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Biofuels Research

Science for America's Energy Future

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Biological and Environmental Research (BER)

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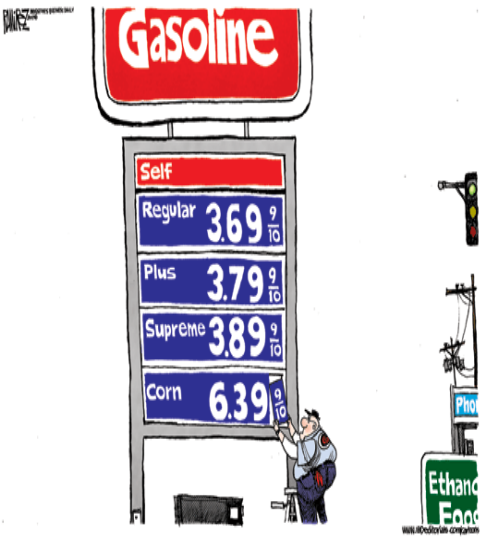
We are big consumers of energy

- We use a lot of gasoline - ~150 billion gallons annually
- We import a lot of oil (from places we don't want to) - ~60%
- Today we make ~13 billion gallons of ethanol mostly from corn
- There isn't enough corn - ~44 billion gallons if we used <u>all</u> corn to make ethanol
- Energy in 1 gallon of gas requires 1.4 gallons of ethanol



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The Challenge of the Facts and Figures

- America has 1/3 of the world's automobiles
- America uses 25% of the world's oil
- Reliance on foreign oil will increase 30% through 2030 and our transportation sector's greenhouse gas emissions will rise 40%
- President Bush 2007 "20 in 10" initiative – reduce gasoline consumption by 20% in 10 years
- Energy Independence Security Act of 2007 – mandate to produce 36 billion gallons of biofuels per year by 2022 (13+ billion gallons projected for 2008

"America is addicted to oil"

President Bush, 2007 State of the Union Address

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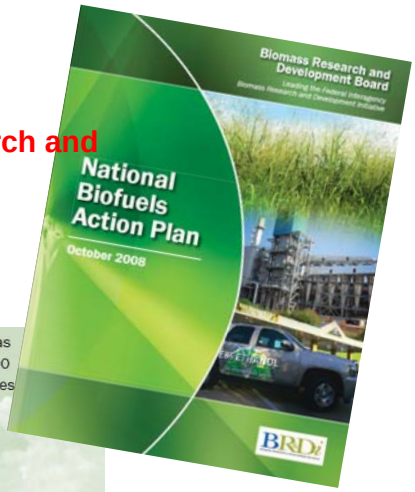
Bioenergy Research is a MultiAgency Effort

Interagency Biomass Research and Development Board



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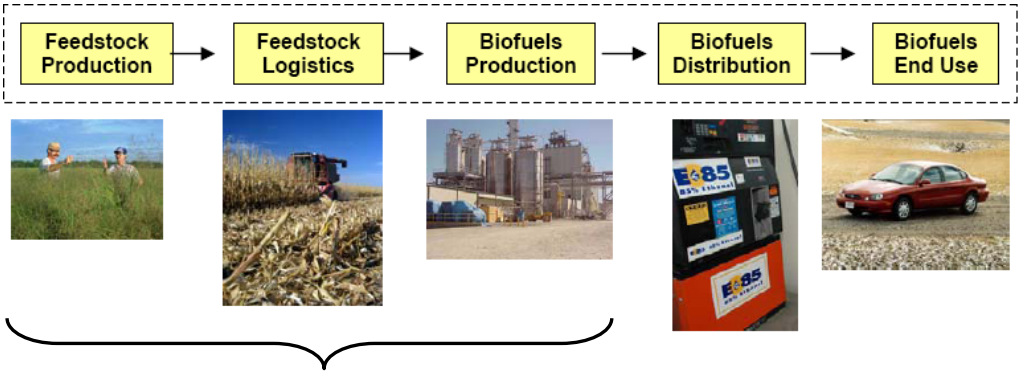
Research Challenges Exist at Every Step



Opportunities in Biology

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Biomass Feedstock

- Trees
- Grasses
- Agricultural Crops
- Agricultural Residues
- Forest Residues
- Animal Wastes
- Municipal Solid Waste

Conversion Processes

- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/Fermentation
- Gasification
- Pyrolysis
- Combustion
- Co-firing

PRODUCTS

Fuels:
- Ethanol
- Renewable Diesel
- Renewable Gasoline
- Hydrogen
- etc

Power:
- Electricity
- Heat (co-generation)

Chemicals
- Plastics
- Solvents
- Chemical Intermediates
- Phenolics
- Adhesives
- Furfural
- Fatty acids
- Acetic Acid
- Carbon black
- Paints
- Dyes, Pigments, and Ink
- Detergents
- Etc.

Food, Feed and Fiber

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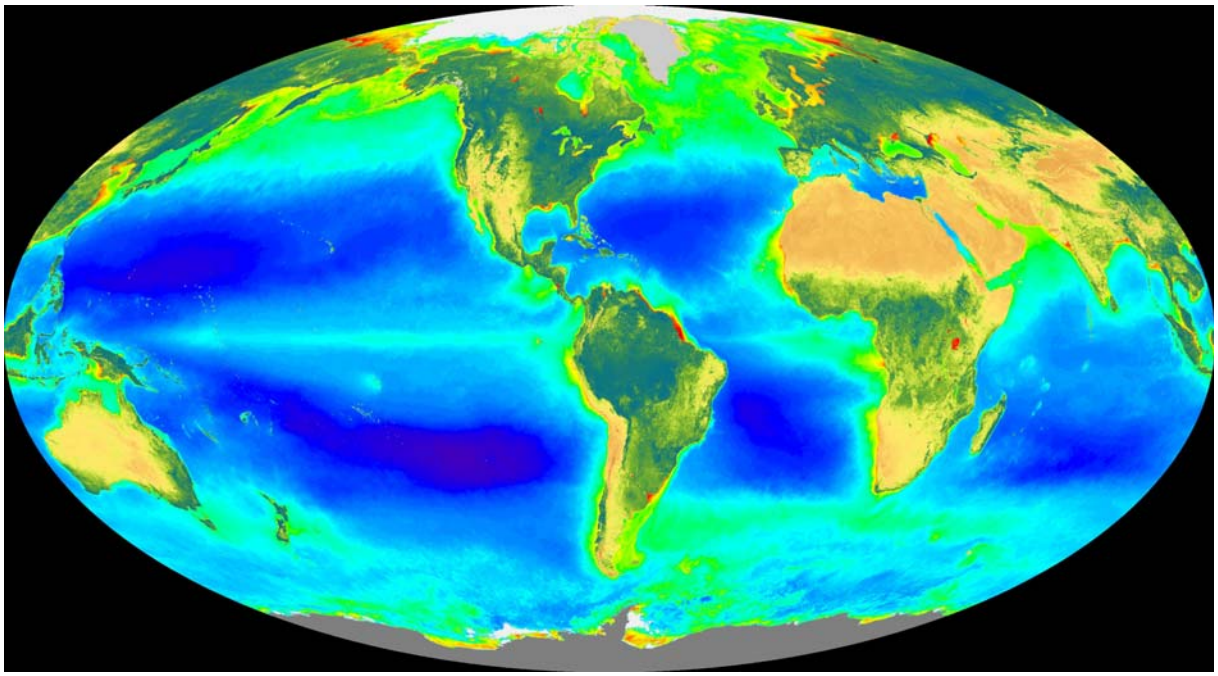
Chlorophyll on Earth!

Plants, cyanobacteria, and algae dominate the biosphere. They live on sunlight, CO_2, and water.



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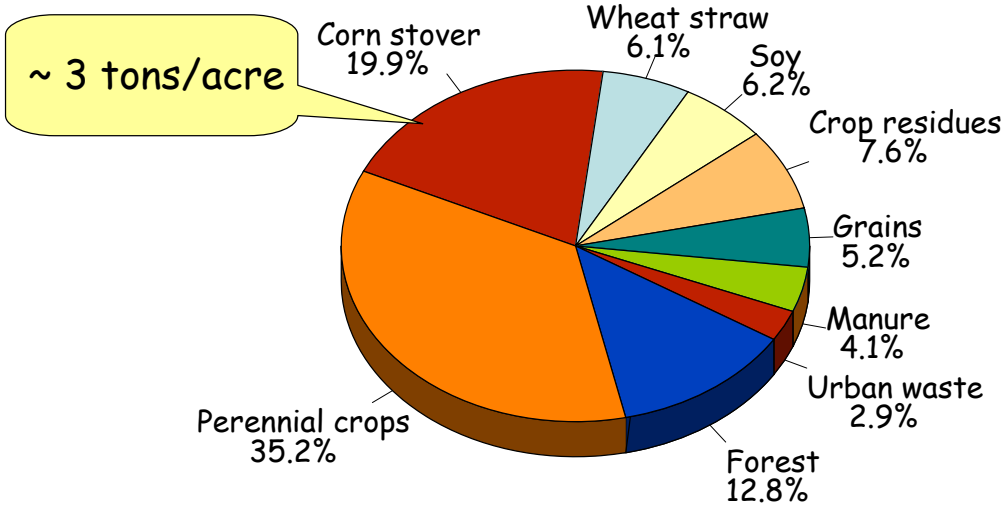
Diverse Feedstocks for Bioenergy = Diverse Research Needs



From: Billion ton Vision, DOE & USDA 2005

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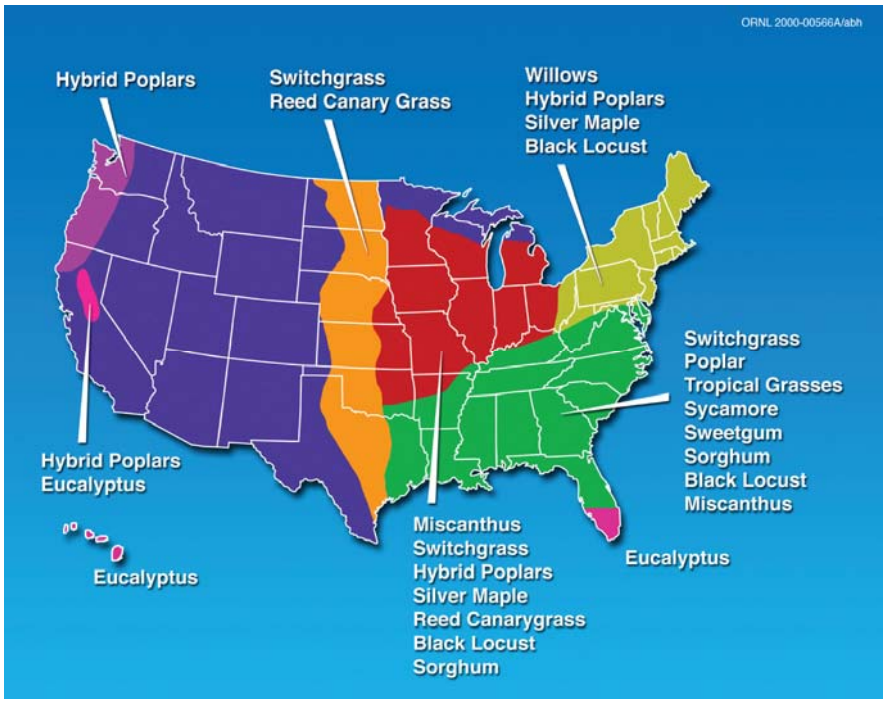
Geographic distribution of biomass crops



Wright et al DOE-ORNL-EERE

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Properties of Optimal Feedstocks

- High Yield (>15 tons/acre/year)
- High water use efficiency
- Low Input (fertilizer, tillage, pesticides)
- High conversion efficiency
- Sustainable
- Stable quality and **quantity** year to year

Crop residues may play a part but high capital costs favor dedicated energy crops

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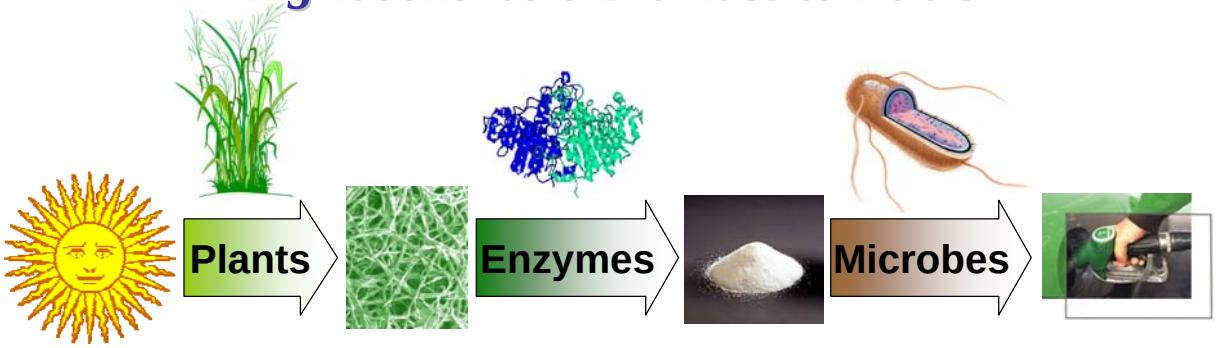
Lignocellulosic Biomass to Fuels



Lignocellulose Monomers

Challenges

- Cellulose and hemicellulose are occluded by lignin
- Lignin is recalcitrant to depolymerization
- Inhibitors released from biomass

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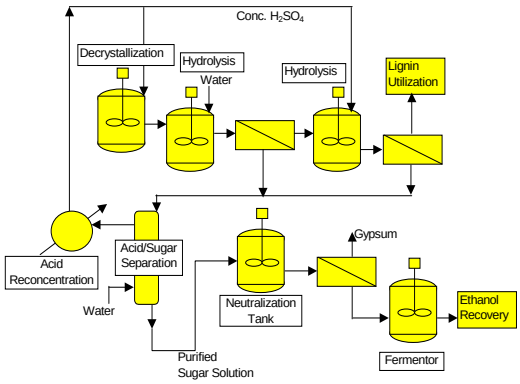
Cellulosic Ethanol: Microbes as Processing Plants

Today we utilize food starch to make alcohol, and complex and costly processing of cellulose

Tomorrow we want to utilize high yield cellulose crops with integrated processes in microbes to convert to alcohols and other fuels



Cellulose Today

Decrystallization
Hydrolysis of Cellulose, Hemicellulose, and Lignin
Multiple Sugar Metabolism
Alcohol Synthesis

Tomorrow?

An integrated process?

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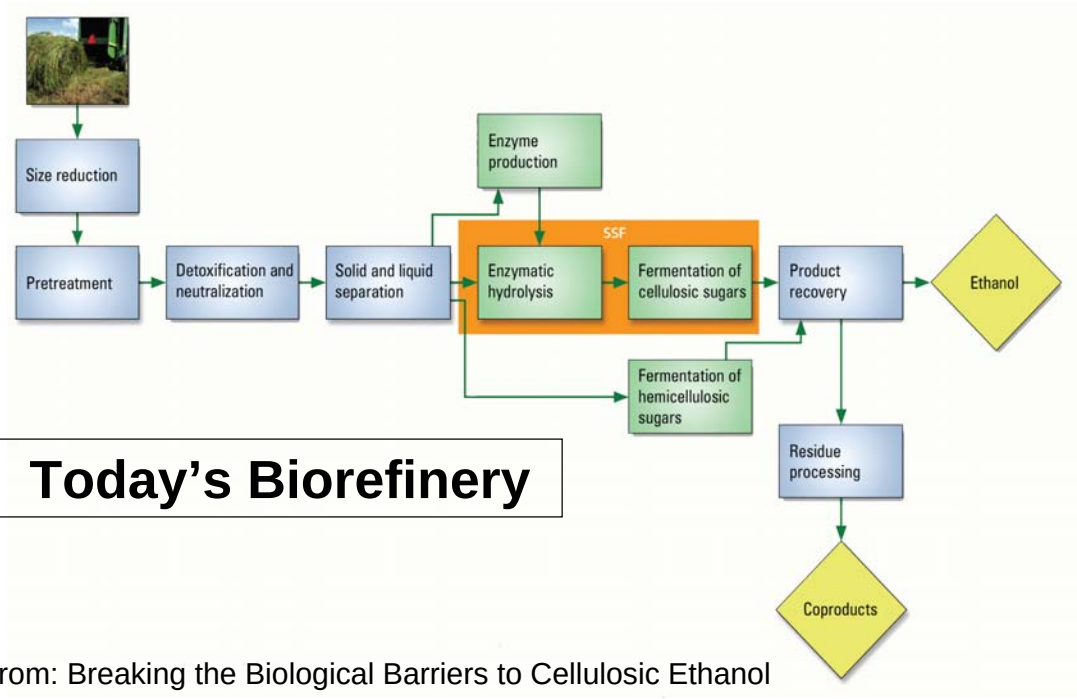
Steps in cellulosic ethanol production



Today's Biorefinery

From: Breaking the Biological Barriers to Cellulosic Ethanol

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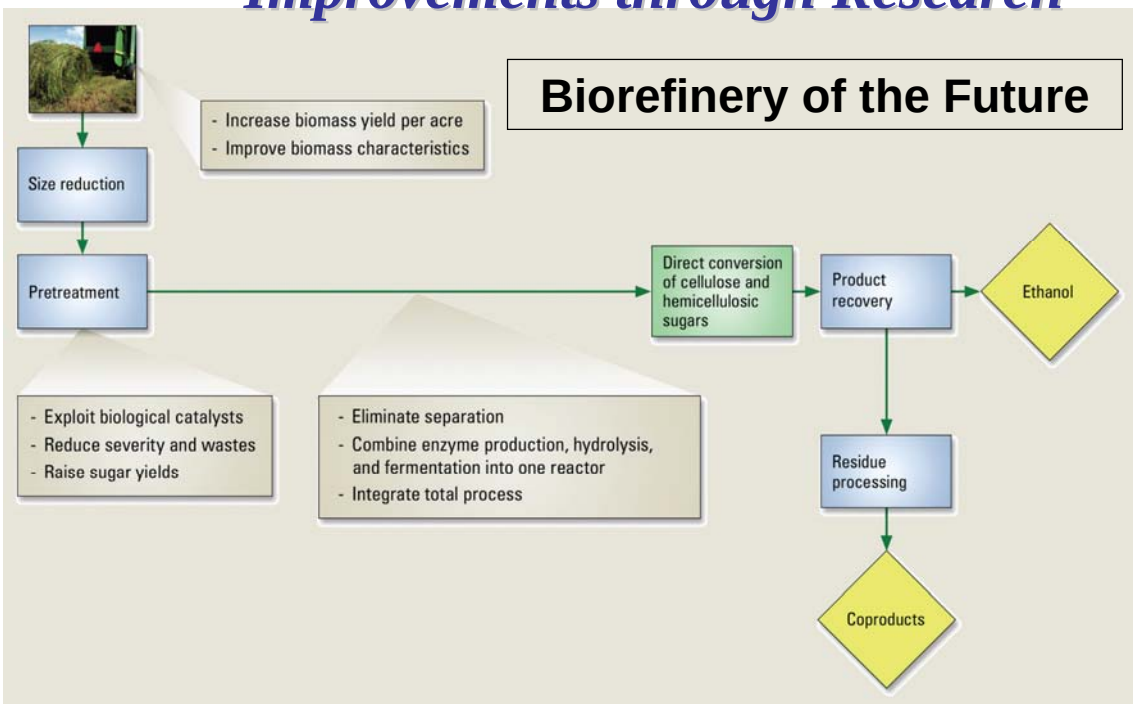
Improvements through Research



From: Breaking the Biological Barriers to Cellulosic Ethanol

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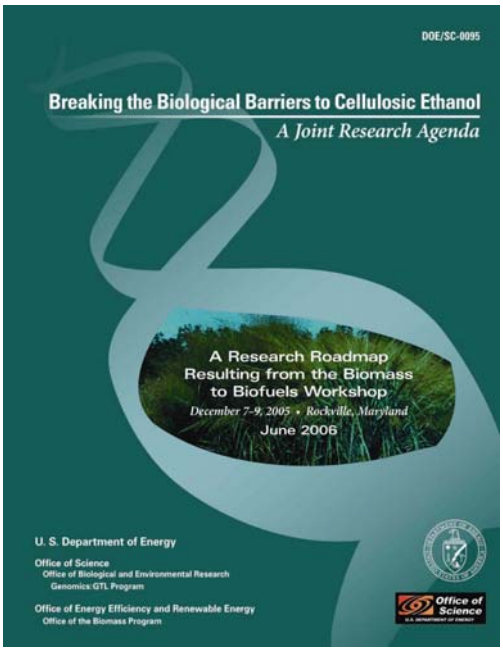
A Path Forward for Energy from Biomass



A joint SC / EERE workshop

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DOE Invests in Bioenergy

Headlines: 2007-2008

U.S. Department of Energy
Energy Efficiency and Renewable Energy

- $23 Million to Five Cellulosic Ethanol Conversion Projects
- $4.4 Million in six Innovative Biofuels Projects at U.S. Universities
- $40 Million to two Small-Scale Biorefineries
- $7.0 Million in five Innovative Biofuels Projects
- $83.3 Million to Develop a Sustainable Biofuels Industry
- $86 Million for three New Cellulosic Ethanol Biorefineries

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- $405 Million for Three Bioenergy Research Centers
- $10 Million for Cellulosic Biofuel Research (DOE/USDA)

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Mission-Inspired Science

BER advances world-class biological and environmental research programs and scientific user facilities to support DOE's energy, environment, and basic research missions.

- **Develop biofuels as a major secure national energy resource.**
- **Understand relationships between climate change and Earth's ecosystems, and assess options for carbon sequestration.**
- **Predict fate and transport of subsurface contaminants at DOE sites.**
- **Develop new tools to explore the interface of biological and physical sciences**

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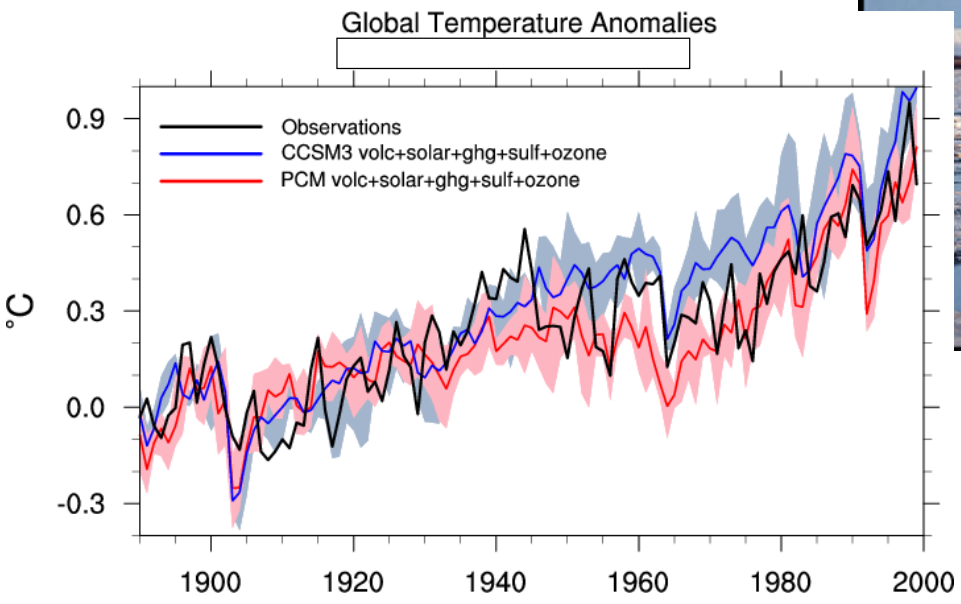
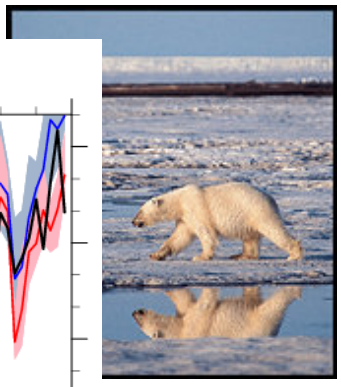
Temperatures are rising





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The BER Approach

- Understanding complex biological and environmental systems across many spatial and temporal scales:

  From the sub-micron to the global, from individual molecules to ecosystems, from nanoseconds to millenia.

- Integrating science with tight coupling between theory, observations, experiments, and models
- Supporting interdisciplinary research to address critical National needs.
- Engaging national laboratories, universities, and the private sector to generate the best possible science.

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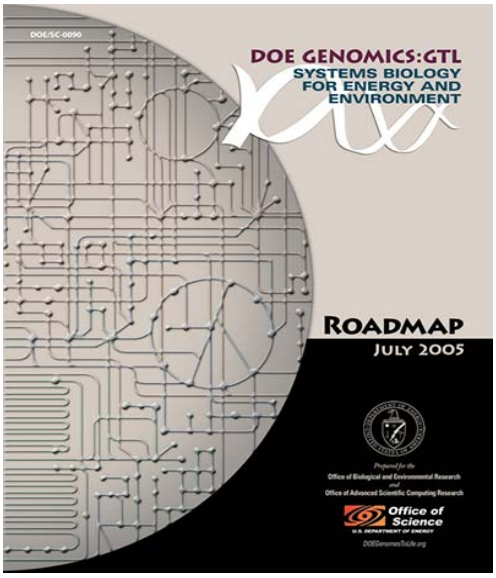
Genomics:GTL



A systems biology focused program supporting fundamental research on plants, microbes, and biological communities.

Mission Science Goals

- Develop biological solutions for intractable environmental problems
- Understand relationships between climate change and earth's microbial systems
- **Support development of biofuels as a major secure energy source**

http://genomicsgtl.energy.gov

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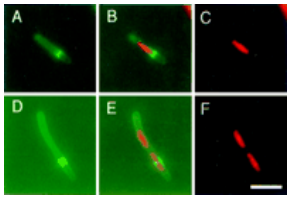
Genomics: GTL
A Systems Biology Research Program

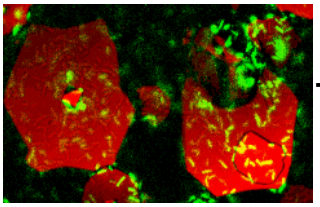
From Molecules to Cells to Ecosystems

Subcellular



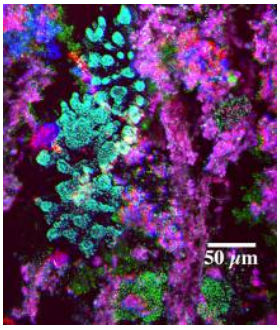
Identification, subcellular location, and dynamics of molecular machines

Cellular



Regulation of gene expression in individual cells

Ecosystems



Who is expressing what, when, where, and under what conditions? How do they work together?

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Microbes are Central to DOE Missions

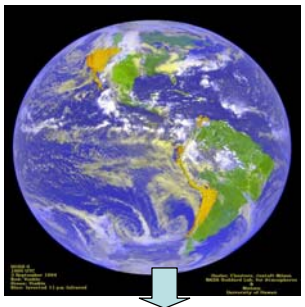
Why Microbes?

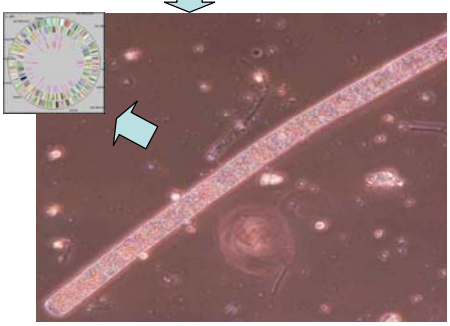
- Foundation of the biosphere and the planet's ability to sustain *all* life.
- Masters at capturing, storing, and transforming energy.
- Most abundant and biochemically versatile life forms possessing diverse and sophisticated capabilities

A Few Microbial Factoids

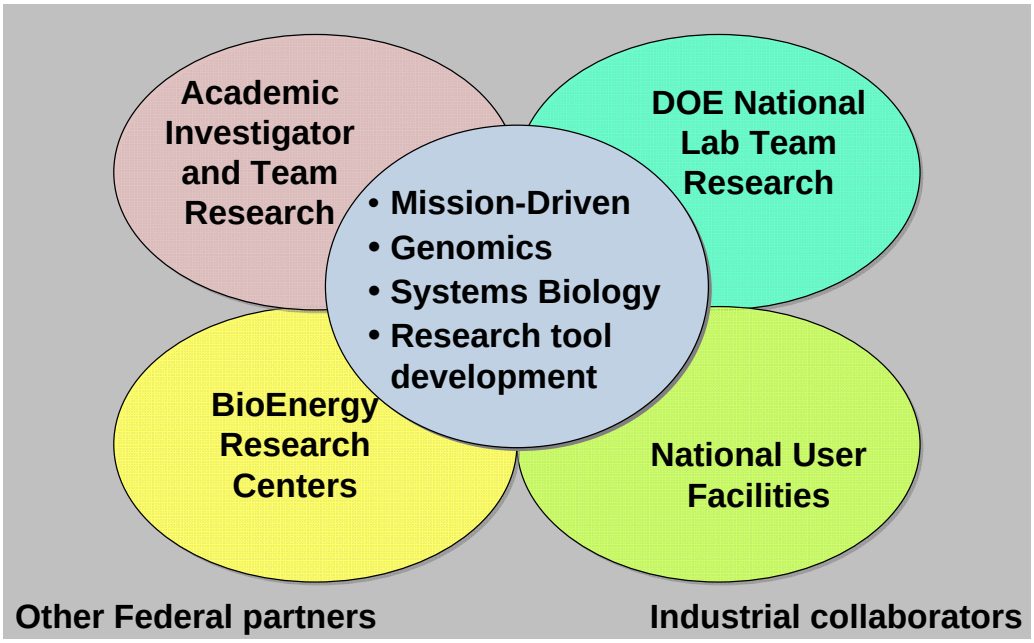
- More microbial biomass on Earth than of all other living things
- Microbes often live and work as communities of many types of microbes
- Microbes are ubiquitous

Ecogenomics – A New Frontier





The GTL Research Enterprise



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Rationale for DOE Bioenergy Research Centers

- Concerns about impact of corn ethanol on **food supply and prices** and **greenhouse gas emissions** make development of **cellulosic biofuels** more urgent
- **Sustainability of bioenergy** will be essential to gain the benefits of next-generation cellulosic biofuels and to winning public acceptance
- The possibility of moving **beyond ethanol** and producing **hydrocarbon fuels** (green gasoline, diesel, and even jet fuel) from plant lignocellulose looks more promising
- The fundamental research pursued at the BRCs will have implications and benefits that extend well beyond the biofuels area

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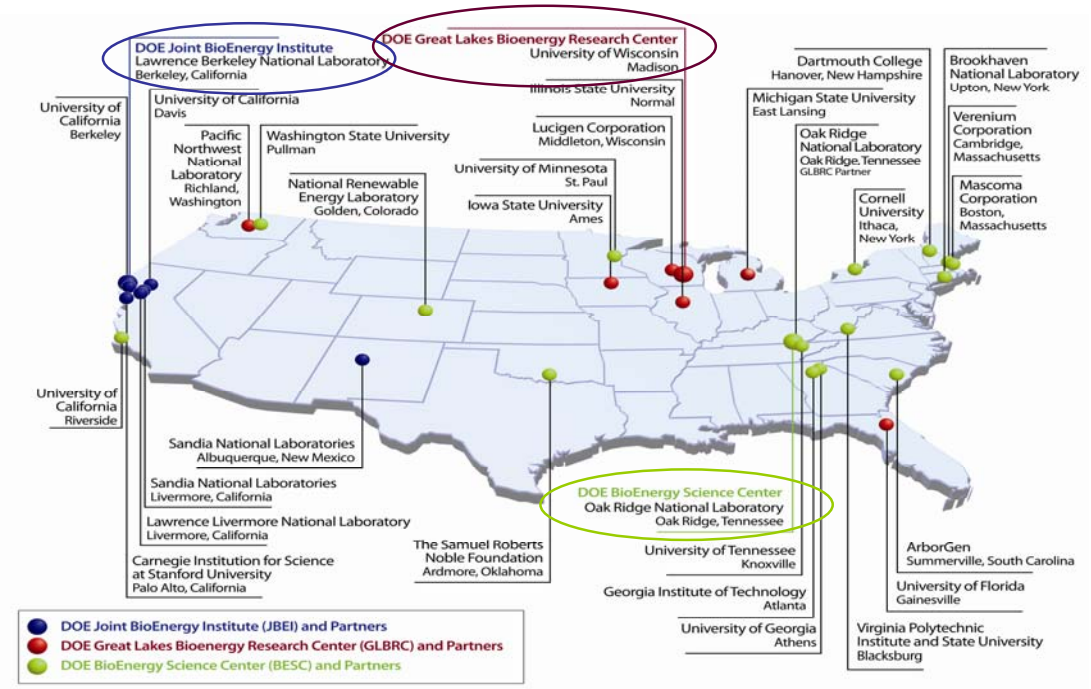
DOE Bioenergy Research Centers: Multi-Institutional Partnerships



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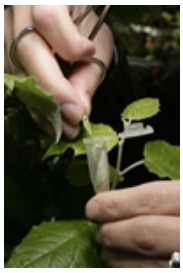
BioEnergy Science Center (BESC)

- Strong central strategic focus on overcoming "recalcitrance" (resistance of plant fiber, or lignocellulose, to breakdown into sugars)
- Longer-term goal of "Consolidated Bioprocessing" (CBP) – one-microbe or microbial community approach going from plants to fuel
- Working directly on energy crops – switchgrass and poplar
- Using metagenomics to find new, more effective cellulases
- Using synthetic biology to make *Clostridium thermocellum* (CBP microbe) more efficient at fermenting and to re-engineer the cellulosome
- Opportunity to test discoveries in a demonstration biorefinery being constructed by the state of Tennessee



BESC
BioEnergy Science Center

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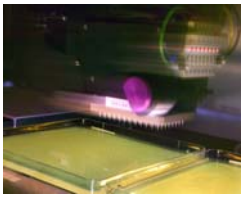
Joint BioEnergy Institute (JBEI)

- Strong basic science-oriented approach, looking for fundamental *transformational*, game-changing breakthroughs in basic science
- Focus on model crops *Arabidopsis* and rice (and on switchgrass) – rapid breakthroughs in model crops transferred to energy crops
- Innovative approach to lignin –change the monomer composition making it more cleavable and its byproducts less toxic to bioprocessing microbes
- Progress on pretreatment – use of ionic liquids as alternative pretreatment method, no toxic byproducts and de-crystallizes the cellulose
- Using synthetic biology to look beyond ethanol to synthesis of butanol, isopentanol, hexadecane, geranyl decanoate (gasoline, diesel, jet fuel)
- Connecting with Bay Area Biotech Community – a hub of bioenergy technology and venture investment



jbei
Joint BioEnergy Institute

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Great Lakes Bioenergy Research Center (GLBRC)

- Agronomic orientation of the two universities. Focus on wide range of plants, including both "model" plants and potential bioenergy crops
- Alternative approach to plants – working to overcome "recalcitrance" of lignocellulose; re-engineering plants to produce more starches and oils for biodiesel
- Alternative approaches to fuels:
  - Exploring chemical catalytic and enzymatic/microbial conversion to produce hydrocarbons – green gasoline, diesel, aviation fuel
  - Developing microbial biorefineries that use sunlight and biomass to generate hydrogen, electricity, or high-energy chemicals
- Sustainability of biofuels production - studying the environmental and socioeconomic dimensions of moving to a biofuels economy

GLBRC
Great Lakes Bioenergy Research Center

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The Joint Genome Institute: A DOE User Facility

- **Sequence and analyze the genomes and metagenomes of a mission relevant organisms and communities**
  - Whole biological systems understanding required for biological applications to DOE missions of critical national needs
  - State of the art capabilities, expert staff in an array of computing and biological research disciplines, workshops, and annotation jamborees

High throughput sequencing line at DOE-JGI in Walnut Creek, CA

Sequencing more than 40 billion base pairs of DNA per year! (More than 13 human genome equivalents)

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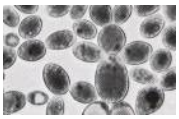
Joint Genome Institute and Bioenergy

Improved Feedstocks

Cellulosic Materials
- Poplar
- Maize/Corn Stover
- Switchgrass
- Brachypodium
- Sorghum

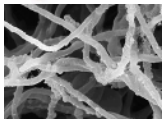
Saccharification → **Sugars** → Fermentation



- *Saccharomyces cerevisiae*
- *Zymomonas mobilis*
- *Thermoanaerobacter ethanolicus*
- *Pichia stipitis*

Ethanol producing organisms

Improved cellulose & lignin degradation



- *Termite hindgut microbiota*
- White Rot Fungus
- *Clostridium thermocellum*
- *Saccharophagus degradans*
- *Acidothermus cellulolyticus*

Genomics is a foundation for bioenergy research

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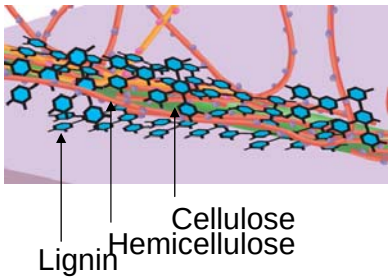
Understanding Lignocellulose Degradation

- Improving lignocellulose degradation key to using non food feedstocks
- Investments focus on understanding degradation through imaging
- Range of techniques with higher risk complement and support BRC needs



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Plant Feedstock Genomics for Bioenergy

- DOE/USDA Joint Research Program
- Supports research on plants for improvement of:
  - Biomass Characteristics
  - Biomass Yield
  - Degradability of Lignocellulose

USDA

http://genomicsgtl.energy.gov/research/DOEUSDA/index.shtml

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Challenges – Bioenergy Feedstocks

- Understand plant cell walls
- Redesign plant cell walls to make biomass more amenable to processing
- Increase biomass yields significantly in an environmentally sustainable way
- Improve resource use efficiency – minerals, water, light

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Research recommendations - Bioenergy feedstocks

- Next generation DNA sequencing for complex grasses
- High throughput genotyping and phenotyping
- Broad availability of common genomic/genetic resources and common genotyping platforms for bioenergy crops
- Innovative solutions for data management & analysis
- Novel tools for cell wall analysis
- Analytical platforms to optimize lignocellulose decomposition & conversion

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Challenges – Biomass Conversion

- Improved biochemical (and thermochemical) conversion technologies
- Scale-up from the bench to demonstration to production
- Parallel, efficient conversion approaches to use diverse local and regional feedstocks
- Harnessing synthetic biology

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Research recommendations – Biomass conversion

- Need for standards and benchmarks across the range of biomass to biofuels – analytical methods, sampling, tools, reference materials
- Development of new catalysts – discovered or engineered
- Flexible demonstration projects to interface with developments in basic research and diversity of feedstocks
- Deeper scientific insights into underlying biomolecular and cellular processes and structures

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Challenges – Socio-economic & environmental issues

- Economic, environmental and societal sustainability: the interface of the production of large volume energy commodities and the socio-economic and environmental systems
- Interfacing with individuals, communities, and countries to make scientifically informed decisions about the role and impacts of biotechnology and the growing bioenergy industry

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Research recommendations - Socio-economic & environmental

- Optimization of bioenergy crops for local environments & distributed versus centralized conversion plants
- Estimation of practical, real world yields
- Identification, definition, quantification, and value of high-nature-value farmland
- Valuation of environmental benefits from biofuels
- Development of mixed land use practices using perennials and low-input systems

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Research recommendations - Socio-economic & environmental, cont'd

- New feedstocks that won't compete for arable lands or that can use degrade lands including waste products
- Quantification of true costs of biomass production and conversion
- Greenhouse gas balances of bioenergy crops and whole bioenergy pathways

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Thank you!

POC: Anna.palmisano@science.doe.gov