Biomass for Bioenergy: an overview of research at ORNL

December 1, 2014
Utrecht University, The Netherlands

Keith L. Kline (presenter)
Virginia Dale, Laurence Eaton, Matt Langholtz, and others, ORNL

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http://www.ornl.gov/sci/ees/cbes/

U.S. DEPARTMENT OF ENERGY

Climate Change Science Institute AT OAK RIDGE NATIONAL LABORATORY

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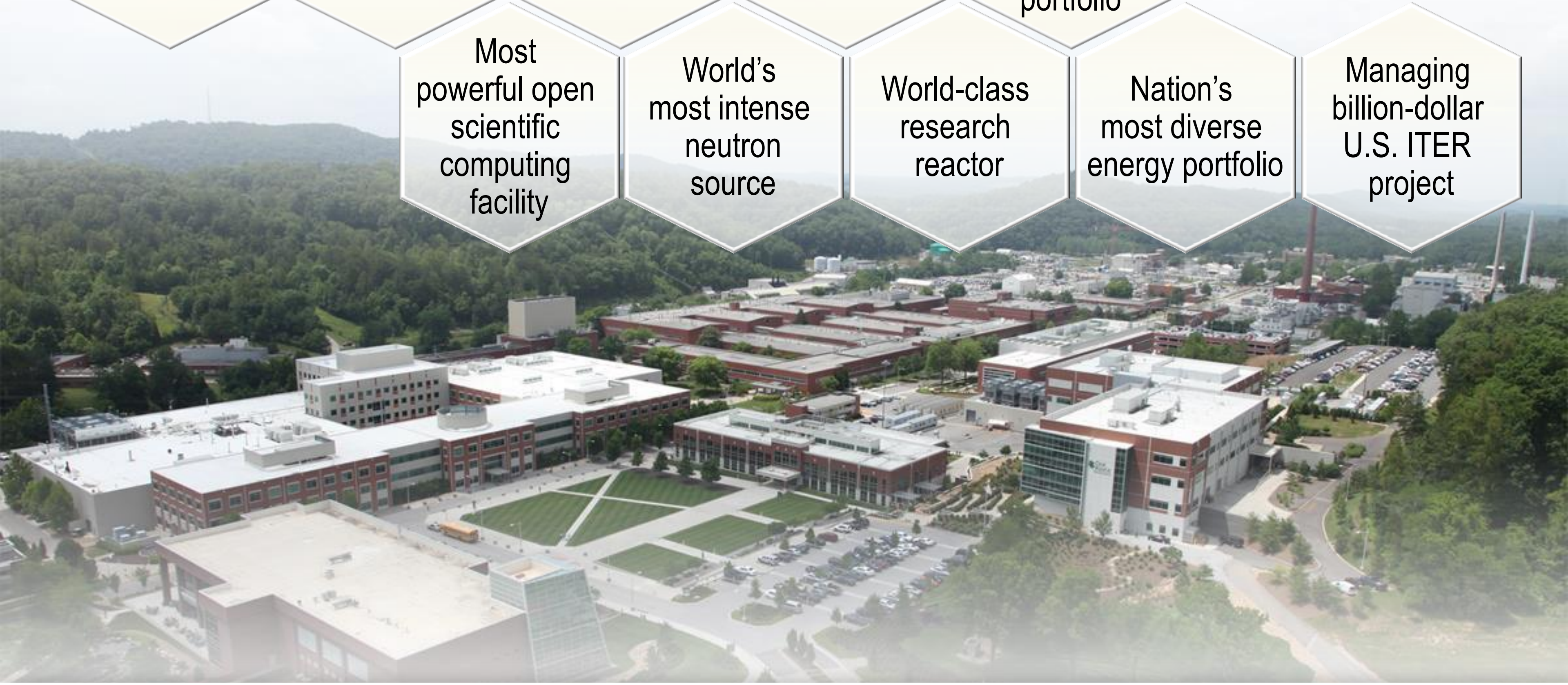
Biomass for bioenergy – Outline

- ORNL and DOE programs
- Feedstock supply analysis
- Sustainability
- Landscape design
- Discussion
- Extra slides: of blend walls and strategies to overcome market barriers

Photo: Ken Goddard, UT Extension

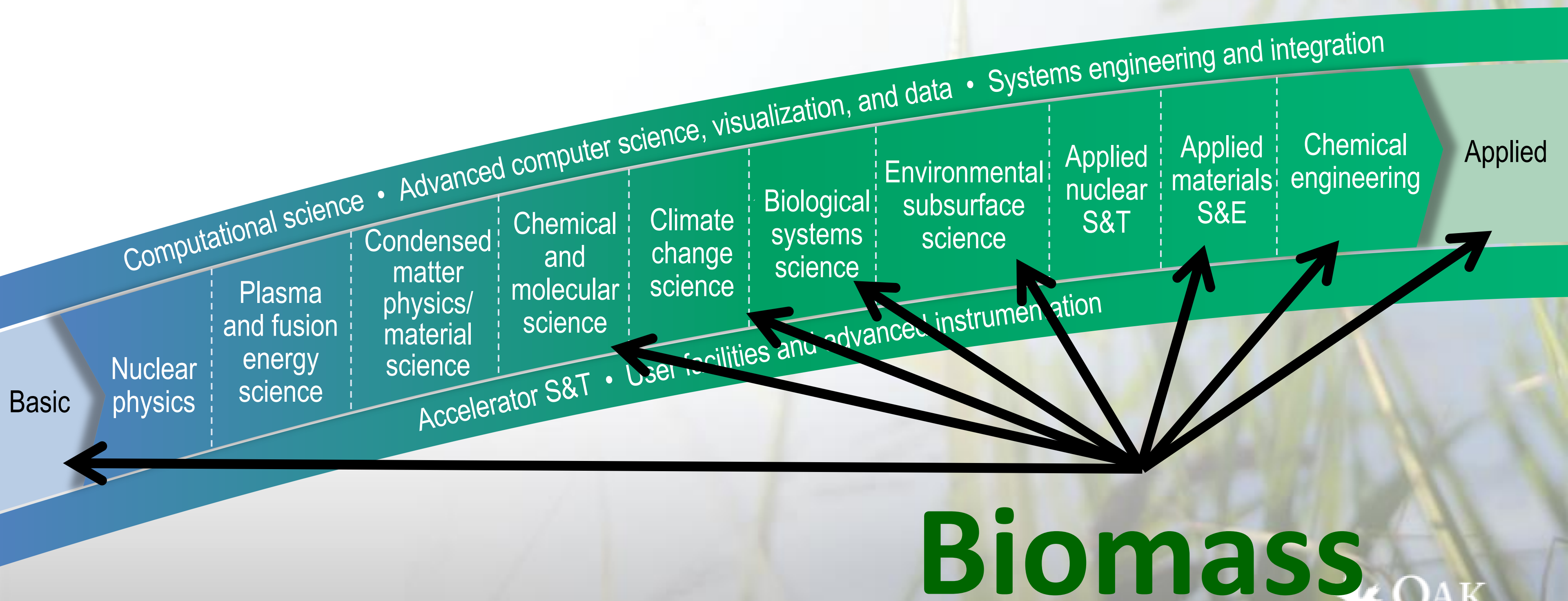
What is Oak Ridge National Laboratory (ORNL)? U.S. Department of Energy’s Largest Science and Energy Research Center:

- $1.65B budget
- 4,400 employees
- 3,000 research guests annually
- $500M modernization investment
- Nation’s largest materials research portfolio
- Most powerful open scientific computing facility
- World’s most intense neutron source
- World-class research reactor
- Nation’s most diverse energy portfolio
- Managing billion-dollar U.S. ITER project



ORNL's Mission

Deliver scientific discoveries that accelerate the development and deployment of solutions in clean energy and global security, and in doing so, create economic opportunities



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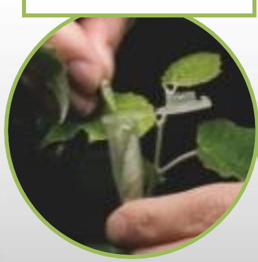
Bioenergy research at ORNL: basic sciences to applications

BESC
BioEnergy Science Center

Molecular biology, chemical and structural analysis and characterization, modeling and simulation

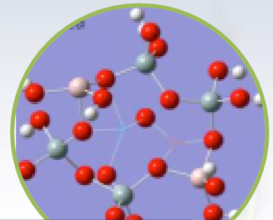
Feedstock development



Biomass deconstruction

Center for BioEnergy Sustainability
Environmental
Socio-economic indicators,
Integrated land management,
Management best practices

Feedstock Supply Analysis
Terrestrial & algal feedstocks,
Advanced logistics,
Supply & price projections

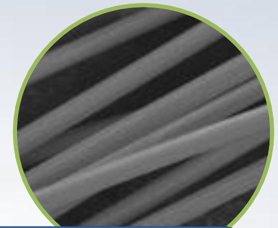


Conversion
Biochemical & thermochemical conversion,
Catalytic upgrading,
Materials of construction

Bioproducts

Biofuels

Biopower



Carbon Fiber Technology Facility
Materials S&E

Lighter weight vehicles

National Transportation Research Center
Engine evaluation
Fuel effects

Transportation biofuels

FLEX FUEL

Oak Ridge National Laboratory

US DOE EERE Bioenergy Technologies Office

DOE Bioenergy Technology Office's Sustainability Activities

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Identifying and addressing the challenges for sustainable bioenergy production through field trials, applied research, capacity building, modeling, and analysis.

Feedstock production and logistics

- Assess and reduce impact on land, water, climate, air quality, biodiversity, and resource use
- Increase landscape productivity

Conversion

- Minimize water consumption, GHG footprint, air pollution, and waste
- Maximize efficiency

ethanol
diesel
gasoline
jet fuel
biopower
bioproducts

End use

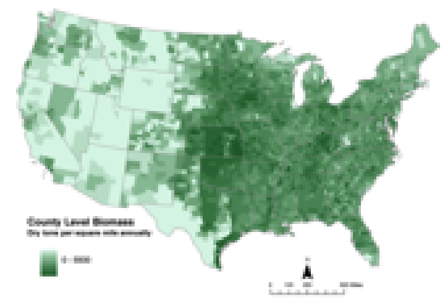
- Evaluate air quality impacts
- Avoid negative impacts on human health

Cross-cutting

- Life-cycle analysis of water consumption and GHG emissions
- Supply chain environmental, economic, and social factors

ORNL supports Bioenergy Technologies Office (BETO) objectives in several platforms

- **Strategic Analysis & Environmental Sustainability**
  - Defining bioenergy sustainability
  - Best Management Practices for energy crops
- **Feedstock Supply & Logistics**
  - Feedstock supply projections
  - Biomass engineering (logistics)



- **Biomass Conversion (Biochemical & Thermochemical)**
  - Catalytic upgrading of ethanol to HC
  - Novel catalyst for bio-oil upgrading
  - Materials compatibility of bio-oils
  - Advanced membranes for separation

- **Demonstration & Market Transformation**
  - High octane renewable super premium fuel

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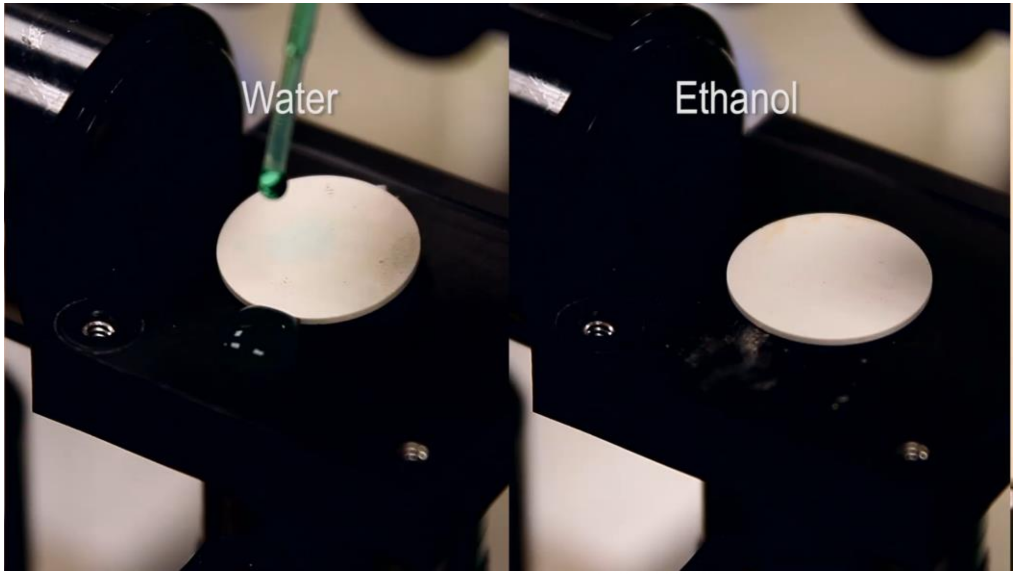
ORNL develops membranes to speed the biomass conversion process

Tunable membranes win R&D 100 Award

- Separations are a common need in both biochemical & thermochemical conversion
  - Oil – water separations
  - Ethanol – water
  - Liquid – vapor phase
- ORNL researchers invented a new class of membranes that can selectively separate molecules in the vapor and liquid phases.
- HiPAS (High Performance Architectured Surface Selective) membranes can be engineered as superhydrophobic or superhydrophilic for use in various stages of the biomass-to-biofuel conversion process.
- These membranes offer an energy-efficient alternative to the distillation process for the biofuels industry.



The same HiPAS membrane can repel water while absorbing ethanol. The tunability of the membrane offers many opportunities for creating greater efficiency, increasing speed, and decreasing costs associated with the production of biofuels. This technology could also benefit the chemical, pharmaceutical, and gas separation industries.

Slide source: Tim Theiss, ORNL

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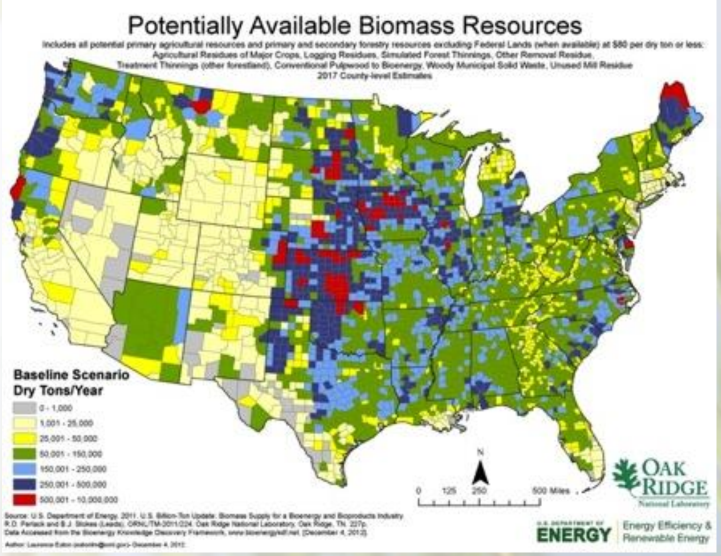
- Sustainability
- Landscape design
- Discussion
- Extra slides: Of blend walls and strategies to overcome market barriers

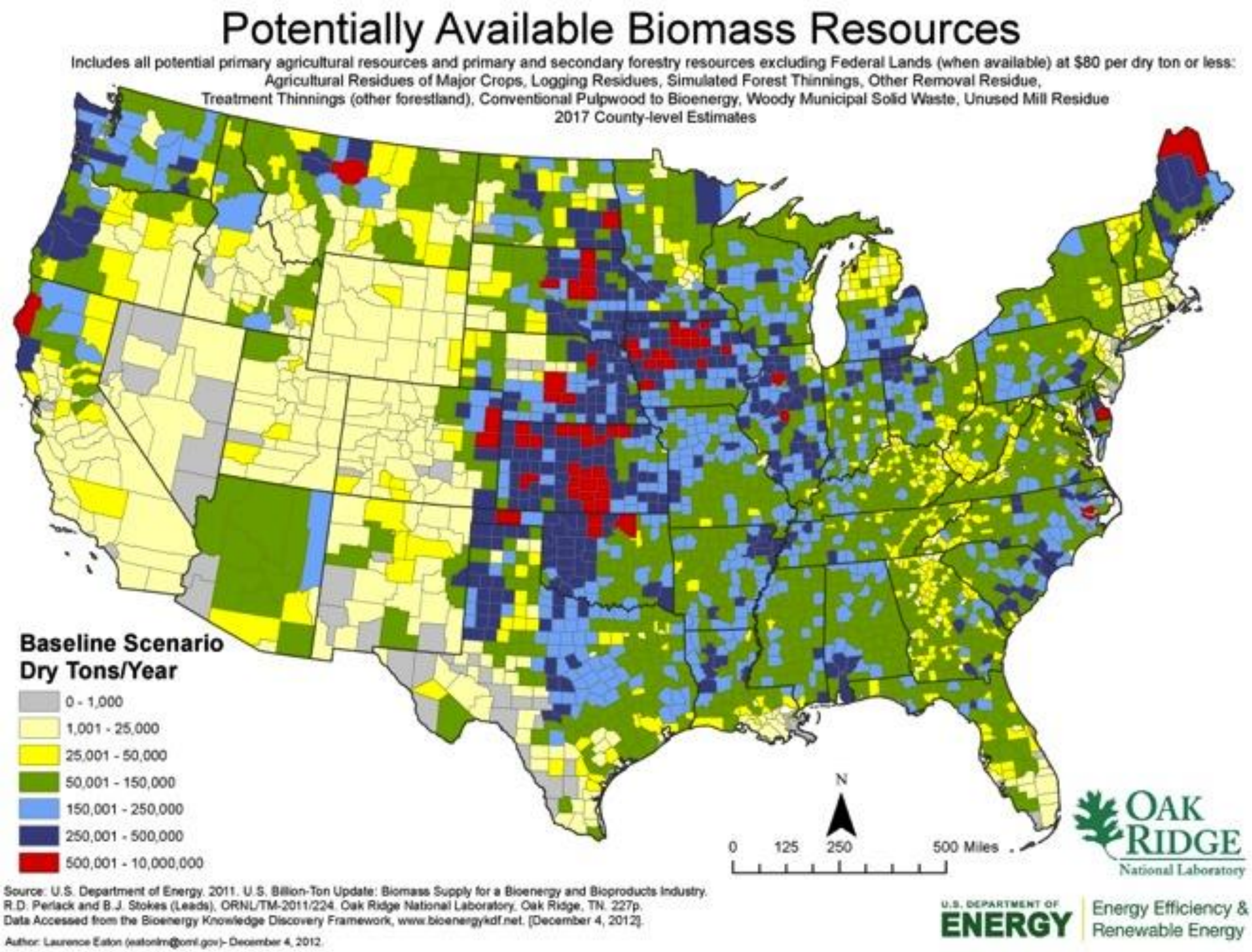


Future resources: US assessment

- Billion-Ton Study of 2005 helped support US renewable fuel volumes
- Billion Ton Update of 2011 included county-level cost & supply projections
- Conclusion: US has ample feedstock to replace up to 1/3 of petroleum with advanced biofuels
- Feedstock is roughly 1/3 cost of fuel: cost reductions and efficiency in feedstock supply are imperative
- Multi-institutional DOE & USDA analysis
  - 20-year projections of economic availability of biomass at county level at any year
  - price, location, scenario
- Primary Resources
  - Forest resources (residues)
  - Ag resources (corn stover)
  - Energy crops (switchgrass)

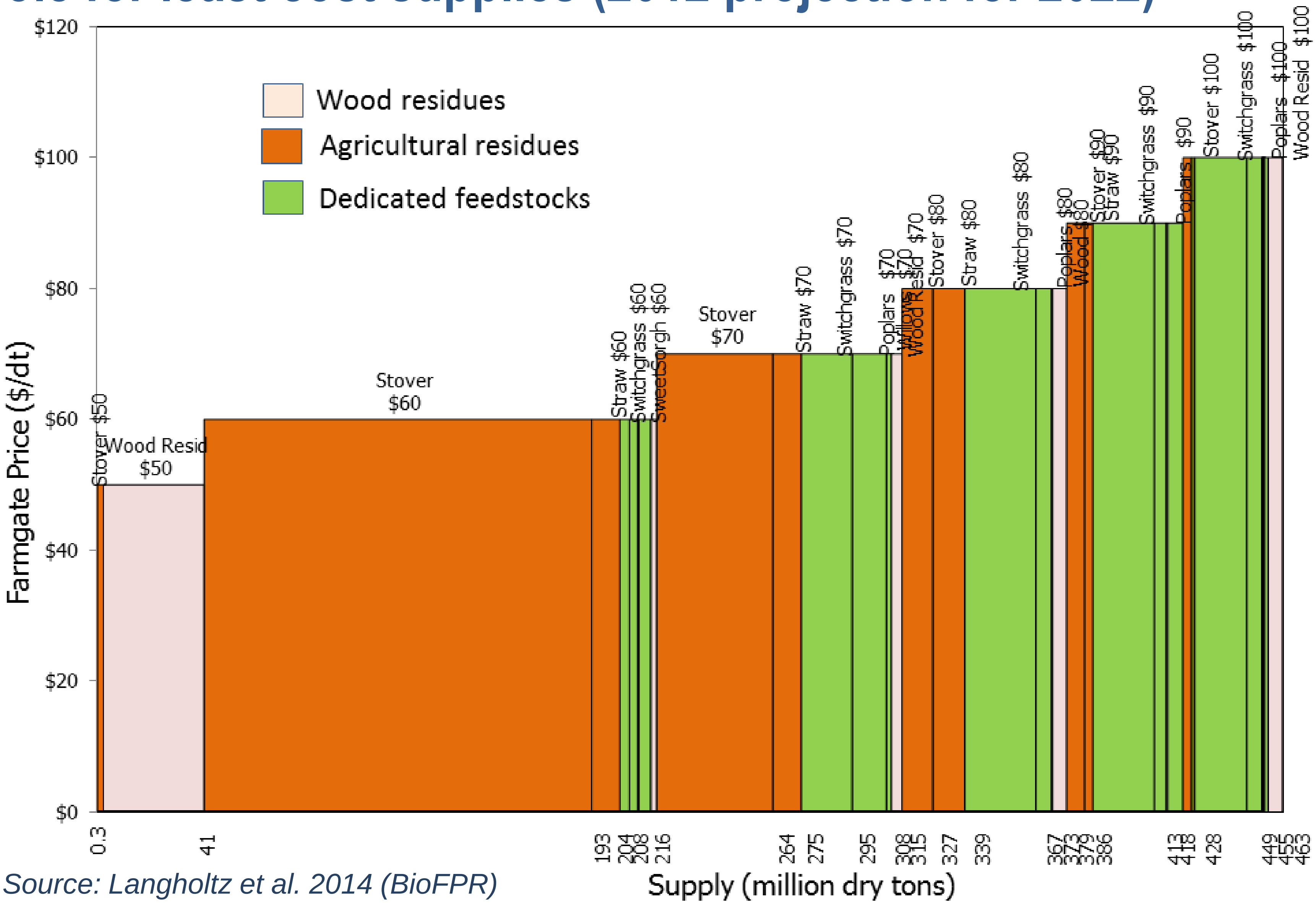
Example: US county-level Supply Projections

All feedstocks -- Baseline scenario -- $60 dry ton^{-1}



155 million DT/yr by 2017 is required to meet EISA targets (85 gal/ton conversion efficiency)

Future sources depend on costs – Residues play major role for least cost supplies (2012 projection for 2022)



Source: Langholtz et al. 2014 (BioFPR)

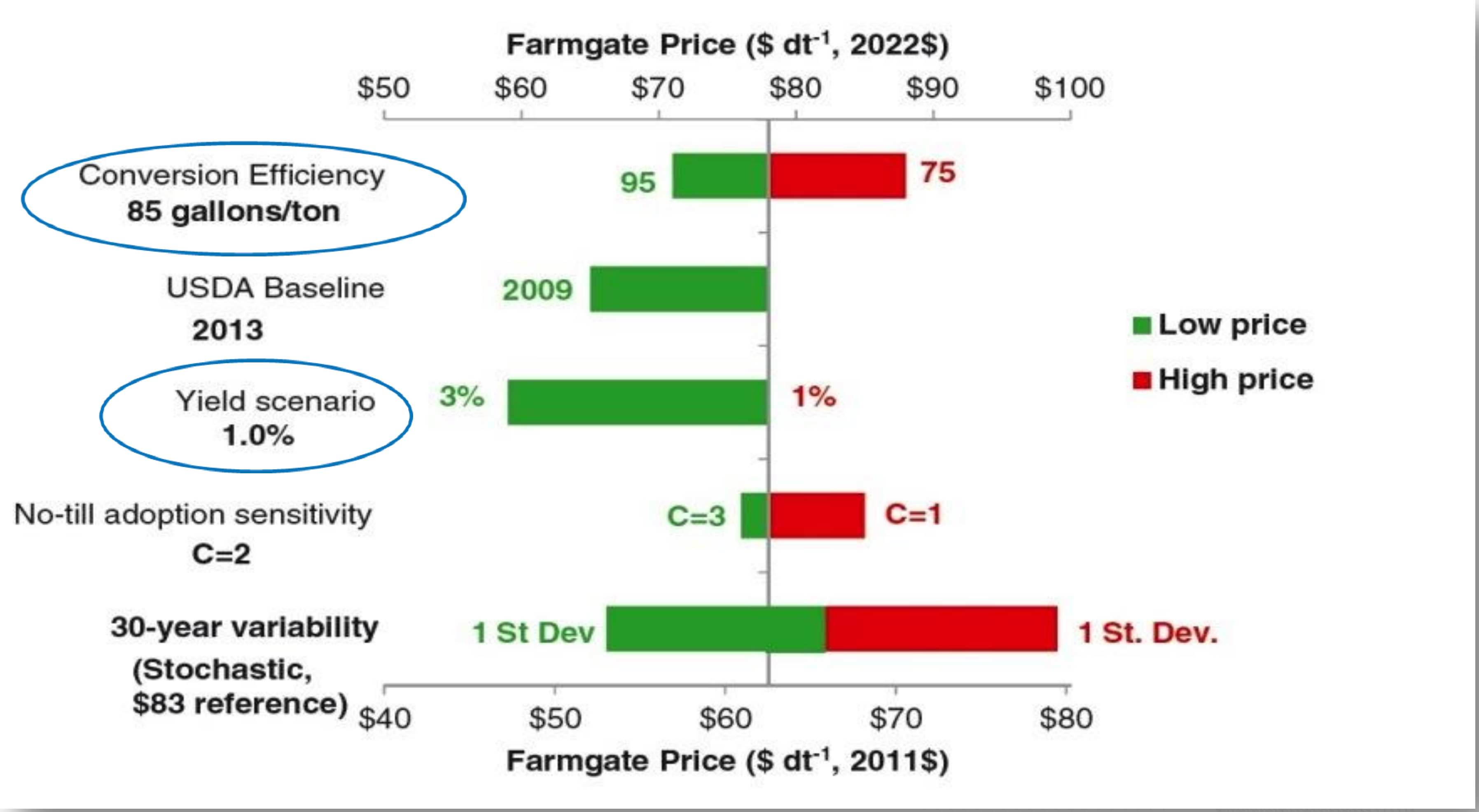
U.S. Bioenergy supply model Billion Ton Update (USDOE 2011)

- Forecasts of potential biomass
  - POLYSYS partial equilibrium model of US agricultural and forestry sectors.
  - 20-year projections of economic availability of biomass (price, location, scenario)

- Forest resources
  - Logging residues
  - Forest thinnings (fuel treatments)
  - Conventional wood
  - Fuelwood
  - Primary mill residues
  - Secondary mill residues
  - Pulping liquors
  - Urban wood residues
  - [Algae is separate study]

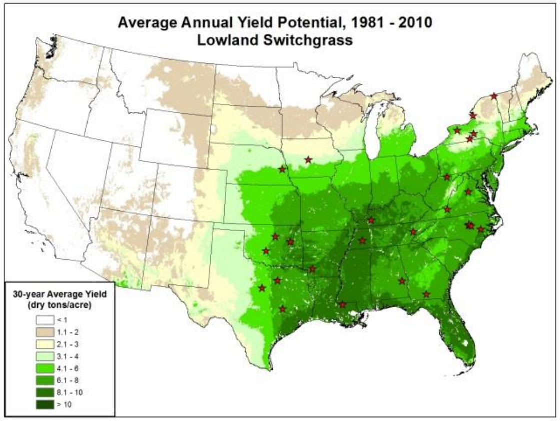
- Agricultural resources
  - Crop residues
  - Grains to biofuels
  - Perennial grasses
  - Perennial woody crops
  - Animal manures
  - Food/feed processing residues
  - MSW and landfill gases
  - Annual energy crop (added for 2011)

Cost and Supply projections in BT Updates are sensitive to productivity

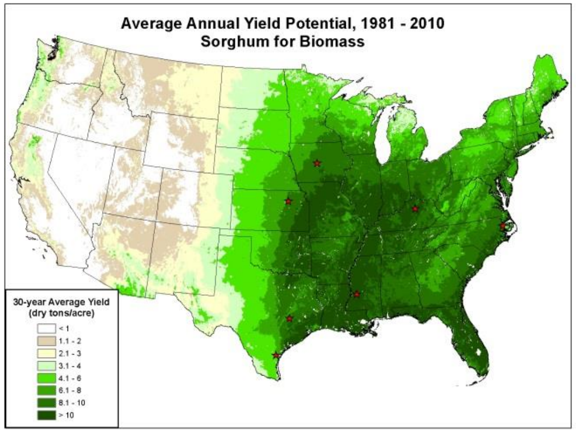


Herbaceous Energy Crops- yield modeling

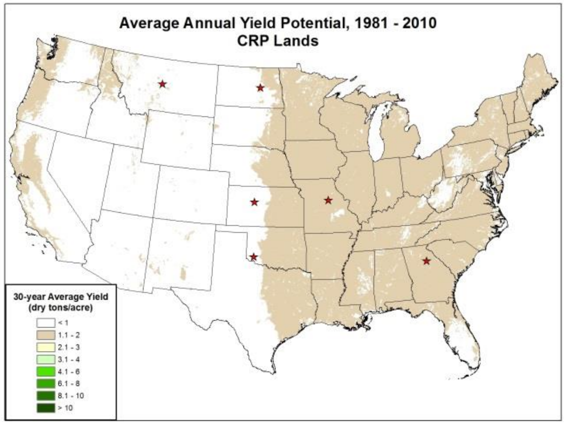
Lowland Switchgrass

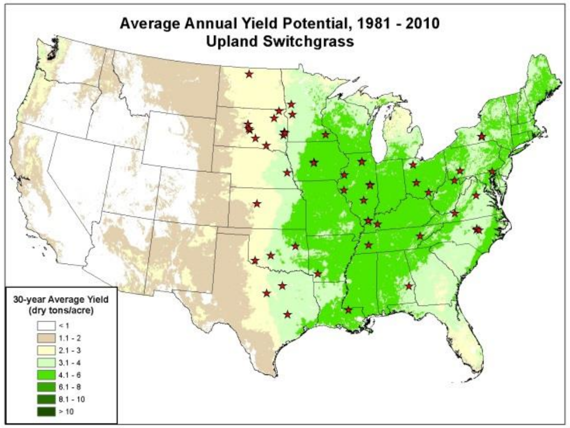


Sorghum

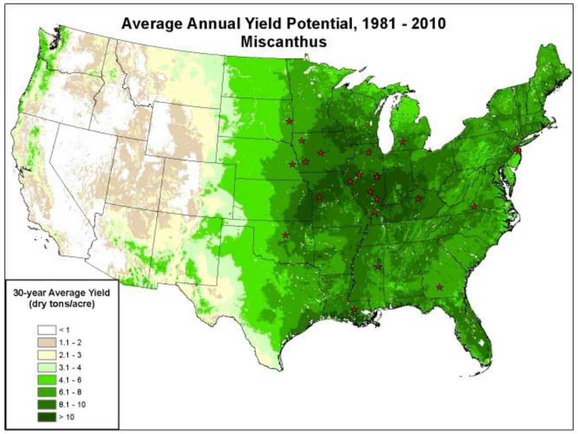


CRP Grasses

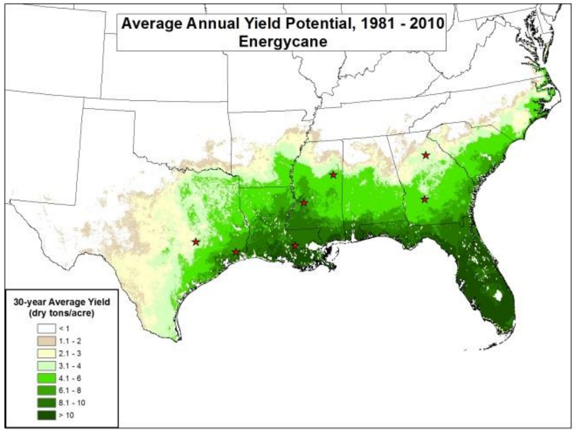




Upland Switchgrass



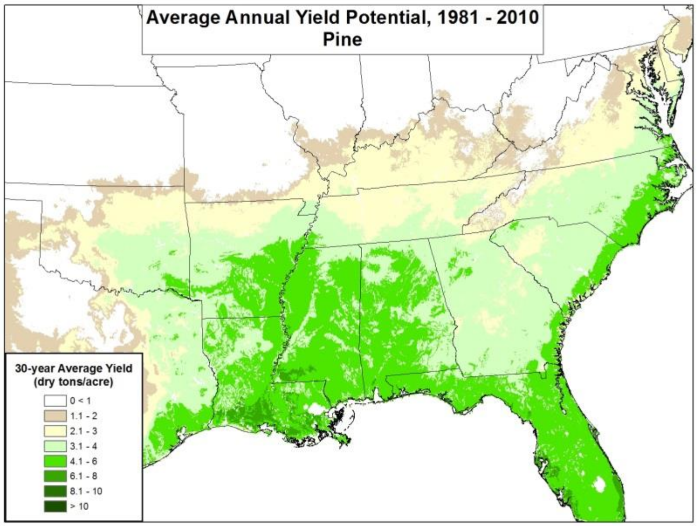
Miscanthus x *giganteus*



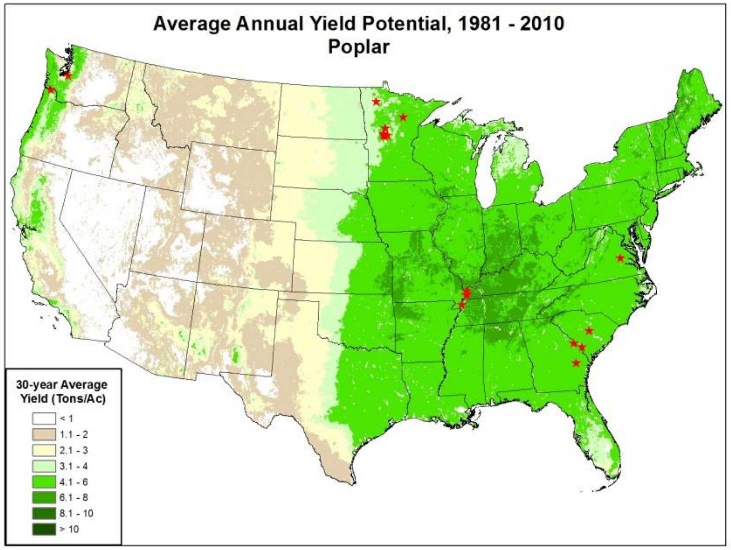
Energycane

Woody Energy Crops- yield modeling

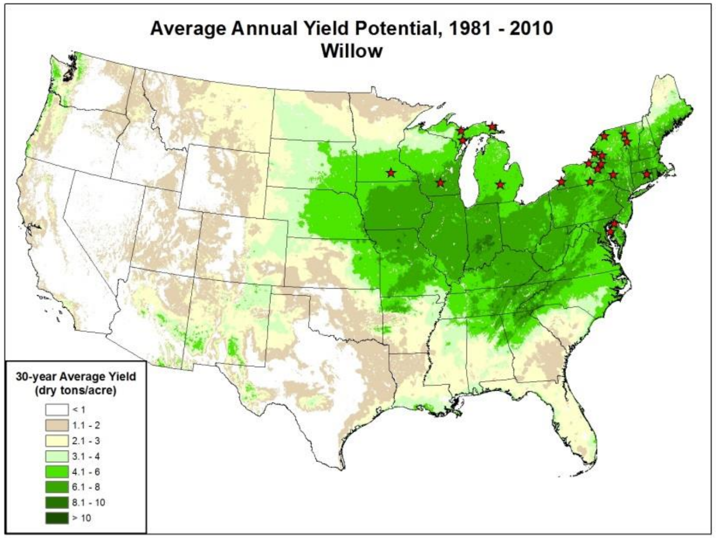
Pine



Poplar



Willow



Plus eucalypts and others…

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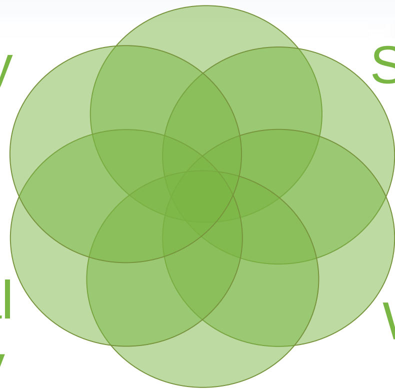
Categories for environmental and socioeconomic sustainability

Greenhouse gas emissions

Productivity

Soil quality



Biological diversity

Water quality and quantity

Air quality

McBride et al. (2011)
Ecological Indicators
11:1277-1289

Social well being

Social acceptability

External trade

Resource conservation

Energy security

Profitability

Dale et al. (2013)
Ecological Indicators
26:87-102.

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

Efroymson et al. (2013) *Environmental Management* 51:291-306.

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Looking at the biofuel supply chain in terms of sustainability indicators

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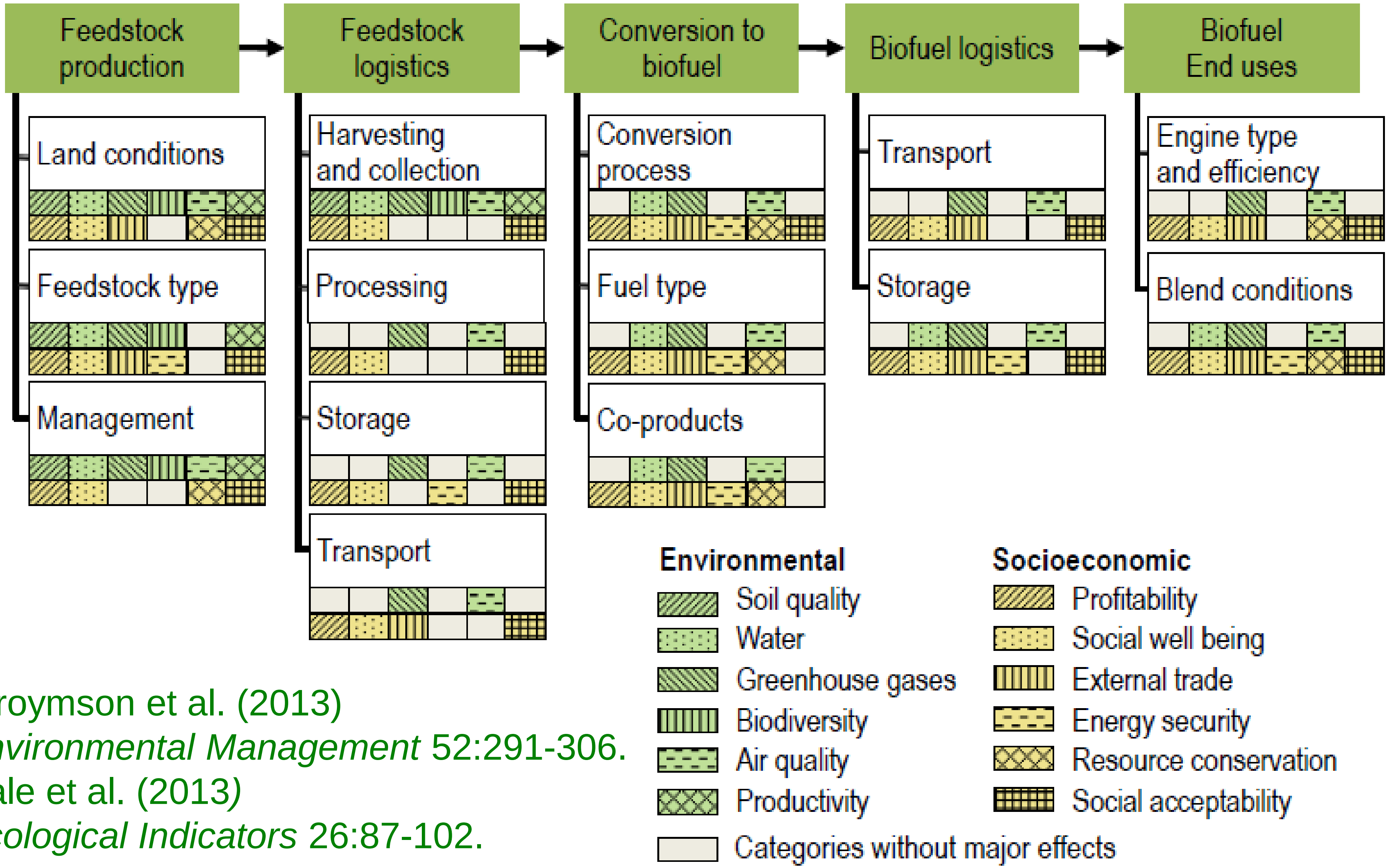


Efroymson et al. (2013)
Environmental Management 52:291-306.
Dale et al. (2013)
Ecological Indicators 26:87-102.

U.S. Department of Energy (DOE) Approach to Assessing Bioenergy Sustainability

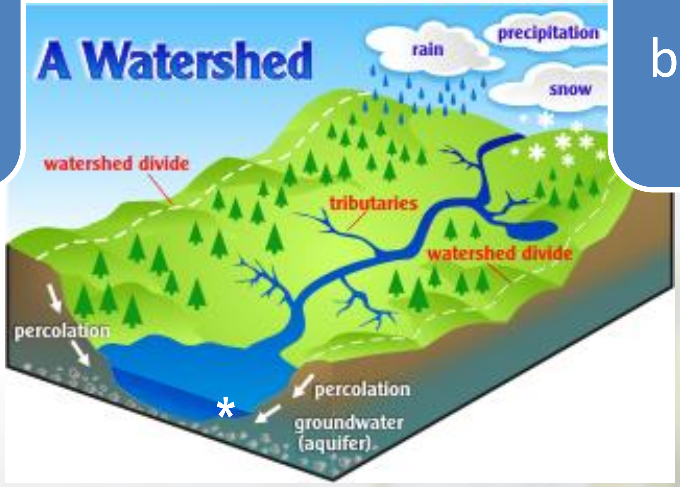
✔ Select Indicators

Establish baselines and targets

Evaluate indicator values

Identify trends and tradeoffs

Develop and test best practices

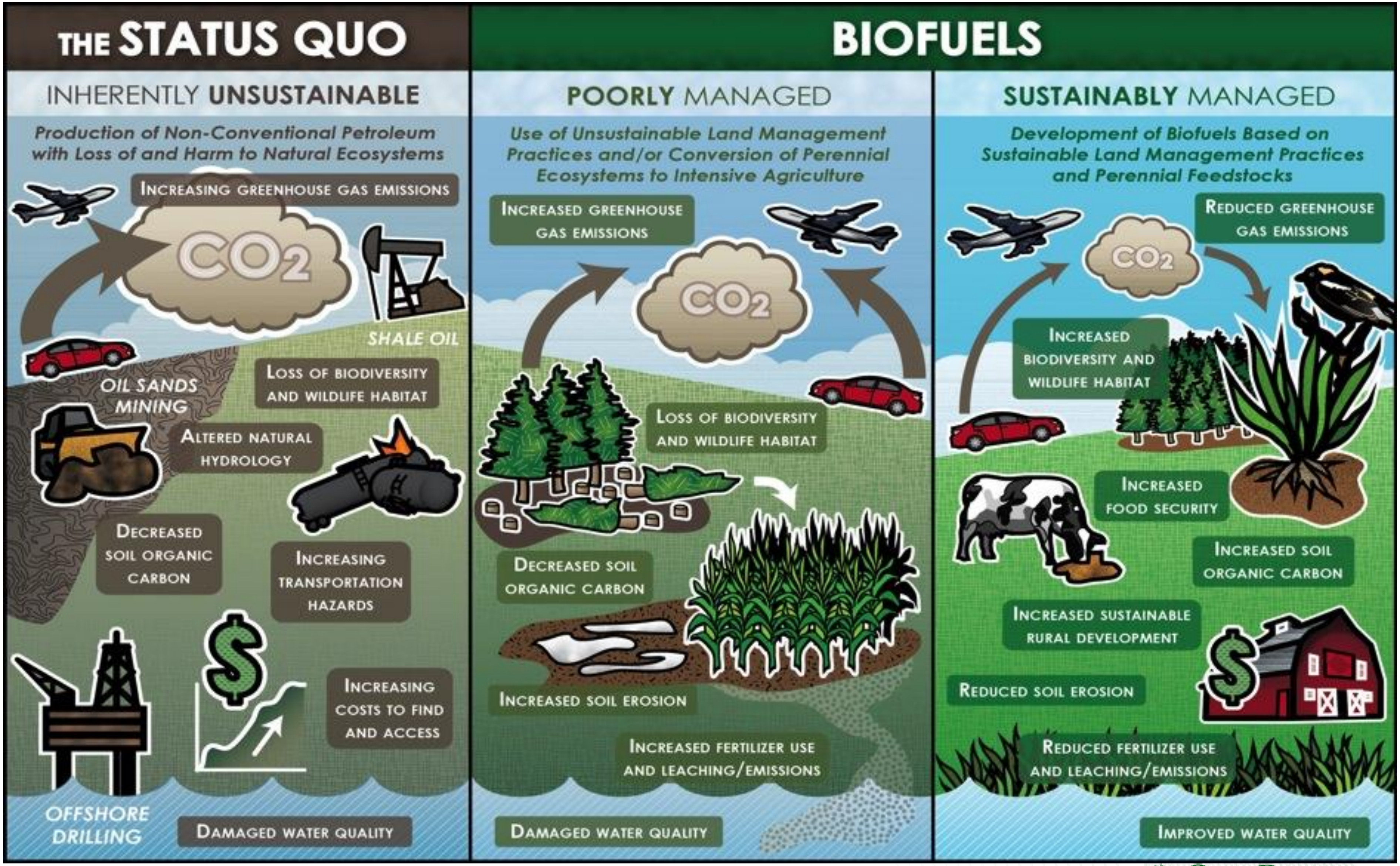


Recommended practices

- Consider management goals and options within the broader context
- Attention to site selection and effects in the
  - location and specification of feedstock
  - handling and transfer of feedstock
  - refinery processing
  - Distribution and use of bioenergy
- Monitoring and public reporting of key measures of sustainability
- Attention to what is "doable"
- Stakeholder engagement throughout process

McBride et al. (2011) Ecological Indicators 11:1277-1289.
Dale et al. (2013) Ecological Indicators 26:87-102.

Biofuels need to be sustainably managed



Dale B et al. (2014) Take a Closer Look: Biofuels Can Support Environmental, Economic and Social Goals. Environmental Science & Technology 48(13): 7200-7203.

Negative impacts of bioenergy can be avoided or reduced by attention to three principles:

1. Identify and conserve priority ecosystem and social services
2. Consider local context, trends, and stakeholders
3. Monitor effects of concern and adjust plans to improve performance over time

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Consider bioenergy as an opportunity to add value through integration by applying landscape design

Landscape design supports planning for improved resource management

- Helps stakeholders identify ways to manage for more sustainable provisions of services including renewable energy
- Takes context, trends and current conditions into consideration

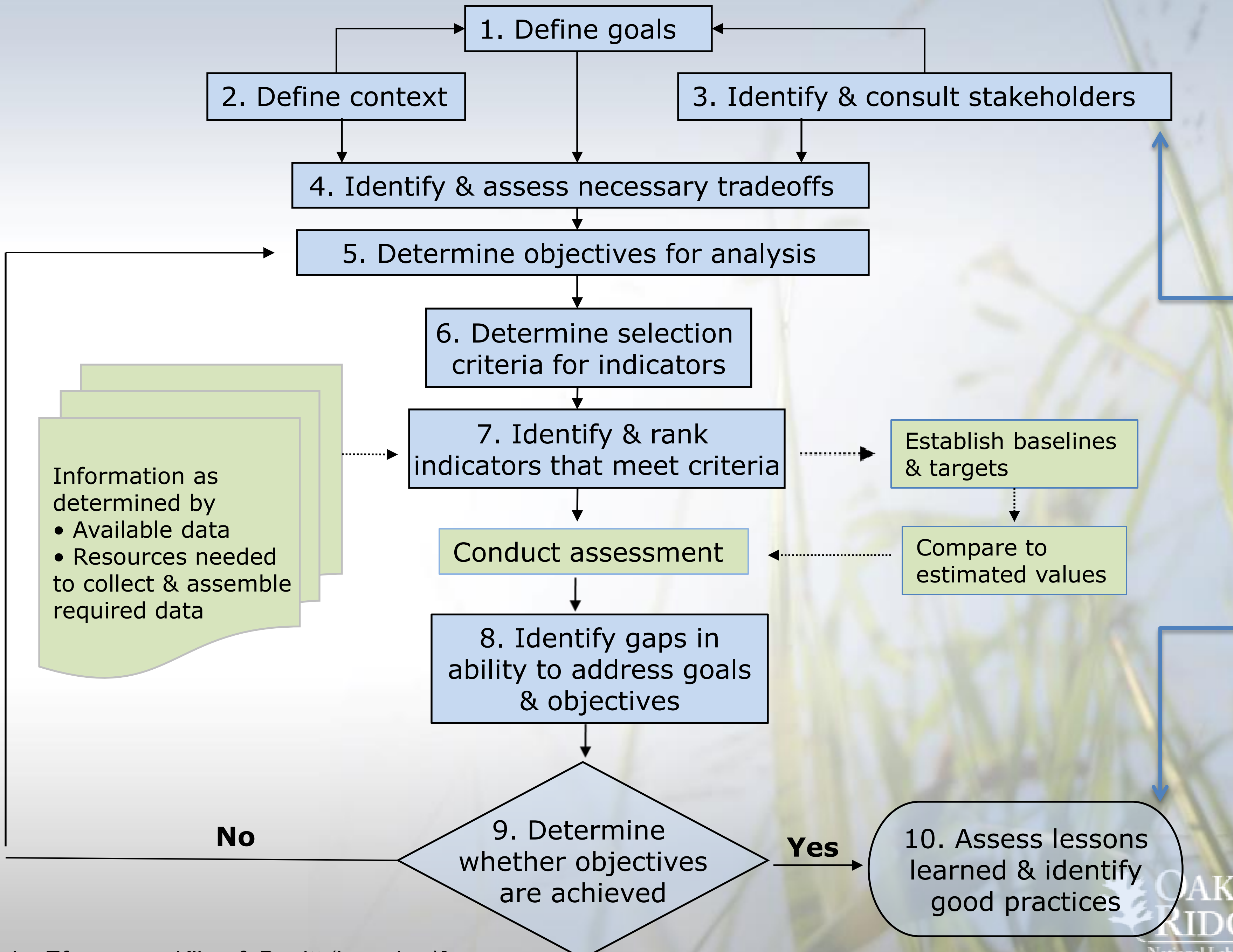
Landscape Design Involves Adapting Indicators to Particular Contexts

- **Indicator set is a starting point for sake of efficiency and standardization**
  - Particular systems may require addition of other indicators
  - Budget may require focus on a smaller set of indicators
  - Some indicators more important for different supply chain steps
- **Protocols must be context-specific**

Efroymson et al. (2013) *Environmental Management* 51:291-306.

Landscape design approaches for bioenergy are place- and time-specific.

- Set goals
  - Involve key stakeholders
  - Develop consensus approach
- Consider constraints
- Address wastes and other opportunities
- Evaluate and apply solutions
- Monitor to support adaptive management



[Dale, Efroymson, Kline & Davitt (in review)]

Pressures and incentives for landscape design

- Legal demands or regulations
- Customer requirements or specifications
- Stakeholder concerns
- Competitive advantage, Reputation loss
- Environmental and social pressure groups
- Understand interactions at relevant scales
- Enable improved outcomes (provision of multiple services)

[Building from Seuring and Muller (2008) Journal of Cleaner Production 16:1699-1710]

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Obstacles to developing and deploying landscape design

- Landowner rights
- Traditional practices
- Up front planning required
- Coordination and outreach, stakeholder engagement
- Complexity/level of effort
- Higher initial costs
- Lack of consensus on objectives, priorities

[Building from Seuring and Muller (2008) Journal of Cleaner Production 16:1699-1710]

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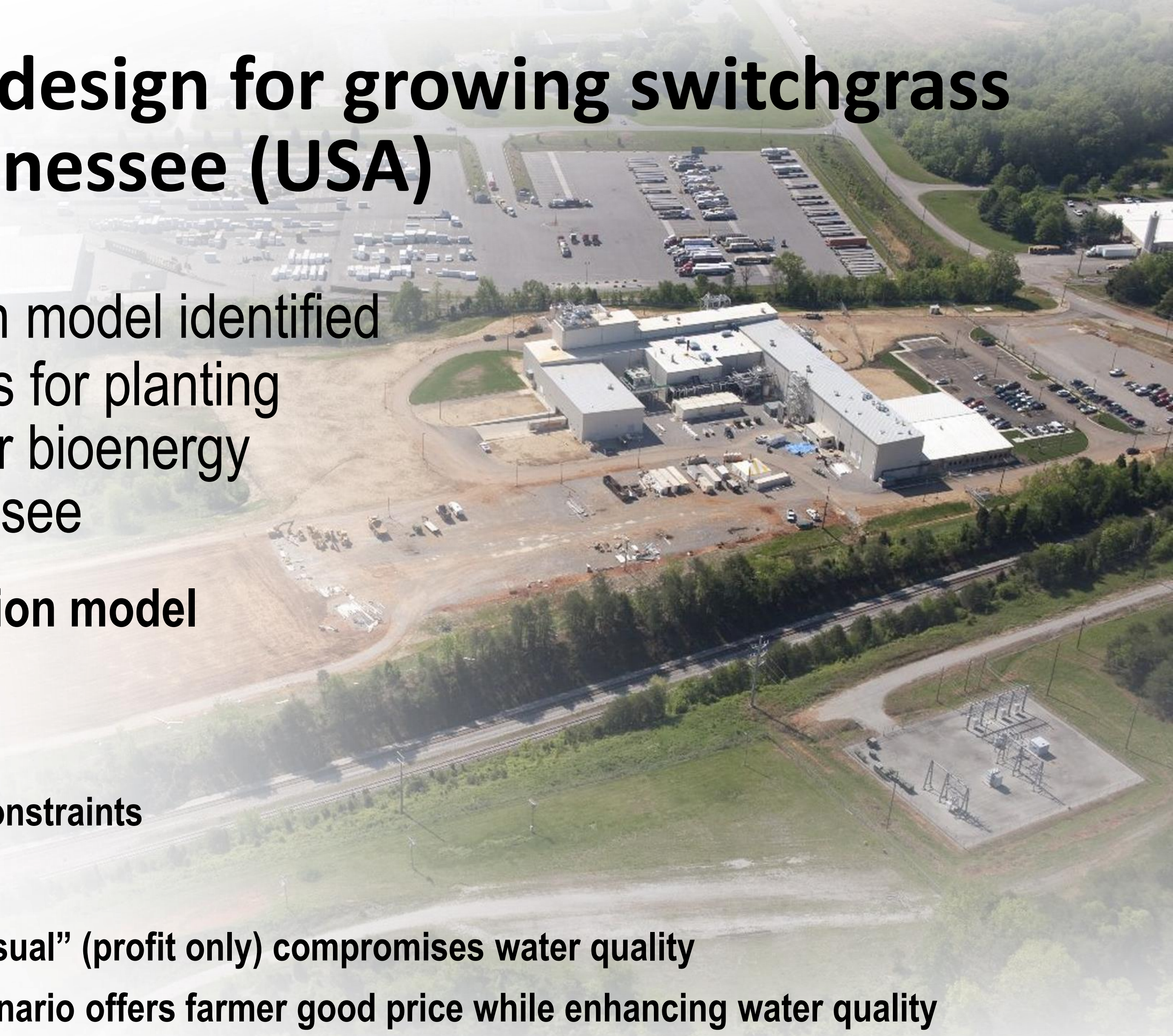
Landscape design for growing switchgrass in east Tennessee (USA)



An optimization model identified "ideal" locations for planting switchgrass for bioenergy in east Tennessee

Spatial optimization model

- **Considers**
  - **Farm profit**
  - **Water quality constraints**
- **Finds**
  - **"Business as usual" (profit only) compromises water quality**
  - **"Balanced" scenario offers farmer good price while enhancing water quality**

[Parish et al., *Biofuels, Bioprod. Bioref*. 6,58–72 (2012)]

Data for indicator approach are being analyzed to help assess switchgrass for 10 counties, Vonore, TN

IBSS
Southeastern Partnership for
Integrated Biomass Supply Systems

Data available from Vonore for most indicators of socioeconomic sustainability

* Information not currently available for Vonore

not an issue in this context

Category	Indicator	Units
Social well-being	Employment	Number of full time equivalent (FTE) jobs
	Household income	Dollars per day
	Work days lost due to injury	Average number of work days lost per worker per year
	Food security #	Percent change in food price volatility
Energy security*	Energy security premium	Dollars /gallon biofuel
	Fuel price volatility	Standard deviation of monthly percentage price changes over one year
External trade	Terms of trade	Ratio (price of exports/price of imports)
	Trade volume	Dollars (net exports or balance of payments)
Profitability	Return on investment (ROI)	Percent (net investment/ initial investment)
	Net present value (NPV)[2]	Dollars (present value of benefits minus present value of costs)

Category	Indicator	Units
Resource conservation	Depletion of non-renewable energy resources	MT (amount of petroleum extracted per year)
	Fossil Energy Return on Investment (fossil EROI)	MJ (ratio of amount of fossil energy inputs to amount of useful energy outputt
Social acceptability	Public opinion	Percent favorable opinion
	Transparency	Percent of indicators for which timely and relevant performance data are reported
	Effective stakeholder participation	Number of documented responses to stakeholder concerns and suggestions reported on an annual basis
	Risk of catastrophe	Annual probability of catastrophic event

Dale et al. (2013) *Ecological Indicators* 26:87-102.

Data available from Vonore for all indicators of environmental sustainability

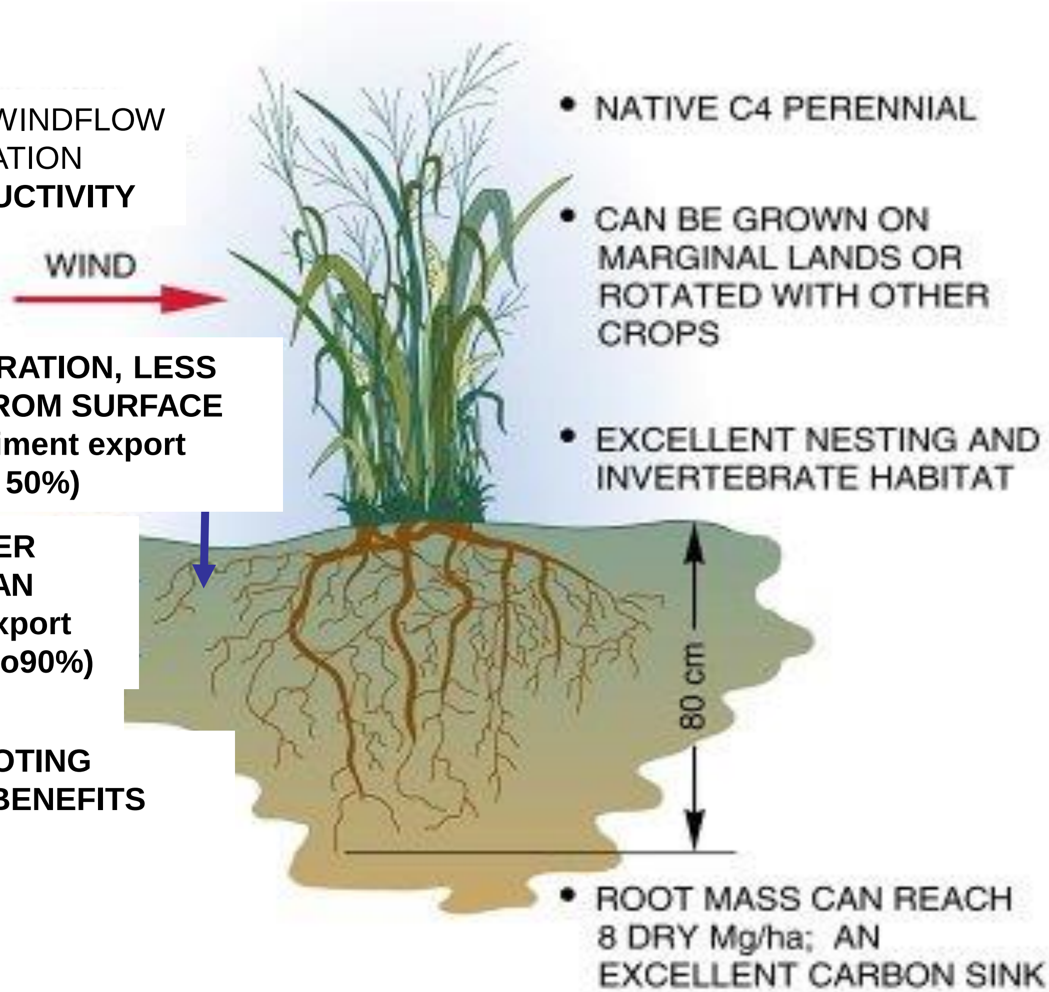
Environment	Indicator	Units
Soil quality	1. Total organic carbon (TOC)	Mg/ha
	2. Total nitrogen (N)	Mg/ha
	3. Extractable phosphorus (P)	Mg/ha
	4. Bulk density	g/cm^3
Water quality and quantity	5. Nitrate concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	6. Total phosphorus (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

Environment	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. (2011) *Ecological Indicators* 11:1277-1289

While switchgrass offers environmental benefits in east Tennessee, the low cost of competing fuels and lack of alternate markets translates to little demand

DECREASED WINDFLOW AND EVAPORATION
- **HIGH PRODUCTIVITY**



HIGH INFILTRATION, LESS EROSION FROM SURFACE FLOW (Sediment export reduction of 50%)

LOWER FERTILIZER APPLICATION THAN CORN (nitrogen export reduction of 25% to90%)

DEEP ROOTING SYSTEM BENEFITS

Dale et al. (2011) *Ecological Applications* 21(4):1039-1054.

DOE Workshops, Case Study of Eucalyptus in Brazil

Arnaldo Walter and Camila de Oliveira, UNICAMP and CTBE, SP, Brazil

- Legal and regulatory framework
  - Land use regulated by Forestry Code (amended in 2012).
  - “Permanent Preservation Areas” & “Legal Reserve Areas” defined
  - Identified appropriate areas for specific uses (e.g., eucalyptus and pines)
  - Foster good practices to reduce environmental impacts
- Institutional framework
  - Forestry Science and Research Institute (IPEF) calls for
    - “Landscape sustainable practices”
    - “Use of degraded areas”.
  - Annual reports on Forestry Management by the industries highlight
    - Improving yield
    - Preserving water resources
    - Reducing & monitoring impacts on biodiversity
    - Adopting social programs
    - Reducing fragmentations
- Design
  - Integrating livestock into plantations
  - Integrating soy into planted forests.
  - Preserving natural vegetation
- Challenges: logistics, infrastructure

Remediation Case Study: New York

Tim Volk, (SUNY and NEWBio Project)

- Community Drivers: use of former industrial land and provision of renewable energy
  - Growing shrub willows on settling basins as alternative to standard geomembrane cap
  - Environmental monitoring willow fields for soils and water quality
  - Starting assessment of social factors in driving biomass use in the region
- Multifunctional systems
  - Sustainable Reuse Remedy
    - ✓ Use organic waste stream from local brewery to create favorable growing conditions
    - ✓ Manage water to minimize leaching to surface and ground water
    - ✓ Produce biomass
  - Shrub willow in highway rights of way for snow drift control and potential biomass production
  - Willow incorporated into riparian buffers
  - Potential for recreation uses

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Southeast U.S. woody biomass case: Mill residues, thinning, co–products of harvest for saw timber and pulp

Trees are cut and sorted by size, qualities.

- Harvest meets Sustainable Forestry Initiative (SFI) standard
- Protection of places providing unique ecosystem services
- Targeting multiple round-wood markets (4): saw timber; pulp; low-value ‘form wood’ to China; remainders to pellets
- All branches and other residues, remain in forest
- Tagging, weighing systems in field supports “Chain of custody”

IEA Task 43: Biomass feedstocks for energy markets

- **Overall approach**
  - Empirical case studies dealing with environmental, economic and social changes over time*
  - Looking for where can methodology* be coordinated to improve consistency and comparability among the individual case studies (to the extent it is possible and useful)
  - Policy messages: Barriers and opportunities to overcome them
- **Case studies**
  - Mobilization of forest* bioenergy supply chains in boreal and temperate forests (Canada, US and N Europe & Australia)
  - Mobilizing agricultural residues for bioenergy and biorefinieries
  - Regional biogas production from organic residues
  - Cultivation of grasslands and pastures – the sugarcane ethanol case
  - Integration of bioenergy crops into agricultural landscapes*

* ORNL is in discussion with IEA Task 43

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"You can't know where you're headed if you don't know where you've been"

And it helps to understand where you are right now.

"Prediction is very difficult, especially about the future"

-Niels Bohr, Danish physicist.

Oak Ridge National Laboratory

Thoughts for discussion

- Studies of global biomass potential often begin with assumed land limitations.
- Do data suggest land is a primary constraint to biomass production?
  - No.
- Needed: Incentives for improved soil/water (resource) management
  - Increase carbon and nutrient retention
  - And capacity to store carbon
- On the sustainability radar:
  - Integrated land-use plans and production systems (ILUP)
  - Urban food-energy systems for nutrient, water and energy recycling

Source: Kline presentation to "Pathways to Climate Solutions: Assessing Energy Technology and Policy Innovation" Workshop organized by the Aspen Global Change Institute; 24-28 February, 2014. Aspen CO.

Thank you!

Center for BioEnergy Sustainability

http://www.ornl.gov/sci/ees/cbes/

This research is supported in part by the U.S. Department of Energy (DOE) Bio-Energy Technologies Office and performed at Oak Ridge National Laboratory (ORNL). Oak Ridge National Laboratory is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725.

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Biomass for bioenergy – Outline

- ORNL and DOE programs
- Feedstock supply analysis
- Sustainability
- Landscape design
- Discussion
- **Extra slides: Of blend walls and strategies to overcome market barriers**

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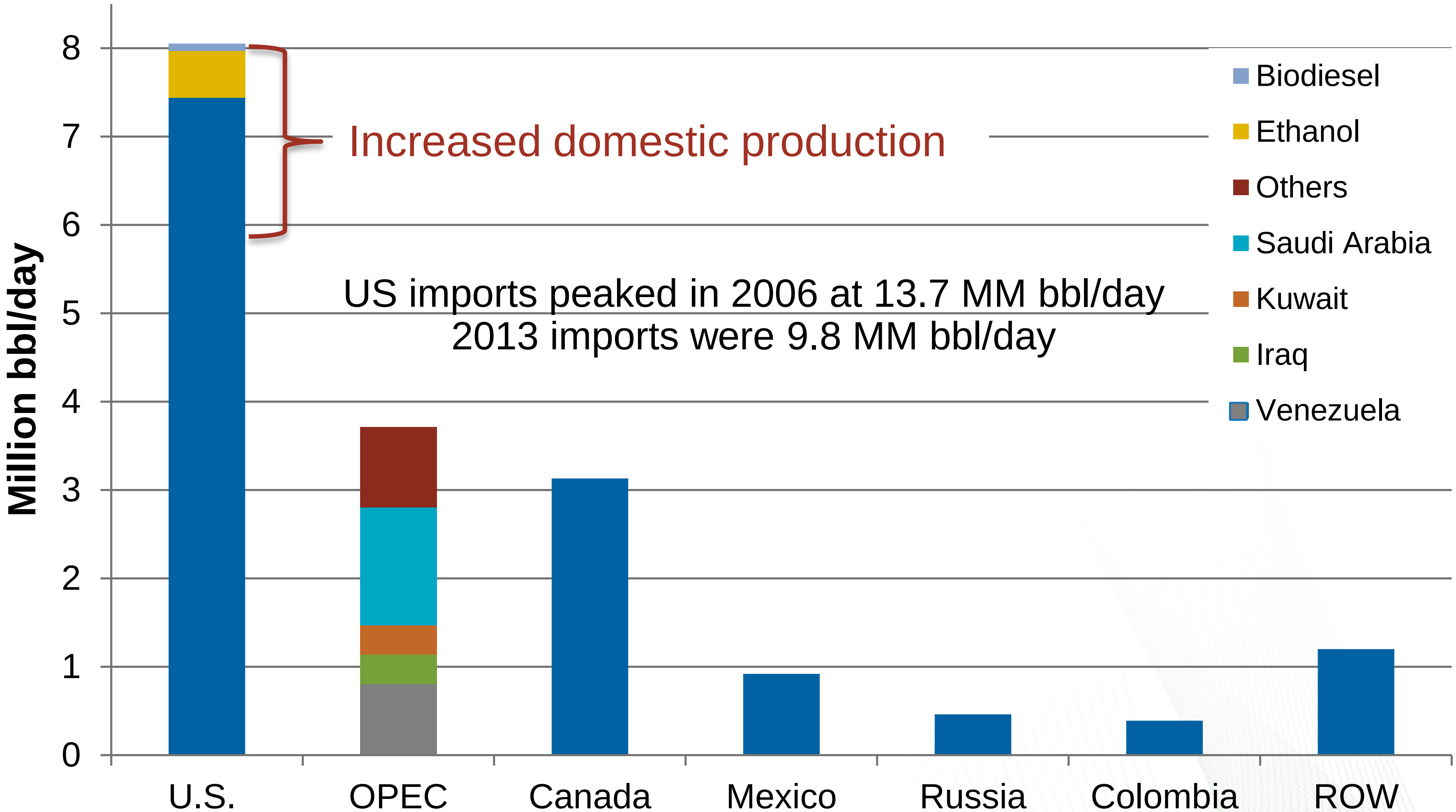
Domestic petroleum production (2013) has increased significantly



Source: Energy Information Agency; http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbblpd_a.htm

Slide Credit: Tim Theiss, ORNL

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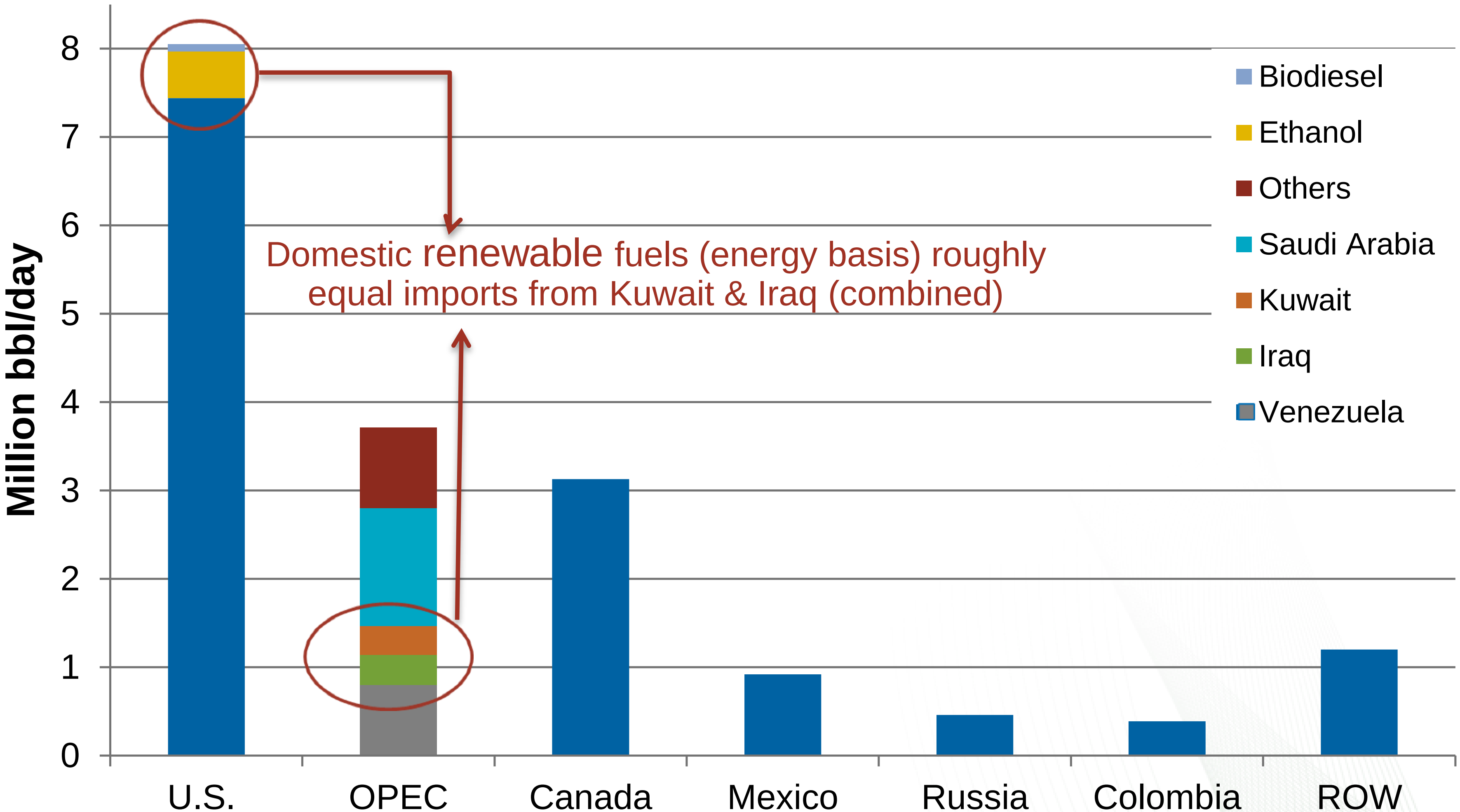
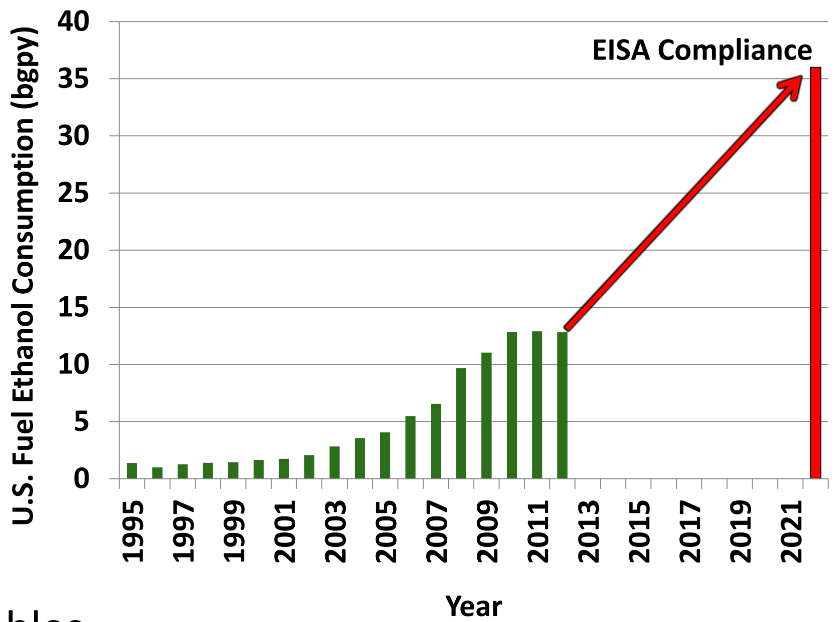


Source: Energy Information Agency; http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbblpd_a.htm

Slide Credit: Tim Theiss, ORNL

U. S. ethanol production is significant

- Currently consuming 13 billion gallons/year (BGY) ethanol
- US gasoline consumption – 135 BGY
- Most gasoline sold is E10 (10% ethanol) – we are ***"at the blend wall"***
- Benchmarking and historical comparisons
  - Current U.S. ethanol production is nearly double that of Brazil
  - Our RFS goal of 36 billion gallons/year renewables…
    - …is greater than the oil imports from Saudi Arabi (19 billion gpy)
    - …is an order of magnitude greater than WWII Germany's coal-to-liquids program (2 billion gpy)

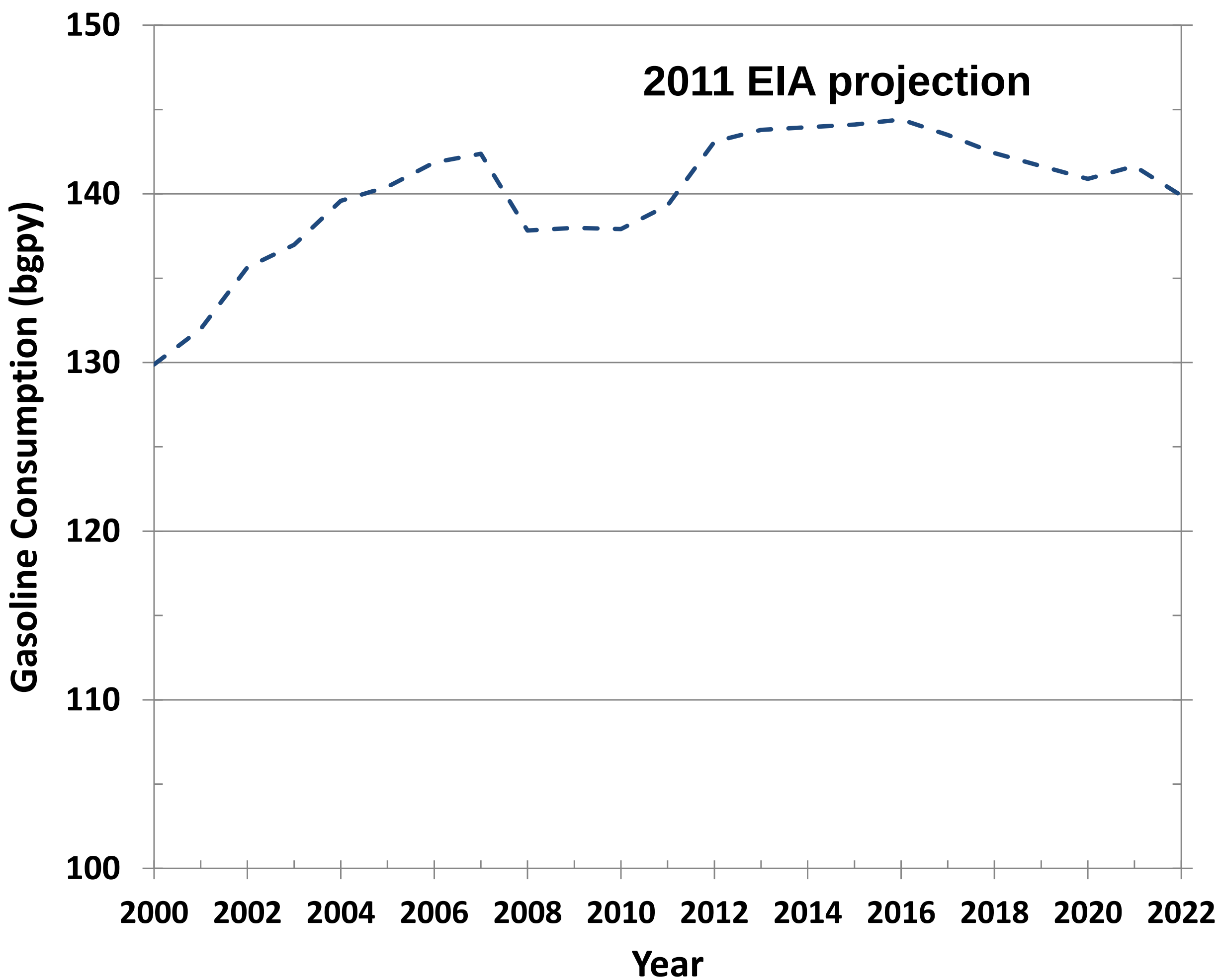


- **Gasoline saved by 1 million electric vehicles: 0.5 Billion gal/yr**
- **Gasoline saved by 10% weight reduction in cars: 5 Billion gal/yr**

Credit: Ron Graves, ORNL

In 2011, EIA projected flat gasoline consumption for next decade

"Motor gasoline" includes E10. Flat demand at ~140 bgpy led to projections of E15 allowing for *up to* 21bgpy ethanol. That was 2011….



http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2011&subject=0-AEO2011&table=11-AEO2011&region=0-0&cases=ref2011-d020911a

Credit: Tim Theiss, ORNL

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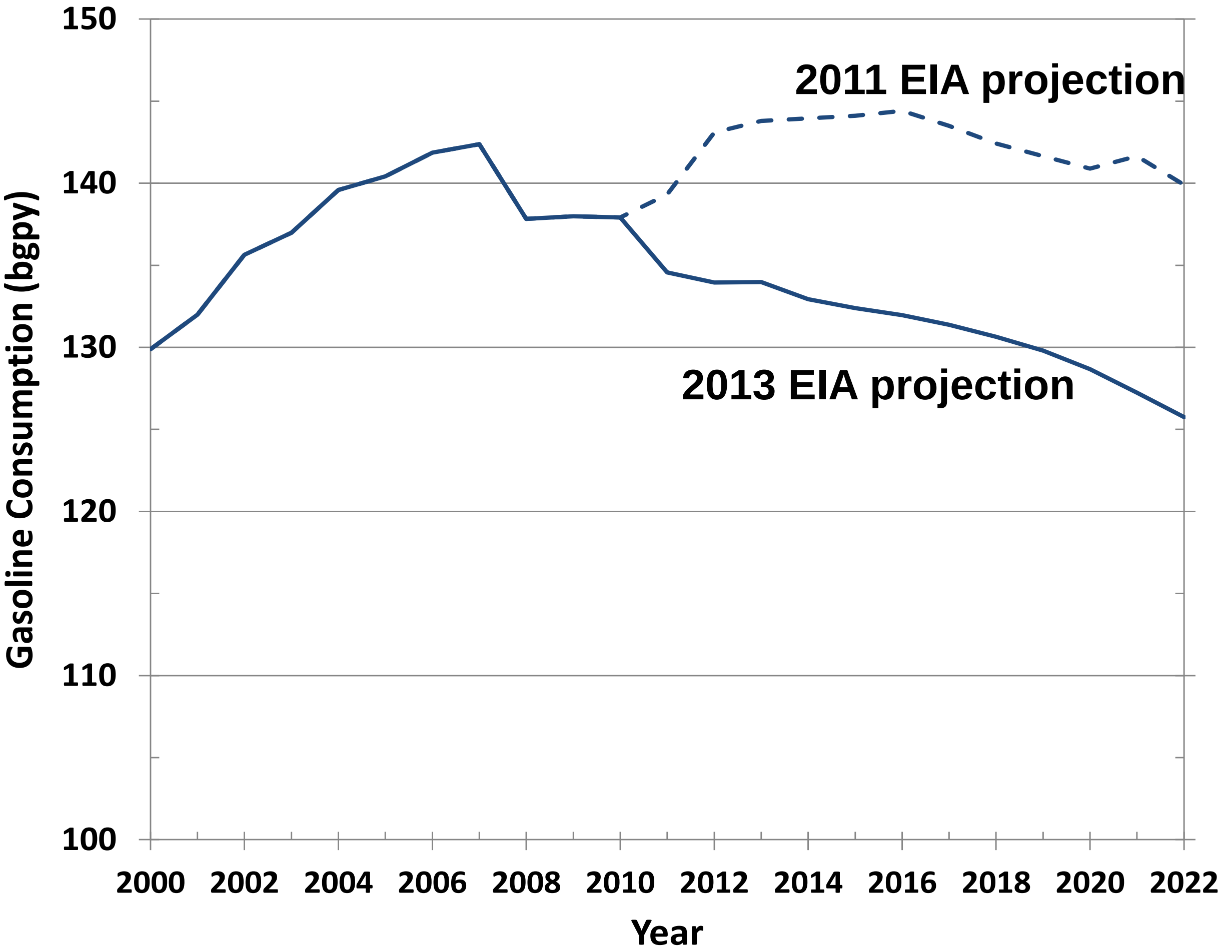
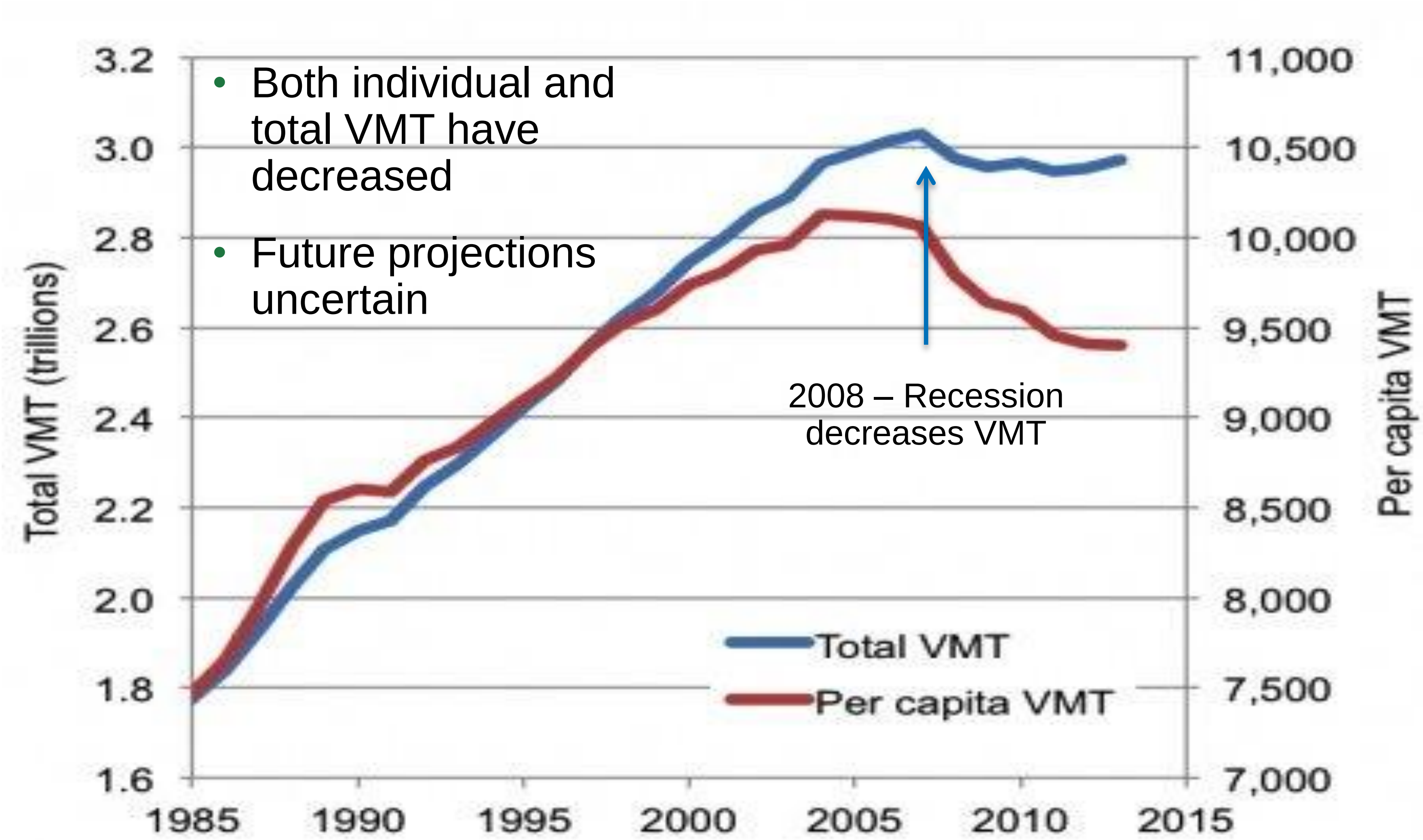
EIA projections reflect declining gasoline consumption. New EPA fuel economy rule finalized in 2012. EIA 2007 projection for 2022 was 160 billion gallons per year, about 35 bgpy more than recent estimate. EISA advanced fuel goal for 2022 = 21 bgpy).



Credit: Tim Theiss, ORNL

The trend in Vehicle Miles Traveled (VMT) has also changed recently

- Both individual and total VMT have decreased
- Future projections uncertain



Source: http://www.ssti.us/2014/02/vmt-drops-ninth-year-dots-taking-notice/

Three Challenges for Transportation:

Can more sensible use of biofuels enable CAFE and RFS simultaneously?

54.5 mpg CAFE by 2025

-per U.S. EPA and U.S. DOT standards (2012 rule)

Fuel Economy Standards

Transportation Industry

>70% less NOx

>85% less NMOG

EPA Tier 3 Emission Regulations

Further reductions in vehicle emissions

-per EPA Tier 3 regulations (2014)

Renewable Fuel Standard

36 billion gallons /yr of renewable fuel by 2022

-per Energy Independence and Security Act of 2007

Credit: Tim Theiss, ORNL

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 ~20-40% ethanol
  - 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 <u>optimized</u> vehicles could improve fuel economy while using more ethanol
  - **Also legal to use in ~16M legacy Flex-Fuel Vehicles**

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

Slide Credit: Brian West, ORNL

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Future biomass for bioenergy sources must address perceived obstacles

- **Markets: lack of security for investment in increased production**
- **Food security and land concerns**
- **LUC-related effects on biodiversity, carbon debt, water**
- **Distribution of benefits and costs**
- **Need for integrated policy across agriculture, forestry, waste management, urban planning, environment, energy…**
- **Sector- and nation-specific challenges: e.g., policies, "blend wall," distribution infrastructure**

Source: Kline presentation to "Pathways to Climate Solutions: Assessing Energy Technology and Policy Innovation" Workshop organized by the Aspen Global Change Institute; 24-28 February, 2014. Aspen CO.

Win-Win LUC Opportunities

Improve soil & water management

- Precision management and nutrient recycling
- Reduce disturbance/tillage intensity
- Crop mix, rotations, cover crops
- Land restoration
- Technology (seed, microbe, equipment)

Increase Efficiency

- Reduce inputs/increase ***yields***
- Open, transparent markets
- Minimize transaction costs
- Prioritize, incentivize, measure

Diversify

- Uses and markets
- Substitution options
- Bases of production

Adopt Systems Perspective

- Multi-scale
- Long term and adaptive
- Integrated land-use plans

Source: K.L. Kline presentation to Coordinating Research Council CRC, Argonne IL, 13 Oct 2013

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Which biomass sources preferable?

Preferred biomass production systems –

- Promote improved land management
- Provide other services to society
- Increase efficiency and help minimize or eliminate:
  - fossil fuels
  - “wastes”
- Reduce “climate forcing” (different from GHG emissions – and worthy of a separate talk)
- Can compete in the local market
- Support adaptive management
- Promote continual improvement toward “sustainability”

What biomass sources are recommended?

- Those that most effectively achieve society goals

Source: K.L. Kline presentation to ESPCA Brazil Advanced School on Bioenergy; October 2014

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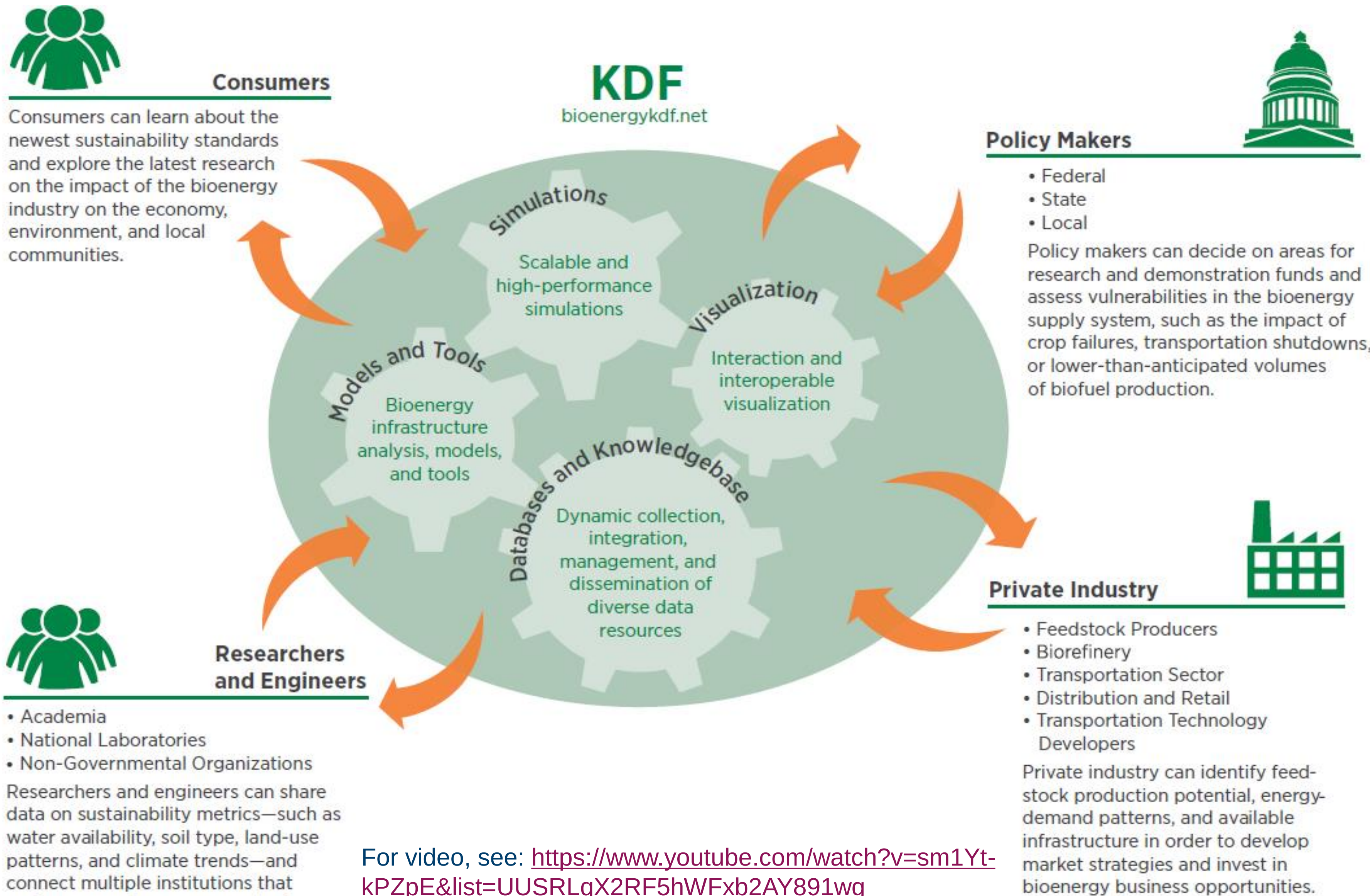
For more information: Bioenergykdf.net

BIOENERGY KNOWLEDGE DISCOVERY FRAMEWORK
KDF
U.S. DEPARTMENT OF ENERGY



For video, see: https://www.youtube.com/watch?v=sm1Yt-kPZpE&list=UUSRLqX2RF5hWFxb2AY891wg

Thank you

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See the website for

- Reports
- Forums
- Other presentations
- Recent publications

- Bibliography slides follow

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Further reading on bioenergy and sustainability:

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