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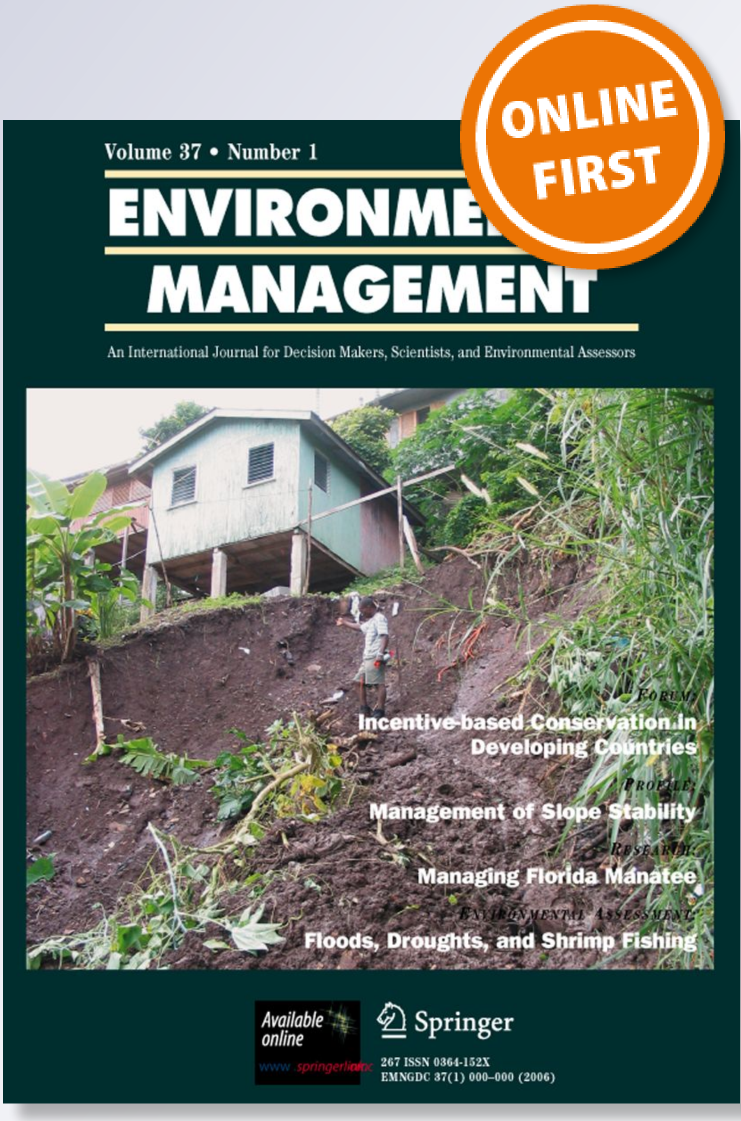

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Environmental Indicators of Biofuel Sustainability: What About Context?

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Abstract Indicators of the environmental sustainability of biofuel production, distribution, and use should be selected, measured, and interpreted with respect to the context in which they are used. The context of a sustainability assessment includes the purpose, the particular biofuel production and distribution system, policy conditions, stakeholder values, location, temporal influences, spatial scale, baselines, and reference scenarios. We recommend that biofuel sustainability questions be formulated with respect to the context, that appropriate indicators of environmental sustainability be developed or selected from more generic suites, and that decision makers consider context in ascribing meaning to indicators. In addition, considerations such as technical objectives, varying values and perspectives of stakeholder groups, indicator cost, and availability and reliability of data need to be understood and considered. Sustainability indicators for biofuels are most useful if adequate historical data are available, information can be collected at appropriate spatial and temporal scales, organizations are committed to use indicator information in the decision-making process, and indicators can effectively guide behavior toward more sustainable practices.

Keywords Baseline conditions · Bioenergy · Natural variability · Spatial and temporal scales · Supply chain · Systems

Introduction

As biofuels are increasingly produced around the world, stakeholders involved in biofuel production, use, and policymaking are attempting to measure sustainability. Sustainability represents multiple dynamic goals rather than a current or future state, and assessments should compare the relative merits of alternative trajectories in meeting these goals. Sustainability incorporates environmental, economic, and social processes and effects that are measured directly or indirectly through sets of indicators (Hecht and others 2009). A challenge in addressing sustainability goals is that their achievement is inherently place-based (Kates 2011; Corbière-Nicollier and others 2011). Hence, understanding the context of a biofuel system is necessary before progress toward sustainability goals can be measured and addressed.

Numerous efforts are under way to develop sustainability indicators for biofuels (van Dam and others 2008; Hecht and others 2009). Dozens of organizations have been formed to promote sustainable biofuel industries, such as the Council on Sustainable Biomass Production in the

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United States (CSBP 2010) and the Roundtable on Sustainable Palm Oil in Southeast Asia (RSPO 2011). Hundreds of indicators are being proposed to address sustainability policy goals that transcend national boundaries [e.g., the Roundtable on Sustainable Biofuels (RSB 2011) and the Global Bioenergy Partnership (GBEP 2010)]. Most environmental sustainability indicators for biofuels can be placed into six broad categories related to soil quality, water quality and quantity, air quality, climate forcing, biodiversity, and vegetation productivity (McBride and others 2011). This article examines how context affects the selection, measurement, and interpretation of these indicators, rather than recommending new indicators or a new taxonomy for indicators.

Developers and users of sustainability indicators must consider the intended use and context of an indicator, or they will struggle with the balance between generality and specificity. While it may be desirable to apply a broad, consistent set of sustainability indicators to all situations, the technical challenges of applying many sustainability indicators can be a barrier to their adoption. The associated costs of measuring a large variety of sustainability factors can be prohibitive, especially for small-scale producers (Lee and others 2011). Moreover, generic suites of indicators provide only general information about aspects of sustainability, and that information may not be of sufficient relevance to a particular situation, or it may even be misleading in some contexts. Turnhout and others (2007) have suggested that the successful application of indicators is specific to each situation. Corbière-Nicollier and others (2011) assert that the context of bioethanol indicator selection should include adaptability of the indicator to the local situation, relevance to the sustainability goals, and reliability of the indicator, including data quality and availability.

In this paper we examine the implications of the context in which environmental sustainability of biofuels is assessed and provide examples to illustrate why the consideration of context is critical for the appropriate selection (or development), measurement, and interpretation of sustainability indicators. Furthermore, we describe how the failure to consider context might result in a potentially biased assessment. The paper is organized to cover aspects of context of a biofuel-related decision that influence selection, measurement, and interpretation of environmental sustainability indicators (Fig. 1). Potential purposes of the assessment are described. Next, aspects of biofuel systems that affect indicator selection, including the supply chain and system management, are discussed. We consider policies and decisions that drive the selection and use of biofuel sustainability indicators. The context of values of individual decision-makers and stakeholders is presented. The importance of place and time (including regional aspects of context, important influences of scale, baselines, and reference scenarios) is noted. We conclude that, to be most useful, sustainability indicators for biofuels need to be selected (or developed), measured, and interpreted with careful consideration of the context in which they are used. Furthermore, major sustainability issues and related indicators vary along the supply chain; policy specifies some indicators that are then subject to context-dependent interpretations; location can influence the relative importance and interpretation of indicators; and the lack of baseline data for some environmental factors does not allow robust interpretations of trends. In practice, appropriate indicators are determined by their intended use.

Purpose of Sustainability Assessment

The purpose of a sustainability assessment determines which indicators are needed and how they are measured or modeled (Fig. 1). Indicators can be used to assess and communicate the status of the environment, sometimes with respect to a target; to monitor trends; to provide early warning signals of changes; to provide evidence concerning causes of observations (Cairns and others 1993; Dale and Beyeler 2001); or to compare (e.g., water quality for biofuel systems as compared with another fuel source, feedstock, or land use). Indicators may be used to measure changes in the environment when best management practices are implemented (Oregon Environmental Council 2011). Some indicators are specified by policies (see Decision and Policy Context below). Definitions, goals, and priorities for sustainability must be clearly stated so there can be a strong relationship with what is measured (Sumner 2004; Davidson 2011). However, there is limited agreement among stakeholders as to exactly which indicators should be included in defining biofuel sustainability for specific purposes (Buchholz and others 2009).

The relative costs and benefits of a potential indicator depend on its intended use (Caughlan and Oakley 2001). For example, where early warning of soil loss is the objective, indicators of soil stability may be more important for sloped and tilled plots than in situations where erosion is likely to be minimal [e.g., flat land with perennial species or no-till management (Blanco-Canqui and Lal 2009)]. Relationships between indicator categories can be used to narrow the list of indicators, consistent with the purpose of the sustainability assessment. For example, indicators of biodiversity may have added value where they reflect changes in environmental conditions, such as land-use or nutrient changes (Schweizer and Matlack 2005; Dauber and others 2010).

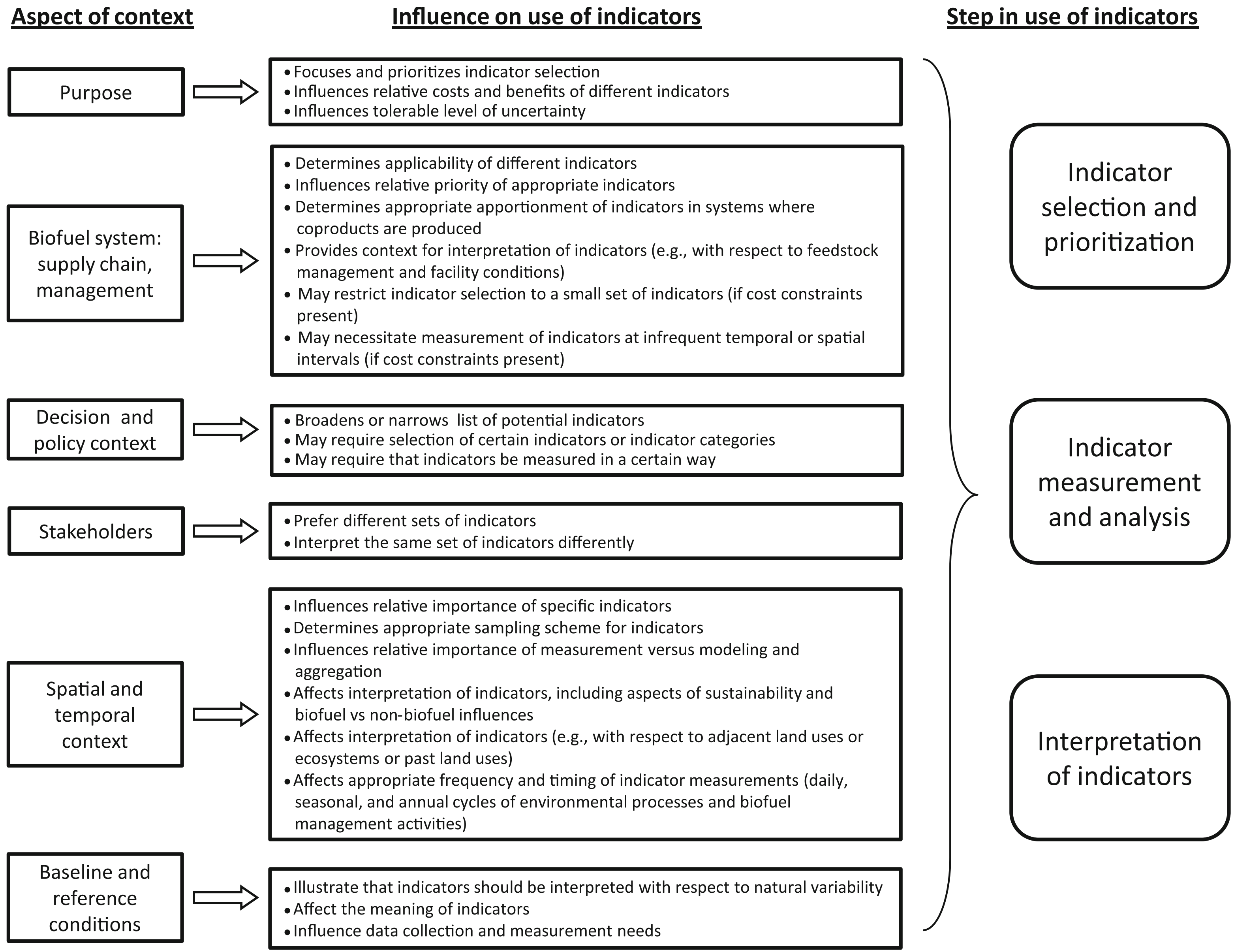

Fig. 1 Aspects of the context of a resource-management question that influence selection, measurement, and interpretation of environmental sustainability indicators for biofuels

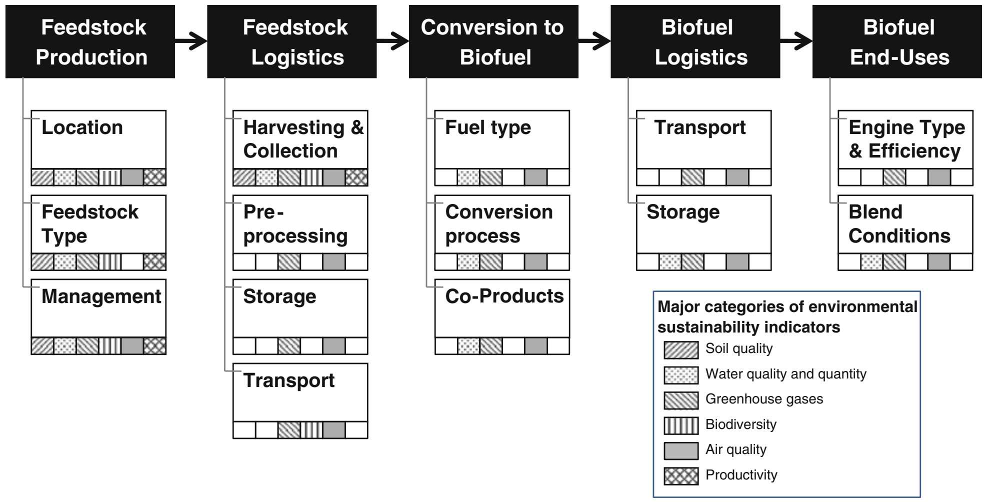

Fig. 2 Stages of the biofuel supply chain, elements within those stages, and categories of environmental sustainability indicators that represent major effects for each element. A *blank box* indicates that the indicator category does not experience a major effect for that element of the biofuel supply chain

The Biofuel System

Supply Chain

The stages and activities of the biofuel supply chain can necessitate different environmental indicators (Fig. 1). The supply chain includes feedstock production, management, and logistics through conversion and end uses. Figure 2 provides a simplified representation of the stages in the biofuel supply chain, including activities and options within each stage, and illustrates the categories of indicators that are important to measure. All of the categories of indicators in Fig. 2 apply to most initial steps of the supply chain (i.e., feedstock production and harvesting), and fewer categories apply to the later stages. The larger number and diversity of categories in the early stages make it more challenging to prioritize and measure an appropriate suite of indicators. Notably, greenhouse-gas indicators are applicable in all fourteen steps of the biofuel supply chain identified in Fig. 2.

Although water and air quality indicators apply to several stages of the supply chain (Fig. 2), relative priorities for monitoring and measurement within those categories can vary greatly. For example, the most important water-quality indicators at the feedstock-production stage may be measures of nutrients in streams; however, in the context of transport and storage, measures of ethanol and hydrocarbons leaking to groundwater are more important (Niven 2005). Hexane can be an important component of local air emissions from biodiesel production because of its use as an extractant for vegetable and algal oils (Hess and others 2009), but emissions of hexane are less important for other stages of production. Ruiz-Mercado and others (2012) proposed a large set of sustainability indicators for chemical processes that are appropriate for the conversion step of the biofuel supply chain.

Greenhouse-gas-emission indicators are important for all stages of the biofuel supply chain (Fig. 2), but the gases emitted can vary depending on stage and context. Some sources involve interaction between feedstock-production systems and soil (e.g., changes in nutrient and carbon stocks); whereas other emissions (mostly CO_2) early in the supply chain result from using fossil fuels to produce inputs (fertilizer and pesticides) and to power farm machines for planting, managing, and harvesting the feedstock. Combustion, fermentation, or other industrial processes produce greenhouse-gas emissions from feedstock conversion, and transportation end uses also produce greenhouse gases. If anaerobic digestion of algal biofuel waste occurs and nitrogen-containing material is applied to soil, methane and nitrous oxide may be emitted (Frank and others 2012). Consequently, greenhouse-gas indicators are measured or modeled differently in the steps of the biofuel supply chain, and these estimates can involve unique sensitivities and uncertainties as well as either direct measurements of specific gases or indirect inferences about them (e.g., from the amount of fuel combusted and the carbon content of that fuel).

Management

The management of biofuel-process related resources can influence sustainability indicator selection, measurement, and interpretation (Fig. 1). Resources that can be affected by management include land, minerals, water, soil, biota, nutrients, and carbon dioxide (for algal biofuels). For example, a soil-organic-matter indicator may be useful for planted feedstock such as *Miscanthus* (Hansen and others

2004) but inappropriate for feedstock based on municipal wastes, pond-grown microalgae, or waste oils. Metal concentrations in soils, waters, and plant tissues may be important indicators for feedstock plots fertilized with biosolids or for historically contaminated sites. For example, cadmium from biosolids has been shown to accumulate in switchgrass cultivars and to reduce yields (Reed and others 1999). Furthermore, indicators related to pesticides should be selected to address chemical applications involved in past and planned land use (Thomas and others 2009). Gene movement may be important to monitor for genetically modified crop plants or algae (Snow and others 2005). Parameters for estimating soil erosion are specific to crop and yield; where smallholder cassava systems in Mozambique are nutrient- and water-limited, yield estimates must be adjusted below ideal values (de Vries and others 2012). Water- or soil-quality indicators for biofuels derived from algae may need to consider salinity where seawater is used (Yang and others 2011). In these examples and in gray-water systems (Subhadra and Edwards 2010), water-quantity indicators may be less important than water quality. Water use can vary with the age of the ethanol production facility (USEPA 2011), and historic trends can be useful for predicting whether water quality or quantity performance can be improved.

Indicators used in the context of bioenergy systems need to reflect appropriate approaches to allocating shares of inputs and effects among all co-products. As biofuel systems produce increasing numbers of marketable co-products, such as food, feed, fiber, nutraceuticals, cosmetics, bio-chemicals, lubricants, and other materials, the measurement of sustainability indicators becomes more complex (Bielicki and others this issue). The choice of allocation method has significant impact, for example, on the greenhouse-gas emissions for biofuel that are estimated by a life-cycle assessment (LCA). There is no consensus on any one method that is most appropriate, in part, because of the diversity of contexts and purposes among assessments (Guinée and others 2009; Gnansounou and others 2009; Wang and others 2011).

Decision and Policy Context

The decision context includes the social, political, and institutional framework in which decisions are made with respect to biofuels (Fig. 1). Policies often determine the purpose and scope of a sustainability analysis and may require analyses of effects of biofuels on aspects of the environment, comparisons with effects of fossil fuels (Wu and others 2009), attributions of observed environmental effects to biofuels (Powers 2007), compliance with targets for certification (van Dam and others 2008), or other actions. Biofuel producers make decisions about feedstock storage, fuel storage, blend conditions, and other parameters that influence the selection of sustainability indicators in the categories shown in Fig. 2.

Currently, greenhouse-gas indicators predominate in many biofuel decisions, even though other categories of environmental sustainability indicators are arguably equally or more important (see, for example, the U.S. Environmental Protection Agency's TRACI tool, Bare and others 2003). Among the most debated sustainability indicators in biofuel policy in the U.S. are those supporting LCA of greenhouse gases for the USEPA Renewable Fuel Standard (USEPA 2010). The U.S. Energy Independence and Security Act of 2007 requires an LCA of biofuels that takes into account direct and indirect effects of land-use change. Indicators of land-use change are controversial because there is no consensus on the definitions, approach, or validity of the various methods applied to estimate indirect effects (Liska and Perrin 2009; DG Energy 2010; Overmars and others 2011; Zilberman and others 2011; Dale and others 2011; Kline and others 2011). This policy context has driven biofuel analysis in the U.S. to emphasize land-use change at federal and state levels (see ARB 2011), while a distinct policy context in Europe has led to a less dominant role of GHG emissions relative to other indicators (Sharman and Holmes 2010).

The selection of ways to measure environmental indicators has large implications for assessing sustainability, and those methods and their associated units are often prescribed by policy. For example, using greenhouse-gas emissions per unit of energy produced (typically grams of carbon equivalent per megajoule) as a standard unit for comparing fossil fuels to biofuels has contributed to analyses that consider the land-use-change effects of fossil fuels to be insignificant (ARB 2011). This conclusion is a result of the relatively large denominator for energy output from oil wells per unit of land occupied as compared to biofuel, the lack of adequate data on land-use and emission effects associated with the full life-cycle of fossil–fuel production, and the absence of accepted methods to define quantitative relationships between effects of oil exploration and production in one region and time frame and the quantity of energy produced in another region or time. Furthermore, where decision contexts aim to capture potentially significant differences in the duration or reversibility of environmental effects of alternative fuels or land uses, the indicators must include time as a variable.

Comparative decision contexts influence the choice of potential environmental sustainability indicators. Some decision contexts require the comparison of biofuel systems with reference scenarios, different energy sources (such as fossil gasoline), alternative land uses, or more specific siting alternatives. For example, feedstock, pipeline, or refinery siting decisions may require comparisons among alternate locations. Water-related indicators were included in a largely socioeconomic conceptual framework for siting biorefineries in the Canadian prairies (Luk and others 2010). Moreover, in comparative sustainability analyses, suites of sustainability indicators may include measures that are expected to be low or negligible with respect to biofuels but significant with respect to the reference scenario. For example, salinity may be an appropriate indicator of water quality in wetland vegetation communities when fossil gasoline produced from oil sands (Trites and Bayley 2009) is compared with ethanol, but salinity may be less important if the scope of analysis is limited to areas without wetlands or to ethanol production options alone. Methane may have a high priority for measurement among the greenhouse gases if livestock operations are compared with or constitute a part of biofuel feedstock production or reference scenarios (Smith and Olesen 2010).

Sometimes the decision context makes it acceptable to adopt a biased indicator, i.e., when the consequences of providing occasional false warnings of unsustainable conditions are preferred to a failure to identify unsustainable conditions. For example, conservative estimates of thresholds for toxicity are common in chemical-risk assessments undertaken in a regulatory context (Suter and others 2000). Another reason for the use of a biased indicator might be its low cost. For example, the rate of water withdrawal from public sources by a biorefinery is an inexpensive indicator of consumptive water use (McBride and others 2011). This indicator is biased because some withdrawn water may be returned to the water supply, but the bias may be acceptable in some situations, given the cost and convenience. In cases where decision makers are comparing alternative energy scenarios or alternative land uses, care is warranted to ensure that indicators are truly comparable and biases are documented and justified.

The precautionary principle (United Nations 1992) relates to bias and illustrates how framing the decision context can influence the selection and interpretation of indicators. The principle advises precautionary action when uncertain but irreversible effects could occur. With precautionary intent, the State of California (ARB 2009) and the U.S. government (USEPA 2010) include ILUC as an indicator of the effects of biofuels while acknowledging large uncertainties in estimates. However, incorporating ILUC values may not lead to actions that are consistent with a precautionary decision context because (1) the ILUC indicators are driven largely by legal requirements (USEPA 2010) and there is no consensus on the approach (CBES 2010; Babcock 2009; Kim and Dale 2011); (2) the ILUC indicators are not equitably applied in comparative decision contexts for all fuel alternatives (ARB Subgroup on Indirect Effects of other Fuels 2010); and (3) supply chain elements and potential indirect effects for traditional fuels are intrinsically distinct from those of biofuels (Parish and others, this issue). Many land-use, soil quality, and biodiversity effects associated with fossil fuels are more certain, enduring, and extensive than those postulated for biofuels (Parish and others, this issue), so measuring these effects would be consistent with the precautionary principle decision context. However, regulatory frameworks commonly focus disproportionately on new technologies and products like biofuels rather than older alternatives (Huber 1983).

In some regulatory contexts, the environmental effects of biofuels must be distinguished from effects of other activities. For example, where the intended use of an indicator is to assess the cumulative effects of multiple watershed activities or to estimate related biotic effects (Efroymson and others 2007), measured nutrient concentrations in receiving waters may be appropriate. However, where the purpose is to understand the contribution from biofuel feedstock production to stream nutrients, the appropriate indicator represents nutrient loadings associated with bioenergy crop management alone (Powers 2007). Such calculations are complicated by diverse contextual variables, data uncertainties, and variability in baseline values; therefore, modeling is typically employed to estimate values.

Policies that call for sustainable biofuels are sometimes implemented through certification processes. The certification of biofuel products can require indicators that are applicable across borders, ecosystems, and biofuel management systems and that follow standard measurement methods. For example, the European Union (EU) Directive 2009/28/EC states that only biofuels that reduce greenhouse-gas emissions and protect areas of high biodiversity and high carbon stocks can be counted toward a renewable fuel target (EU 2009; Di Lucia 2010). The extent to which recommended indicators are applied in certification schemes of particular jurisdictions or projects may depend on the relative ease of compliance, degree of enforcement, and attractiveness of bypassing certification. Potential bypasses might include pathways to alternative markets (Di Lucia 2010; Huertas and others 2010) or process changes that result in the inapplicability of a particular indicator (e.g., use of private water wells where the indicator measures only metered public water consumption). The development of certification systems for biofuel sustainability, along with component indicators, is best accomplished through an adaptive-management process specific to a particular context (van Dam and others 2008).

The decision context for a given indicator helps determine tolerable confidence levels for sustainability measurements and modeled results. For example, the current paucity of experience with the management of lignocellulosic crops (Dale and others 2010) and algae translates to low certainty regarding the sustainability of many aspects of commercial production of biofuels from these feedstocks. This level of uncertainty may be acceptable for decisions that can be changed with relative ease as new information becomes available (e.g., initial choice of feedstock) but not for others (e.g., establishing regulatory threshold values for compliance or making major long-term investments in infrastructure). Over time, as experience with different feedstock-production pathways accumulates, the types and degrees of uncertainty affecting sustainability indicator measurement and interpretation will be increasingly understood.

Stakeholders

Indicators are expressions of values (Bossel 1997; Kates and others 2005; Turnhout and others 2007) and reflect stakeholders' backgrounds and intentions for use of the resources. Stakeholders concerned about sustainability of biofuels range from policy makers to individual decision makers, such as farmers or conversion-facility managers, to groups interested in particular aspects of sustainability (e.g., biodiversity). Different stakeholders have distinct values, technical knowledge, authority, needs for information, and ways of communicating. Aspects of stakeholder contexts for indicators include the conditions the stakeholder perceives to be relevant; technical expertise and aptitude of those who choose the indicators; the purpose; and the confidence in the processes by which the indicators are created, measured, and conveyed (Cash and others 2003). The importance of these influences may be underestimated but becomes apparent when groups are negotiating the selection of sustainability indicators.

Different stakeholders often desire unique sets of indicators of biofuel sustainability, and they may interpret the same indicators and their importance in different ways. For example, the biofuel sustainability certification scheme associated with EU Directive 2009/28/EC focuses on greenhouse gases, land with high carbon stock, and biodiversity. However, interviews with government officials in Mozambique, a country considering its options to access EU markets, showed that land use and food production were higher priority issues for biofuel sustainability than the three environmental categories in the Directive (Di Lucia 2010). Thus, sustainability indicators implemented in the Directive might have been different if biofuel-exporting nations outside Europe had a more active role in their selection.

The context of sustainability assessments and relevance of indicators can change over time as new information becomes available, environmental conditions change, new stakeholders and priorities emerge, and the degrees of leverage that individual stakeholders exert ebb and flow. This dynamic has been termed the evolving "issue domain" (Jenkins-Smith and Sabatier 1999; Clark and Cash 2006) and has been analyzed specifically for bioenergy (Johnson and others 2012, this issue). For example, up until the early 2000s, typical LCAs of ethanol production focused on effects per kilometer of travel (see references in Sheehan and others 2004). However, when researchers included farmers in a participatory stakeholder process to analyze implications of using corn stover to produce ethanol, the farmers suggested that nutrient flows and yields be better represented in the analysis, which added an emphasis on the sustainability of farm operations and effects per hectare of land (Sheehan and others 2004).

Spatial and Temporal Context

Locations and timing of measurements of the sustainability of biofuels affect the choice of indicators, as well as how they are measured and interpreted (Fig. 1). Related factors include the regional context and spatial and temporal scales of analysis, including how local measures are aggregated to larger scales. For instance, Table 1 illustrates how aspects of streams and their regional context, as described later in this section, might alter aspects of environmental sustainability as well as the selection, measurement, and interpretation of relevant water-quality and -quantity indicators.

Location

The relative priorities and interpretations of environmental indicators for biofuels are influenced by the location of measurement. Regional variables include climate and soil variables, past and present land management and disturbance regimes, and vegetation.

Greenhouse-gas flux is determined partly by weather, prevailing vegetation, and soil conditions as well as by past and current land-management practices. For example, N_2O emissions depend on interactions among cultivation practices, fertilizer use, climate, soil drainage, and soil texture (Bouwman and others 2002); thus, the importance of N_2O as an indicator of greenhouse-gas flux varies similarly. In addition, the relative accuracy of different indicators for estimating carbon sequestration may vary with region and land-use history. For example, in a study of abandoned agricultural lands in southeastern Ontario, Canada, the time since abandonment was a better predictor than soil type for estimating carbon sequestration (Foote and Grogan 2010). The use of vegetation classes to estimate carbon stocks can be misleading in forest ecosystems with recent disturbances (Lackmann 2010; Magnani and others 2007). Social and cultural factors vary widely with location and affect the

Table 1 Examples of ways that stream context might alter the selection, measurement or interpretation of hydrologic sustainability indicators for biofuels

Context characteristic	Aspect of environmental sustainability potentially affected	Importance for indicators
Stream order	Flow and effects of nutrient inputs are more integrated in higher order streams; temperature regimes and sediment delivery are more critical measures in lower order streams	Relative priority of water-quality indicators
Location and extent of land area in biofuel production relative to other land uses in watershed	Nutrient concentrations in streams may be determined by a few point-sources or non-point sources. Effects of land management for biofuel depend on relationships among location, extent, and types of land uses	Interpretation of water-quality indicators
Weather, including season (dry versus wet) and extreme events	Most environmental indicators (e.g. water quantity and quality, sediment loads, hypoxic area, air quality and others) are highly sensitive to weather, especially extreme weather conditions	Timing of measurement of water-quality and -quantity indicators
Climate	Climate patterns and shifts can influence measurements related to productivity, groundwater or surface-water volumes and flows, and other indicators	Interpretation of water, land and air-related indicators
Regional biota	Biotic composition and diversity affects some indicators (e.g., nitrogen content), and biotic indicators of water quality in one region may not be appropriate for other regions	Selection of water-quality indicators
Land management: agro-chemical application	Different chemicals have different environmental pathways and persistence periods. For example, there may be a specific time frame after application when chemicals may be found in nearby streams	Location and timing of measurement of water-quality indicators
Land management: drainage practices and crop rotation	Sediment levels may increase following plowing and harvesting; timing varies by crop type and rotation periods	Location and timing of measurement of water-quality indicators
Land management: riparian management	Presence, composition, diversity, and growth rates of riparian vegetation can affect shading, stream temperature, and biota	Utility and relevance of potential water-quality indicators
Water management	Algal feedstock ponds and all biorefineries may recycle/reuse water to reduce consumption	Interpretation of water-quantity indicators
Surrounding land uses: competing water demands	Withdrawals for industrial purposes, dense housing developments, etc., may alter flow levels	Interpretation of water-quantity indicators
Surrounding land uses: drainage	Peak and minimum flow conditions may vary with permeability, drainage, hydrodynamics, and other factors exogenous to biofuels	Location and timing of measurement of water-quantity indicators
Surrounding land uses and disturbances	Sediment levels increase when land is cleared; influxes of woody debris and sediment may increase because of forest fires, beetle outbreaks, or other disturbances	Timing and interpretation of water-quality indicators
Land-use history	Stream morphology and measurements may reflect land-use history	Interpretation of water-quality indicators

use of inputs and tillage, as well as the relevance of candidate environmental sustainability indicators.

Location also influences the relative importance and meanings of different soil-quality indicators. Indicators of soil nitrogen may be critical in some contexts, whereas soil phosphorus may be more important in others [e.g., in some tropical ecosystems (Vitousek and Sanford 1986)]. While phosphorus is rarely limiting in temperate terrestrial ecosystems (Vitousek and others 2010), sustainability analyses of U.S. biofuel feedstocks may require increasing emphasis on the element due to water quality concerns and declines in easily mined U.S. deposits (Vaccari 2009). Specific indicators are warranted to monitor the effects of amending particular soils with lime, fertilizers, and other inputs.

The regional context of soil conditions, climate, and prevailing vegetation types influences the relative importance of water sustainability indicators. For example, water-quantity indicators may be given a high priority in arid or semiarid environments or where the water table is in decline (Barton and others 2010). Water flow affects aspects of stream habitat, such as temperature and geomorphic features (Ward and others 2002). Measures of water quantity during low-flow conditions may be more important in streams than in lakes, where important indicators of biofuel sustainability are nutrient concentrations or changes in primary production.

Water-quantity indicators have region-specific interpretations. The rate of water use from the Ogallala Aquifer is significant in Texas, but groundwater consumption is of lesser concern in the Illinois farm belt (Lee and others 1981; Roberts and others 2007). Indicators of flow are affected by the draining of wetlands; the ditching and tiling of floodplains for agriculture; and the construction of irrigation channels, roads, dams, and reservoirs (Table 1).

Water-related measures are influenced by human activities upstream of the measurement location that may affect the interpretation of indicators (Table 1). Surface water impairment in the United States is often associated with construction, nonpoint pollution with phosphorus and nitrogen from agriculture (Carpenter and others 1998; Alexander and others 2008), or urban runoff (Meyer and others 2005) that affect soil erosion and suspended sediment load. Measured values of water-quality and -quantity indicators are influenced by the locations and spatial extent of biofuel crops in relation to the entire watershed area in which they are grown (Dale and others 2010) (Table 1).

The selection and interpretation of biodiversity indicators should be specific to the region where they are applied. For example, indicators may be selected to reflect site-specific recovery plans and habitat requirements for locally endangered species (Fellers and Kleeman 2007). Smeets and Faaij (2010) note that the spatial areas required to protect biodiversity can be estimated based on expert judgment and global ecosystem analysis, but effective protected areas are best derived when site-specific conditions are considered and biodiversity goals are specified. Similarly, common ecosystem measures (such as total vegetative cover; species richness; and presence, density, or cover of particular indicator species) have region- and scale-specific interpretations and should reflect the purpose of the assessment.

Transferring indicators that were developed and tested in particular regions to other locations requires cautious interpretation (Table 1). For example, Pollard and Yuan (2010) found that an indicator based on three aquatic insect orders [Ephemeroptera, Plecoptera, and Trichoptera (or EPT)], which is a common measure of stream quality, is a less consistent measure of increasing benthic fine sediment in waters across the United States than are organism traits (e.g., percent clinging taxa). Thus, at the national scale, general categories of organisms are more accurate indicators of fine sediment loads than are specific taxa.

Spatial Scale and Aggregation

The scale of data collection and analysis should match the intended use of the sustainability indicator. Both scales are determined by jurisdictional boundaries, the area targeted as a source of biomass feedstock or "fuel shed," feedstock management, extant monitoring programs, funds and infrastructure available for monitoring, and other assessment-specific factors, as well as by the extent of environmental influences (e.g., watershed or airshed). Veldkamp and others (2001) argue that a multiscale approach to measurement should be employed for most sustainability questions concerning land use, and Parish and others (this issue) assert that multiscale analysis is appropriate for most assessments of the environmental sustainability of biofuels. In one vision of agricultural sustainability, agronomic constraints are dominant at the field scale, microeconomic constraints at the farm scale, ecological constraints at the watershed or landscape scale, and macroeconomic constraints at the national or transnational scale (Lowrance and others 1986).

Whereas some indicators are applicable to multiple spatial scales, others are applicable only to specific scales (Ness and others 2007). Indicators of pesticide concentrations in soil are most pertinent to the local scale. While greenhouse-gas emissions are of interest because they convey information about effects on the Earth's climate, they can be measured or modeled at any spatial scale (although different levels of confidence and sources of uncertainty apply). For example, in measurements of N_2O emission in a fen meadow, soil variables and denitrification and nitrification variables were major sources of uncertainty at the point scale, but those uncertainties in soil characteristics averaged out at the field scale (Nol and others 2010). Measurements of changes in biodiversity are confounded by estimates of species composition, habitat diversity, and ecosystem function made at the local scale that do not necessarily capture broader effects on biodiversity and habitat alteration at the landscape scale (Ranney and Mann 1994). Modeling rather than measurement of species ranges is often more feasible for regional and larger scales, but simulations can be uncertain, projecting either too much or too little habitat (Austin 2007). Kline and others (2009) note that the scales of available data affect assumptions in global economic modeling of land-use change.

Choosing the spatial (and temporal, see below) extent for analysis begins with a clearly defined purpose and corresponding scope of study. In LCAs, a system boundary, which includes scale assumptions, is defined in relation to a functional unit of analysis and an inventory of inputs, outputs, and known effects associated with the selected process and function. The International Organization for Standardization LCA standard recommends that criteria related to mass, energy, and environment guide specific decisions on what to include in or exclude from the system boundary and subsequent selection of criteria and indicators (ISO 2006). Transparent documentation of how system boundaries are determined for assessments and indicators is recommended.

It is sometimes appropriate to consider landscape features beyond the focal area of a biofuel-related decision because the spatial extent of analysis can affect the interpretation of some environmental sustainability indicators. For example, pollination services depend on the proportion of upland natural habitat within several kilometers of an agricultural site (Kremen and others 2004). Habitat services can be enhanced or decreased depending on the adjacent ecosystem (Efroymson and others 2010). Wildlife species abundance in an isolated habitat patch may not be as useful an indicator of sustainable populations as (1) the abundance measure for a set of patches connected by corridors through which the wildlife move (Rosenberg and others 1997) or (2) the presence/absence of species that can move between disjoint habitat patches (Offerman and others 1995).

Selecting indicators that facilitate the appropriate attribution of large-scale effects to biofuels is difficult. For example, while biofuel crop management could affect the areal extent of the hypoxic zone in the Gulf of Mexico (Costello and others 2009), and thus, the area of hypoxia is a candidate indicator of biofuel-related water quality and fisheries sustainability, that area varies widely, independent of land use for biofuels. Forces influencing the extent of the hypoxic zone include interactions among a host of natural conditions (ocean-shelf morphology, wind and water currents, rainfall patterns, and runoff) and anthropogenic activities (sewage and industrial-waste discharges and land-use practices) (Dale and others 2010). Furthermore, the reported extent and location of hypoxia are influenced by the specific dates of measurement, definitions, and sampling methods. Without the context of historic data measured using consistent methods, the areal extent, trends, and causes of hypoxia in the Gulf are difficult to interpret.

While the aggregation of local or point measures to larger scales is necessary for some purposes, consolidated estimates must be created and used with caution. Local nutrient measurements are sometimes aggregated to estimate regional status of nutrient flux in aquatic systems. However, broad spatial averaging of soil-quality values or of water-quality values conveys little information, whereas measures of the proportion of locations in a jurisdiction exceeding an adverse-effect level may be useful. Attempts to extrapolate fine-scale ecological knowledge to regional scales reveal that too much consolidation can cause trends and relationships to be so smoothed that they are meaningless (Rastetter and others 1992). Furthermore, aggregation of data to support sustainability indicators at very large scales creates computational challenges.

Spatial aggregation of data to the desired scale of assessment may be problematic because of the "Modifiable Areal Unit Problem" familiar to geographers (Gehlke and Biehl 1934). Statistical results have been shown to vary dramatically depending on where boundaries are drawn and what delineates the boundaries of the aggregation (Openshaw and Taylor 1979). Using smaller areal units for analysis leads to greater statistical variability among individual results. Conversely, selecting larger boundaries decreases statistical variability but leads to a loss of information about local processes. Thus, there is a trade-off between choosing indicators that best fit data to statistical measures and obtaining information at more-detailed spatial resolutions.

Temporal Context

Accurately assessing environmental sustainability of a biofuel requires that measurements be collected over enough time and at appropriate temporal resolution to meet the intended use. Indicator measurements should be timed to reflect key environmental and biofuel-management processes. Where the purpose of an indicator is to quantify effects relative to a historical trend, data must be collected for sufficient periods of time to quantify the trend and to elucidate the roles of other influences. For example, the depth of an aquifer that appears to be at steady state when measured for several months may be in obvious decline when measured over decades (Pfromm and others 2011). Sustainability analysis for biofuel production often involves projecting indicator values for decades into the future. Models that calculate indicator values should be calibrated and validated at the appropriate temporal scales. To put projections into temporal context, the baseline data for the same indicators should be analyzed for a historical time period of similar duration. Unfortunately, requisite data are often not available, making it difficult to attribute projected changes to biofuels or other causes and to estimate levels of confidence in the projections. Thus, the availability of temporally explicit data is an important part of the context for selecting and for interpreting indicators.

Energy-crop management choices influence the recommended timing of indicator measurements. Seasonal aspects that should be reflected in measurement frequency include timing of crop harvest and rotations as well as the time required to complete the cycling of related nutrients and carbon. Crop yields vary across years; for example, farm-level coefficients of variation for corn yield across the U.S. range from about 0.2 to 0.4 (Harwood and others 1999). Therefore, plant productivity indicators should be measured annually along with seeding and crop-removal dates and relevant weather variables. Sustainability analyses should consider the full rotation period associated with land management for biofuel production. Crop rotations often involve irregular cycles in response to the opportunities and constraints presented by ever changing markets, technology and weather.

Perennial crops provide challenges for selecting the appropriate frequency and duration of indicator measurement. For instance, switchgrass takes at least three years to reach full yield potential (Parrish and Fike 2005), and the duration of maximum yields is uncertain, with the estimated stand lifespan ranging from 10 years (Mooney and others 2009) to much longer with proper management (Fike and others 2006; Parrish and Fike 2005). Also challenging are the time periods associated with biomass sourced from forests. Bioenergy derived as a co-product of hardwood timber management, for example, can involve rotation periods spanning several decades (Kline and Coleman 2010).

Many other aspects of natural variability affect the frequency and duration of environmental indicator measurement. Measurements of water quality and flow are strongly affected by seasonality and are most reliable when measured for several seasons or even years (Table 1). Similarly, indicators of biodiversity, such as numbers of species, may be affected by the timing of migration, nesting, and other aspects of life history. Likewise, air quality tends to change throughout the year as temperatures rise and fall, wind patterns change, and seasonal land management contributors like prescribed burns are conducted (McCarthy and others 2007). Hence, air quality is often measured by the number of days during which regulatory standards are exceeded. However, attributing regulatory exceedences to particular energy-system activities is difficult, because there may be delays in effects associated with chemical fate and transport, as well as confounding sources.

Stochastic environmental processes, such as precipitation and associated water levels, can necessitate simulations for long time periods or averaging of some temporal measurements of biofuel sustainability. Montenegro and Ragab (2010) highlighted the importance of long-term calibration and validation of a hydrological model to generate accurate predictions of daily stream flow for use in estimating flow and groundwater recharge under land-use and climate-change scenarios in a semi-arid zone in Brazil. Only through accurate temporal modeling was it possible to discern the minimal effects on water availability associated with conversions from pastureland to castor bean biofuel feedstocks. Indicators of hypoxia in the Gulf of Mexico are best presented as five-year running averages of hypoxic area because of the large interannual variation caused by precipitation extremes, ocean and wind currents, and hurricanes (Scavia and others 2004).

Historical conditions may sometimes be more important than contemporary measures in determining aspects of sustainability. Harding and others (1998) examined diversity of stream invertebrates and fish in forested watersheds with different land-use histories and found that historic land uses were better predictors of biodiversity than were contemporary land uses (Table 1). Similarly, site-specific disturbance history can provide better estimates of forest carbon stocks than can current forest classifications or ecosystem types (Lackmann 2010).

The expected duration of a potential environmental effect can influence the recommended duration and frequency of measurement or the simulated time in a model. Land change may be relatively reversible (e.g., an agricultural plot or marginal land converted to a biofuel feedstock plot) or irreversible (e.g., loss of salt marsh habitat to subsidence). Indicators that can account for reversibility or lack thereof are required if the purpose is to equitably compare the effects of energy technologies over time.

Baseline Conditions and Reference Scenarios

For environmental sustainability indicators to be interpreted accurately, measures of baseline conditions prior to biofuel production must be understood (Fig. 1). Moreover, the elements of well-documented reference scenarios (conditions, activities, and trends that would prevail in the future in the absence of biofuel production) affect the interpretation of indicators. Baseline trends and reference scenarios reflect natural variability, short-term events (Hardman-Mountford and others 2005; Strömquist and others 1999), longer term trends, and policies. For example, interpretations of effects of biofuels on land use are different in regions where the baseline and reference projections indicate persistent abandonment or loss of farmland (the situation in the US, much of Europe, and in zones of shifting agriculture in the developing world), compared to regions where they indicate persistent agricultural expansion (ARB Time Accounting Subgroup 2010). Climate change, including regional shifts in precipitation patterns and possible changes in evapotranspiration rates, is one part of the reference scenario (Hardman-Mountford and others 2005) that should be considered in long-term sustainability analyses. Biotic parameters such as population richness or species abundance may vary based on natural processes such as predator-prey dynamics (Sih and others 1998; Mittelbach 1986; Levine 1976) or stochastic events that are unrelated to biofuels, and these are part of the assessment context. The purpose of a biofuel assessment may necessitate that baselines and reference scenarios be estimated at particular temporal and spatial scales (Strömquist and others 1999).

Measurements of baselines and reference scenarios help analysts determine whether effects can be attributed wholly or in part to biofuels. For example, if marginal or degraded lands are used for bioenergy crops, indicators of sustainability collected over a long time period can reveal improvements in soil conditions compared to baseline conditions (Blanco-Canqui 2010; Cherubini and Jungmeier 2010). In one case, measurements associated with baselinecondition soils clarified the meaning of indicators of carbon sequestration by *Miscanthus* plantations in Denmark, allowing researchers to attribute a portion of the soil organic matter to the feedstock vegetation (Hansen and others 2004). In contrast, estimates of water demand for bioenergy crops that have a high rate of evapotranspiration (Wu and others 2009) can be misleading if the full water cycle and water demand under alternative land uses are not taken into account (Fingerman and others 2010).

Many natural and anthropogenic factors can confound the interpretation of indicators of biofuel sustainability if their dynamics are not understood as being part of non-biofuel baseline conditions and reference scenarios. For example, because historic disturbance regimes are often the primary factor determining ecosystem carbon dynamics (Kurz and Apps 1999; Thornton and others 2002), estimated effects of land management for biofuels are sensitive to whether the reference case incorporates disturbance regimes (Dale and others 2011; ARB Comparative and Alternative Modeling Approaches Subgroup 2010). Similarly, extrapolations of trends and indicators beyond the measured period may not be appropriate, particularly when policy incentives and subsidies are involved (Liu and others 2008).

Conclusions and Recommendations

Sustainability should always be assessed within a well-defined context (Sydorovych and Wossink 2008). Context influences the selection, measurement, and interpretation of appropriate indicators of sustainability of biofuel systems (Fig. 1). Because of the potential for large-scale effects of biofuels and increasing awareness of the impacts of fossil-fuel alternatives, sustainability indicators are under development for both broad and specific purposes. Suites of environmental indicators can provide useful measures of the effects of different energy-supply pathways if selected appropriately and interpreted accurately. However, generic sets of indicators should be treated only as a starting point for selecting indicators for particular situations because of the different local concerns and purposes for measurement, the varied characteristics of biofuel and alternative energy systems, the range of stakeholders and their priorities, diverse regional environments, and differing scales of application. Some of the key aspects of context that influence the usefulness and interpretation of environmental sustainability indicators include the expense and difficulty of obtaining the indicator measures, the availability of baseline data, natural environmental variability, the consistency between the purpose and the scale of available indicators, and the degree of stakeholder confidence and ownership, including willingness to use the indicators to improve the sustainability of their operations.

Some environmental sustainability indicators for biofuels, such as nitrate in water, may be measured or modeled similarly in different contexts and scales. Other indicator categories, such as biodiversity, may depend more on local and regional variables.

While this paper has addressed the importance of decision context in indicator development, it is just as important to examine the influence of indicator choice on decisions. For example, decision makers should be aware of potential biases and misinterpretations that can emerge when indicators involve multiple factors related to energy produced, time, or coproducts. Moreover if particular environmental indicators are emphasized (e.g., uncertain effects on land use as per the precautionary principle), biofuel development might be delayed or discouraged (Liska and Perrin 2009).

The consideration of the context of biofuel sustainability assessments points to several recommendations. More attention should be given to context-specific issues that affect selection, prioritization, measurement, and interpretation of indicators of biofuel sustainability to complement the many ongoing efforts that are focused on developing general suites of indicators. These latter efforts may be useful for addressing national- and international-scale goals, as well as for developing a comprehensive list from which to select project-specific indicators, but they should be accompanied by caveats regarding their use in particular situations. For example, the scales at which indicators are measured or modeled must match the intended use. More effort should be put into formulating the purpose of particular sustainability analyses to reveal pertinent aspects of context.

Sustainability indicators and supporting models should be tested and verified for use in a wide range of contexts before use in policy or other broad applications to ensure that they provide useful and reliable measurements. Sustainability indicators for biofuels are most useful if adequate and relevant historical data are available, if organizations are committed to take measurements, and if the application and interpretation of indicators lead to more sustainable practices.

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