Indicators to Support Environmental Sustainability of Bioenergy Systems

Allen C. McBride, Virginia H. Dale, Latha M. Baskaran, Mark E. Downing, Laurence M. Eaton, Rebecca A. Efroymson, Charles T. Garten Jr., Keith L. Kline, Henriette I. Jager, Patrick J. Mulholland, Esther S. Parish, Peter E. Schweizer, and John M. Storey

Center for BioEnergy Sustainability
Oak Ridge National Laboratory

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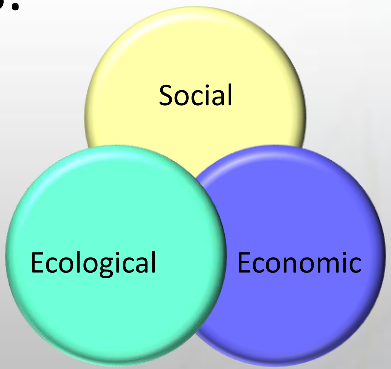
Key Points

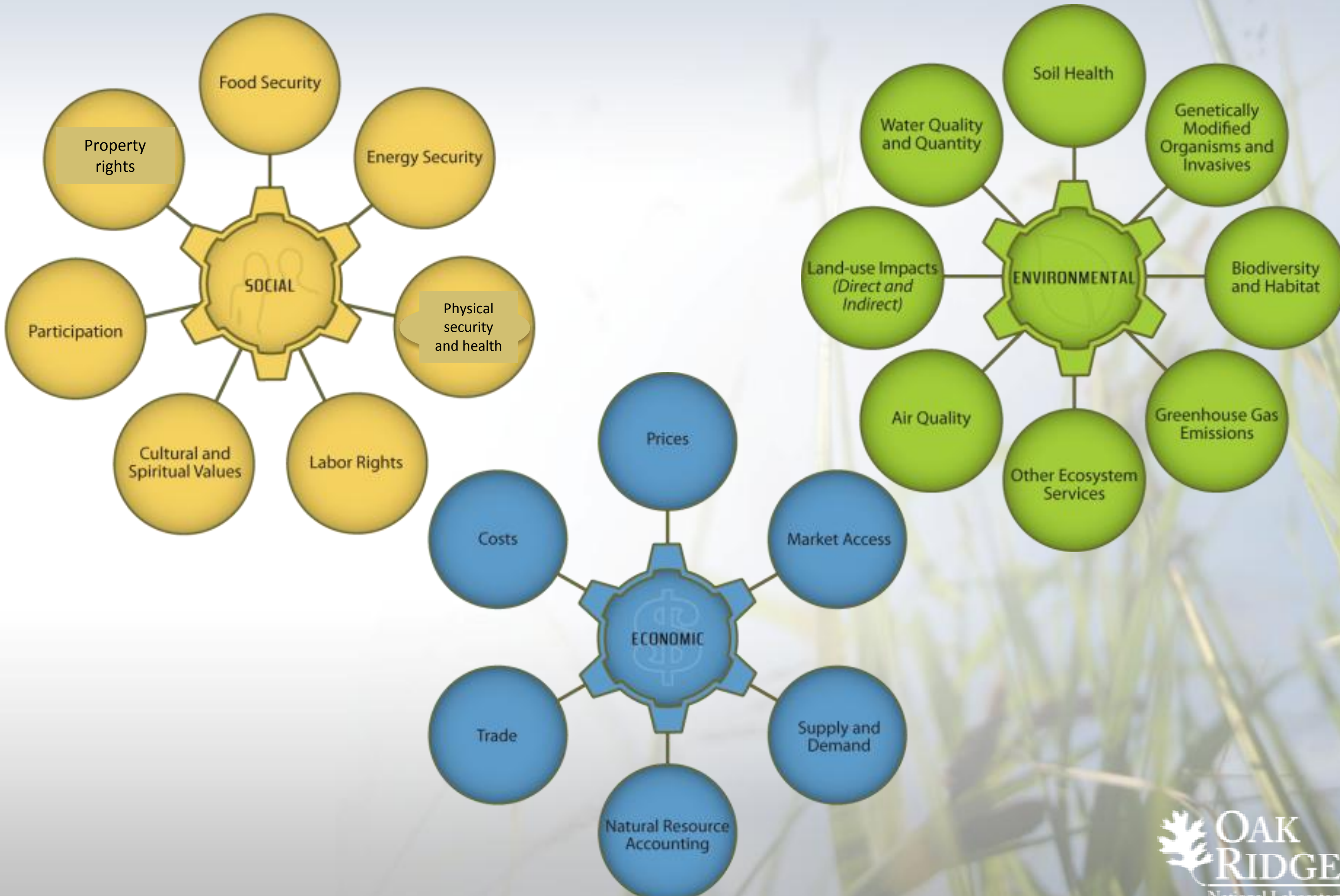
- Sustainability is contextual, relative (more/less) and process based
- Sustainability implications of bioenergy choices are large and complex
- There is an opportunity to design land use to optimize socioeconomic and ecologic benefits of bioenergy
- Scale(s) matter
- You can only manage what you can measure
- Must consider a suite of measures:



Roadmap for Talk

- Definitions
- Efforts to determine sustainability indicators
- Process for indicator selection
- Environmental indicators
  - Soil quality
  - Water quality and quantity
  - Greenhouse gas emissions
  - Biological diversity
  - Air quality
  - Productivity
- Interpreting indicator measurements
- Adapting suite for particular contexts
- Next steps in developing suite
- Landscape design

Sustainability is the capacity of an activity to continue while maintaining options for future generations.



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Key Definitions

- **Indicator** is a measure of performance
  - Purpose influences the choice of indicators (from Cairns *et al.* 1993).
    - To assess the condition of the environment
    - To monitor trends in condition over time.
    - To provide an early warning signal of changes in the environment
    - To diagnose the cause of an environmental problem.
  - Tradeoffs between desirable features, costs, and feasibility often determine the choice of indicators.
    - Contrast environmental cost of dependence on fossil fuel to potential value added of renewable fuel options

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Indicators Should Be

- Technically effective
  - Are sensitive to stresses on system
  - Respond to stress in a predictable manner
  - Are anticipatory: signify an impending change in the ecological system
  - Have a known response to natural disturbances, anthropogenic stresses, and changes over time
  - Have known variability in response
  - Are integrative: the full suite of indicators provides a measure of coverage of the key gradients across the ecological systems

- Practically useful
  - Are easily measured
  - Predict changes that can be averted by management actions
  - Consider spatial and temporal context of measure
  - Are broadly applicable across the system of interest and to other systems

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

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Process for Indicator Selection

- Select indicators within idealized framework
- Caveats
  - Measure what is measurable today
    - Effects of greatest interest
    - Interpret indicators in light of
      - How they change over time and space
      - How other factors change over time and space
      - Full suite of socioeconomic and environmental metrics
  - Plan to obtain new measures more closely related to effects of interest

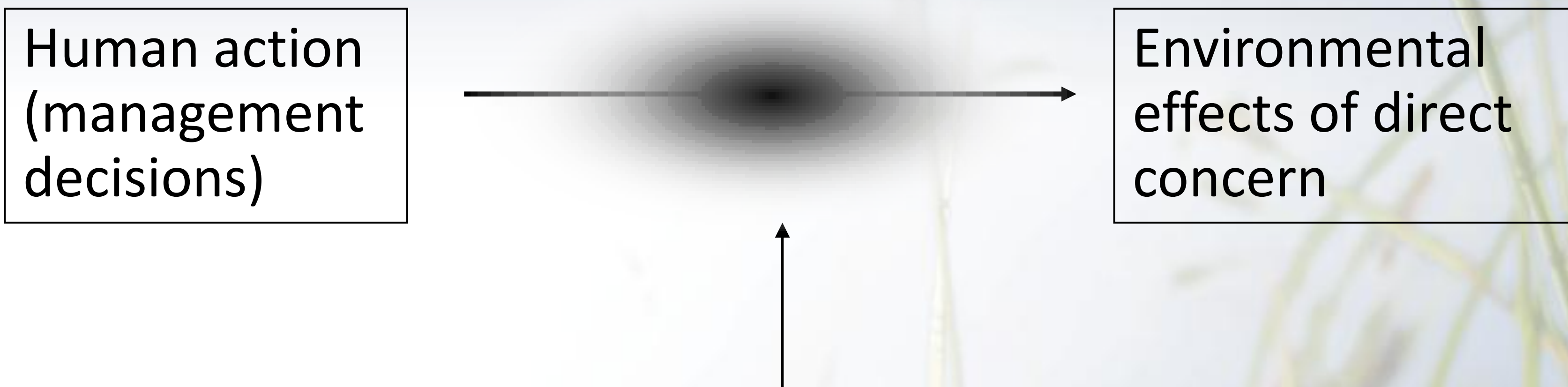
Einstein: "Not everything that can be counted counts, and not everything than can be counted should be counted."

Some Groups Working to Develop Indicators for Bioenergy Sustainability

- GBEP (Global Bioenergy Partnership)
- BRDi (Biomass Research & Development)
- RSB (Roundtable on Sustainable Biofuels)
- CSBP (Council on Sustainable Biomass Production)

- These efforts often focus on management practices, but knowledge is limited about which management practices are environmentally sustainable.
- These suites can be too numerous and/or too broad for practical implementation.

Approach

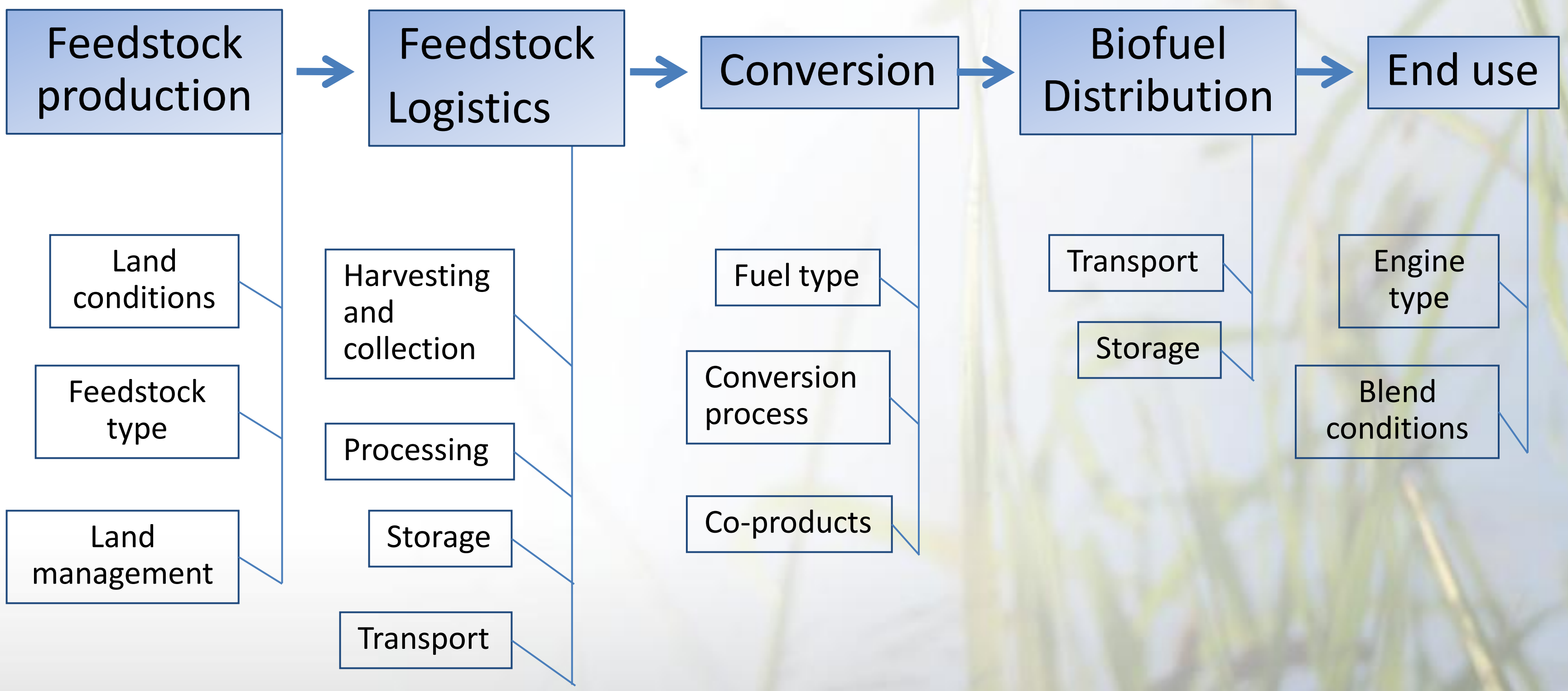


- Causal chain: We selected indicators downstream from management, but not too far.
- We aimed for indicators that could be measured empirically, but modeling is sometimes inescapable

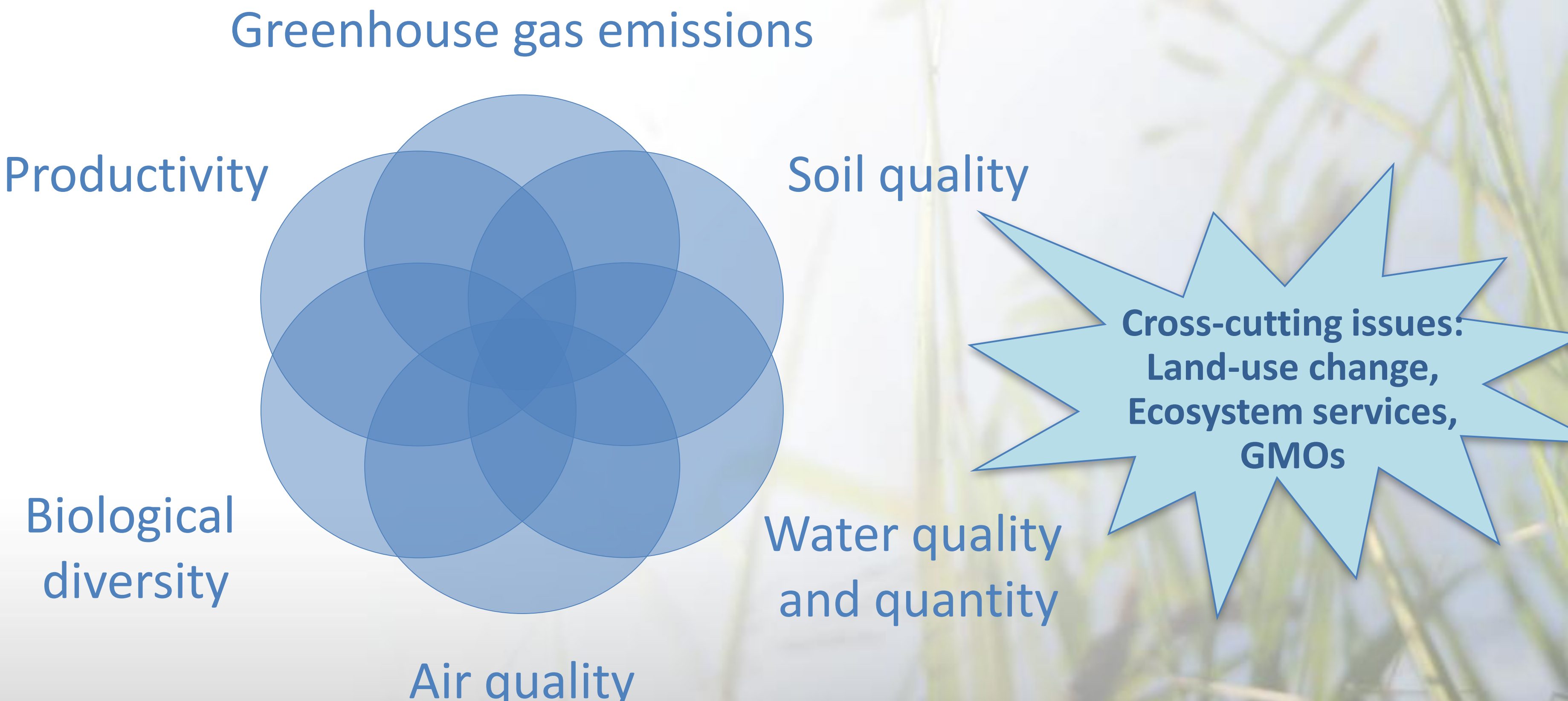
The Set of Indicators Should be Widely Applicable

- Useful to:
  - Policymakers
  - Agronomists
  - Producers
- Improve empirical underpinning for management indicators

Set of Indicators Should Apply to Entire Supply Chain



Ecological Indicators of Bioenergy Feedstock Sustainability



Soil Quality

Indicators

- Total organic carbon (Mg/ha)
- Total nitrogen (Mg/ha)
- Extractable phosphorus (Mg/ha)
- Bulk density (g/cm^3)

Related environmental concerns

- Carbon balance
- Nutrient availability and mineralization
- Cation exchange capacity
- Humification
- Eutrophication potential
- Infiltration
- Water holding capacity

Key contextual variable

- Soil type

Water Quality and Quantity

Indicators

- Nitrate concentration (mg/L)
- Total P (mg/L)
- Suspended sediment (mg/L)
- Herbicides (mg/L)
- Base flow (L/s)
- Peak storm flow (L/s)
- Consumptive water use (m^3/ha/day for production, m^3/day for processing)

Related environmental concerns

- Eutrophication
- Potability
- Habitat degradation
- Erosion
- Water availability

Key contextual variable

- Precipitation

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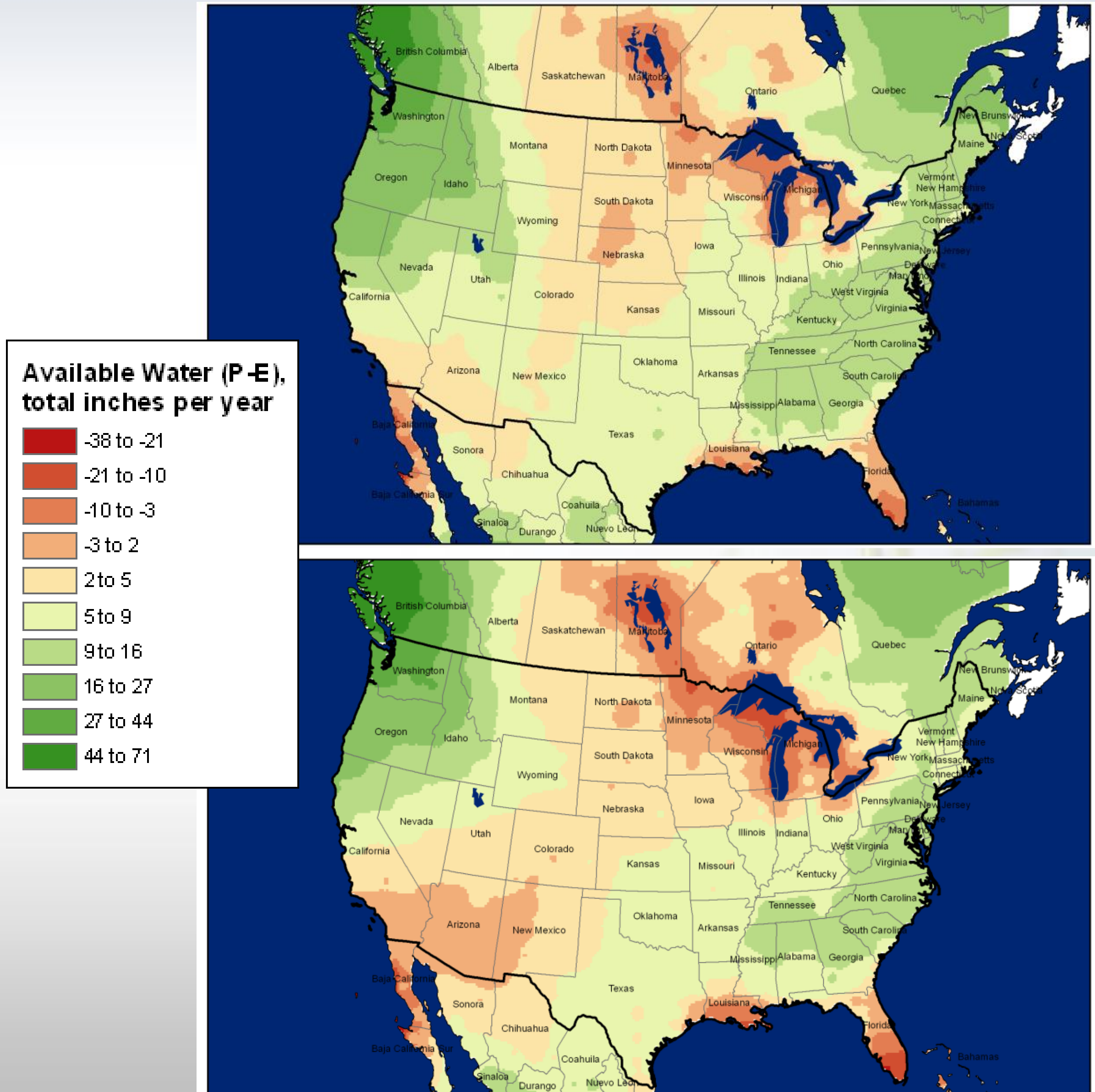
Projected Change in U.S. Available Water by 2100

(Based on CCSM3 run with the A1FI emissions scenario)



Current Decade

(2000-2009)

End of Century

(2090-2099)

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Greenhouse Gas Emissions

Indicator

- Net carbon equivalent emissions or sequestration (kgC_{eq}/GJ)
  - CO_2: calculated using life cycle analysis (e.g., GREET)
  - N_2O: estimated using process or statistical models (e.g., DAYCENT)

Sources and sinks

- CO_2: Changes in stocks
- CO_2: Fossil fuel use
  - Manufacture & transport of agricultural inputs
  - On-site agricultural operations
  - Processing and conversion
  - Transportation
- N_2O: Nitrification and denitrification in soil
- N_2O: Fertilizer production
- Methane typically less important than N_2O or CO_2.

Biological Diversity

Indicators

- Presence of taxa of special concern
- Habitat area of taxa of special concern (ha)

Examples of taxa of special concern

- Rare species
- Keystone species
- Taxa likely to be affected by bioenergy systems
  - Arthropods
  - Birds
  - Small mammals
  - Ground flora
  - Aquatic organisms



Air Quality

Indicators

- Tropospheric ozone (ppb)
- Carbon monoxide (ppm)
- Particulate matter less than 2.5µm diameter ($PM_{2.5}$; µg/m^3)
- Particulate matter less than 10µm diameter (PM_{10} ; µg/m3)

Related environmental concerns

- Health
- Visibility
- Plant productivity

Ozone and secondary $PM_{2.5}$, formed from precursors, must be modeled (e.g., CMAQ calibrated to local conditions).

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Productivity

Indicator

- Aboveground net primary productivity ($gC/m^2/yr$)

- Allows comparison between natural and production land
- Can be measured using conventional ecological techniques, or using yield as proxy
- Management-related contextual variables particularly important

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Baseline Variables

Baseline variables characterize business-as-usual conditions, for comparison with bioenergy systems.

- Some baselines are directly comparable with indicators
  - Condition of land, air, water affected by bioenergy systems
  - Pre-implementation indicator measures or measures on proxy sites
- Baselines should also characterize energy or production systems displaced by bioenergy
  - Fossil fuel
  - Products displaced by co-products

Contextual Variables

- Contextual variables measure characteristics of bioenergy systems that affect indicators and are needed to interpret indicators.
- Different kinds:
  - Beyond human control (more or less)
    - Dynamic
    - Static over scale of years
  - Aspects of system management
    - Other nearby human activities
    - Bioenergy systems themselves

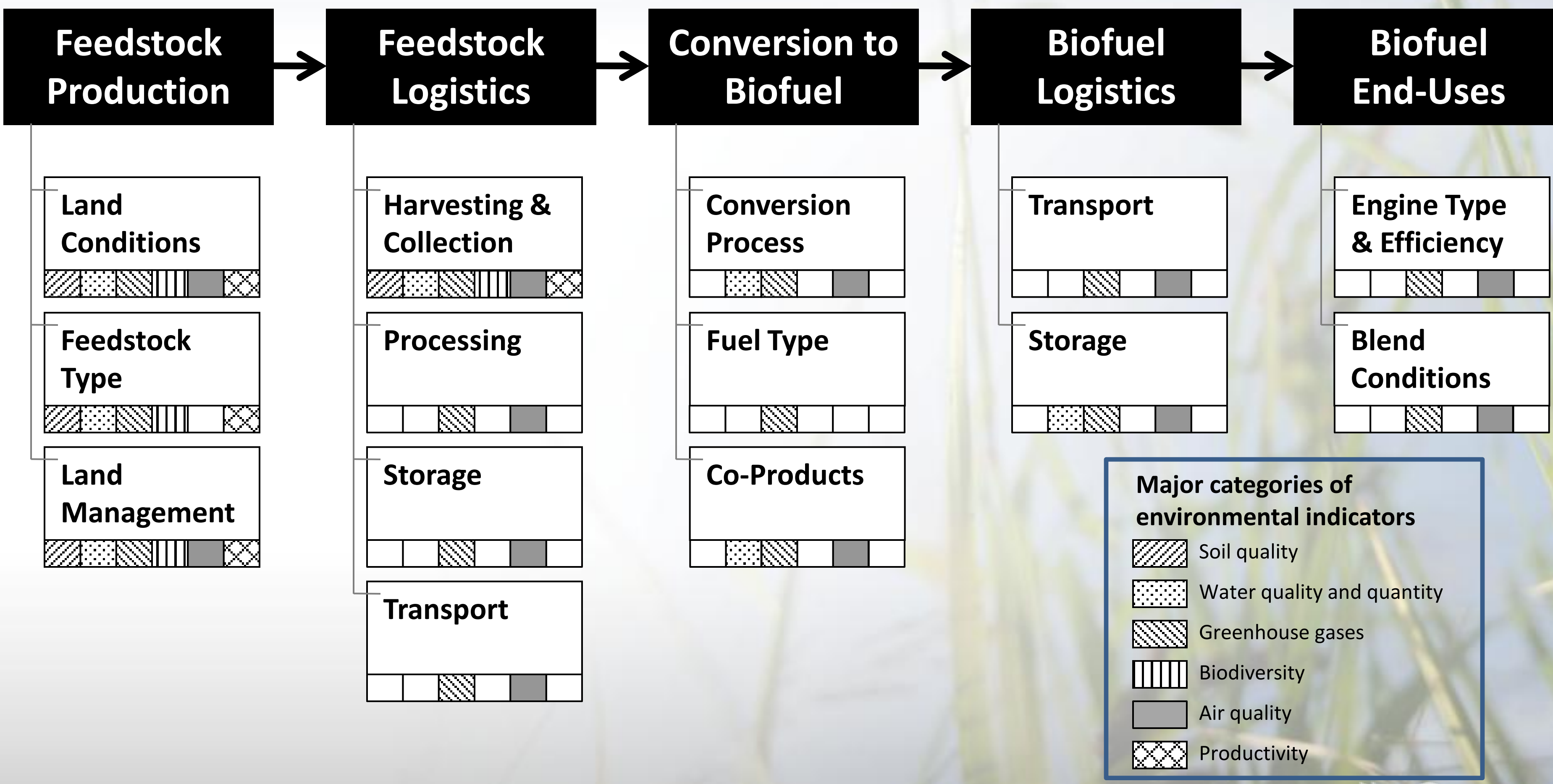
Indicator Suite Should Change Over Time

- Experience with bioenergy systems
- Technological advancement

Adapting Suite to Particular Contexts

- Suite presented here is a starting point for the sake of efficiency and standardization
- Particular systems may require addition of other indicators
- Budget may require subtraction of some indicators
- Different categories of indicator more important for different supply chain steps
- Protocols must be context-specific

Contexts for Environmental Indicators of Sustainability in the Biofuel Supply chain



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Testing the Indicator Suite

- Indicators should be tested in a variety of systems
- Testing essential for next steps
  - Evaluate utility
  - Measure variability
  - Establish protocols
  - Establish targets
- Context-specific knowledge
- Paired watershed experiments are ideal

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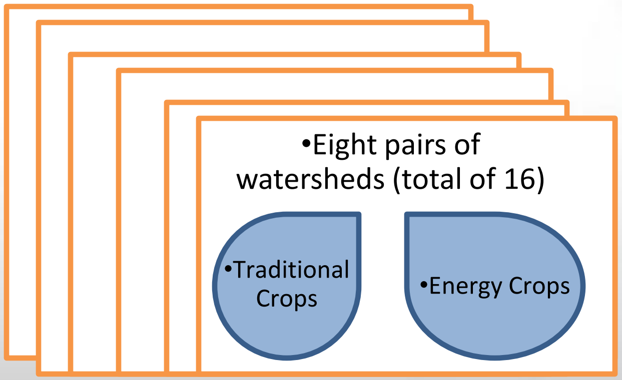
Experimental Testing using Paired Watersheds

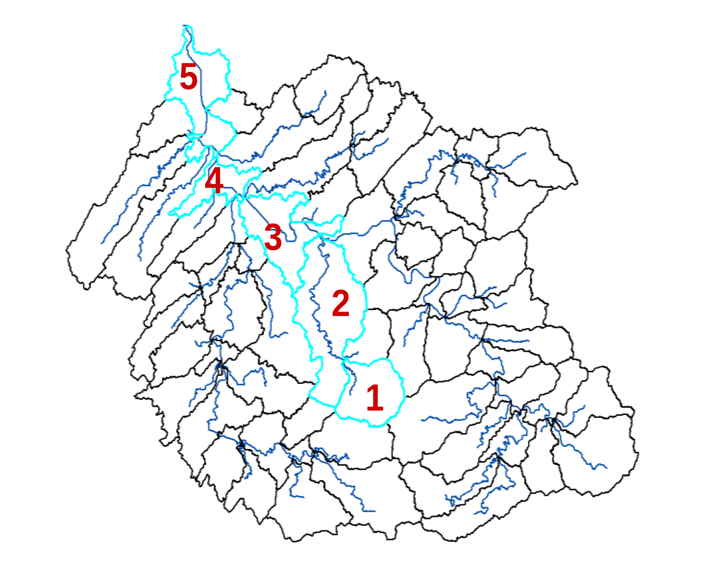
- Hypothesis: bioenergy systems can be designed to be sustainable at a watershed scale
- Test using economic and environmental indicators measured from paired watersheds
- Pairs are similar except for bioenergy crops
- Use extant and new data on environmental effects associated with feedstocks produced to supply the Vonore, TN, demonstration-scale biorefinery
- Also test with a water quality and economic model embedded within a spatial optimization approach

Vonore Pilot-Scale Biorefinery

Watershed Experimental Design

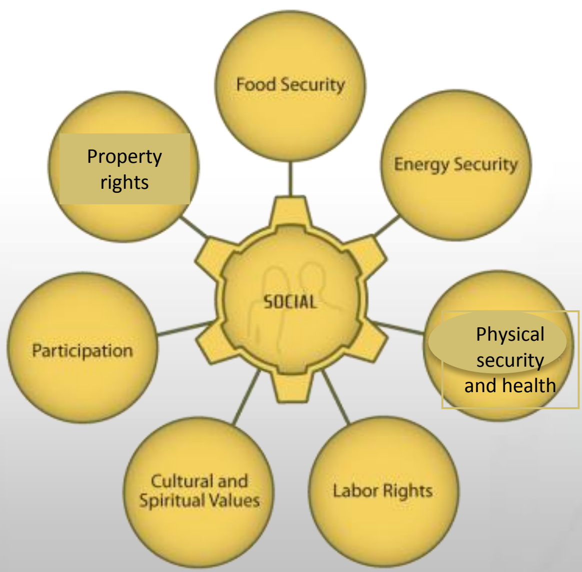


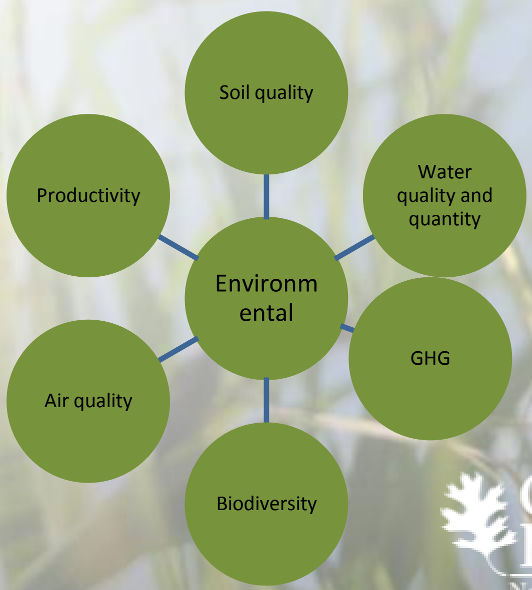
Data collected on economic and environmental measures of sustainability



Social and Economic Indicators

- Holistic approach: The suite of indicators of environmental sustainability presented here is intended to help advance efforts by GBEP, RSB, CSBP, etc., to develop full suites of indicators for environmental, social, and economic sustainability.
- Next Step: Identify socioeconomic indicators of sustainability

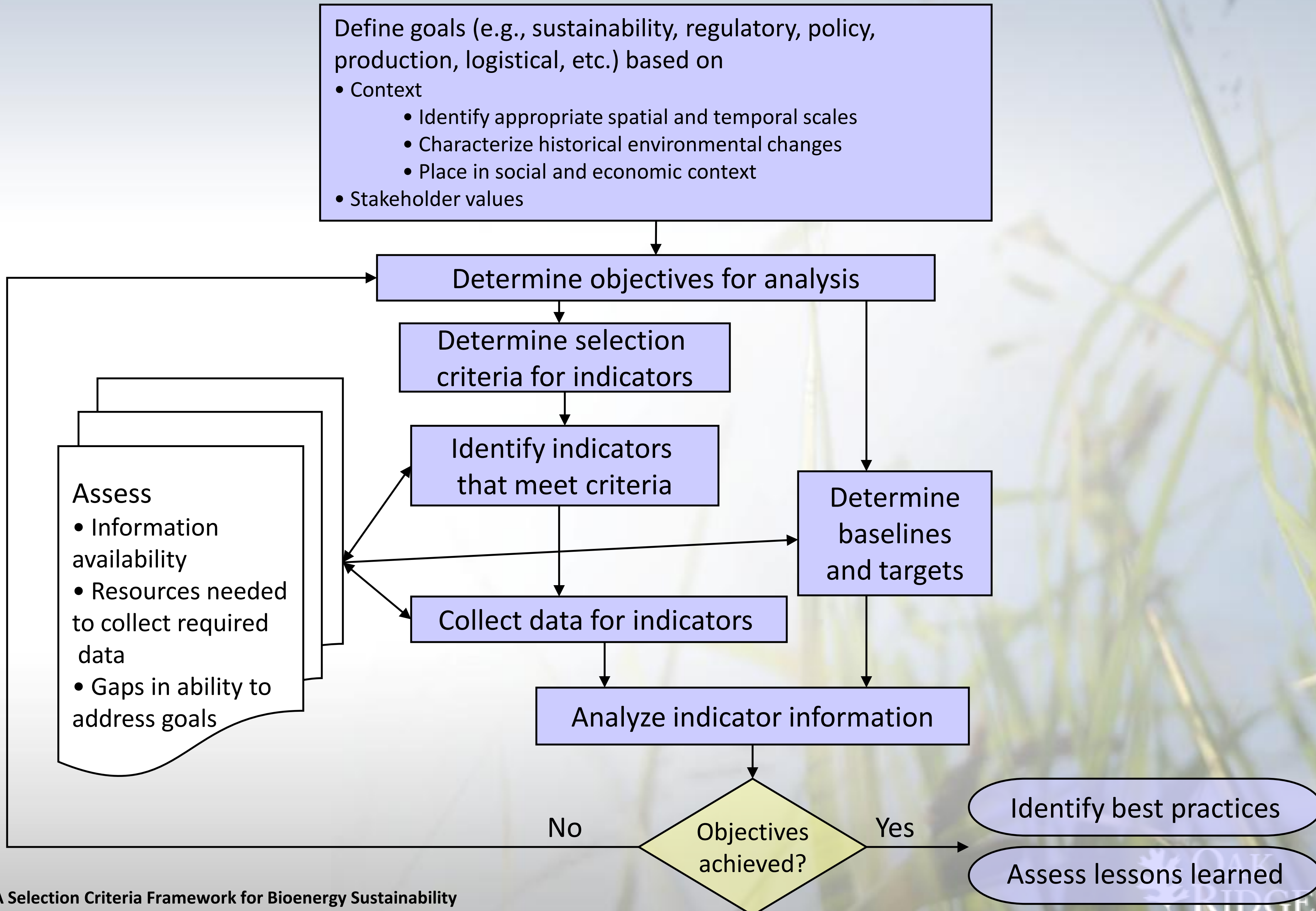




Interpreting Suite as a Whole

- Because the indicators were selected to constitute an integrated suite, multivariate statistical methods should be applied to measured values.
- Some indicators may tend to change in the same direction and with correlated magnitudes as other indicators; such information is useful to land managers in weighing environmental tradeoffs in decision-making.

Framework for Selecting Sustainability Indicators for Bioenergy



A Selection Criteria Framework for Bioenergy Sustainability

A paper to be submitted as a "Perspective" for *Biofuels, Bioproducts and Biorefineries.*

Authors (Order TBD): Virginia H. Dale, Marcia Davitt, Rebecca A. Efroymson, and Keith Kline [Oak Ridge National Lab]

Consider indicators within entire system (interactions and feedbacks) as an opportunity to design landscapes that add value

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