 2016. doi: 10.2172/1271651.

Introduction to the BRCs

- CBI – Brian Davison
- JBEI – Aindrila Mukhopadhyay
- CABBI – Andrew Leakey
- GLBRC – Tim Donohue
- Working with BRCs and IP – Jennifer Gottwald, WARF
- QA



The Center for Bioenergy Innovation and Sustainable Aviation Fuels

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August 15, 2023
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CBI Vision and Innovation Targets

The Center for Bioenergy Innovation vision is to accelerate domestication of bioenergy-relevant, non-model plants and microbes to enable high-impact innovations within the sustainable aviation fuels (SAF) domain.

Innovation Targets

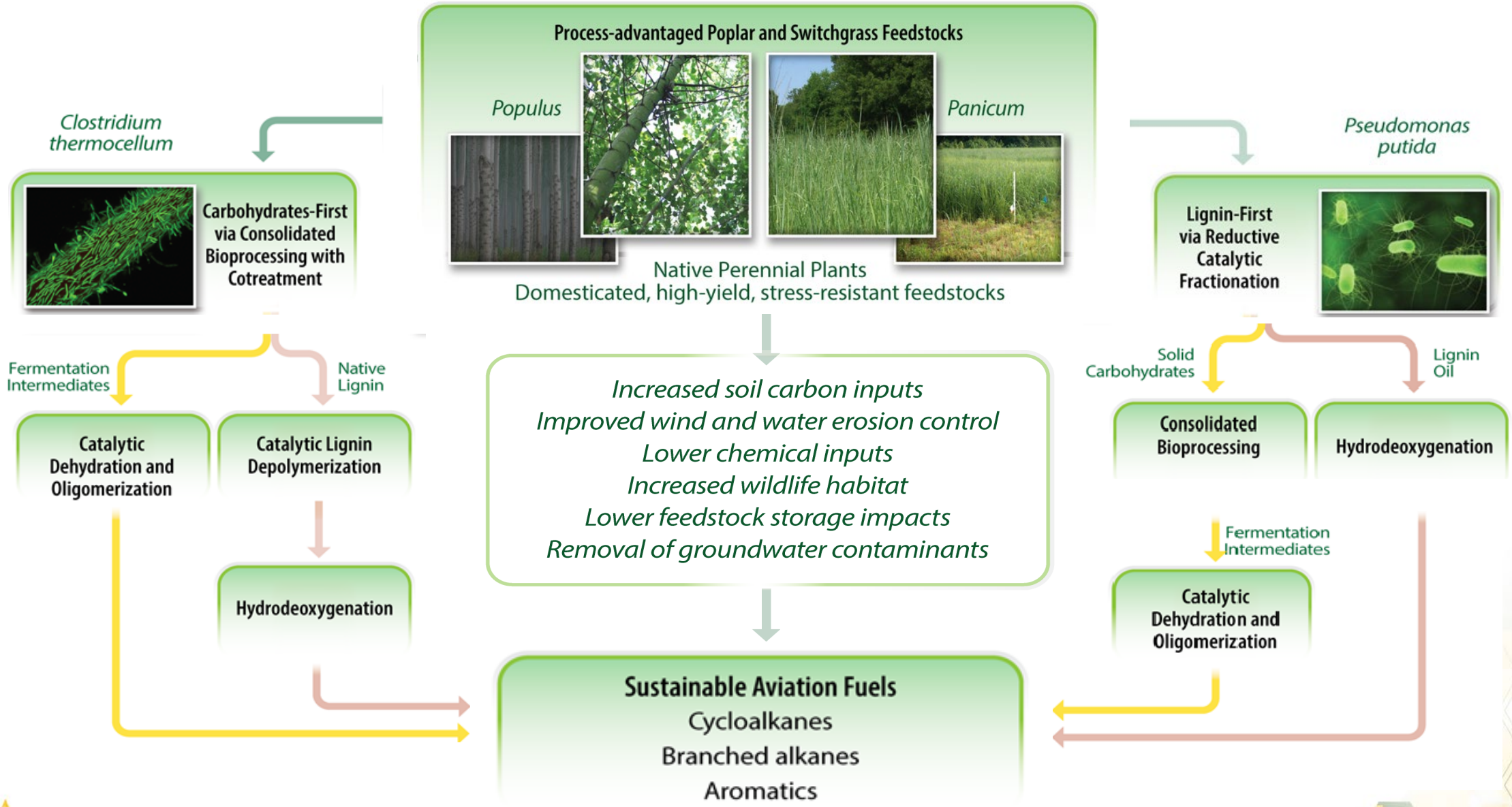
1. Develop sustainable, process-advantaged biomass feedstocks

2. Refine consolidated bioprocessing with cotreatment to create fermentative intermediates

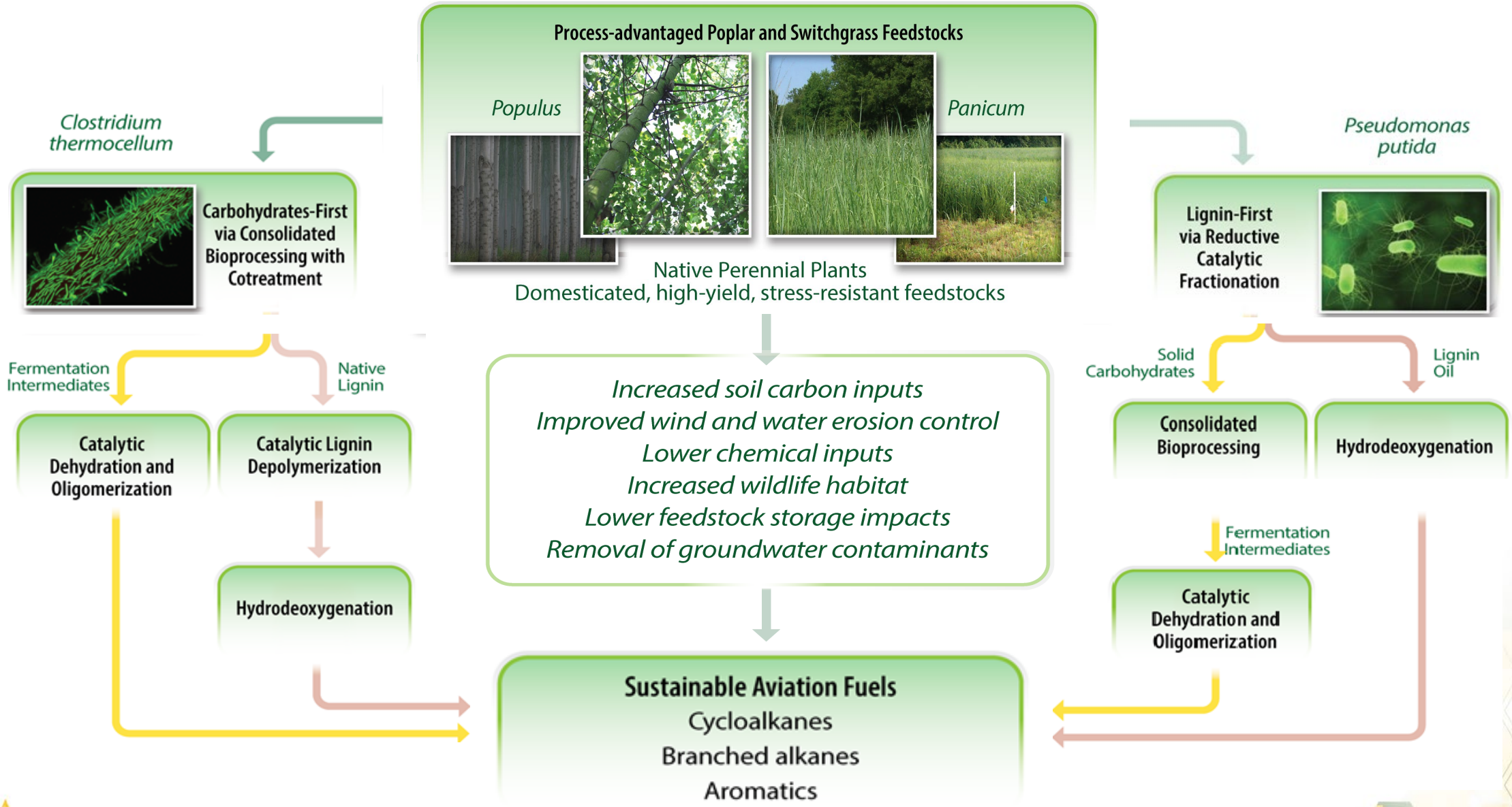
3. Advance lignin valorization for bio-based products and aviation fuel feedstocks

4. Improve catalytic upgrading for SAF blend stocks certification

CBI research structure and approach



CBI Research Structure and Approach



There is Significant Economic Impact of Variation in Plant Yield and Composition for Poplar

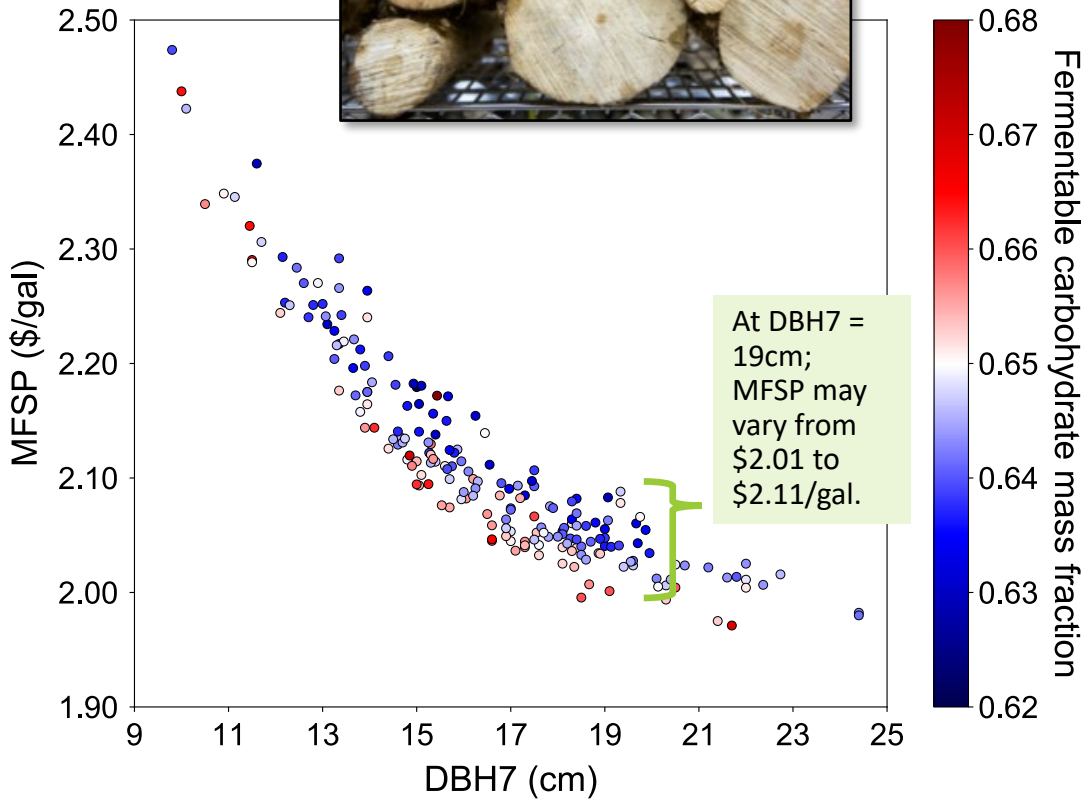
- There is a wide range of variation in natural populations of perennial biofeedstock

Approach

- Improved HTP compositional analytics provides the full range of natural variation
- The poplar supply chain simulation model was used to estimate the cost of poplar based on tree size delivered to the biorefinery.
- Technoeconomic sensitivity was performed on representative sample of 204 poplar clones from GWAS population wrt biomass yield and carbohydrate composition.
- Utilized Aspen Plus model based on the NREL biomass conversion base case (pretreatment, enzymes, and fermentation) into ethanol intermediate.

Outcome

- **Biomass yield (as DBH7) was the strongest influence on economics due to high variation and feedstock costs.**
- **After biomass yield, composition (i.e., feedstock quality) becomes an equally important parameter on MFSP.**



MFSP (minimum fuel selling price) vs DBH7 and fermentable carbohydrate

Happs, Bartling, Doeppke, Harman-Ware, Clark, Webb, Biddy, Chen, Tuskan, Davis, Muchero, and Davison "Economic Impact of Yield and Composition Variation in Bioenergy Crops: *Populus trichocarpa*" *Biofuels, Bioproducts and Biorefining* (2020): dx.doi.org/10.1002/bbb.2148

CBI Proof-of-Process(es): Tier α/Tier β SAF Goal

- **Proof-of-Process Goal:** Demonstrate that the CBI feedstocks-to-fuels process supports upgrading of carbohydrates and lignin from corn stover, process-advantaged switchgrass and process-advantaged poplar into a tunable portfolio of branched alkanes, cycloalkanes, and aromatics for use as components in complete SAF.
- Three feedstocks
  - Stover
  - Poplar
  - Switchgrass
    - We have gathered and milled 30 kg of each
- Two major possible workflows
  - Carbohydrate 1st/Lignin 2nd
    - CBP/RCF/upgrading
  - Lignin 1st/Carbohydrate 2nd
    - RCF/CBP/upgrading
- Outcome: three possible blendstocks into Tier α/Tier β tests
  - Aromatics
  - Branched alkanes
  - Cycloalkanes

Poplar Innovations Inc.

OAK RIDGE National Laboratory

UNIVERSITY OF GEORGIA

NREL NATIONAL RENEWABLE ENERGY LABORATORY

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Massachusetts Institute of Technology

CBI is collaborating with WSU Heyne lab to perform the Tier α/Tier β SAF tests

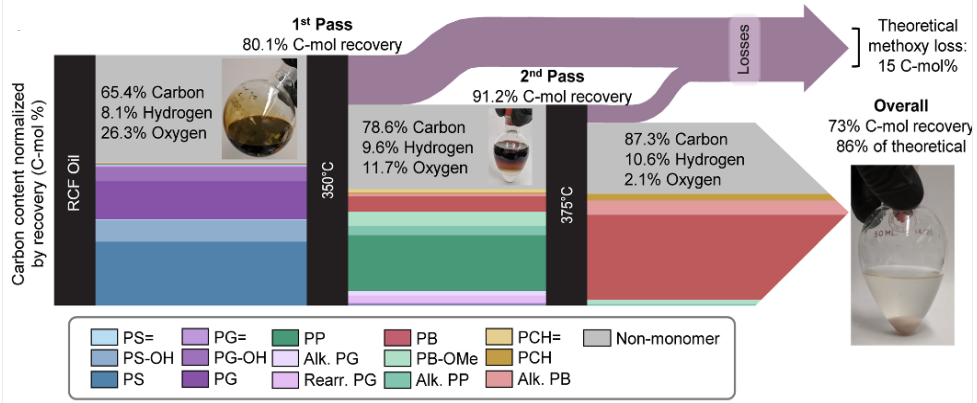
WASHINGTON STATE UNIVERSITY TRI-CITIES

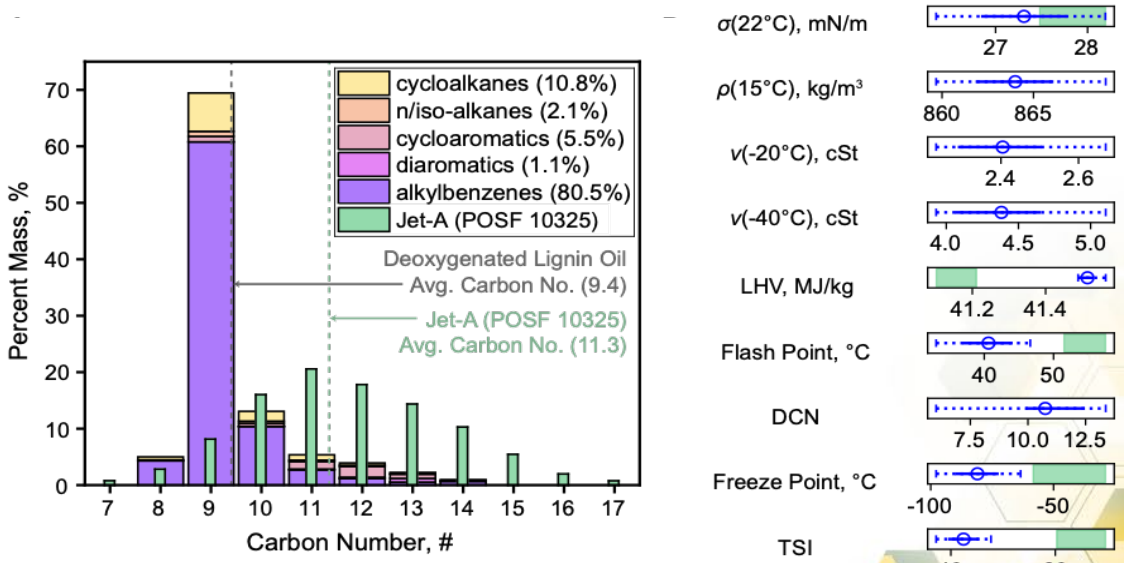
cbi

CBI and SAF to date

- CBI began additional upgrading to SAF hydrocarbons work in 2019
- We have preliminary results on
  - upgraded reductive catalytic upgrading of lignin oils into a possible blendstock
  - Upgraded ethanol into hydrocarbons
- Fall 2022: began the coordinated proof-of-process
- Continue discussions and outreach to end-users

ASTM 4054 Tier α testing of deoxygenated lignin oil



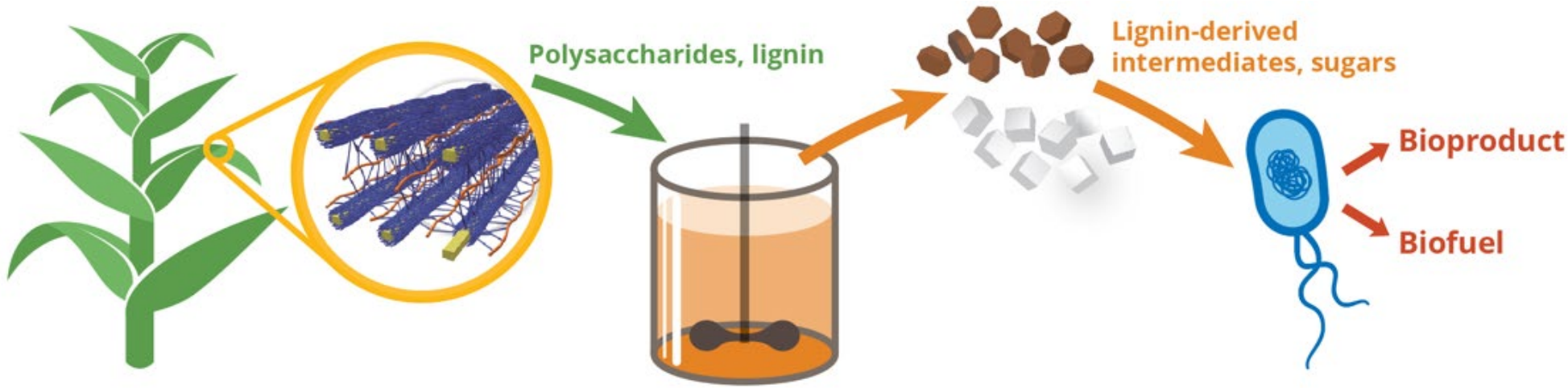


Stone et al, 2022. *Joule* 6:2324-2337 doi.org/10.1016/j.joule.2022.08.005

JBEI

Joint BioEnergy Institute

CAFFI Seminar: JBEI SAF Update



Aindrila Mukhopadhyay, VP Biofuels and Bioproducts, JBEI

2023.08.15

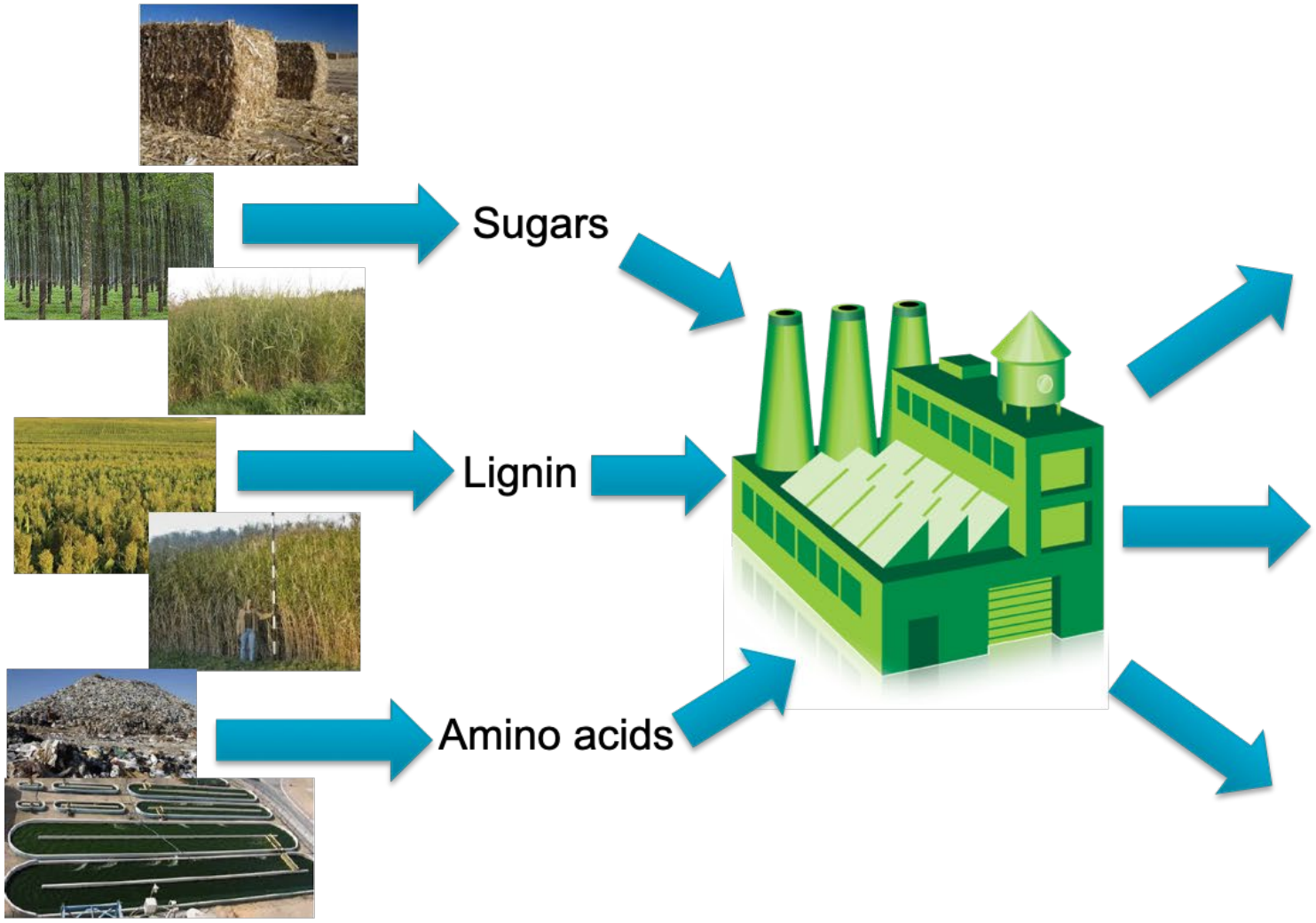
JBEI Mission and impacts

JBEI By the Numbers

- 1112 Publications
- 76.6k Citations
- 167 IP Licensed
- 362 Patent Applications
- 120 Issued Patents
- 12 Start-ups

JBEI Mission:
Establish the scientific knowledge and new technologies to transform the maximum amount of carbon available in bioenergy crops into biofuels and bioproducts.

Building a Sustainable Aviation Enterprise

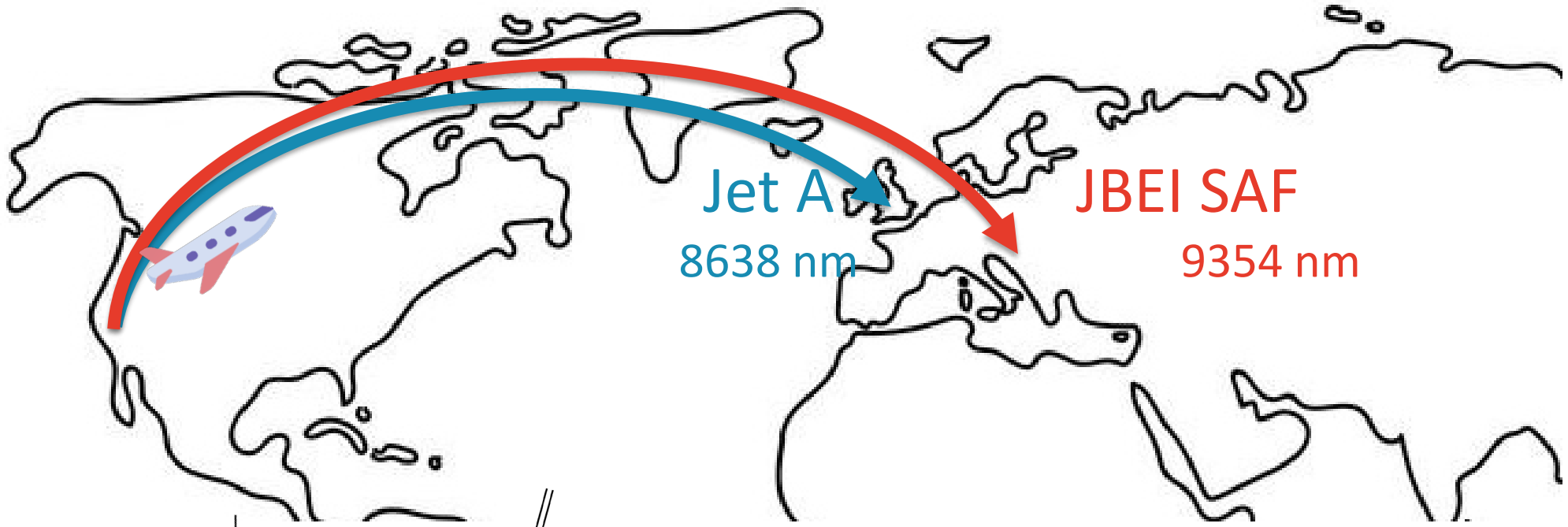


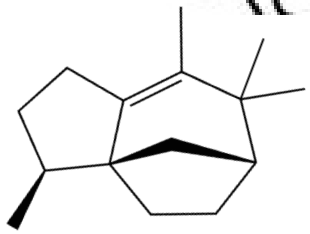
Sustainable Fuels:
- Drop-in blendstocks
- Higher energy density fuels for enhanced ranges

Interior Cabin:
- Renewable fabrics
- Polymers
- Fire retardant materials

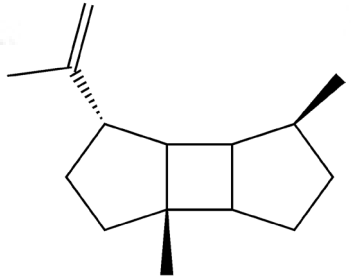
Airframe:
- Renewable carbon fiber
- Renewable carbon composites

JBEI's Sustainable Aviation Fuel Targets

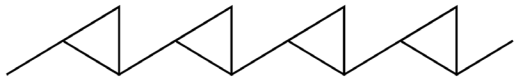




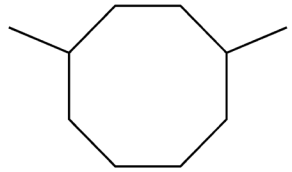
Epi-isozizaene



Prespatane



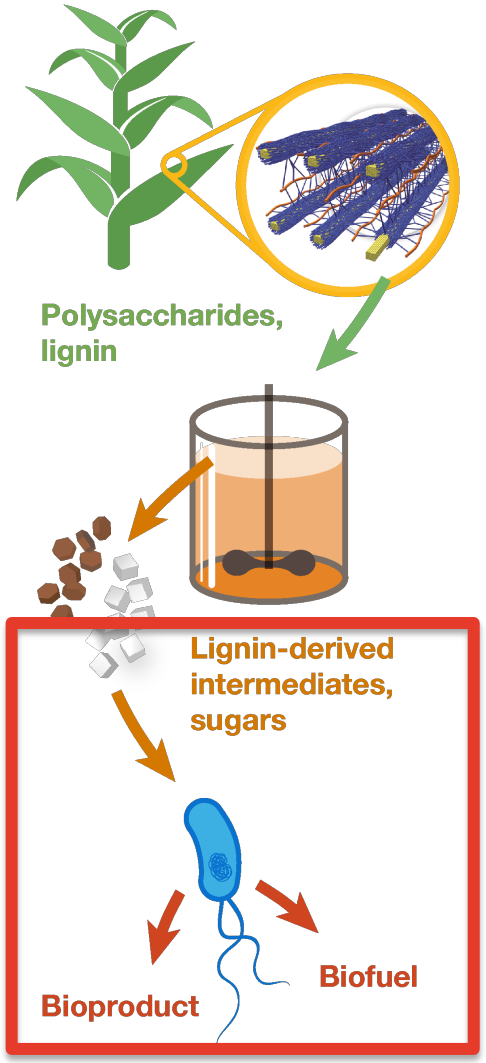
Polycyclopropanes

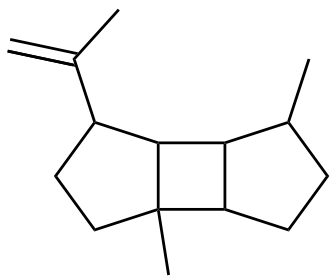


DMCO

Highly energy dense sustainable aviation fuels (SAFs) improve range and economics

JBEI's Sustainable Aviation Fuel Targets





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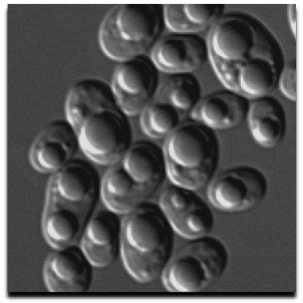
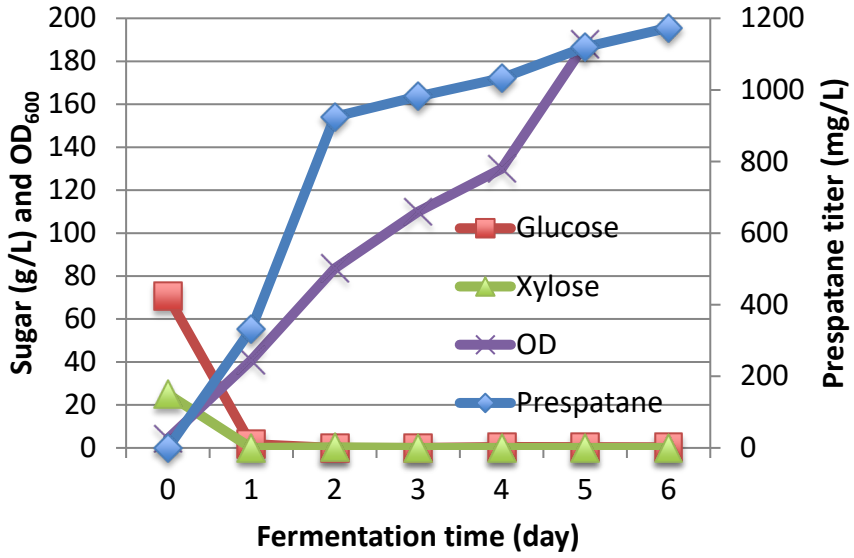
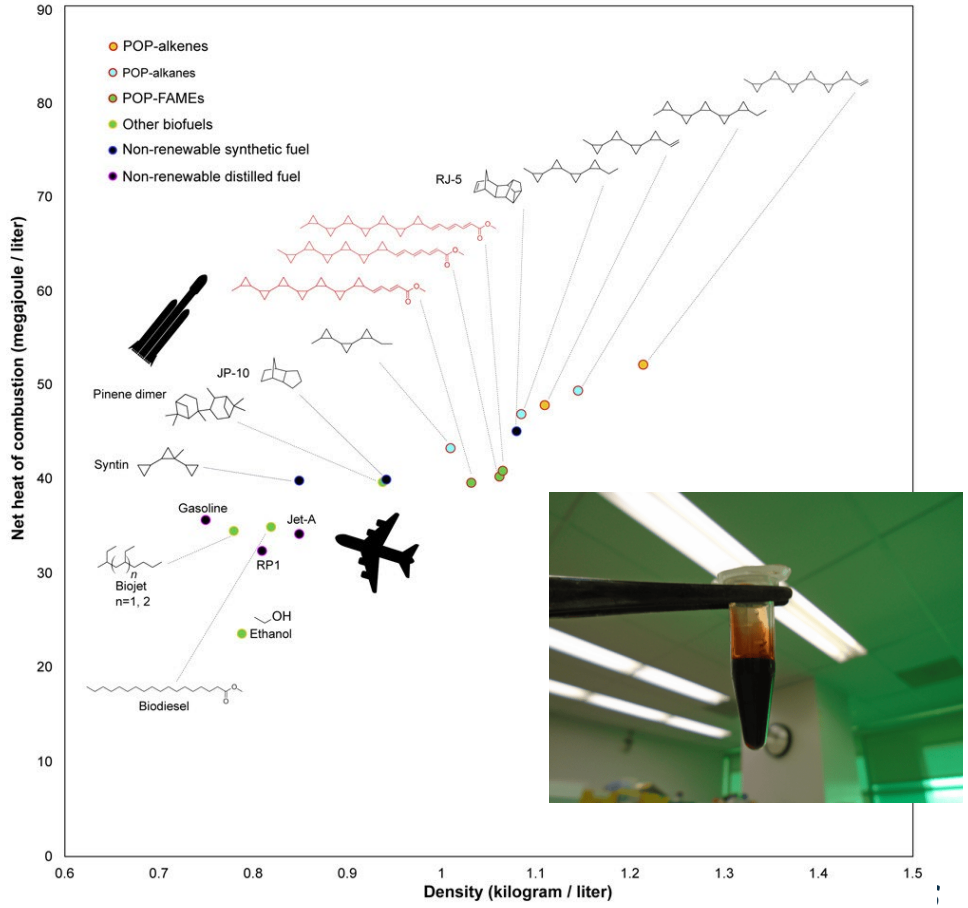


Oleagenous yeast



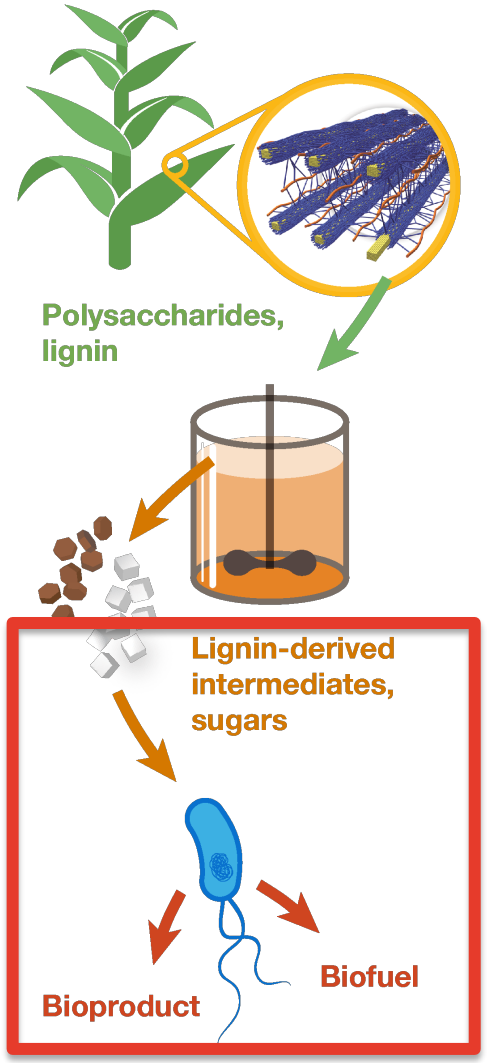
Fuelimycin A

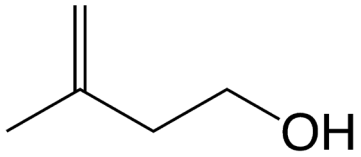


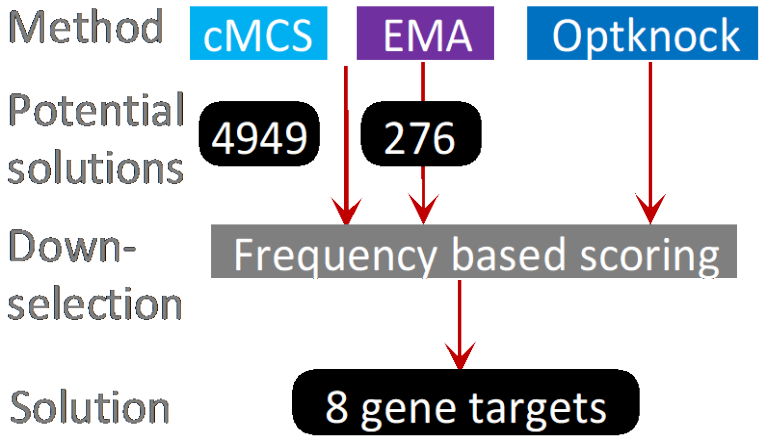
Geiselman et al. 2020 *Mic. Cell Factories.*

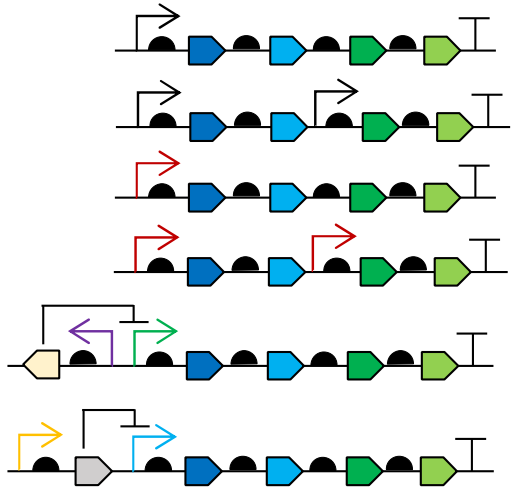
Cruz-Morales et al. 2022 Joule

Engineering production of isoprenol in several microbial strains









P. putida

We have engineered many microbial strains to produce isoprenol and improved the titers rates and yields.

Dimethylcyclooctane (DMCO) is produced from isoprenol using a 3-step conversion process

JBEI

NAWCWD

Polysaccharides, lignin

Lignin-derived intermediates, sugars

Isoprenol

Isoprenyl acetate

DMCO

Chemical Catalysis

Isoprenol

Auto Fuel:
Co-Optima "Top Ten" Blendstock:
Higher Octane Higher Efficiency

Isoprene

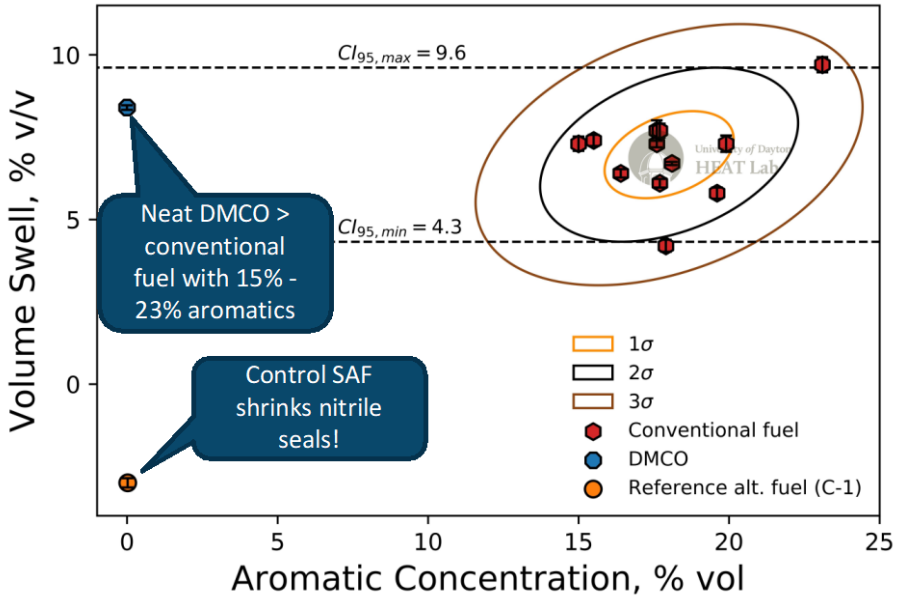
Industrial Chemical:
Green Synthetic Rubber

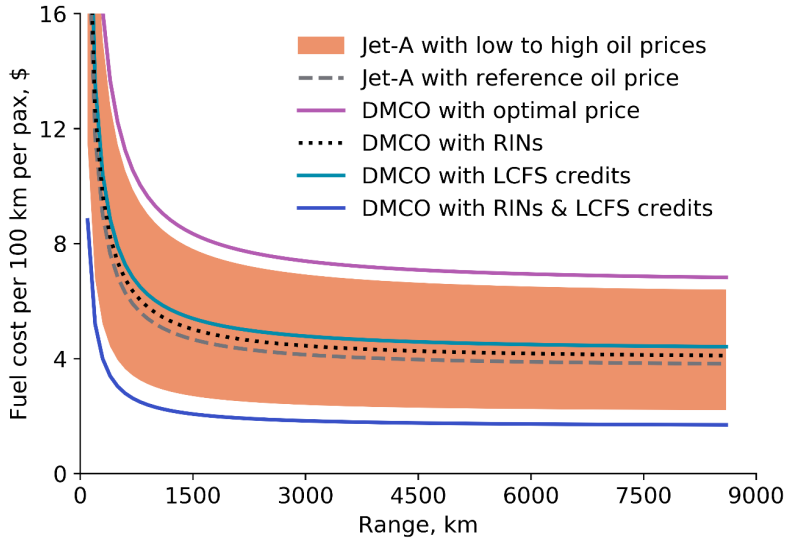
DMCO

Aviation Fuel:
High-Performance SAF

DMCO Achieves Better Performance than Jet-A1/JP-8 and Enables 100% SAF

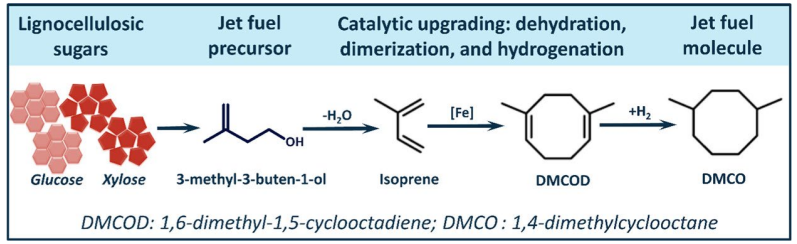
- DMCO can eliminate aromatics in jet fuel
- DMCO enables 100% SAF
  - 30% DMCO/70% HEFA is 100% renewable drop-in, with better performance
- Estimated commercial fleet-level fuel savings
  ~ ≤ 8.6% with full DMCO adoption by 2025:
  Greatest impact on larger, long-haul planes
- DMCO increases energy density by 9.2% relative to Jet-A, can replace petroleum derived aromatics in blend w/ paraffinic bio-jet fuels like HEFA



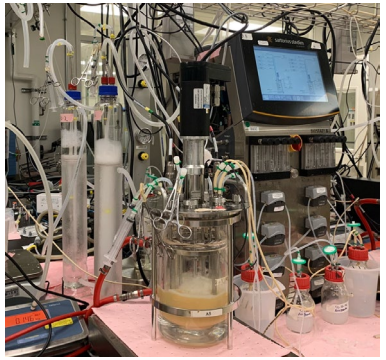


Baral et al. 2021 *ACS Sus. Chem. Eng.*

Scale-up for Production of Isoprenol for DMCO

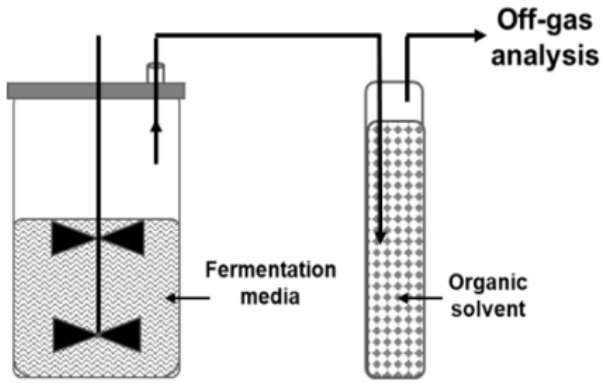


Roesenkoetter et al., Green Chem, 2019

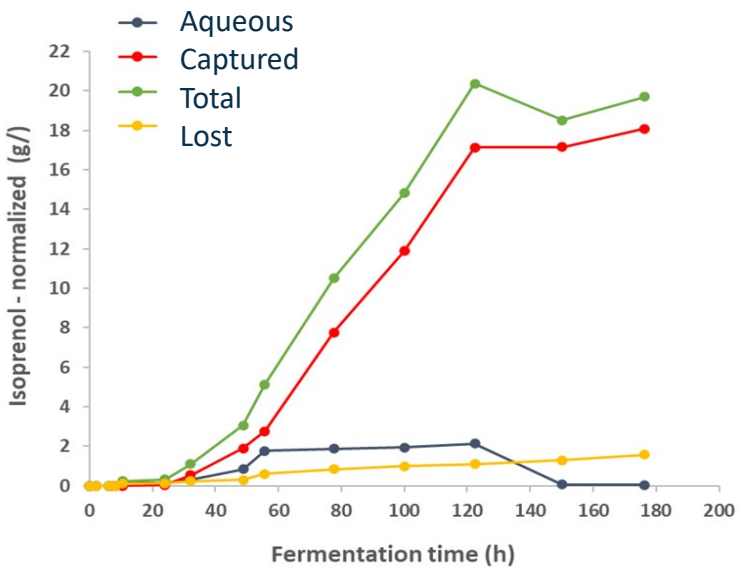


2L scale-up: Separations Consortium

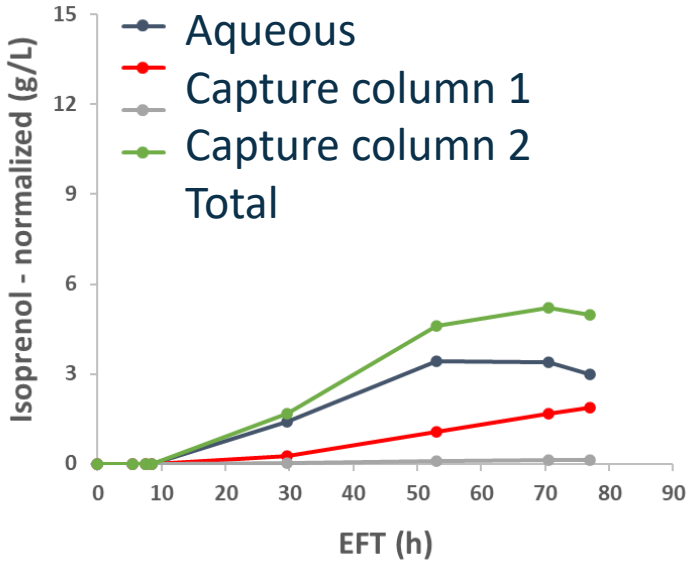
300L scale-up: US Navy



BIOPROCESSING SEPARATIONS CONSORTIUM



At 2L scale offgas stripping can fully replace organic overlays

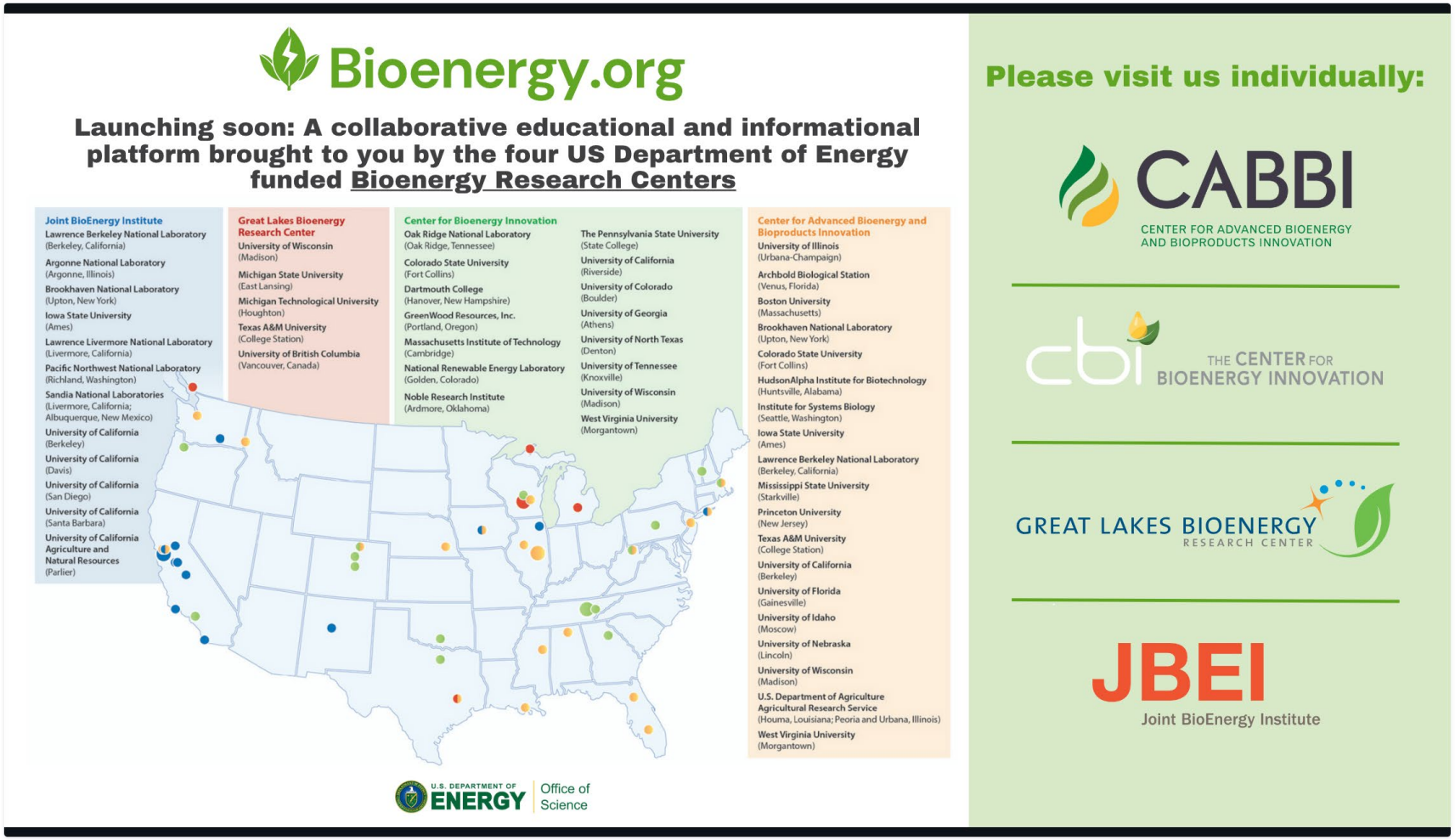


Scalability to 300L fermentation is challenged by back pressure and reduced aeration rates – toxicity limits titers

JBEI's Aviation Program

Formal and informal collaborations with aviation leaders

BRC Synergies for Carbon-negative biomanufacturing



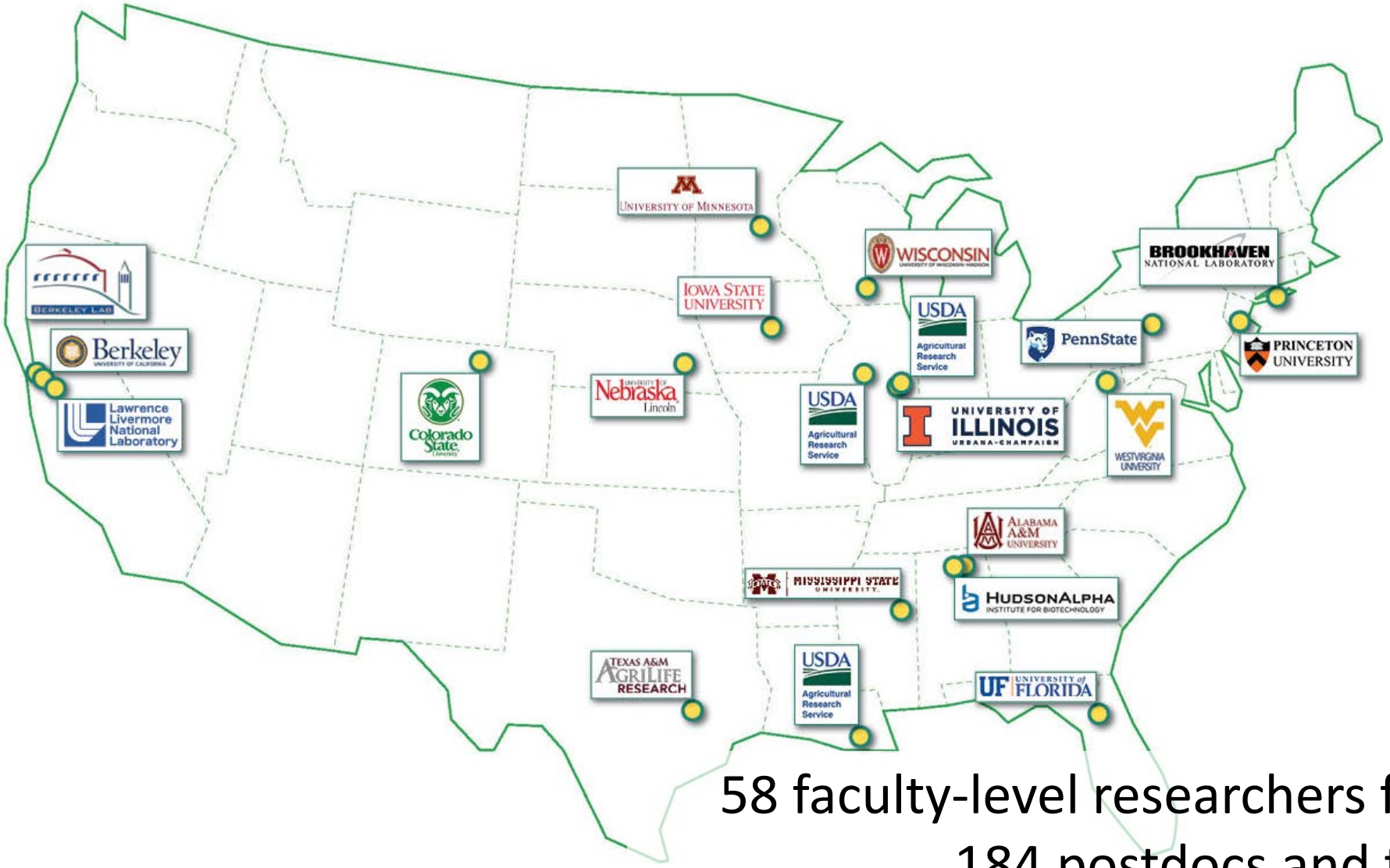
- Shared Research objectives
- Shared strains and feedstocks
- Shared tools and data
- Coordination of TEA and LCA models
- Collaborative studies on strain engineering. Enzyme discovery, and bioprocess development

Thank you to DOE BER for funding!

www.jbei.org


CABBI
CENTER FOR ADVANCED BIOENERGY
AND BIOPRODUCTS INNOVATION
Andrew Leakey
leakey@illinois.edu
CAAFI seminar
June 2023
ILLINOIS
U.S. DEPARTMENT OF
ENERGY

Partners & Personnel



58 faculty-level researchers for renewal

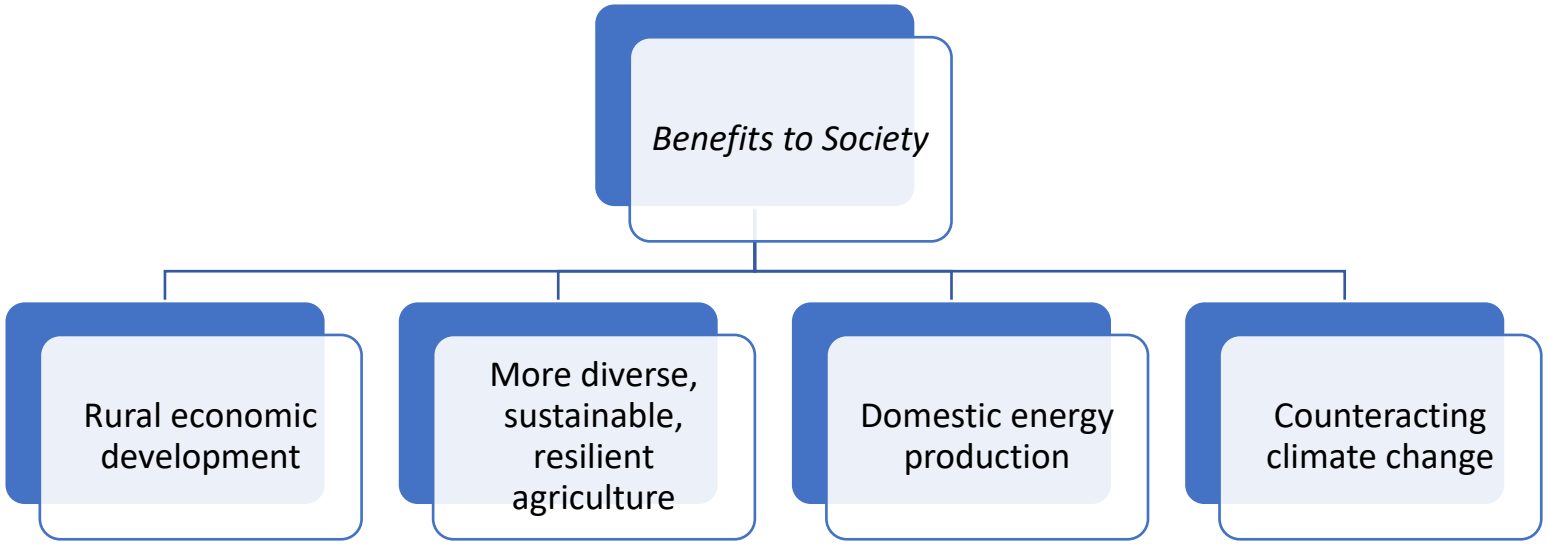
184 postdocs and technicians

143 graduate and undergraduate students

BRC PROGRAM PURPOSE, BENEFITS

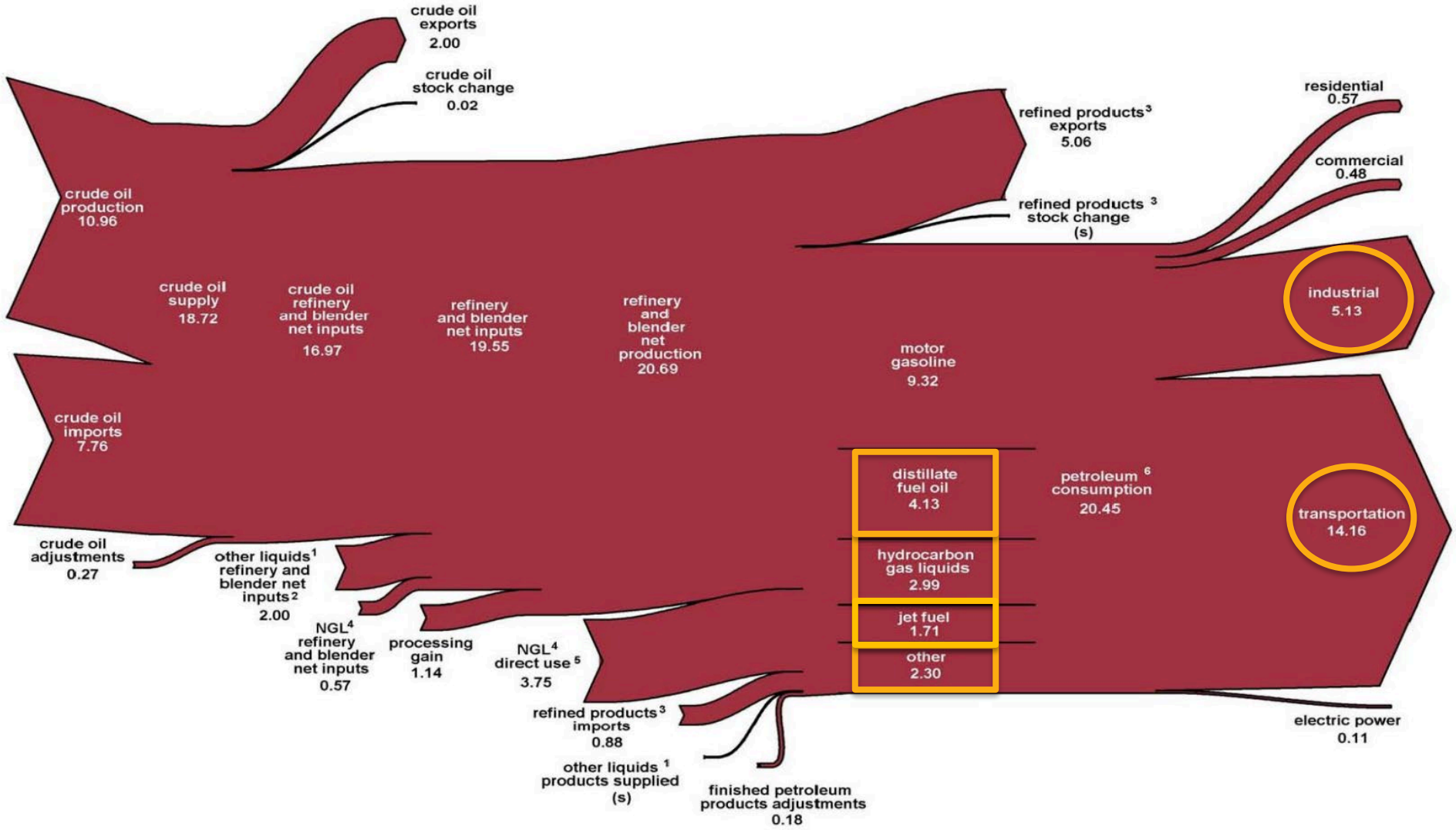
Purpose

Provide the scientific discoveries and new technologies to develop an economically viable and ecologically sustainable domestic biofuel and bioproducts industry from dedicated bioenergy crops



U.S. petroleum flow, 2018

million barrels per day



CABBI RESEARCH THEMES

SUSTAINABILITY

Optimizing the economic value and environmental benefits of bioenergy and bioproducts

FEEDSTOCK PRODUCTION

Developing more productive, resilient, and sustainable crops that produce oil and other high-value products

MISCANTHUS

SORGHUM

SUGARCANE

CONVERSION

Pioneering synthetic biology to develop microbes that create new chemicals and upgrade plant products

BIOPROCESSING

READY-TO-USE FUEL

COMPONENTS FOR HIGH-VALUE CHEMICALS

SUGARS

Issatchenkia orientalis

Saccharomyces cerevisiae

FATTY ALCOHOLS; CITRAMALATE; 3-HYDROXYPROPIONIC ACID (3-HP); TRIACETIC ACID LACTONE (TAL)

LIPIDS

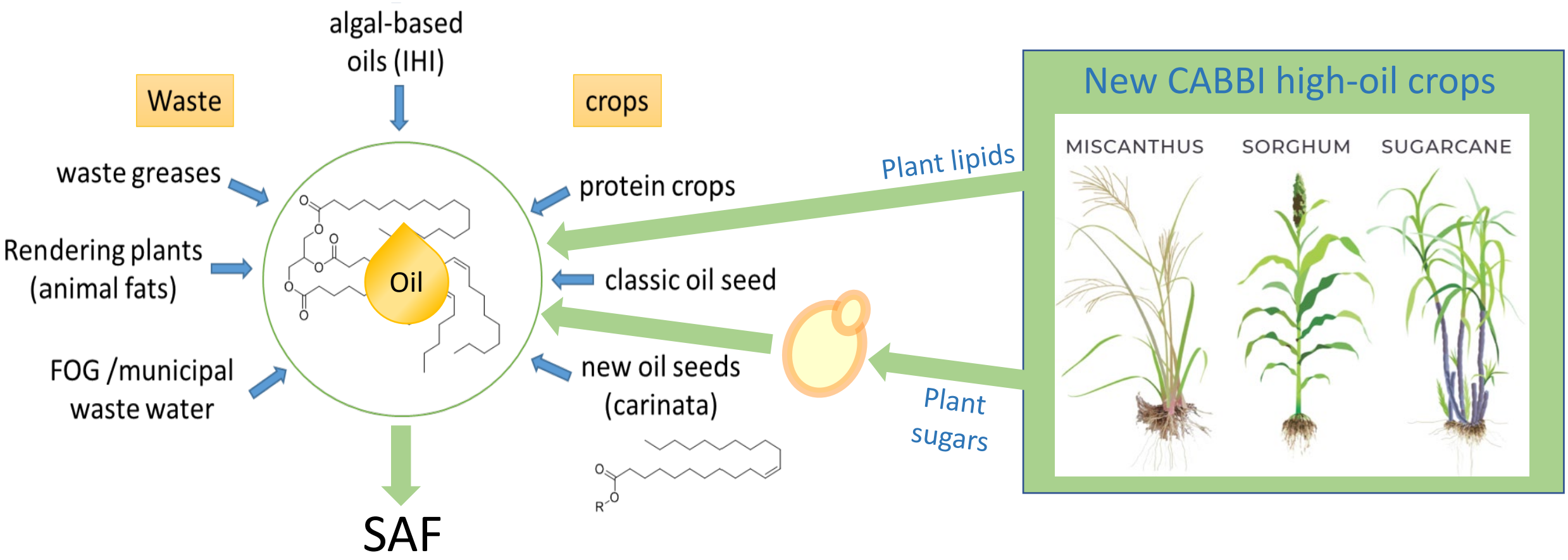
Rhodosporidium toruloides

Yarrowia lipolytica

DICARBOXYLIC ACIDS; POLYUNSATURATED FATTY ACIDS

BIOFUELS & BIOPRODUCTS

Expanding capacity for the primary source of biodiesel, renewable diesel and renewable jet fuel: *lipids*



"Feedstocks are the primary <u>cost</u> contributor to biofuels. Rethinking feedstock sourcing and the means of reducing costs while doing less harm to watersheds and land is a critical activity" Sustainable Aviation Fuel: Review of Technical Pathways, BETO, 2020

CABBI Teamwork — Successfully Completed Oilcane 1.0 (Pilot-Scale Demonstration of Feedstocks to Fuels)

University of Illinois

Greenhouse Planting & Processing of Biomass

ILLINOIS IBRL

Mississippi State University

Field Planting

MISSISSIPPI STATE UNIVERSITY

University of Florida

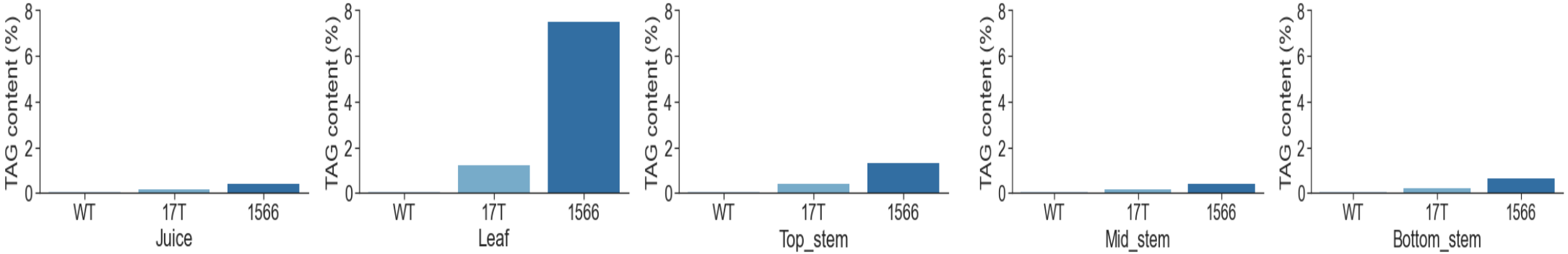
Field Planting

UF UNIVERSITY of FLORIDA

Transgenic lines

1. WT
2. 1566
3. 17T

2020 Oilcane trials in Florida

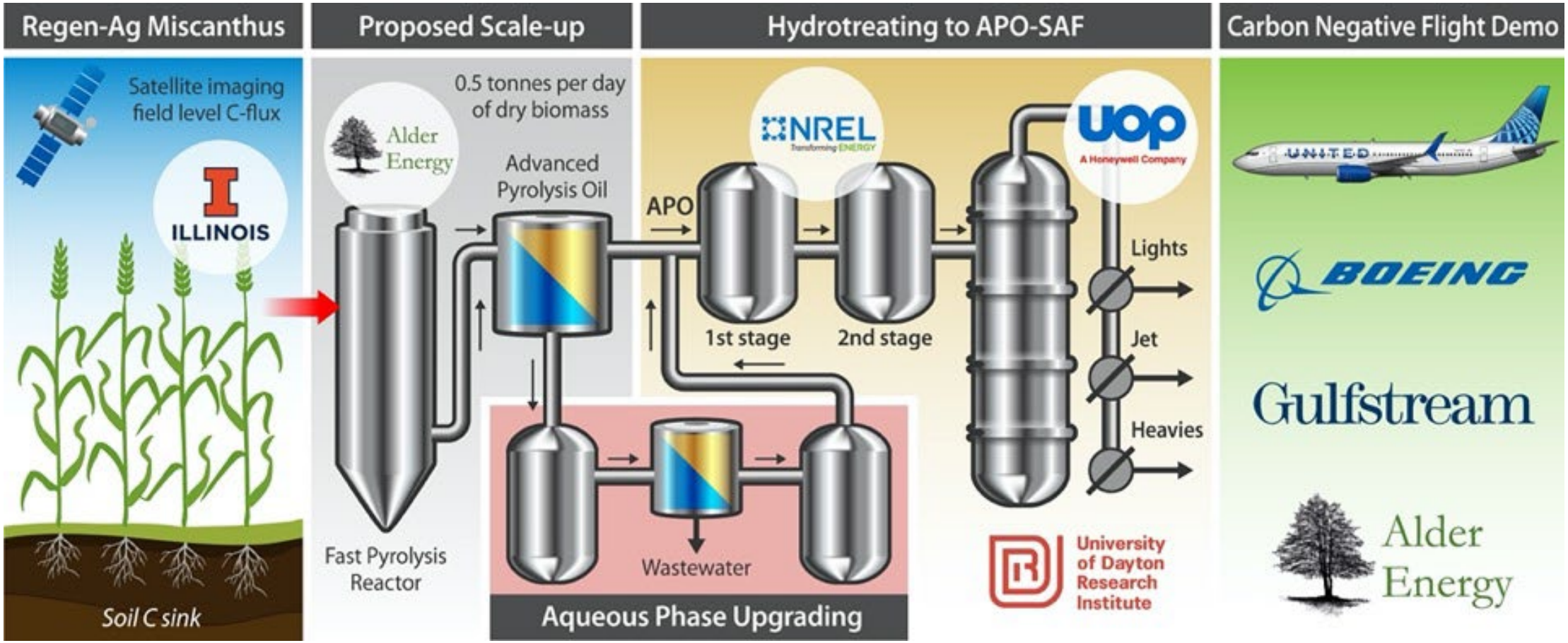


Even higher oil contents produced in 2021 trials…

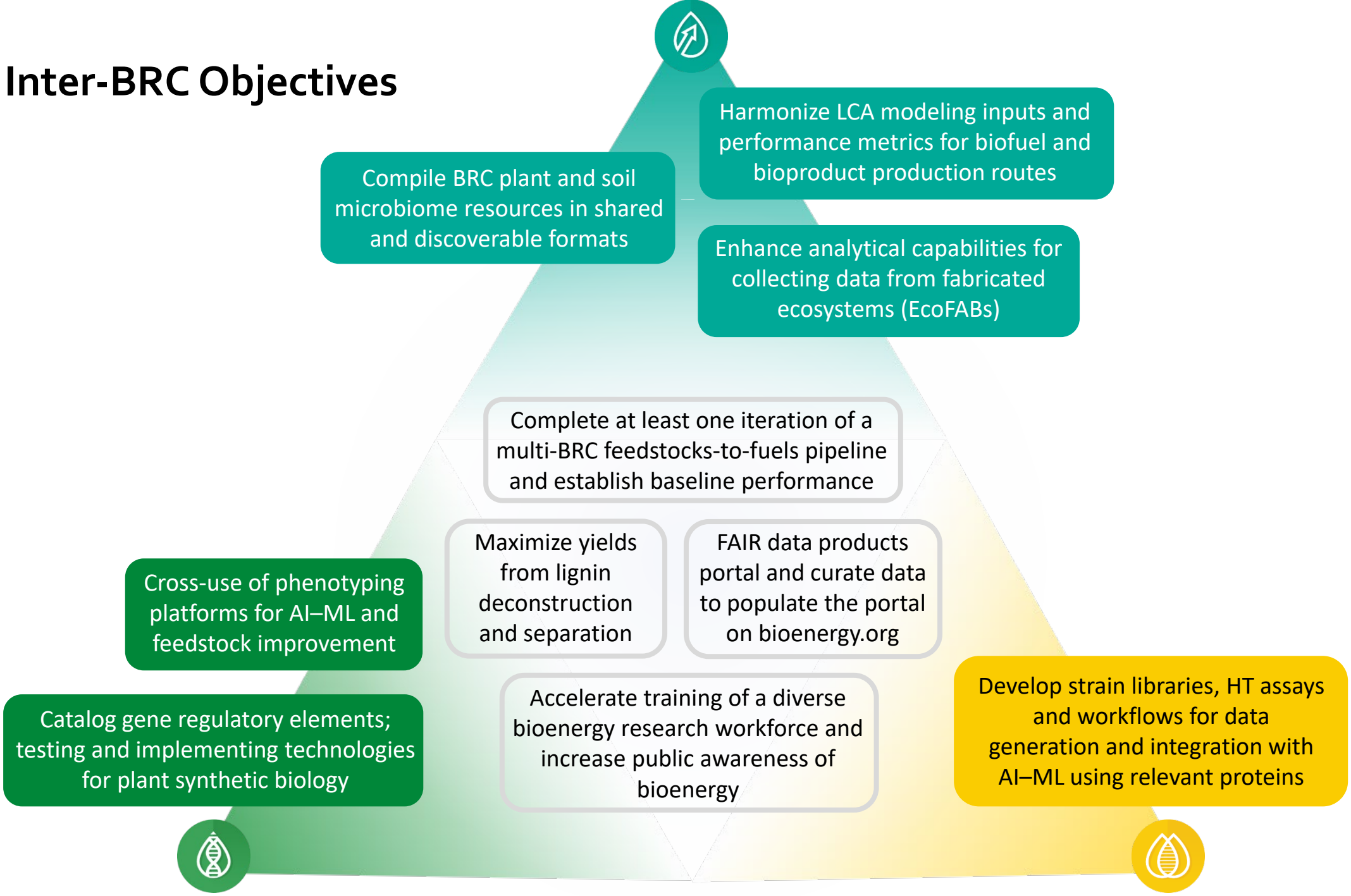
Altpeter, Shanklin et al. (in prep)

Partnerships for T2M:

Example project - Field-to-Fuel Production of Carbon-Negative Sustainable Aviation Fuel from Regenerative Agriculture Biomass



Inter-BRC Objectives



CABBI IP

IMPROVED BIOPROCESSING

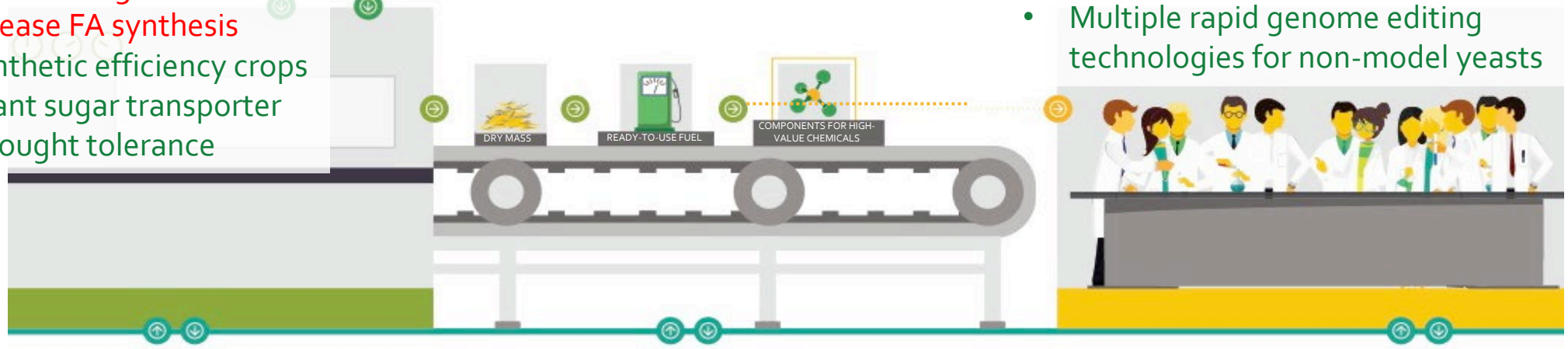
- Fatty Acid (FA) separation and recovery
- Yield of oil and sugars from lipid-producing biomass
- High solids loading for cellulosic sugar production

IMPROVED MICROBES

- Metabolic engineering for production of succinic acid, methyl ketones
- New-to-nature photoenzyme design and production
- Multiple rapid genome editing technologies for non-model yeasts

IMPROVED FEEDSTOCKS

- Production of high-TAG sorghum
- ATP Factors to increase FA synthesis
- Increased photosynthetic efficiency crops
- Broad spectrum plant sugar transporter
- Biostimulant for drought tolerance

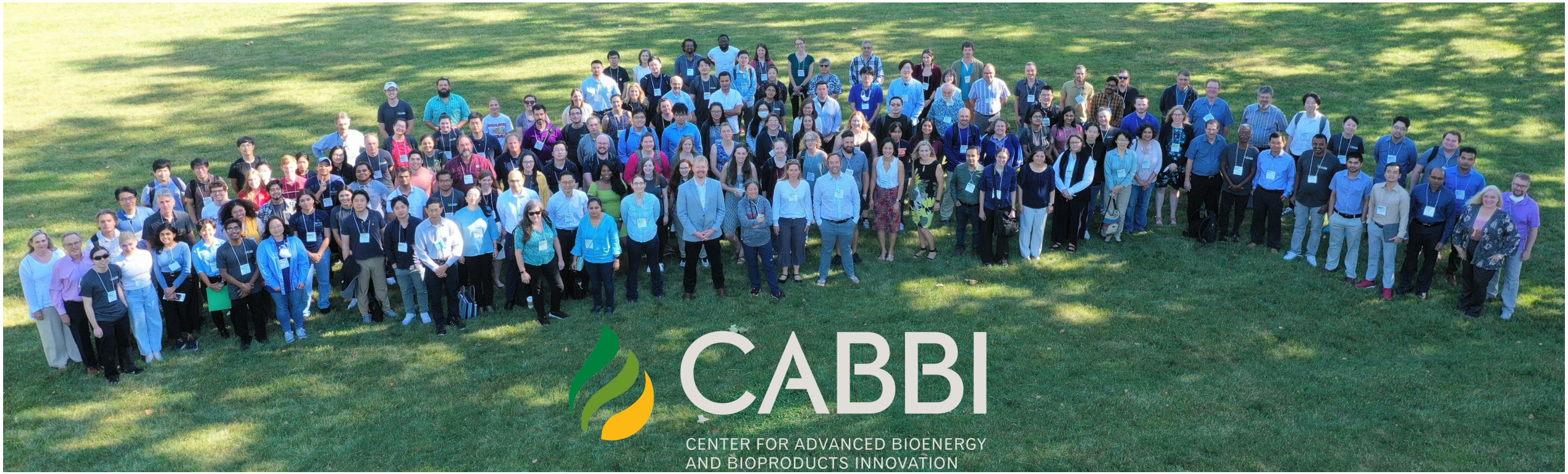


IMPROVED FIELD SENSORS/ANALYSIS

- Airborne and satellite imaging for crop and soil monitoring
- Sub-canopy imaging of crop development

IMPROVED LAB SENSORS/ANALYSIS

- Multiplexed proteomics
- Genome-wide protein copy-number determination



Contact:

Questions?

http://www.cabbi.bio

RISE INTERNSHIP

Engage with underrepresented undergrads at RISE!

Research Internship Sustainable Bioenergy (RISE) is a summer internship program offering bioenergy research opportunities for undergraduates from groups currently underrepresented in STEM. During the 10-week program, students gain experience in plant biology, agronomy, synthetic biology, genetics, environmental sciences, chemical engineering, or civil & environmental engineering. Successful applicants receive a stipend and have housing and travel expenses covered by the Center for Advanced Bioenergy and Bioproducts Innovation.

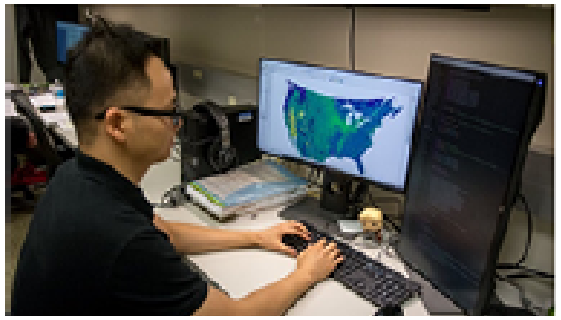
Sponsors will have the opportunity to:

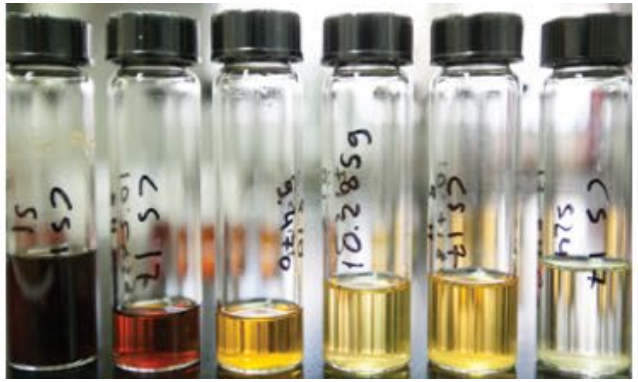
- Participate in welcome event for students;
- Lead professional or career development workshops for program participants;
- Provide formal or informal mentors from your company; and
- Participate in program wrap-up events including student research presentations.

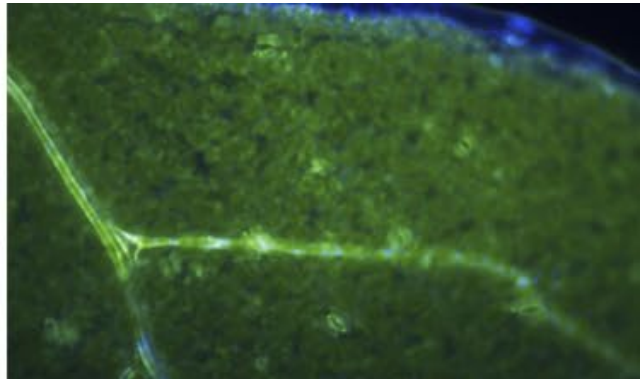
FOR ADDITIONAL INFORMATION, CONTACT:
Tracy Parish, director of corporate and foundation relations, at tparish@illinois.edu or (217) 265-0880.

COLLEGE OF LIBERAL ARTS & SCIENCES ▪ UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

22-379-APR22





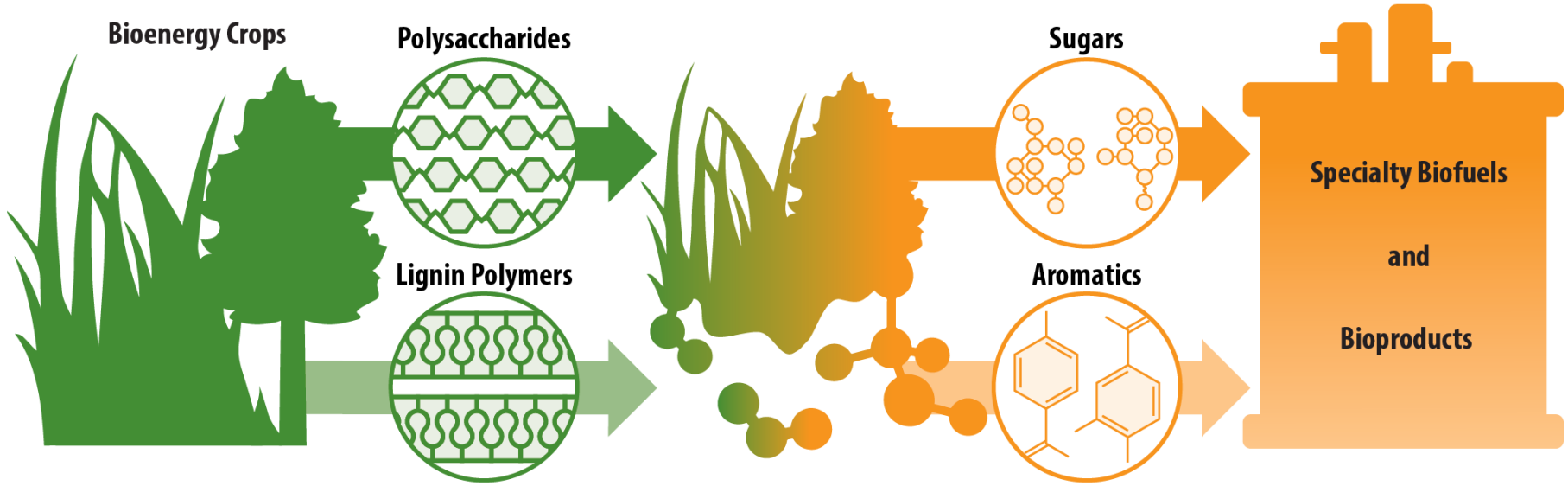
CAAFI BRC Webinar

Tim Donohue

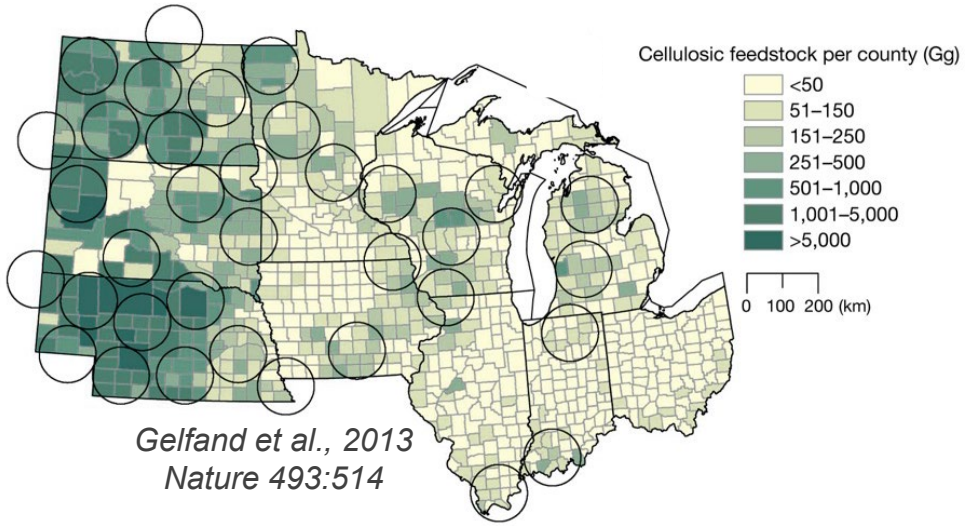
Ira L Baldwin & UW Foundation Fetzer Professor of Bacteriology UW-Madison
Director Wisconsin Energy Institute, Great Lakes Bioenergy Research Center
tdonohue@bact.wisc.edu

August 15, 2023

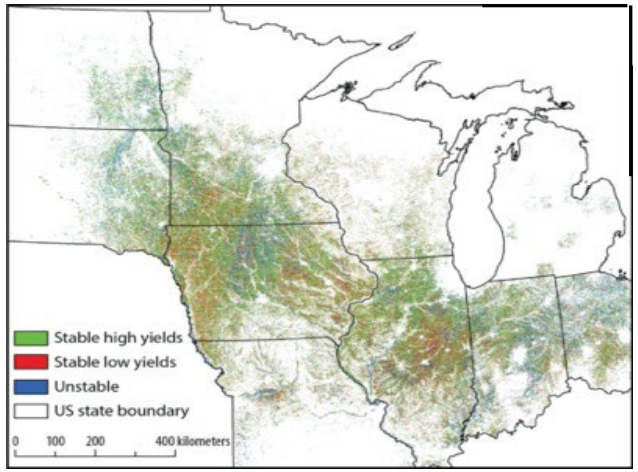
Lands to Host Bioenergy Crops



- Productive
- Perennials
- Polycultures
- Placement



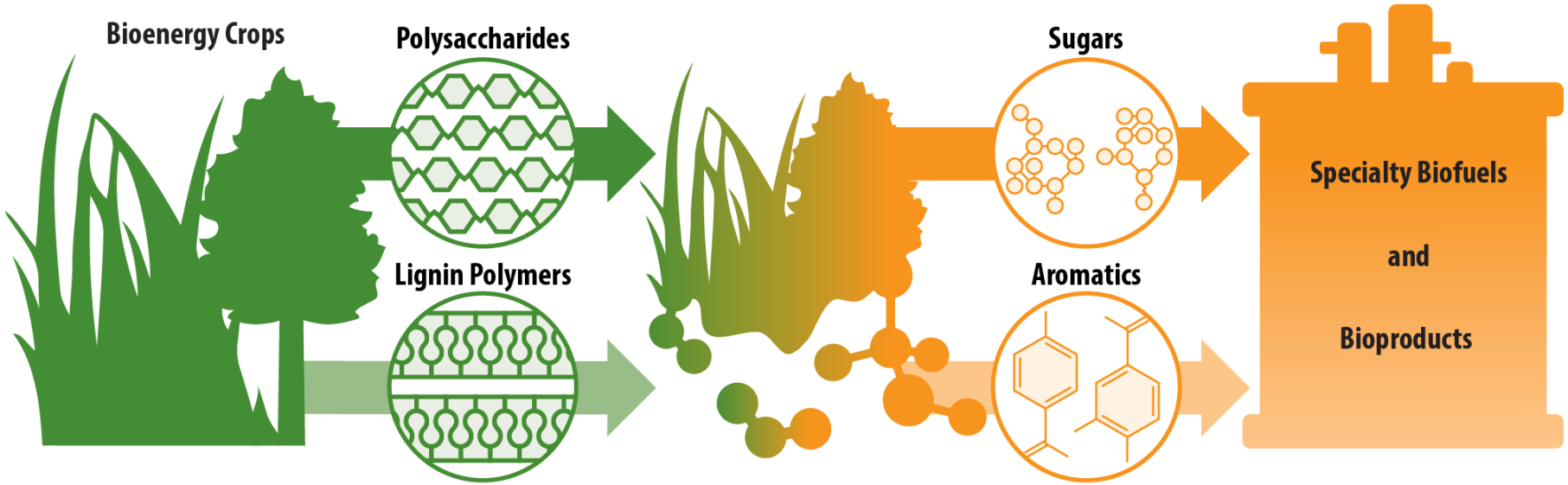
Gelfand et al., 2013
Nature 493:514



Basso et al., 2019 Science Reports 9:5774

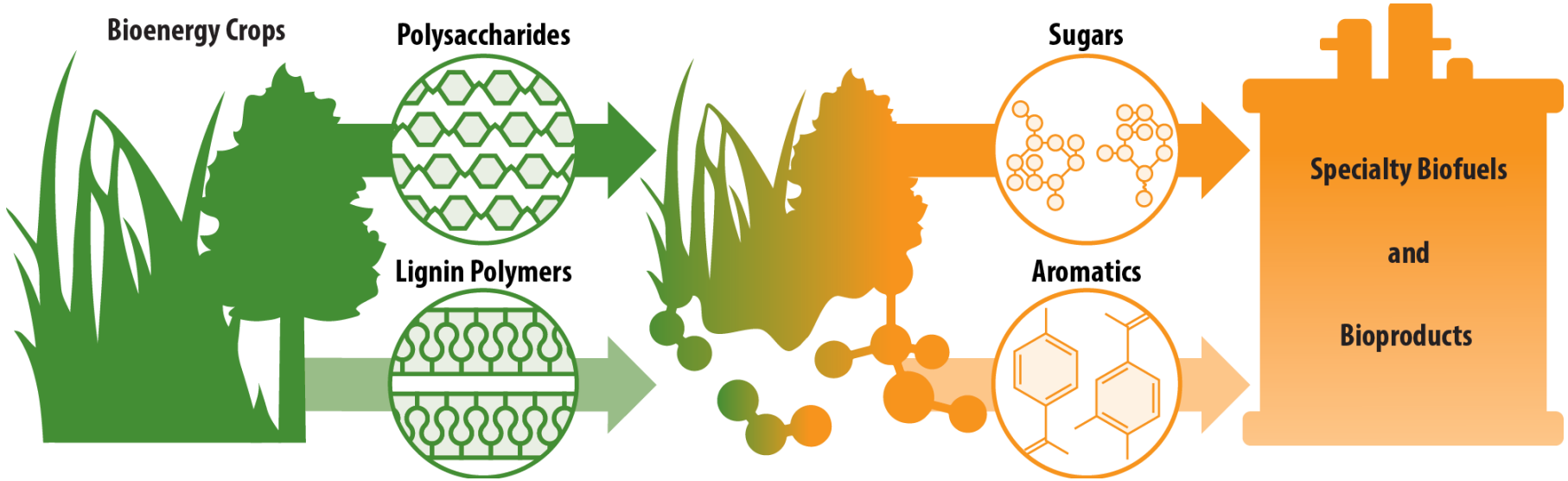
- Environmental and socioeconomic benefits

GLBRC Bioenergy Crops



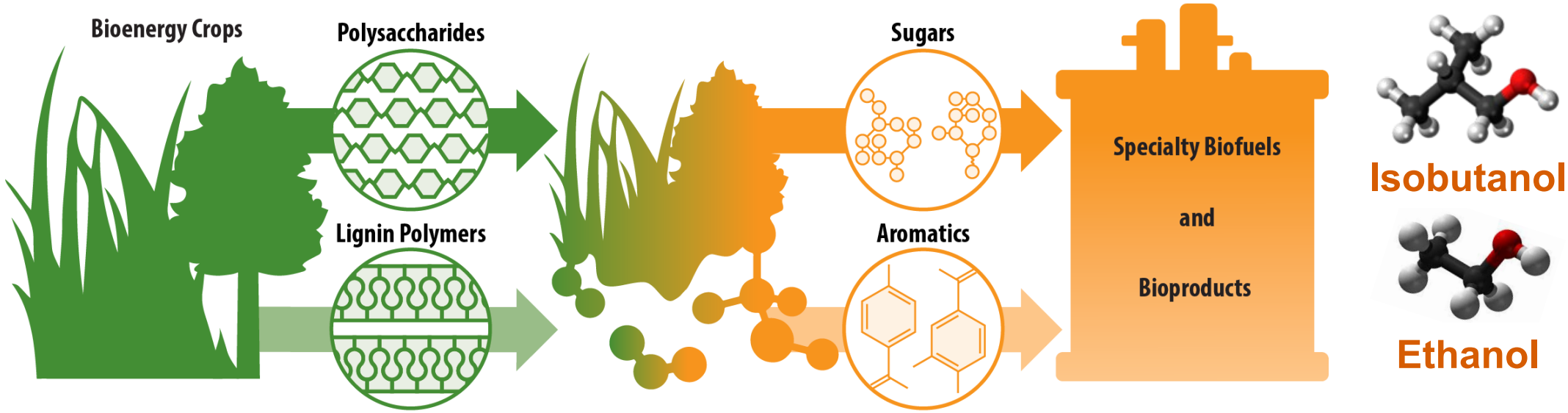
- Poplar, Switchgrass, Sorghum, Mixed species
- Genome-informed breeding
- Plant-microbe-soil interactions to improve crop yields, quality, carbon sequestration, ecosystem services

GLBRC Biomass Pipeline



- Cost-effective, feedstock-agnostic biomass deconstruction
  - Sugar (to fuels) and aromatic (to chemicals) streams
- Genome-informed knowledge to
  - engineer industry-ready microbes
  - mitigate impact of crop, soil, and weather variation on conversion

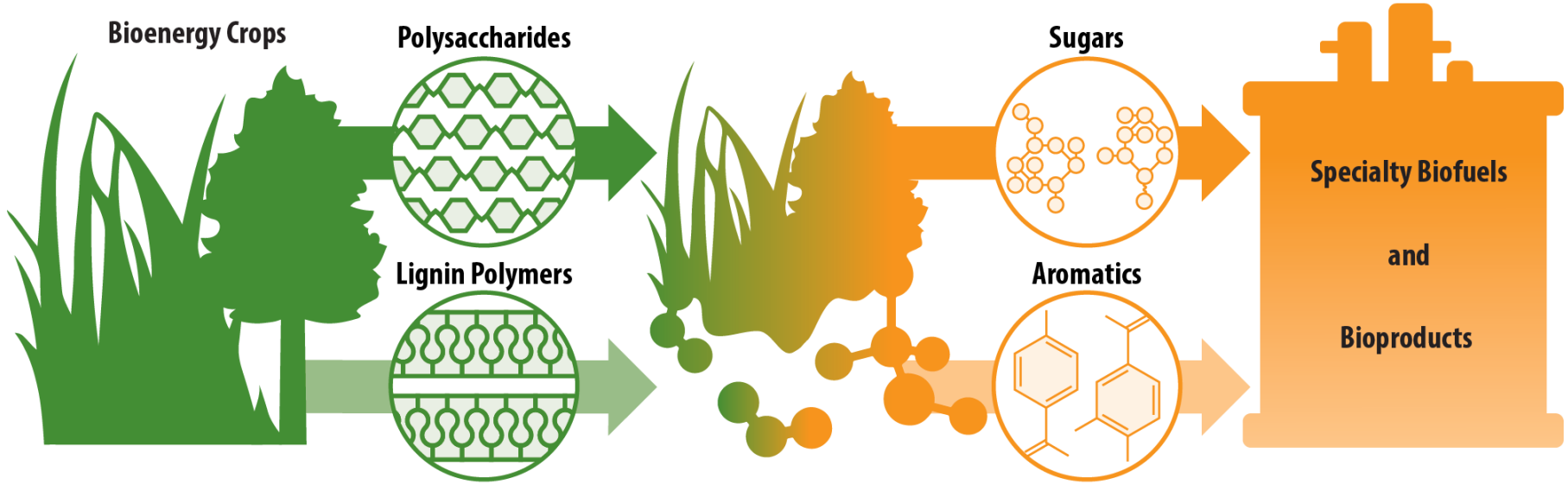
GLBRC Biomass ATJ Strategy



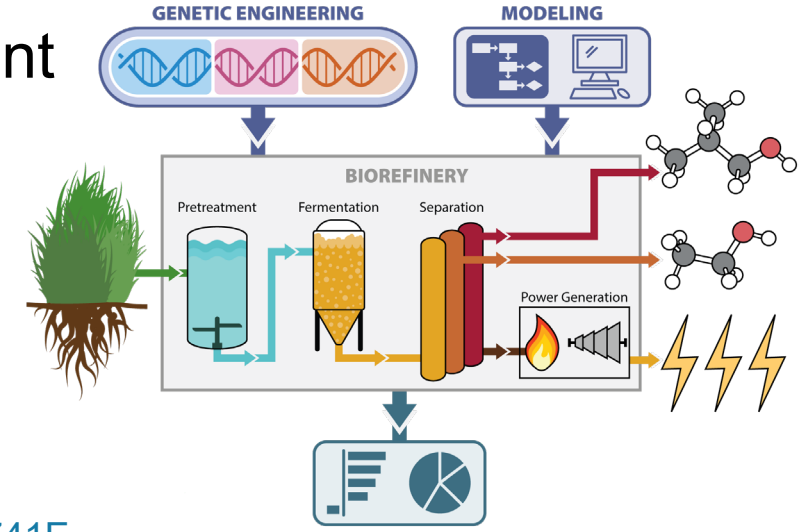
- Cellulosic sugars (~60% of biomass) to alcohols (isobutanol, ethanol)
  - Alcohols approved as SAF blend stocks
  - Compatible with catalytic upgrading
  - Overcome bottlenecks in fermenting deconstructed cellulosic sugars

https://www.astm.org/Standards/D1655.htm, 2018
https://www.astm.org/Standards/D4054.htm, 2017
Geleynse et al., 2018 ChemSusChem https://doi.org/10.1002/cssc.201801690

GLBRC ATJ Strategy

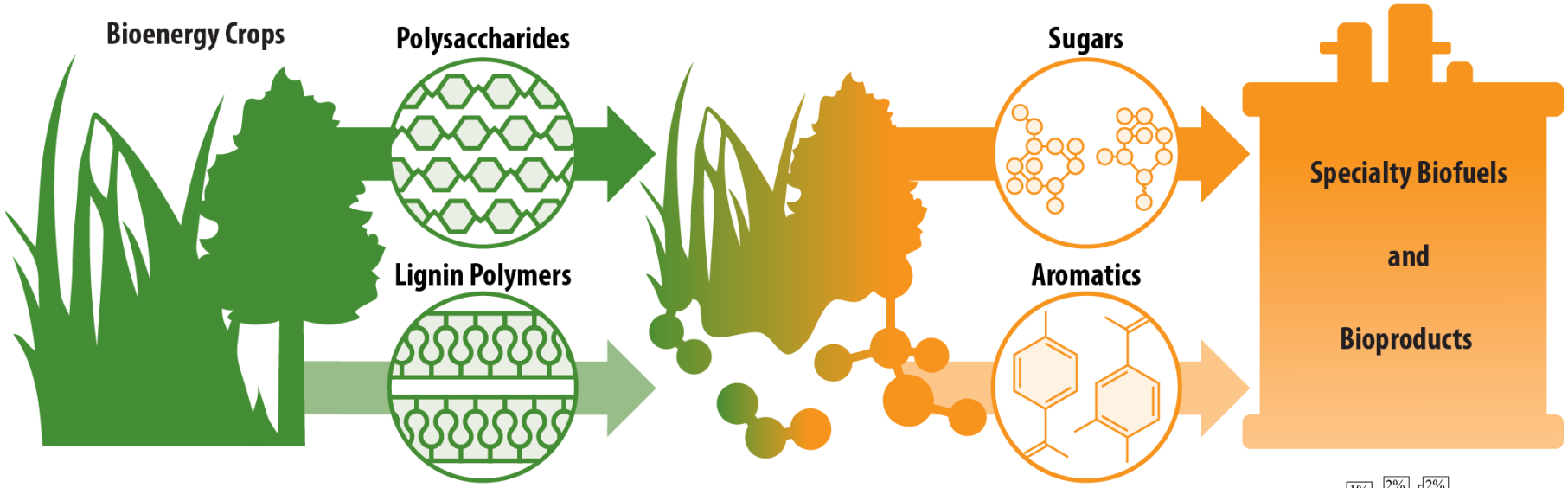


- Engineered industry-ready bacteria, yeast to ferment cellulosic sugars to SAF-compatible alcohols
  - Balance R-T-Y with growth, energy and stress
  - TEA-informed targets for process improvements

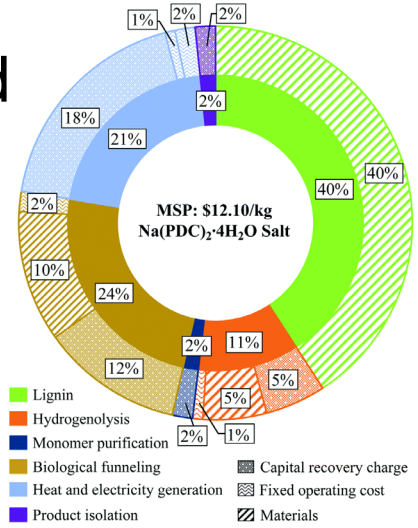


Liu et al., 2020 Metab. Eng, https://doi.org/10.1016/j.ymben.2020.06.005
Pastore de Lima et al., 2023 Sustainable Energy & Fuels https://doi.org/10.1039/D2SE01741E

GLBRC Aromatic Conversion

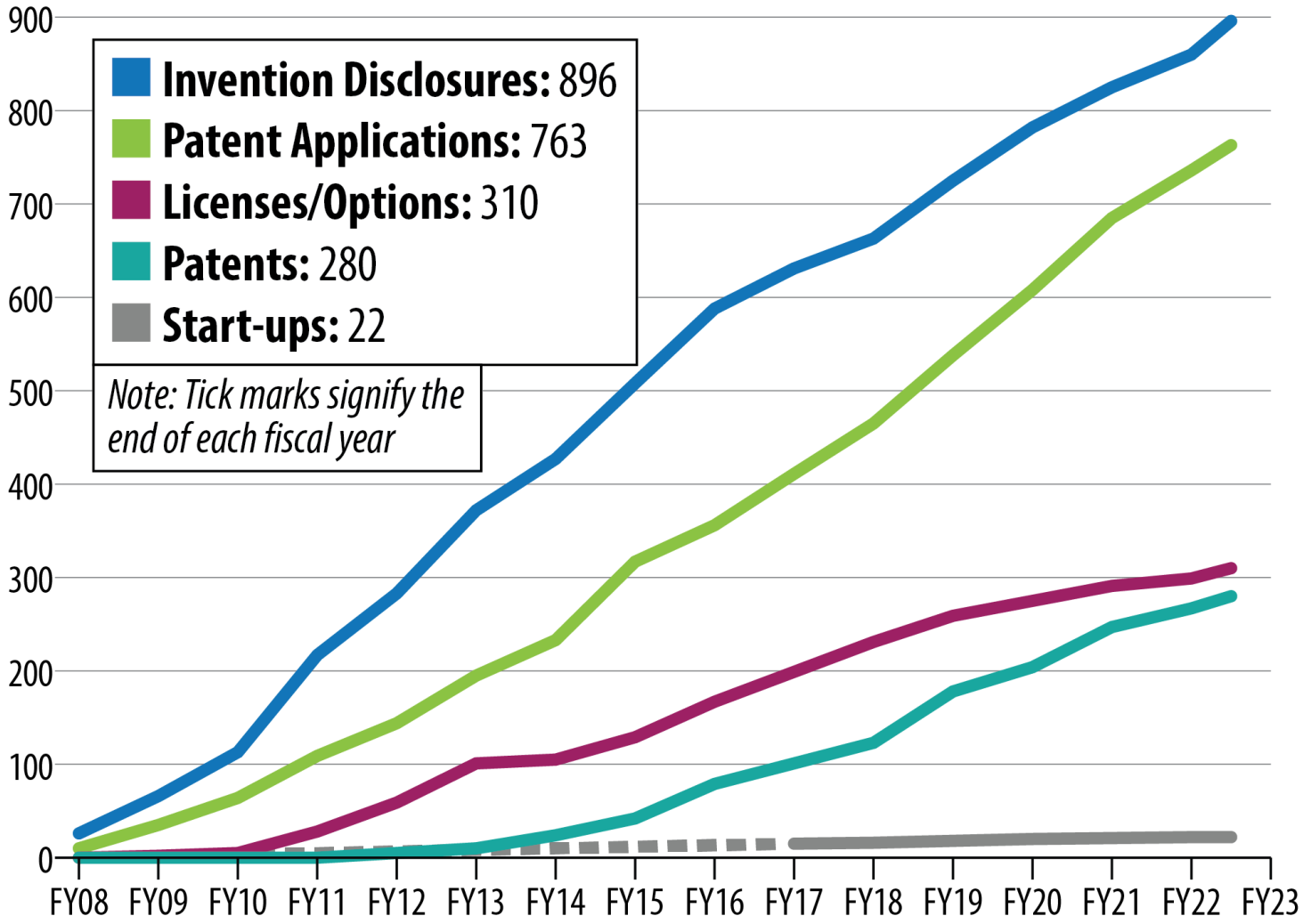


- Industry-ready bacterium that naturally funnels mixed aromatic streams (~30% of biomass) to bioproducts
  - Aromatics for SAF (and more)
  - Chemicals (lubricants, polyesters, nylon, others)
  - TEA-informed opportunities and challenges



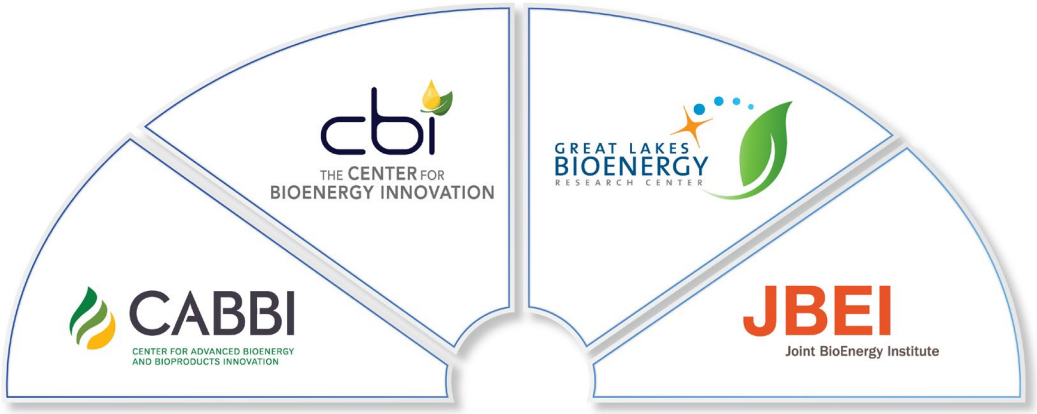
Perez et al., 2022 Green Chemistry https://doi.org/10.1039/D1GC03592D

BRC technology metrics*



*March 2023

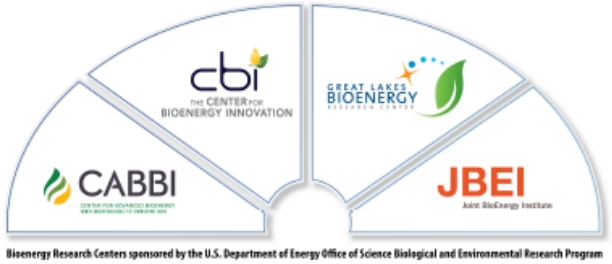
New efforts in collaborative BRC IP marketing



Bioenergy Research Centers sponsored by the U.S. Department of Energy Office of Science Biological and Environmental Research Program

BRC booth at
ABLC March 2023, October 2022;
Commercializing Industrial Biotech May 2022, Sept. 2023

BREAKING DOWN BARRIERS



Bioenergy Research Centers sponsored by the U.S. Department of Energy Office of Science Biological and Environmental Research Program

The Four Centers

Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), led by the University of Illinois at Urbana-Champaign. CABBI is integrating recent advances in agronomics, genomics, biosystems design, and computational biology to increase the value of energy crops, using a "plants as factories" approach to grow fuels and chemicals in plant stems and an automated foundry to convert biomass into valuable chemicals that are ecologically and economically sustainable.

Center for Bioenergy Innovation (CBI), led by Oak Ridge National Laboratory. CBI is accelerating the domestication of bioenergy-relevant plants and microbes to enable high impact, value-added coproduct development at multiple points in the bioenergy supply chain.

Great Lakes Bioenergy Research Center (GLBRC), led by the University of Wisconsin–Madison in partnership with Michigan State University. GLBRC is developing science and technological advances to ensure sustainability at each step in the process of creating biofuels and bioproducts from lignocellulose.

Joint BioEnergy Institute (JBEI), led by DOE's Lawrence Berkeley National Laboratory. JBEI is using the latest tools in molecular biology, chemical engineering, and computational and robotics technologies to transform biomass into biofuels and bioproducts.

TOP 10 TECHNOLOGIES

Scan for detailed descriptions:

RAPID ASSEMBLY OF GRNAS FOR MULTIPLEX CRISPR
Dr. Xiaohan Yang

BENEFICIAL MICROBIAL COMMUNITY FROM SORGHUM PHYLLOSPHERE
Dr. Ashley Shade

ALKANOLAMINES FOR LIGNIN EXTRACTION IN BIOMASS PRETREATMENT
Dr. Blake Simmons

INCREASED ETHANOL PRODUCTION IN CLOSTRIDIA
Dr Jonathan Lo

GREEN ACETAMINOPHEN FROM LIGNIN
Dr. John Ralph

Find us at ABLC or contact us after!

Jennifer Gottwald, WARF, jennifer@warf.org
Yiying Xiong, GLBRC, Yiying.Xiong@wisc.edu
Brian Davison, CBI, davisonbh@ornl.gov
Robin Johnston, JBEI, rjohnston@lbl.gov

Marketing handouts and links

BRCs Engaging Industry

BRC IP Contacts

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