Cellulosic Biofuels: continued R&D challenges during pioneer biorefinery deployment

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U.S. DEPARTMENT OF ENERGY

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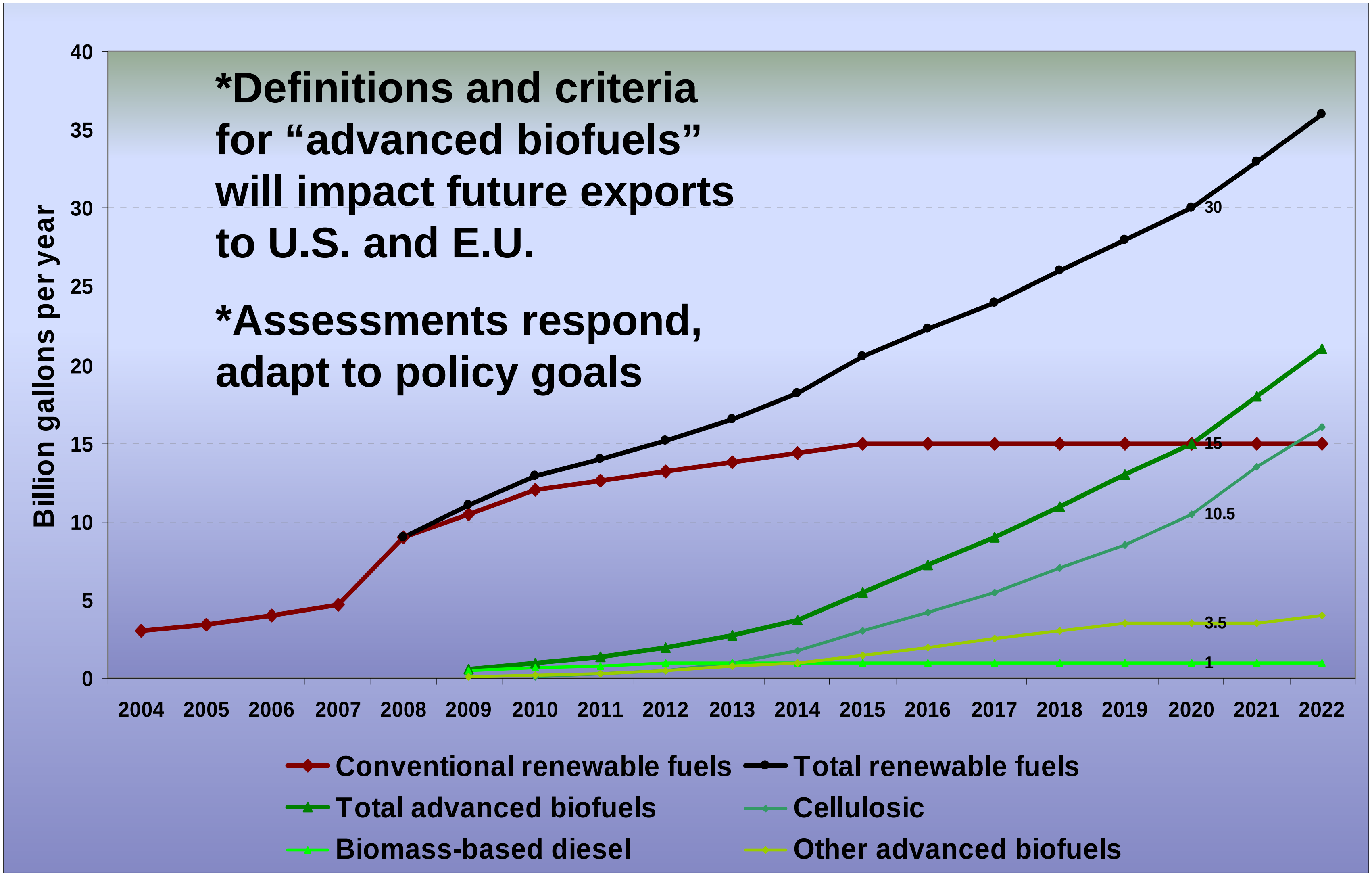
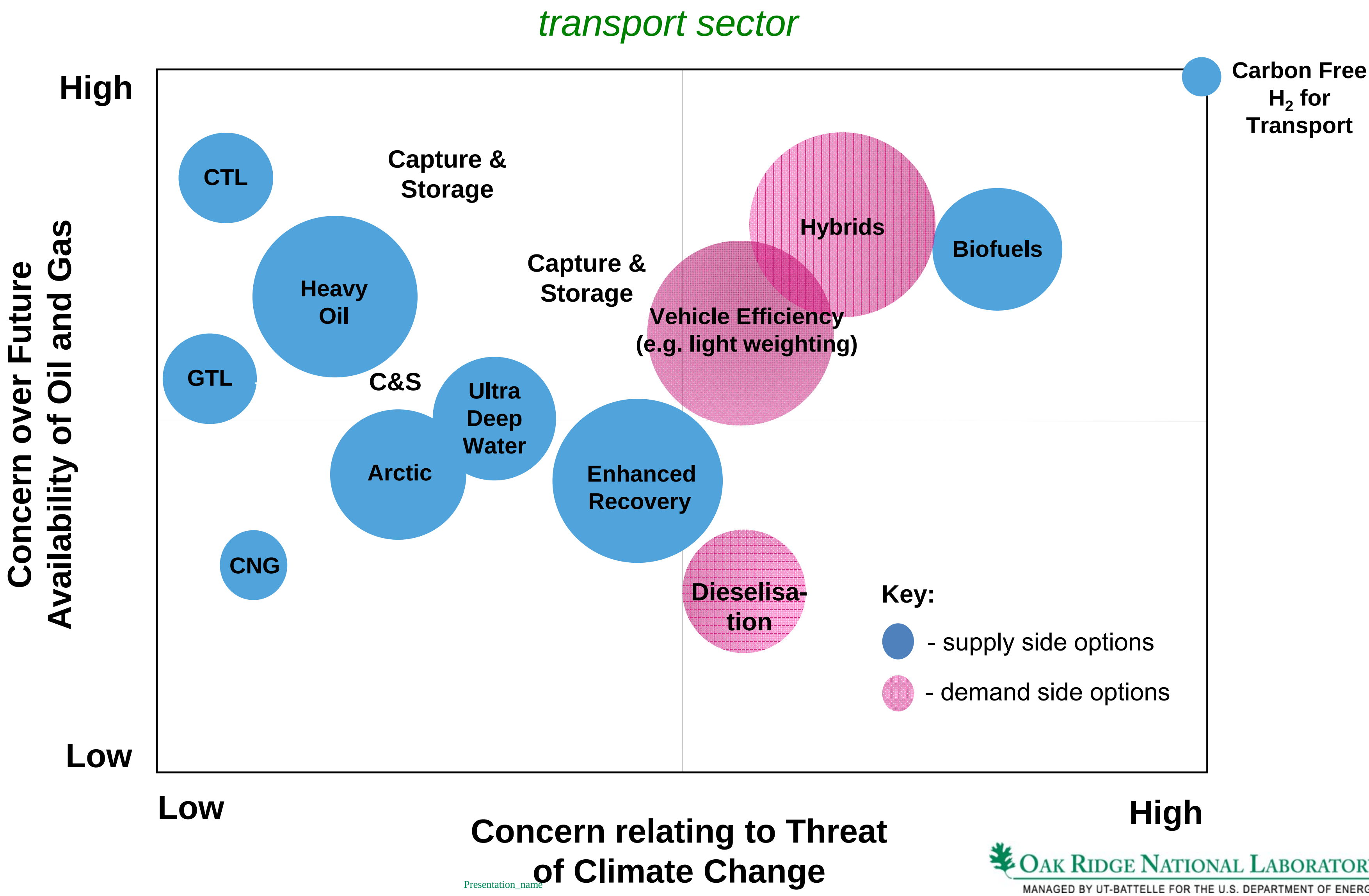
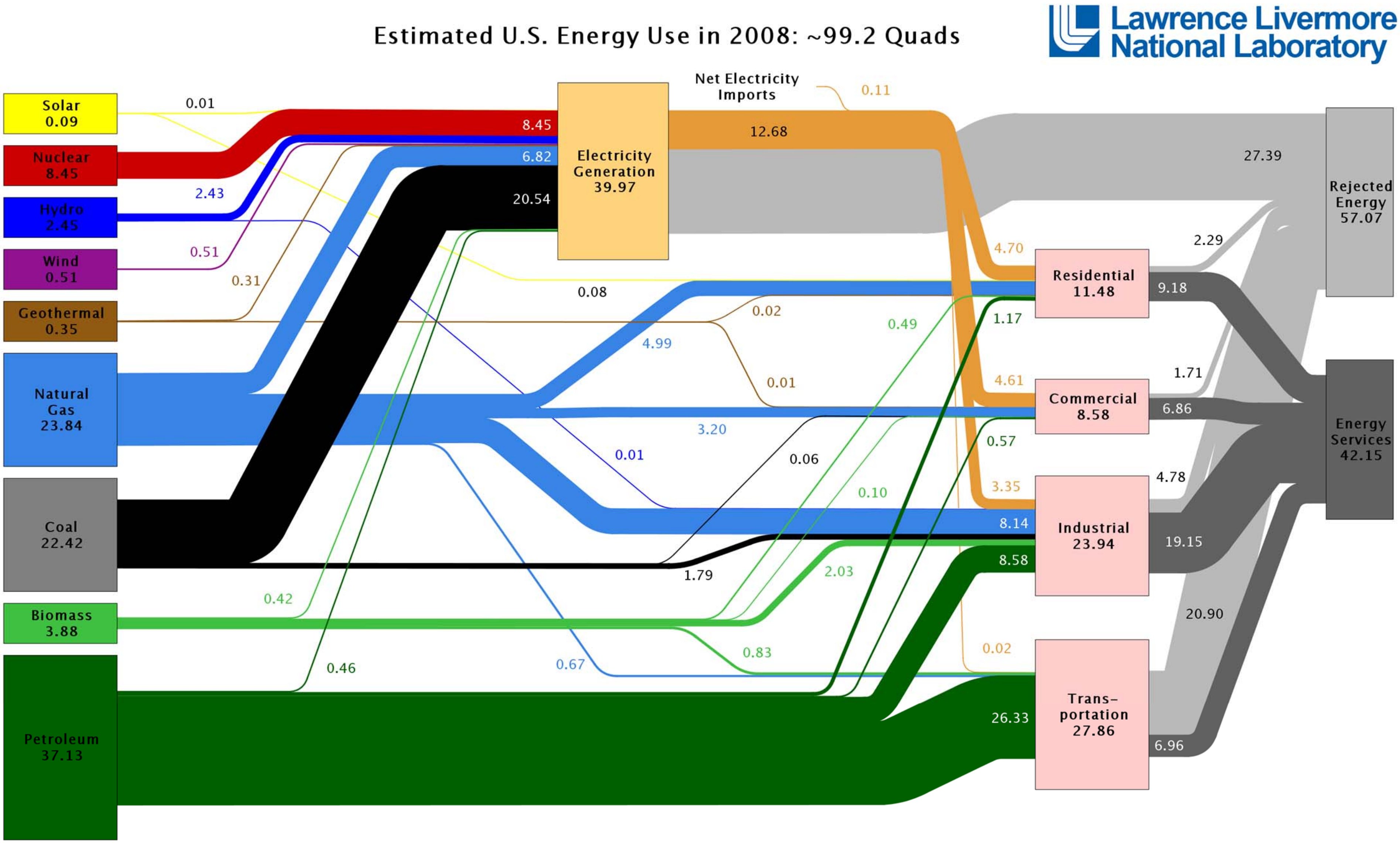
Energy Independence and Security Act (EISA 2007)



Technology Options for Transportation – from BP



Energy (and mass) flows are not all interchangeable

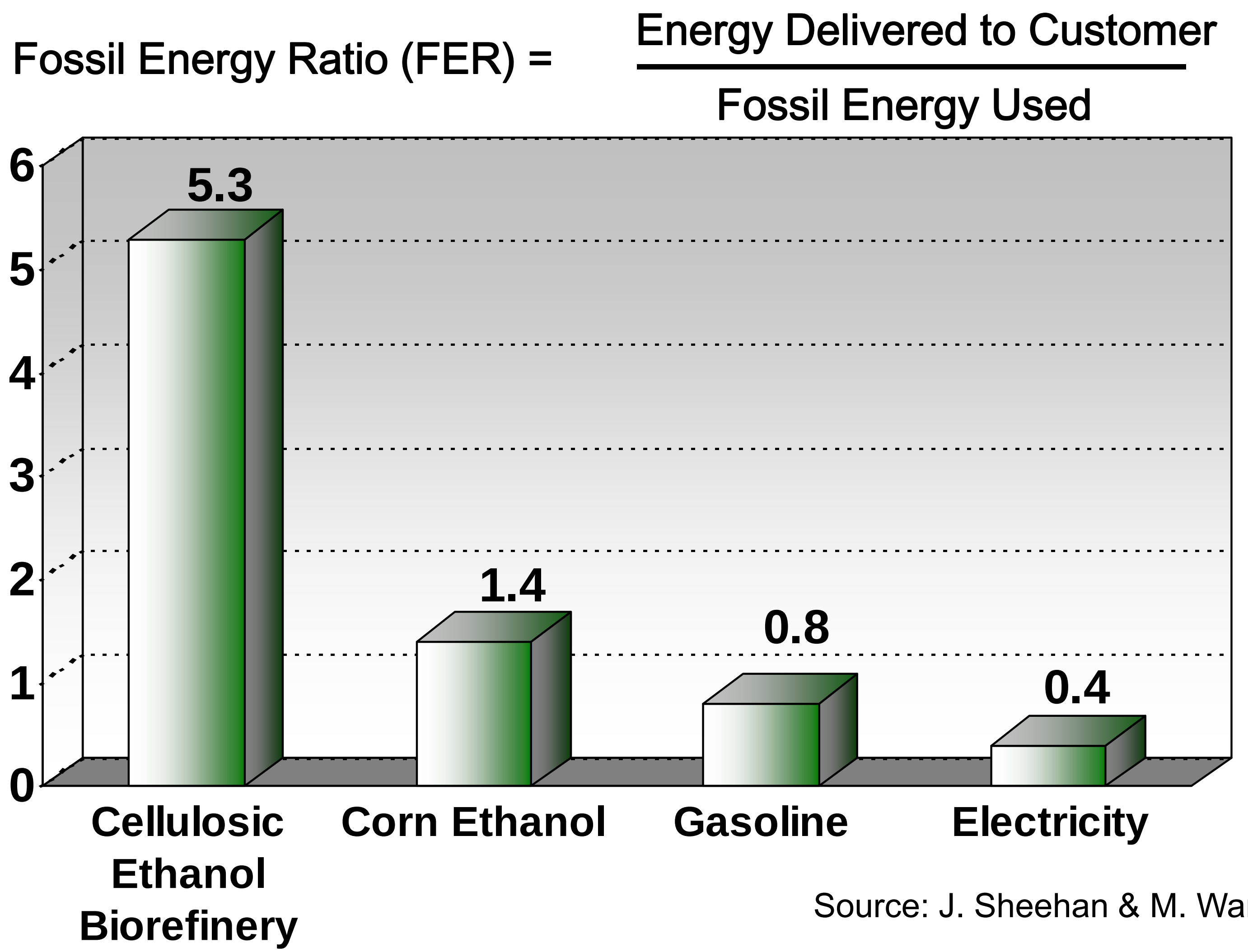


Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Why still biofuels?

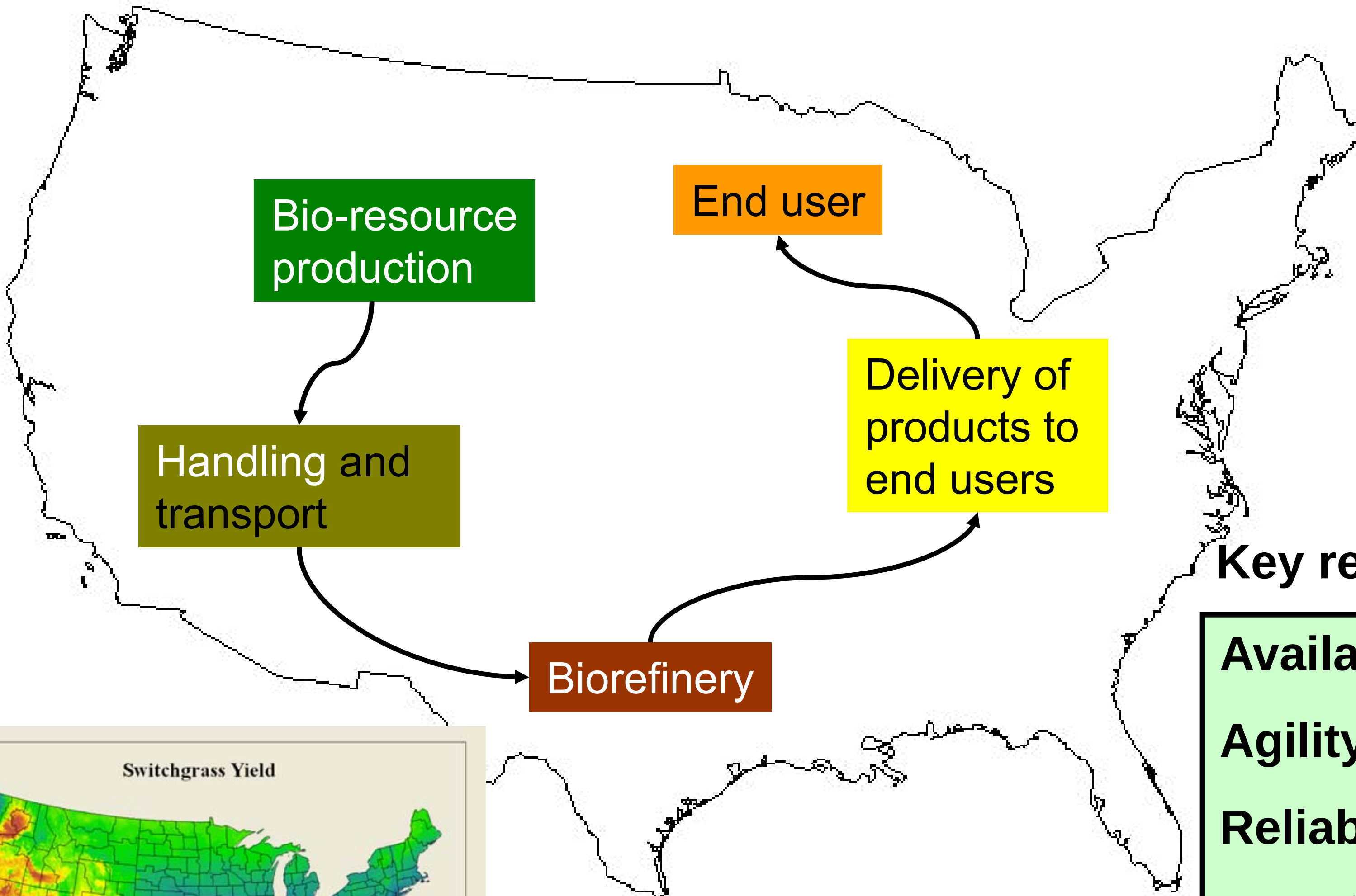
- The unique role for biomass
  - *"… Biomass is our only renewable source of carbon-based fuels and chemicals"* – Ray Miller, DuPont, 2005
  - Essential for liquid based transportation fuels (gasoline, diesel, and especially jet)
- An important part of most broad assessments and scenarios for a low-carbon future
- The potential capacity exist for significant impact in magnitude and sustainabililty

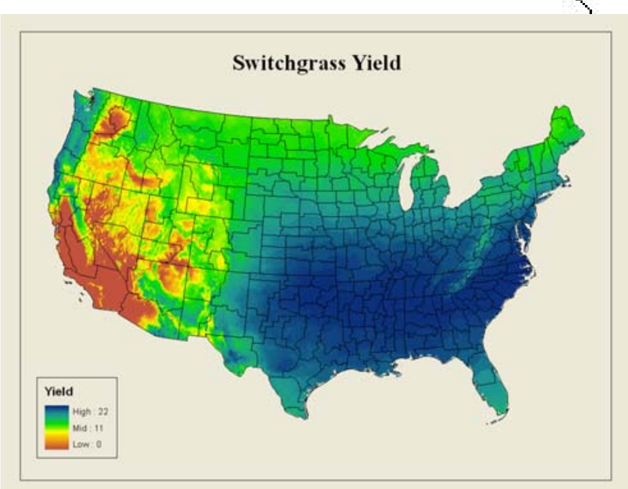
Fossil Energy Replacement Ratio



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

Bioenergy is analogous to other existing energy networks





Key requirements

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

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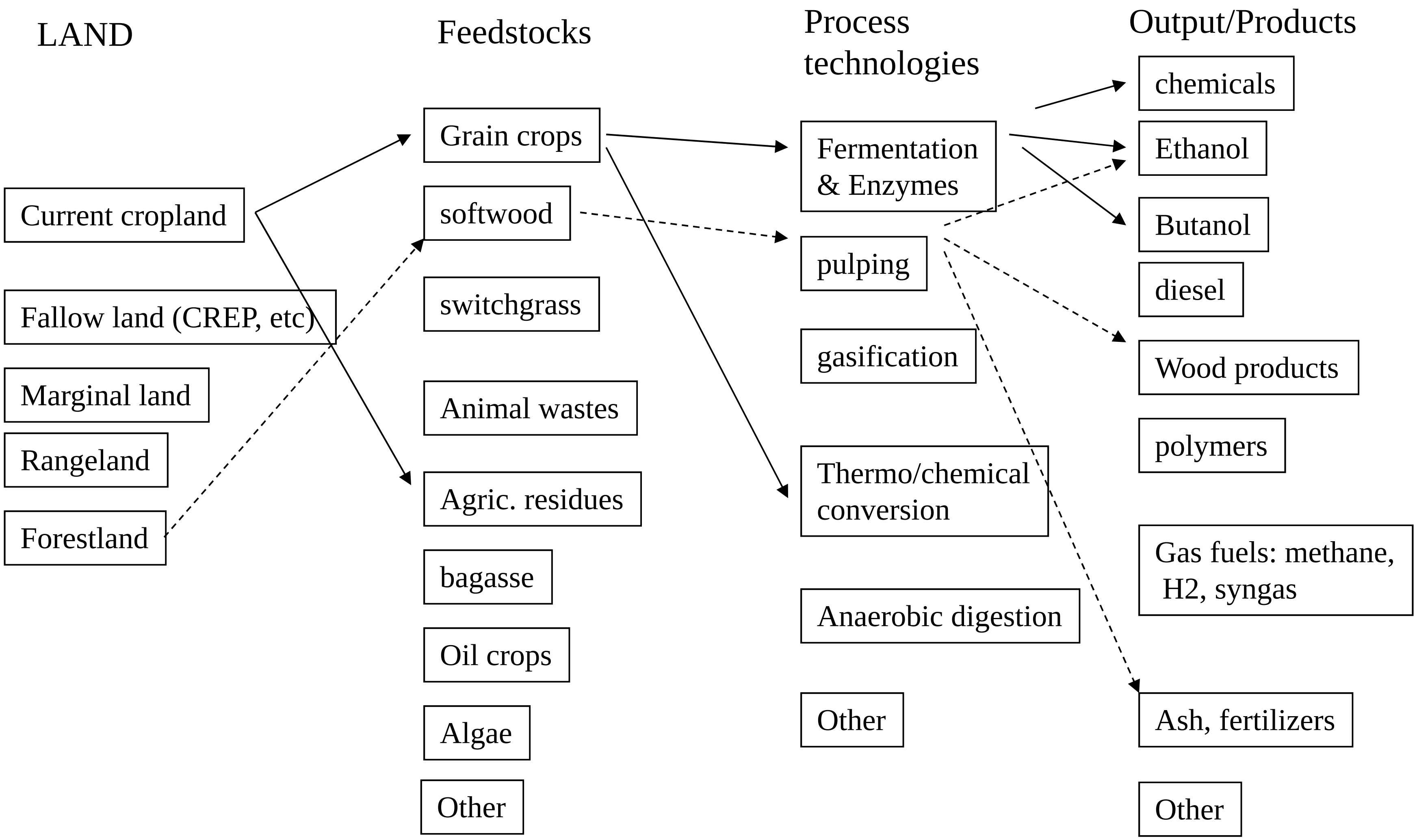
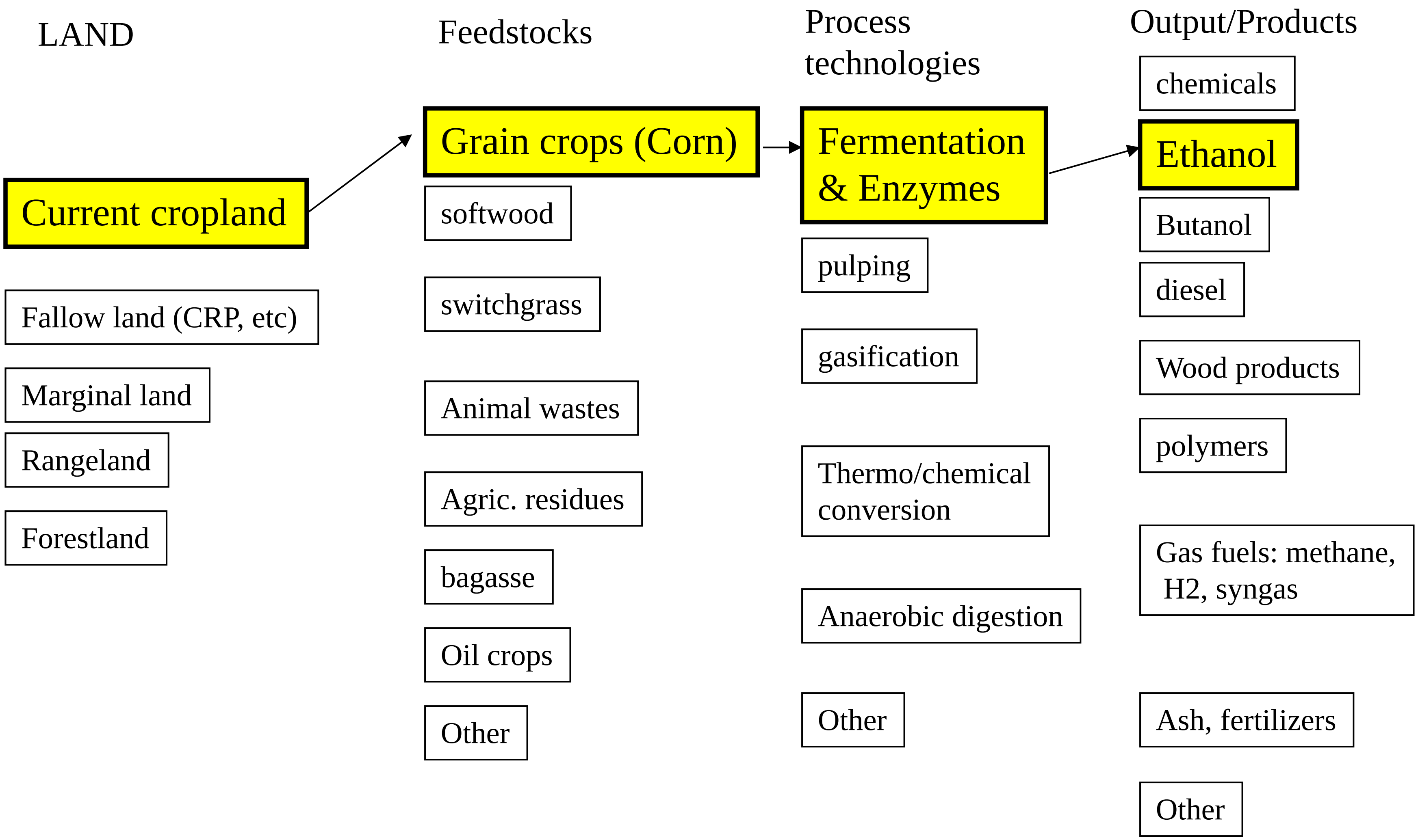
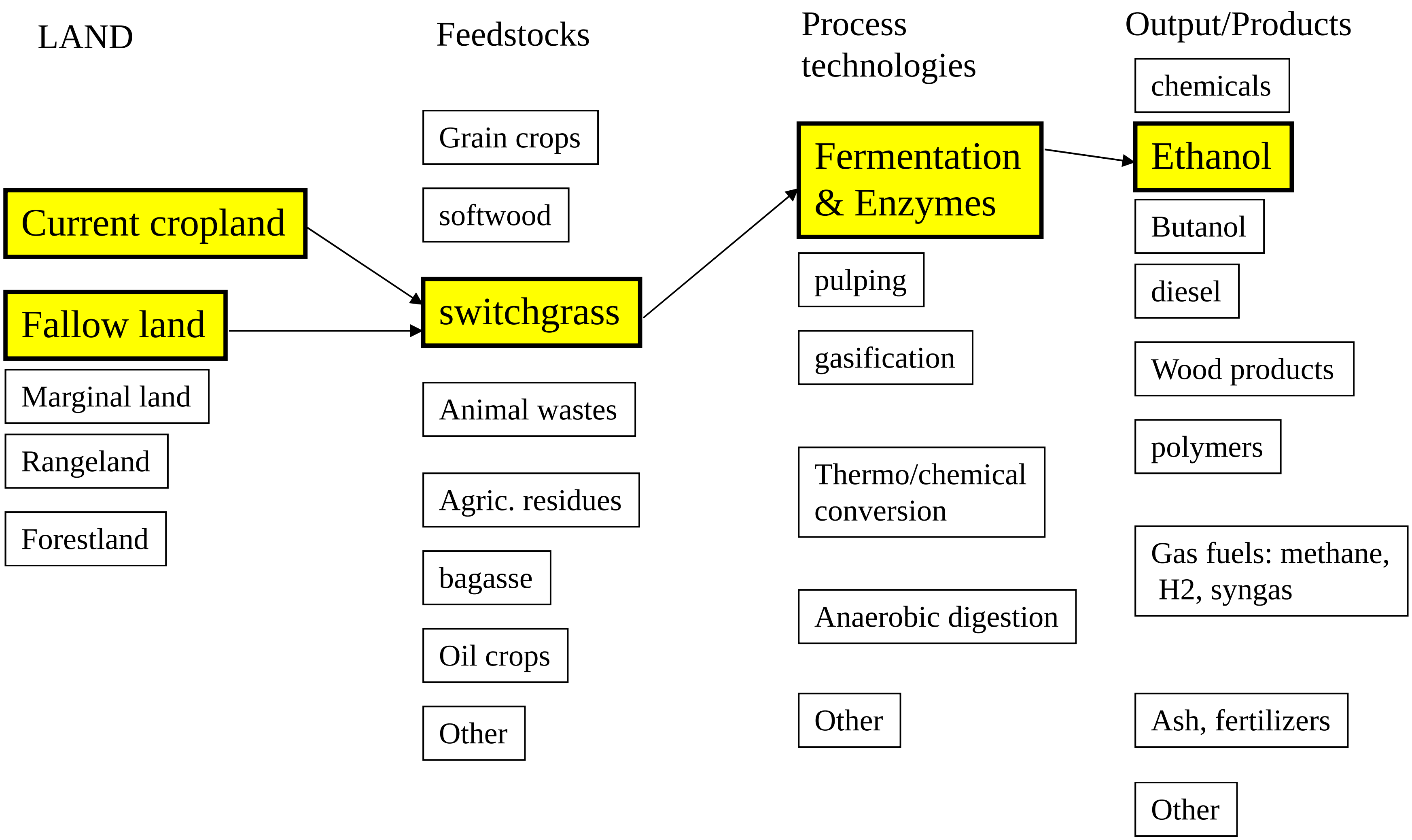
Biomass Utilization is a multi-factorial problem (multiple choice)



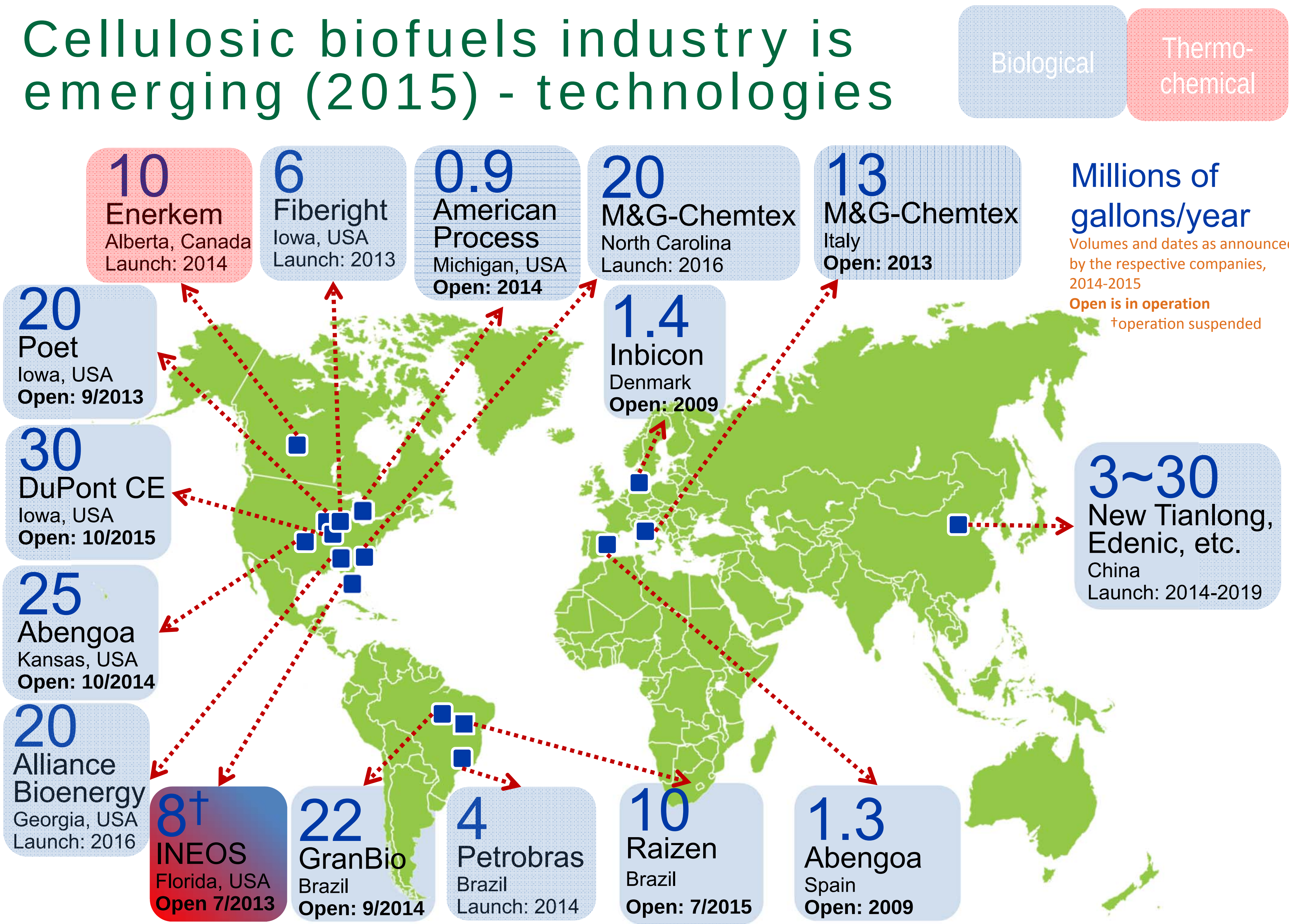
Biomass Utilization: current Corn Bioethanol



Biomass Utilization: Gov. Bredesen's announcement of switchgrass to bioethanol might follow this path



Cellulosic biofuels industry is emerging (2015) - technologies



Total projected capacity 180~220 M gal/y

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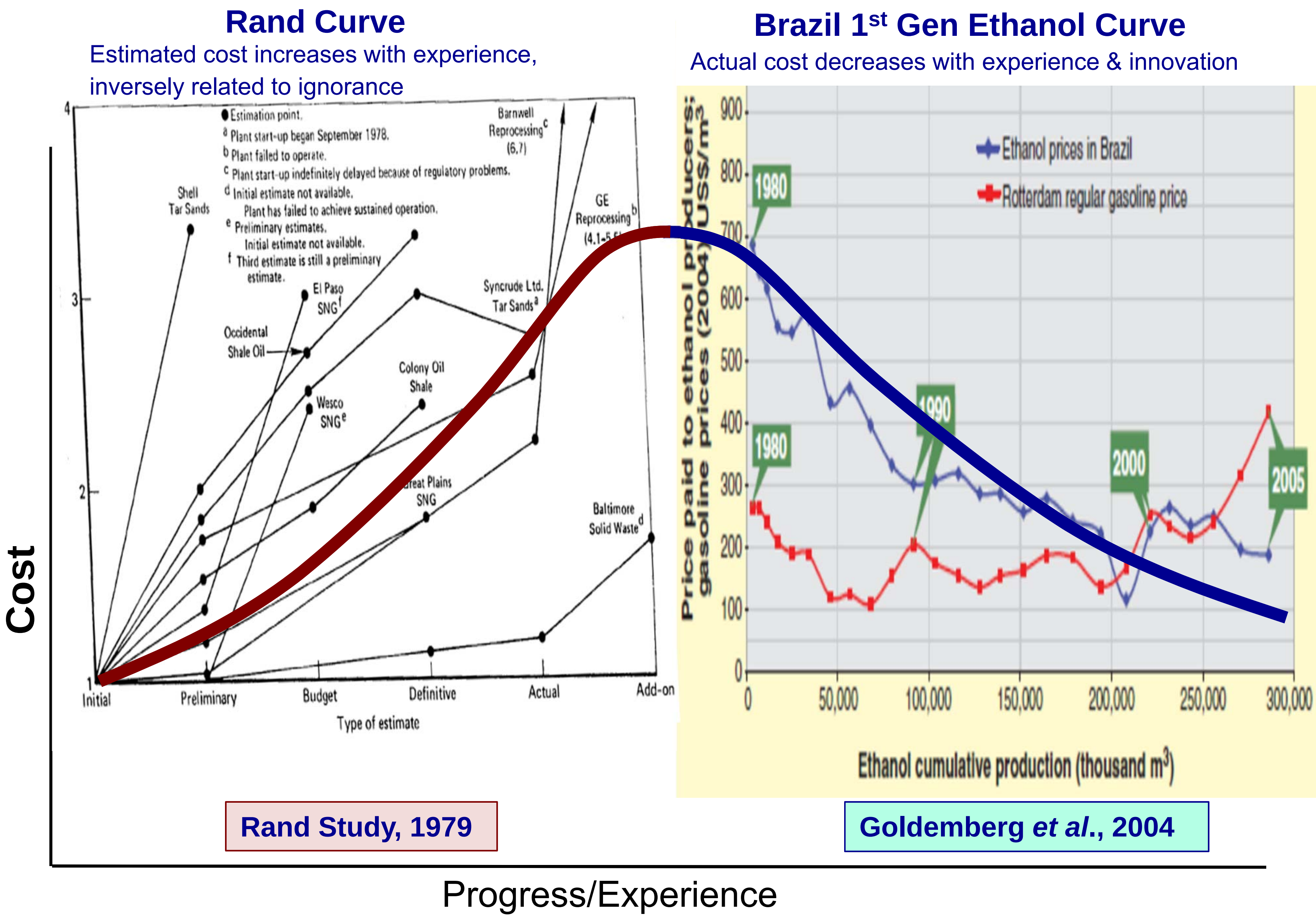
Critical factors affecting deployment and scale-up of U.S. bioenergy industries

Feedstocks	Logistics and Land-Water Use	Conversion Technologies	Products and Utilization
Insufficient yield	**Spatially dispersed feedstock sources**	**Insufficient yield, rate, and titer**	**Biofuel demand - ethanol blend wall, development of new biofuels (e.g., bioJet)**
Tolerance to environmental stresses (e.g., drought)	**Low bulk density and high moisture content of feedstock**	**Feedstock composition (e.g., recalcitrance)**	Compatibility with existing infrastructure
Amendment requirements (e.g., fertilizer)	**Biomass stability during storage**	**Marketable co-products**	Policy stability (e.g., RFS)
Adoption of genetically modified crops	**Feedstock displacement of cropland**	High capital costs and investment risk	Certification of new fuels
Halophytes, saline agriculture	Indirect land use change	Scalability tradeoffs	
Algae	Scalability tradeoffs	**Direct production of drop-in fuels**	
	Water requirements		

Factors where **advanced biotechnologies** are anticipated to make a significant impact are indicated in **bold type.**

Davison et al., 2015. "The impact of biotechnological advances on the future of U.S. bioenergy," *Biofuels, Bioprod. Biorefin.* 9:454 (2015).

Taking stock: new technology activation "energy"



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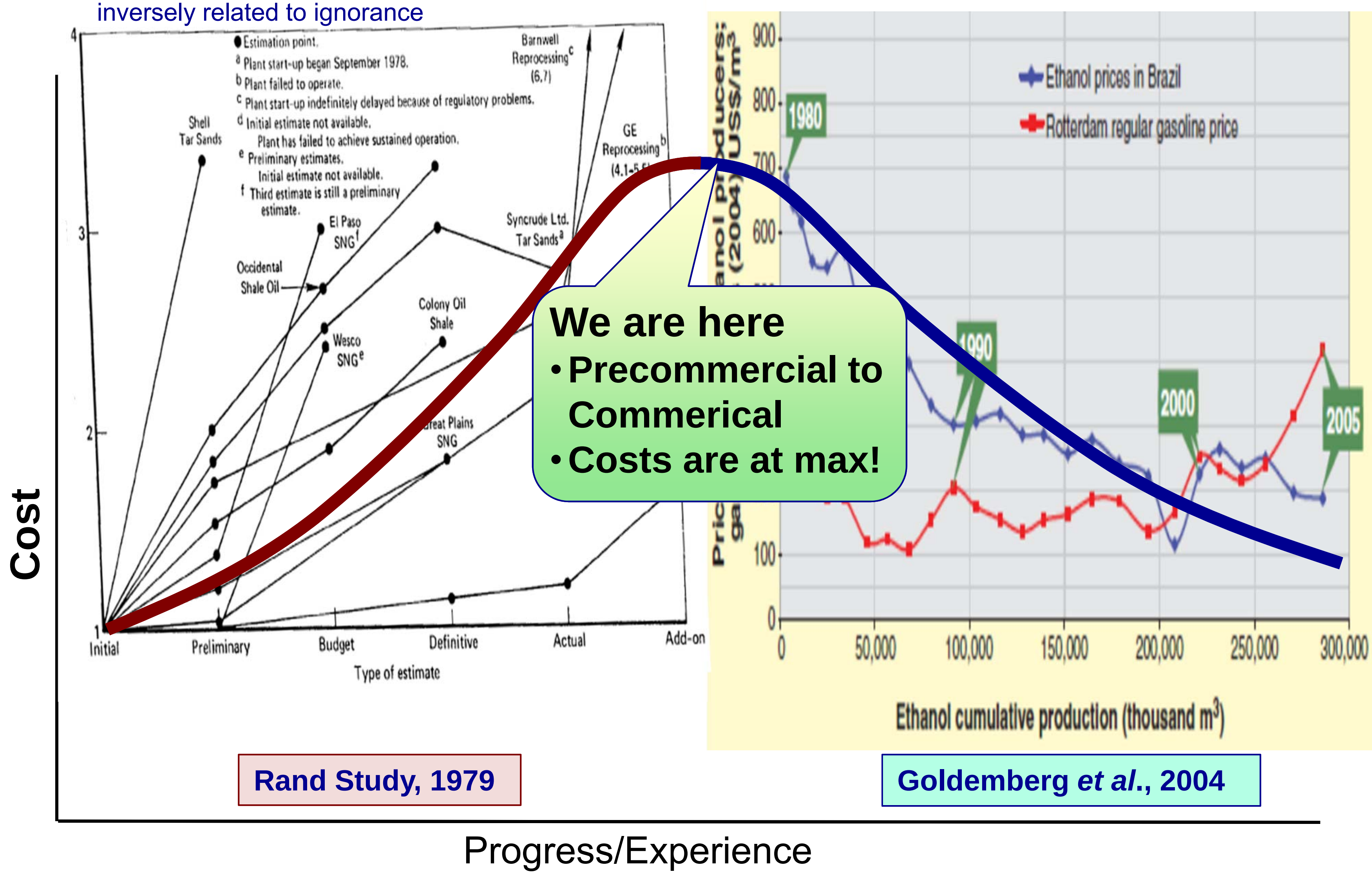
Taking stock: new technology activation "energy"

Rand Curve

Estimated cost increases with experience, inversely related to ignorance

Brazil 1st Gen Ethanol Curve

Actual cost decreases with experience & innovation



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Major components of the biofuels supply chain

Feedstocks	Logistics & Land Use	Conversion Technologies	Conversion Products	Utilization
Grain crops			Chemicals	Gasoline engines
Switchgrass	Land type	Fermentation	Ethanol	Diesel engines
Woody crops	Land use	Pulping	Butanol	
Animal wastes	Planting	Gasification	Diesel	Improved engines
Agricultural residues	Harvesting	Thermo / chemical	Gasoline / hydrocarbons	Flex-fuel engines
Bagasse	Post-harvest processing	Anerobic digestion	Wood products	Bioplastics
Oil crops	Transport		Polymers	Biomaterials
Algae			Methane	

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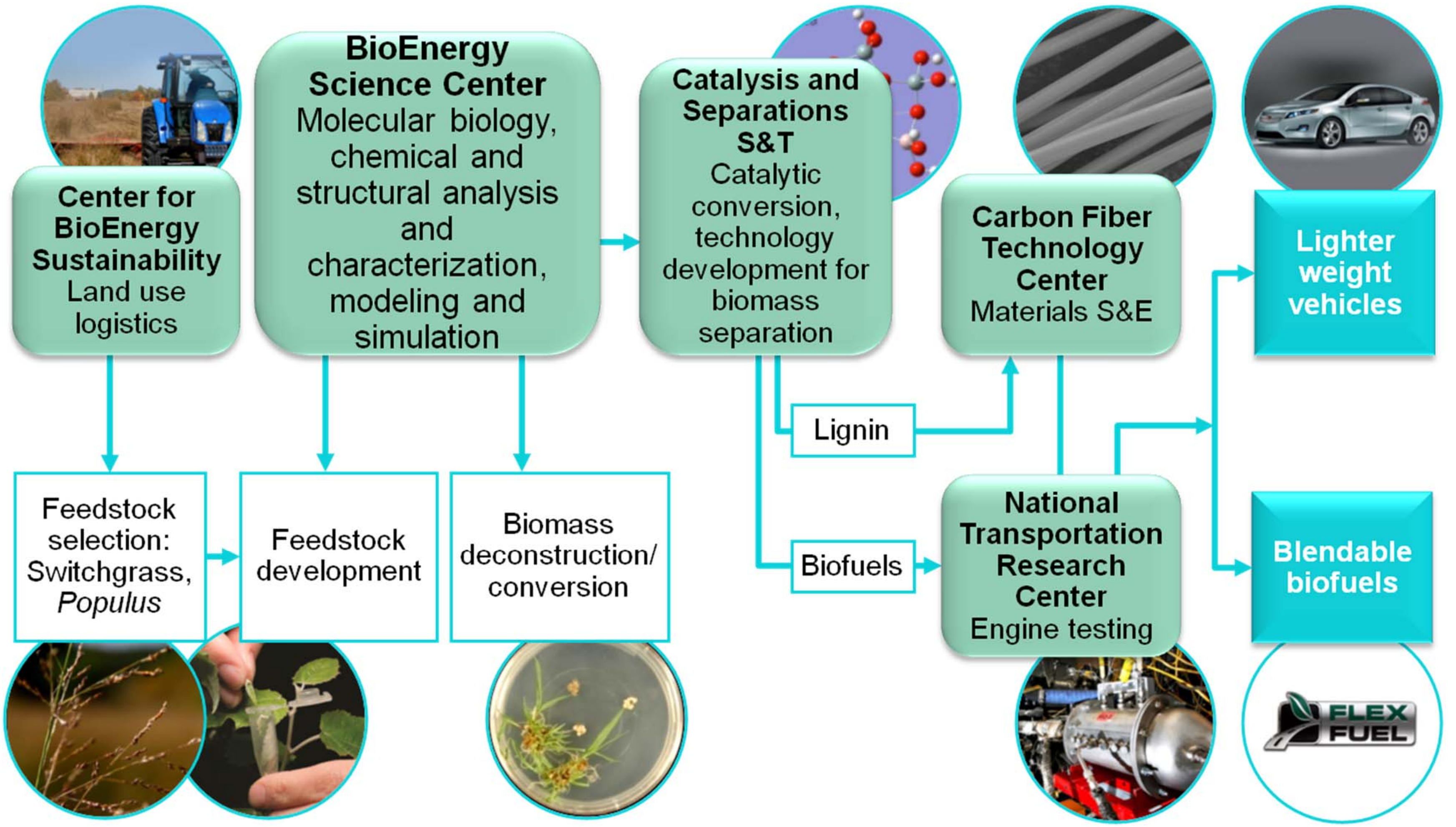
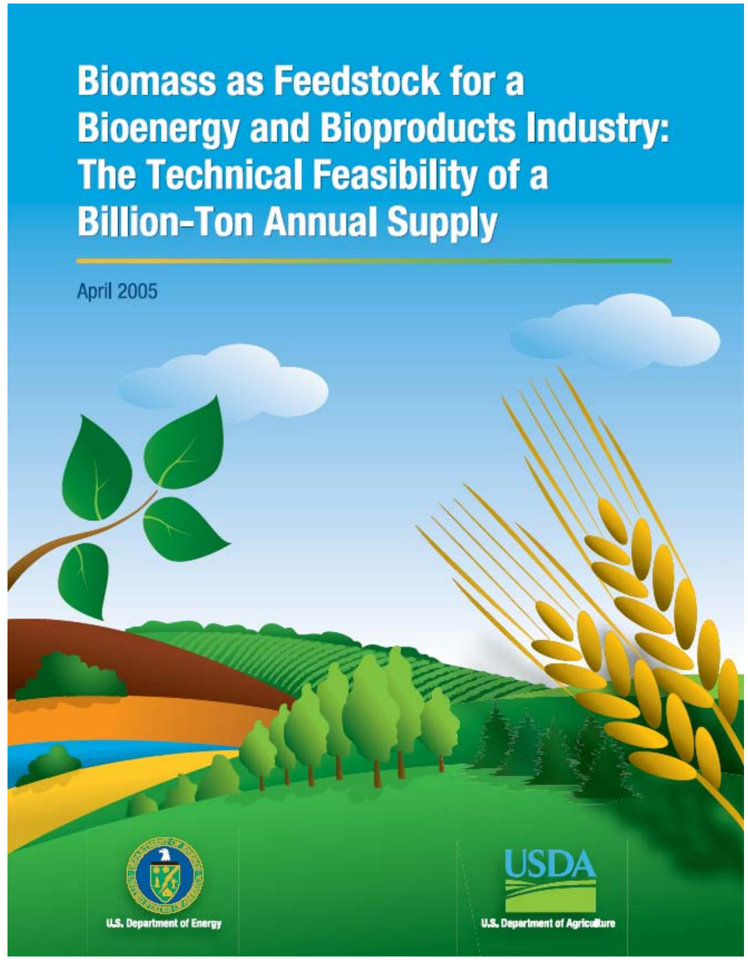
Bioscience and biotechnology for sustainable mobility



Are there sufficient amounts of biomass?

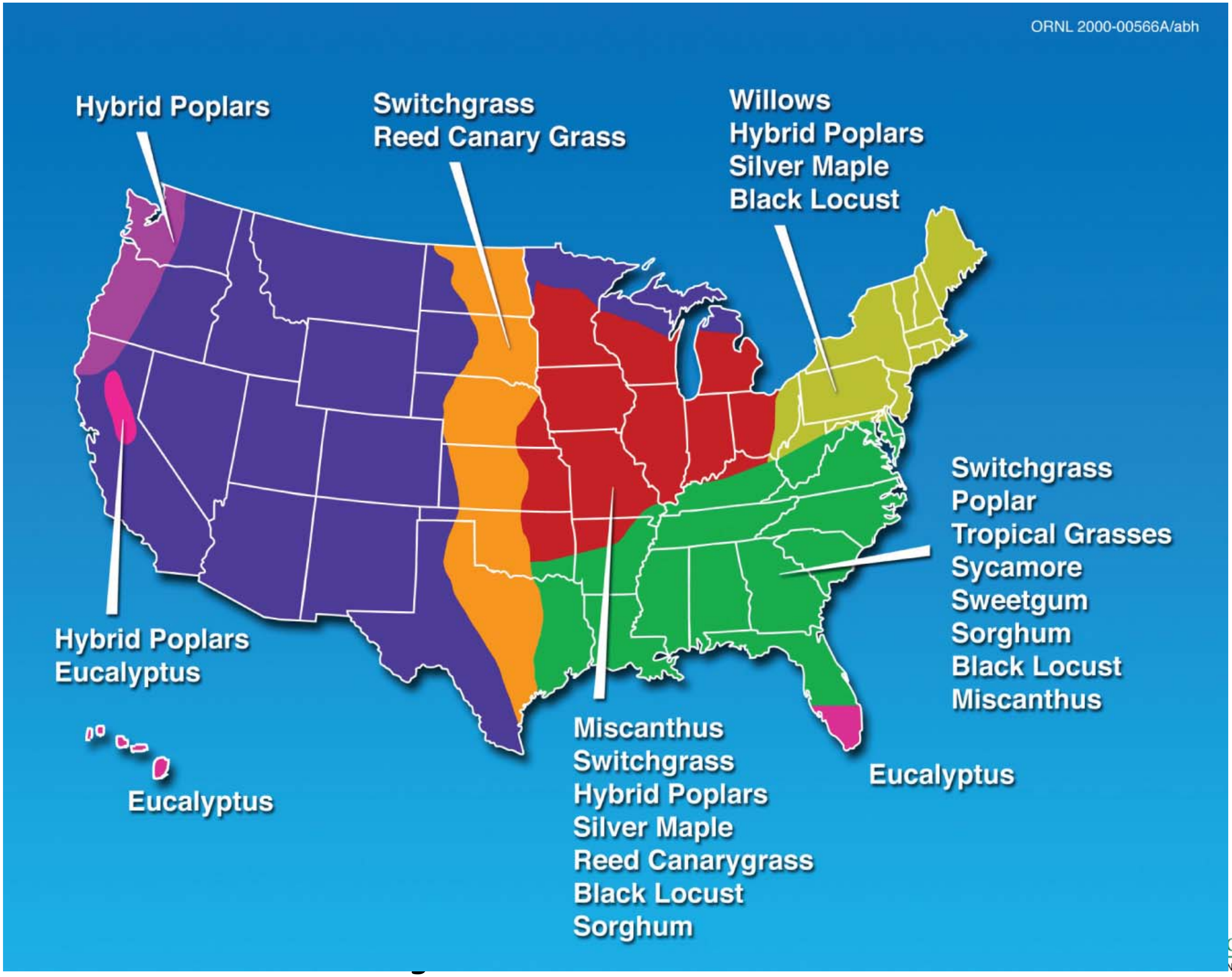
- Yes, land resources of the U.S. can sustainably supply more than 1.3 billion dry tons annually and still continue to meet food, feed, and export demands
- Required changes are not unreasonable given current trends and time-frame for bio-industry scale-up and deployment



Robert Perlack, Lynn Wright, Anthony Turhollow, Robin Graham (ORNL); Bryce Stokes, Donald Erbach (USDA)

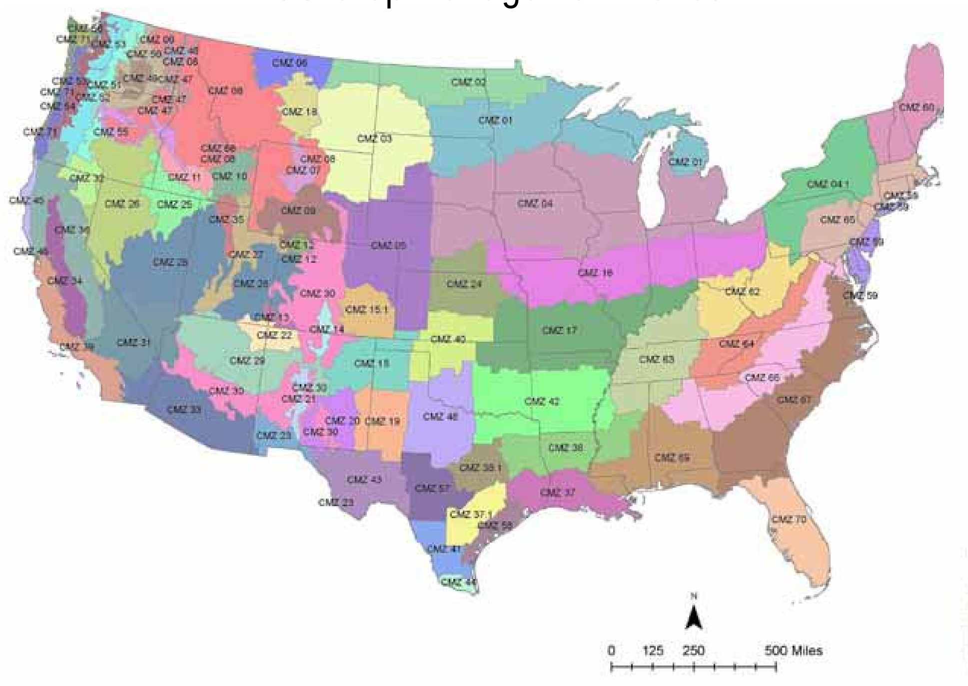
http://www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

Geographic distribution of biomass crops

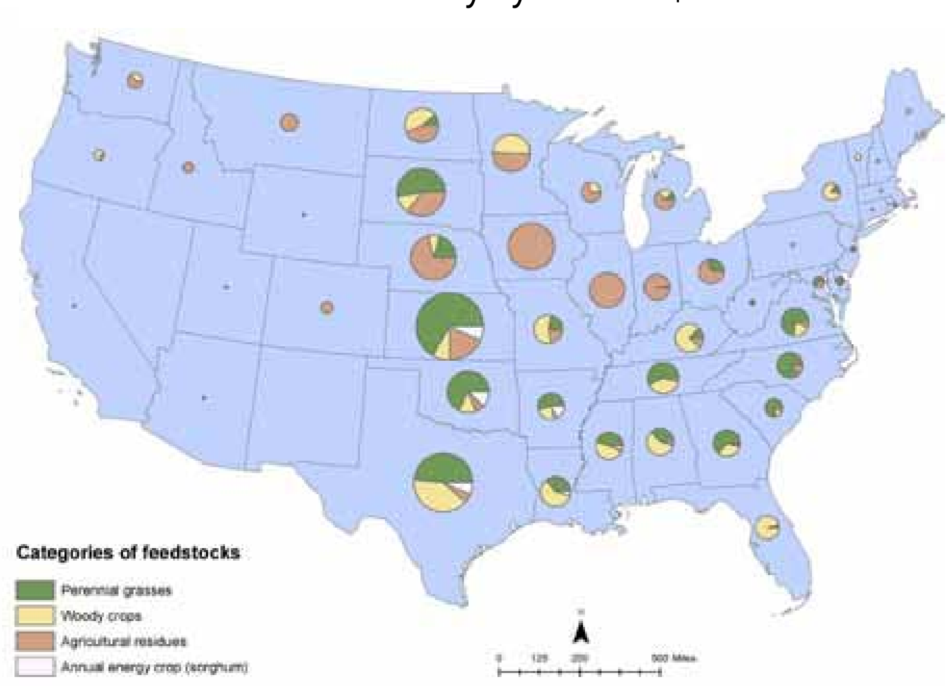


U.S. feedstock mix depends on region

NRCS Crop Management Zones



Feedstock Availability by State at $60/ton



Source: U.S. Department of Agriculture. Natural Resources Conservation Service.

Source: U.S. Department of Energy 2011. *U.S. Billion-Ton Update*: *Biomass Supply for a Bioenergy and Bioproducts Industry*.

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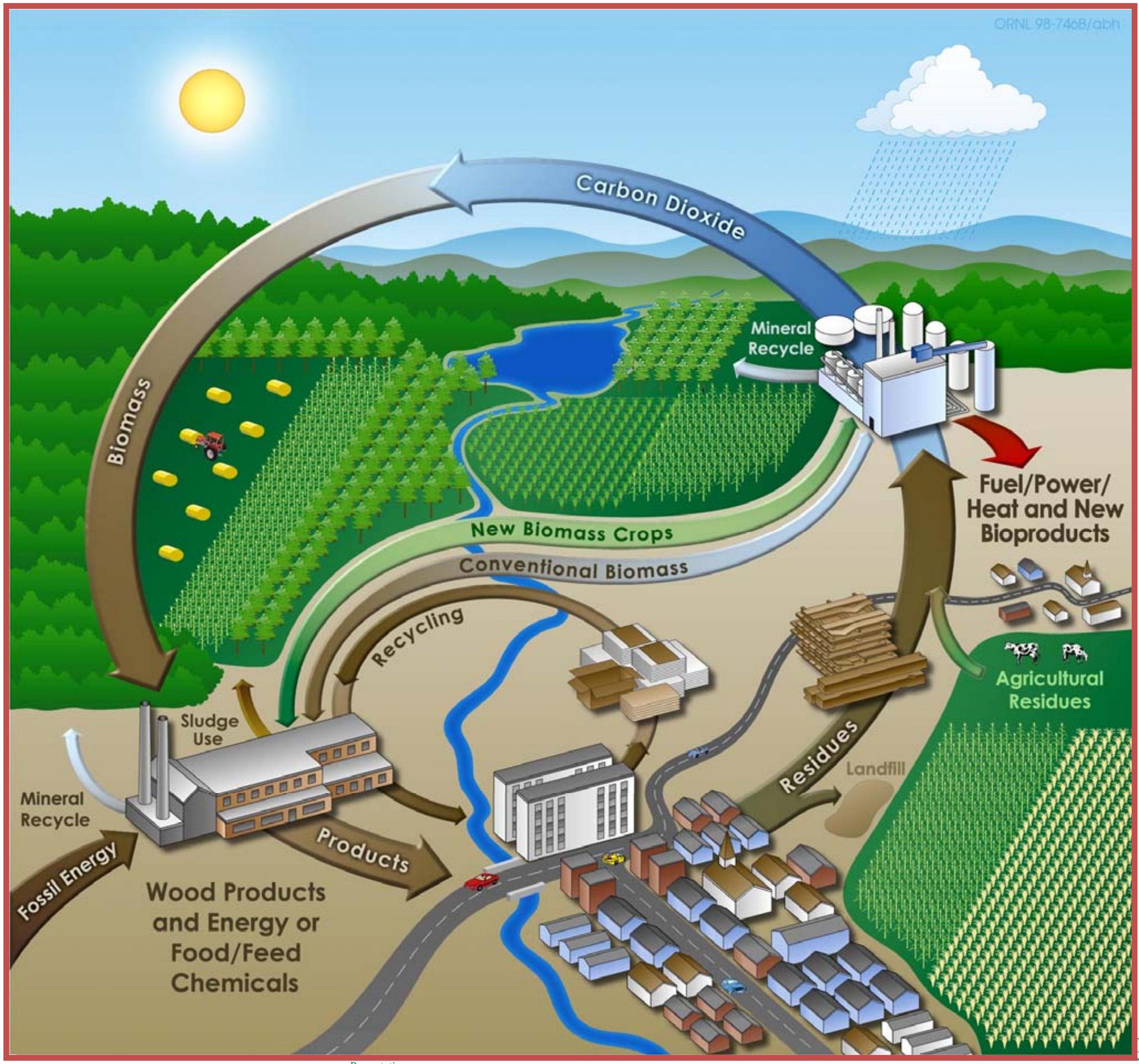
Can this system be sustainable?



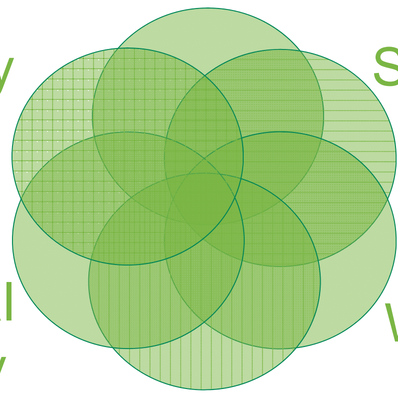
Indicators of bioenergy sustainability are being evaluated

Advance common definitions of environmental and socioeconomic costs and benefits of bioenergy systems

Greenhouse gas emissions

Productivity

Soil quality



Biological diversity

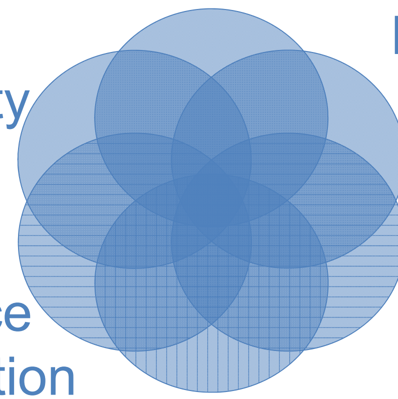
Water quality and quantity

Air quality

Social well being

Social acceptability

External trade



Resource conservation

Energy security

Profitability

Recognize that measures and interpretations are <u>context</u> specific

Also modifying/developing sustainability indicators for algal biofuels

Dale et al., *Ecological Indicators* (2013)

Identified Indicators of Environmental Sustainability

Category	Indicator	Units
Soil quality	1. Total organic carbon (TOC)	Mg/ha
	2. Total nitrogen (N)	Mg/ha
	3. Extractable phosphorus (P)	Mg/ha
	4. Bulk density	g/cm^3
Water quality and quantity	5. Nitrate concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	6. Total phosphorus (P) concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	7. Suspended sediment concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	8. Herbicide concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	9. storm flow	L/s
	10. Minimum base flow	L/s
	11. Consumptive water use (incorporates base flow)	feedstock production: m^3/ha/day; biorefinery: m^3/day

Category	Indicator	Units
Greenhouse gases	12. CO_2 equivalent emissions (CO_2 and N_2O)	kgC_{eq}/GJ
Biodiversity	13. Presence of taxa of special concern	Presence
	14. Habitat area of taxa of special concern	ha
Air quality	15. Tropospheric ozone	ppb
	16. Carbon monoxide	ppm
	17. Total particulate matter less than 2.5µm diameter ($PM_{2.5}$)	$\mu g/m^3$
	18. Total particulate matter less than 10µm diameter (PM_{10})	$\mu g/m^3$
Productivity	19. Aboveground net primary productivity (ANPP) / Yield	gC/m^2/year

McBride et al. Indicators to support environmental sustainability of bioenergy systems. *Ecological Indicators 11:*1277-1289 (2011)

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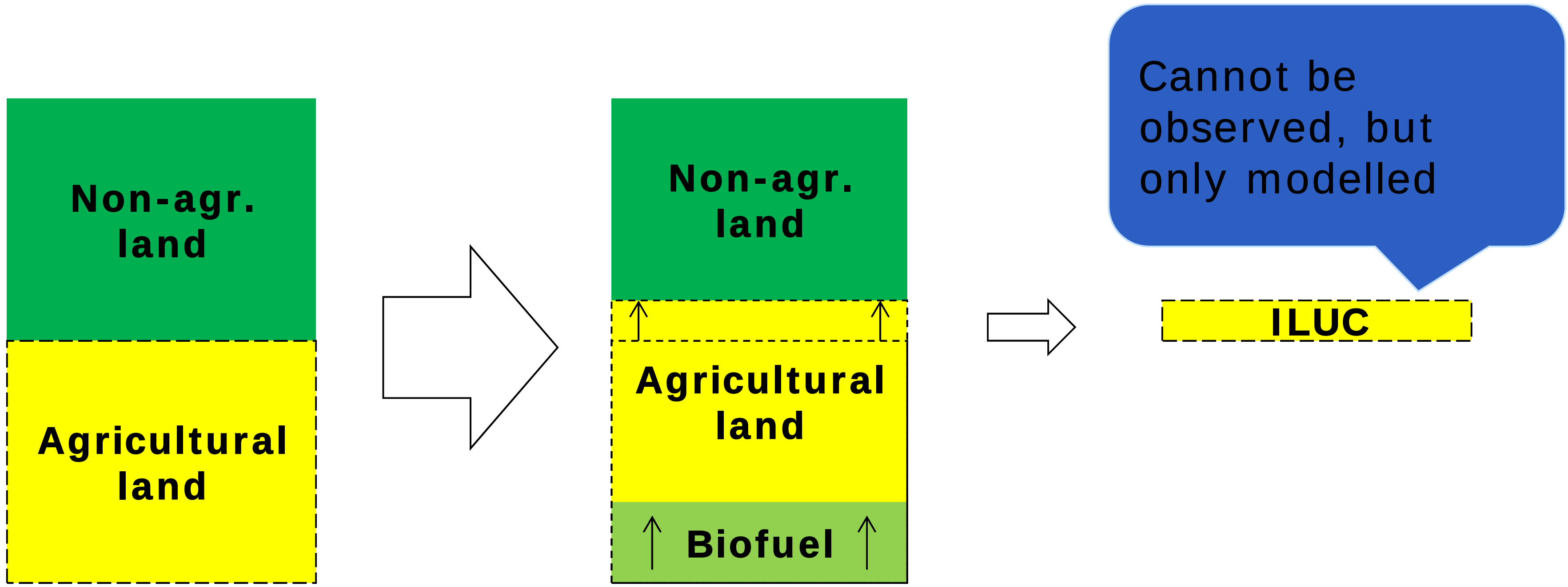
What is Indirect Land Use Change (ILUC)?



from presentation to European Commission, Dec. 2012, J. Batista cabinet Oettinger

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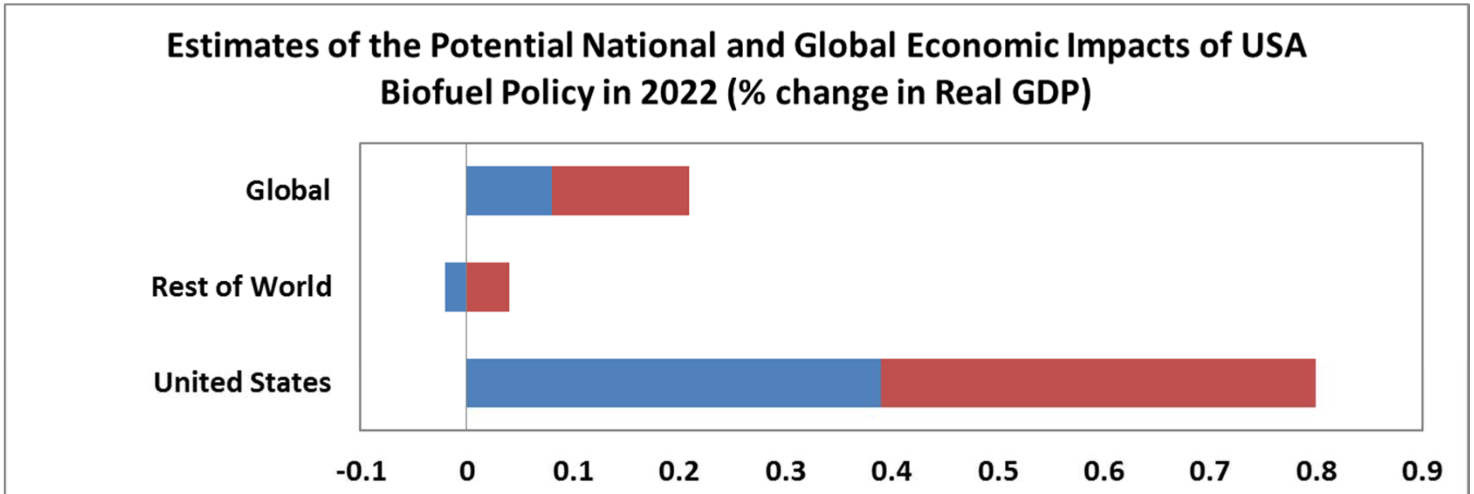
Evaluating the benefits of USA biofuels

- Questions:
  - What are the economic benefits from biofuel use in the USA so far?
  - What are the potential benefits of the advanced biofuel targets?



	United States	Rest of World	Global
Conventional Biofuels	0.39	-0.02	0.08
Advanced Biofuels	0.41	0.04	0.13

Change in Size of Regional Gross Domestic Product (%)

- Positive economic effects on US economy; largely neutral in rest of world
- Advanced biofuels have economic benefits comparable to conventional biofuels

G Oladosu or K.Kline, "A dynamic simulation of the ILUC efects of biofuels use in the USA", Energy Policy (2013)

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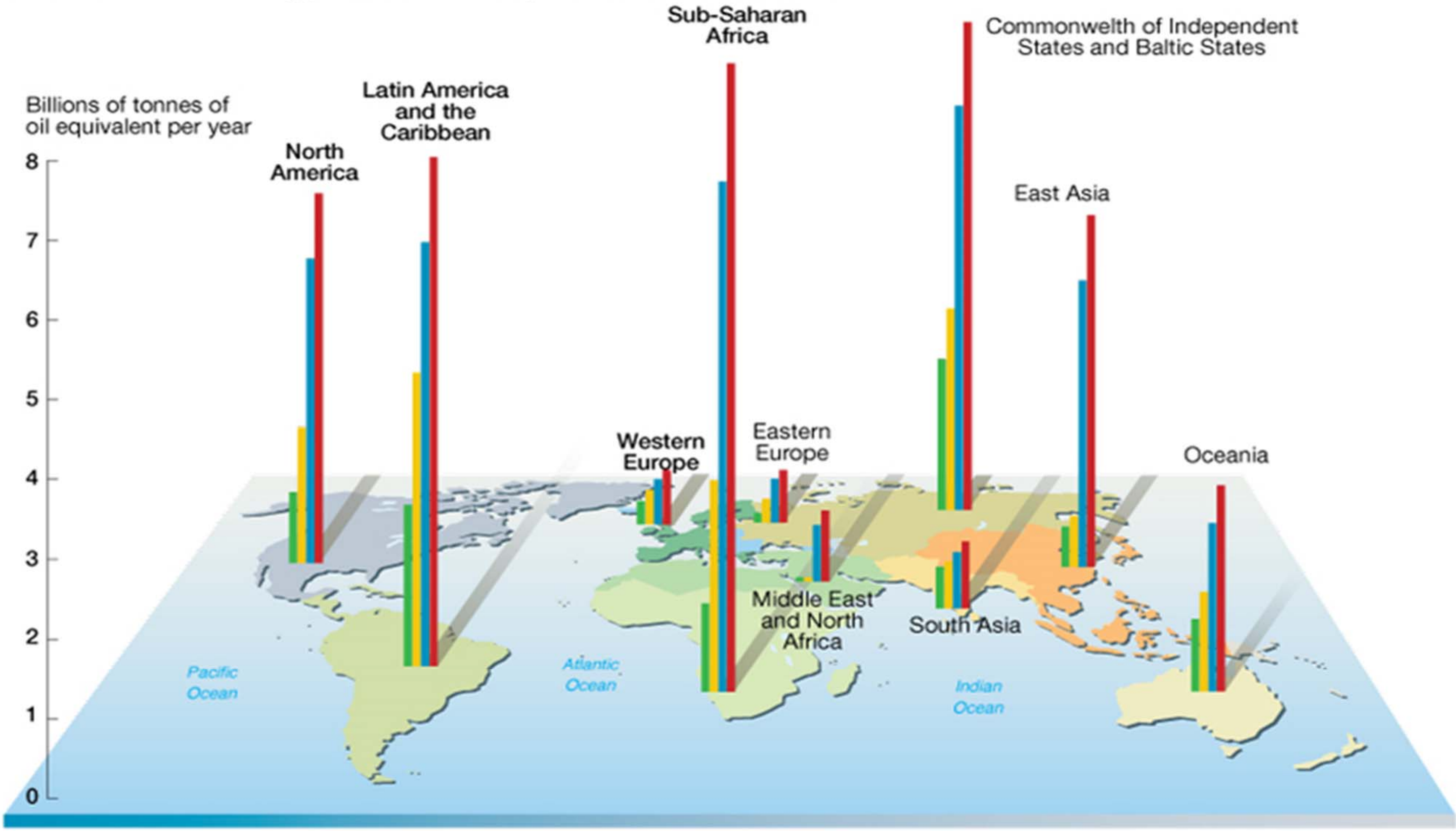
World bioenergy technical potential in 2050



Scenarios

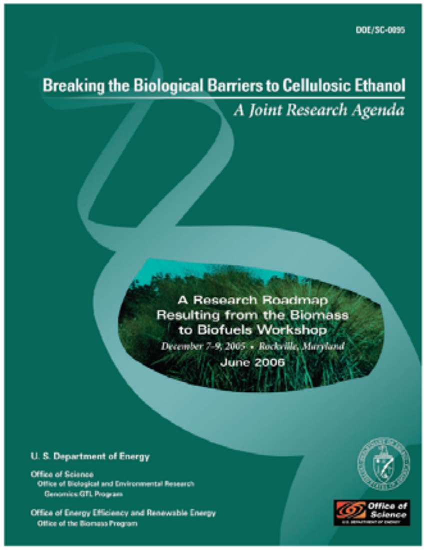
	Green	Yellow	Blue	Red
Animal production system	Mixed	High	Landless	Landless
Conversion efficency	High	Mixed	High	High
Level of technology	Very high	Very high	Very high	Extremely high
Water supply	Rainfed	Irrigation	Irrigation	Irrigation

Note: Commonwealth of Independent States includes Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine and Uzbekistan

Source: Smeets *et al.*, *Progress in Energy and Combustion, Science, 2007.*

Scientific bottlenecks as of 2006

- With a deeper understanding of:
  - The resistance of lignocellulosic biomass to deconstruction
  - The genetic controls of plant composition and ultrastructure
  - Bioenergy crop domestication and sustainability
  - The structure and function of cellulases and other plant cell wall depolymerizing enzymes
  - The microbial cell's mechanisms for toxicity response
- We could envision:
  - Dedicated bioenergy crops
  - Consolidated bioprocessing – cellulase production and ethanol fermentation combined
  - Beyond "ethanol" to advanced biofuels
  - Improved pretreatments



DOE Biomass to Biofuels Workshop (12/2005)
Roadmap (7/2006)

http://doegenomestolife.org/biofuels/b2bworkshop.shtml

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BioEnergy Science Center:
An Integrated Strategy to Understand Biomass Recalcitrance

www.bioenergycenter.org

BESC
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BioEnergy Science Center (BESC)

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A multi-institutional, DOE-funded center performing basic and applied science dedicated to understanding biomass recalcitrance and improving yields of biofuels from cellulosic biomass

300+ People in 17 Institutions

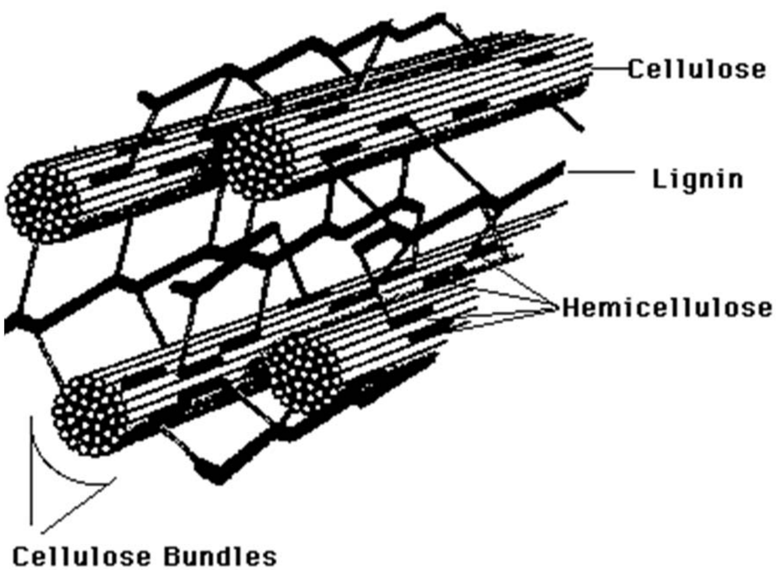
- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Samuel Roberts Noble Foundation
- ArborGen, LLD
- Ceres, Incorporated
- Mascoma Corporation
- DuPont
- GreenWood Resources

- University of Georgia
- University of Tennessee
- Cornell University
- Dartmouth College
- West Virginia University
- Georgia Institute of Technology
- University of California--Riverside
- North Carolina State University
- University of California—Los Angeles

www.bioenergycenter.org

BESC BioEnergy Science Center

The challenges: Lignocellulosic biomass is complex and heterogeneous



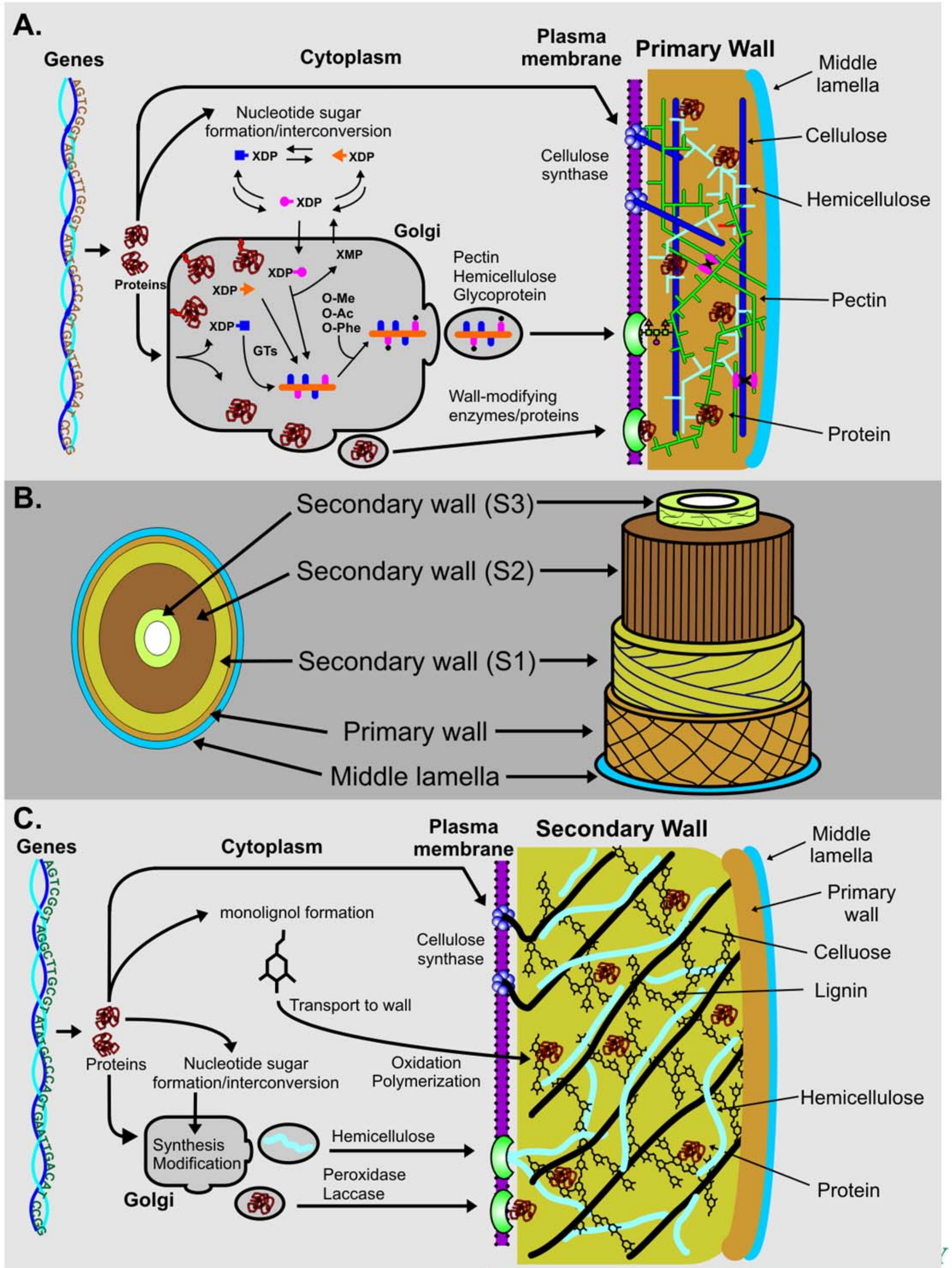


Fig. II.2. Biosynthesis of primary and secondary walls: from genes to polymers. A.

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Access to the sugars in lignocellulosic biomass is the current critical barrier for cellulosic biofuels

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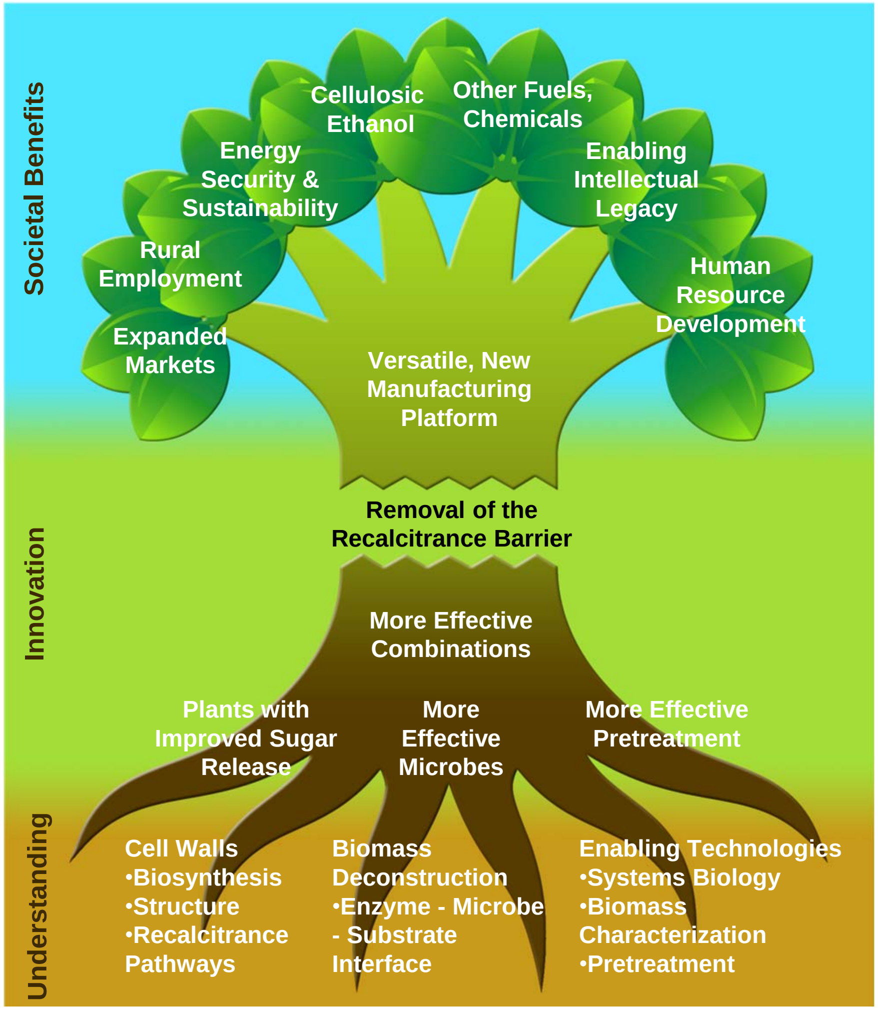
- Overcoming this recalcitrance barrier will cut processing costs significantly and be used in most conversion processes.
- This requires an integrated, multi-disciplinary approach.
- ***BESC believes biotechnology-intensive solutions offer greatest potential.***



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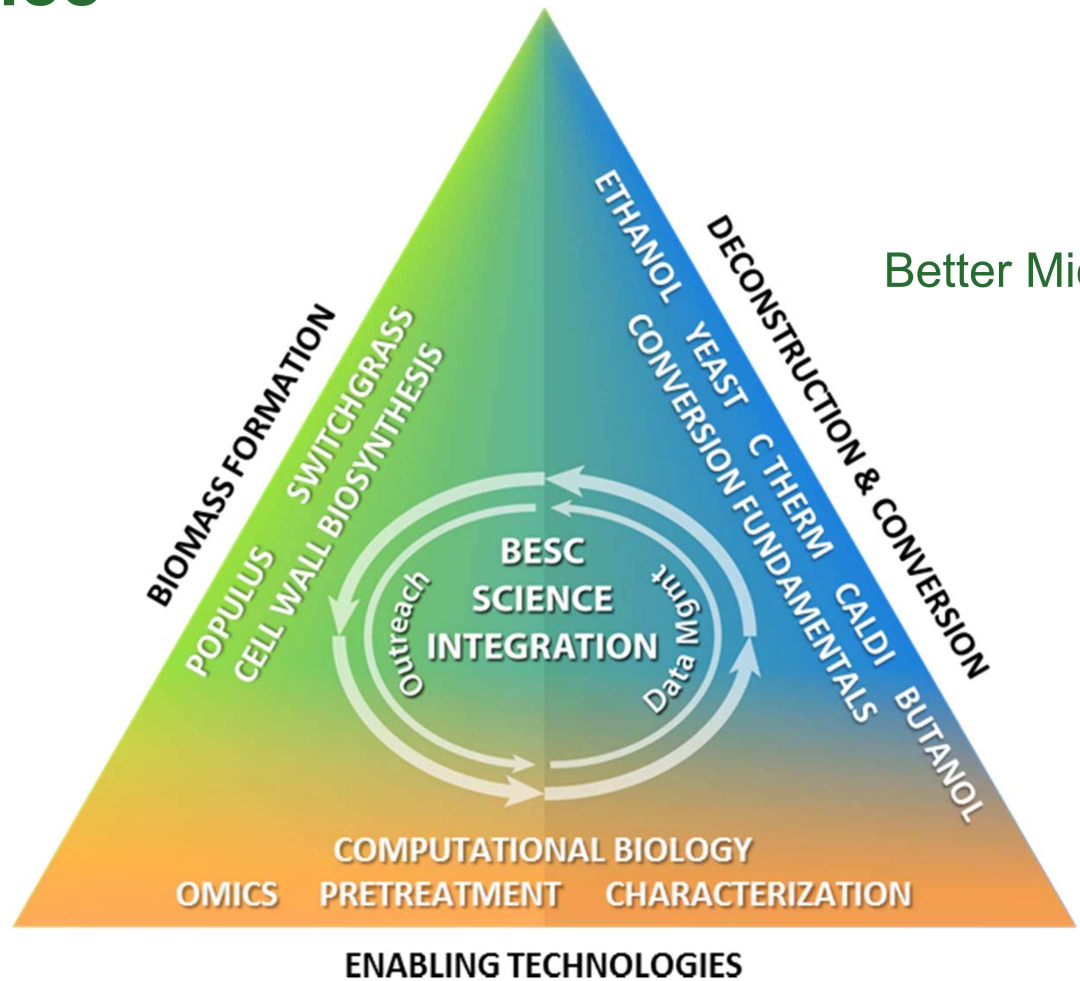
BESC is organized into three focus areas to understand biomass recalcitrance

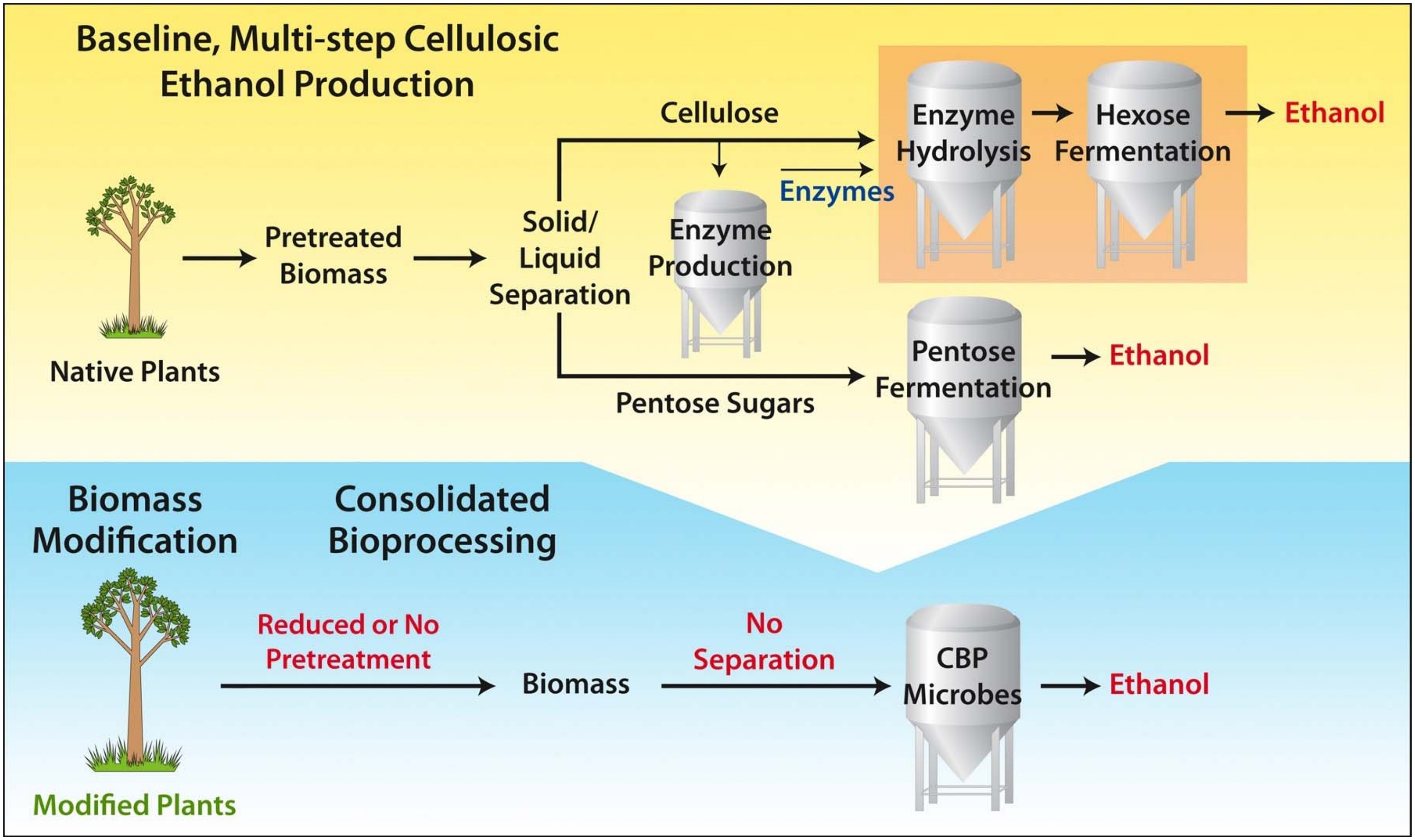
Better Plants

Better Microbes



Better Tools and Combinations

Biomass Fermentation Options: Reduction of Process Steps by Using CBP



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Feedstocks: then and now

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Where we started	Where we are today
Lignin and cellulose accessibility believed to be the primary roots of recalcitrance	The four major wall polymers (cellulose, lignin, hemicellulose and pectin) contribute to reduced biomass recalcitrance
Low transformation efficiencies for switchgrass	Developed and utilized high (90%) efficiencies for switchgrass
Range of natural variation and genetic control of recalcitrance within a species not established	Most comprehensive systems-biology study of *Populus* and switchgrass natural variance
Natural or transgenic reduced recalcitrance perennials not available	Field trials of BESC TOP lines reveal robust reduced recalcitrance phenotypes and agronomic performance

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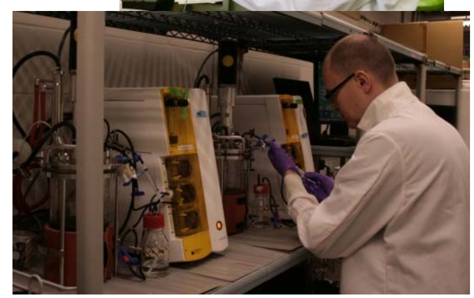
Microbial deconstruction: then and now

Where we started	Where we are today
Processes envisioned based on fungal cellulases	*C. thermocellum* demonstrably better than industry-standard fungal cellulase
Aggressive thermochemical pretreatment thought to be universally required	Data and analysis supporting the potential for processing with little or no thermochemical pretreatment
Functional genetic systems for cellulolytic anaerobes not described	Genetic tools developed for both *C. thermocellum* and *Caldicellulosiruptor*; systematized, higher throughput genetic system development can be envisioned
Recombinant microbes not used in the biofuel industry	Mascoma engineered yeasts used in ~20% of corn ethanol production, C5-utilizing strains available for cellulosic ethanol production



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Enabling technologies: then and now

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Where we started	Where we are today
Gold standard for biomass composition was NREL method requiring ~5 g per sample and over two weeks' effort	High-throughput pipeline for analysis of composition and sugar release for thousands of samples per year
Limited selection of cost-effective, efficient pretreatment strategies	Options for reduced severity to new efficient protocols (CELF)
Limited polysaccharide epitope antibodies were just beginning to be used for imaging	Glycome profiling now medium throughput and validated for analyses of cell wall structure and automated
Very large biological datasets were genomic and primarily used in medical screening fields, not in bioenergy	Metabolomics analysis coupled with genetic information to identify metabolite-gene associations

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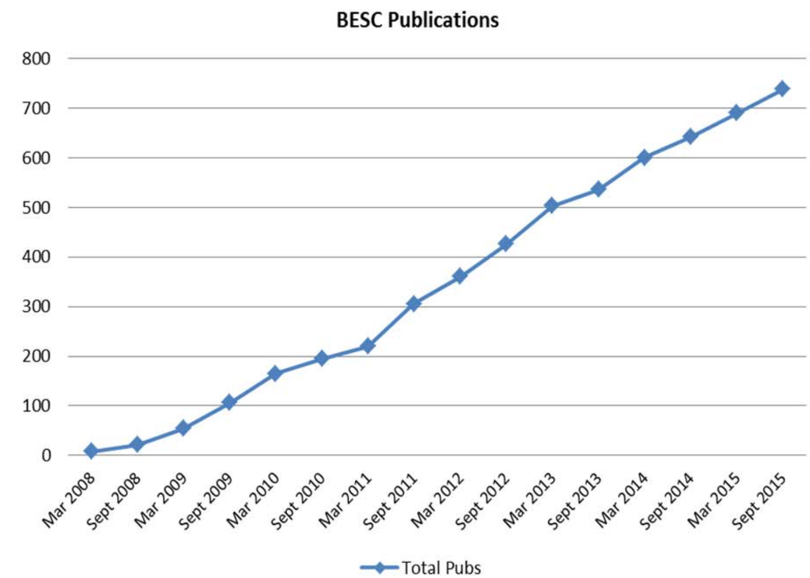
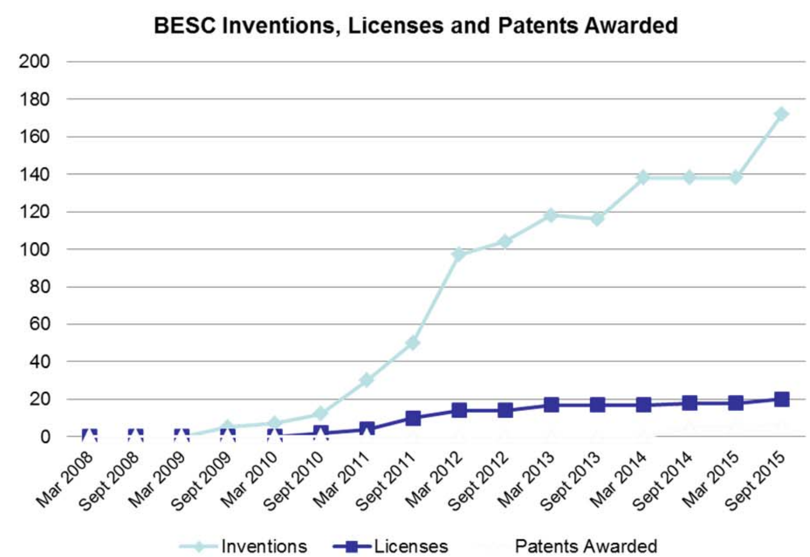
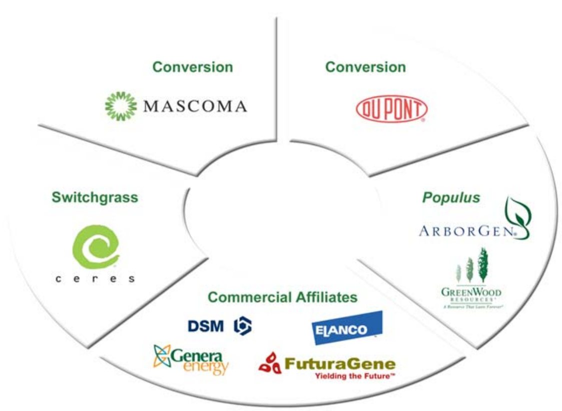
BESC key metrics (as of September 2015)

- 748 publications through Year 8
  - 104 in Year 8
  - 10% in high-impact journals (>9.5)
  - 13,204 citations
- 172 invention disclosures
- 58 patent applications
  - 6 patents awarded
- 20 licenses/options
- 224 alumni







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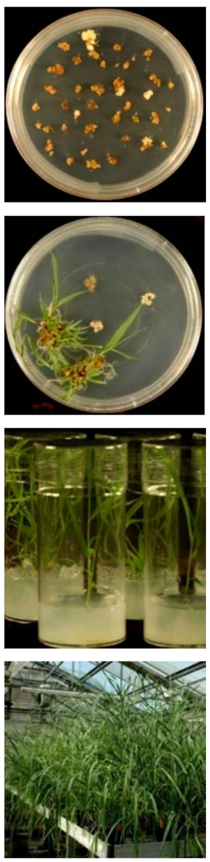
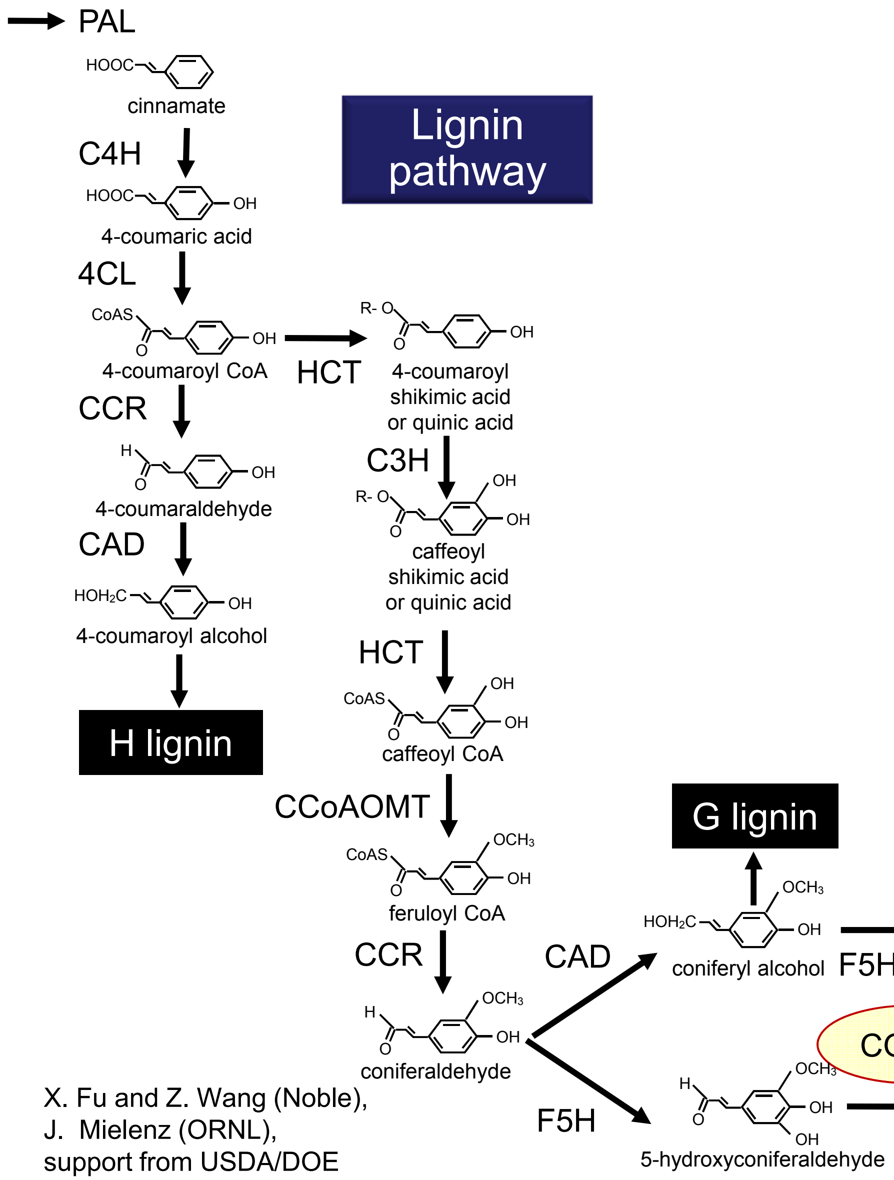
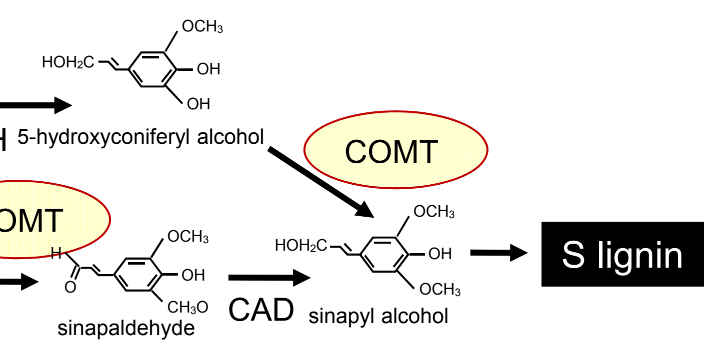
Genetic Block in Lignin Biosynthesis in Switchgrass Increases Ethanol Yields

Agrobacterium-mediated transformation of switchgrass







X. Fu and Z. Wang (Noble), J. Mielenz (ORNL), support from USDA/DOE

Wild-type (L) and 3 transgenic switchgrass plants (R)

THE SAMUEL ROBERTS NOBLE FOUNDATION

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Top performing transgenic greenhouse plants must be evaluated in the field

- Greenhouse plants have minimal stresses
- The stresses in a field may result in plants responding differently
- First year field-grown data is qualitatively consistent and second-year field grown data is better

Baxter, *et al.*, "Two-year field analysis of reduced recalcitrance transgenic switchgrass," *Plant Biotech J, 2014.*

Comparison of Fermentation of Transgenic and Control SWG by Three CBP Bacteria

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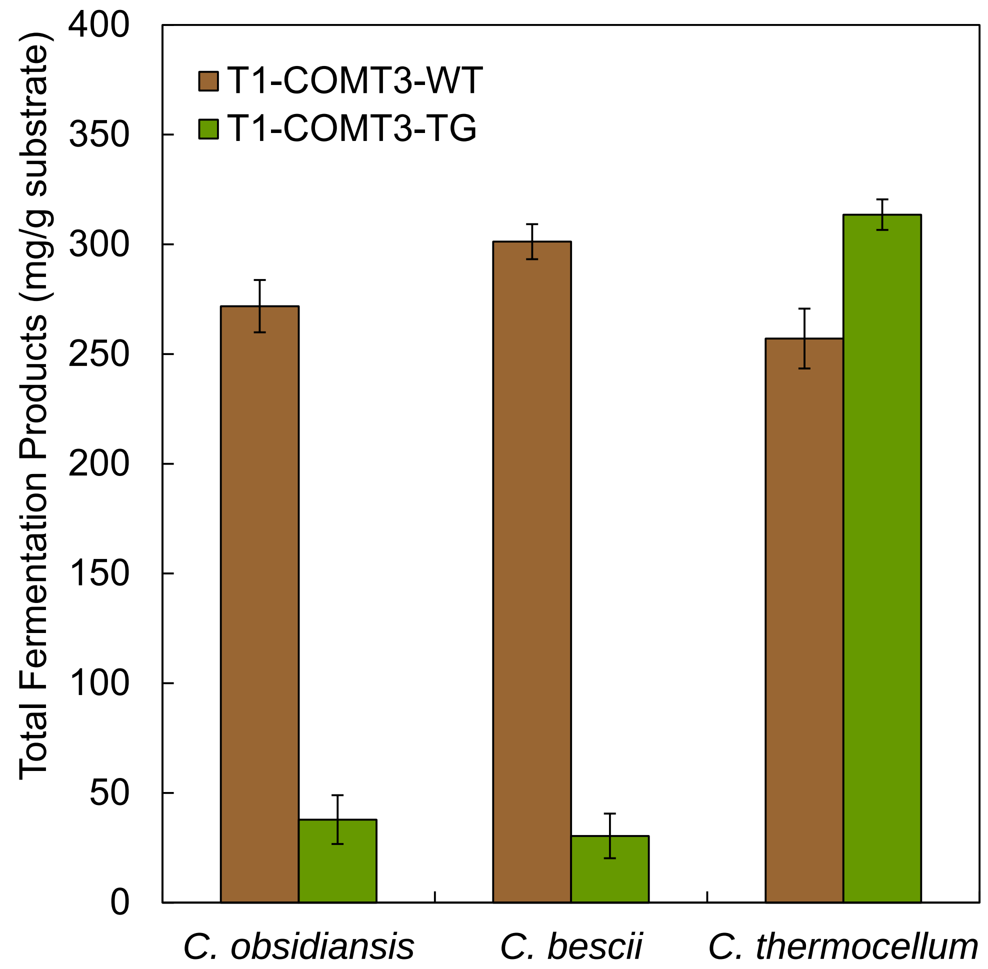
- Fermentation Conditions:
  - *C. obsidiansis* and *C. bescii*
    - 75° C and 125 rpm
  - *C. thermocellum*
    - 58° C and 125 rpm
  - Uniform Media

- Fermentation of identical batches of Control (CTRL) and transgenic (TG) COMT3 switchgrass with *C. obsidiansis*, *C. bescii*, and *C. thermocellum* shows a differential of inhibition between the three CBP microorganisms



Total Fermentation Products
(Acetate+Lactate+Ethanol)

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Yee et al., 2015, submitted

Cellulosome Changes in *C. thermocellum* on Different Biomass Substrates

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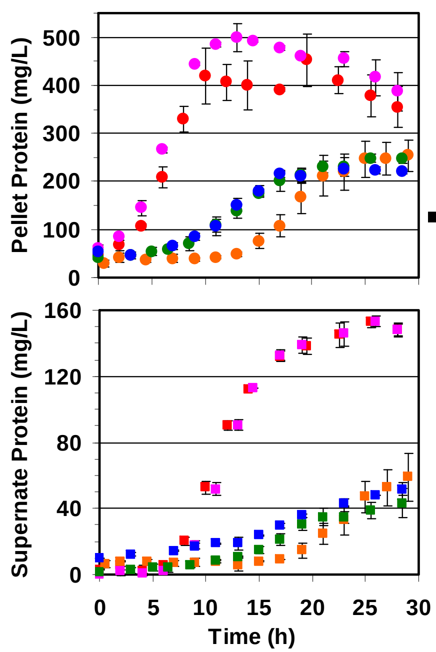
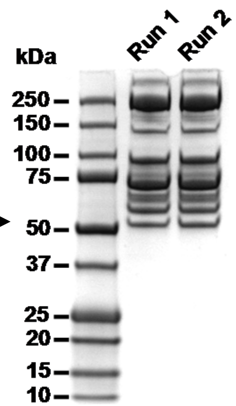
Fermentation



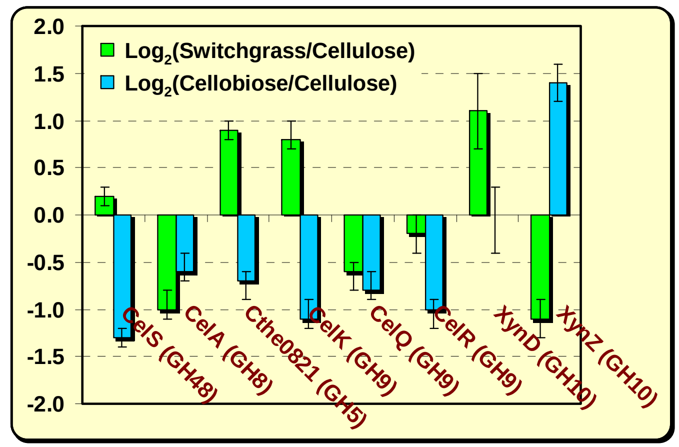
- Pretreated Switchgrass
- Cellobiose
- Amorphous Cellulose
- Avicel - ^{14}N
- Avicel - ^{15}N
- Avicel-Pectin
- Avicel-Xylan
- Avicel-Pectin-Xylan

Affinity Purification



Shot-gun LC-MS/MS Identification

Metabolic Labeling Quantitation



- ***C. thermocellum*** **alters its cellulosome catalytic composition depending upon the growth substrate**
- **We identified and experimentally verified 16 “new” cellulosome components**
- **Insights aid in constructing designer cellulosomes with tailored enzyme composition for industrial ethanol production**

Citation: “Raman B, *et al*. (2009) Impact of Pretreated Switchgrass and Biomass Carbohydrates on *Clostridium thermocellum* ATCC 27405 Cellulosome Composition: A Quantitative Proteomic Analysis. PLoS ONE 4(4): e5271. doi:10.1371/journal.pone.0005271”

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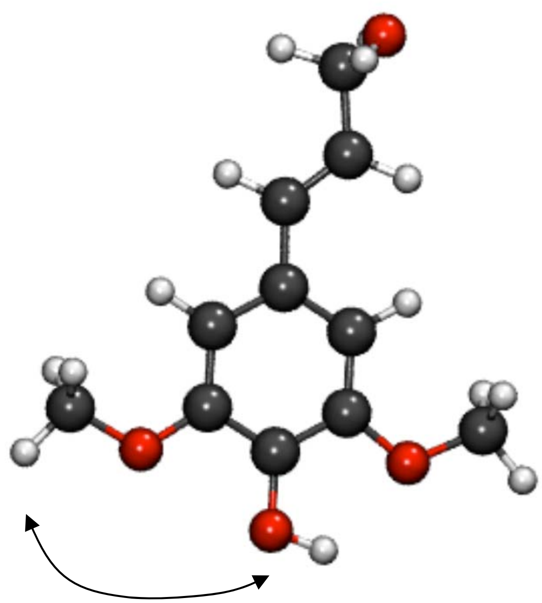
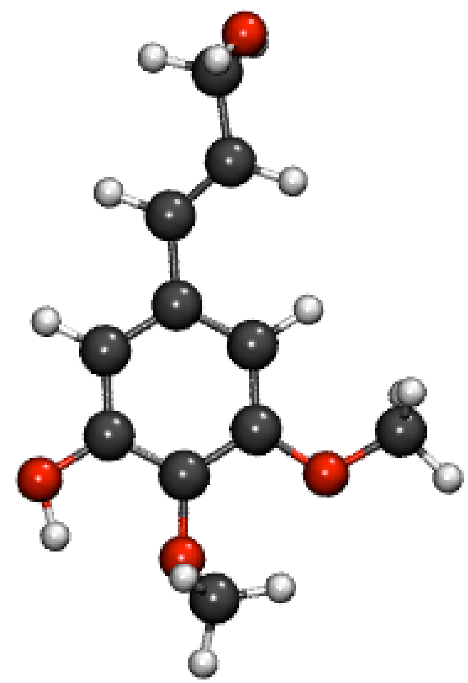
New Lignol Molecule Found in COMT TG SWG Extracts

- GC-MS detected numerous compounds including a newly identified isosinapyl alcohol, preferentially in the COMT TG lines
- Identity confirmed by chemical synthesis and analysis
- Isosinapyl alcohol was determined to have mild inhibitory properties toward yeast and *E. coli*.



Sinapyl alcohol



Isosinapyl alcohol

Tschaplinski et al., 2012

Combining modified switchgrass with engineered *C. thermocellum* improves yield

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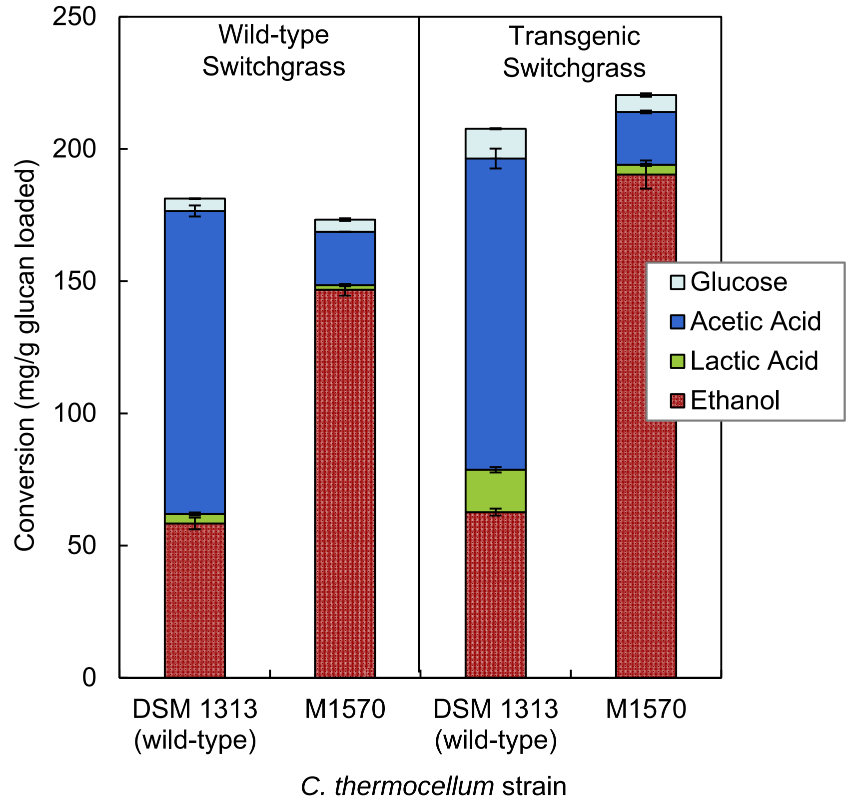
Significance

- First report of use of a microbe engineered to produce increased amounts of a biofuel on a bioenergy feedstock modified for the same purpose. Results demonstrate the potential additive advantages from combining a modified feedstock with an engineered consolidated bioprocessing microorganism.

Outcome

- Fermentation of the modified COMT switchgrass by *C. thermocellum* mutant M1570 had superior conversion relative to the wild-type control switchgrass line with an increase in conversion of approximately 20%.
- Ethanol was the primary product, accounting for 90% of the total metabolites with conversion of 0.19 g ethanol/g glucan loaded and 0.27 g liberated.



Conversion (mg/g glucan loaded) for *C. thermocellum* mutant M1570 and wild-type DSM 1313 strains on both transgenic (T1-3-TG) and wild-type (T1-3-WT) switchgrass, which were pretreated with dilute acid. The standard deviation is from the average of triplicate buffered serum bottle fermentations.

Yee *et al.*, *Biotechnology for Biofuels* 7:75, 2014.

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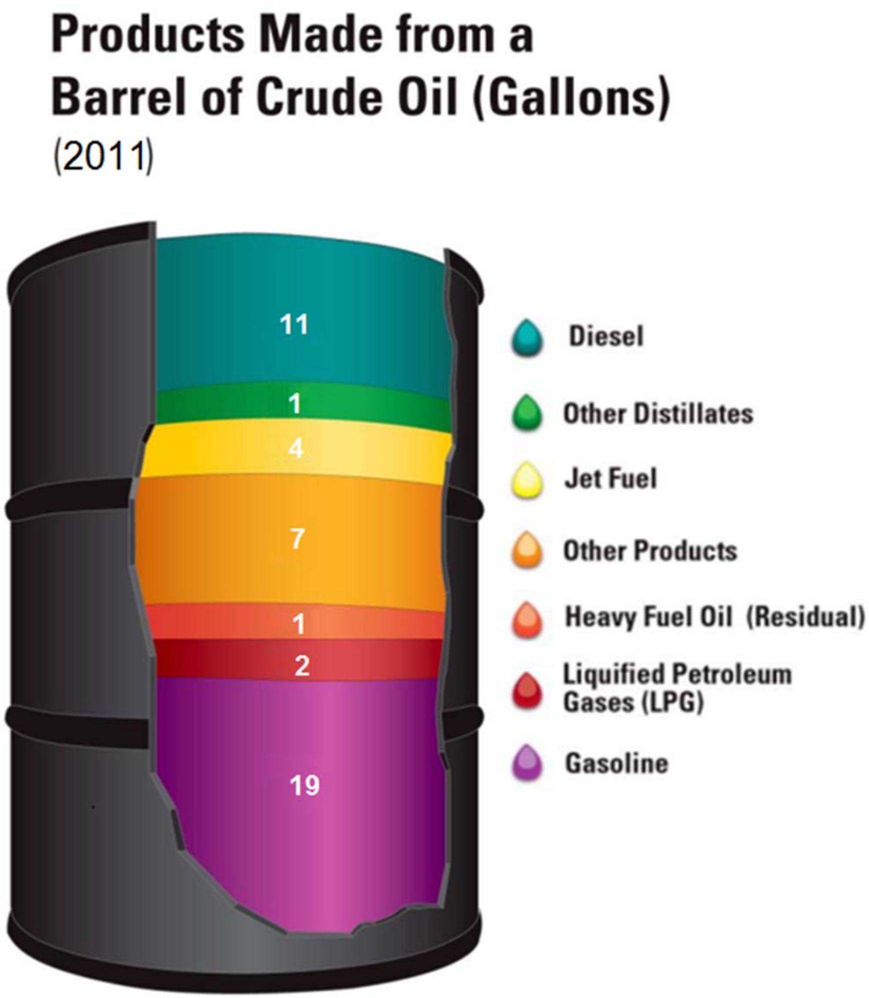
Replacing the Whole Barrel



- Cellulosic ethanol only displaces gasoline fraction of a barrel of oil (about 40%)
- Reducing dependence on oil requires replacing diesel, jet, heavy distillates, and a range of other chemicals and products
- Greater focus needed on RDD&D for a range of technologies to produce hydrocarbon fuels and displace the entire barrel of petroleum

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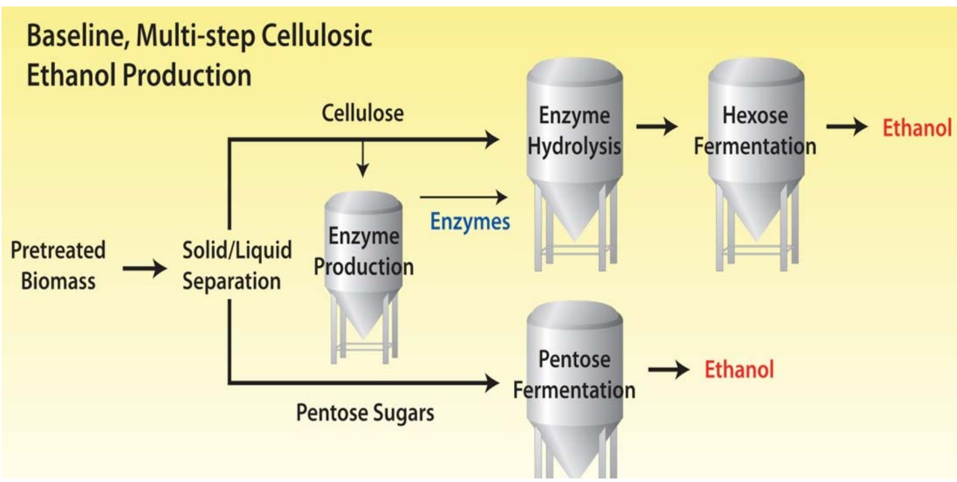
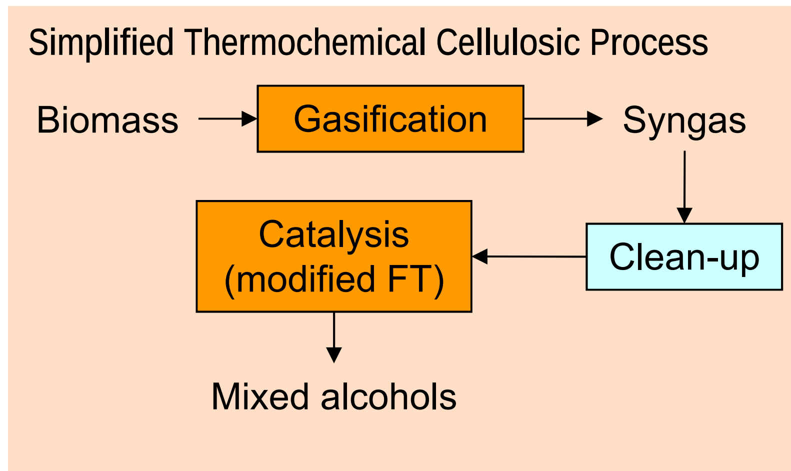
Cellulosic Conversion Improvement Strategies

- State of art versus theory
  - Biological has lower theoretical yield (~100 gal/ton) but higher achieved yields (70-85 gal/ton) and potential co-products
  - Thermochemical has highest theoretical yield (~120+ gal/ton) but much lower achieved yield (50-65 gal/ton) and less desirable coproducts (i.e., methanol)





Technology - A general platform for converting fermentation streams to hydrocarbon blend-stock

“Beyond the Ethanol Blend-wall”

“Uses existing infra-structure for distribution”

Fermentation stream or distilled alcohol → Catalyst → Blend-stock +Water + VOC → Fractional Collection

Jet Fuel

Diesel

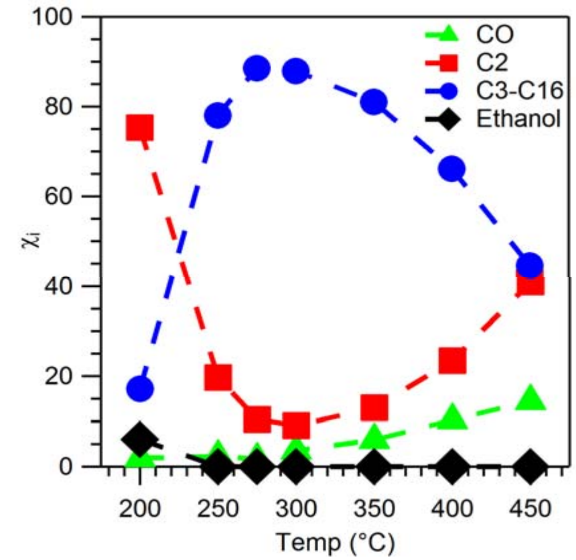
JP-8

Gasoline

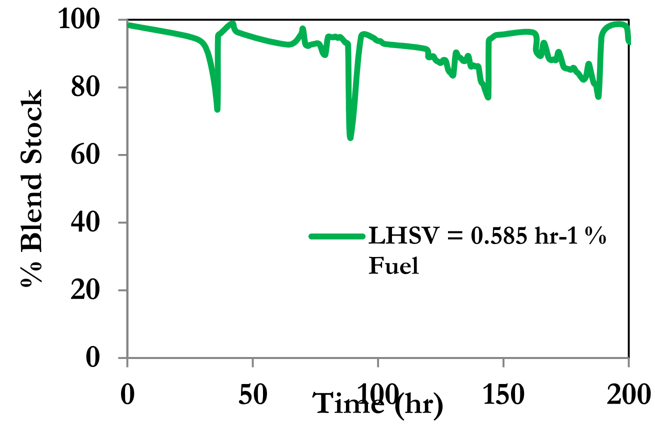
Bio-mass derived fuel are highly desirable because they are from renewable source, reduce foreign oil dependence, and allow compliance with regulatory requirements

Catalytic ethanol upgrading into hydrocarbon blendstocks

- Licensed to Vertimass, LLC in March 2014
- Catalytic conversion of ethanol to C_3 to C_{15} blend-stock
  - Stoichiometric conversion (100%) to HC and water
  - 350°C and atmospheric pressure
  - No added hydrogen
  - Durable catalyst (tested for >200h)
  - Water concentration had no significant impact of ethanol conversion process so direct ethanol fermentation streams could be employed
  - Actual fermentation streams and distillates converted to hydrocarbon blend-stock
  - Engine experiments at ORNL show combustion similar to gasoline
  - Energy balance is slightly exothermic from estimate using Hc of blend-stock
- Heterobimetallic catalyst more versatile than monometallic one
- Comparable estimated costs



Constant LHSV of 2.93 h^{-1}



Sample Catalyst Regeneration

http://bioenergycenter.org/besc/industry/technology.cfm?ID=11

Is a "Renewable Super Premium"* a better path for ethanol?

- Engine efficiency can improve with increasing ethanol (in properly designed future engines/vehicles)
  - Chemical octane number + latent heat of vaporization permit higher compression ratio, optimized combustion phasing, increased power (downspeeding/downsizing)
- Likely that optimum blend is ~E20-E40
  - Energy density penalty is *linear* with ethanol concentration, power and efficiency gains are *non-linear*
  - Tradeoff in efficiency, cost, and fuel economy
  - Ideal blend in optimized vehicles could improve fuel economy while using more ethanol
  - Also legal to use in ~16M legacy FFVs

* "*Renewable Super Premium*," "New regular," "High Octane Base Fuel…" Regardless of name, high octane blends have significant potential

Improving lignin processing in the biorefinery

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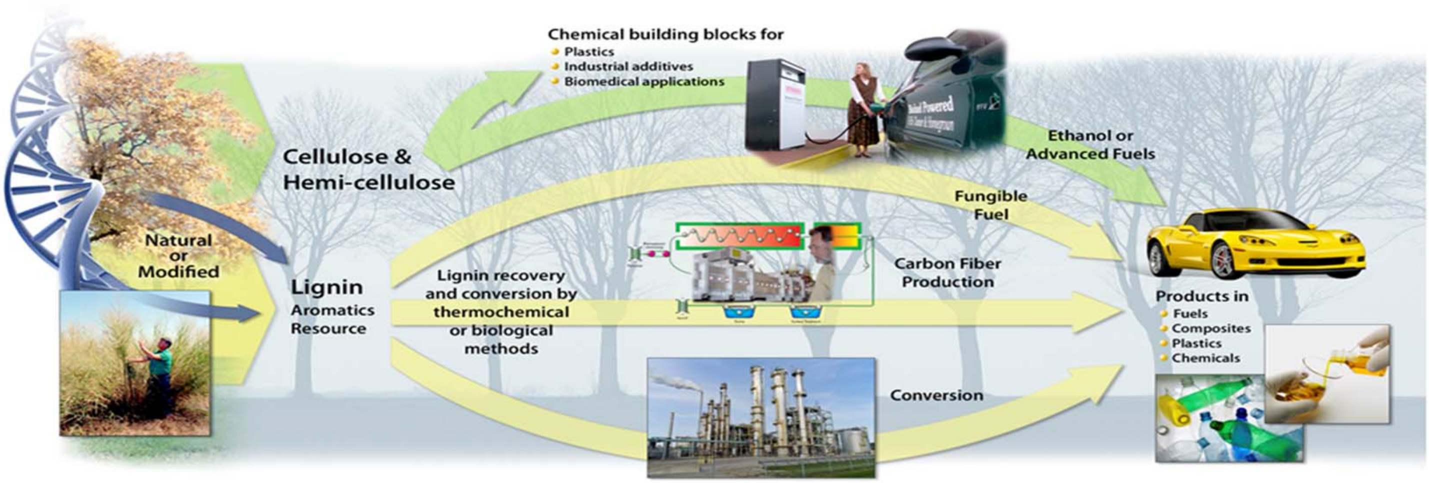
- Lignin is a major component of terrestrial lignocellulosic biomass.
- The effective utilization of lignin is critical for the accelerated deployment of the advanced cellulosic biorefinery.
- Lignin is a viable, commercially relevant sustainable feedstock for a new range of materials and uses.
- Discovery of genetic variants in native populations of bioenergy crops and direct manipulation of biosynthesis pathways have produced lignin feedstocks with improved for recovery and conversion.
  - Advances in analytical chemistry and computational modeling detail the structure of the modified lignin and direct bioengineering strategies for future targeted properties.
- Refinement of biomass pretreatment technologies has further facilitated lignin recovery
- These will enable new uses for this biopolymer, including low-cost carbon fibers, engineered plastics and thermoplastic elastomers, polymeric foams, fungible fuels, and commodity chemicals.
- Future research
  - to what extent the lignin structure in plants can be altered to yield a product that can be readily recovered via pretreatment, and
  - has the appropriate tailored structures to be valorized for materials, chemicals and fuels.



Ragauskas, *et al.*, *Science* 344(6185), *2014.*

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Biotechnology can lead to new feedstocks and new processes with new challenges

- New Biofeedstocks
  - Accelerated breeding will provide crops with improved fuel conversion and growth but have a 5-10 y deployment
    - Better nutrient and stress tolerance
  - GMO terrestrial crops (add 5 y for permitting)
  - "In planta" co-products can be important – but the bulk matter will still be lignocellulose
- New Bioproducts
  - Advanced biotechnology can make many new co-products
    - Fuels – hydrocarbons or oils (beyond the "blendwall")
    - Higher value but commodity (e.g., succinic, propanediol, PHA)
    - Current plans mostly use sugars not cellulosics
  - Challenge for higher value products is matching scale and cost with fuels
    - What happens when a competitor opens a similar biorefinery?
    - Use of lignin

Advanced biotechnology game-changers to be monitored

- Parallel improvement of yield and convertibility in biofeedstocks and residues
- Robust easily convertible lignocellulosic feedstocks and residues with minimal pretreatment
- Rational agronomic improvements of feedstocks for yield and sustainability (such as low nitrogen and water use and increase soil organic carbon fixation).
- Ability to control the rhizosphere (the soil microbial communities) to improve biofeedstock traits
- Economic stable bioconversions able to handle biofeedstock variability
- New tools to rapidly and rationally genetically engineer new microbial isolates with unique complex capabilities (such as for new enzymes, fuels, or products or for harsh conditions such as pH or temperature)
- Rational reproducible control of carbon and energy flux in microbes (such as decoupling growth from metabolism)
- Ability and understanding to reproducibly overcome fermentation product inhibition by cellular redesign while maintaining yield and rate.
- Stable high rate microalga lipid production in open systems
- Expanded compatible biotechnology processes to co-products while producing fuels-such as from lignin.

Davison et al., 2015. "The impact of biotechnological advances on the future of U.S. bioenergy," *Biofuels, Bioprod. Biorefin.* 9:454 (2015).

Science and Technology are critical but policy is also important

- Active policy debates on
  - Sustainability
    - Life cycle assessments - LCA (carbon, water and energy balances)
    - Land-use change (LUC) and indirect land-use change (ILUC)
  - Food vs. fuels
  - The "Blend Wall"
    - How much ethanol can go into gasoline in typical engines?
    - Market is almost saturated with E10 in U.S.
  - Fungible or "drop-in" fuels
- Externalities on
  - Capital and financing
    - Estimate EISA goal will require 100-300 biorefineries of 50-100M gal/y in US
  - Feedstock deployment and agriculture incentives

Challenges

- U.S. - The growing schism between climate and energy security communities will delay deployment
  - U.S. may lose current technology and feedstock edge
  - Unstable policy and unstable markets make ROI risky
- Resource availability is uneven across world
- GMO as feedstocks and in conversion
- Water use and technologies are underappreciated
- Which advanced biofuel? To which end-use?
  - There are no clear renewable alternatives to biofuels for diesel or jet markets
  - Lignin potentials
- There are positive challenges
  - Bioresources done right could help stabilize rural development
    - in U.S. and
    - In developing countries (e.g., sub-Saharan Africa)

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Bioenergy scientists need to respond to our publics

- Arm yourself with knowledgeable talking points; example
- *Nature Climate Change* April 2014 Liska et al.
  - "Biofuels from crop residues can reduce oil carbon and increase CO2 emissions"
  - Washington Post: **"Biofuels worse than gasoline"**

- Assumes:
  - 75% of stover removed
  - Ignore use of lignin for fuels
  - Not based or compared to best current models that account for management and are in RFS

- Consensus
  - most farmers and studies only remove <25%
  - Current and future cellulosic biorefineries use lignin for heat and power
  - EPIC, GREET

Community outreach in bioenergy science education is becoming self-sustaining

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Farming for Fuels lessons reach thousands of students through hands-on science activities

- BESC in collaboration with the Creative Discovery Museum (CDM) in Chattanooga, Tennessee, developed hands-on lesson plans for students in 4^{th}, 5^{th} and 6^{th} grades.
- *Farming for Fuel* lessons educate students about the carbon cycle, lignocellulosic biomass as substrate for the production of biofuels and the technical and economic obstacles to a bio-based fuel economy.

Science Night events reach thousands of families

- In the last 2 years, >100 Science Nights were presented nation-wide reaching more than 25,000 students, parents and teachers.

"Hub and Spoke" model allows economical outreach national outreach using partnering with regional science centers and museums. Over six years, the outreach program has steadily expanded from Chattanooga across Tennessee to currently active hubs in Georgia, Texas, Michigan, Illinois, Florida, Oklahoma, Idaho, Montana, Washington, Oregon and Utah.

- ➢ A marker of self-sustaining success is that now 75% of the support for the hands-on activities now come from the schools, hubs, and other sources.
- ➢ This approach has allowed BESC to steadily increase hands-on science contacts to over 25,000 in the last year and over 145,000 students, parents, and teachers in the past six years.

CREATIVE DISCOVERY MUSEUM

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Biofuels:

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ORNL: Tim Theiss, Virginia Dale, Keith Kline, Chaitanya Narula,

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