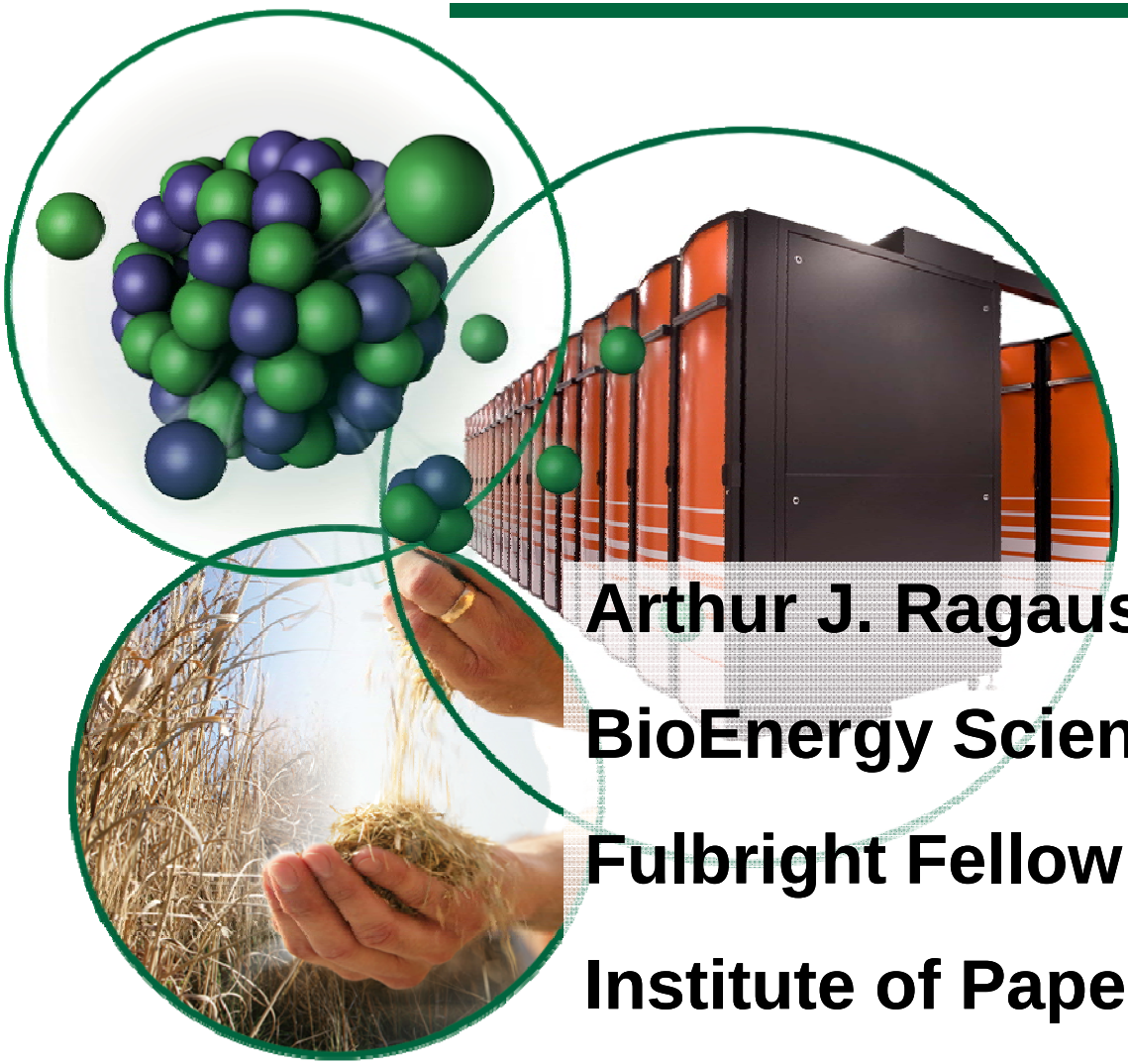
New Energy Research:
An Industry-Governmental Partnership



Arthur J. Ragauskas, PhD

BioEnergy Science Center

Fulbright Fellow Alternative Energy

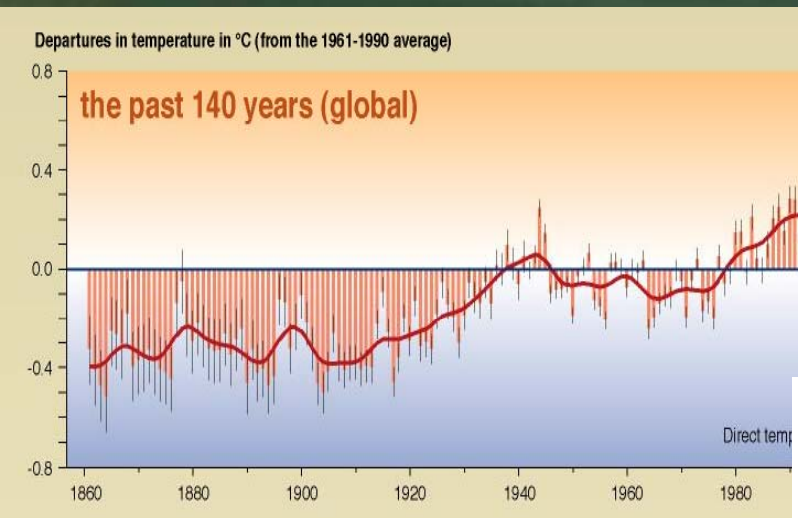
Institute of Paper Science and Technology

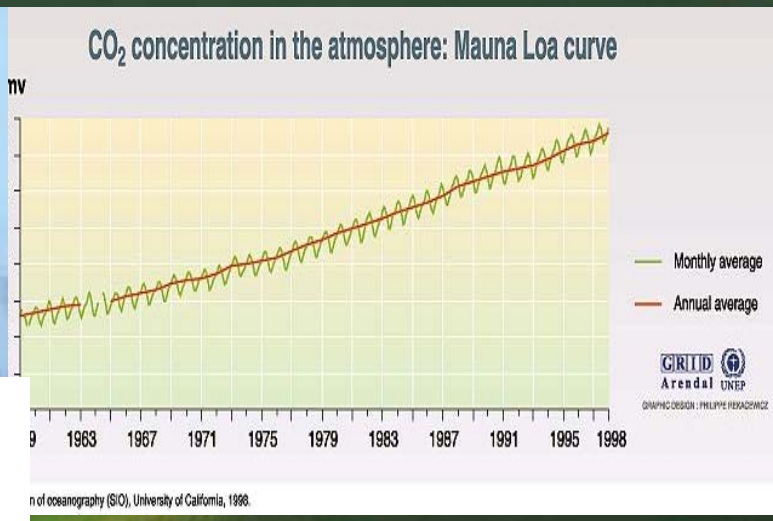
School of Chemistry & Biochemistry

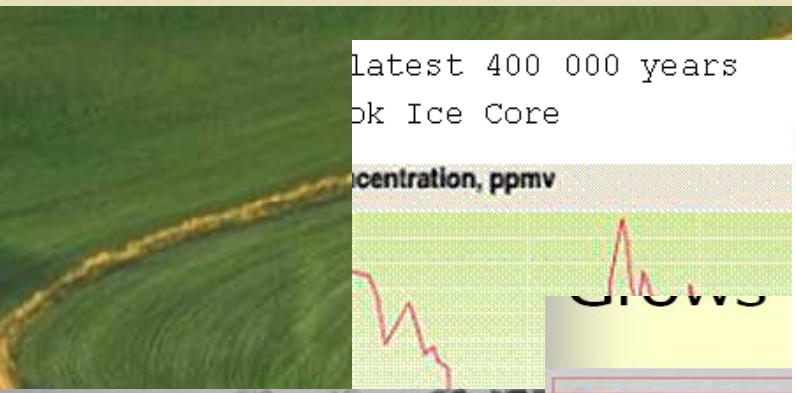
Georgia Institute of Technology

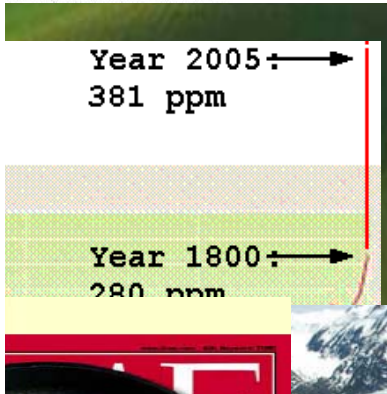
U.S. DEPARTMENT OF ENERGY

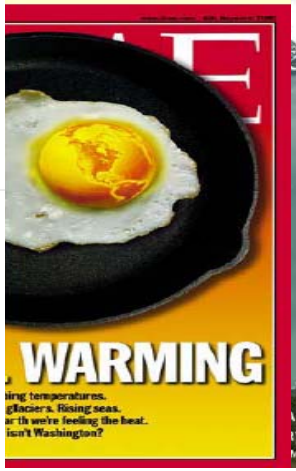
Sustainability
Global Societal Concern





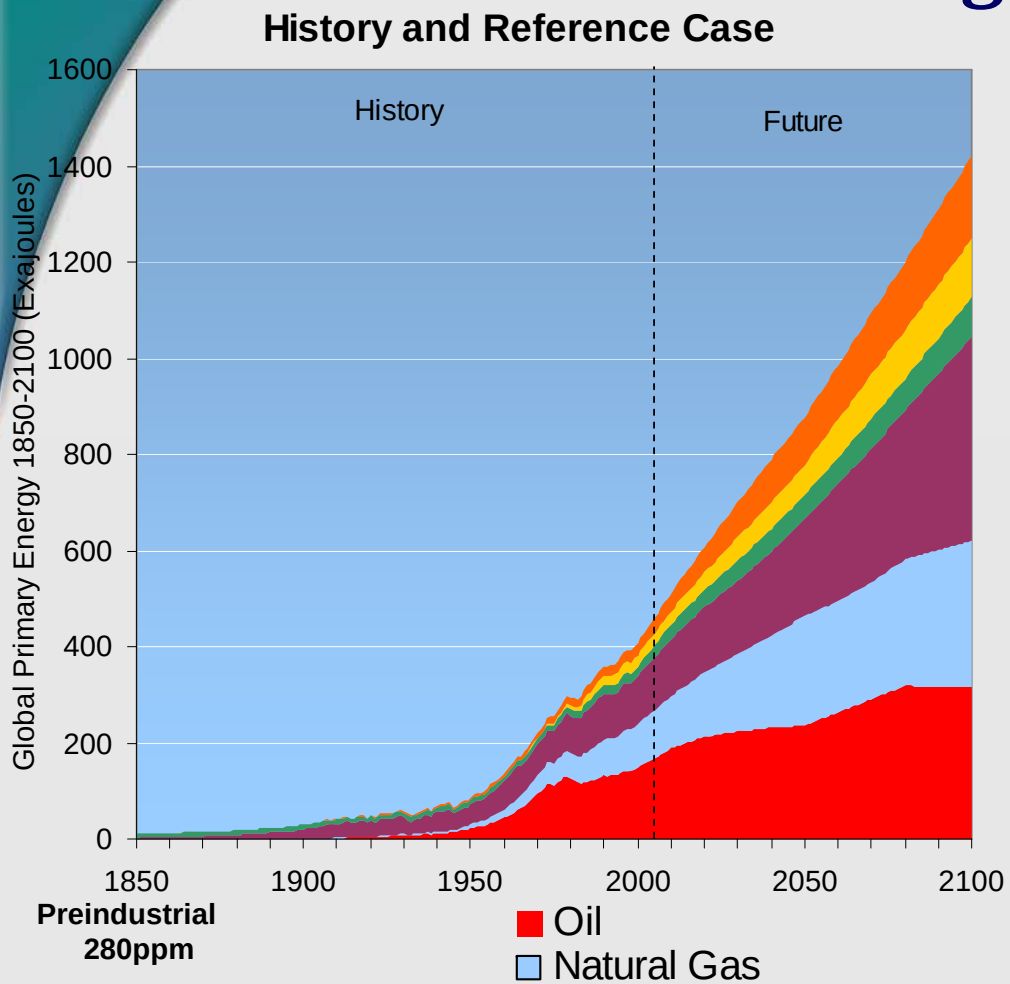


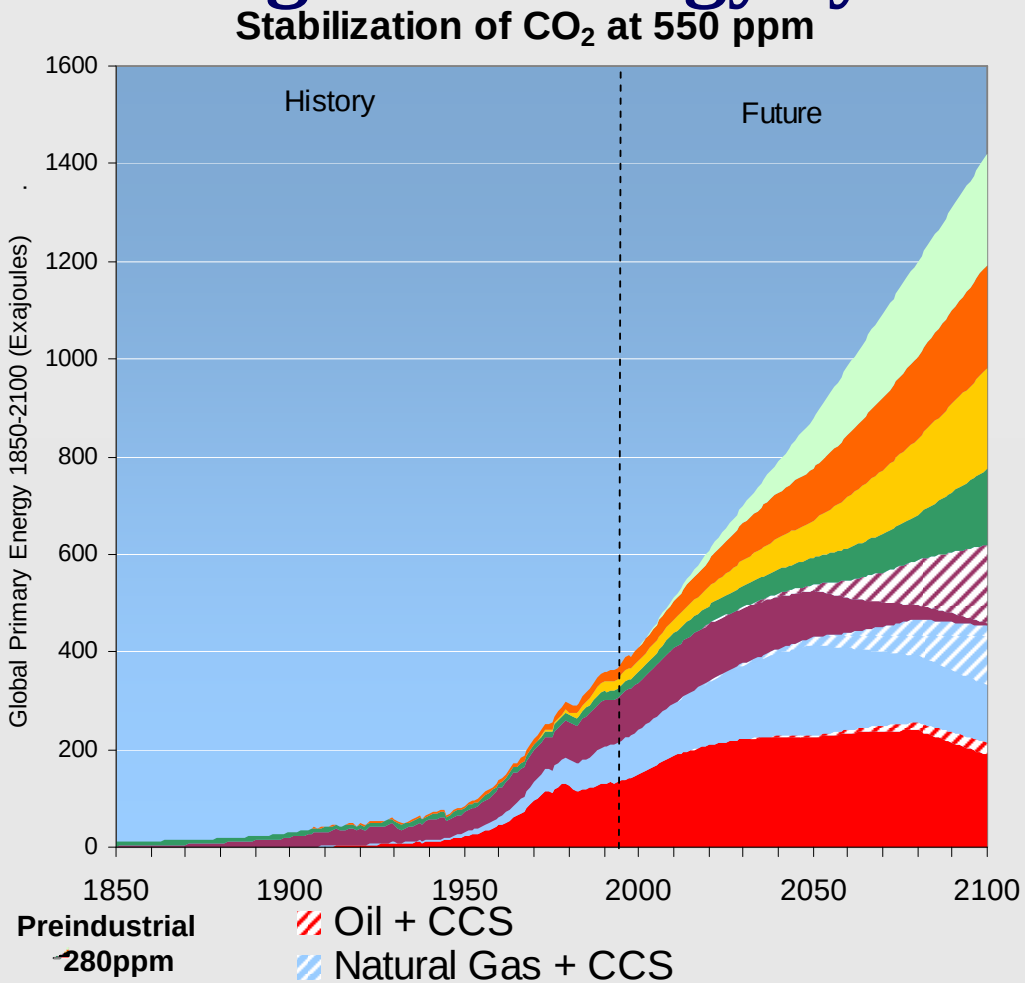




GTSP
Global Energy Technology Strategy Program

Stabilization of CO_2 concentrations means fundamental change to the global energy system



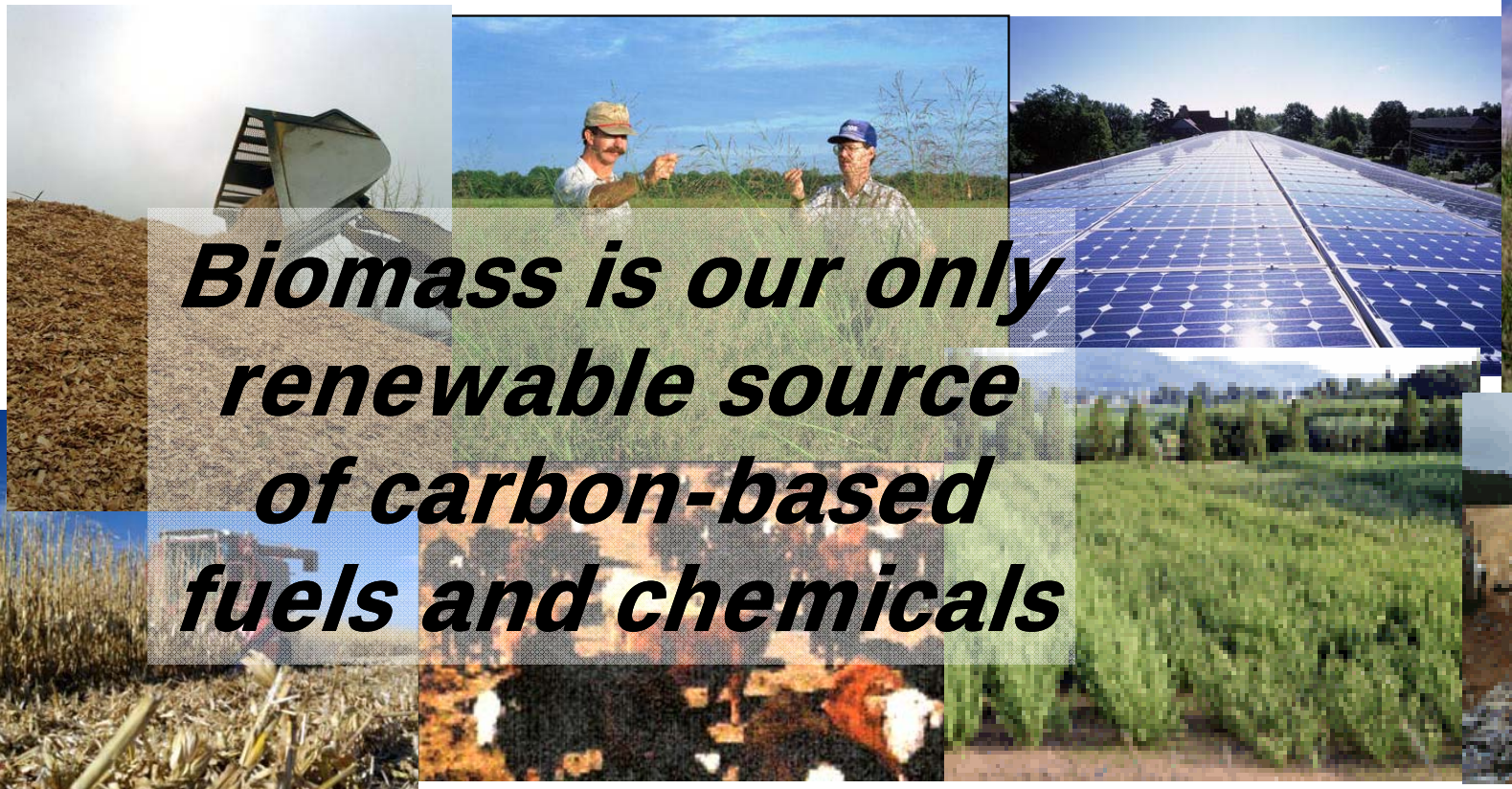


Source: Jae Edmonds

Battelle | JGCRI Joint Global Change Research Institute | University of Maryland | Pacific Northwest National Laboratory, Operated by Battelle for the U.S. Department of Energy

The Unique Role of Biomass

While the growing need for sustainable electric power can be met by other renewables…



Biomass is our only renewable source of carbon-based fuels and chemicals

Source: Ray Miller, DuPont, Jan. 2005

DUPONT
The miracles of science™

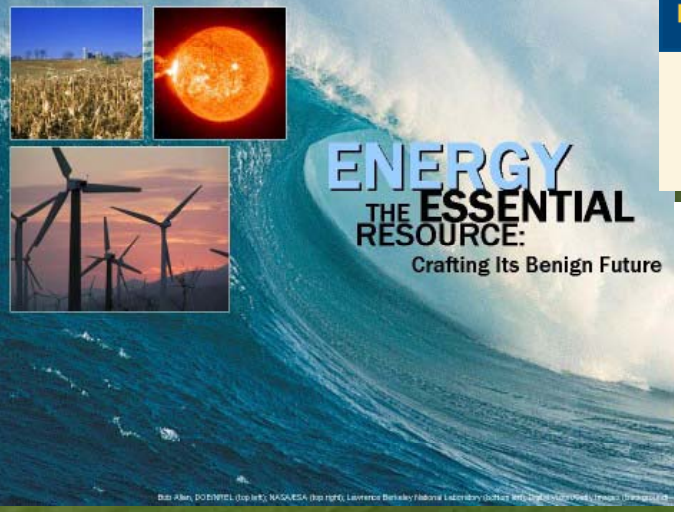
Research Opportunities: New Industrial Economy

David Morris - early 1980s

- **Coined the term "carbohydrate economy"**
- **Envisaged shifting society's engine toward renewable, environmentally benign materials from agro/forestry-based materials**

- Agricultural Risk Protection Act of 2000 Title III: Biomass R&D Act of 2000, established the Biomass Research & Development Board.

arpa·e
Advanced Research Projects Agency • ENERGY



KNOWLEDGE EXCHANGE *Series* February 2006 ESMAP

Potential for Biofuels for Transport in Developing Countries

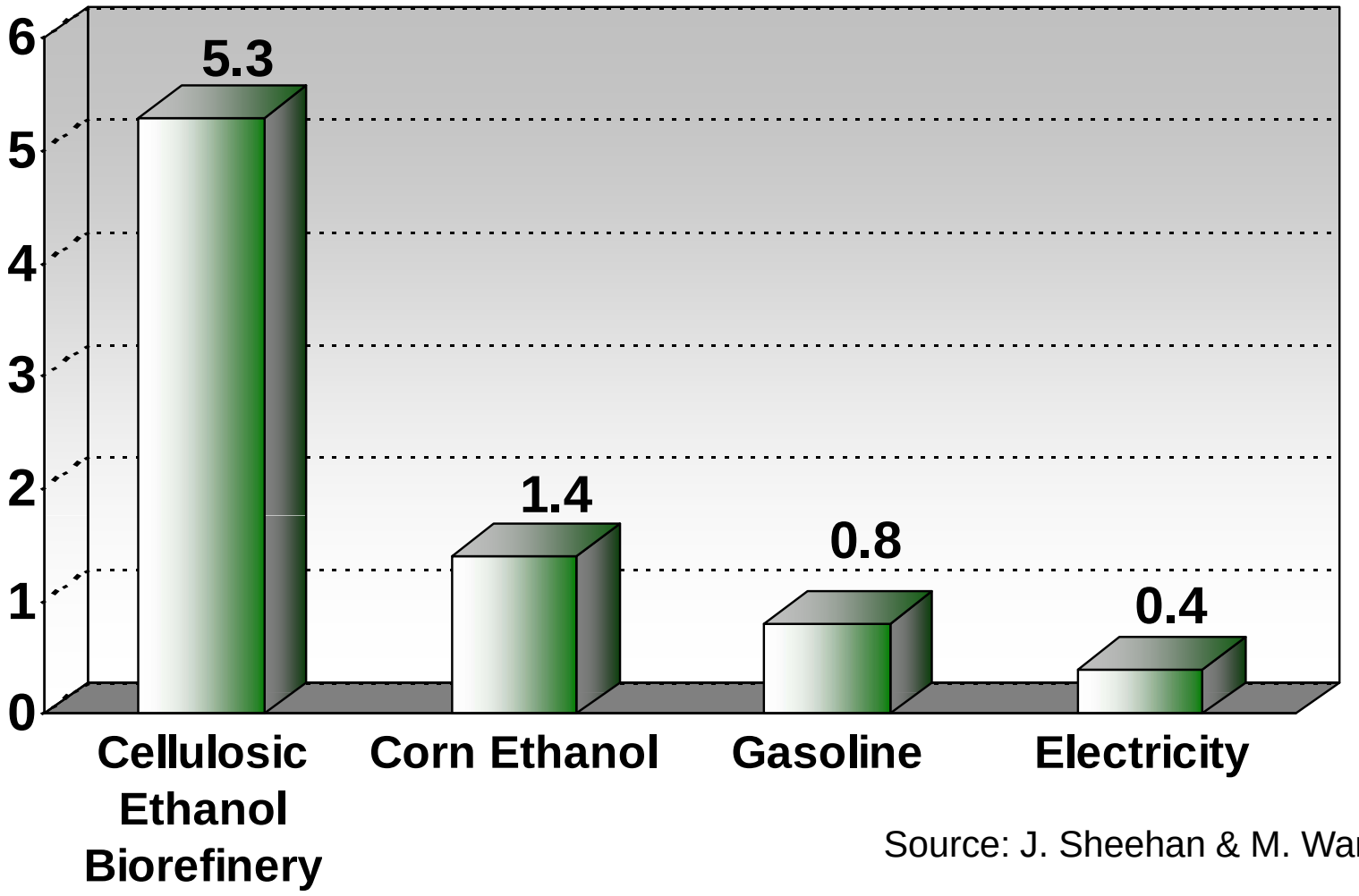
DOE GENOMICS:GTL
SYSTEMS BIOLOGY FOR ENERGY AND ENVIRONMENT
OFFICE OF SCIENCE
U.S. DEPARTMENT OF ENERGY

DARPA

Dr. Arden L. Bement, Jr.
Director, National Science Foundation

Fossil Energy Replacement Ratio

$$\text{Fossil Energy Ratio (FER)} = \frac{\text{Energy Delivered to Customer}}{\text{Fossil Energy Used}}$$



Source: J. Sheehan & M. Wang (2003)

The “30 by 30” goal

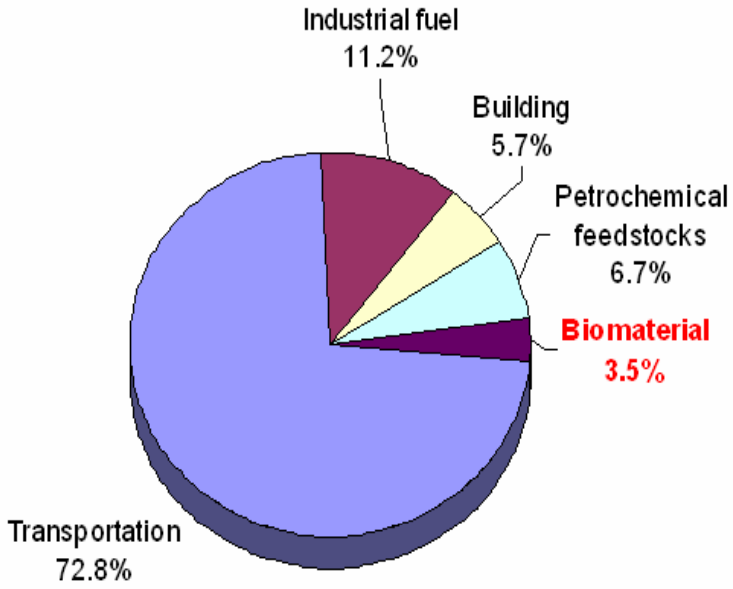
- **US petroleum consumption**
  - **329 billion gallons/year**
  - **>1000 gallons/year per person**
- **Goal set by Congress: Replace 30% gas and diesel consumption with biofuels by the 2030**
- **Requires approximately one billion dry tons of biomass for 60 billion gallons using current technology**

“20 in 10” goal from 2007

- **Decrease U.S. petroleum consumption by 20% in 10 years —“20 in 10”**
- **Grow production of renewable fuels to 35 billion gallons per year**

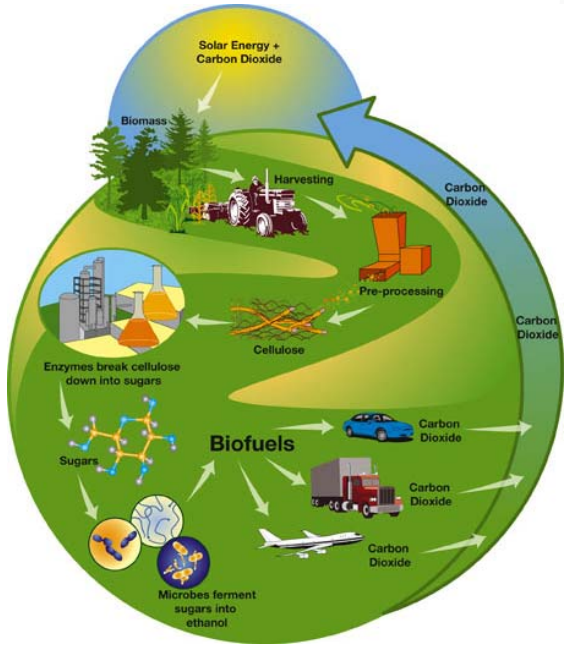
Energy Independence and Security Act

2008 Farm Bill

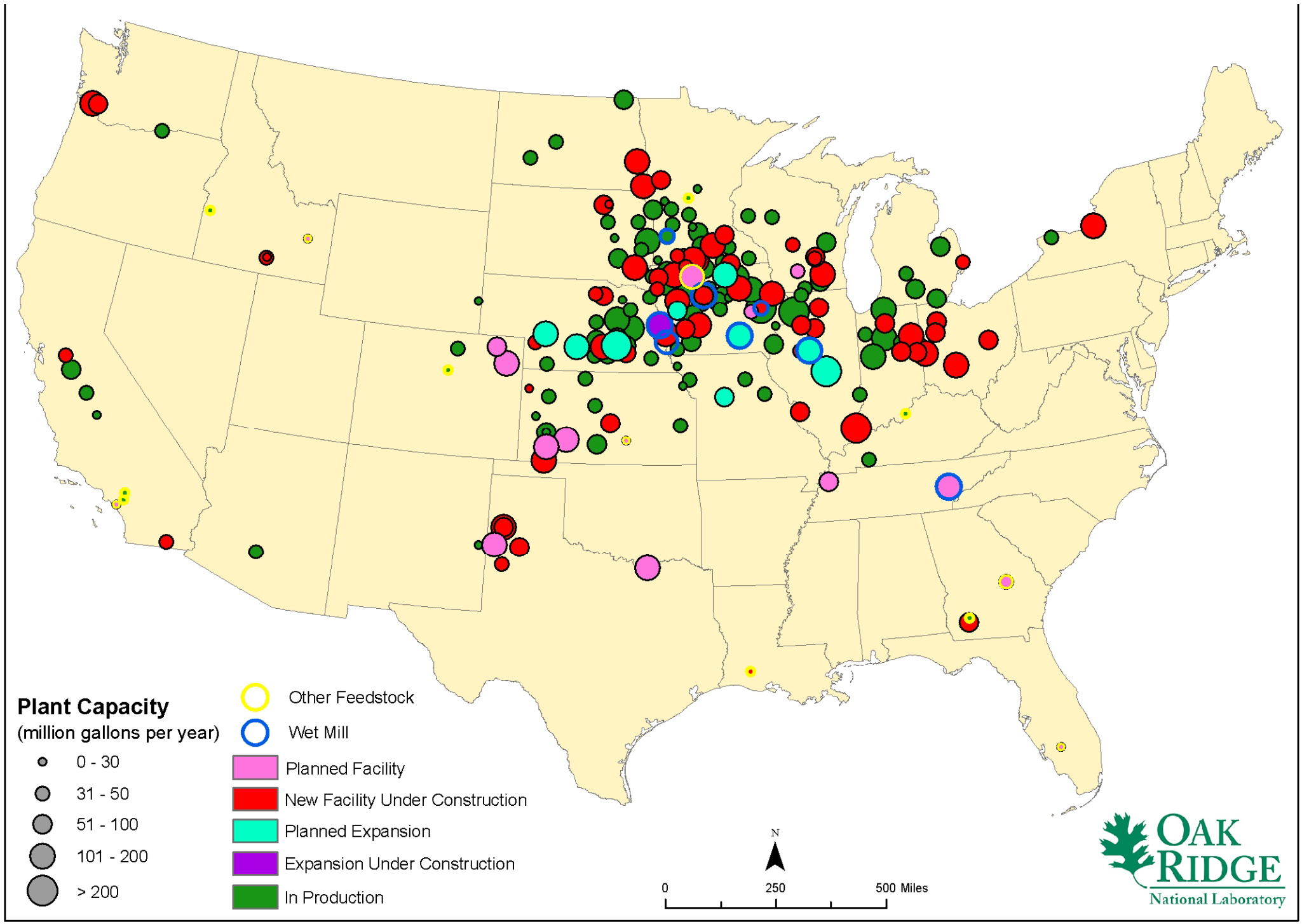


Predicted Petroleum Use in 2025-2030

Source: Winning the Oil Endgame, RMI 2005, and *NRC 2000

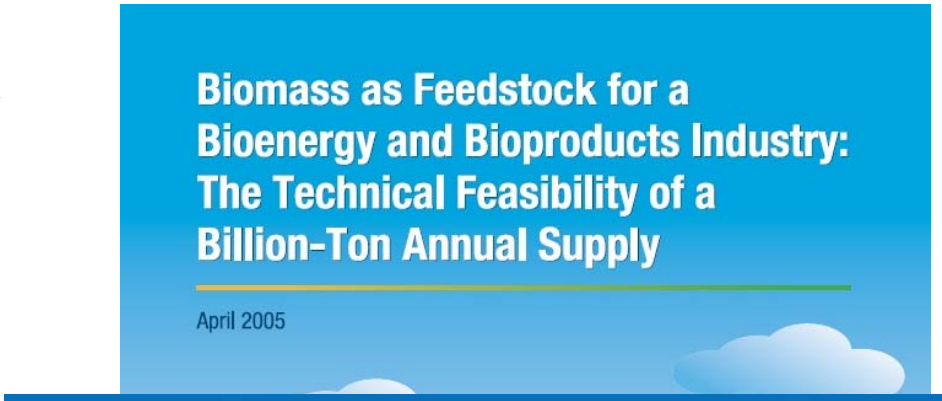


Current and Future Ethanol Biorefineries



Are there Sufficient Amounts of Biomass?

- **Yes, land resources of the U.S. can sustainably supply more than 1.3 billion dry tons annually and still continue to meet food, feed, and export demands**
- **Required changes are not unreasonable given current trends and time-frame for bio-industry scale-up and deployment**



http://v

DOE Office of Biomass Programs - Leveraging Partnerships to Achieve Goals

- **Commercial-Scale Biorefineries (up to $272 million)**
  - **Four cost-shared, integrated biorefinery demonstration projects to produce 130 million gallons of cellulosic ethanol in 5 years using variety of conversion technologies and cellulosic feedstocks**
- **10%-Scale Biorefinery Validation (up to $200 million)**
  - **Cost-shared, integrated biorefinery demonstrations using cellulosic feedstocks to produce renewable fuels; one-tenth of commercial scale**
  - **Seven selectees announced for a total investment of $200 million**
- **Ethanologen Solicitation (up to $23 million)**
  - **Five selected research teams working on microorganisms**
- **Enzyme Solicitation (up to $33.8 million)**
  - **Four selected research teams working on inexpensive enzyme systems for commercial biomass hydrolysis**
- **Thermochemical Solicitation (up to $16.7 million)**
  - **Integration of gasification and catalyst development**
  - **Pyrolysis oil stabilization**
- **Joint DOE-USDA Solicitation ($18 million)**
  - **Biomass R&D Initiative: 20 awards**

The Strategic Need for ARPA-E Stemmed from "Rising Above the Gathering Storm" Report

Rising Above the Gathering Storm, 2006
(National Academies)

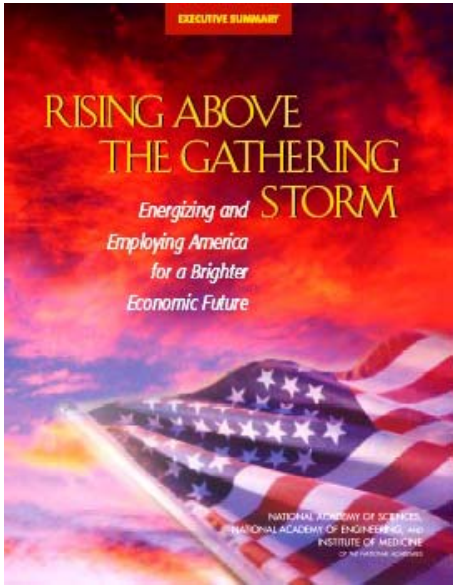
- Establish an Advanced Research Projects Agency for Energy (ARPA-E)
- "Creative, out-of-the-box, transformational" energy research
- Spinoff Benefit – Help educate next generation of researchers
- Secretary Chu (then Director of Berkeley National lab) on committee

America COMPETES Act, 2007

- Authorizes the establishment of ARPA-E

American Recovery and Reinvestment Act of 2009
(Recovery Act)

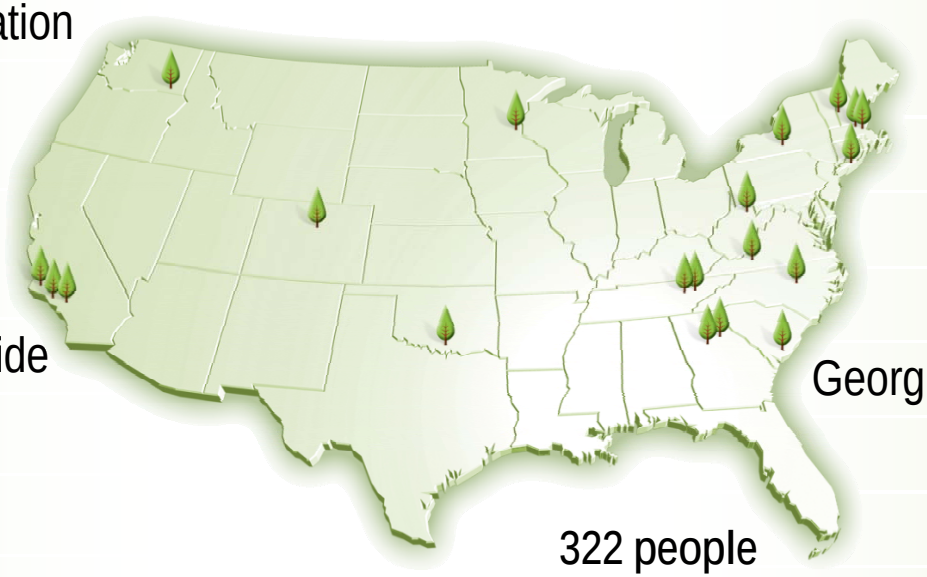
- $400M appropriated for ARPA-E
- President Obama launches ARPA-E in a speech at NAS on April 27, 2009



BioEnergy Science Center

BESC: A multi-institutional DOE-funded center dedicated to understanding and modifying plant biomass recalcitrance

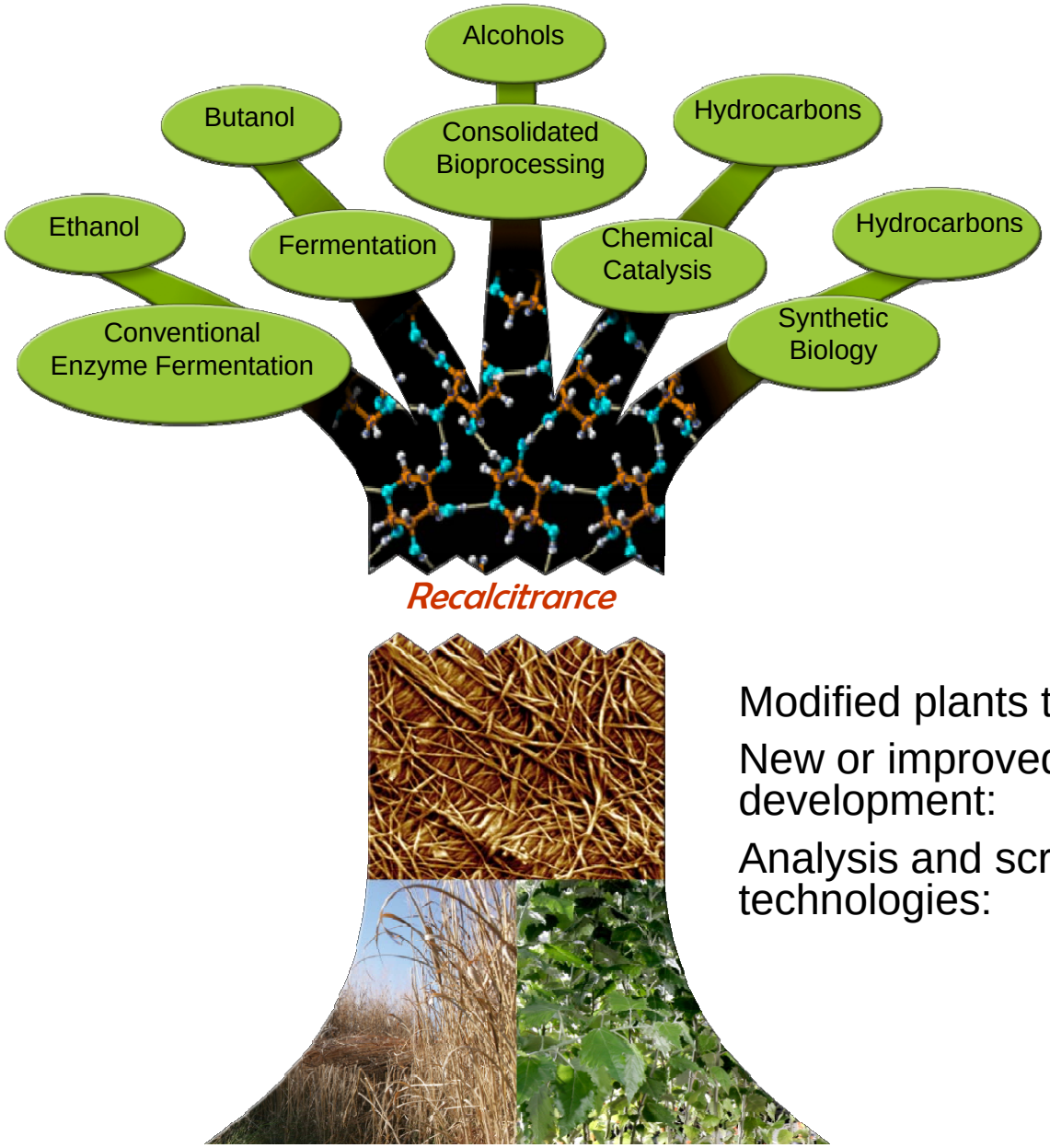
- Samuel Roberts Noble Foundation
- National Renewable Energy Laboratory
- Brookhaven National Laboratory
- University of California–Riverside
- Cornell University
- Washington State University
- University of Minnesota
- North Carolina State University
- Virginia Polytechnic Institute
- University of California–Los Angeles



322 people
in 20 institutions

- Oak Ridge National Laboratory
- University of Georgia
- University of Tennessee
- Dartmouth College
- Georgia Institute of Technology
- West Virginia University
- ArborGen, LLC
- Ceres, Incorporated
- Mascoma Corporation
- Verenium Corporation

Access to the Sugars in Lignocellulosic Biomass is the Current Critical Barrier

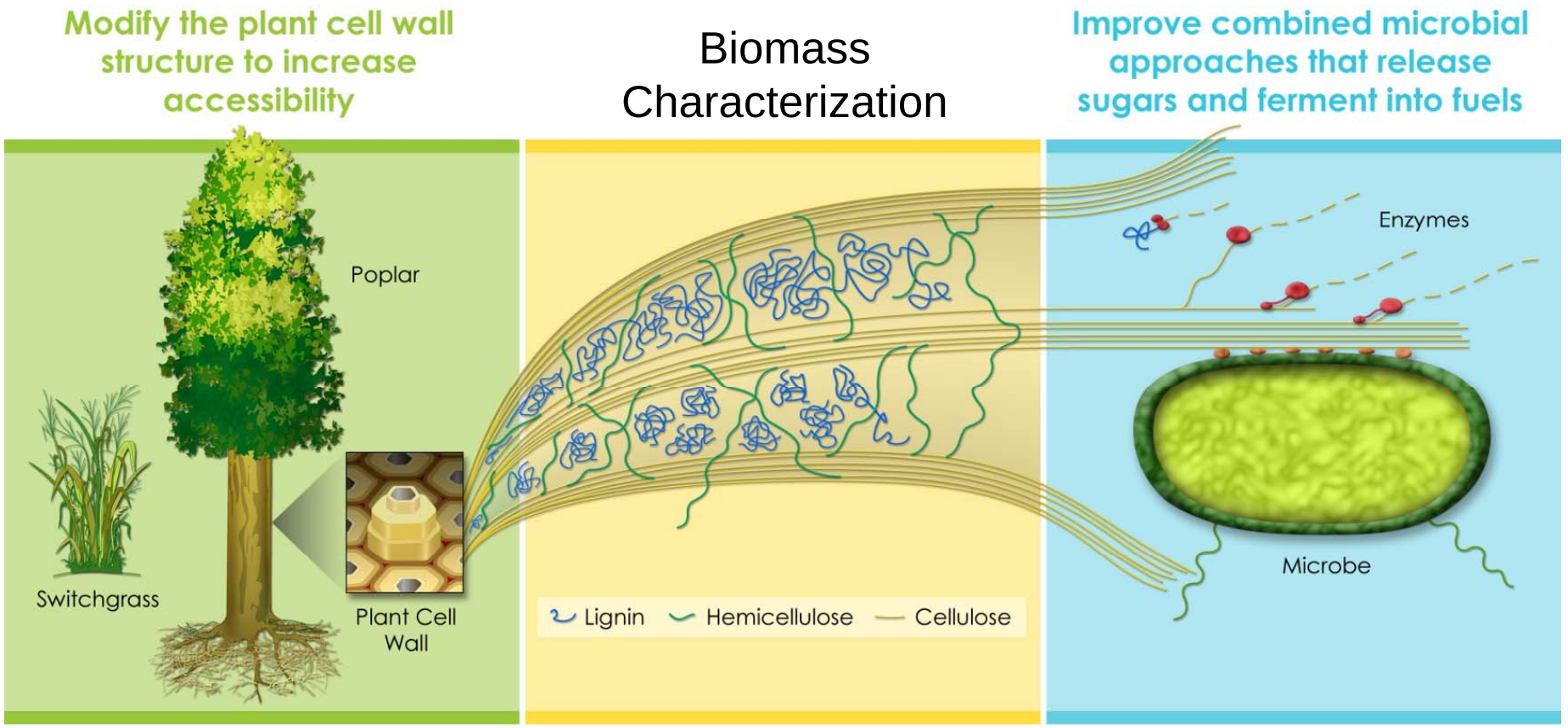


- Solving this will cut processing costs significantly and be used in most conversion processes
- This requires an integrated multidisciplinary approach
- Timeframe

	Planned	Actual
Modified plants to field trials:	Year 5	Year 4
New or improved microbes to development:	Year 4-5	Year 3-4
Analysis and screening technologies:	Year 3 on	Year 2 on

BioEnergy Science Center

A Multi-pronged Approach to Increase the Accessibility of Biomass Sugars



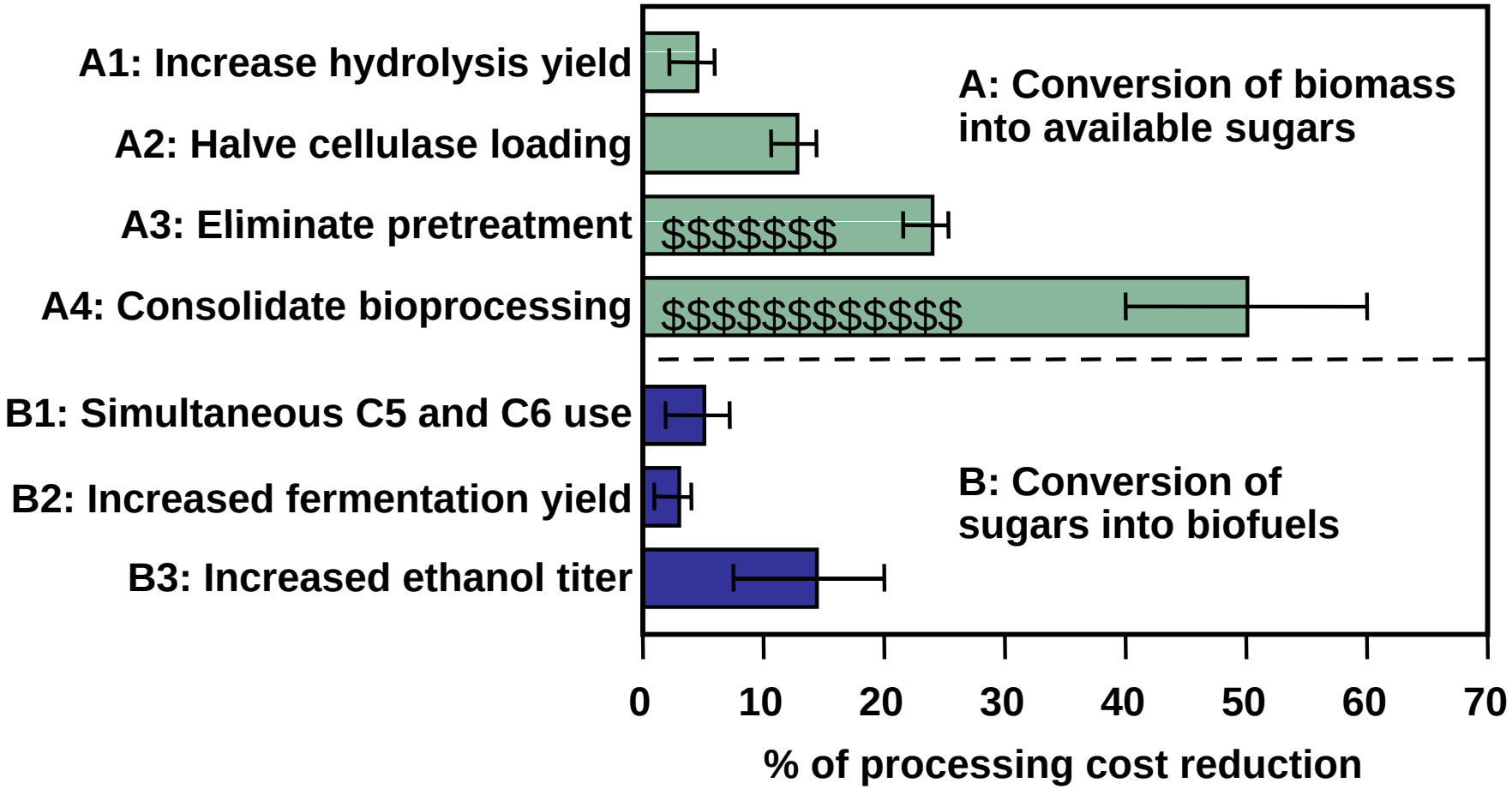
Both utilize rapid screening for relevant traits followed by detailed analysis of selected samples

Switchgrass example (USDA-BESC)

Yeast example (Mascoma-BESC)

BioEnergy Science Center

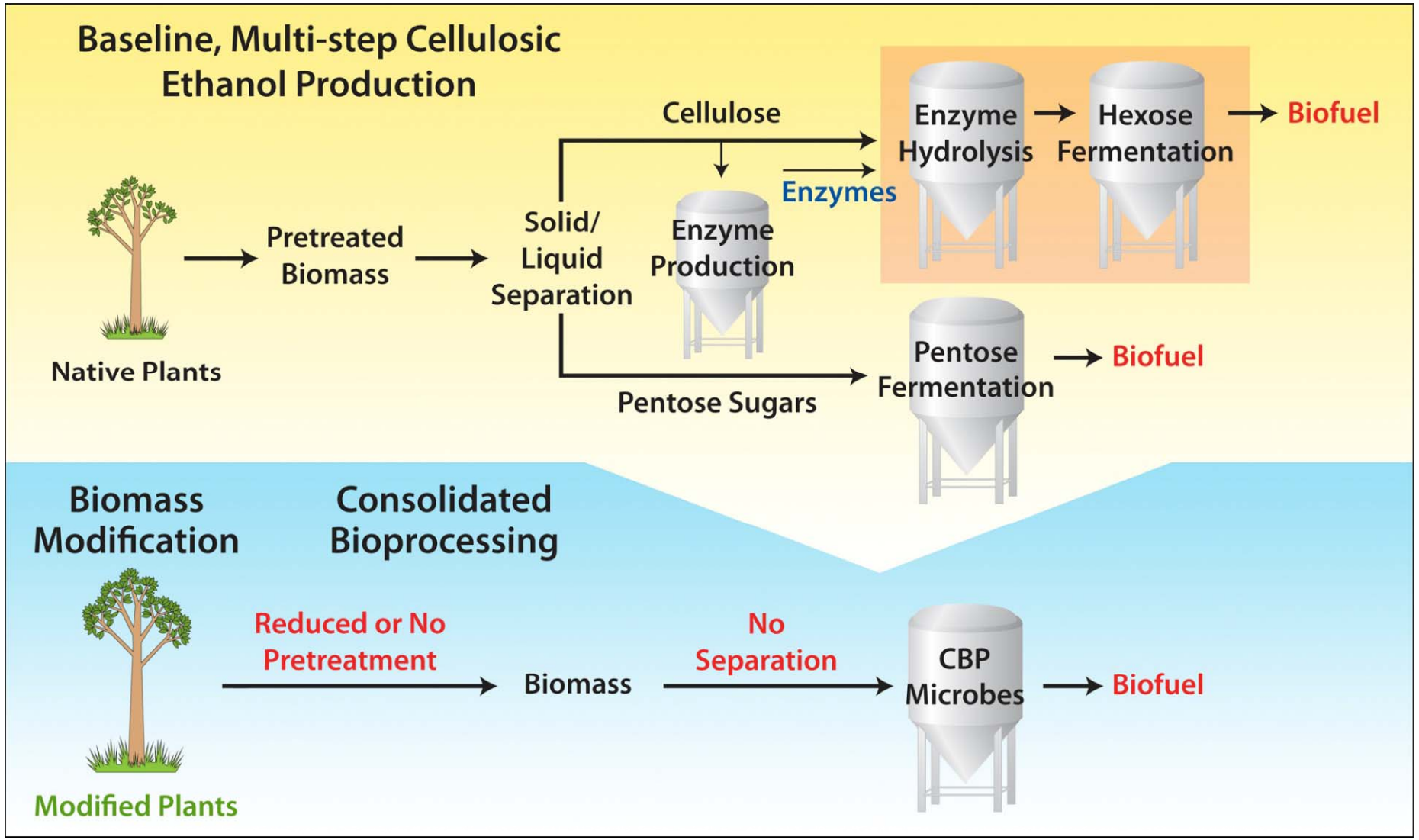
Comparative impacts of R&D on biomass processing cost



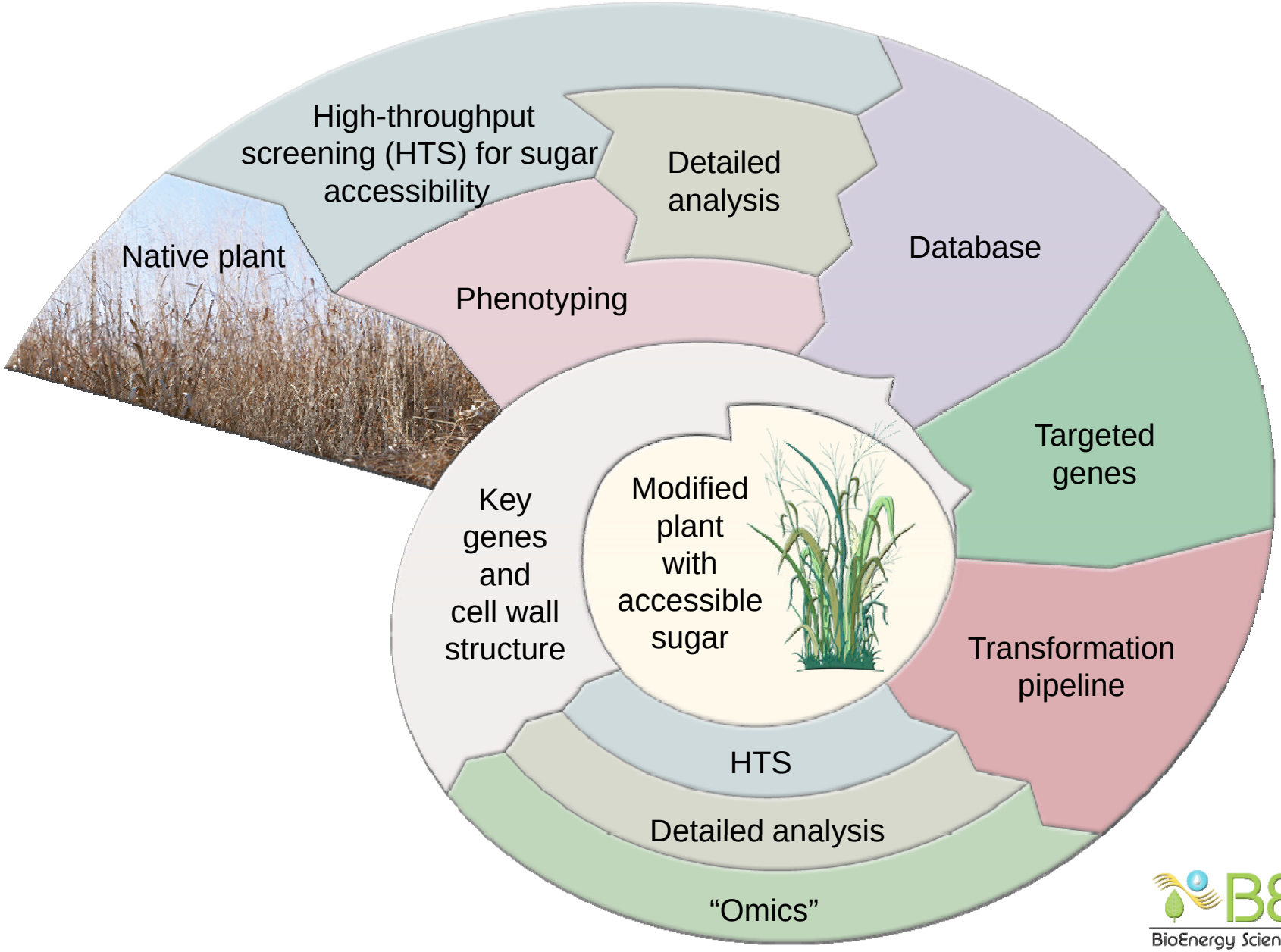
Without overcoming biomass recalcitrance (A), cellulosic biofuels will be more expensive than corn biofuels. Improved sugar conversion (B) is not enough.

Ref: Lynd, L.R., M.S. Laser, D. Bransby, B.E. Dale, B. Davison, R. Hamilton, M. Himmel, M. Keller, J.D. McMillan, J. Sheehan, C.E. Wyman, "How Biotech can transform biofuels," *Nature Biotechnology* 26:169-172 (2008)

BESC Will Revolutionize How Biomass is Processed



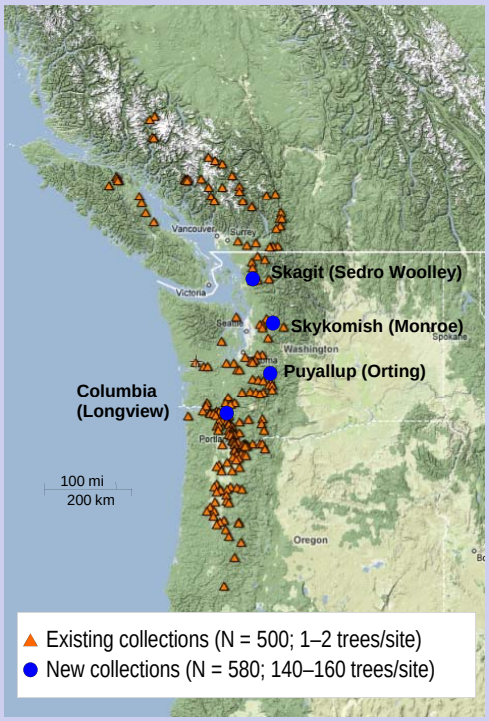
What Genes Control Cell Wall Synthesis (and Access to the Sugars)?



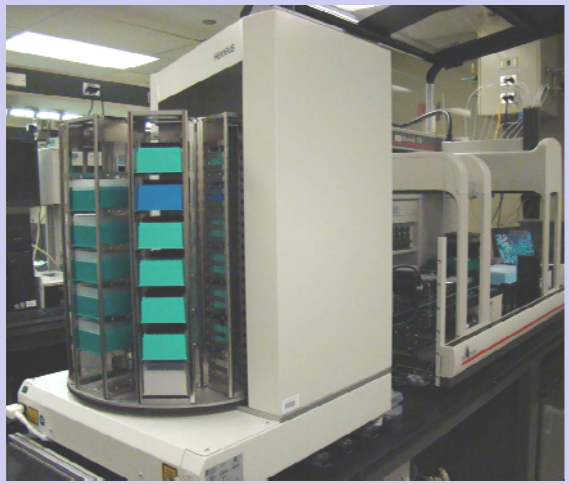
Mining variation to identify key genes in biomass composition and sugar release

U.S. DEPARTMENT OF ENERGY

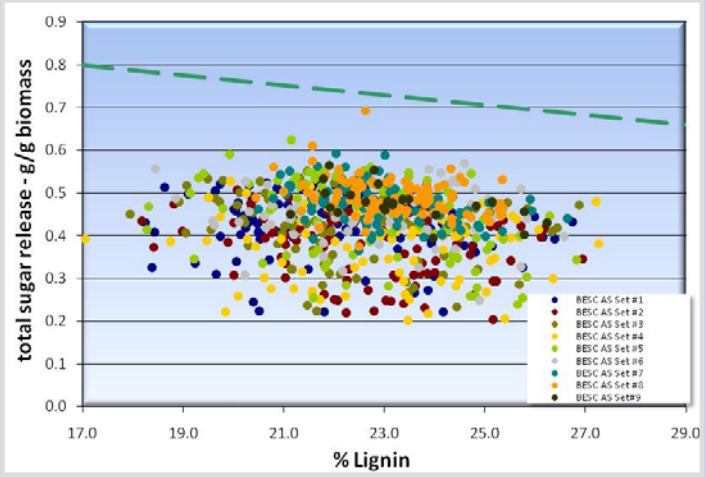
Collected 1300 samples for *Populus* association and activation-tag study



Developed high-throughput characterization pipeline



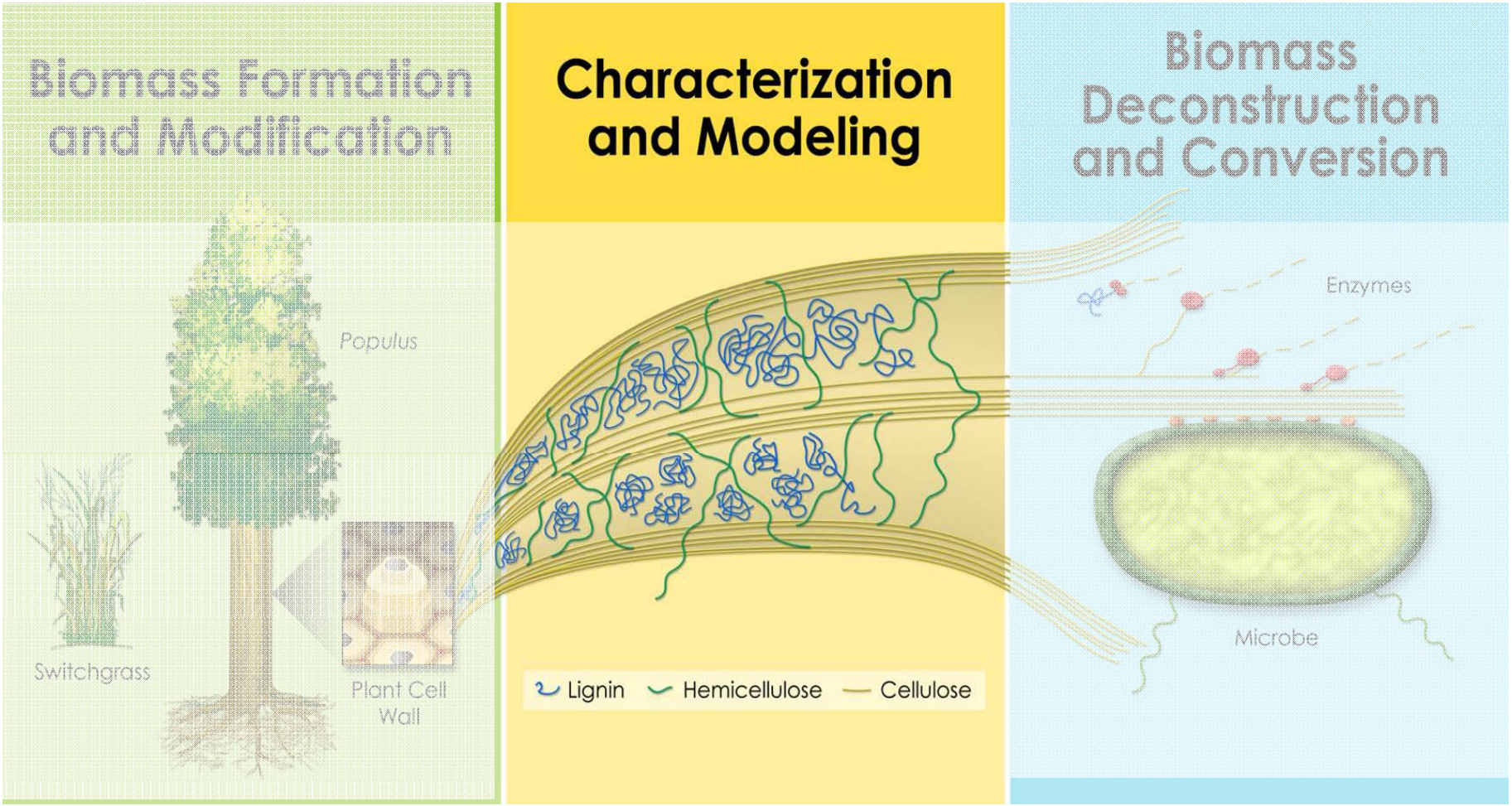
Screen showed high level of natural diversity



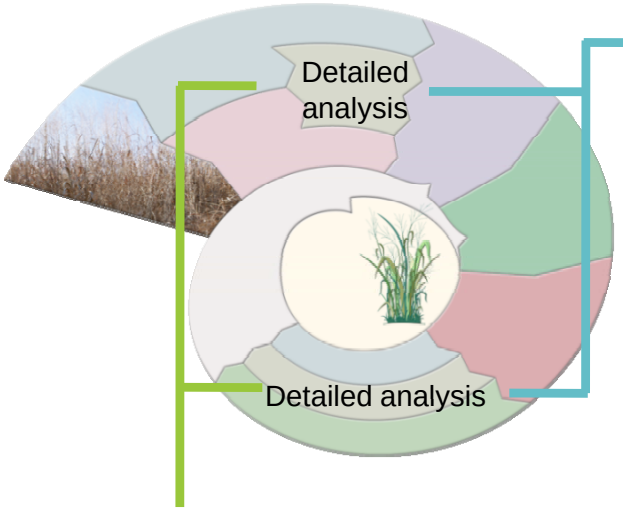
- Hot water as pretreatment only
- Sugar release varies from 25% to >90% of theoretical value
- Using common gardens to distinguish the genetic vs environmental effects

BESC BioEnergy Science Center

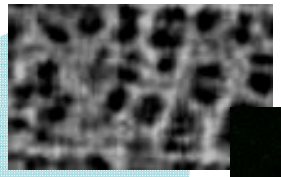
Strategy Part 2:Understanding the Plant Cell Wall



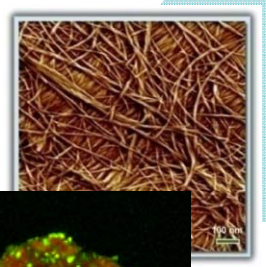
Detailed Analysis of Specific Samples Inform Cell-wall Chemistry and Structure



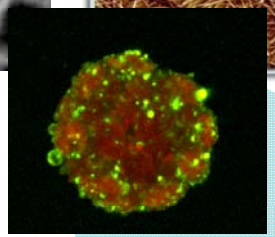
Imaging



Bio-ultraCAT for 3-D density of *Populus* cell walls

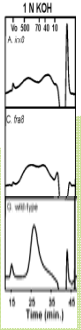


AFM of switchgrass showing cellulose microfibrils

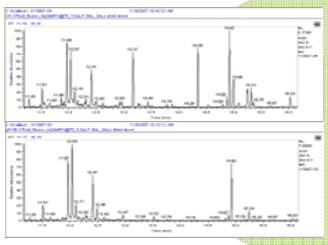


Immunolocalization using wall antibodies on *Populus* protoplasts

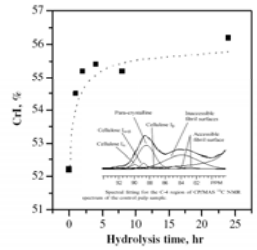
Chemistry



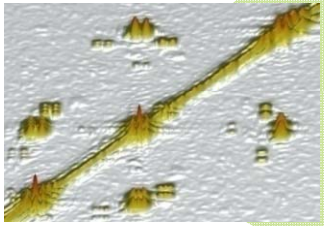
Fractionation and chromatography



Mass Spectrometry for key metabolites



NMR for cellulose crystallinity



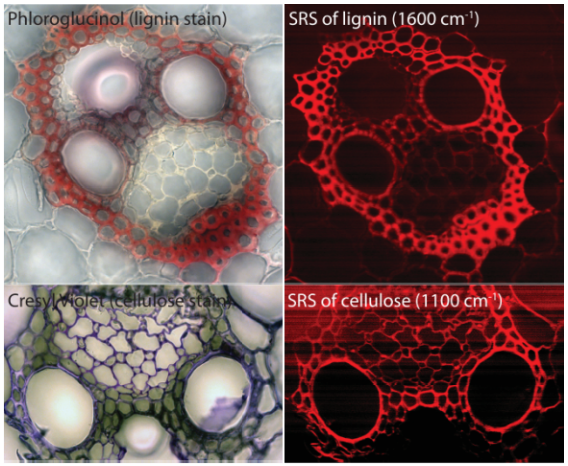
2D ^{1}H-NMR sees altered bonds in polysaccharides and lignin in biomass

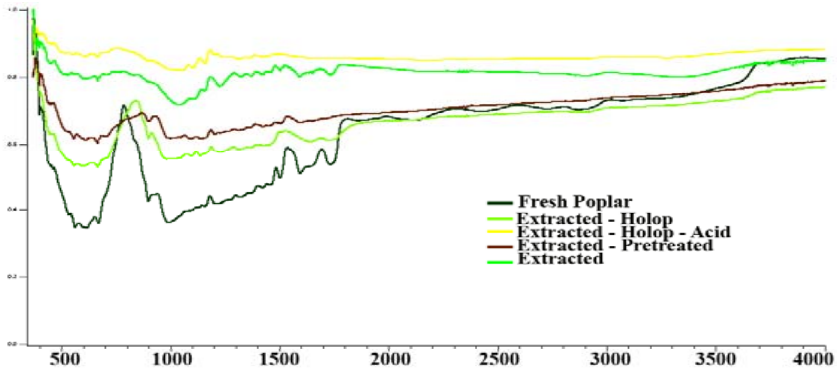
BioEnergy Science Center

New Techniques Begin to Link Images with Chemistry

- Imaging alone gives us
  - Shapes and structures
  - Gross compositional and structural variations
  - Localized affinities
- New techniques:
  - Stimulated Raman Microscopy – Harvard/NREL
  - Raman and Mass Spec – Notre Dame
  - In vivo ROS - UFL
  - Scanning Near-field Acoustic Photothermal Spectroscopy – ORNL
- Scale and resolution are the issues

SRS for cellulose and lignin – Ding et al.



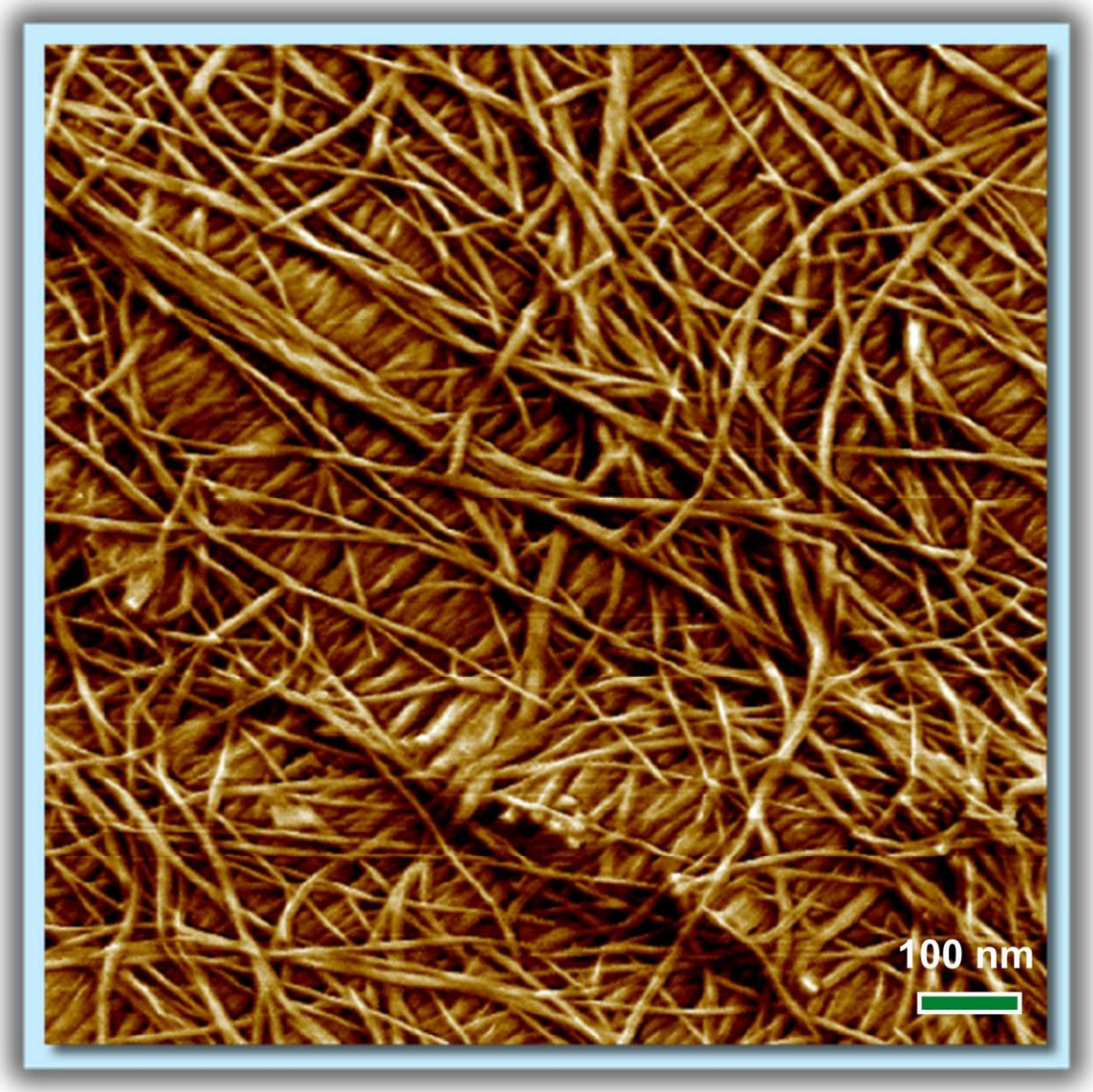


Spectra of treated Populus - Thundat et al.

BioEnergy Science Center

unpublished

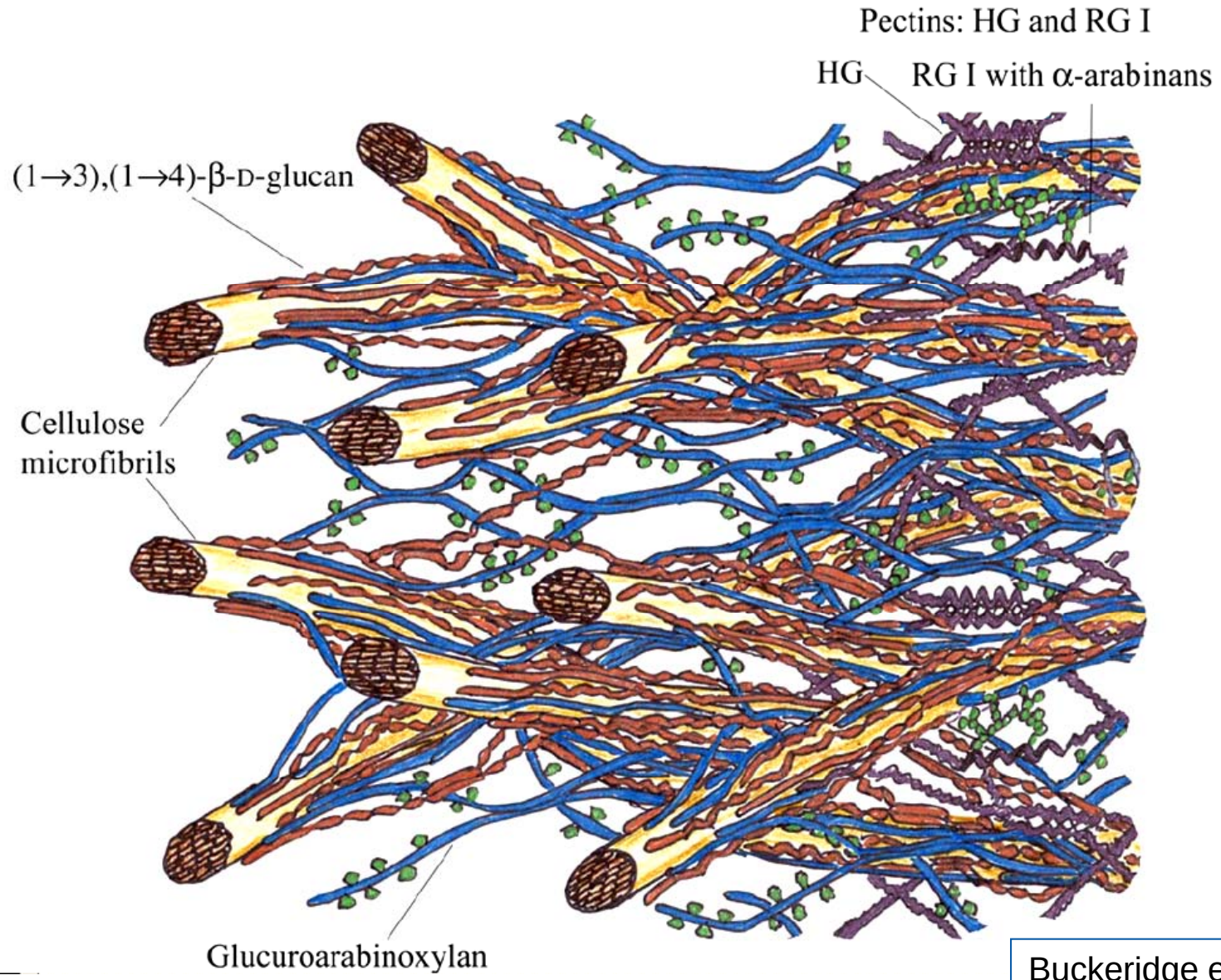
Switchgrass – Atomic Force microscopy (AFM)



Crystalline cellulose microfibrils

NREL, Ding, et al, unpublished results

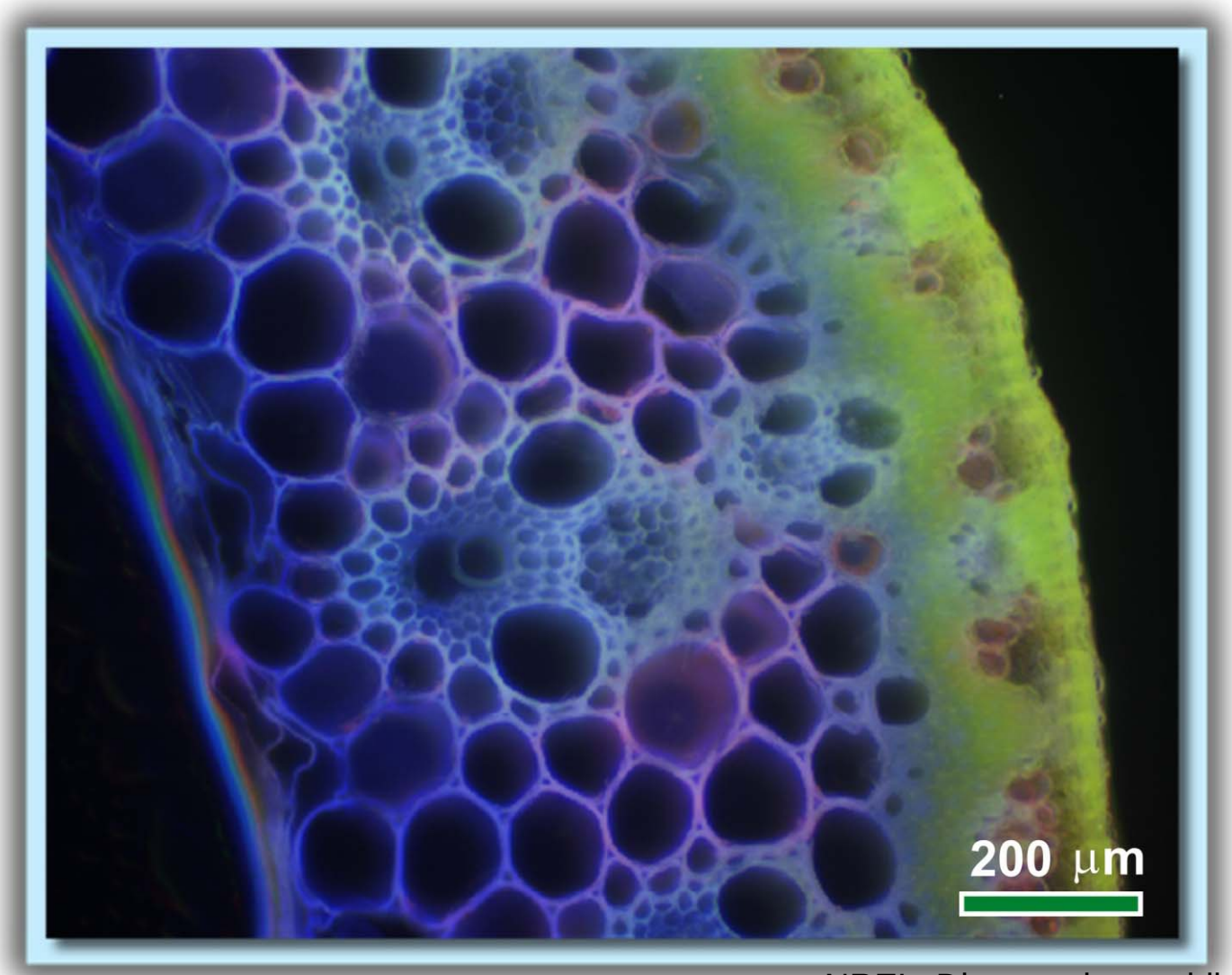
Plant Cell Wall Models



Buckeridge et al., 2004

BioEnergy Science Center

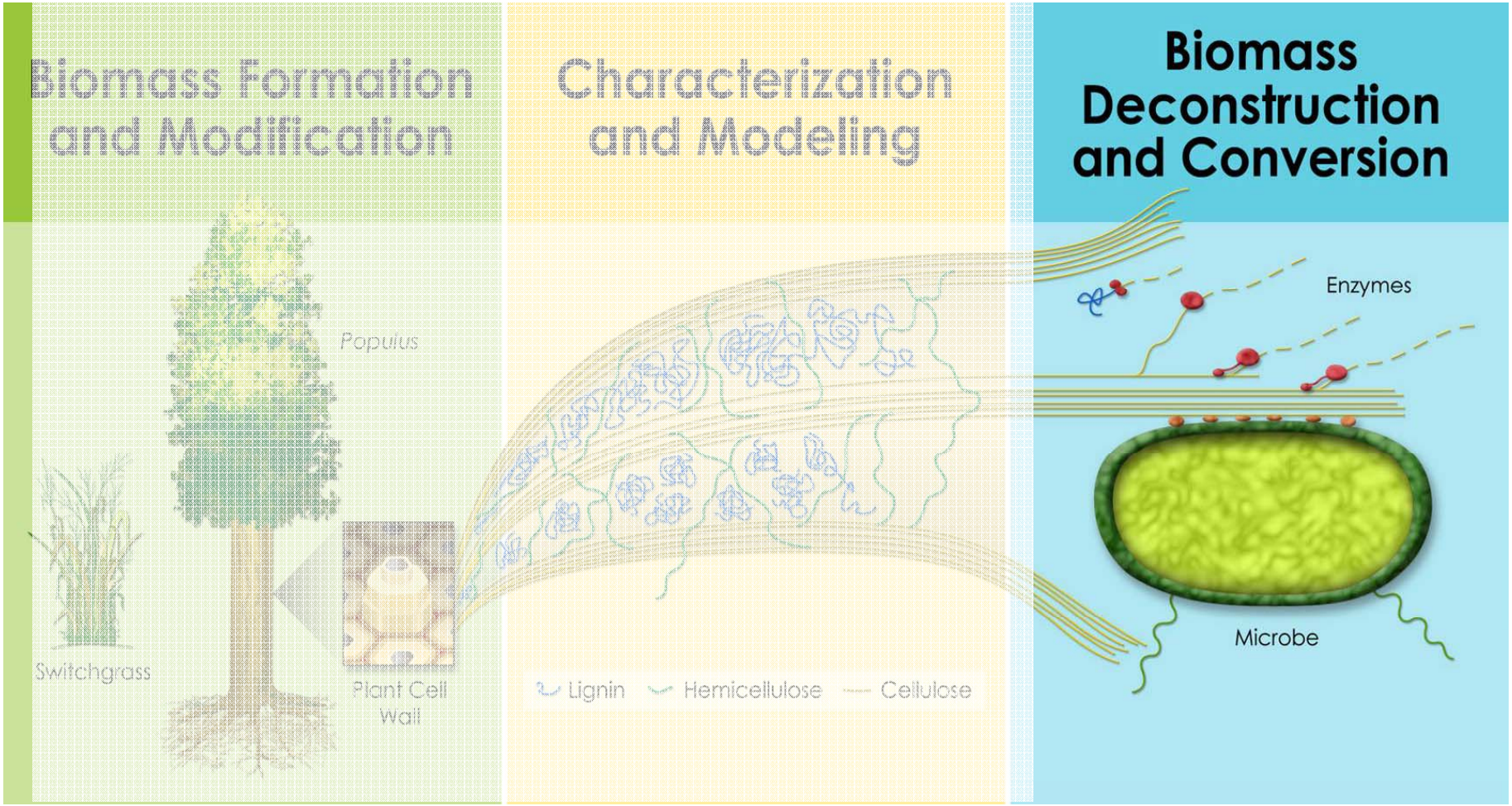
Switchgrass – Fluorescence Microscopy



NREL, Ding, et al, unpublished results

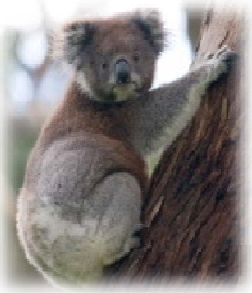
Fluorescence signals primarily come from **chlorophyll, lignin, carotenes, and xanthophylls in plants**, each with a different wavelength (color), lignin fluorescence is blue-greenish. Determine cell liginfication by using different filter sets

Strategy Part 3: Identify, Understand and Manipulate "Biological Catalysts" to Overcome Recalcitrance



Exploring Novel Environments for Enzymes

- Rumen endosymbionts
- Caecum endosymbionts
- Coleopteran larvae
- Biotraps
- Shipworms
- Fungi



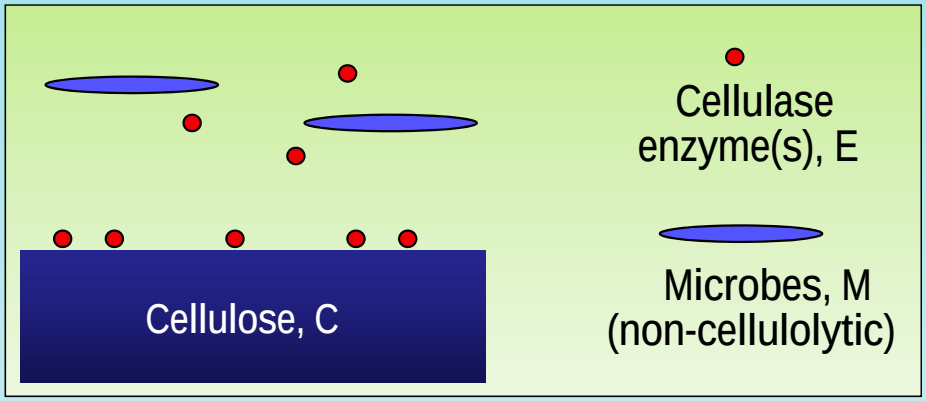
Biodiversity Access for New Biocatalysts

- Hypothesis: Will higher temperature anaerobic microbes be more effective?
- State-of-the-art cultivation techniques to isolate novel high-temperature microbes with powerful lignocellulolytic enzymes
  - Collect samples from thermal biotopes
  - Establish primary enrichment cultures at relevant temperatures and conditions

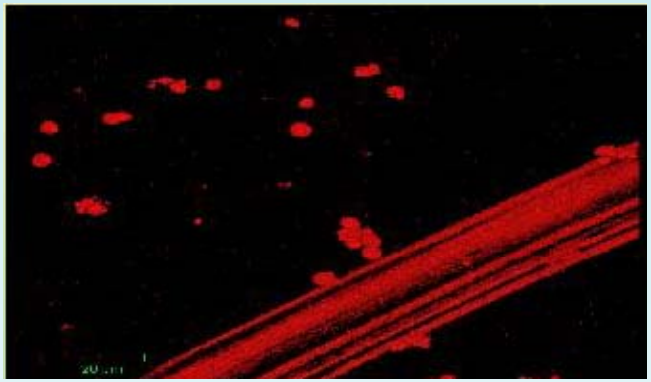
Sampling at Yellowstone National Park October 2007 and July 2008

Microbial Hydrolysis and Enzymatic Hydrolysis: A Fundamentally Different Relationship Between Microbes and Cellulose

Enzymatic hydrolysis (classical approach)

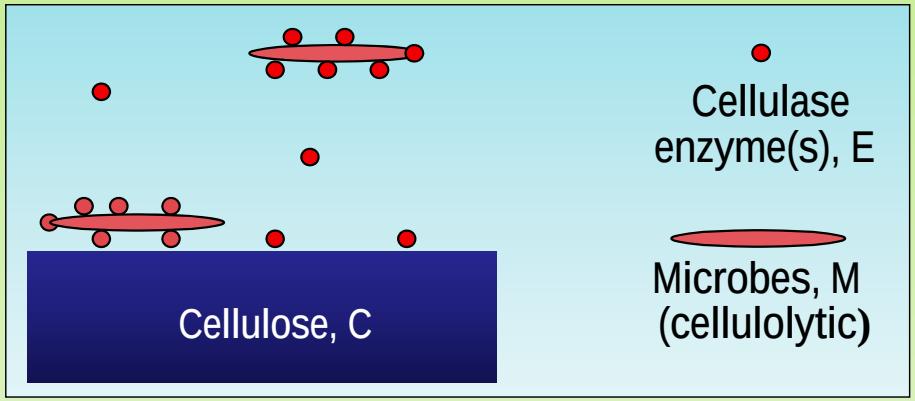


- Hydrolysis mediated by CE complexes
- Enzymes (several) both bound and free
- Cells may or may not be present

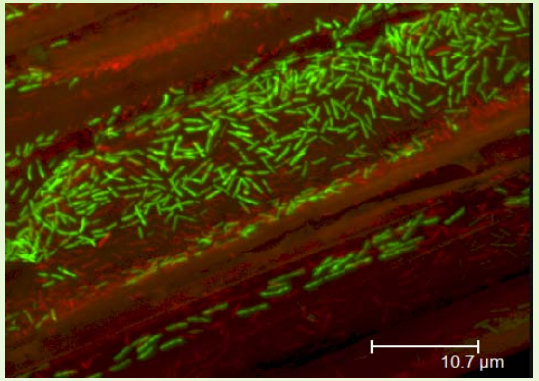


Yeast, enzymes with biomass, Dumitrache and Wolfaardt

Microbial hydrolysis (CBP)



- Hydrolysis mediated mainly by CEM complexes
- Enzymes both bound and free
- Cells both bound and free

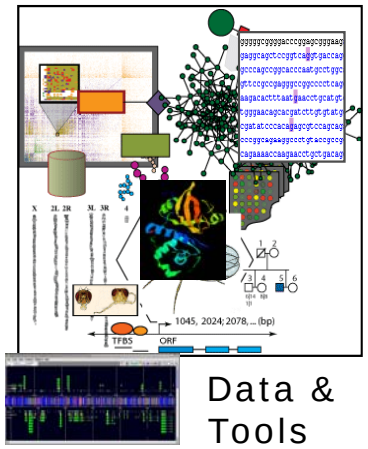


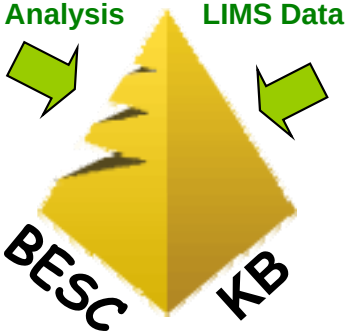
***C. thermocellum* on poplar, Morrell-Falvey and Raman, ORNL**

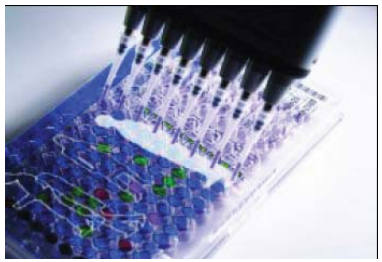
BESC Knowledge Base

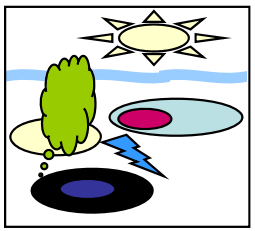
Knowledge Base Mission

- Analyze and present integrated data and results in the context of cell and organism systems biology







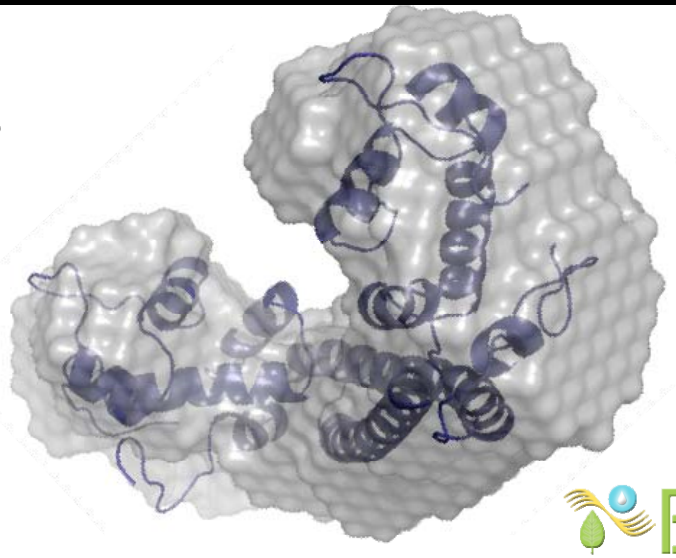


- **BESC Knowledge discovery and data mining environment for *design* of experiments**
- ***Interpretation of BESC experimental* data thru integration with community / reference data such as genomes, pathways, networks, ontologies**
- Integrate diverse data types across BESC **data to provide new insights in to cell wall recalcitrance, etc.**
- **Provides systems level representations, knowledge, data, and information on key plants, microbes, and molecules**
- **Serves as a biological discovery / data mining platform for larger community**

BioEnergy Science Center

BESC Leverages High Performance Computing and Neutron Capabilities

- BESC shares samples and insights with another BER project to develop lignocellulosic biomass relevant analyses using neutron and simulations



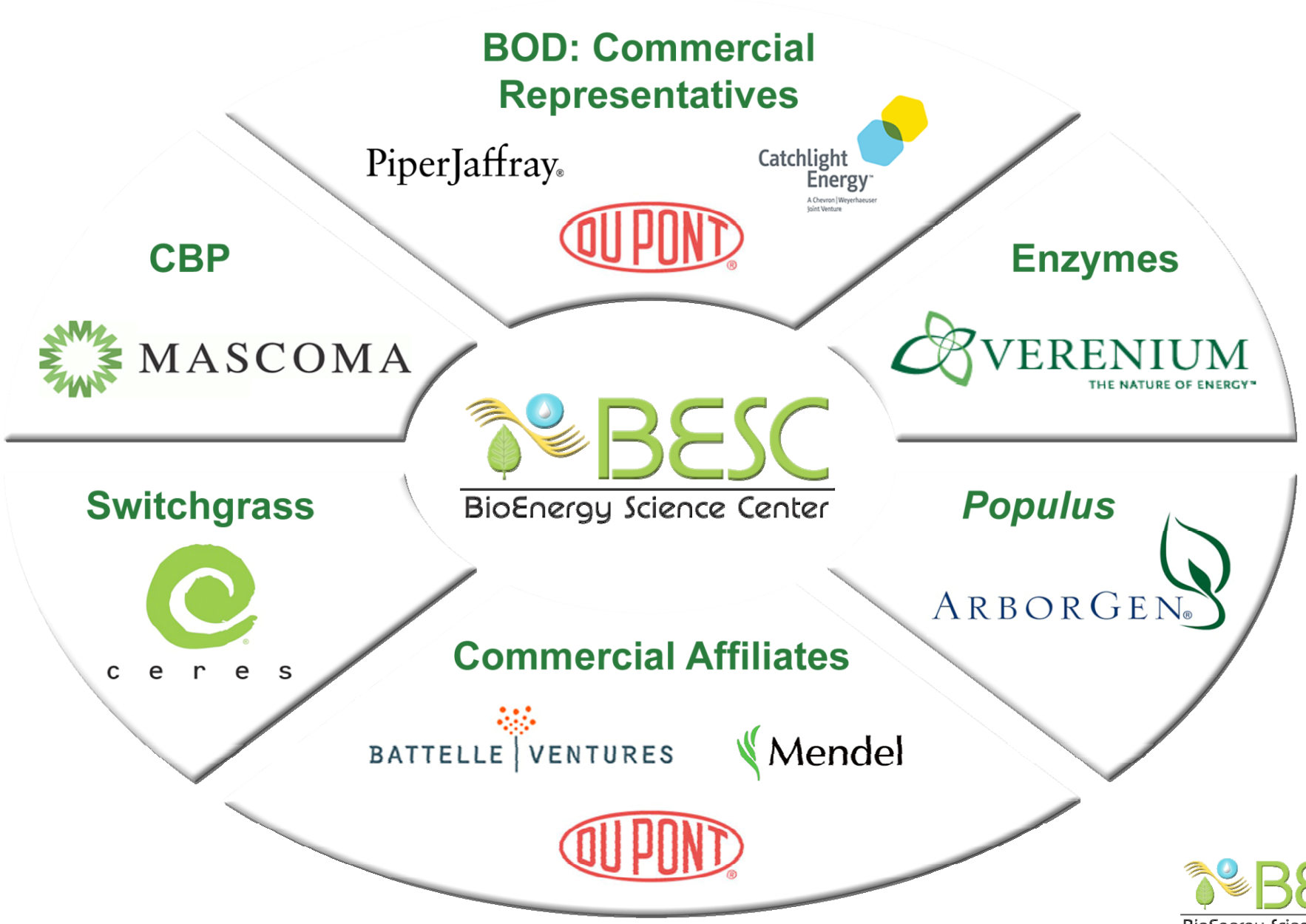
BESC
BioEnergy Science Center

Influencing Next Generation of Scientists

- **National Geographic**, The Jason Project, filmed and generated an **educational module** on bioenergy with BESC researchers
  - This module is available from www.jason.org
- Created an interactive biofuels outreach lesson for students in **Grades 3-8**
  - Piloted more than 220 lessons which reached over 6,000 students
  - Partnered with the Creative Discovery Museum
- Piloted ten Biofuels Family **Science Nights** with an average attendance of **250 people**

- **Three Key Issues:**
  - **Can we perform the conversion efficiently?**
    - **Yes, we can**
  - **Can we produce sufficient usable biomass**
    - **Yes (enough to make a difference),**
  - **Can we accomplish this with long-term sustainability**
    - **Yes, if we are smart enough**
- **Significant R&D investments from DOE, ARPA-E, USDA, NSF, EPA, US states, private industry**
- **Partnership of states/academia/ governmental/industry with farmers is a critical factor in our collective success**

Industrial partners facilitate strategic commercialization



Thank you

SCIENCE RETREAT DECEMBER 2008

SCIENCE RETREAT JUNE 2009

DOE Bioenergy Research Centers

DOE GENOMICS:GTL SYSTEMS BIOLOGY FOR ENERGY AND ENVIRONMENT

OFFICE OF SCIENCE U.S. DEPARTMENT OF ENERGY

Office of Science U.S. DEPARTMENT OF ENERGY

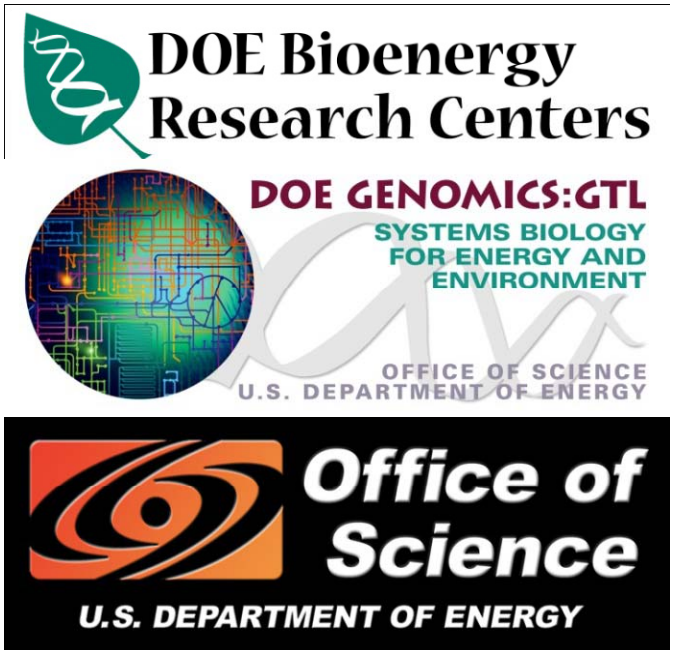
BESC is a U.S. Department of Energy Bioenergy Research Center supported by the Office of Biological and Environmental Research in the DOE Office of Science

BESC BioEnergy Science Center

Thank you

BESC is a U.S. Department of Energy Bioenergy Research Center supported by the Office of Biological and Environmental Research in the DOE Office of Science

US State Department



BESC BioEnergy Science Center