Review

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A framework for selecting indicators of bioenergy sustainability

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Abstract: A framework for selecting and evaluating indicators of bioenergy sustainability is presented. This framework is designed to facilitate decision-making about which indicators are useful for assessing sustainability of bioenergy systems and supporting their deployment. Efforts to develop sustainability indicators in the United States and Europe are reviewed. The first steps of the framework for indicator selection are defining the sustainability goals and other goals for a bioenergy project or program, gaining an understanding of the context, and identifying the values of stakeholders. From the goals, context, and stakeholders, the objectives for analysis and criteria for indicator selection can be developed. The user of the framework identifies and ranks indicators, applies them in an assessment, and then evaluates their effectiveness, while identifying gaps that prevent goals from being met, assessing lessons learned, and moving toward best practices. The framework approach emphasizes that the selection of appropriate criteria and indicators is driven by the specific purpose of an analysis. Realistic goals and measures of bioenergy sustainability can be developed systematically with the help of the framework presented here. © 2015 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

Bioenergy production using renewable biofeedstocks offers opportunities for enhanced sustainability, including improving rural economies and energy security. At this early stage of developing technology, bioenergy systems are flexible, and there is an opportunity to develop policies and management practices that will contribute to increased sustainability.[1] Defining and establishing metrics to effectively quantify sustainability poses significant challenges: there are many aspects of sustainability, and distinguishing the effects of bioenergy on the environment and society from the effects of alternative or baseline activities is difficult. Due to the typical non-linear effects of changes to complex systems, pinpointing cause-effect linkages is challenging. Determining how to select and use these metrics is the focus of this paper. Indicators can be useful tools for decision-makers if they provide a practical and accepted way to assess relative sustainability. While decision-support tools can help in identifying indicators that are pertinent for a particular system,[2] systematic approaches for selecting and using indicators are rare.[3,4]

Ongoing efforts have developed what amounts to a shopping list of potential indicators that cover diverse aspects of sustainability. Our aim is to provide a framework for selecting and evaluating a suitable set of sustainability indicators for analysis of bioenergy processes and systems.

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This approach considers sustainability goals, stakeholder goals, and the context of particular problems, as suggested by others.[5–8] We review general selection criteria for indicators and highlight particular needs and analyses related to bioenergy sustainability. We frame the discussion by defining bioenergy sustainability and outlining the role of the regulatory context.

Bioenergy sustainability goals

Sustainability provides for the environmental, economic, and social needs of the present without compromising the capacity of future generations to meet their own needs.[9] It relates to a product life cycle that replenishes resources and is constrained by human and environmental needs over the long term.[10]

Environmentally, bioenergy sustainability refers to the interaction of biophysical and ecological properties (such as soil conditions, surface and ground water quality and quantity, air quality, biodiversity, greenhouse gas emissions, and productivity)[11] with environmental stressors, including human activities at several scales. Environmental sustainability may imply efficient use of natural resources, such as water[12] and energy, and benign disposal or mitigation of wastes.[7] Decisions about bioenergy management practices and the mix of feedstocks must consider variability of the ecoregions where bioenergy is produced.

Economically, bioenergy sustainability encompasses the relative costs associated with the life cycle of a complete supply chain and all its elements. Economic sustainability means that cultivation, processing, distribution, and end-use costs to purchasers of bioenergy are economically competitive with those of other energy sources and that social equity is facilitated while avoiding the imposition of unfair burdens on any particular locale, region, or demographic group. For producers, risks, costs, and benefits must be perceived as being competitive or advantageous relative to alternative land-use and energy options. Economic sustainability tends to improve when purchases of supplies for production and borrowed capital are reduced, cash flow is adequate to cover operational expenses on time, and profits increase.[7]

Sociopolitically, bioenergy sustainability implies equitable access to energy and ecological resources and ensures that bioenergy production does not deprive people of access to staple food and fiber crops[13] or disrupt livelihoods (e.g. employment, income, or safety).[14] The concept of bioenergy sustainability includes respect for workers' rights to equitable wages and working conditions, with safety a primary goal. Human health and welfare implications of bioenergy are especially important for marginal populations and developing countries, which rely on biomass as a primary fuel.[13] In a study of bioelectricity systems in Uganda, social aspects of sustainability played a larger role than did economic aspects in determining the viability of a bioenergy production project.[15]

Regulatory context for bioenergy

The regulatory context of a problem or situation gives rise to specific priorities, which in turn shape the definition of goals and objectives for analysis and the choice of indicators. For example, requirements under US state and federal laws and regulations differ from regulations crafted by the European Commission (EC) (http://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria). Some of the regulations addressing impacts of bioenergy production (e.g. effects on water and soil quality, land use, greenhouse gas (GHG) emissions, carbon sequestration, and biodiversity) are highlighted below.

Title II of the US Energy Independence and Security Act (EISA) of 2007 focuses on 'energy security through increased production of biofuels' and defines reporting requirements for estimated environmental impacts of energy technologies (US Public Law 110-140). EISA requires a life-cycle assessment (LCA) of biofuel emissions, and this LCA must include both direct emissions from bioenergy production and indirect emissions from any land-use change elsewhere in the world caused by the bioenergy production.[16] Compliance with EISA requires measures of air, water, hypoxia, soil, pathogens, ecosystem health, biodiversity, and non-native vegetation. EISA-mandated LCAs must also consider trade of renewable fuels and feedstocks and environmental impacts outside the USA caused by biofuel production driven by the Renewable Fuel Standard (RFS). The RFS requires transportation fuel sold in the USA to contain a minimum volume of renewable fuels.[17]

The California Air Resources Board (ARB) established a low carbon fuel standard (LCFS), aiming 'for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020' (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). LCFS goals include reducing GHG emissions to 1990 levels by 2020, reducing the state's dependence on petroleum, and creating a market for clean transportation technology. The regulation assigns scores for the carbon intensity of different biofuel production pathways (e.g. corn ethanol, sugarcane ethanol, cellulosic ethanol from farmed trees, and cellulosic ethanol from forest waste) based on a modified version of the Global Trade Analysis Project (CARB-GTAP) model and GHG emissions obtained by using the 'California-modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (CA-GREET) model' (http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm), building on the GREET platform developed by Argonne National Lab.[18]

The EU is acting to improve the sustainability of energy options across Europe.[19] The EC's Renewable Energy Directive (RED) has established a bioenergy target to be reached by 2020, aimed at promoting the security of energy supply, promoting technological development and innovation and providing opportunities for employment and regional development, especially in rural and isolated areas.[19,20] Aware of the implications for developing countries, the EU intends that growth in biofuel markets will benefit both European producers and developing nations.

Efforts to identify sustainability indicators for bioenergy

The demand for sustainability indicators has come from several directions. There has been an emphasis by LCA advocates, regulators, and the climate change community on GHG emissions that can overshadow other environmental, social and economic aspects of sustainability. There has also been disproportionate focus on the 'sustainability requirements' for bioenergy without adequate support to apply comparable criteria and approaches to alternative energy sources and land management systems such as agriculture. Furthermore, many people active in the development and promotion of sustainability standards are employed as researchers and consultants with self-interests in expanding the demand for modeling, certification, verification, and related studies (e.g. LCA, Product Codes, chain of custody, and sustainability audits).

Recognition of the need for comparable bioenergy sustainability indicators and associated measures has resulted in efforts to establish a standard suite of indicators. A suite of indicators can serve as a reservoir from which to compose subsets of indicators that meet specific goals. General agreement exists about the relevance of soil and air quality, water quality and quantity, GHG emissions, productivity, and biodiversity as categories of indicators of environmental sustainability.[11] However, some indicators focus on management practices even though there is limited knowledge about which practices are 'sustainable'. Furthermore, most existing approaches use indicators that are too numerous, costly, broad, or difficult to measure.[11,14] This paper reviews some existing approaches and then presents a framework for indicator selection. Prior efforts (discussed later) have done much to define terms and to build consensus for the need to measure diverse components of sustainability.

The multitude of standards and certification schemes for bioenergy sustainability can be categorized in many different ways. One distinguishing variable is the object of analysis which can range from a specific supplier to a national policy. An approach designed to show compliance with a certification scheme or demonstrate that a product is 'fit for purpose', will usually focus on a prescriptive set of indicators and documentation that must be prepared or presented to demonstrate that specific thresholds or limits are met. Other approaches are designed to assess specific research questions related to the sustainability of processes, products, projects, policies, and programs; these can be less prescriptive about documentation; are not necessarily concerned about threshold values; and focus more on replicable methods for data collection, measurement, and analysis. Both certification schemes and other sustainability assessments can operate at multiple scales and be led by private or governmental entities.

The multistakeholder, international Roundtable on Sustainable Biomaterials (RSB) provides an example of a voluntary certification scheme. The RSB is a private endeavor that brings together farmers, companies, non-governmental organizations (NGOs), experts, governments, and inter-governmental agencies concerned with ensuring the sustainability of biomaterials production and processing. The RSB has established a set of *principles* that describe 'the general intent of performance' (e.g. reflecting sustainability goals and objectives in the terminology of this article) and *criteria* that represent 'objective of performance which is specifically and measurably operationalizing a principle' – similar to what we refer to in this article as indicators.[21] An RSB *indicator* reflects the 'outcome specifying a single aspect of performance' or performance for a specific measurement associated with a criterion.[21]

RSB principles include compliance with domestic and international laws for bioenergy production; design and operation under transparent and participatory processes; mitigation of climate change; consistency with human rights requirements; contribution to the social and economic development of local, rural, and indigenous peoples and communities; maintenance of food security; avoidance of negative impacts on biodiversity, ecosystems, and areas of high conservation value; improvement or maintenance of soil health; optimization of surface and groundwater use; minimization of air pollution; cost-effective production; and maintenance of land rights. Guidance for compliance with principles and criteria is given by the RSB, such as recommending that areas of high conservation value be mapped, native crops be preferred, ecosystem functions and services for an area of biomaterial production be locally identified, buffer zones (such as riparian zones) be identified and protected, and ecological corridors be identified and protected.

As of March 2, 2015, the EC recognized the RSB and 18 other voluntary schemes as acceptable ways to document compliance with its sustainability criteria.[22] The approaches recognized by the EU must fulfill criteria related to GHG savings and land use, the latter to avoid disturbance to areas of high carbon stocks and biodiversity. Different voluntary schemes have been recognized; some are designed for a specific production pathway and others are designed for any product.

The Global Bioenergy Partnership (GBEP) (http://www.globalbioenergy.org/) promotes bioenergy for sustainable development at the national level. The GBEP is coordinated by the Food and Agriculture Organization (FAO) of the United Nations and includes 9 other international organizations and the world's major economies among its 14 member nations. The GBEP Task Force on Sustainability has developed a set of sustainability categories[23,24] that it labels 'criteria', indicators (measurable outcomes), and benchmarks for bioenergy sustainability that could help identify best practices.[25] The GBEP indicator categories include environmental, social, and economic considerations. The GBEP also acknowledges that the target level of an indicator will more often be determined based on social rather than on scientific considerations.

A few of the many other endeavors geared toward devising sustainability indicators, standards, or principles relevant to bioenergy include those of the Council on Sustainable Biomass Production (CSBP), Biomass Market Access Standards (BMAS), Keystone Alliance for Sustainable Agriculture, the Sustainable Forestry Initiative, the World Wildlife Fund of Germany, and the Sustainable Biodiesel Alliance, as well as efforts that target particular feedstock crops such as sugarcane (e.g. Bonsucro-Better Sugarcane Initiative, Greenergy) and oil palm (e.g. Roundtable for Sustainable Palm Oil). While forestry standards groups such as the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) address sustainable forest management for production of any forest product, they do not require GHG emissions accounting and therefore need to link to another method or scheme to document compliance with GHG-related criteria. The California Air Resource Board established a special working group to address sustainability issues of biofuels that are used in California to support implementation of the LCFS (http://www.arb.ca.gov/fuels/lcfs/workgroups/lcfssustain/lcfssustain.htm).

Researchers have proposed less formal lists of sustainability indicators for bioenergy. McBride *et al.* recommend a list of 19 indicators for environmental sustainability for bioenergy in six categories: soil, water, air, GHG emissions, biodiversity, and plant productivity.[11] Evans *et al.* propose indicator categories of price, efficiency, GHG emissions, availability, limitations, land use, water use, and social impacts for electricity generation from biomass.[26] Dale *et al.* identified 16 socioeconomic indicators of bioenergy sustainability that fall into the categories of social well-being, energy security, trade, profitability, resource conservation, and social acceptability.[14] These efforts are driven more by the need for consistent approaches that could facilitate comparable, science-based assessments[27] than by the need for compliance certification. While some indicators are commonly identified by experts,[28] this framework presents an approach for indicator selection that addresses key components of the three pillars of sustainability (social, environmental, and economic) and science literature that has emerged to support their measurement.

Most of these efforts are concerned with environmental, economic, and social aspects of sustainability. Some emphasize quantitative indicators, others emphasize more qualitative goals, and others stress documentation requirements to permit audit and verification. Some favor sustainability goals that may be more socially than scientifically determined. And while most are moving toward the development of a general set of indicators, there exists no widely accepted framework for selecting goal-relevant and/or contextually meaningful indicators.

Framework for selecting and evaluating indicators for bioenergy sustainability

The need for indicators that clearly reflect defined aspects of sustainability and other project goals and objectives for analysis requires more attention. The challenge stems not from the absence of effective indicators *per se* but from the lack of a deliberative process for translating sustainability goals and assessment objectives into practical, cost-effective, and useful indicators to guide planning and decisions at a variety of scales.

We propose a framework (Fig. 1) that helps guide indicator selection toward relevance to specific sustainability goals and the values that shape them and to the objectives of the particular bioenergy-sustainability analysis. The framework allows stakeholders to articulate their priorities and values and hence to narrow the long list of potential indicators to those most useful in a particular situation. Determining what groups constitute relevant stakeholders and coming to a resolution of goals among those groups is neither trivial nor easy. Diverse perspectives and groups have an interest in bioenergy project outcomes and implications.[29] Use of the framework should increase the prospects for *saliency* (relevance to stakeholders),[30] facilitating the development of indicator suites that are well-suited to stakeholder goals and priorities.

The diagram in Fig. 1 represents an interdependent relationship among goals, context, and stakeholder values. These aspects of the framework should be defined concurrently, because discussions in one area inevitably raise questions within another. For example, a comprehensive analysis of goals leads to questions about the context in which the goals are set. Who the stakeholders are depends both on context and how overarching goals are defined. The goals themselves vary in meaning for different stakeholders, and acceptability of trade-offs depends on the stakeholders. Goals are value-driven, and bioenergy indicators may be thought of as measures of those values.[31] Because multiple communities (e.g. policymakers, scientists, industry representatives, farmers, or particular sectors of the public) with differing priorities and values have a stake in bioenergy sustainability, an indicator-selection process that ensures that values do not get buried beneath technical details is more likely to provide lasting results. Hence, the process of selecting indicators can be hampered by apparently irreconcilable differences among stakeholders. It is sometimes better to retain a larger set of indicators rather than to seek efficiency and disenfranchise key stakeholder groups. In other situations, one stakeholder may stymie progress, and the larger group may decide to move forward on the indicator selection process while acknowledging that some concerns are not being addressed. In the following sections, we discuss the steps in the framework depicted in Fig. 1.

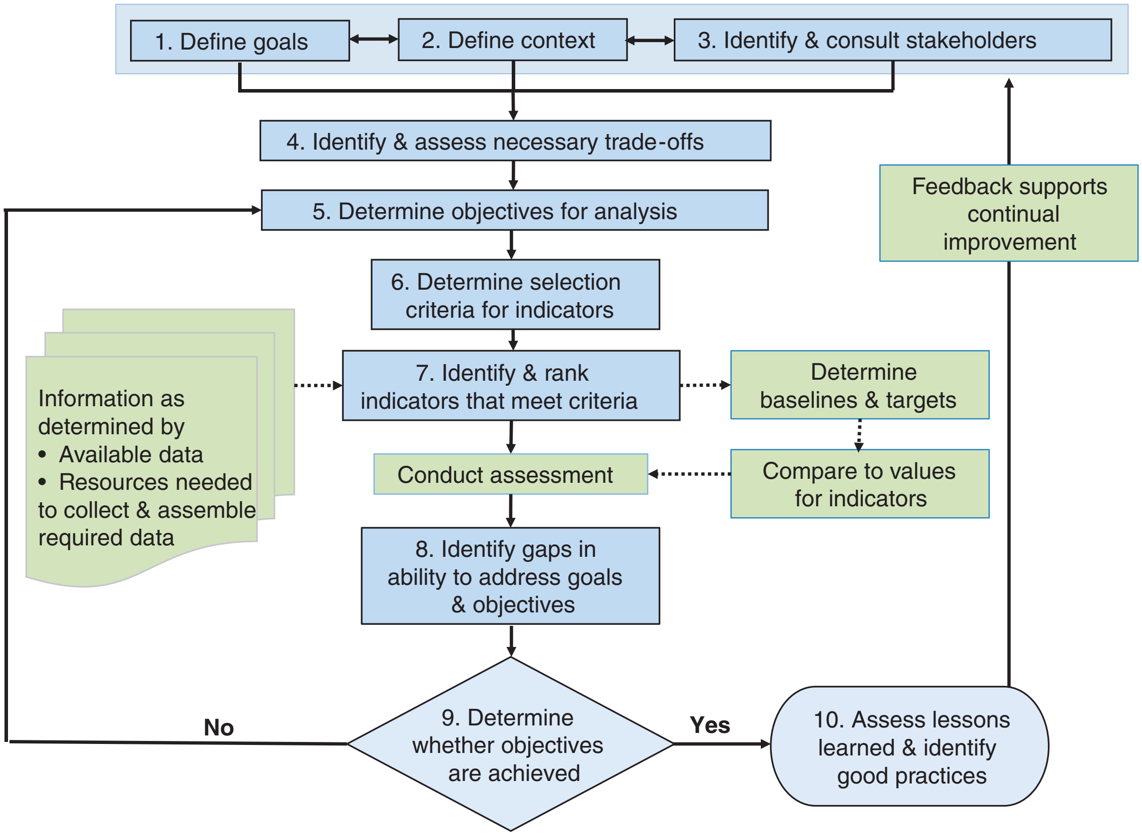

Figure 1. A framework for selecting and evaluating indicators of bioenergy sustainability. Steps for the framework are shown in blue; supporting components of the assessment process are in green. Note that steps 1, 2, and 3 interact and occur concurrently.

Define the goals

Goals for bioenergy projects or programs can include moving toward environmental, economic, or social sustainability targets; meeting regulatory or policy standards; conducting research; meeting expectations for land management; meeting logistical needs; or other goals (Fig. 1). Setting the goals is strongly determined by the stakeholders who are engaged and the context of analysis. Different stakeholders often have different perspectives about assessment goals and scale. For example, a federal agency may be concerned about the national-scale deployment of bioenergy technologies. An association of farmers might be interested in farm-level price stability of a particular crop. A state agency may want to determine the relative suitability of different sites or land conditions for cultivating perennial crops. Industry may focus on profitability and complying with laws and regulations. NGOs typically focus on specific interests of their constituencies and opportunities to increase support or raise funds. Ideally an assessment would include all key stakeholders and would be led by an entity that all participants view as being impartial. The network of 22 Landscape Conservation Cooperatives (LCCs) across the USA provides an example of multistakeholder participation to define goals in a structured environment.[32] The LCCs are self-directed partnerships between federal agencies, states, tribes, NGOs, universities, and other entities that collaboratively define science needs and jointly address issues within a defined geographic area.[32]

Define the context

Context is important for prioritizing sustainability indicators for biofuels.[8] This step in the framework entails identifying the socioeconomic, cultural, institutional, political, and regulatory environments and the spatial and temporal extent for consideration. For analyses at the regional or local scale, the context includes historical land uses and alternative land uses. If a community has particular concerns about its economic future (e.g. a dominant industry has moved away from the community) or its environment (e.g. water quality is poor), these concerns are part of the context of bioenergy sustainability and influence the goals. While the need to describe contextual details may seem obvious, failure to frame a particular situation in this way can result in unintended biases in the selection of indicators,[8] such as spatial and temporal biases.[33]

Context includes spatial and temporal scales and must be defined in conjunction with sustainability and other goals (Fig. 1) because the scope of the goals determines the spatial and temporal boundaries for the analysis. Consideration must be given to the geographic extent and the time periods encompassed by the sustainability goal or objective for analysis. Some indicator efforts may be designed to monitor the status and trends of particular regions, watersheds, fuel sheds (areas providing feedstock), or national programs. A global scope may be appropriate for some analyses, such as those designed to consider climate impacts, national or multinational policies, and issues related to imports, exports, and energy security associated with displacing fossil fuels with biofuels. While many environmental analyses of biofuels have used global-scale models to consider issues such as indirect land-use change and climate change, the results are highly uncertain[34] and provide little useful guidance to local decision-makers on the trade-offs with the many other aspects of sustainability. Furthermore, questions about how and where to produce biofuels, effects on welfare, and the influence of local context are best considered at the regional, watershed, or fuel-shed scale and in accordance with the scale of investment and management decisions and where effects on many ecosystem and social parameters are more readily evaluated.

Identify and consult stakeholders

Stakeholders may be defined as individuals, groups, businesses, or organizations that can affect or be affected by a process or project under consideration. Some environmental organizations take this concept another step by representing specific species (often threatened, endangered, or charismatic) as stakeholders. Some sustainability standards have indicators requiring that all stakeholders be 'engaged' (e.g. provided adequate opportunity to learn about and comment on the proposal and that the parties responsible for the proposal be able to demonstrate their responsiveness to legitimate concerns and grievances presented by stakeholders). Establishing processes and providing evidence of free, prior, and informed consent of local stakeholders is required by some sustainability certification standards and some developing countries that are exploring large bioenergy projects (e.g. Mozambique regulations for rural development and land leases[35]).

Stakeholder values, perspectives, and information needs constrain the goals, time frame, underlying assumptions, and other aspects of the decision-making process.[36] A key concern is determining who makes judgments about which stakeholders, sustainability goals, and issues are to be considered in indicator selection and who legitimately represents stakeholder groups. Who leads the process and applies this framework is crucial, and ideally the leader is recognized by all as a non-partial, honest broker. While land managers, policymakers, community organizations, and others with a stake in bioenergy sustainability could identify indicators that meet their own needs, these indicators are unlikely to lead to viable decisions unless other stakeholders are also offered the opportunity to articulate their goals. Just the cost and feasibility of measurement may require multiple stakeholders to be involved. Including diverse stakeholders early in the process[37] is crucial, because each represents a unique epistemic community and therefore brings different priorities, values, and meanings to the indicator-selection process. While considerable emphasis is put on the credibility (scientific accuracy) of indicators, it is equally important to address their legitimacy, which entails 'the process of fair dealing with the divergent values and beliefs of stakeholders'.[30] For example, farmers and scientists have differing perceptions of sustainability.[7] Also, scientists can have a different purpose in mind for indicators than decision-makers.[31]

Some indicators tend to be dominated by the concerns and priorities of industrialized countries[33] or specific agency mandates. If project context includes non-industrialized regions, stakeholders representing those regions should be involved. It is also important to be aware that concepts of *scientific credibility* can vary, as cultural contexts vary, and as perceptions of expertise range from indigenous knowledge to Western notions of the scientific method.[38] Therefore, a broad cross-section of stakeholder goals should be systematically considered[39] as part of indicator development.

Stakeholders may have aligned or competing goals. Fulfilling regulatory requirements or guidance is a common obligation that may overlap with sustainability goals. In contrast, employment, income, environmental, and production targets often conflict or involve trade-offs among subsets of stakeholders. For example, a proposed project may improve incomes and enhance environmental conditions for some people while shifting burdens to others. Some woodlot managers may be more concerned about personal compensation and yield, whereas other stakeholders might be more interested in water quantity and quality. A farmer who is considering growing bioenergy crops may at the same time be considering the trade-offs of bioenergy versus traditional crops and how choices affect financial risk. Furthermore, stakeholder needs, goals, and priorities are not static but change over time, and the context and individual circumstances evolve.

Identify and assess necessary trade-offs

Whenever goals are articulated by multiple parties, it is likely that some goals may conflict, or resources may not be adequate to evaluate information pertinent to all goals. A transparent, structured, and participatory process is recommended for assessing potential conflicts, negotiating trade-offs and making decisions.[14,32] Sustainability goals and requirements within one jurisdiction can work counter to sustainability goals in another area.[40] Similarly, focusing on one aspect of sustainability (e.g. environmental considerations) may jeopardize another aspect (e.g. social needs). If efforts to achieve one target result in prohibitively high costs for bioenergy, then other environmental, social, and economic sustainability targets are compromised. Similarly, if efforts to have a profitable operation result in social and environmental costs, sustainability is also compromised. Trade-offs are often inherent when comparing goals associated with different bioenergy technologies (e.g. rural employment versus greenhouse gas emissions).

Whereas some sets of indicators may be pertinent to multiple goals (e.g. regulatory and sustainability goals), they may not be able to accommodate *all* goals. Sets of potential indicators selected in response to particular questions may not reflect all aspects of the bioenergy system that various stakeholders value.

Determine objectives for analysis

The objectives for a particular sustainability analysis will determine its scope, spatial and temporal scales, necessary comparisons, and data requirements. Objectives flow from overarching goals but differ from them in providing details that define the types of analyses that are conducted.

Regulatory analyses may require comparisons among fuel types, comparisons to standards, or comparisons to baseline conditions or reference scenarios.[8] For example, the California Air Resources Board requires comparison of the carbon intensity of alternative energy technologies.

Assessments may be retrospective and focused on data collection and assimilation, or they may be prospective and use modeling projections. An objective may be to assess the long-term capacity of the land to maintain yields under different management options. Assessments of trends may focus on a variety of ecosystem, economic, or social attributes. For example, the RSB includes two principles that require the evaluation of trends through measurement or modeling: mitigation of climate change; and contribution to the social and economic development of local, rural, and indigenous peoples.

Scientists and policymakers often need to be able to differentiate effects resulting from bioenergy from effects resulting from previous or alternative activities. Hence, an objective for analysis is to determine baseline conditions, trends, and likely future conditions. One option is to make informed projections based on the historical baseline. However, this approach is feasible only for those regions where trend data are available for proposed indicators. And significant uncertainty always applies to future conditions or to 'alternative pasts'. Adequate historic data are lacking for many aspects of environmental, economic, and social sustainability in many geographic regions. A simplified business-as-usual (BAU) reference scenario – assuming that current observed conditions continue into the future – may be preferred and could be more accurate than informed projections in some situations.[41] A significant drawback to any informed projection is a reliance on 'behavioral assumptions'.[42] For example, comparisons between the BAU case and other projections are often confounded by significant, unanticipated shifts in land or water management have occurred.

One assessment objective that cannot be undertaken with sustainability indicators alone is distinguishing indirect effects of bioenergy from effects of other land-use and resource management practices. Projected or modeled indicators might be able to provide information about direct effects of new bioenergy production, but they cannot be used to establish causality in assessments of activities occurring elsewhere.

Determine selection criteria for indicators

Selection criteria are developed and implemented to determine the particular suite of indicators to use. This step is a critical and challenging aspect of bioenergy sustainability measurement and is at the heart of the indicator-selection framework. 'The importance of indicator selection cannot be overemphasized since any long-term monitoring program will only be as effective as the indicators chosen.'[43] This step of the framework involves modifying general selection criteria for indicators in a context-specific way, specifying criteria that are pertinent to objectives for particular sustainability analyses, and considering the suite of potential indicators in relation to goals and objectives holistically.

Several established selection criteria for environmental indicators are pertinent to sustainability indicators for bioenergy choices, no matter what the objectives of the analysis. Indicators should (i) be easily measured (feasible and cost-effective); (ii) be sensitive to stresses in the system; (iii) respond to stress in a predictable manner; (iv) be anticipatory (signify an impending change in key characteristics of an ecological or socioeconomic system); (v) predict changes that can be averted by management actions; and (vi) be integrative (meaning that collectively the suite of indicators provides a measure of the key variables in the focal system).[27] The general criterion of legitimacy to stakeholders, as already discussed, is also important. While these general selection criteria are universally applicable to all indicators, their meaning varies within each context and according to specific assessment goals. For instance, what may be cost-effective in one situation may be cost-prohibitive in another.

Many of the concerns that hamper the use of ecological indicators[42] are useful in guiding selection of sustainability indicators for bioenergy. These include (i) oversimplification resulting from the selection of only one or just a few indicators, (ii) unclear or ambivalent goals that can result in the measurement of incorrect variables for the place and time under study, and (iii) difficulty in validating information provided by indicators.[44]

The clear articulation of goals and objectives for analyses provides a lens through which selection criteria for indicators should be considered. This filter ensures that irrelevant criteria (and therefore irrelevant indicators) are eliminated from consideration. Information, data and indicators are only useful if they help people to meet desired standards or outcomes.[45]

Analyses of bioenergy sustainability may involve widely differing goals and objectives, and indicators and criteria for their selection should reflect objectives of the particular situation. For instance, objectives involving trend analysis require indicators that are measurable on a regular basis, but they do not require land managers or program managers to attain specified targets. Other approaches such as the GBEP aim to support specific development goals and best practices and therefore recommend that indicators be linked with targets. If the objective of an analysis is to identify scenarios of bioenergy production that meet defined performance thresholds, then indicators should be selected that provide useful information about changes relative to the defined targets. If the objective of an analysis is to determine whether progress has been made toward a sustainability goal, then selection should prioritize indicators that are sensitive enough to provide timely data on changes relative to the goal. If the objective of an analysis is to compare alternative crops at any scale, the indicators should measure relevant properties for each crop studied. Comparisons of alternative planting locations or management regimens should involve indicators that are measureable at the local scale and sensitive to differences at the plot scale. Indicators that are meant to compare life-cycle effects of alternative energy or fuel policies should apply to a broadly defined scale rather than to only farm production or biorefineries or to properties of only one fuel type.

Historical information is often needed to fully understand trends in indicator values, and the availability of that information affects the selection of indicators. For example, comparisons between bioenergy production steps and past land attributes require historical data. Defining baselines requires that potential indicators be measurable for appropriate past periods. Yet most efforts to develop indicators, even very comprehensive schemes, do not address the need to document reference scenarios, baseline conditions, and trends for sustainability analyses.

If the objective of an analysis is to conduct prospective assessments of sustainability, the indicators must be able to be modeled or statistically projected into the future. If the goal is to conduct life-cycle analyses for bioenergy, the indicators should be measurable with respect to the stages of the life cycle where effects are not negligible. The uncertainty associated with indicator values that are intended to contribute to regulatory policy for bioenergy should be known or measurable.

Selection criteria that are applicable to a *suite* of indicators may be different from those that are applicable to *individual* indicators.[4] The interpretations of individual indicators may depend on the entire suite of which they form a part, and therefore, interpretation varies as the suite is modified to meet particular goals. Together, the suite of indicators should be able to integrate sustainability information to meet various objectives.

Identify and rank indicators meeting the selection criteria

In selecting indicators for assessing bioenergy sustainability, the land managers, regulators, or others conducting analyses determine the set of indicators that *as a group* best meets the selection criteria. Each individual indicator should be evaluated according to its intended purpose within a particular suite. For example, the GBEP proposes that technical experts rate each potential indicator on scientific merit (i.e., established relationship between the indicator and goal); that decision makers rate each indicator for practicality and utility (usefulness for decision-making); and that all stakeholders rate the indicators for relevance to their values. Moreover, stakeholders should be involved in developing unambiguous indicator definitions.

Ranking indicators may require multiple iterations. The initial pass may result in several suites of indicators that meet the selection criteria. Subsequent passes may involve determining which of the indicators fits within available budgets and is best suited to the goals and objectives for analysis, according the perceptions of the key stakeholders. The process, like criteria selection, may be enhanced by devising a scheme that facilitates ranking according to a variety of perspectives or through query and response check lists.

This framework builds upon the work of several efforts that have developed guidelines for identifying and ranking indicators for other purposes (e.g. conservation[46]). Past experiences underscore the need to budget up front for the costs of developing and applying monitoring and evaluation systems and to assure that data collection and analysis balance what is doable with available funds and what is desirable in terms of outcomes.

Identify gaps in ability to address goals and objectives

After the assessment is complete, the users of the framework should evaluate whether the specific objectives for analysis are achievable with the selected indicators, existing data, and resource constraints. If measuring a set of indicators requires resources that are not obtainable, it may be necessary to revise goals or objectives and revisit the criteria- and indicator-selection processes (Fig. 1). Similarly, an examination of available data may show that large spatial or temporal gaps in data negate the value of the indicator. Testing the validity and ability of indicators to perform as planned is a critical step that should be completed before too much time and effort is invested in data collection. Policymakers may require data representations that are easily communicable to a larger audience.[47] Scientists may require a higher level of granularity. The general public may need visual displays that are readily understandable. And producers may need to be assured about economic impacts.

Determine whether objectives are achieved

It is important to obtain feedback on the effectiveness of indicators as information is provided to stakeholders. Evaluating the achievement of stated objectives using pre-established criteria is fairly straightforward while trying to gauge perceptions about whether broad goals were achieved may be challenging. If stakeholder feedback reveals perceptions of ineffectiveness, the user of the indicator selection framework should attempt to determine the source of the perception. Are the indicators themselves in dispute, or was the manner in which the data were collected, interpreted, summarized and presented inappropriate (e.g. too much granularity)? Or perhaps the spatial or temporal scale was believed to be inappropriate for the goal. At this point, decision makers may find it necessary to revisit the goal definition step and ultimately modify the objectives or the indicators.

As data are collected and evaluated, it is not unusual to discover that some indicators are unnecessary or even detrimental to goals. Care must be taken to assure that indicator suites are providing information that supports objectives and constructive decisions. The development literature is filled with cases where project emphasis on reaching specific indicator targets (e.g. trees planted or schools built) undermined achievement of the overall goals (e.g. forest ecosystem services and education). Furthermore, over time it is often possible to identify less expensive or more accurate indicators to meet needs, or proxy indicators that can adequately replace multiple individual indicators.

Assess lessons learned and identify good practices

The importance of periodic assessment cannot be overstated. Too often, when the stakeholder engagement stage is completed, or a specific project is finished, the participants scatter and valuable lessons are lost. Even with successfully met goals, stakeholders are always able to pinpoint aspects of the endeavor that they would approach differently were they to repeat the process. Also crucial at this stage is the discussion and documentation of significant success factors and good practices for applying the indicator suite. While the term 'best management practices' is common, what is actually meant is good practices that can be continually improved.[48]

The opportunity for continual improvement is indicated in Fig. 1 by a line going from step 10 back to the stakeholders, context and objective setting boxes. Sustainability is not a fixed state but an aspirational goal. Contextual conditions and stakeholder groups change over time. Environmental conditions, social needs and priorities, and markets interact dynamically. Mechanisms for continual improvement are an essential part of the framework supporting assessment of sustainability of bioenergy systems.[49]

Concluding comments

Some of the key steps in selecting and evaluating indicators include clearly defining sustainability and other goals and objectives for analysis, developing practical criteria for selecting indicators that relate to the goals, and applying the criteria to select indicators of bioenergy sustainability. The focus should be on those indicators that contribute the most value toward achieving goals. The iterative process facilitated by the framework, including the refinements based on stakeholders' involvement, contributes to goal clarification and continual improvement in the use of indicators to assess progress of bioenergy systems toward sustainability.

Many challenges are associated with these steps. Ideally, the objectives for analysis should be defined only after potential synergies and trade-offs among stakeholder goals are considered but this is always challenging and becomes untenable at large scales. Some of the key objectives (e.g. comparisons with baselines and assessments of trends) require data that are accurate, reliable, and guaranteed to be available over the long term.

By using this framework to select sustainability indicators for analyses of bioenergy projects, decision makers should be able to avoid some of the burdens and costs that are often associated with the adoption of an existing scheme or less structured methods of indicator selection. Selecting indicators using a formal framework can (i) contribute to stakeholders' understanding of sustainability and other goals, (ii) ensure that important stakeholder concerns and priorities are considered in the indicator selection process, (iii) develop an indicator suite that is well-suited to the sustainability goals and objectives of the analysis, and (iv) yield a good cost-to-benefit ratio. Clearly defining goals and objectives and applying practical criteria for selecting indicators are key initial steps in developing an effective framework for analysis. Applying the framework at project inception provides an explicit commitment to transparency that can increase legitimacy and help build supportive constituencies for subsequent steps in project development. Furthermore, such up-front thinking can save money in the long run.

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