Bioenergy Research Centers

DOE EPSCoR Annual Program Review
and Workshop
Oak Ridge, Tennessee

July 24, 2008

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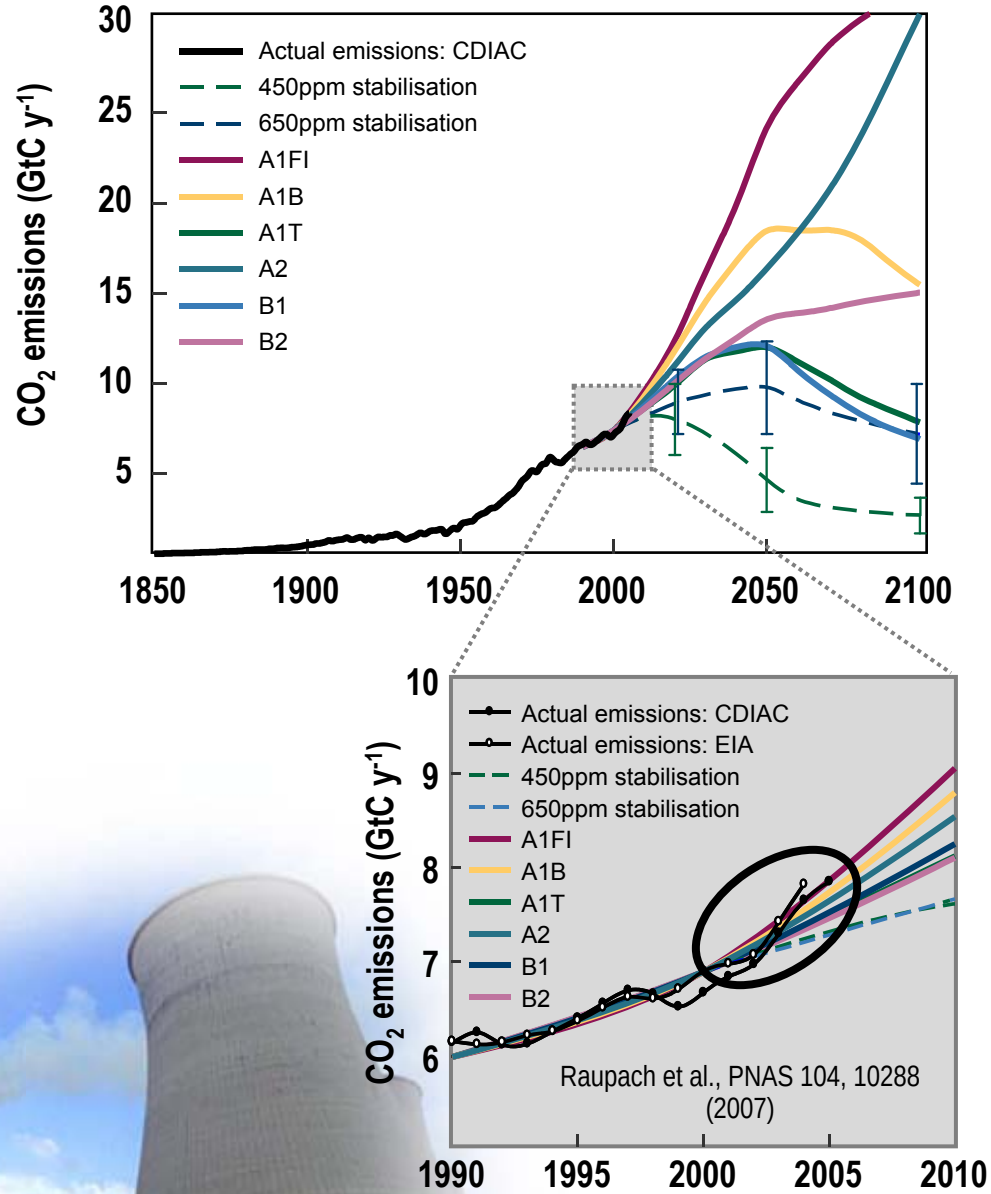
Associate Laboratory Director
Biological and Environmental Sciences

Human activity is affecting global climate

- Growth rate of atmospheric CO_2 is increasing rapidly
  - 1990s: 1.3% per year
  - 2000–2006: 3.3% per year
- Three processes are contributing to this increase:
  - Growth in world economy
  - Increase in carbon intensity
  - Decline in efficiency of CO_2 sinks on land and in oceans
- Climate forcing is both **stronger** than expected and **sooner** than expected

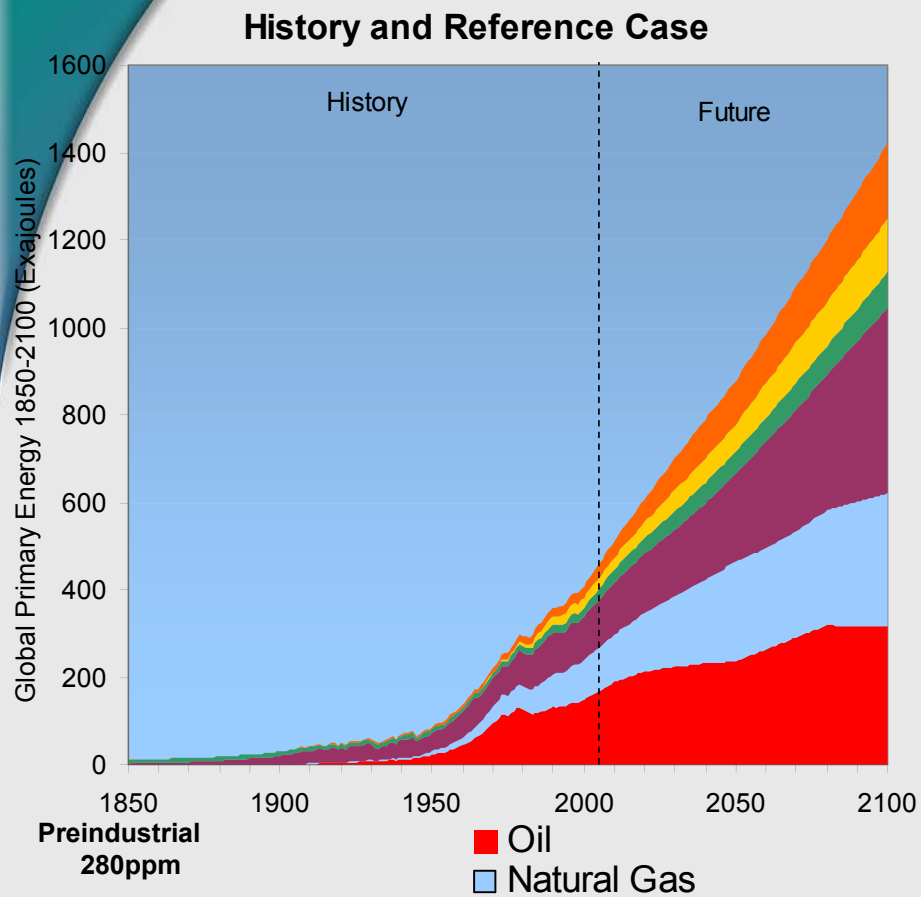


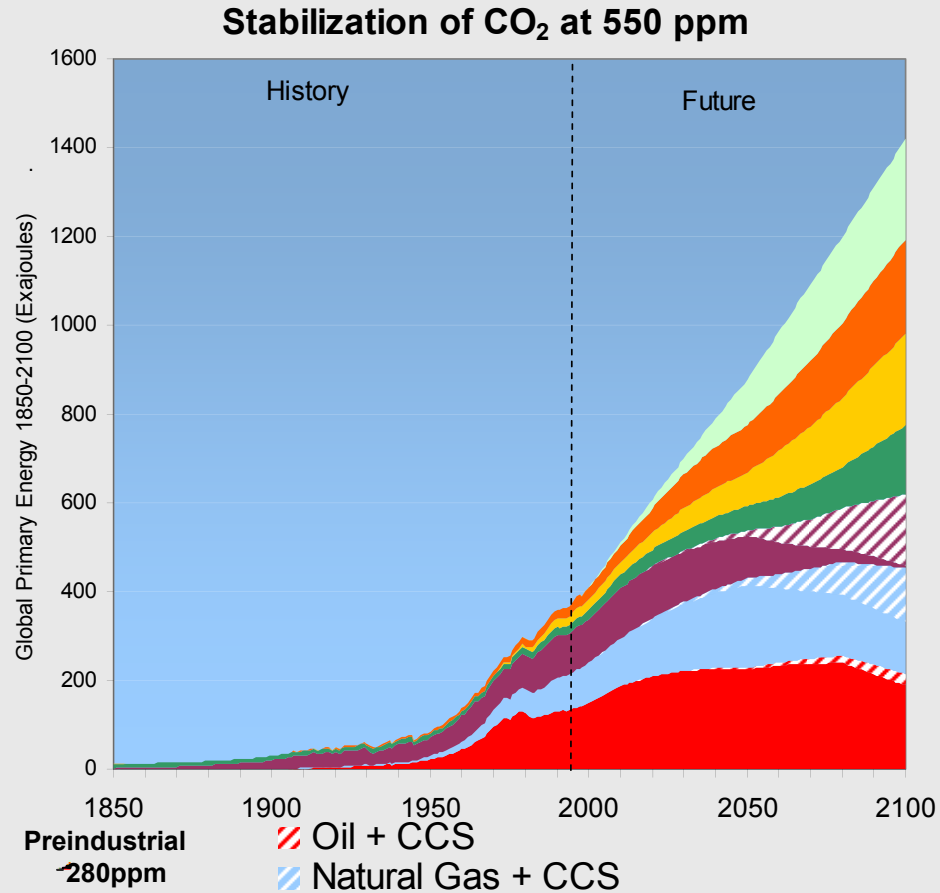
GTSP

Global Energy Technology Strategy Program

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

Source: Jae Edmonds

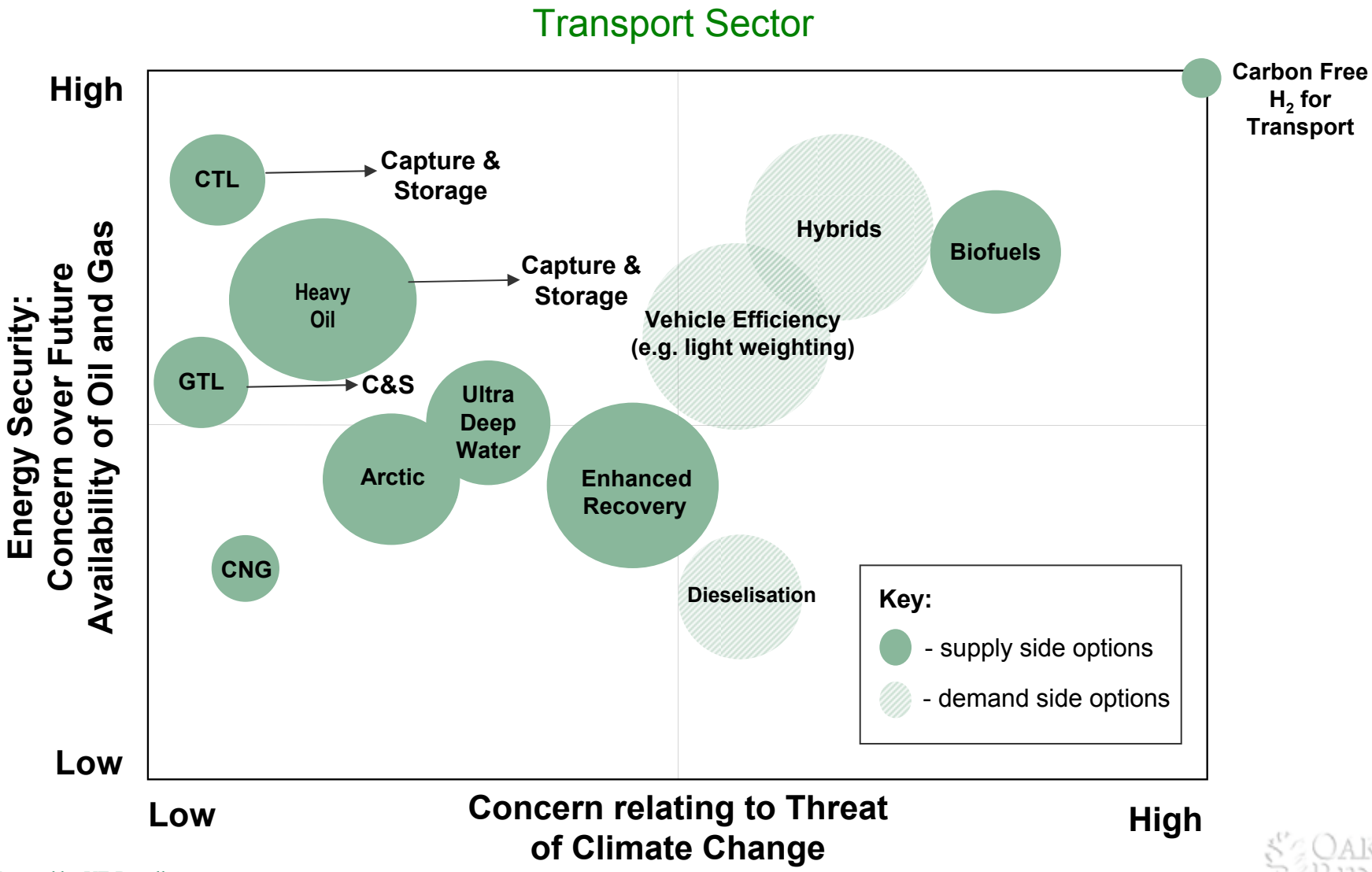




- Oil
- Natural Gas
- Coal
- Biomass Energy
- Non-Biomass Renewable Energy
- Oil + CCS
- Natural Gas + CCS
- Coal + CCS
- Nuclear Energy
- End-use Energy

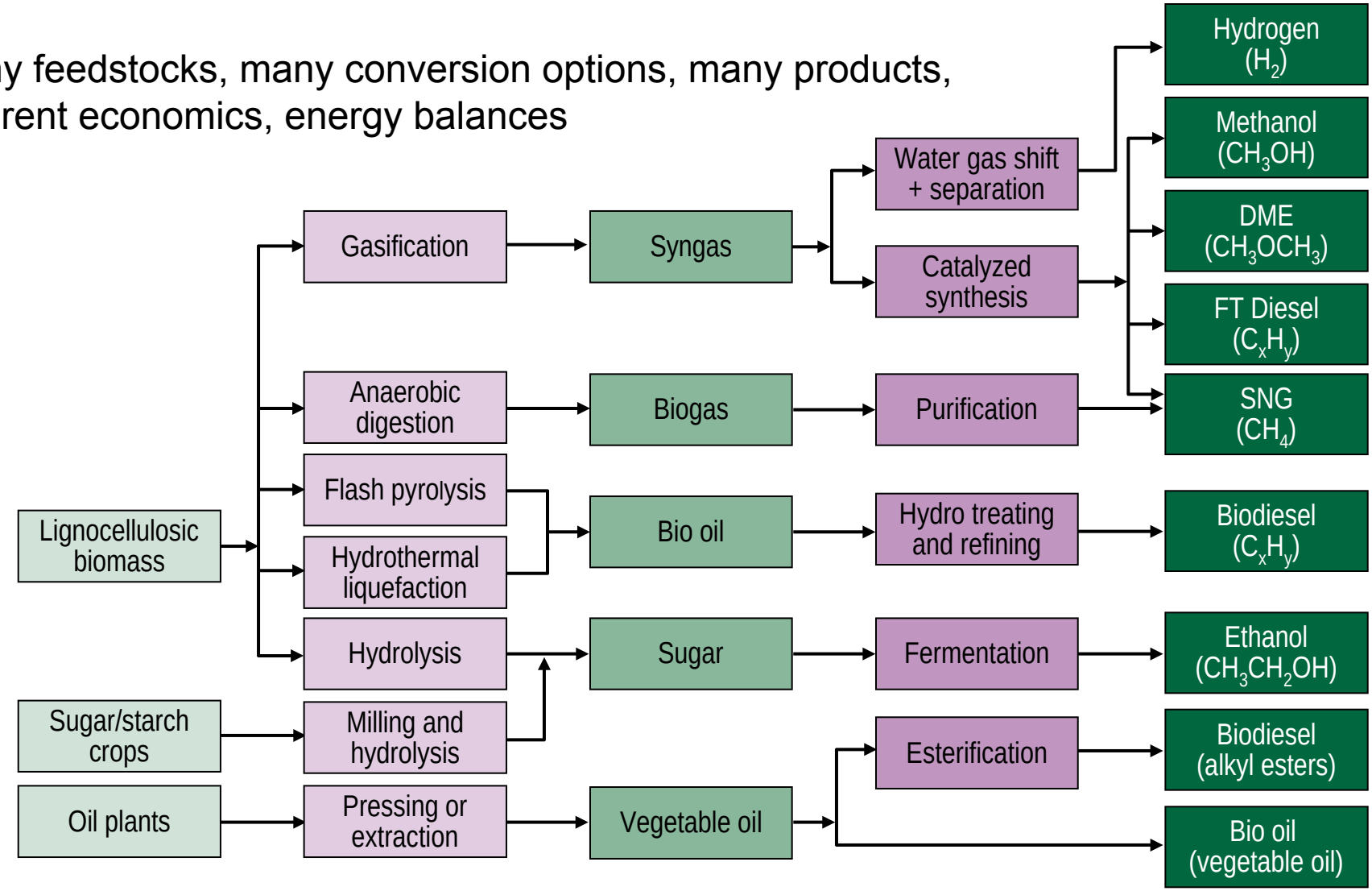
Battelle | JGCRI Joint Global Change Research Institute | UNIVERSITY OF MARYLAND | Pacific Northwest National Laboratory Operated by Battelle for the U.S. Department of Energy

Technology Options for Transportation (Source: Koonin, BP)



Conversion routes for biomass

Many feedstocks, many conversion options, many products, different economics, energy balances



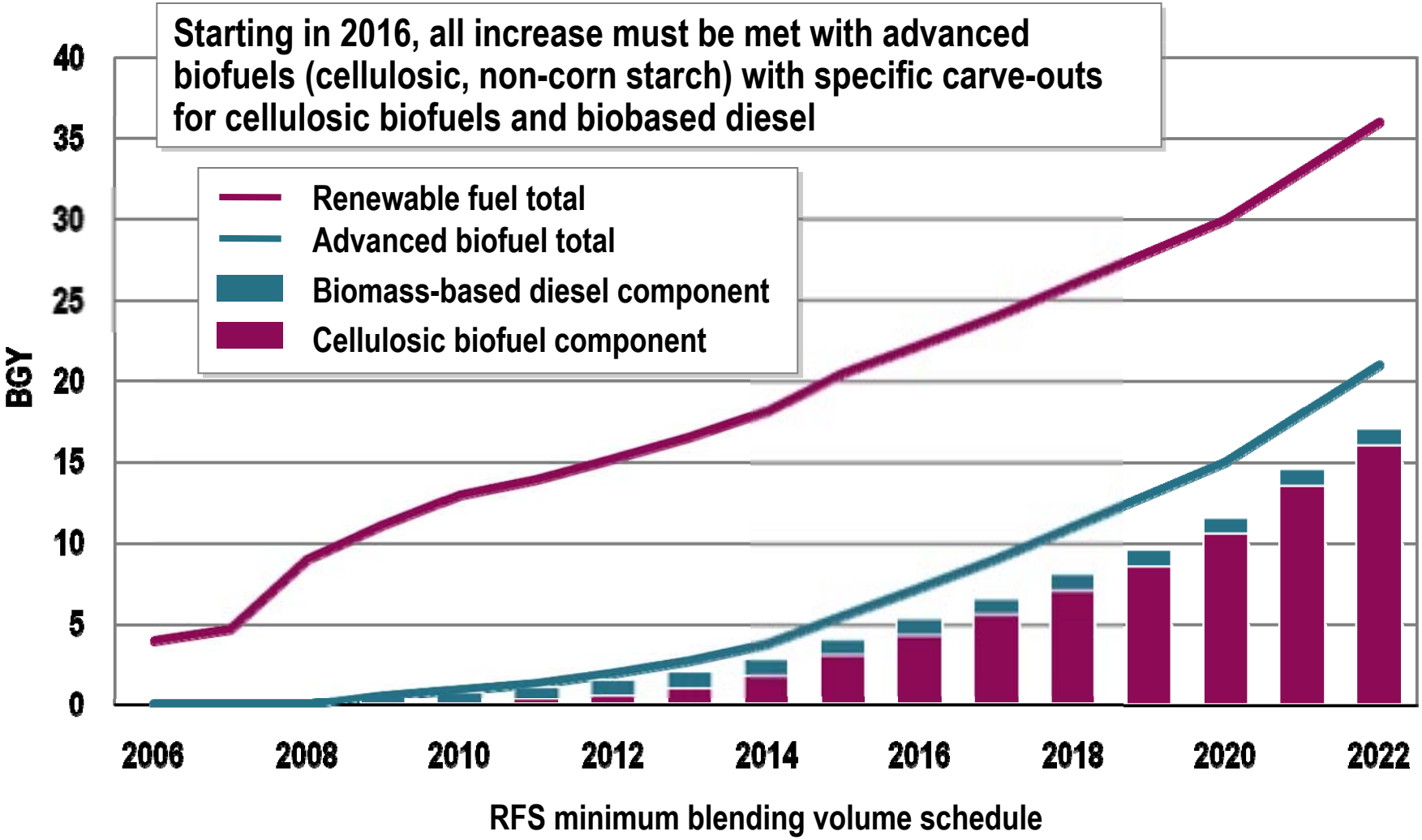
Source: Carlo N. Hamelinck, "Outlook for Advanced Biofuels," PhD Thesis, Utrecht University, The Netherlands, 2004

Billion Ton Study (2005): Established potential for a significant biomass resource

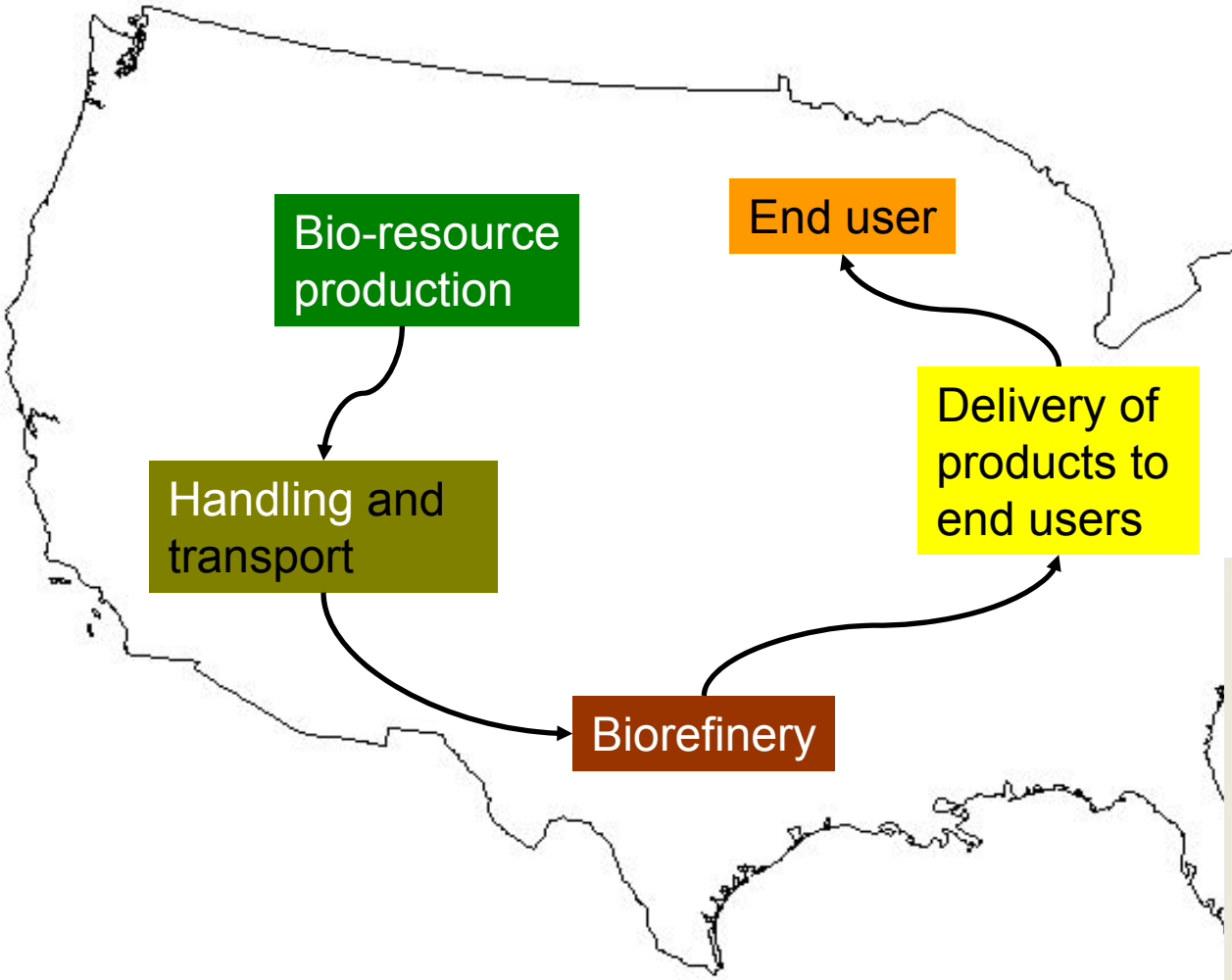
- "30 by 30" initiative: Displace 30% of transportation fuel demand by 2030
  - Requires production of 60 billion gallons per year (BGY)
- "20 in 10" initiative: Displace 20% of gasoline demand by 2017
  - Requires production of 35 BGY
- Energy Independence and Security Act of 2007 (EISA): Mandatory Renewable Fuel Standard (RFS) of 7.5 BGY by 2012

- Conducted by ORNL for DOE and USDA
- Basis for subsequent initiatives

EISA requirements

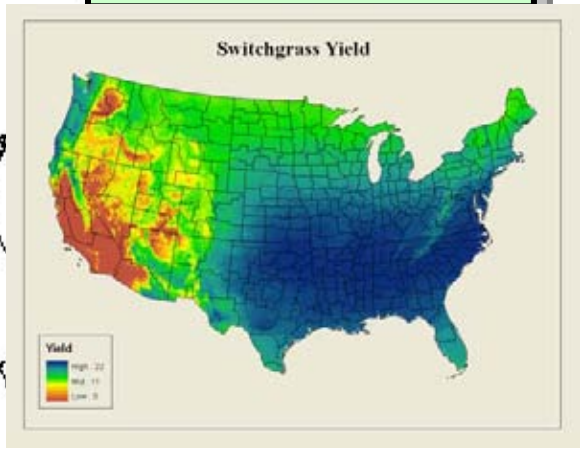


Bioenergy is analogous to other existing energy networks



Key requirements

- **Availability**
- **Agility**
- **Reliability**
- **Sustainability**
- **Security**



We cannot meet our goals to displace petroleum without lignocellulosic biomass

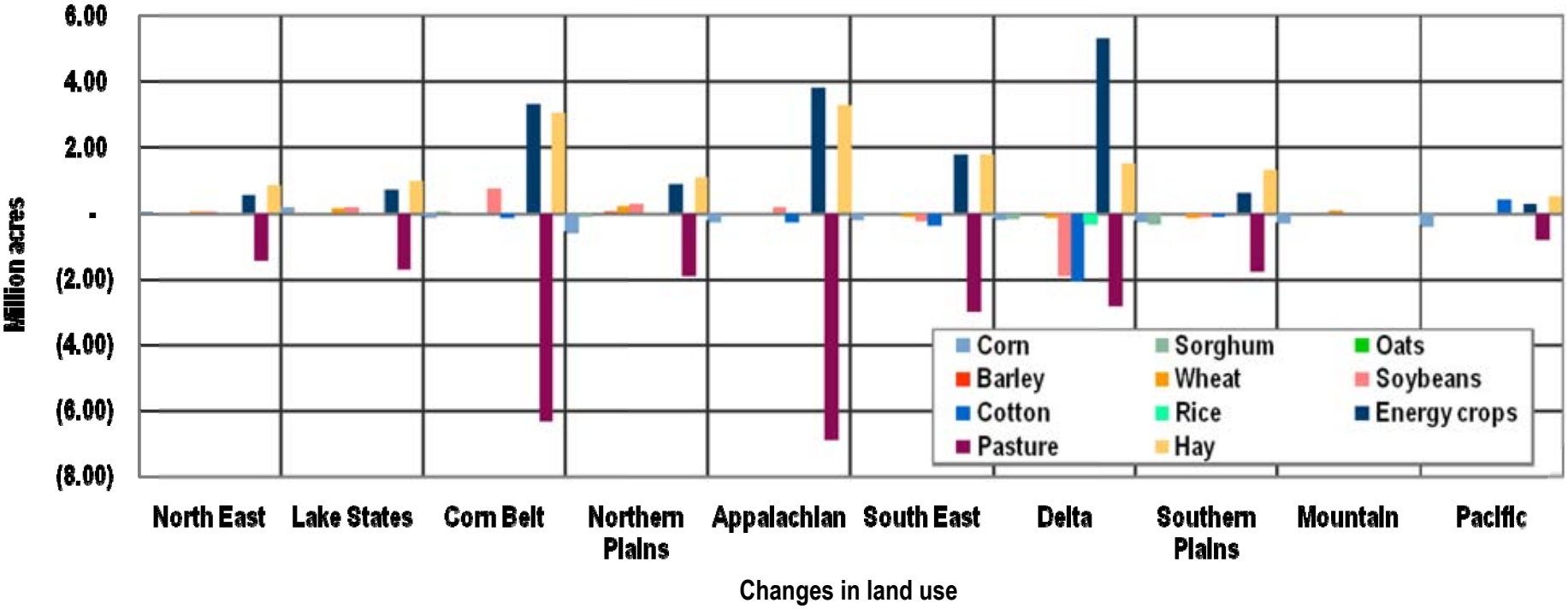
How will EISA affect land use?

Today: ~455 million acres of cropland

- 349 million acres in active use to grow crops
- 39 million acres of idle land and conservation reserve program land
- 67 million acres used as pasture

By 2022: Potential conversion of 31 million acres to other uses

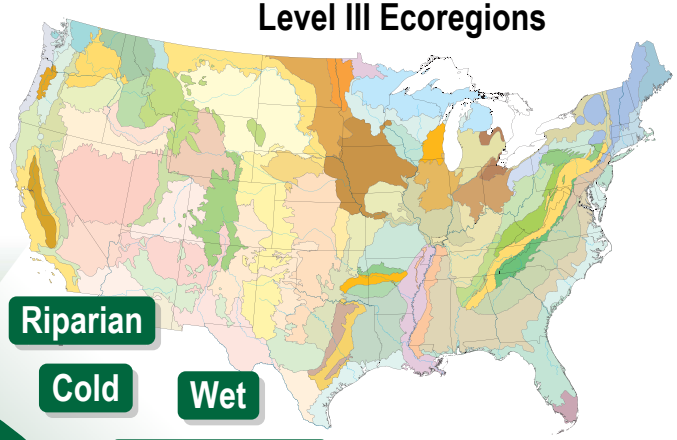
- 26 million acres of pasture used instead to grow energy crops and replace lost forage
- 5 million acres of active cropland converted to energy crops
  - Delta: Cotton land
  - Northern plains: Marginal corn land



Source: Dr. Robert Perlack,ORNL

The challenge of sustainability

Level III Ecoregions



Poplar
Corn
Crop residues
Cover crop
Grass
Manure
Skidder tires
Fertilizers
No till
Single cut
Riparian
Cold
Wet
Near refinery
Adjacent forest
20% of watershed
Patchy
5% of watershed
Blocky
CRP
Ag field
Native forest
Pasture
Erosion
Runoff
Soil carbon
Wildlife
Water quality

Feedstock type
Feedstock location
Feedstock extent
Environmental attributes
Original conditions
Feedstock manage-ment

Address all 6 dimensions globally

Source: Dr. Virginia Dale,ORNL

Oak Ridge National Laboratory

Major DOE Biofuels Project Locations

Geographic, Feedstock, and Technology Diversity

for the Department of Energy

OAK RIDGE National Laboratory

Regional Biomass Energy Feedstock Partnership
2008 Bioenergy Crop Trials

OAK RIDGE National Laboratory

Bioenergy

Science Transforming Energy Technologies

Imagine: • A sustainable, carbon-neutral biofuels economy that meets over 30% of U.S. transportation fuel needs (cars and trucks) without competing with food, feed, or export demands.

- The development of biofuels—especially lignocellulose biofuels—represents a major scientific opportunity that can strengthen U.S. energy security and protect the global environment.
- Biofuels can be essentially carbon-neutral or even carbon-negative – as plant feedstocks grow, they reabsorb the carbon dioxide emitted when biofuels are burned, and they can store carbon dioxide in their roots.
- To produce lignocellulosic biofuels, or biofuels from plant fiber, cost-effectively on a commercial scale will require transformational breakthroughs in basic science focused on both plants and microorganisms and processing methods.
- The challenge is the recalcitrance of the plant cell wall – plant fiber has evolved over the millennia to be extremely resistant to breakdown by biological or natural forces.
- Many scientists believe we are within reach of major breakthroughs in developing cost-effective methods of producing liquid fuels from lignocellulose in the near- to mid- term.
- The environmental sustainability aspects associated with bioenergy derived from feedstock crops – water, soil quality, land-use changes, genetically altered plants, carbon balance – must be addressed proactively.

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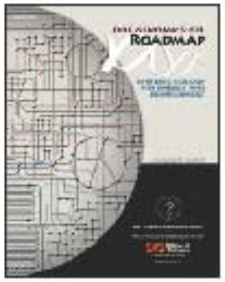
Source: Dr. Raymond Orbach, DOE

DOE Bioenergy Research Centers



Grand Science Challenges:

- Using a systems biology approach, understand the principles underlying the structural and functional design of living systems — plants and microorganisms.
- Develop the capability to model, predict, and engineer optimized enzymes, microorganisms, and plants — bioenergy and environmental applications.

"Basic Research Needs" for cellulosic ethanol (and other biofuels) production:

The emerging tools of systems biology are being used to help to overcome current obstacles to bioprocessing cellulosic feedstocks to ethanol and other biofuels– metagenomics, synthetic biology, high-throughput screening, advanced imaging, high-end computational modeling.

- **DOE BioEnergy Science Center** – led by Oak Ridge National Laboratory, includes 9 partnering institutions. This center focuses on the resistance of plant fiber to breakdown into sugars and is studying the potential energy crops poplar and switchgrass.
- **DOE Great Lakes Bioenergy Research Center** – led by University of Wisconsin-Madison in partnership with Michigan State University, includes 6 other partnering institutions. This center is studying a range of plants and is exploring plant fiber breakdown and how to increase plant production of starches and oils, which are more easily converted to fuels. This Center also focuses on sustainability, examining the environmental and socioeconomic implications of moving to a biofuels economy.
- **DOE Joint BioEnergy Institute** – led by Lawrence Berkeley National Laboratory, includes 5 other partnering institutions. This center focuses on "model" crops of rice and *Arabidopsis thaliana* in the search for breakthroughs in basic science and is exploring microbial-based synthesis of fuels beyond ethanol.

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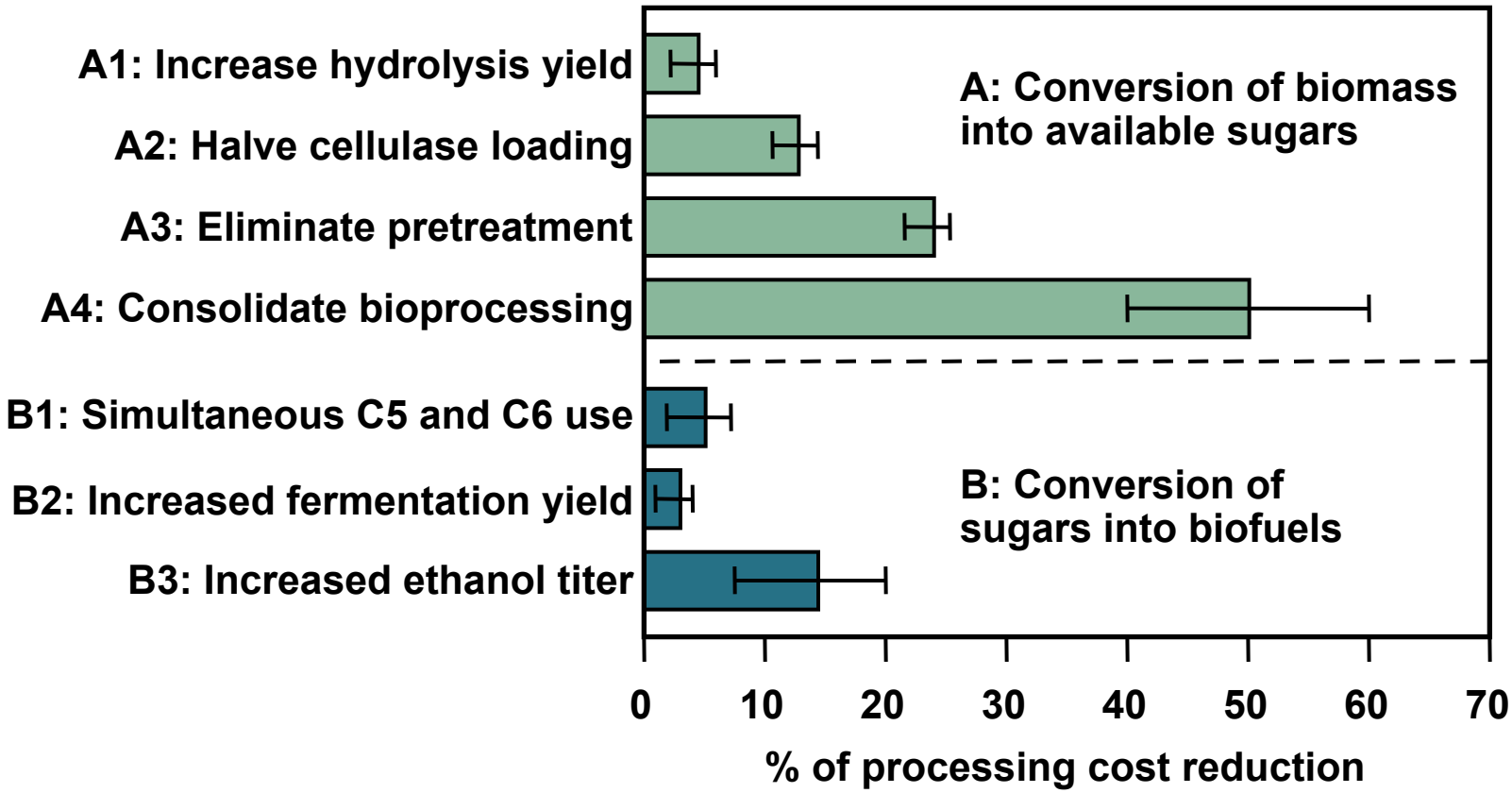
Source: Dr. Raymond Orbach, DOE

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, "Energy Biotechnology: Targeting a Revolution" Nature Biotechnology , Feb 2008

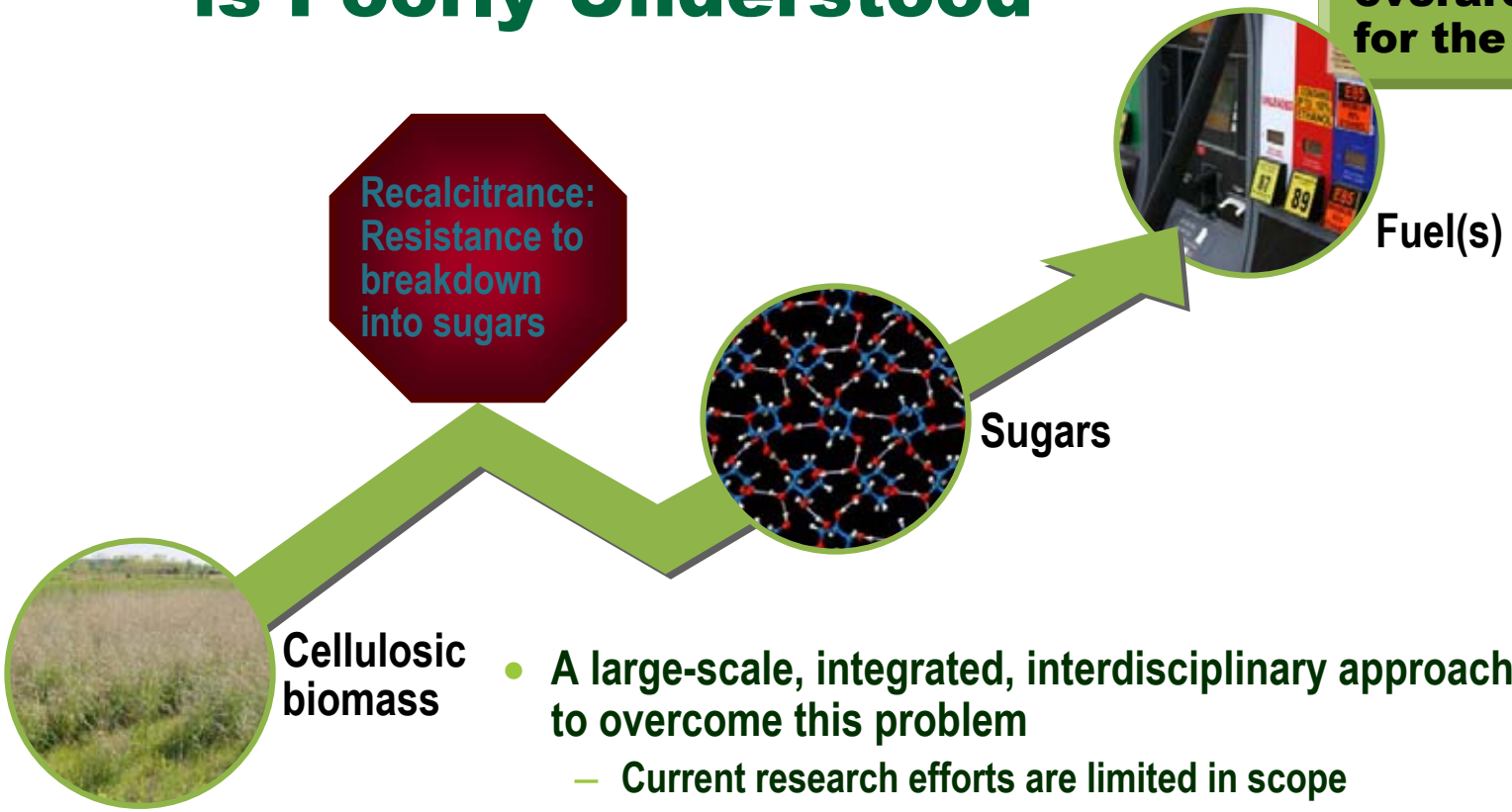
The BioEnergy Science Center

- Oak Ridge National Laboratory
- University of Georgia
- University of Tennessee
- National Renewable Energy Laboratory
- Georgia Tech
- Samuel Roberts Noble Foundation
- Dartmouth
- ArborGen
- Verenium
- Mascoma
- Individuals from U California-Riverside, Cornell, Washington State, U Minnesota, NCSU, Brookhaven National Laboratory, Virginia Tech

- Funded by the US Department of Energy Office of Science at $135M over five years
- World-class cross-disciplinary science and proven ability to rapidly impact biomass to biofuel conversion
- Positioned to attack the most important current barrier to the emergence of a cellulosic biofuels industry – biomass recalcitrance
- Unique anchor facilities at the core partners
- Home base at the UT/ORNL Joint Institute for Biological Sciences
- *http://bioenergycenter.org*

The Fundamental Science of Biomass Recalcitrance is Poorly Understood

Overcoming recalcitrance is the single coherent overarching theme for the BESC



- A large-scale, integrated, interdisciplinary approach is needed to overcome this problem
  - Current research efforts are limited in scope
  - BESC will launch a broad and comprehensive attack on a scale well beyond any efforts to date
- Without advances, a cellulosic biofuels industry is unlikely to emerge
- Knowledge gained will benefit other biofuels and biofeedstocks

Oak Ridge National Laboratory

Three Focus Areas to Overcome Recalcitrance

Biomass formation and modification	Characterization and modeling	Biomass deconstruction and conversion
• What gene products control cell wall structure, composition, and recalcitrance? • How will changes in cell wall structure and composition affect plant productivity, pest resistance, and/or sustainability?	• What structural and compositional elements contribute to recalcitrance? • Can new analytical methods, systems biology data, and computational models enable predictive simulation of lignocellulose formation and deconstruction?	• What limits the rate of biomass deconstruction, and how can these limits be overcome by altered biocatalysts? • Will the combination of altered cell walls with better conversion offer a breakthrough?
Challenge: Identify genes that control biomass production and cell wall synthesis	**Challenge:** Understand the complexity of plant cell wall structure and its relationship to recalcitrance	**Challenge:** Improve deconstruction rates and understand how microbes and enzymes attack biomass substrates

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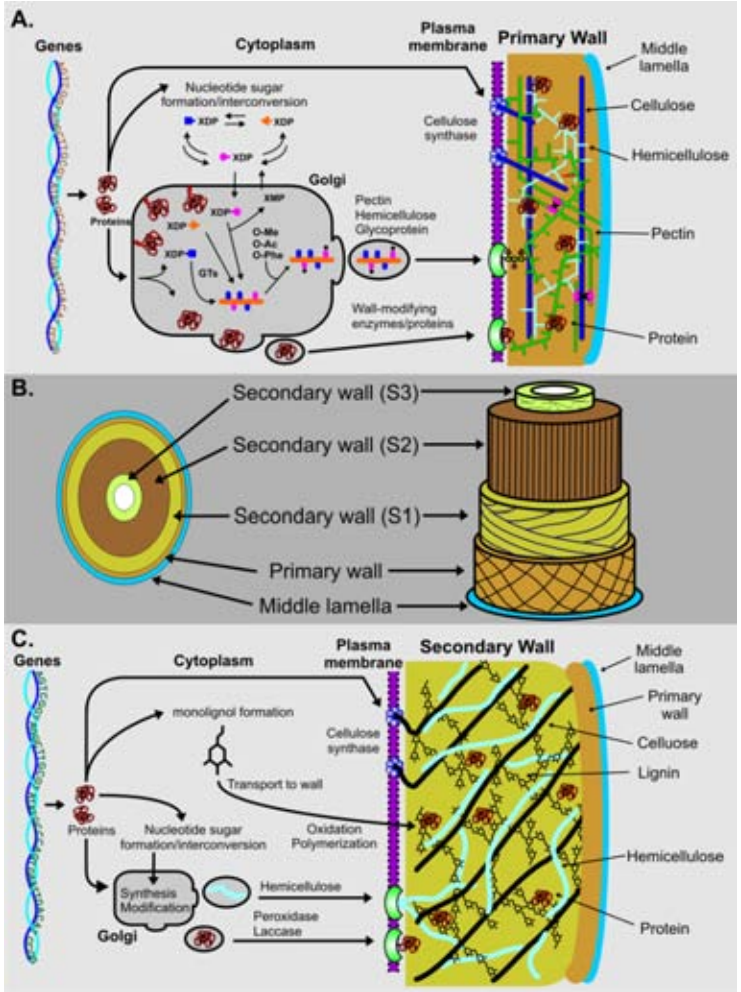
The challenge: Lignocellulosic biomass is complex and heterogeneous

Most plant cell wall genes are unknown in function



- **Gene discovery for biomass recalcitrance**
  - **Random**
    - **Study natural variation**
    - **Study randomly modified populations**
      - **Activation tagged *Populus***
  - **Targeted**
    - **Identify candidate genes**
    - **Modify gene expression**

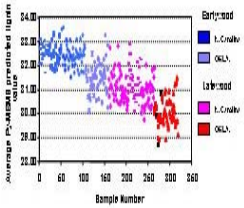
What genes influence recalcitrance in what way?

Transformation Pipeline

High-throughput Phenotyping

Cell Wall Biosynthesis Database

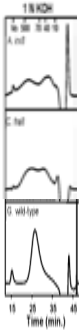
HTS Pipeline



Sugar Release Assay

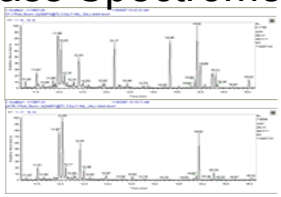
Analytical Pyrolysis

Chemistry

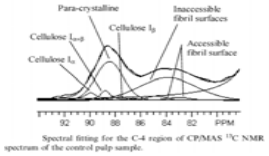


Imaging

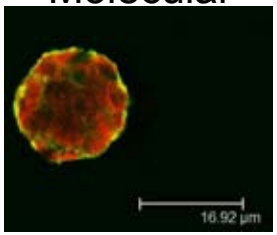
Mass Spectrometry

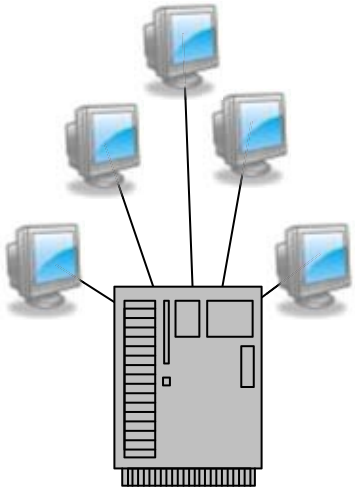


NMR



Molecular





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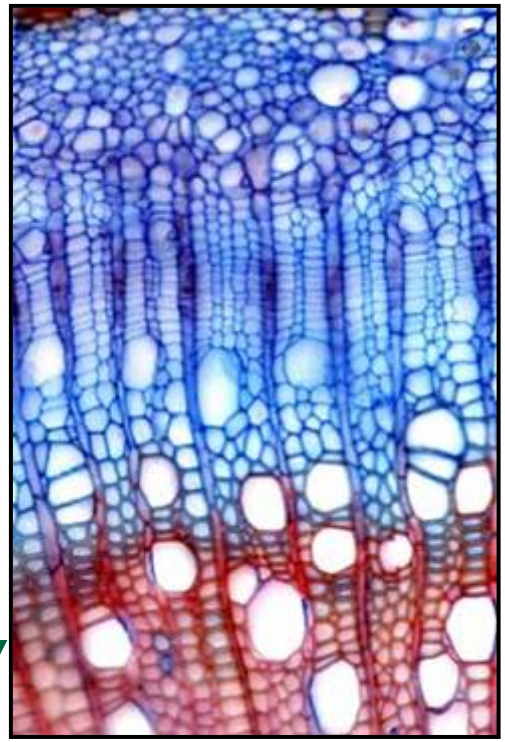
Targeted Gene Discovery: we are looking for cryptic wood phenotypes



Differentiation

Cambial zone

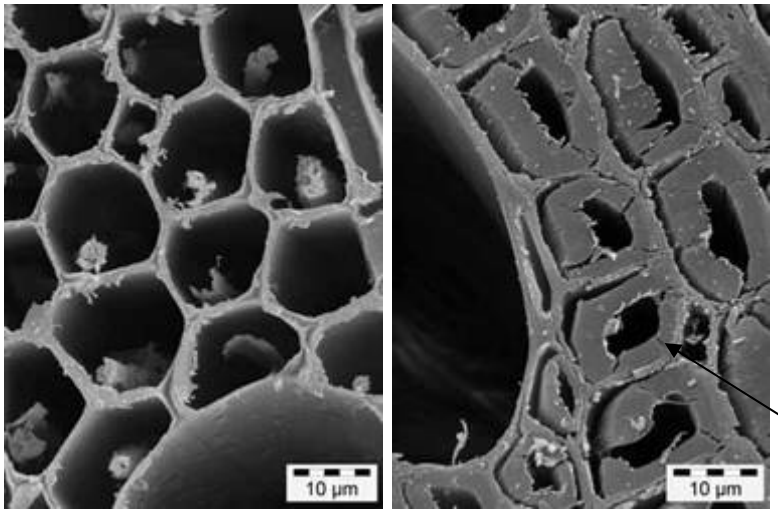
Young Xylem

Mature Xylem

Transverse section in a poplar stem (safranin-astra-blue coloration)

- **Identify key-genes involved in xylem differentiation**
- **Focus on tension wood and G-fiber**

Normal wood



Tension wood

G-fiber

Tension wood is produced in response to mechanical and gravitational stimuli
Tension wood is a convenient biological model
Tension wood is a major defect for wood quality in poplar

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for the Department of Energy

Images courtesy of Gilles Pilate, INRA-Orléans

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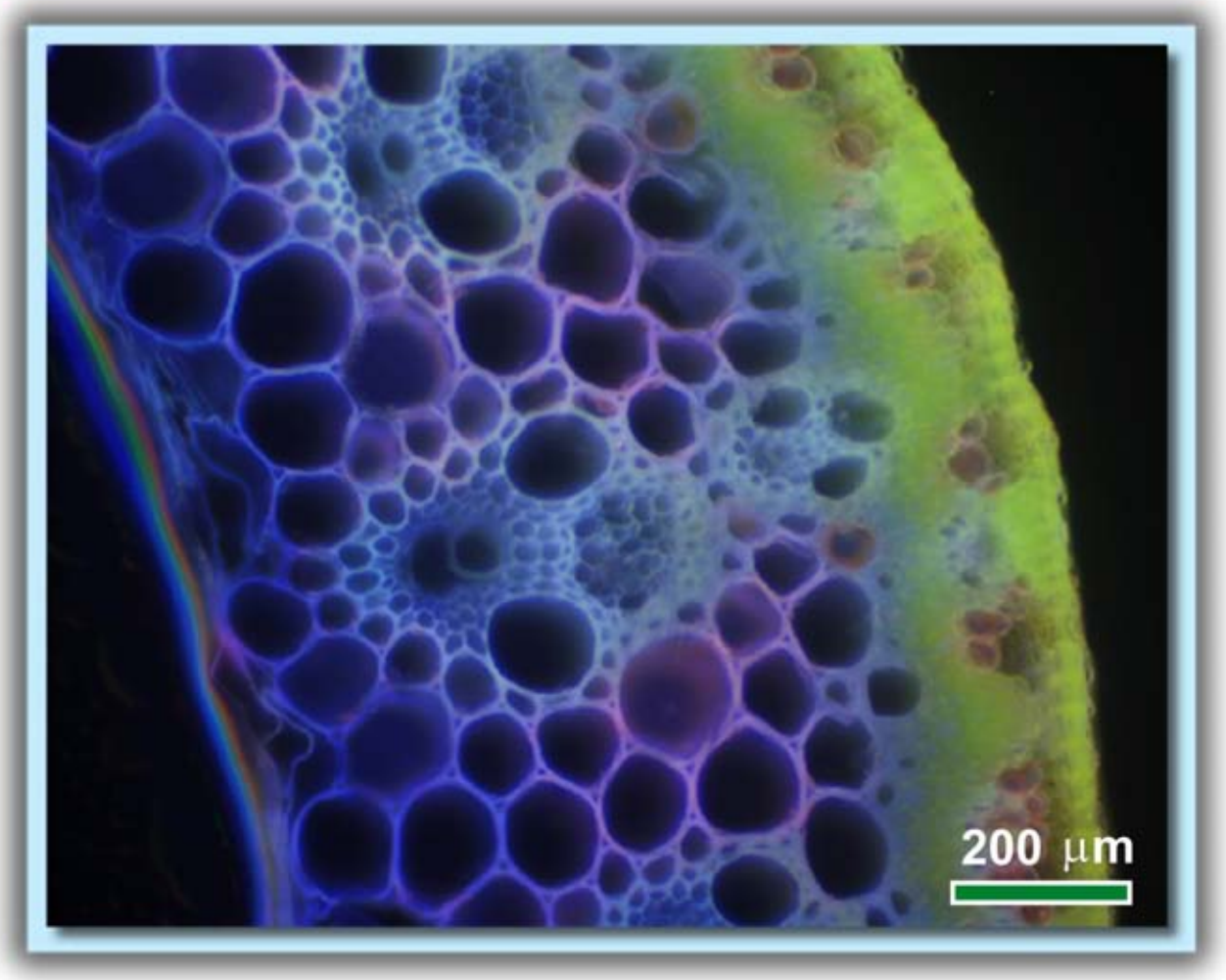
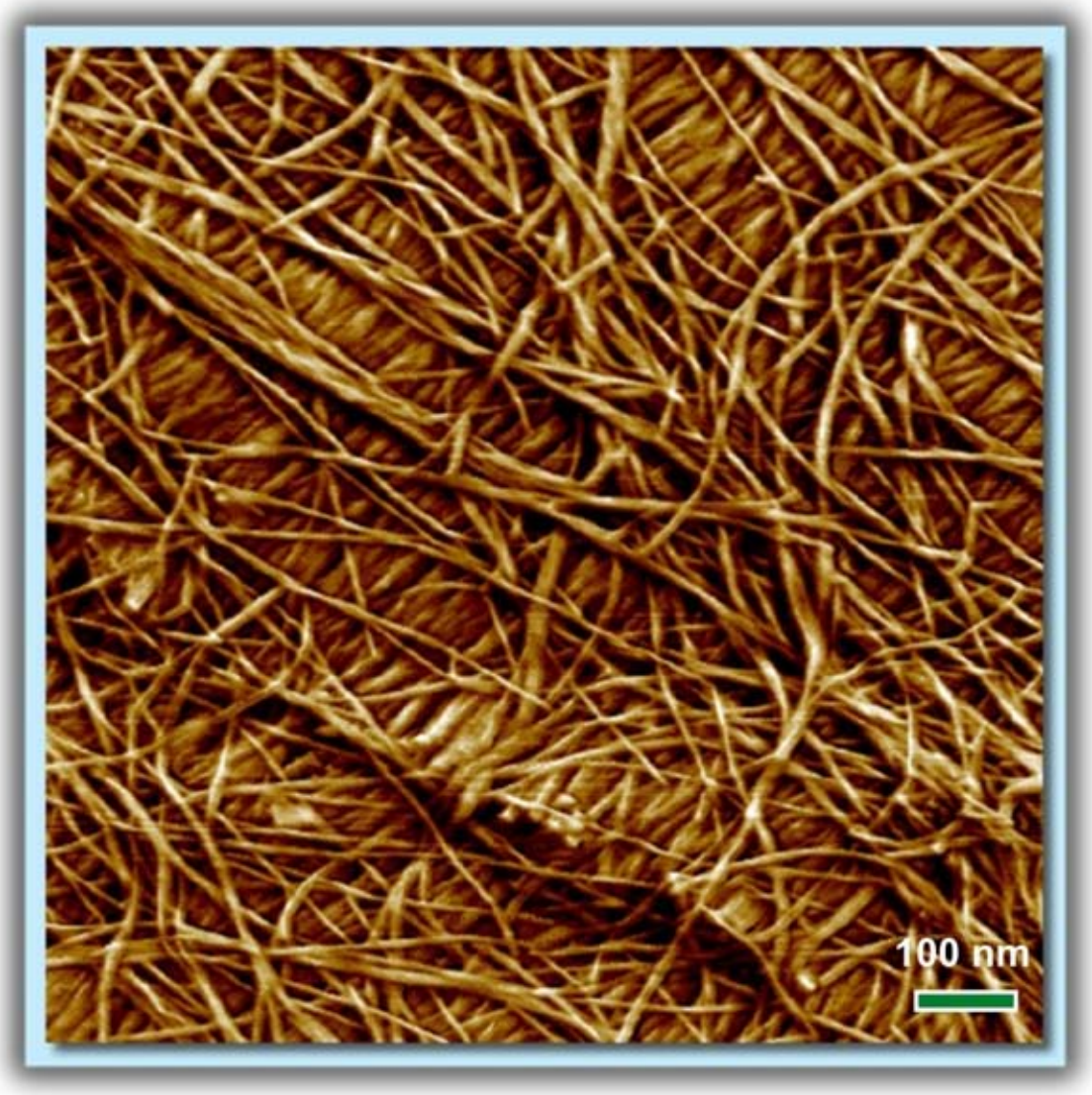
Switchgrass – fluorescence microscopy



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

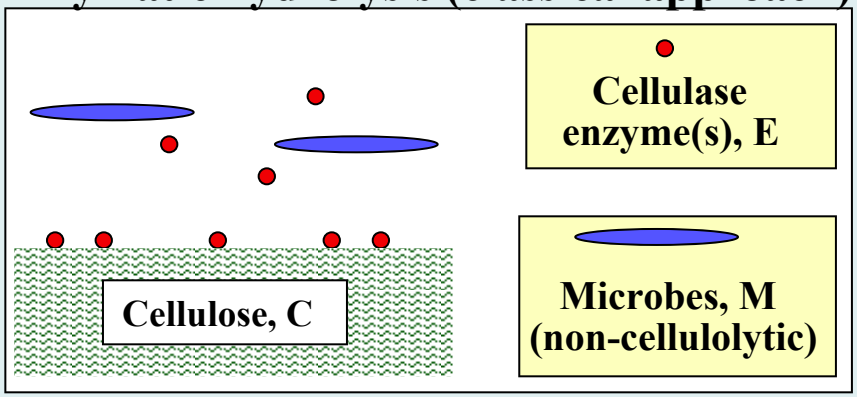
Switchgrass – Atomic force microscopy (AFM)



Ding, et al, unpublished results

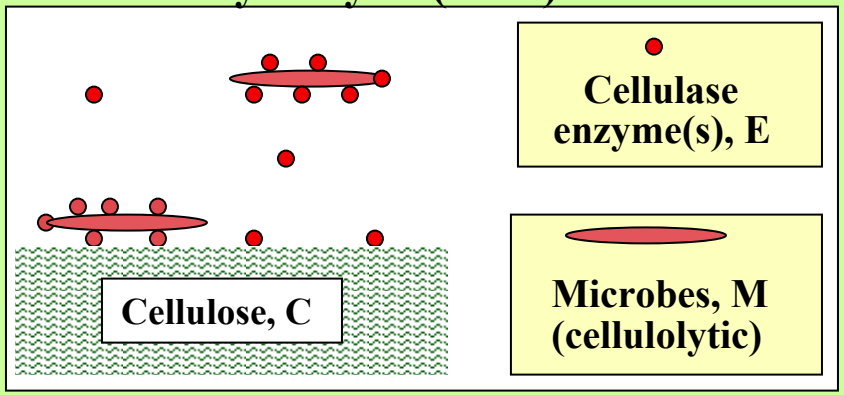
Microbial Hydrolysis and Enzymatic Hydrolysis: A Fundamentally Different Relationship Between Microbes and Cellulose

Enzymatic hydrolysis (classical approach)

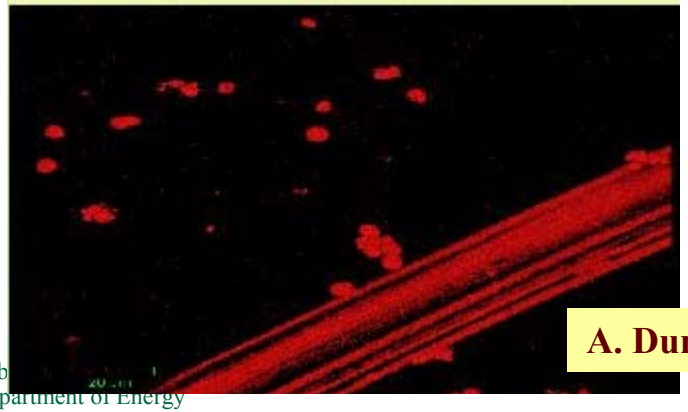


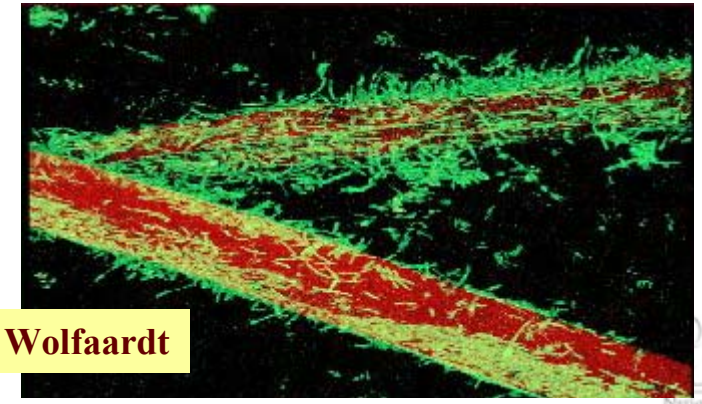
- Hydrolysis mediated by CE complexes
- Enzymes (several) both bound & free
- Cells may or may not be present

Microbial hydrolysis (CBP)



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

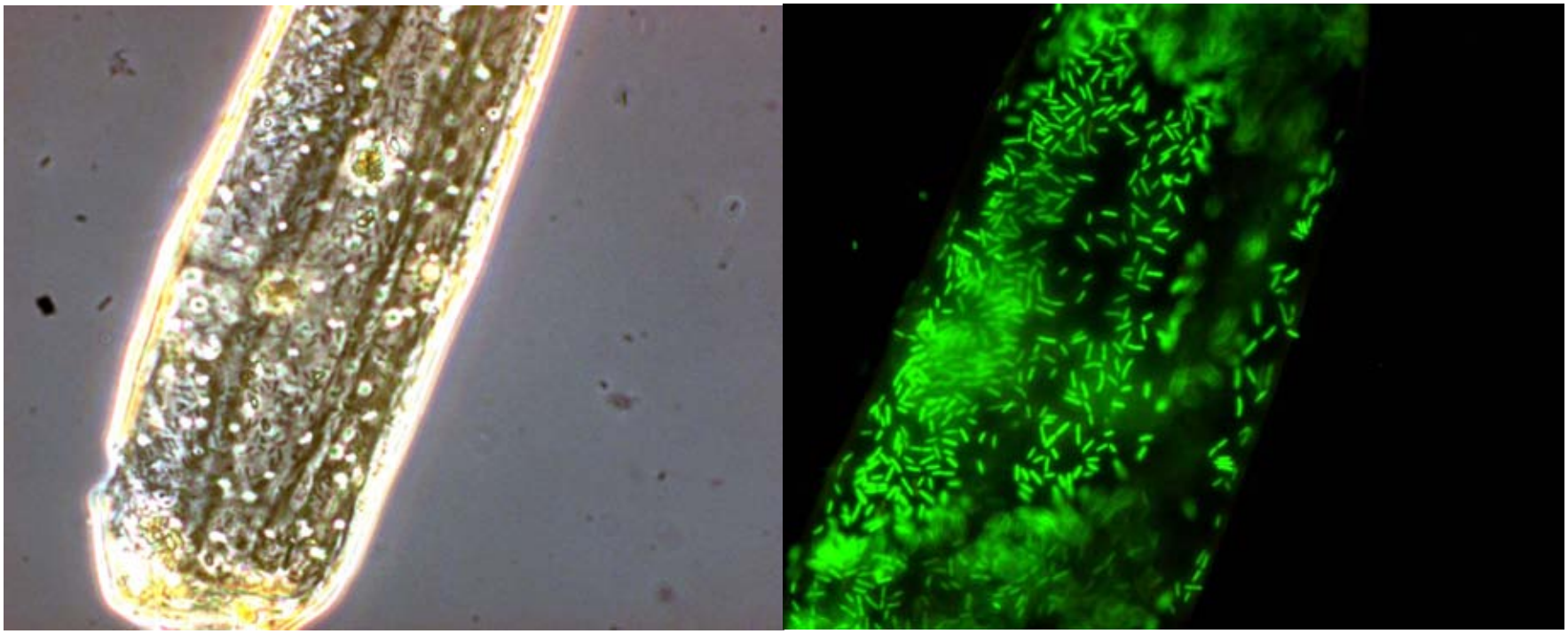




A. Dumitrache & G. Wolfaardt

Image of Obsidian Pool Consortium Members Attached to Pretreated Switchgrass

- Growth mainly on solid particles
- Testing of different fluorescence stains to image bacterial cells



James Elkins/ Sue Carroll

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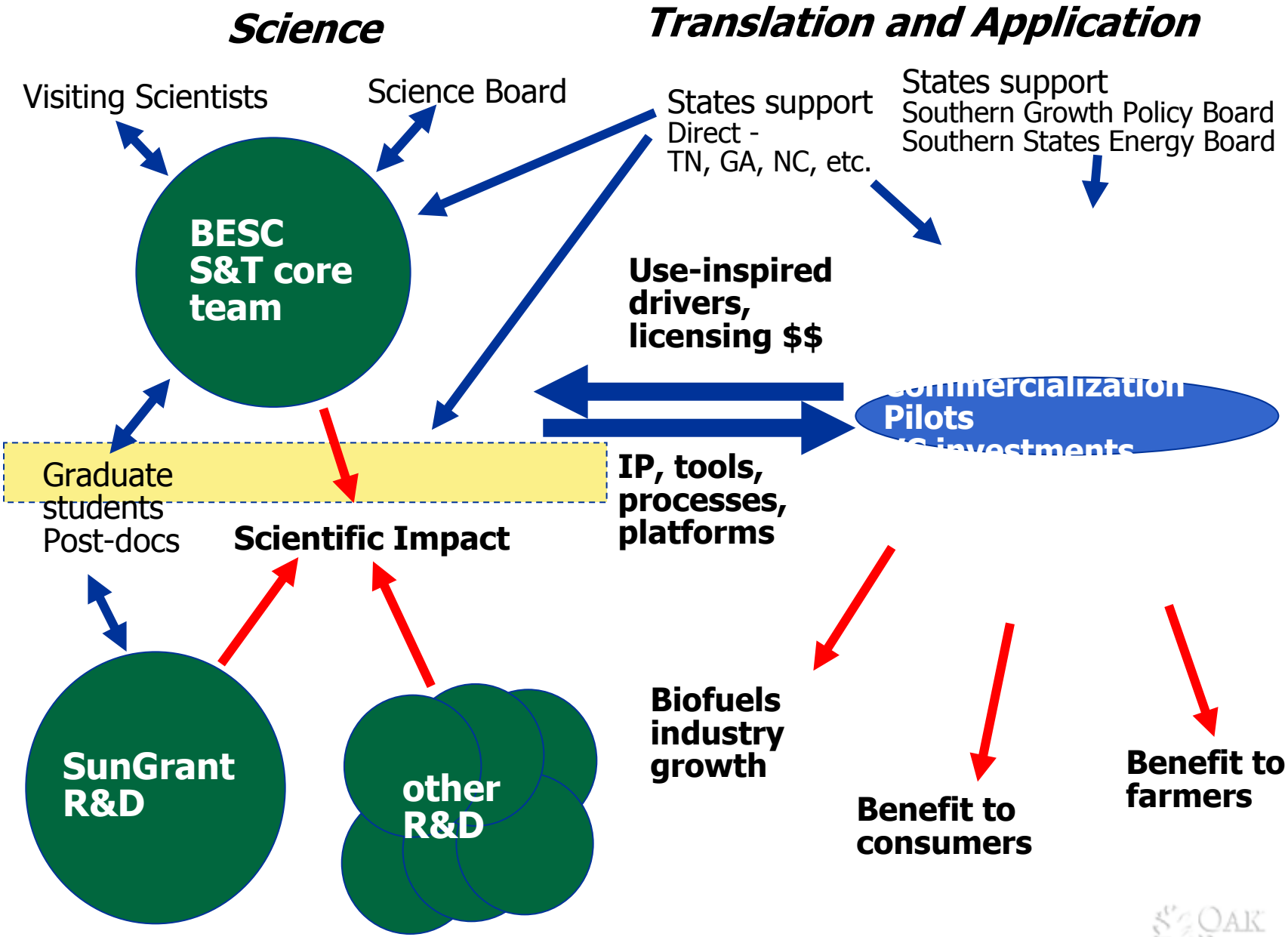
BESC is a U.S. Department of Energy Bioenergy Research Center supported by the Office of Biological and Environmental Research in the DOE Office of Science

BESC and the Southeast