Sustainability Indicators for Bioenergy Systems and Applicability to Genetically Modified Organisms (GMOs)

12th International Symposium on Biosafety of Genetically Modified Organisms, St. Louis, MO, Sept. 18, 2012

Presented by Rebecca A. Efroymson (efroymsonra@ornl.gov)
Center for BioEnergy Sustainability
Oak Ridge National Laboratory
http://www.ornl.gov/sci/ees/cbes/
Director: Virginia H. Dale (dalevh@ornl.gov)

Collaborators: LM Baskaran, MR Davis, ME Downing, LM Eaton, CT Garten, MR Hilliard, KL Kline, HI Jager, MH Langholtz, PN Leiby, AC McBride, PJ Mulholland, GA Oladosu, ES Parish, PE Schweizer and JM Storey

Main points

- Practical assessment of sustainability costs and benefits requires
  - A limited suite of indicators
    - Applicable to all energy options
  - Adjustments of indicators to particular contexts
- Prioritization of sustainability indicators for GMOs will
  - Begin with generic suite
  - Emphasize particular indicators
  - Refine suite where needed, based on new traits, public concerns, and familiarity with uses (species/trait/environment combinations)

Sustainability Indicators

Measurements that provide information about the effects of human activities on the environment, society or economy

Indicators should be

- Useful
  - Policymakers
  - Producers
- Technically effective
  - Sensitive to stresses on system
  - Anticipatory: signify impending change
  - Having known variability in response
- Practical
  - Easily measured
  - Relevant to context of measure
  - Broadly applicable
  - Predictive of changes that can be averted by management actions

Dale and Beyeler. 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1: 3-10.

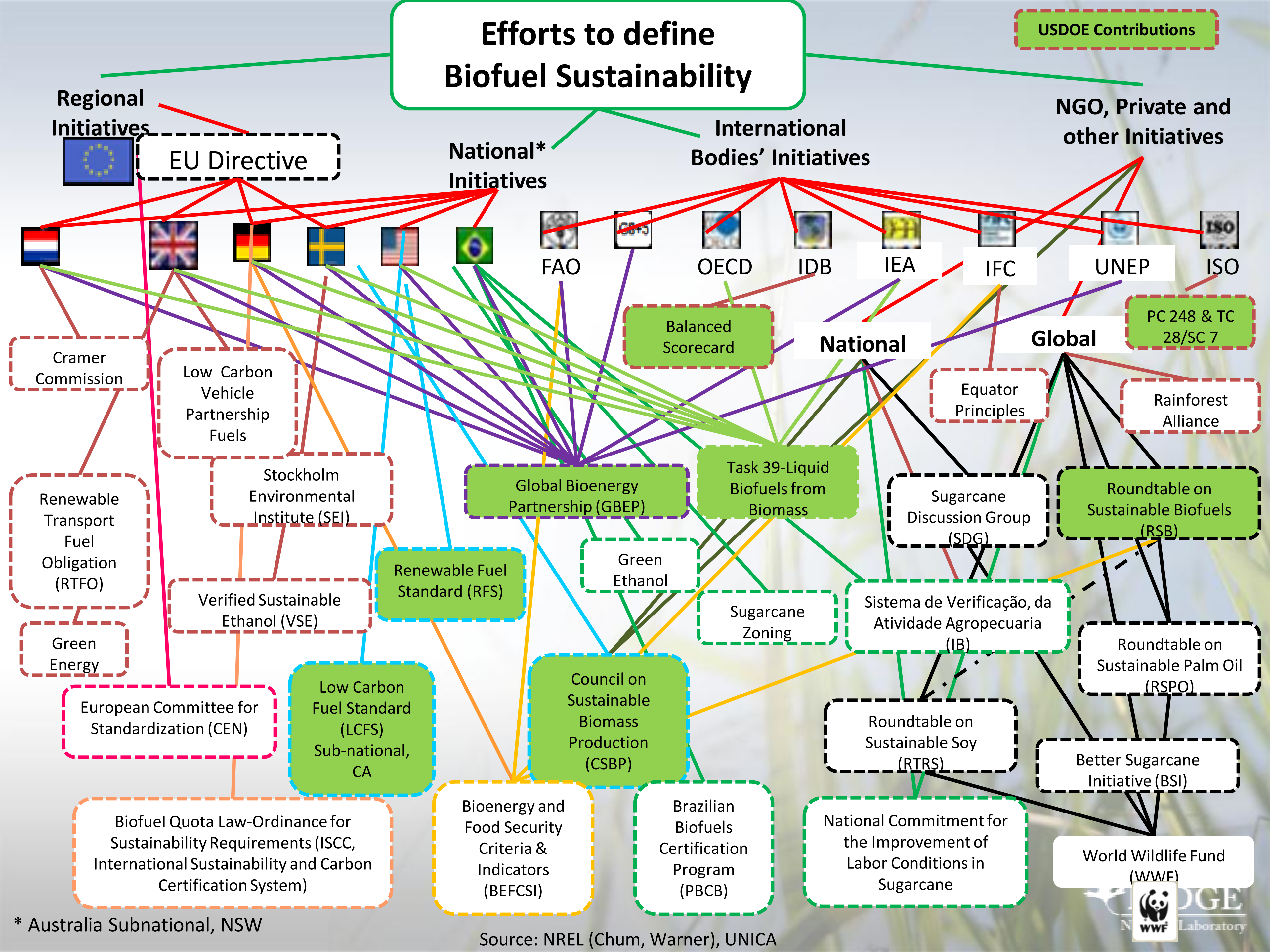
Many initiatives are exploring indicators for sustainability – e.g. for bioenergy…

- ISO (International Organization for Standardization)
- GBEP (Global Bioenergy Partnership)
- CSBP (Council on Sustainable Biomass Production)
- RSB (Roundtable on Sustainable Biofuels)
- Many more

BUT

- Some indicators focus on management practices although knowledge is limited about which practices are "sustainable"
- Implementation is limited by indicators being too
  - ✓ Numerous
  - ✓ Broad
  - ✓ Costly
  - ✓ Difficult to measure

OAK RIDGE National Laboratory


Efforts to define Biofuel Sustainability
USDOE Contributions
Regional Initiatives
EU Directive
National* Initiatives
International Bodies' Initiatives
NGO, Private and other Initiatives
FAO
G8+5
OECD
IDB
IEA
IFC
UNEP
ISO
Balanced Scorecard
National
Global
PC 248 & TC 28/SC 7
Cramer Commission
Low Carbon Vehicle Partnership Fuels
Equator Principles
Rainforest Alliance
Stockholm Environmental Institute (SEI)
Global Bioenergy Partnership (GBEP)
Task 39-Liquid Biofuels from Biomass
Sugarcane Discussion Group (SDG)
Roundtable on Sustainable Biofuels (RSB)
Renewable Transport Fuel Obligation (RTFO)
Green Ethanol
Renewable Fuel Standard (RFS)
Sugarcane Zoning
Sistema de Verificação, da Atividade Agropecuaria (IB)
Verified Sustainable Ethanol (VSE)
Green Energy
Roundtable on Sustainable Palm Oil (RSPO)
European Committee for Standardization (CEN)
Low Carbon Fuel Standard (LCFS) Sub-national, CA
Council on Sustainable Biomass Production (CSBP)
Roundtable on Sustainable Soy (RTRS)
Better Sugarcane Initiative (BSI)
Biofuel Quota Law-Ordinance for Sustainability Requirements (ISCC, International Sustainability and Carbon Certification System)
Bioenergy and Food Security Criteria & Indicators (BEFCSI)
Brazilian Biofuels Certification Program (PBCB)
National Commitment for the Improvement of Labor Conditions in Sugarcane
World Wildlife Fund (WWF)
WWF
* Australia Subnational, NSW
Source: NREL (Chum, Warner), UNICA

What can we learn from indicators, criteria, principles, & standards for GMOs that have been developed by partnerships and certification schemes for bioenergy sustainability?

Roundtable on Sustainable Biofuels

- For indicators on "technologies used" and "microorganisms "used" (including GMOs): Provide evidence that risk assessment was conducted prior to certification
  - Identifying impacts on stakeholders, communities, industries, society, environment
  - Demonstrating social and environmental benefits compared to alternatives
  - Identifying mitigation measures
  - Identifying "measures" to monitor these aspects of biofuel operation, impacts, mitigation measures and efficacy
- And that
  - Technologies comply with laws and scientific protocols
  - Measures to prevent migration have been implemented
  - Cooperation with stakeholders is occurring
  - Native crop could not provide same function with higher yield or environmental or social performance

(actual text much more detailed)

RSB is an international, multistakeholder initiative to create a certification system with sustainability standards, principles, criteria

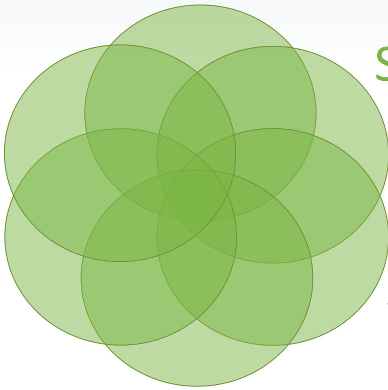
OAK RIDGE National Laboratory

Council on Sustainable Biomass

- Sustainability standard (developed by multi-stakeholder organization) including principles, criteria, and indicators for cellulosic bioenergy industry
  - Conservation practices should limit potential for spread of crop and "problematic genetic material" outside the production area
  - "The structure and ecological functioning of unmanaged native vegetation should not be altered or threatened by managerial activities such as use of genetically modified organisms"

OAK RIDGE National Laboratory

Categories for indicators of environmental and socioeconomic sustainability



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

Dale et al. (In review) *Ecological Indicators*

Recognize that effects may be positive or negative and the selection, measurement and interpretation are context-specific

[Efroymson et al. (2012) *Environmental Management*]

OAK RIDGE National Laboratory

Categories of environmental sustainability indicators

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

Categories of socioeconomic sustainability indicators

Category	Indicator	Units
Social well-being	Employment	Number of full time equivalent (FTE) jobs
	Household income	$ 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	$/gallon biofuel
	Fuel supply stability	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	$ (net exports or balance of payments)
Profitability	Return on investment (ROI)	% (net investment/ initial investment)
	Net present value (NPV)[2]	$ (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	% favorable opinion
	Transparency	% 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. [In review]

What about the context of assessments of bioenergy sustainability?

Purpose of assessment
- Assess current condition
- Monitor trends
- Provide early warning signal
- Diagnose cause

Stakeholder values

Spatial and temporal context
- Location
- Time
- Scale

Biofuel system
- Feedstock
- Supply chain
- Feedstock management

Decision context
- Policy
- Certification
- Comparison with alternatives

Baseline and reference conditions

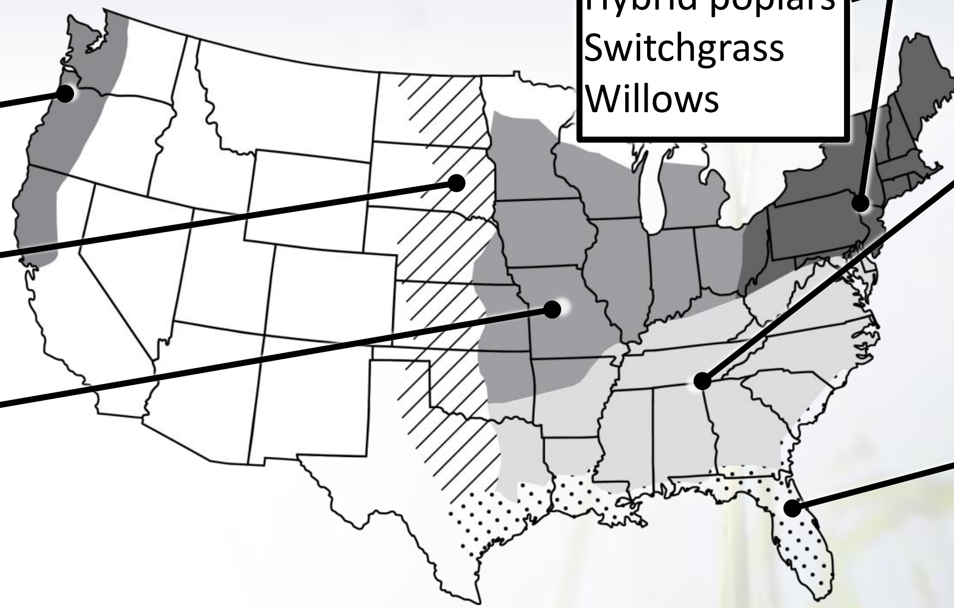
Context affects selection (prioritization), measurement, and interpretation of indicators

Efroymson, R. A., V. H. Dale, K. L. Kline, A. C. McBride, J. M. Bielicki, R. L. Smith, E. S. Parish, P. E. Schweizer, D. M. Shaw. 2012. Environmental indicators of biofuel sustainability: What about context? *Environmental Management* DOI 10.1007/s00267-012-9907-5

Examples of contexts

Different crops grow better in specific regions. Genetically modified versions of many are under development.

Dale et al. (2011)



Different feedstocks may have specific environmental concerns; e.g., where algae are grown in brine, salinity may be an appropriate indicator

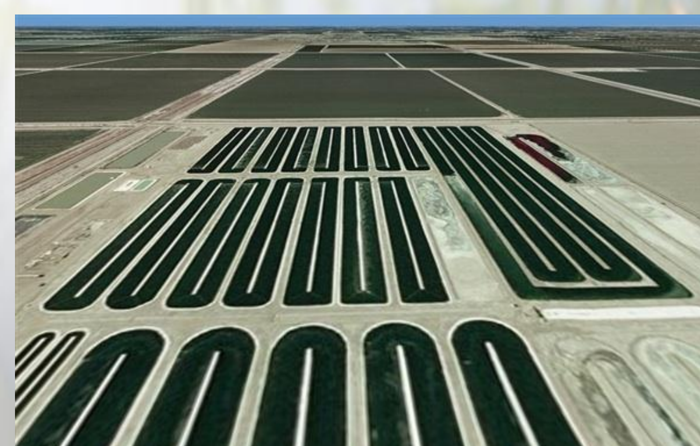
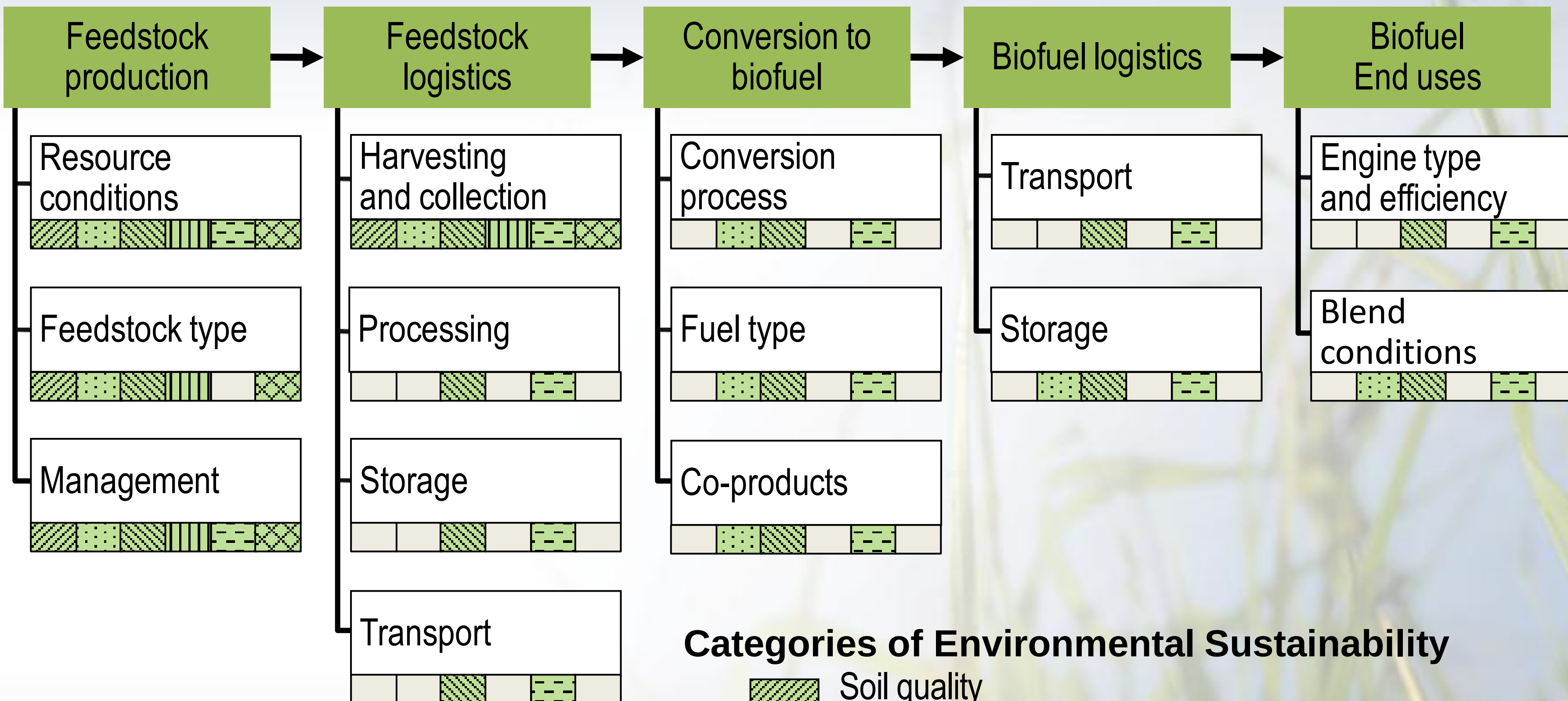
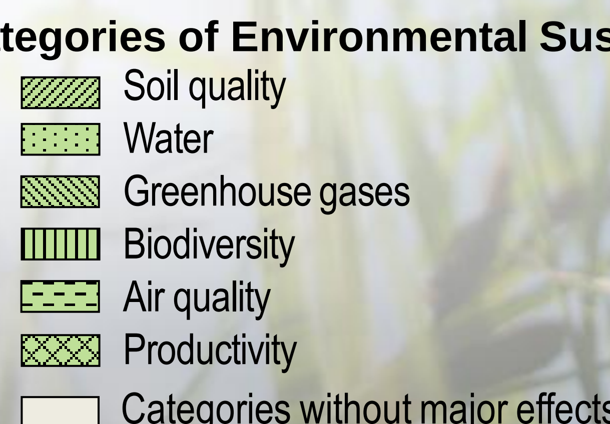


Photo from Pacific Northwest National Lab

Oak Ridge National Laboratory

The biofuel supply chain and environmental sustainability indicators

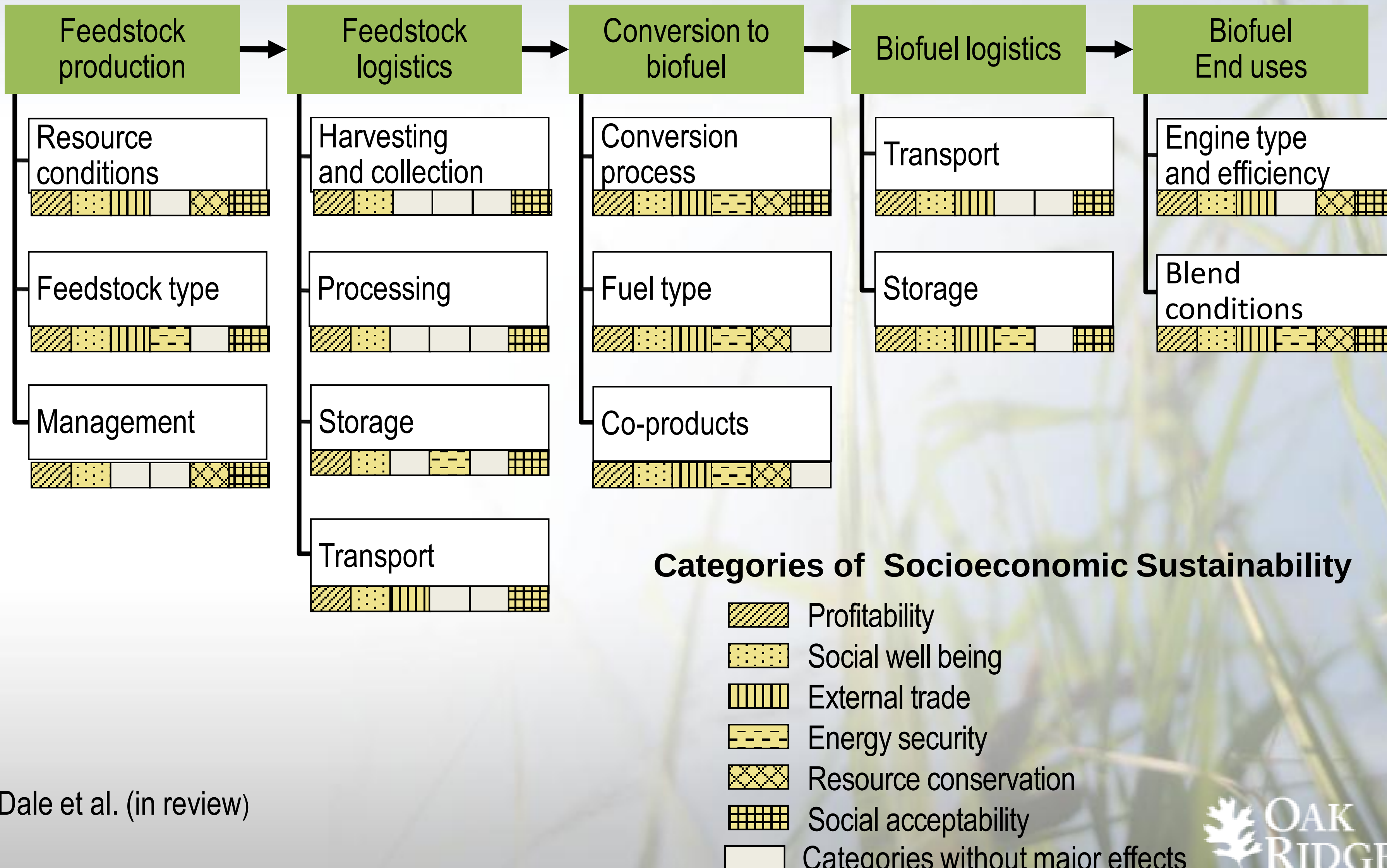




Efroymson et al. (2012). Environmental indicators of biofuel sustainability: What about context? Environmental Management

OAK RIDGE National Laboratory

The biofuel supply chain and socioeconomic sustainability indicators



Dale et al. (in review)

Which components of the supply chain are affected by GMOs?

Feedstock production

- >32 million acres of genetically modified corn in US; insect and weed control; primarily animal feed
- Research on enhanced accumulation of cellulases in transgenic maize seed
- Research on switchgrass (altered lignin content & composition)
- Research on increased lipid production in algae; tolerance to stressors

Feedstock logistics (harvesting, collection, transport)

INL image

- Potential occupational exposures
- Potential dispersal

Conversion to biofuels

- Switchgrass (depolymerization of cellulose & hemicellulose by engineered *E. coli*)
- Macroalgae (alginate depolymerization and ethanol fermentation by *E. coli* engineered with genes from *Pseudoalteromonas* sp. and *Vibrio splendidus*)

End use

- New fuel chemistry possible

Oak Ridge National Laboratory

Which sustainability indicators may be affected by GMOs?

Soil quality > if engineered for lower nutrient requirements

Water quality > if engineered for lower nutrient requirements

Water use < if engineered for lower water use

Biodiversity < or > if more or less invasive than non-engineered crop

Productivity > if engineered for greater yields

Profitability > if engineered for increased productivity
< if high costs of regulatory compliance or advertising to increase social acceptability

Employment and **External trade** are related

Social acceptability

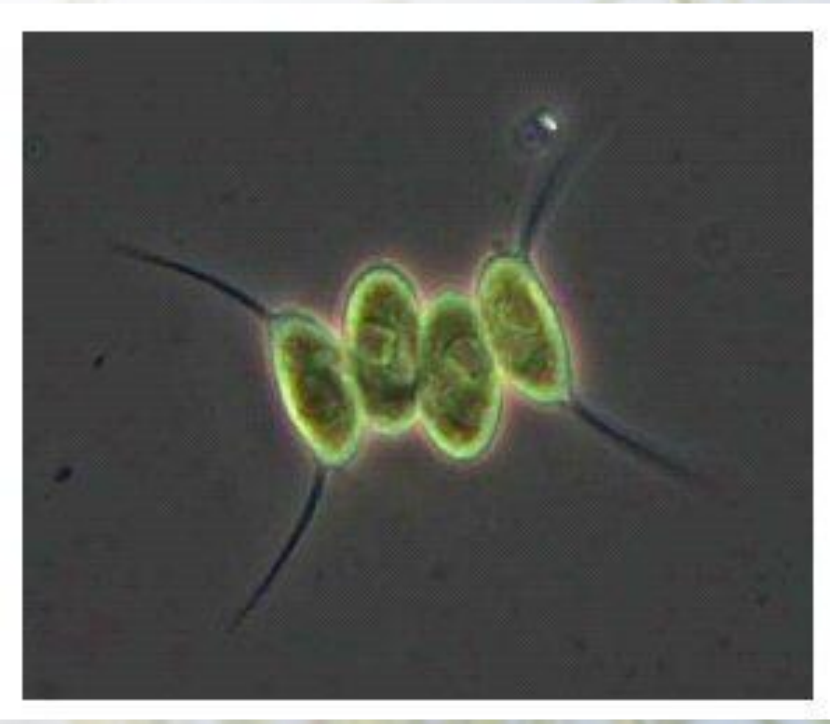
- **Public opinion** < possible
- **Stakeholder participation** > social acceptability if effective stakeholder participation
- **Risk of catastrophe** > or < non-GMO but expected low. Unfamiliar organism/environment combinations. (Indicator created for petroleum comparison)

OAK RIDGE National Laboratory

What refinements to sustainability indicators might be needed for GMOs?

Background

- Product (novel traits) more important than process (technologies) for evaluating risk, sustainability (NRC 1987, Tiedje et al. 1989, Snow et al. 2005)
- Novel traits possibly more common with genetic engineering than with horizontal gene transfer in evolutionary time
- Unanticipated effects could occur, especially in early field tests
- Indicators of effects may be needed



Scenedesmus for biodiesel, EPA-funded project, Nelson et al.

What refinements to sustainability indicators might be needed for GMOs?

Predictors of potential adverse effects of GMOs

- Probability of release
- Abundance of organisms released (predictor of establishment)
- Survival rate and fitness
- Reproduction rate
- Probability of dissemination to distant sites
- Interactions with other organisms
- Probability of genetic exchange
- **Observed effects**

(Alexander 1985)

Algae raceway in Israel. Source: NREL, ANL

All of these predictors may be indicators of effects, but direct measures of effects (when we know what those effects may be) are the most direct indicators of sustainability

Oak Ridge National Laboratory

What refinements to sustainability indicators might be needed for GMOs?

Indicator	Description	Indicator category
Familiarity	Number of uses of GMO feedstock without adverse environmental effects	Social acceptability • Risk of catastrophe • Public opinion Biodiversity
Invasiveness	Presence and abundance measures if species of concern is feedstock rather than valued component of environment	Biodiversity • Presence/absence • Abundance • Relative abundance
Containment	Genetic material measured outside the project area	Social acceptability Biodiversity

OAK RIDGE National Laboratory

Type of genetically modified feedstock—Greater potential concern about algae

	Genetically modified algae & cyanobacteria	Vascular crop plants
Familiarity	Low familiarity with use	Greater familiarity; no catastrophic problems
Containment	More difficult to contain; potential biological containment	Easier to contain with physical barriers
Monitoring	More difficult to monitor	Easier to monitor visually
Invasiveness	Some are cosmopolitan, but low knowledge about others	Greater knowledge for most species
Traits	Potential for wide range of traits to be modified	Wide range of traits have been modified already
Gene transfer	Horizontal gene transfer to unrelated species documented	Gene transfer to related species
Social acceptability	Potential concerns about environmental effects of released microorganisms	Rather high in U.S.

Sustainability—What is next?

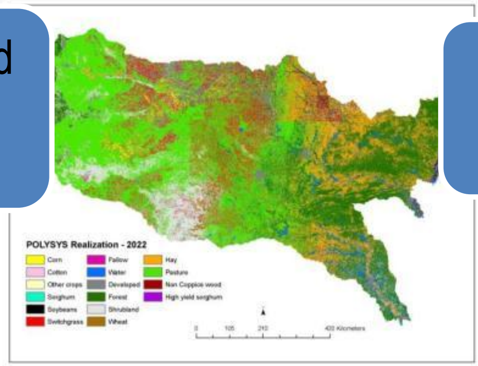
Select Indicators ✓

Establish baselines and targets

Evaluate indicator values

Identify trends and tradeoffs

Develop and test 'best' practices

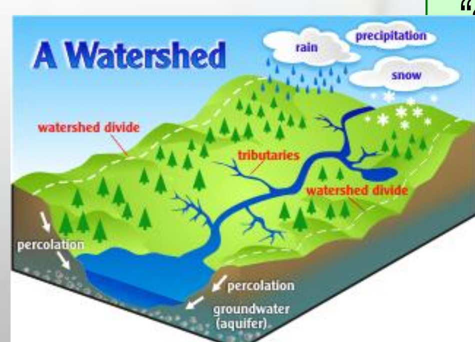


Facilitating establishment of sustainable industry

- Establishing indicators of sustainability
  - Defining indicators – what are critical few?
  - Determining existing baseline conditions and sustainable targets
  - Testing indicators of sustainability in specific contexts
- Evaluating trends and effects of tradeoffs for several aspects of sustainability
- Developing tools for multi-criteria spatial decision support to define & refine optimal management
- Conducting multi-variate assessment of "sustainability"

Collaborators include:

- Other DOE Labs (5)
- Other federal agencies
- Bioenergy teams (3)
- Certification efforts (4)
- Universities (7)
- Industry (7)



OAK RIDGE National Laboratory

Thank you!

Center for BioEnergy Sustainability

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

Photographs provided by ORNL
unless indicated otherwise

See the CBES website for

- **Reports**
- **Forums**
- **Other presentations**
- **Recent publications**

References

- Alexander M. 1985. Ecological consequences—Reducing the uncertainties. Issues in Science and Technology 1:57-68.
- Catford JA, PA Vesk, DM Richardson, P Pysek. 2012. Quantifying levels of biological invasion: towards the objective classification of invaded and invasible ecosystems. Global Change Biology 18:44-62
- Dale VH, SC Beyeler 2001. Challenges in the development and use of ecological indicators. Ecological Indicators 1: 3-10.
- Dale VH, KL Kline, LL Wright, RD Perlack, M Downing, RL Graham. 2011. Interactions among bioenergy feedstock choices, landscape dynamics and land use. *Ecological Applications* 21:1039-1054
- Dale, VH, RA Efroymson, KL Kline, MH Langholtz, PN Leiby, GA Oladosu, MR Davis, ME Downing, LM Eaton, MR Hilliard. In review. Indicators to support assessment of socioeconomic sustainability of bioenergy systems. Ecological Indicators.
- Efroymson RA, Dale VH, Bielicki J, McBride A, Smith R, Parish E, Schweizer P, Kline KL, Shaw D. 2012. Environmental indicators of biofuel sustainability: What about context? Environmental Management DOI 10.1007/s00267-012-9907-5
- Hagedorn C, Allender-Hagedorn S. 1997. Issues in agricultural and environmental biotechnology: Identifying and comparing biotechnology issues from public opinion surveys, the popular press and technical/regulatory sources. Public Understanding of Science 6:233-245
- Bokinsky et al. 2011. Synthesis of three advanced biofuels from ionic liquid-pretreated switchgrass using engineered Escherichia coli. PNAS. www.pnas.org/cgi/doi/10.1073/pnas.1106958108
- McBride A, VH Dale, L Baskaran, M Downing, L Eaton, RA Efroymson, C Garten, KL Kline, H Jager, P Mulholland, E Parish, P Schweizer, and J Storey. 2011. Indicators to support environmental sustainability of bioenergy systems. *Ecological Indicators* 11(5) 1277-1289.
- NRC. 1987. Field testing genetically modified organisms: framework for decisions. Washington, DC: National Research Council.
- Parish ES, M Hilliard, LM Baskaran, VH Dale, NA Griffiths, PJ Mulholland, A Sorokine, NA Thomas, ME Downing, R Middleton. 2012. Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels, Bioprod. Bioref*. 6(1):58-72.
- Snow AA, DA Andow, P Gepts, EM Hallerman, A Power, JM Tiedje, LL Wolfenbarger. 2005. Genetically engineered organisms and the environment: Current status and recommendations. Ecological Applications 15:377-404.
- Tiedje JM, RK Colwell, YL Grossman, RE Hodson, RE Lenski, RN Mack, PJ Regal. 1989. The planned introduction of genetically engineered organisms—Ecological considerations and recommendations. Ecology 70:298-315.
- Wargaki et al. 2012. An engineered microbial platform for direct biofuel production from brown macroalgae. Science 335:308-313