2015 DOE Bioenergy Technologies Office (BETO) Project Peer Review

Bioenergy Sustainability: How to Define & Measure It

Date: March 23, 2015
Technology Area Review:
Analysis & Sustainability

Principal Investigator: Virginia Dale
Organization: Oak Ridge National Laboratory

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

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Goal Statement

- Goal: Enable long- term supply of sustainable feedstock & bioenergy
  A. Advance common definition of environmental & socioeconomic costs and benefits of bioenergy systems
  B. Quantify opportunities, risks, & tradeoffs associated with sustainable bioenergy production in specific contexts
- Relates to BETO objectives
  - Establish performance metrics for bioenergy sustainability
  - Build consensus on specific definitions & ways to quantitatively measure bioenergy sustainability
  - Provide a consistent & evidence-based message on meaning of bioenergy sustainability
  - Build methodology to measure & assess sustainability
- Tangible outcomes for US
  - Agreement on definitions of bioenergy sustainability
  - Tools for quantification, aggregation of measures, & visualization
  - Examples of how to quantify sustainability in particular contexts

Quad Chart Overview

Timeline

- Project start date: FY09
- Project end date: FY17
- Percent- complete: 63%

Barriers

- St-B: Consistent, science-based message on bioenergy sustainability
- St-C: Sustainability data across the supply chain
- St-D: Implementing indicators and methodology for evaluating and improving sustainability
- St-G: Land use and innovative landscape design

Budget

- FY10-12: \$2034k (DOE)
- FY13: \$700k (DOE)
- FY14: \$700k (DOE)
- FY15-17: \$2200k (DOE)

Partners

- Stakeholders: Council on Sustainable Biomass Production (CSBP), Biomass Market Access Standards (BMAS), Global BioEnergy Partnership (GBEP), Roundtable for Sustainable Biomaterials (RSB), National Council on Air and Stream Improvement (NCASI)
- Other DOE Labs engaged (but no direct costs): NREL, ANL, INL, PNNL
- Other agencies: USDA, EPA, USFS, FAO (Food and Agriculture Organization), IEA (International Energy Agency)
- Universities: Univ. Tennessee, NC State Univ., Texas A&M, Great Lakes Bioenergy Research Center (GLBRC), Utrecht Univ., NSF Research Collaborative Network (RCN) led by Michigan Tech
- Industry: Arborgen, Ceres, Dupont, Genera, Institute for Forest Biotechnology, Weyerhaeuser, Plum Creek, Noble Foundation

Project Overview

- History of project 4.2.2.40
  - FY09: Initiated by DOE based on PI's experience with indicators
  - Challenges:
    - ➢ Bioenergy sustainability not well defined
    - ➢ Existing approaches use indicators that are too
      - ✓ Numerous
      - ✓ Costly
      - ✓ Broad
      - ✓ Difficult to measure
    - ➢ Some indicators focus on management practices but knowledge is limited about which practices are "sustainable"

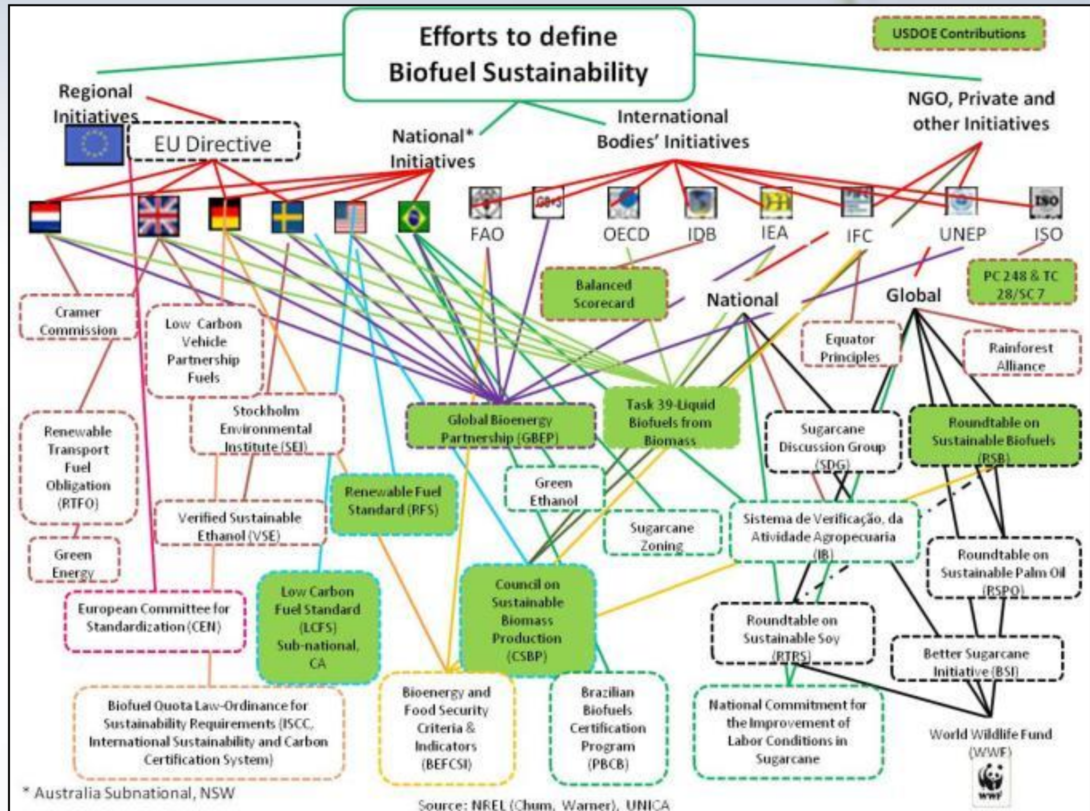


Chart of many initiatives exploring indicators for sustainability (Source: NREL & UNICA)

- Led to first objectives of project
  - Review existing sustainability indicators
  - Assist BETO in defining sustainability for bioenergy and determining indicators for use at the national scale
  - Determine ways to implement and evaluate sustainability indicators for bioenergy decisions

Previous Accomplishments (2009 to mid-2013)

- **Evaluated key challenges for bioenergy sustainability ***
  - **Interaction between land use & bioenergy**
    - Led BETO's Land-use change workshop and report
    - Biofuels, causes of land-use change, & the role of fire [Kline & Dale 2008. *Science* 321:199]
    - Land use – climate change – energy nexus [Dale et al. 2011. *Landscape Ecology* 26(6):755-773]
  - **Developing a balanced, science-based perspective about bioenergy**
    - Participated in Ecological Society of America (ESA) workshop and its products
      - Sustainable biofuels redux [Robertson et al. 2008. *Science* 322(5898): 49–50]
      - Biofuels: Implications for land use and biodiversity [Dale et al. 2010. ESA report]
      - Interactions among bioenergy feedstock choices, landscape dynamics & land use [Dale et al. 2011. *Ecol. App.* 21:1039-1054]
    - Biofuels, Done Right [Kline et al. 2009. *Issues in Science and Technology* 25(3): 75-84]
  - **Communications**
    - Communicating about bioenergy sustainability [Dale et al. 2013. *Environ. Manage.* 51:279-29]
  - **Regional approaches**
    - Bioenergy sustainability at the regional-scale [Dale et al. 2013. *Ecology and Society* 15(4): 23]
    - Multi-scale comparison of gasoline and ethanol [Parish et al. 2013. *Environ. Manage.* 51: 307-338]
    - Importance of context [Efroymson et al. 2013. *Environ. Manage*. 51:291-306]
- **Proposed sustainability indicators for bioenergy ***
  - **Ecological indicators** [McBride et al. 2011. *Ecological Indicators* 11:1277-1289]
  - **Socioeconomic indicators** [Dale et al. 2013. *Ecological Indicator*s 26: 87-102]
- **Applied proposed approach ***
  - **Multimetric spatial optimization of switchgrass** [Parish et al. 2012. Biofuels, Bioprod. Bioref. 6(1):58-72]
  - **Indicators for bioenergy sustainability applied to Eucalyptus** [Dale et al. 2013. International Journal of Forestry Research]

*** Shared findings with industry, universities, NGOs, land holders & other stakeholders**

Overall Approach

Code for checks	
✔	Completed
✔	Tested in East TN
✔	Reviewed

Fig. 2.38 in BETO's Multi-Year Program Plan (MYPP)

Summary of approach: Indicators

Best practices

Project Management Approach (1)

– ***Team:***
  - Virginia Dale, landscape ecologist (principal investigator)
  - Latha Baskaran, watershed modeling
  - Rebecca Efroymson, risk assessment
  - Keith Kline, energy specialist and international issues
  - Esther Parish, geographer
  - Nate Pollesch, mathematician
  - Mike Hilliard, optimization analyst

– ***Supplemental team***
  - Other ORNL staff
  - Scientists at other DOE Labs
  - University partners
  - Other agencies: USDA, EPA, FAO, IEA
  - Private partners: Industry and NGOs

– ***Review of progress***
  - Workshops that foster discussion
  - Publications in peer reviewed journals
  - Presentations at conferences
  - Engagement with stakeholders

Landscape Design Workshop participants at Weyerhaeuser Facility

Project Management Approach (2)

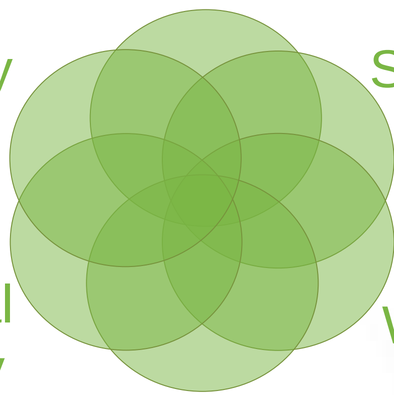
Key means for monitoring progress

- **Milestones defined & delivered**
  - Annual update of project plan
  - Quarterly reports & conference calls with BETO
- **Resources & partnerships leveraged**
  - Southeastern Partnership for Integrated Bioenergy Supply Systems (IBSS) – supported by USDA
  - International Energy Agency (IEA) Task 43
  - Coordination with other National Labs
    - Landscape design workshops planned & held in conjunction with Argonne National Lab
    - Testing of indicator-to-best practices (BP) approach
- **Risks defined & addressed**
  - Risk definition part of annual plan
  - Report to BETO on how risk addressed

Approach:
Indicators
↓
Best practices

2 - Technical Accomplishments

Goal A. Advancing common definitions of environmental & socioeconomic costs and benefits of bioenergy systems



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

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

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

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

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Categories of Socioeconomic Sustainability Indicators

Ten minimum practical measures

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 output
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.

Sustainability should Apply to

- Entire supply chain
- Diverse feedstocks
- All conversion pathways

Feedstock production → Feedstock Logistics → Conversion → Biofuel Distribution → End use

- **Feedstock production**
  - Land conditions
  - Feedstock type
  - Management
- **Feedstock Logistics**
  - Harvesting and collection
  - Processing
  - Storage
  - Transport
- **Conversion**
  - Conversion process
  - Fuel type
  - Co-products
- **Biofuel Distribution**
  - Transport
  - Storage
- **End use**
  - Engine type and efficiency
  - Blend conditions

(Example shown is biofuel, but concepts are applicable to bioenergy as well)

Dale et al. (2013) *Environmental Management* 51(2): 279-290.

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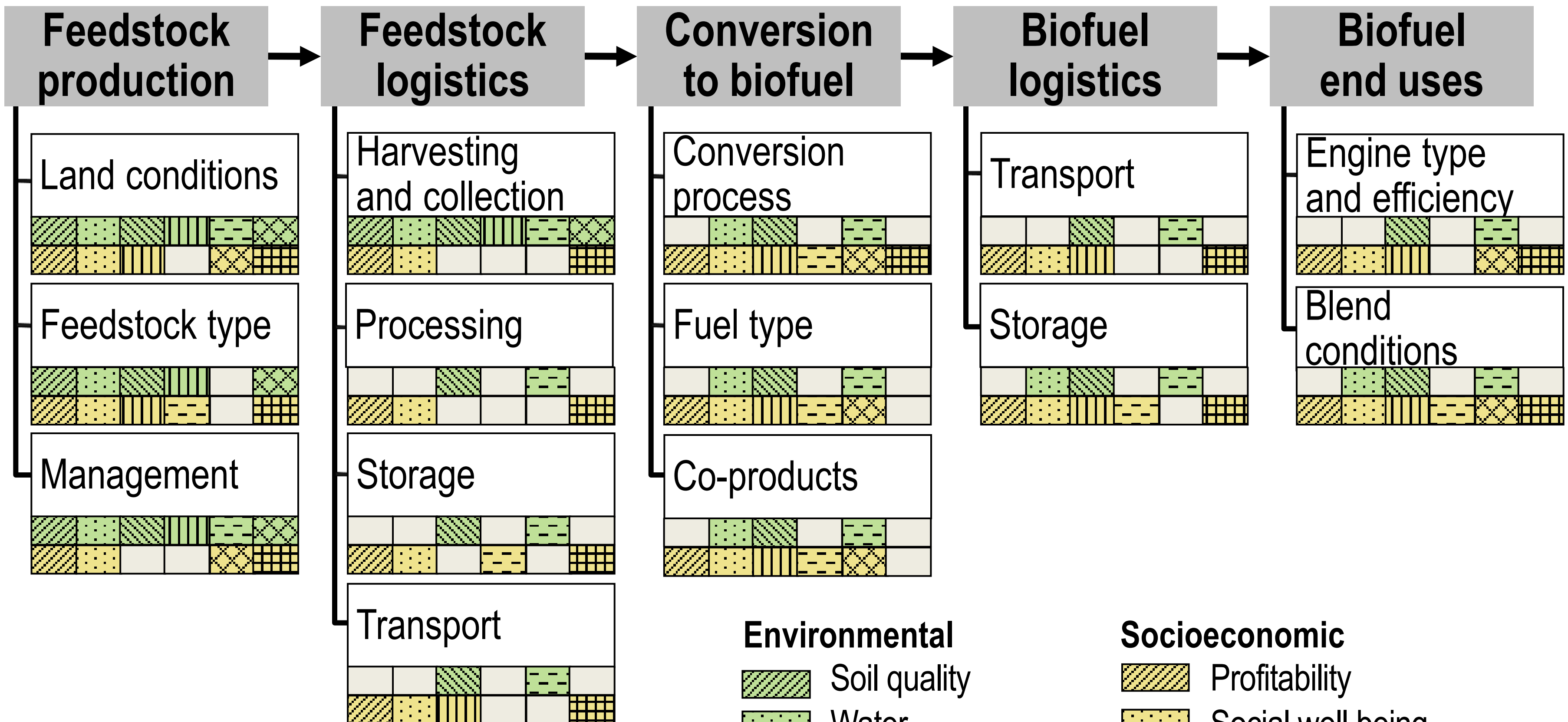
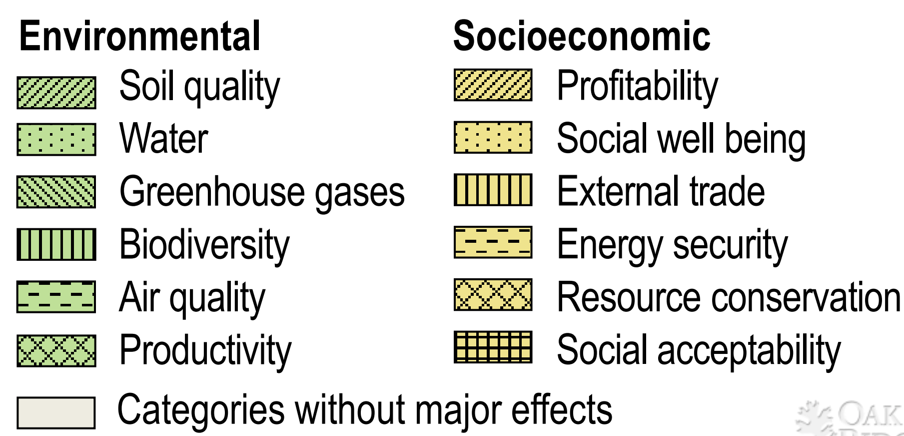
Consider Biofuel Supply Chain in terms of Sustainability Indicators



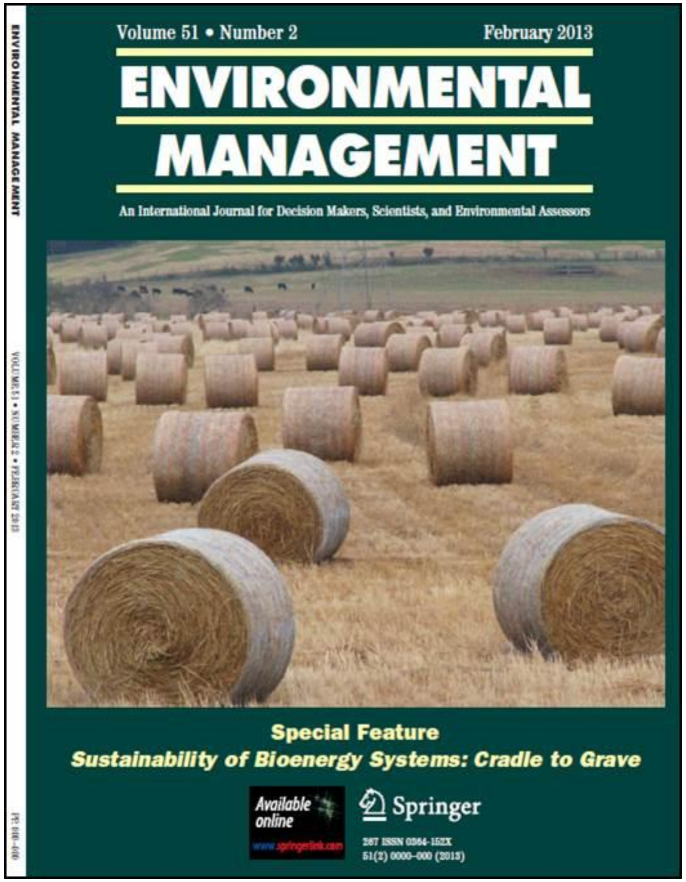


Efroymson et al. (2013) *Environmental Management* 51:291-306.

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

Worked with Others to Advance Common Definitions of Environmental & Socioeconomic Costs & Benefits of Bioenergy

- **Key partners (see http://www.ornl.gov/sci/ees/cbes/Collaborations.shtml)**
  - National Council for Air and Stream Improvement (NCASI)
  - National Science Foundation Research Collaboration Network on Bioenergy Sustainability
  - ORNL workshops: (http://www.ornl.gov/sci/ees/cbes/)
  - Bioenergy Sustainability: Cradle to Grave [Special feature in Feb 2013 issue of *Environmental Management*]
  - BETO workshops on landscape design
- **Assisted BETO by providing reviews and analysis when requested, for example**
  - GBEP (Global Bioenergy Partnership)
  - RSB (Roundtable on Sustainable Biomaterials)
  - FAO (Food and Agriculture Organization)
- **Worked to establish common basis for certification:**
  - BMAS (Biomass Market Access Standards)
  - IEA (International Energy Agency) Task 43
  - ISO (International Organization for Standardization)



[ORNL's engagement with international partners presented by Keith Kline]

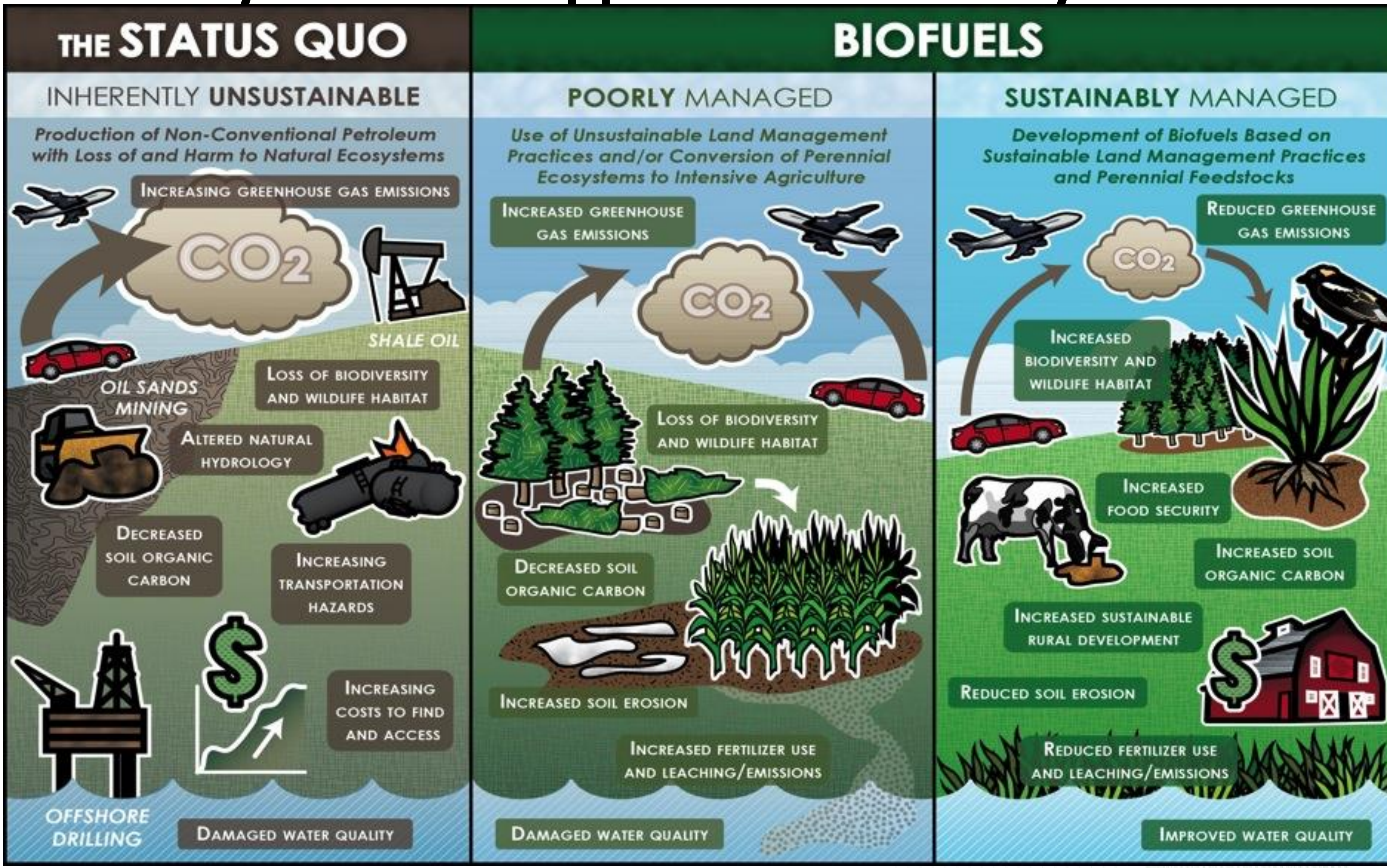
2 - Technical Accomplishments (cont.)

Goal B. Quantify opportunities, risks & tradeoffs associated with sustainable bioenergy production in specific contexts

- **Developing/testing tools for assessment of progress toward bioenergy sustainability**
  - ➢ Developed or adapted needed tools for assessment of bioenergy sustainability
    - ✓ Mathematical aggregation
    - ✓ Multi-Attribute Decision Support Systems (MADSS)
    - ✓ Landscape design approach
  - ➢ Developed framework for using indicators
    - ✓ Reviewed BPs
    - ✓ Showed how sustainably managed biofuels support sustainability goals
  - ➢ Focused on particularly challenging indicators
    - ✓ Biodiversity
    - ✓ Water Quality
- **Case studies of evaluating progress toward bioenergy sustainability**
  - ➢ Switchgrass in east Tennessee - applied Multi-Attribute Decision Support Systems (MADSS)
  - ➢ Pellet production in SE US - testing landscape design
  - ➢ Feedstocks in other regions - testing indicator approach

    E.g., NCSU, NEWBio, and Pan American RCN with Michigan Tech

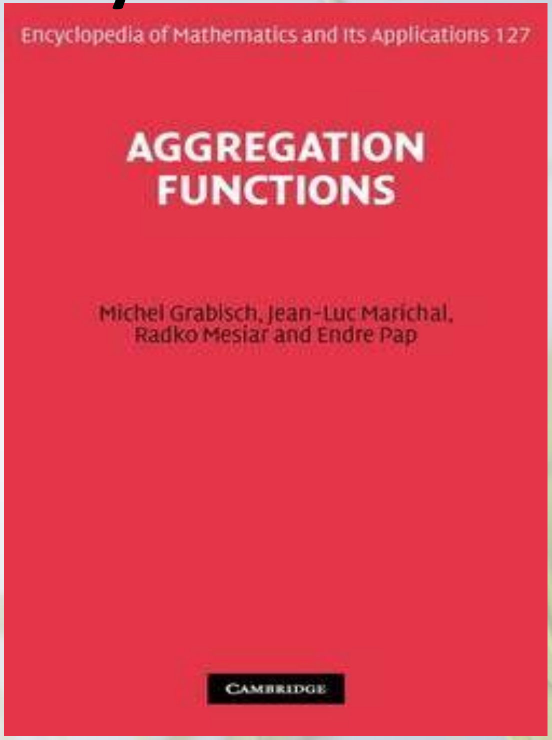
Identified Opportunities for Management of Biofuel Systems to Support Sustainability Goals



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

Conducting Mathematical Analysis of Aggregation Functions Applied to Bioenergy Sustainability

- **Challenges in bioenergy sustainability assessment**
  - ✓ Diverse production pathways
  - ✓ Varying environmental & sociopolitical sensitivities
  - ✓ Varying data quality & availability
- **Hence bioenergy sustainability assessments must be**
  - ✓ Flexible
  - ✓ Adaptable for assessment
  - ✓ Mathematically rigorous
- **Factors for determining appropriate aggregation strategies**
  - ✓ Desired assessment application
  - ✓ Characteristics of indicator data
- **Development of sustainability assessment protocol**
  - ✓ Bridges the gap between identification of bioenergy sustainability indicators and the creation of assessment and visualization tool
  - ✓ Addresses current challenges in sustainability assessment



We are applying *Aggregation Functions* to formalize the application of aggregation theory to bioenergy sustainability.

- **Anticipated products**
  - Pollesch and Dale (In press) Applications of aggregation theory to sustainability assessment. *Ecological Economics*
  - Pollesch and Dale (in prep) Toward a sustainability target assessment tool for bioenergy: Key components and requirement specifications.
  - Development, testing, & deployment of visualization tool
    - Providing rigorous means to aggregate information
    - Available for general usage (via KDF)

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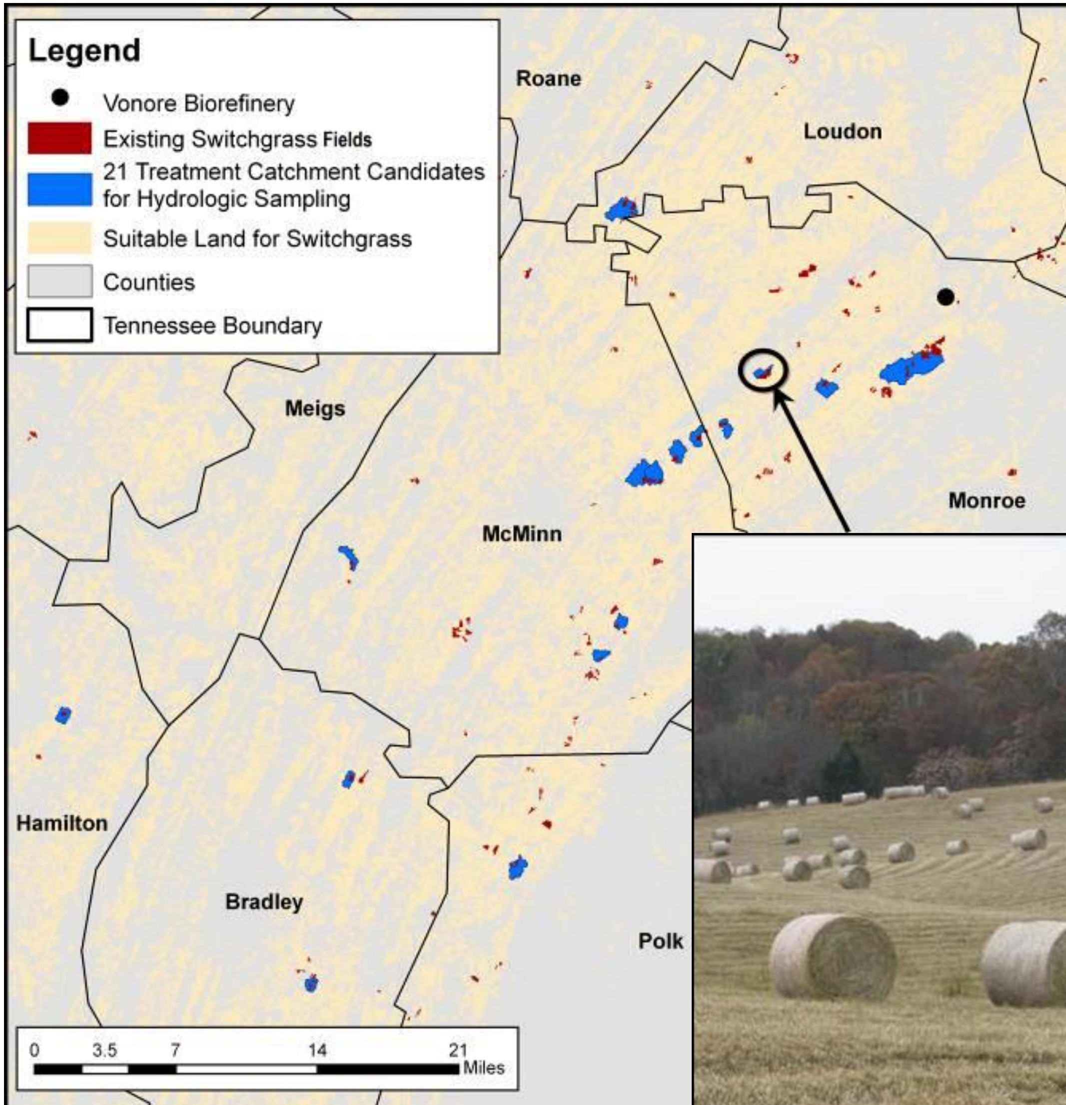
Using Multi-Attribute Decision Support System (MADSS): to compare sustainability of 3 scenarios in east Tennessee

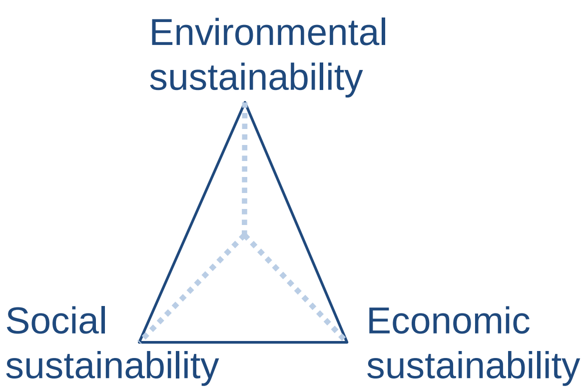
Leverages data from SE Partnership for Integrated Biomass Supply Systems (IBSS)

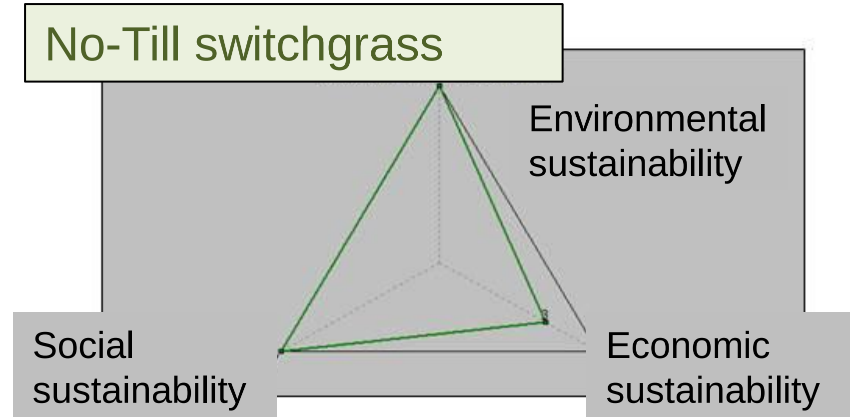


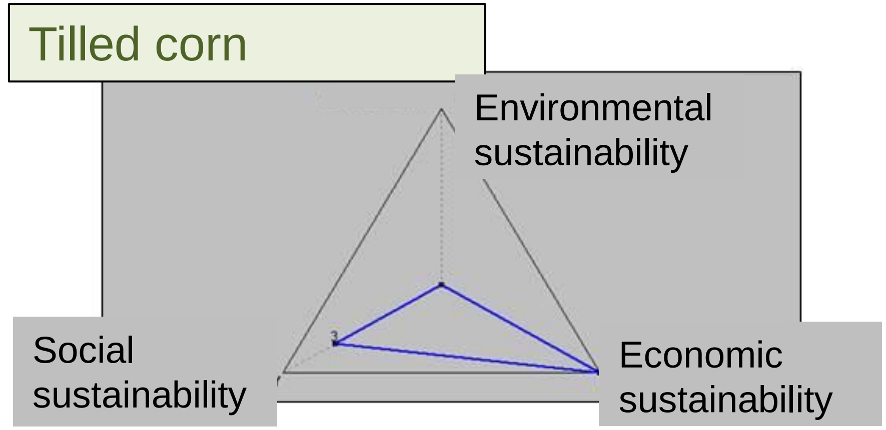
Case Study of MADSS Applied to East TN:

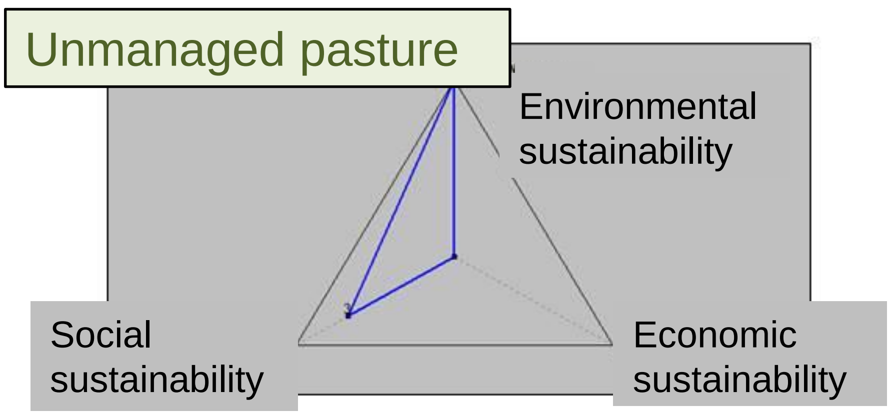
Determines relative contributions of three "pillars" to overall sustainability

Key to chart







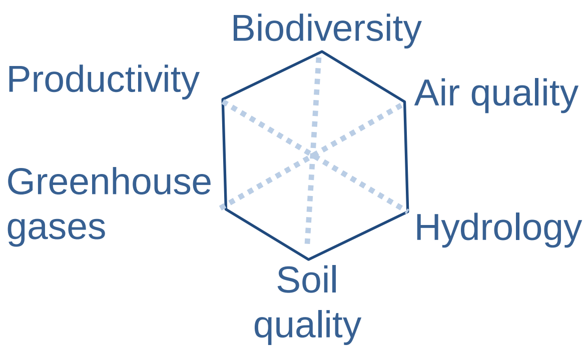


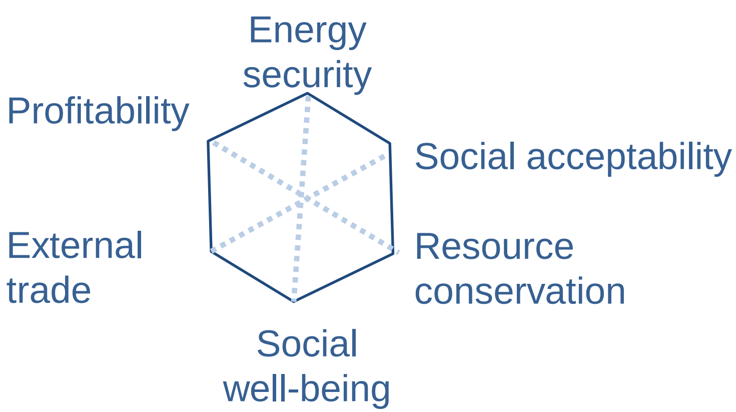
[Parish et al. (In review) Assessing multimetri aspects of sustainability. Ecosphere]

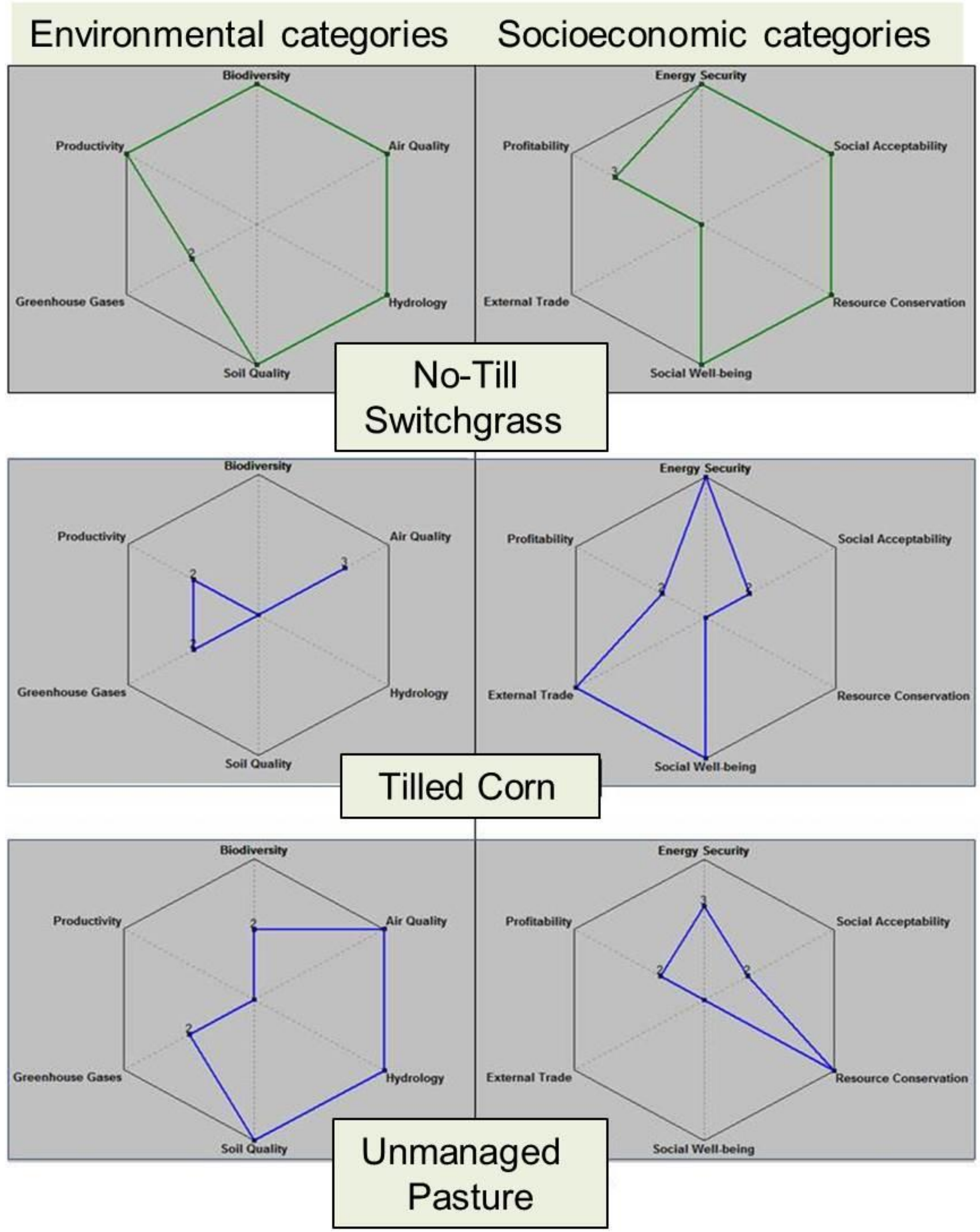
Case Study of MADSS Applied to East TN:

Rates environmental & socioeconomic sustainability

Key to chart







[Parish et al. (In review) Assessing multimetric aspects of sustainability. *Ecosphere*]

Developing Landscape Design Approach

- **Landscape design workshop**
  - Focused on bioenergy production systems
  - Integrates other components of the land, environment & socioeconomic system.
- **Tangible actions that can enable & expand sustainable development of the bioeconomy**
- **Southeast US opportunities using woody materials**
- **Workshop report, agenda, participant list, tour guide, & presentations at** http://web.ornl.gov/sci/ees/cbes/workshop.shtml.

New Bern, North Carolina, March 4-6, 2014
Organizers: ORNL, ANL, BETO & NCASI

Follow up workshop at Argonne National Lab (Cristina Negri will discuss)

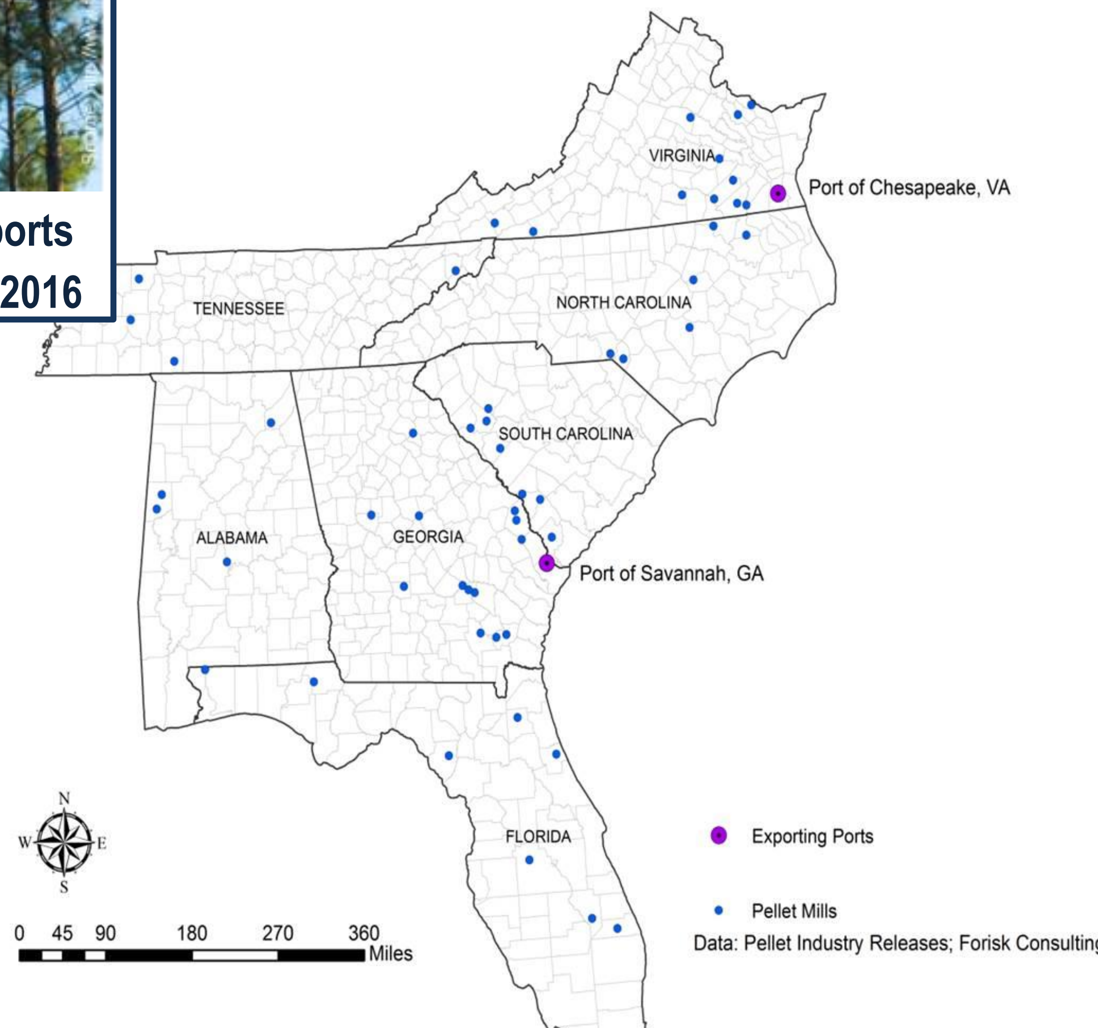
Proposed Landscape Design Approach

[Dale et al. (In review) Incorporating Bioenergy into Sustainable Landscape Designs. *Renewable & Sustainable Energy Reviews*]

Next Step in Application of Landscape Design: Test Approach for Southeastern Pellet Mills

Example: exports at risk, US pellet exports Valued $650M in 2013, > $1B (est.) by 2016

Location of pellet mills in Southeast US



Advisory team:

- NCASI
- Weyerhaeuser
- Plum Creek

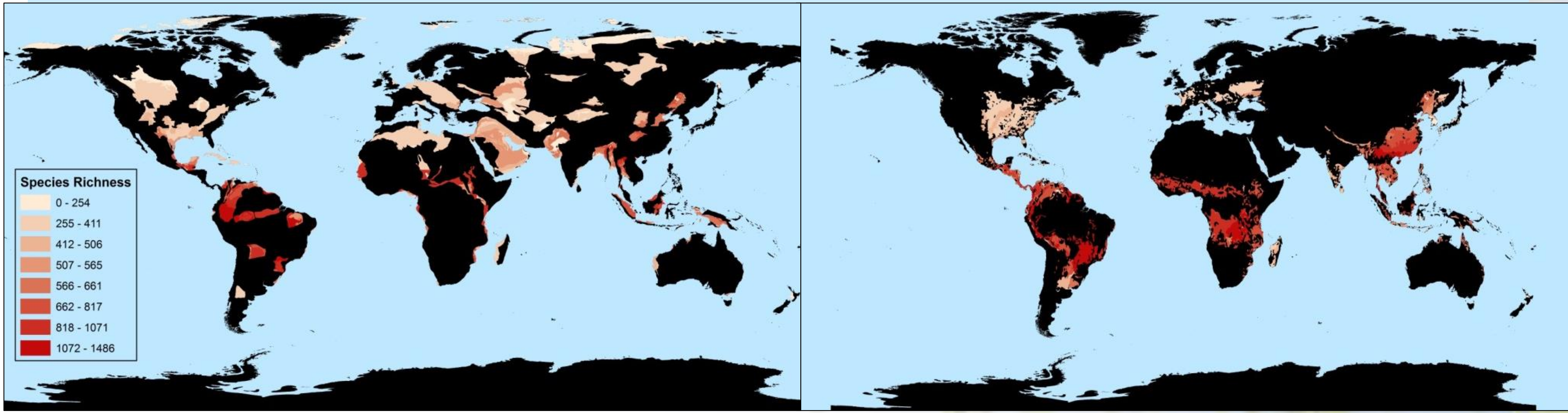
Collaborators:

- NCSU: Bob Abt
- USDA: Karen Abt
- Utrecht University: Floor Van der Hilst, Anna Duden, Steef Hanssen

Comparing Biodiversity Risks from Biofuels versus Gasoline

Overlay of Species Richness onto Locations with Sources of Fuel

Petroleum reserves | Bioenergy feedstock production areas



- Petroleum exploration activities projected to affect
  - > 5.8 billion ha of land and ocean worldwide (3.1 billion ha on land)
  - Much in remote, fragile terrestrial ecosystems or off-shore oil fields that would remain relatively undisturbed if not for interest in fossil fuel production.
- Biomass production for biofuels projected to affect
  - ~ 2.0 billion ha of land
  - Most located in areas already impacted by human activities.

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Dale VH, ES Parish, KL Kline (2015). Risks to global biodiversity from fossil-fuel production exceed those from biofuel production. *Biofuels, Bioprod. Bioref.*

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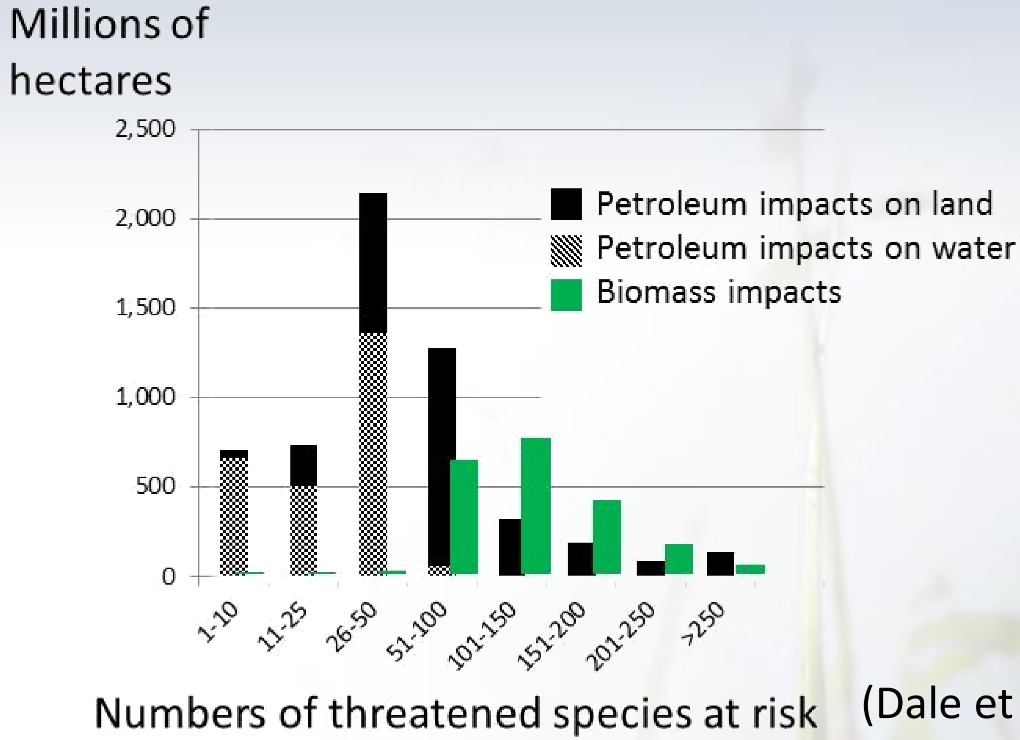
Biofuel Expansion could Impact Threatened Species



(Dale et al. 2015)

Negative effects of biofuel production on biodiversity & ecosystem services can be avoided or reduced & positive effects enhanced by*:

- Identifying & conserving priority biodiversity areas
- Recognizing that effects of biofuel feedstock production on biodiversity & ecosystem services are context specific
- Applying location-specific management of biofuel feedstock production systems.

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*[Joly et al. 2015 – Chapter in SCOPE book – to be released in April 2015]

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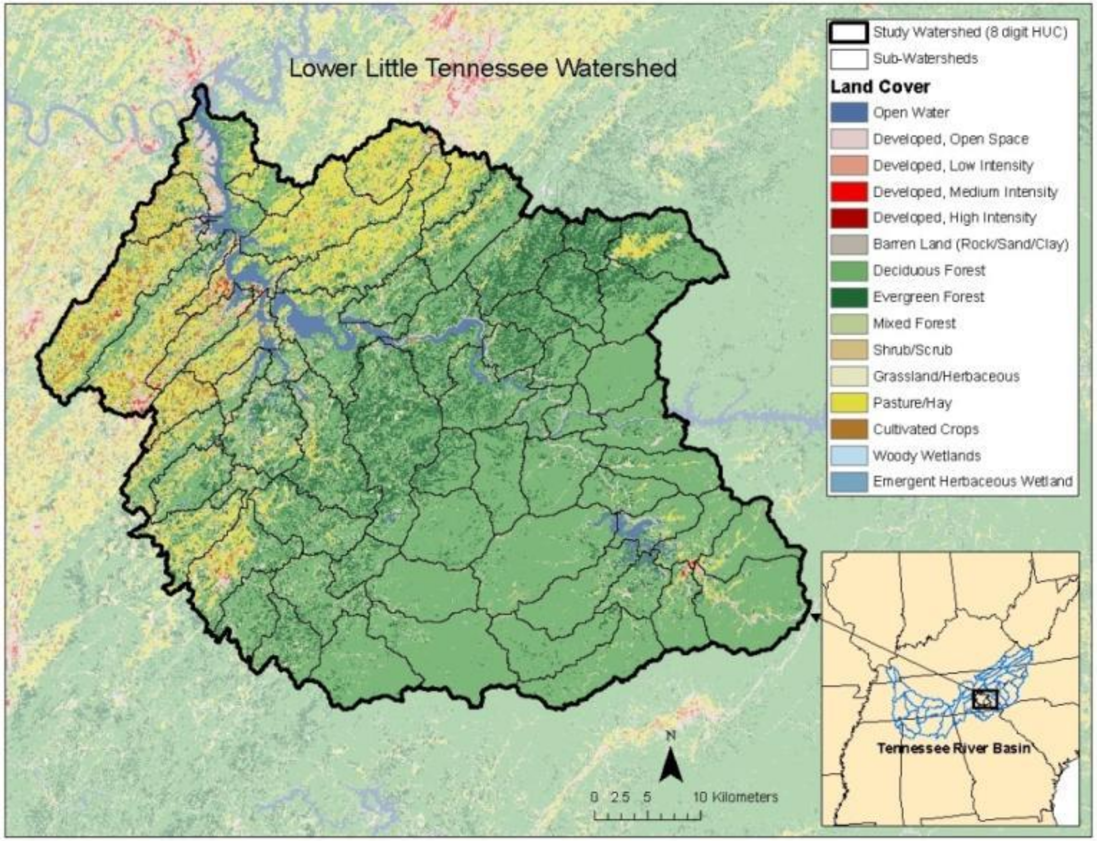
Identifying Cost Effective Surrogate for Measuring Water Quality Effects Associated with Bioenergy



Consider multiple effects:

Land-use change

⇩

Changes in water quality

⇩

Changes in habitat

⇩

Changes in species

EPT richness = number of distinct taxa in the insect orders

- Ephemeroptera (mayflies)
- Plecoptera (stoneflies)
- Trichoptera (caddisflies)

[Baskaran et al. (in prep) Aquatic macroinvertebrate as water quality indicators for switchgrass-based land-use change across Tennessee.]

Reviewing Best Practices (BPs) for Bioenergy

- **Many BPs developed for forestry & other bioenergy feedstocks**
  - Some are applicable to bioenergy sustainability, but others are too general
  - Typically focused on a single sustainability category but may be useful for meeting other objectives (e.g., water quality BPs often promote soil quality)
- **Most management practices have particular focus**
  - For energy crops are focused on productivity
  - For harvesting forest biomass are focused on soil & water quality
- **BPs need to be expanded**
  - Are needed for
    - Water quantity
    - Biodiversity
    - Greenhouse gas emissions
    - Air quality
  - Need to be related to particular sustainability targets

- **Regional research is needed**
  - To identify BPs appropriate for particular bioenergy systems
  - To consider tradeoffs in implementing BPs for different aspects of sustainability

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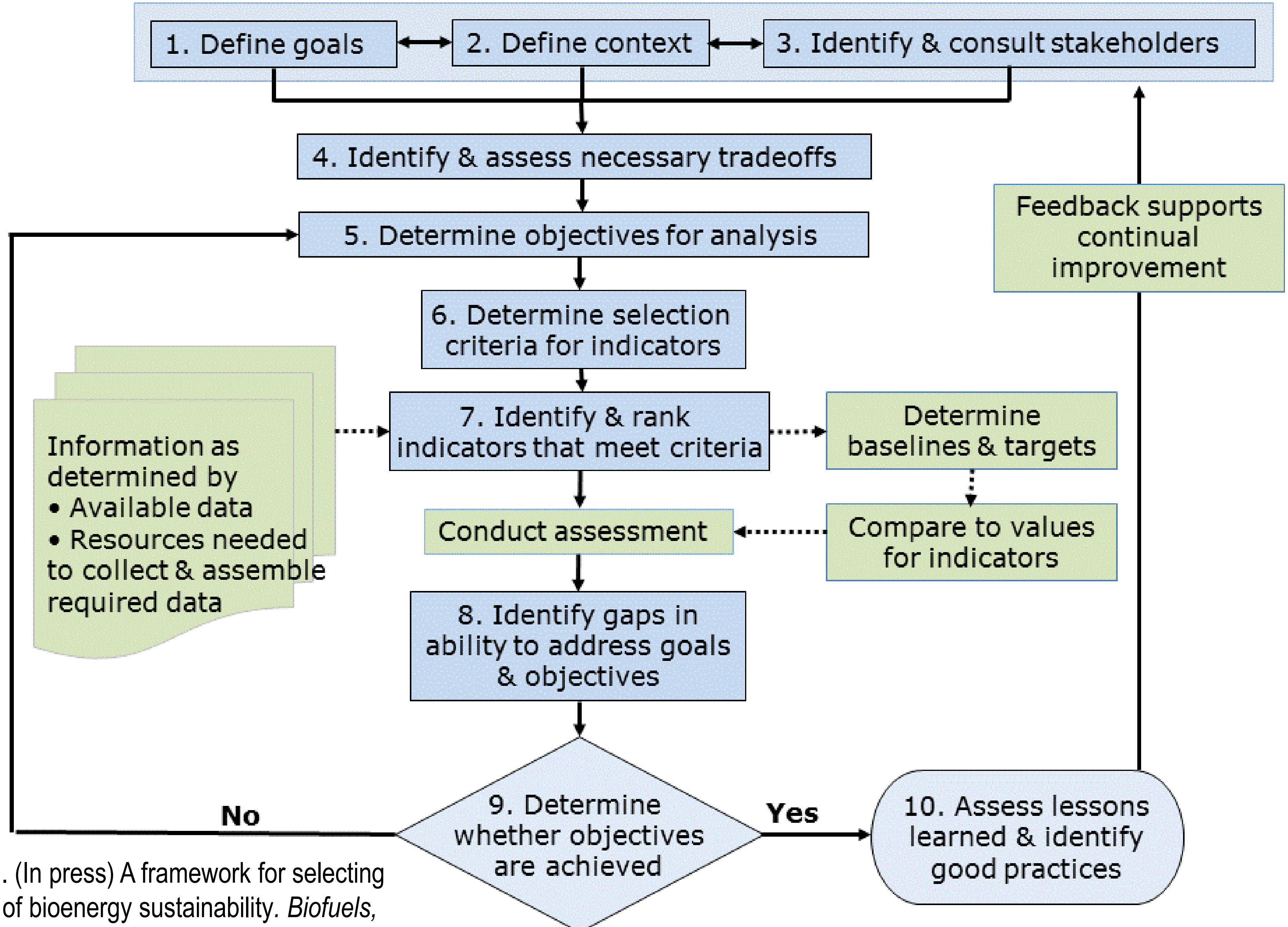
Developed Framework for Selecting Indicators to Assess Progress Toward Bioenergy Sustainability



[Dale et al. (In press) A framework for selecting indicators of bioenergy sustainability. *Biofuels, Bioproducts & Biorefining*.]

4 – Relevance

Measures of Success for Project

- **Environmental & socioeconomic aspects of sustainability are critical to commercially viable and sustainable bioenergy industry**
  - Bioenergy sustainability is recognized as being context specific
  - Assessment of sustainability of bioenergy systems is deployed across the industry
  - Interactions & trade-offs for different bioenergy scenarios are considered
  - Environmental, social, & economic indicators are assessed across the supply chain.
- **Best practices for sustainable bioenergy production based on**
  - Targets, baselines, & trends in particular contexts
  - Environmental & socioeconomic sustainability of bioenergy systems
  - Landscape designs of sustainable bioenergy systems
- **Aggregation & visualization tools support robust assessment of progress toward sustainable bioeconomy**

5. Future Work

- **Develop <u>case study</u> of use of woody biomass in the SE US using landscape design approach to enhance progress toward sustainability**

- **Identify environmental, social, & economic <u>incentives and barriers</u> and <u>best practices</u> for deployment of sustainable bioeconomies**

- **Complete and test <u>aggregation</u> theory as applied to sustainability of bioenergy systems**

- **Test & deploy <u>visualization tool</u> of measures of progress toward sustainable bioenergy**

- **<u>Evaluate overall approach</u> to assess progress toward bioenergy sustainability & its application in industry**

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Summary (1)

- **Approach**
  - ✓ From indicators to baseline & targets to evaluation to trends & tradeoffs to best practices
  - ✓ Working toward robust analysis tools to quantify and visualize progress toward sustainability
- **Technical accomplishments**
  - ✓ Identified set of environmental & socioeconomic indicators that advance common definition of costs and benefits of bioenergy systems
  - ✓ Quantified opportunities, risks, & tradeoffs associated with sustainable bioenergy production in specific contexts
  - ✓ Began adoption of aggregation theory for assessment of bioenergy sustainability
  - ✓ Developing understanding of how to assess progress toward bioenergy sustainability
- **Relevance**
  - ✓ Focusing on sustainability of bioenergy across entire supply chain
  - ✓ Considering environmental & socioeconomic aspects of sustainability
  - ✓ Quantitative tools to assess progress toward bioenergy sustainability
- **Critical success factors and challenges**
  - ✓ Establishment of a baseline for assessing sustainability of feedstock supply (i.e., production, harvest/collection, & processing)
  - ✓ Using sustainability data across the supply chain
  - ✓ Defining best practices for sustainable bioenergy production
  - ✓ Deployment of tools for aggregation, visualization & considering trade-offs among different stakeholder objectives & different bioenergy systems

Approach:

Indicators

↓

Best Practices

Summary (2)

- **Future work**
  - Test landscape design approach to enhance progress toward sustainability for case study of woody biomass
  - Determine barriers, incentives & BPs for particular case studies of bioenergy sustainability
  - Develop & apply methods to aggregate & visualize progress toward bioenergy sustainability
  - Test overall approach
- **Technology transfer**
  - Inclusion of information in BETO's Knowledge Discovery Framework (KDF) allows for archiving & sharing
  - Dissemination via 17 journal articles & book chapters and >50 presentations in past two years
  - Many presentations & exchanges with colleagues from industry, other national labs, federal agencies, universities, & nongovernmental organizations
  - Provided tools, ideas, & material
    - To other scientists (e.g., Kristen Johnson, Keith Kline, SCOPE report, IEA TASK 43)
    - To industry (e.g., NCASI)
    - To certifications efforts (e.g., ISO, BMAS)

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Additional Slides

Note that presentations, workshops, awards, and other activities are covered at the website for the ORNL Center for BioEnergy Sustainability: http://www.ornl.gov/sci/ees/cbes/

Progress Since 2013 Review of 4.2.2.40

- Strengths (select quotes from 2013 review)
  - "This project is a foundational effort and is already an important reference point for the biofuel sustainability community."
  - "The effort to build consensus toward minimum datasets, standardized metrics, and metadata is increasingly being viewed as essential to the progress of science across the spectrum from medicine to agriculture. This project has made good progress to date."
- Weaknesses/challenges (select quotes from 2013 review)
  - "Moving forward, continued success and full realization of the objectives …will require that increasing efforts be allocated to outreach and consensus building beyond DOE and its bioenergy technology areas."
    - **Response: Much effort spent on outreach and consensus building in 2013-15**
  - "While there is some risk that the project may be heading toward a somewhat complex framework involving 35 different metrics, it is hard to think of what metrics might be removed at this point. The researchers may be overly ambitious in setting their sights on a set of metrics that are broadly applicable across many different applications and scenarios. It may be more realistic to think about allowing for more flexibility in the exact form of these metrics for a given context."
    - **Response: Our framework paper and approach presents a way to select indicators depending on the context, goals and stakeholders involved. The visualization tool should make such flexibility possible in the process aggregating indicators.**
  - "The scope of the project is quite large and difficult to evaluate each individual element in detail given the time limitation of presentation formats. Data is always going to be a limiting factor in analysis, particularly with ecological indicators where geography is important. That begs the question whether such analyses will be feasible and implementable by other researchers even with technological transfer of the framework approach."
    - **Response: We are working with other teams (e.g., NEWBio, NCSU and the RCN) to test and foster means of transferring the approach.**

Results of 2013 Review		
Evaluation Criteria	Sustainability Platform Mean	This Project
Critical success factors	6.8	7.4
Future work	7.0	7.6
Project approach	7.2	8.6
Project relevance	8.0	9.4
Technical progress	7.0	8.2
Overall weighted average	7.0	8.3

OAK RIDGE National Laboratory

Acronyms

- BETO = Bioenergy Technologies Office
- BMAS = Biomass Market Access Standards
- BP = Best Practices
- CBES = Center for Bioenergy Sustainability (at Oak Ridge National Lab)
- CSBP = Council on Sustainable Biomass Production
- EPA = US Environmental Protection Agency
- EPT richness = number of taxa in the insect orders Ephemeroptera, Plecoptera, & Trichoptera
- FAO = Food and Agriculture Organization
- GBEP = Global BioEnergy Partnership
- GLBRC = Great Lakes Bioenergy Research Center
- IBSS = Southeastern Partnership for Integrated Bioenergy Supply Systems (supported by USDA)
- IEA = International Energy Agency
- INL = Idaho National Laboratory
- ISO = International Organization for Standardization
- MADSS = Multi-Attribute Decision Support Systems
- NCASI = National Council on Air and Stream Improvement
- NCSU= North Carolina State University
- NEWBio = Northeast Woody/Warm Season Biomass Consortium (supported by USDA)
- NGO = Non-governmental organization
- NREL = National Renewable Energy Laboratory
- NSF = National Science Foundation
- RCN = Research Collaborative Network (a project at Michigan Tech supported by NSF)
- RSB = Roundtable for Sustainable Biomaterial
- SCOPE = Scientific Committee on Problems of the Environment
- USDA = US Department of Agriculture

Journal Articles & Book Chapters: 2013 to 2015

For more information see http://www.ornl.gov/sci/ees/cbes/

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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 ($PM_{2.5}$)	µg/m^3
	18. Total particulate matter less than 10µm diameter (PM_{10})	µg/m^3
Productivity	19. Aboveground net primary productivity (ANPP) / Yield	gC/m^2/year

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