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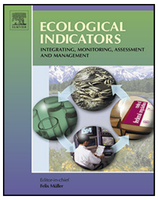

# Environmental indicators for sustainable production of algal biofuels

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## ABSTRACT

For analyzing sustainability of algal biofuels, we identify 16 environmental indicators that fall into six categories: soil quality, water quality and quantity, air quality, greenhouse gas emissions, biodiversity, and productivity. Indicators are selected to be practical, widely applicable, predictable in response, anticipatory of future changes, independent of scale, and responsive to management. Major differences between algae and terrestrial plant feedstocks, as well as their supply chains for biofuel, are highlighted, for they influence the choice of appropriate sustainability indicators. Algae strain selection characteristics do not generally affect which indicators are selected. The use of water instead of soil as the growth medium for algae determines the higher priority of water- over soil-related indicators. The proposed set of environmental indicators provides an initial checklist for measures of algal biofuel sustainability but may need to be modified for particular contexts depending on data availability, goals of stakeholders, and financial constraints. Use of these indicators entails defining sustainability goals and targets in relation to stakeholder values in a particular context and can lead to improved management practices.

## 1. Introduction

Sustainability considerations influence the development of alternative sources of energy, including algal-based bioenergy. Algae hold promise as a future source of liquid fuel in part because of anticipated sustainability benefits such as the use of degraded, non-agricultural land (Gao et al., 2012; NRC, 2012), high productivity per land area (Clarens et al., 2010), potential net greenhouse-gas (GHG) emissions benefits (Sander and Murthy, 2010), and potential use of wastewater as a nutrient source (Woertz et al., 2009; Craggs et al., 2012). However, technologies, scenarios, and supply chains are still under development, and sustainability costs and benefits are influenced by the choice among many options (e.g., open pond versus photobioreactor, the latter being a closed device for generating biological products that uses sunlight or sugars for energy).

Progress toward sustainability can be estimated using indicators, which represent environmental or socioeconomic elements of sustainability (NRC, 2010a; McBride et al., 2011). The focus of this paper is on environmental indicators of sustainable biofuel production.

The evaluation and selection of environmental sustainability indicators for algal biofuels have not kept pace with those activities for other feedstocks. Indicators of the sustainability of bioenergy pathways have been proposed by many institutions and researchers [e.g., Roundtable on Sustainable Biomaterials (RSB, 2010), Global Bioenergy Partnership (GBEP, 2011), McBride et al. (2011)] and are under development by others such as the International Organization for Standardization (ISO, 2010). Most indicators, principles, and standards for bioenergy have focused on terrestrial, vascular plant feedstocks such as corn, switchgrass, and forest products (CSBP, 2012). Some compilations of indicators and standards mention algae in the context of potential risk from genetically modified organisms (RSB, 2010; Fritsche, 2012). The U.S. National Research Council (NRC, 2012) published potential environmental impact and resource requirement metrics for the sustainable development of algal biofuels and listed the most important potential sustainability concerns but did not identify the most likely benefits or a practically measurable set of environmental sustainability indicators. Hence, technology development for algal biofuels is moving rapidly in the absence of clear means to define and quantify its sustainability.

A practical set of sustainability indicators is needed for algal biofuel processes and site-specific applications for several reasons. Indicators can be used to compare effects of different circumstances under which biofuels are produced, including different initial conditions. Alternatively, algal biofuel systems may be compared with business-as-usual fossil gasoline (Harto et al., 2010) or alternative diesel systems (Dinh et al., 2009; Harto et al., 2010). Indicators can be used to screen technologies for feasibility. Furthermore, indicators may be used to help with facility siting

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(Venteris et al., 2014). And indicators may be used as an early warning signal of changes in the environment (Cairns et al., 1993; Dale and Beyeler, 2001) of an algae system or of system collapse. They can also be used to diagnose the cause of a problem.

A set of practical environmental sustainability indicators for bioenergy was proposed by McBride et al. (2011) to include six categories: soil quality, water quality and quantity, air quality, GHG emissions, biodiversity, and productivity. The indicators and indicator categories were science-based, considered many national and international efforts, and were intended to apply to a wide range of bioenergy systems, pathways, locations, and management practices, as well as feedstocks. The focus was on feedstock production–annual and perennial plants and residues from agriculture, forestry and related industry. Even for vascular feedstocks, the generic set of indicators developed by McBride et al. (2011) requires the adjustment of indicators for some contexts (Efroymson et al., 2013), particularly for applications with limited budgets. While GBEP does not address the applicability of their 24 sustainability indicator categories to particular feedstocks, some are implicitly mentioned (e.g., harvest levels of wood resources), and algae are not (GBEP, 2011).

Some analyses have considered how indicators apply to specific feedstocks. For example, Dale et al. (2013a) previously considered the applicability of a generic list of sustainability indicators (McBride et al., 2011) to *Eucalyptus*. They found that sustainability issues were consistent with those of other terrestrial feedstocks, but that the prioritization of environmental concerns was specific to *Eucalyptus*, with invasiveness and water use being particularly important for that feedstock. Though not addressed by this study, social acceptability was also important to sustainability of *Eucalyptus* for biofuel.

This analysis identifies environmental sustainability indicators that pertain to the majority of algal biofuel systems. The evaluation is based on how well salient characteristics of those biofuel systems, algae cultures, and strain selection characteristics match candidate indicators and selection criteria for indicators. This manuscript also discusses the indicator set in the context of future technology development. A wide variety of algal biofuel supply chains are under development with more than 60 pathways proposed (NRC 2012). We focus on eukaryotic, photoautotrophic microalgae and cyanobacteria as feedstock organisms and consider the entire supply chain. The key question addressed in this manuscript is which environmental indicators of sustainability are especially important for biofuels produced from algae.

## 2. Approach

To select sustainability indicators for algal biofuels, we consider the broad range of indicators that have been recommended for bioenergy. Large sets of indicators, such as those recommended by GBEP and RSB, are examined. Special emphasis is placed on indicators proposed by McBride et al. (2011), which represent a focused, scientifically based, and practical set that were selected from a broad range of sources. We consider differences between algal biofuel and terrestrial biofuel systems and between the biology and production methods for algae and vascular plants. Algae strain selection characteristics are also part of analysis, for they lead to particular sustainability benefits or concerns or an emphasis on particular indicators. We examine indicators in six environmental categories – soil quality, water quantity and quality, GHG emissions, biodiversity, air quality, and productivity. Indicators are selected based on specific criteria discussed below.

### 2.1. Criteria for indicator selection

The criteria for selecting sustainability indicators for algal biofuels include the following characteristics, as defined by Cairns et al. (1993),Dale and Beyeler (2001), and Catford et al. (2012).

1) Practical. Indicators should be straightforward and inexpensive to measure or simulate.
2) Widely applicable. Indicators that are only applicable to a small subset of algal biofuel pathways are not considered.
3) Predictable in response. For example, an indicator of biodiversity must consistently respond to a change in biodiversity.
4) Anticipatory of future changes. Adequate warning of a culture crash can lead to preventive management interventions and hence is particularly important for productivity.

**Table 1**
Characteristics of algae and algal biofuel supply chain compared to vascular terrestrial feedstocks and their supply chains, and consequences for selection of environmental sustainability indicators.

| Property of algal biofuel | Consequence for sustainability indicator |
|---|---|
| No local soil resource use | Soil nutrient indicators not important |
| Large quantities of water used as culture media with evaporation from open ponds | Water quantity indicators important |
| Some algae grown in salt or brackish water | Salinity important water quality indicator; consumptive water use may be less important an indicator |
| $CO_2$ supplements needed | This $CO_2$ factored into greenhouse gas emissions indicator |
| Low slope lands required with no tilling | Sediment loading less important |
| Productivity of ponds susceptible to crashes | Pond crash frequency and presence or densities of responsible organisms are candidate indicators |
| Crop protection methods different | Indicators of chemicals other than herbicides (e.g., fungicides) may be needed |
| Photobioreactors (PBRs) not interacting with ecosystem | Productivity in PBRs not ecosystem-related |
| Toxins produced by algae may be occupational hazards | Indicator (e.g., toxin) measurable/predictable at local scale |
| Breaches from natural disasters possible | Timing of indicator measurement important |
| Many algae cosmopolitan (broad range) | Presence of algae often not a useful indicator of invasion or biodiversity |
| Blooms are important concern | Abundance more useful than presence as indicator of potentially invasive species |
| Frequent harvesting needed because of high growth rates | System-specific harvesting process and fate of waste important determinants of indicators |
| Different air pollutants emitted from different production and logistics processes[a] | Air quality indicators tailored to supply chain |
| Fuels may differ in structure and manufacturing process | Air quality indicators custom fit to product |
| Variety of potential supply chains | Practical indicators applicable to most supply chains |
| Commercial-scale development in the future[b] | Indicators should be able to be modeled |

[a] For example, some production processes may emit volatile organic compounds, while others may not. If biomass is dried, particulates are an important indicator, but if wet extraction is used, particulates are not an important indicator.

[b] This is also applicable to cellulosic feedstocks.

5) Independent of scale. Indicators that are independent of temporal and spatial scale are more generally applicable to sustainability assessments, but some environmental indicators (e.g., tropospheric ozone) violate this criterion. Also, for many indicators (e.g., water quality, biodiversity), it is not advisable to aggregate values from inside and outside ponds.
6) Responsive to management. Whereas temperature and light could be indicators of productivity, they cannot be effectively managed in open-pond systems.
7) Sufficient and non-redundant when considered collectively. Indicators should not be strongly correlated.

In addition, past data should be available in consistent units (Cairns et al., 1993). For example, Catford et al. (2012) eliminate indicators of invasion diversity and evenness indices that have been measured inconsistently across past studies. However, an advantage of the incipient development of algal biofuel facilities is that selected indicators can be measured consistently in the future.

## 3. Differences between algae and terrestrial bioenergy supply chains

Differences between algae and terrestrial plant feedstocks, as well as their supply chains for biofuel, influence the choice of appropriate sustainability indicators (Table 1). Algal biofuel production interacts with aspects of the environment across the entire supply chain (Fig. 1), Algal biofuel supply chains differ somewhat from other bioenergy supply chains. For example, crop protection methods are different (Table 1). Interactions between feedstock production systems and environmental variables differ between open pond systems and closed photobioreactors (Table 2). The magnitude of environmental effects may be greater during construction and decommissioning of open ponds for algae than for terrestrial bioenergy crops because of the change from land to water and back. As with other bioenergy systems, water quantity and air quality are affected throughout the supply chain (Fig. 1).

Feedstock selection is the first step in the supply chain. Algae are selected or genetically modified based on characteristics that favor productivity, survival or other aspects of sustainability, such as a lack of known toxin production (Table 3). Characteristics related to environmental sustainability include $CO_2$-absorbing capacity, limited nutrient requirements, and ability to flourish in brackish or saline water.

**Table 2**
Comparison of primary environmental variables differing between open and closed cultivation systems.

| Parameter | Open ponds | Photobioreactor |
|---|---|---|
| Land area | Higher | Lower |
| Water requirement | Higher | Lower |
| Loss of added $CO_2$ | Higher | Lower |
| Productivity | Lower | Higher |
| Cleaning of container | Not needed | Required |
| Contamination risk | Higher | Lower |

The use of water, nutrients, and $CO_2$ is different for algae and terrestrial feedstocks. The majority of water used in algae production is for growth media rather than for biomass, as in vascular plants. Many algal biofuel systems can use brackish or briny ground water or seawater rather than freshwater, and much of the water may be recycled, as little is incorporated in biomass. Unlike vascular plants, algae do not extract nutrients or water from local soil. Algae have the potential to remove nutrients from wastewater (Cai et al., 2013). Carbon dioxide is needed as an input for phototrophic algal systems, and collocation with $CO_2$ sources may be needed (Roberts et al., 2013).

Extreme weather events may affect terrestrial crops and aquatic algal biofuel crops and their environmental effects differently, but they lead to similar potential for crop loss. Drought can affect both terrestrial crops and open-pond algae with regard to the need for irrigation and replacement of evaporated water, respectively. Storms can cause slow leaks, overtopping of ponds, or sudden releases of pond water, and these losses of nutrients and biomass can have environmental effects on adjacent waters and aquatic biota (Gressel et al., 2013).

The timing of harvest is different for algae and terrestrial crops. High algal biomass growth rates lead to more frequent (and

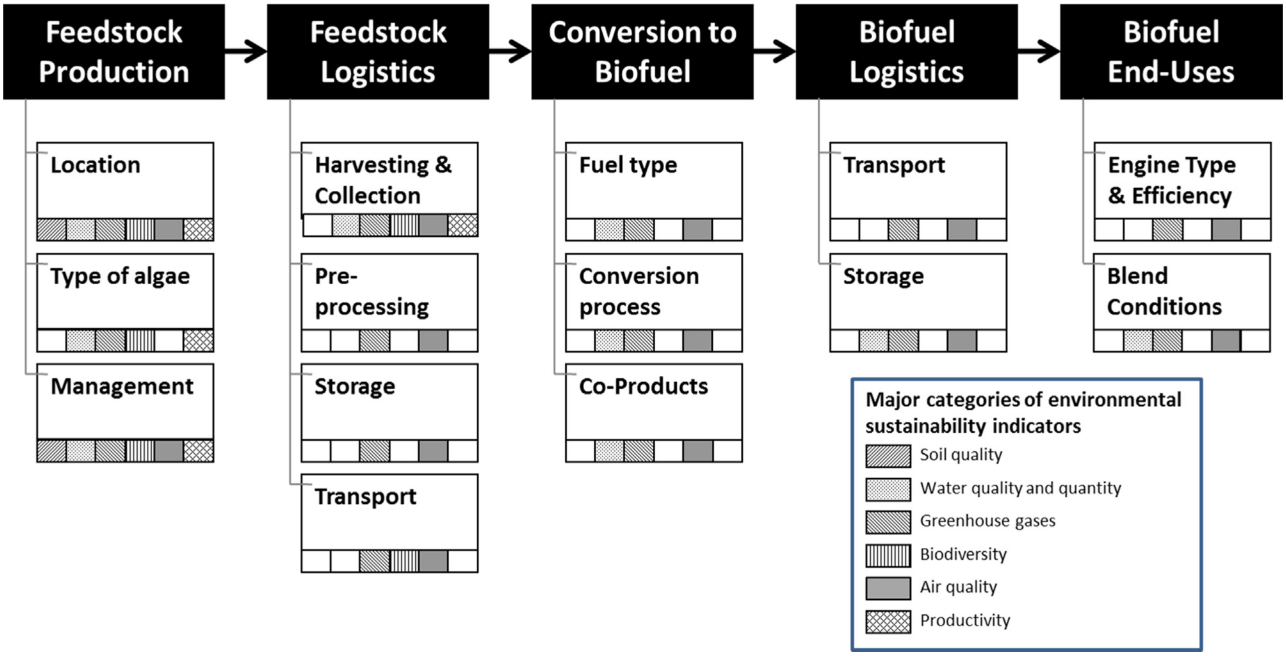

**Fig. 1.** Stages of common algae biofuel supply chains, elements within those stages, and categories of environmental effects that often represent major effects for each element. A blank box indicates that the category is not appreciably affected by that element of the supply chain. This figure adapted for algal biofuels from Fig. 2 in Efroymson et al. (2013).

**Table 3**
Characteristics that are desired for new strains of algae to be used to produce biofuels (based on Jones and Mayfield, 2012; Araujo et al., 2011; NRC, 2012; Gressel et al., 2013).

| High photo-conversion efficiency |
|---|
| Rapid and stable growth |
| Ability to absorb light in inverse proportion to culture density |
| High lipid content (for biodiesel) |
| Easy production and high value of coproducts |
| High $CO_2$-absorbing capacity |
| Limited nutrient requirements |
| Genetic stability |
| No detectable toxins |
| Ability to flourish in brackish, briny, or wastewater |
| Robustness toward shear stresses in photobioreactors |
| Competitiveness against wild native strains in open ponds |
| Resistance to predators, viruses, fungi in open ponds |
| Resistance to crop protection chemicals (algaecides, herbicides, antibiotics, antiseptics, etc.) |
| Tolerance to temperature variations, pH, salinity |
| Harvestability (e.g., sedimentation rate, self-flocculation ability) |
| Capability for secretion of hydrocarbons by live organisms |
| Extractability (influenced by cell volume, cell wall thickness, toughness) |
| Digestibility |

sometimes continuous) harvesting compared to terrestrial feedstock systems (Milledge and Heaven, 2013). In temperate climates, algae have a seasonal production pattern that affects the biofuel system and sustainability requirements. As a result, surplus biomass is available in the fall when temperatures drop (Behnke, 2013). This biomass can be transformed to a commercially viable coproduct such as defatted animal feed (NRC, 2012; Behnke, 2013) or digested and applied to land as fertilizer (Frank et al., 2012).

Unlike terrestrial crops, algae in photobioreactors rarely interact with the surrounding ecosystem. In contrast, algae in open ponds are part of the ecosystem in several ways, as they are connected through air and sometimes linked by pathways to ground water or surface water, although liners are intended to disconnect the organisms from soil. Mammals and birds can visit these ponds and ingest and subsequently disperse their contents.

Most biofuel feedstocks tend to have the same sustainability implications as farming for food or fiber or growing wood for

**Table 4**
Set of 16 proposed generic environmental indicators for sustainability of algal biofuels, as derived from many national and international recommendations for sustainability indicators, criteria, and standards for bioenergy.

| Category | Indicator | Units | Reference that discusses methods used to collect data |
|---|---|---|---|
| Soil quality | Bulk density | $g/cm^3$ | Doran and Jones (1996) |
| Water quantity | Peak storm flow | L/s | Buchanan and Somers (1969) |
| | Minimum base flow | L/s | Buchanan and Somers (1969) |
| | Consumptive water use (incorporates base flow) | feedstock production: $m^3$/ha/day; biorefinery: $m^3$/day | Feedstock production: calculated from flow measurements. Biorefineries: reported total water withdrawn used as proxy. |
| Water quality | Nitrate concentration in streams (and export) | concentration: mg/L; export: kg/ha/yr | Rice et al. (2012) |
| | Total phosphorus (P) concentration in streams (and export) | concentration: mg/L; export: kg/ha/yr | Rice et al. (2012) |
| | Salinity | Conductivity (no units) | Rice et al. (2012) |
| Greenhouse gases | $CO_2$ equivalent emissions ($CO_2$ and $N_2O$) | $kgC_{eq}/GJ$ | Spreadsheet models (e.g., GREET; Frank et al. 2011a,b) |
| Biodiversity | Presence of taxa of special concern | Presence | Various methods exist depending on taxa selected |
| | Habitat of taxa of special concern | ha | Various methods exist depending on taxa selected (e.g., Turlure et al., 2010) |
| | Abundance of released algae | Number/L | Initially calculated from known biomass in culture and estimated release rate or estimated using genetic markers |
| Air quality | Tropospheric ozone | ppb | Combination of sources and methods necessary, for example: EPA Mobile Source Observation Database, Community Multiscale Air Quality model (for example: Appel et al., 2007), reports from biorefineries, collation of vehicle use with emissions data per fuel type (for example: Gaffney and Marley, 2009). |
| | Carbon monoxide | ppm | |
| | Total particulate matter less than 2.5 $\mu$m diameter ($PM_{2.5}$) | $\mu g/m^3$ | |
| | Total particulate matter less than 10 $\mu$m diameter ($PM_{10}$) | $\mu g/m^3$ | |
| Productivity | Primary productivity or yield | gC/L/year or based on chlorophyll a | Berkman and Canova (2007) |

timber. However, algal biofuels might have different occupational hazards, such as a potential for toxin production or emission of harmful particulates if biomass is dried (Table 1). These hazards are more common in industrial processes than in crop production.

The storage and transport of algae and terrestrial feedstock are very similar. Therefore, these processes do not have unique implications for indicator selection for algal biofuels.

Options for conversion processes and transport of fuel are generally similar for algae and terrestrial bioenergy feedstocks, but the emphases can be different. The choice between conversion processes that use wet algae (e.g., hydrothermal liquefaction, which can also be used for terrestrial crops) and dry algae can affect interactions with air quality. One conversion process that is used for algae but is different from terrestrial processes is the direct secretion of ethanol by live algae (Luo et al., 2010). There has been more emphasis on drop-in fuels produced by algae than for terrestrial crops. Drop-in fuels make pipeline transport possible and can obviate the need for blending (see Fig. 1).

Algal-based fuels may be different in structure, impurities, and manufacturing process from other biofuels and petroleum fuels. Hence algae-based fuels may result in different effluents or emissions from those of competing fuels. Refineries for algal biofuels have the potential to produce biodiesel, green diesel, green gasoline, aviation fuel, ethanol, methane, and many coproducts (Pienkos and Darzins 2009). The likeliest coproducts with a large commercial market are animal feedstuffs (NRC 2012).

Most contemporary sustainability assessments of algal biofuels would occur prior to commercial development and therefore evaluate future scenarios. This emphasis on the future is similar to that of cellulosic sustainability assessments but different from analyses of corn grain ethanol and soybean diesel, for which commercial development is ongoing. Hence, the sustainability implications of cellulosic and algal-based biofuels are based on demonstration biofuels facilities, uses of the biomass for other purposes, or models.

## 4. Indicators of sustainability of algal biofuels

Our analysis of sustainability of algal biofuels identifies 16 indicators that fall into six categories: soil quality, water quality and quantity, air quality, GHG emissions, biodiversity, and productivity (Table 4). These indicators were selected using the criteria presented above to be a minimum, practical, and scientifically based set and are described below. Additional indicators that are applicable in particular contexts, have insufficient information about importance in algal biofuel systems generally, or may be applicable in the future, depending on technology development, are presented in Table 5.

### 4.1. Indicators of soil quality

Soil quality is an important sustainability category for terrestrial bioenergy feedstocks such as crops that draw nutrients from the soil, and petroleum, for which exploration and production can contaminate soil. Soil quality affects productivity of vascular bioenergy crops and ecosystems but not algae used for biofuels. The main linkages of algal biofuels to soil quality are via short-term excavation for construction and ultimate decommissioning. Erosion is minimal because flat lands are preferred for algal biofuel facilities (Table 1), although berms can erode if they are not lined (Lundquist et al., 2010). Thus, many indicators, including soil organic carbon, total nitrogen, and extractable phosphorus (McBride et al., 2011), are not major determinants of sustainability of algal biofuel production as they are for biofuels from terrestrial feedstocks (Table 1). The NRC (2012) did not include soil quality as an important determinant of sustainable development of algal

**Table 5**
Set of ancillary environmental indicators for sustainability of algal biofuels that are applicable in particular contexts, have insufficient information, or may be applicable in the future, depending on technology development.

| Category | Indicator | Units | Reference that discusses the methods used to collect data | Applicability to algal biofuels |
|---|---|---|---|---|
| Soil quality | Total organic carbon (TOC) | Mg/ha | Doran and Jones (1996) | Applicable if digested algae are mixed with soil as a means of waste treatment |
| | Total nitrogen (N) | Mg/ha | Bremner and Mulvaney (1982) | Applicable if digested algae are mixed with soil as a means of waste treatment |
| | Extractable phosphorus (P) | Mg/ha | Nelson et al. (1953) | Applicable if digested algae are mixed with soil as a means of waste treatment |
| Water quality | Suspended sediment concentration in streams (and export) | Concentration: mg/L; export: kg/ha/yr | Rice et al. (2012) | Applicable only during construction |
| | Herbicide concentration in streams (and export) | Concentration: mg/L;export: kg/ha/yr | Rice et al. (2012) | Applicable only to herbicide-resistant strains |
| | Metals | Concentration; mg/L | EPA (1994) | Not enough information available yet to determine if particular metals should be monitored |
| | Toxin concentration in cultures | Concentration; mg/L | e.g., FWR (1994) | May be necessary for unfamiliar strains or if blooms of opportunistic cyanobacteria occur |
| | Crop protection chemicals (e.g., antibiotic, disinfectant) | Concentration, mg/L | Methods specific to chemical | Not enough information available yet to determine if particular chemicals will be used broadly |
| | Flocculants | Concentration, mg/L | Methods to be determined and specific to flocculant | Applicable only where flocculants are used; not enough information yet to determine if these chemicals will be used broadly or released to natural waters |
| Air quality | Volatile organic compounds | Concentration, g/m$^3$ | EPA (1999) | More research is needed |
| Productivity | Pathogen densities | Number of cells or particles/L for desired species or indicator species | Methods dependent on pathogen, e.g., Brenner et al. (2010) | Some pathogens may be important to measure in some cultures |

biofuels. However, aspects of soil quality, such as salinity and bulk density, are worthy of consideration, and waste disposal and comparative studies with other fuels are worthy of discussion.

Local soil salinization could occur when briny ground water is pumped to the surface for use in open ponds or photobioreactors or when water overtops saline ponds. The footprint of brine scars where oil drilling occurs can last many decades (Jager et al., 2005; Parish et al., 2013). Similarly, salinization of soil and water is a sustainability concern for agriculture in the Central Valley of California (Schoups et al., 2005). GBEP recommends that in places where soil salinization is a hazard, soil electrical conductivity (EC) should be measured, for example, using USDA's electrical conductivity test (USDA, 2001; Chapter 5; GBEP, 2011). However, soil salinization indicators would be of low priority for most locations because of the small footprint.

In contrast to soil nutrients, bulk density, another measure proposed by McBride et al. (2011), is an important indicator relevant to subsoils below liners after ponds are removed or filled in (Table 1). For situations where there is a high risk of soil compaction, bulk density could be measured according to USDA's bulk density test (USDA, 2001; Chapter 4) following decommissioning. Changes in bulk density could affect future productive capacity of the soil and hence are proposed to be part of the minimum set of sustainability indicators (Table 4).

Nutrient levels in soil could be affected if soil is amended with anaerobically digested algae (Table 5). The extent and frequency of such applications are uncertain, so soil nutrient measurements are not recommended at the current time.

In comparative studies of algal biofuel with biofuel from other sources or with petroleum diesel, many soil quality variables may be important to measure. In these comparisons the percentage of land for which soil organic carbon is maintained or improved (GBEP, 2011) could provide useful information.

### 4.2. Indicators of water quantity

The importance of water quantity indicators for the sustainability of algal biofuels is clear from the requirement of large volumes of nutrient-containing water as growth media (Murphy and Allen, 2011), water for separation processes employed for biomass harvesting and fuel extraction (Luo et al., 2010), and water sometimes used for spray-cooling of photobioreactors (NRC, 2012). Because significant water volume is not used to build biomass, much of it can be recycled. However, evaporation is significant in open pond systems (NRC, 2012; Talent et al., 2014) (Table 1).

Consumptive water use is water withdrawal and loss through evaporation, runoff, or incorporation into a product. Consumptive water use is the only resource requirement indicator that we propose for algal biofuels (Table 4). Consumption or withdrawal is useful for evaluating water-use efficiency of particular technologies or pathways (GBEP, 2011). For example, the direct secretion of ethanol without harvesting and extraction avoids significant water usage (Luo et al., 2010). NRC (2012) proposes that indicators of the sustainability of freshwater requirements for growth of algae include consumptive freshwater use (kg water/kg fuel produced) and energy return on water invested (mJ/L) (Mulder et al., 2010).

Consumptive water use alone does not capture water quantity sustainability relative to local availability (NRC, 2012). For this reason GBEP (2011) suggests that water withdrawals be expressed as a percentage of total actual renewable water resources or as a percentage of total annual water withdrawals. The alternatives that we recommend are (1) to interpret the consumptive water use indicator for algal biofuels with respect to water use for other local activities and (2) to add minimum base flow and peak storm flow as indicators of water quantity (see McBride et al., 2011) (Table 4). These indicators incorporate the spatial and temporal context of water usage. Consumptive water use is not as important for algal biomass production when brackish or saline waters are used (Table 1).

All water quantity indicators are influenced by evaporation. Even where briny or brackish waters are used, increasing salt content may necessitate additions of freshwater (NRC, 2012; Venteris et al., 2013; Talent et al., 2014).

### 4.3. Indicators of water quality

Water quality of effluents from algal biofuel facilities and receiving waters is influenced by the source of the water, nutrients and other amendments, and by the efficiency of nutrient use. Depending on the purpose of a sustainability assessment, either total nutrient concentrations in water bodies or nutrient mass exported, which represents the contribution of the algal biofuel system, may be important sustainability indicators. The quality of the culture water is not typically an environmental sustainability issue.

Four generic water quality indicators for bioenergy are concentrations of nitrate, total phosphorus, suspended sediment, and herbicide concentration in streams, as well as the loadings of these chemicals and materials exported to streams (McBride et al., 2011). Nutrient measures are recommended for algae production (Table 4), because slow leakage to groundwater or surface water may occur through ponds to many ecosystems, and breaching of pond berms would be a rare but real possibility that could lead to eutrophication of neighboring waters (Table 1). If treated wastewater is used as a nutrient source, downstream concentrations of nutrients in streams may be positively affected by algae cultivation, but the risks to productivity from variable water chemistry and added microbes have yet to be overcome at large scale (Shurin et al., 2013). Recycling of nutrients and algae would also affect water quality (Murphy and Allen, 2011).

Some common indicators of water quality would not be very pertinent to algal biofuels. Algal cultures should not be a source of significant suspended sediment, because ponds are usually located at a distance from surface waters; they are located on relatively flat land (Benemann et al., 1982; Darzins et al., 2010; Wigmosta et al., 2011); there is no tilling of soil; and excess biomass is not released to natural waters (Table 1). Herbicide concentrations would only be important sustainability indicators if herbicide-resistant strains are used (Table 5), so we do not include them in the proposed set. As algal biofuels move toward commercial development, antibiotics or antiseptic agents may become important crop protection chemicals (Table 5).

Because algae may be grown in coastal waters or saline or brackish groundwater (Table 1), salinity of ground water or surface water will sometimes be an important sustainability indicator (Table 4), as recommended by the NRC (2012) and proposed for this minimum set of indicators. For example, Araujo et al. (2011) found that *Chaetoceros gracilis* (Heterokontophyta) and *Tetraselmis tetrathele* (Chlorophyta) are among the many species that can grow in saline water and produce high levels of lipids for biodiesel (see strain selection characteristics, Table 3). Unintentional leakage from open ponds or injection of saline waste into the ground could lead to the possible salinization of ground water or surface water in some environments.

The importance of measuring other contaminants of natural waters that potentially originate from algae cultivation systems is, as yet, unknown. Preliminary studies have measured metals in algae cultures originating from produced waters and soils with high elemental background levels (Sullivan, 2013), but the significance of these metals for human health or ecological risk is unclear (Table 5). Toxins potentially produced by unfamiliar strains or opportunistic cyanobacteria should be monitored

(Table 5). However, the ability to detect unknown toxins from less familiar strains is uncertain. Pathogens infecting algal cultures do not need to be monitored outside of algal cultures, because the source of these pathogens would be neighboring soils or waters.

Harvesting processes could raise water quality issues, depending on the methods used. Harvesting methods can include sedimentation, flotation, flocculation, centrifugation and filtration, or combinations of these (Uduman et al., 2010; Milledge and Heaven, 2013). While most methods do not have implications for water quality, flocculation may require chemicals that would need to be measured in effluents or possibly streams (Table 5). Potential flocculants include inorganic chemicals such as aluminum and iron salts, synthetic organic polymers, and natural inorganic and organic products (Milledge and Heaven, 2013; Vandamme et al., 2013). Algae cultivated in brackish water and seawater tend to require higher flocculant concentrations than freshwater species (Sukenik et al., 1988). Because it is uncertain if flocculation will be a dominant harvesting method in the future and which flocculants will dominate, we do not propose flocculant water quality indicators for most algal biofuel production.

### *4.4. Indicators of GHG flux*

GHG flux associated with algal biofuel occurs at every step of the supply system. To determine net GHG emissions of these pathways, many factors need to be considered. $CO_2$ can be added from flue gas, reducing power plant emissions (Kadam, 1997; Orfield et al., 2014). Losses of $CO_2$ from open ponds influence net emissions (Table 1). Although $CO_2$ can be temporarily sequestered from industrial processes by algae (Menetrez, 2012), the decomposition rate of waste biomass is also pertinent (Fernandez et al., 2012).

Processes in the biofuel supply chain that demand high energy input can lead to comparable $CO_2$ emissions. Stirring cultures is a power-intensive (Stephenson et al., 2010) and therefore a $CO_2$-emitting process. Similarly, moving the water to and from the dewatering step, as well as thermal drying, is energy- and $CO_2$-intensive (Frank et al., 2012; Weschler et al., 2014). $CO_2$ is also related to nutrient demand (Clarens et al., 2011) and productivity (Frank et al., 2012). Frank et al. (2012) found that calculations of net GHG emissions were highly dependent on biogas production parameters, including “yields from digesters, yields from gasification, fugitive emissions, nutrient recovery rates, and electrical efficiency of the [Combined Heat and Power] generator.”

Fugitive methane and $N_2O$ may also be emitted during the cultivation process. Emissions from open ponds have not been studied (NRC, 2012). Methanogenesis is possible from anaerobic cultures, especially if they crash, but the process is expected to be rare. $N_2O$ emissions have been measured from *Nannochloropsis salina* (Eustigmatophyceae) under a nitrogen headspace (Fagerstone et al., 2011), and *Nannochloris* (Chlorophyta) in coastal open-pond systems have been found to have high emissions of $N_2O$ during senescence (Florez-Leiva et al., 2010). But emissions are expected to be low under aerobic conditions.

Frank et al. (2012) estimated methane and $N_2O$ emissions from anaerobic digestate solids used as crop fertilizer, based on the Intergovernmental Panel on Climate Change (IPCC) proportions for organic fertilizer. IPCC (2010) acknowledges that emissions factors vary widely based on region, climate, and soil chemistry. The estimates for fugitive methane and $N_2O$ for algal biofuels were 14% and 23% of the whole pathway GHG emissions, respectively (Frank et al., 2012). Emissions from catalytic hydrothermal gasification processes may be lower than those from anaerobic digestion (Frank et al., 2012).

Other options for waste disposal can affect net GHG emissions. For example, Luo et al. (2010) assumed that annual disposal of cyanobacteria biomass would be via deep well injection, which could result in a slight net GHG reduction for the photobioreactor system.

GHG emissions indicators also reflect land-use change that would be attributable to algal biofuel systems. Land converted to algal biofuels is expected to include industrial brownfields, rangelands, deserts, abandoned or unproductive farmland, dredge spoil islands, or other coastal areas (NRC, 2012). Depending on the $CO_2$ storage associated with the baseline land condition, the algal biomass production system may increase sequestration (e.g., if the prior land use was a brown field or desert with little vegetation) or decrease it (e.g., in the unlikely case that the previous land cover was forest).

Carbon-dioxide-equivalent emissions is a commonly endorsed and scientifically based indicator for tracking net GHG emissions. This indicator accounts for the 100-year global warming potential of methane being 25–34 times that of $CO_2$ (IPCC, 2007; Shindell et al., 2009) and of nitrous oxide being 300 times that of $CO_2$ (NRC, 2010b). This indicator is highly adaptable to changes in technology, because all GHG emissions can be translated into these units.

Under large-scale commercial development, changes in albedo and potential effects on local weather conditions should be studied, as well as GHG emissions. Recent papers show that tradeoffs between carbon sequestration and local warming or cooling from albedo are an important research area (Jackson et al., 2008), including research on bioenergy crops (Georgescu et al., 2013).

### *4.5. Indicators of biodiversity*

Algal biofuel production could affect aquatic or terrestrial biodiversity. Two general biodiversity indicators proposed for sustainability of bioenergy include presence and habitats of taxa of special concern (McBride et al., 2011). “Taxa of special concern” can encompass valued, invasive, or undesirable species, genera, or functional groups. Here we discuss the biodiversity of the algae culture itself as well as the aquatic and terrestrial biodiversity of the surrounding landscape.

For most pond cultures, an indicator of pond diversity is not necessary, as maintaining diversity in pond cultures will rarely be an environmental goal. In many algal biofuel systems, a monoculture is desired, but invasion by other algae, bacteria, zooplankton, and other organisms is likely (see section on productivity). In some biofuel systems, cultures of algae could be diverse, with select combinations of strains of algae decreasing risk from grazers (Mayfield et al., 2013), or multiple species (Stockenreiter et al., 2012) or trophic levels (Smith et al., 2010) potentially increasing productivity.

Moreover, monitoring the presence of feedstock species at a distance from open ponds is not a priority unless nonnative species or strains are used (Gressel et al., 2013). Many eukaryotic microalgae and cyanobacteria are cosmopolitan in their spatial distributions (Hoffmann, 1994, 1996), so their dispersal through air (Grönblad 1933), soil, or via animal vectors (see References in NRC, 2012) from ponds should not affect biodiversity (Table 1).

However, if there is a breach in a pond or photobioreactor and large quantities of algae and nutrients are released to aquatic ecosystems, then some algal taxa may bloom, potentially causing changes in the native community. Measures of abundance are superior to measures of occupancy as indicators of invasiveness or blooming of algae, and abundance of the introduced species or strain is recommended as an indicator of aquatic biodiversity (Table 4). Relative measures of alien species richness (Catford et al., 2012) are not recommended in this case, because for monocultures only one introduced species would be of concern. In addition to monitoring the abundance of algae, we recommend the presence or absence of valued (e.g., rare) aquatic species as an indicator.

The indicators “presence of taxa of special concern” and “habitat area of taxa of special concern” for the particular context are appropriate indicators for effects on terrestrial species (Table 4). Terrestrial habitat displacement or fragmentation effects can result from the infrastructure of ponds, photobioreactors, and buildings for conversion and storage. These displacement effects are typical of any industry. Moreover, wildlife may drink from algal biofuel ponds, with potential toxic effects to individuals from metals, salinity, or toxins from opportunistic cyanobacteria (Kotut et al., 2010). Population demographic effects are also possible if migrants change their trajectories because of a new water source. Following the measurement of these indicators of biodiversity, more detailed measurement and analysis of effects may be needed.

### 4.6. Indicators of air quality

Air quality indicators relate to regional human health, occupational health, or ecosystems. Air emissions can occur during feedstock production, processing, and transportation and use. McBride et al. (2011) recommended a suite of four indicators, namely tropospheric ozone, carbon monoxide, total particulate matter less than 2.5 $\mu$m in diameter (PM2.5) and total particulate matter less than 10 $\mu$m in diameter (PM10). The NRC Committee on Sustainable Development of Algal Biofuels suggested that air quality indicators may include concentrations of volatile organic compounds (VOCs) and odorous secondary metabolites for open pond systems; particulates for active drying processes; air concentrations of solvent used for extraction processes; and particulates, hydrocarbons and acid gases for pyrolysis, if used (NRC, 2012). We propose that concentrations of odorous chemicals be considered a social sustainability indicator rather than an environmental sustainability indicator, so they are not included here. GBEP (2011) recommends consideration of $NO_x$ and $SO_2$, as well as large and small particulates. The GREET model estimates emissions of six EPA criteria pollutants: CO, VOCs, nitrogen oxides, sulfur oxides, PM10 and PM2.5 (Frank et al., 2011a), without a judgment about their relative importance compared to other measures. Aerosols and acid gases have also been considered (NRC, 2012).

Evidence supporting the selection of particular indicators of air quality for algal biofuels is varied, with some chemicals actually measured and others assumed to be important based on emissions from natural ponds containing algae, tailpipe emissions from other biofuels, and preliminary scientific results (see Appendix 1). Few studies of air emissions from algal biofuels are available, but one study of emission rates for a marine vessel operating on 50% hydrotreated algae diesel [and 50% ultra-low sulfur diesel (ULSD)] suggests that PM2.5 is an appropriate sustainability measure, as well as $NO_x$ and CO (Khan et al., 2012). All were reduced when the fuel blend was used, compared to the ULSD.

The selection of particular air quality indicators depends on the exact pathway and supply chain for algal biofuel (Appendix 1) and the purpose of the assessment. Particulates are important to measure if drying biomass is part of the fuel pathway and are always important for end-use, but they are less important at the conversion step if crude oil is extracted from wet algae (e.g., Moreno, 2013). Ozone is a useful integrative air quality indicator because it is formed by a reaction of sunlight with nitrogen oxides and hydrocarbons and removes aldehydes. However, it is not easy to attribute ozone to particular vehicle and fuel sources, because it may be formed at a distance away from the source. Thus, the purpose of the sustainability assessment will determine whether ozone is a useful indicator.

Some indicators apply primarily at the local or occupational scale (e.g., toxins, VOCs). VOCs have been detected as emissions from open ponds (personal communication from Paul Zimba in NRC, 2012). These chemicals may also be emitted from solvents used in extractions (e.g., toluene or hexane for upgrading the product following hydrothermal liquefaction, Liu et al., 2013). No evidence suggests that combustion of algal biofuels produces VOCs in greater quantities than non-algal biofuels.

We propose that air quality indicators for algae include tropospheric ozone, carbon monoxide, PM2.5 and PM10 (Table 4). More research is needed to understand whether VOCs should be selected as an air quality indicator for algal biofuels (Table 5).

### 4.7. Indicators of productivity

Productivity is a measure of the efficiency of biofuel production, and it may also be an economic or environmental measure. Aboveground net primary productivity, defined as the net flux of carbon from the atmosphere to the aboveground parts of green plants per unit time, is an environmental sustainability measure for biofuel derived from vascular plants, because of its relationship with photosynthesis and respiration (McBride et al., 2011). Aboveground net primary productivity sometimes includes algae (e.g., Ewe et al., 2006), but the term “aboveground” implies that there are roots belowground. Primary productivity is also related to secondary productivity, or the efficiency of generation of biomass of consumers in an ecosystem. For photosynthetic organisms, yield of biomass (and ultimately, fuel) is related to primary productivity. As with biodiversity and other indicators, it is important to assess both the productivity of algae and productivity of the neighboring and displaced ecosystems.

The productivity of algae is influenced by many abiotic environmental conditions, including temperature (Waller et al., 2012), light (Wondraczek et al., 2013), and wind-blown materials in arid or semi-arid areas that become sediment in open ponds and that constitute ash in conversion processes (J. Sullivan, Los Alamos National Laboratory, pers. comm. May 2013; Sayre, 2013). Neutral lipid production by some strains is enhanced under nitrogen limitation (Li et al., 2011). Biotic conditions such as microbial community structure and the abundance of predators, pathogens, and self-shading by other algae also affect productivity (Kazamia et al., 2012; Shurin et al., 2013). Whether productivity of algae represents an environmental indicator relates to the extent to which algal biofuel cultures are part of the ecosystem, which is determined by how the efficiency of production relates to other environmental variables and whether algae are available for consumption.

Another linkage between productivity and environmental sustainability is the relationship with land area. Algae cultures grown for biodiesel are anticipated to use a small fraction of the land area required to produce biodiesel by vascular plants (Groom et al., 2008; Clarens et al., 2010). This environmental benefit can be quantified with a productivity indicator that has land area in the denominator.

Clearly, the primary productivity of algae in photobioreactors is not related to many environmental variables other than net GHG emissions (which can be measured more directly) and therefore is not as important a measure of environmental sustainability in closed systems as it is for terrestrial feedstocks (Table 1). The primary production associated with closed systems would not be related to secondary production in most contexts. Algae productivity would typically be more related to economic sustainability than environmental sustainability.

The feasibility of open pond cultivation (and to a lesser extent, cultivation in closed photobioreactors) is highly dependent on controlling contamination and culture collapse (Gao et al., 2012; Letcher et al., 2013) through crop protection (Smith and Crews, 2014). Potential agents of collapse include zooplankton predators, viruses, bacteria, fungi, and competitive algae. The frequency, extent, and duration of culture collapses may be measurable or predictable, affecting yield. The density of particular pathogens or parasites or their DNA may be an early warning sign of culture collapse (e.g., Letcher et al., 2013), but the most important pathogens to measure in each region for each desired monoculture are unknown. Some researchers are measuring environmental conditions and metagenomes of algal samples from collapsed ponds to develop probes that may serve as early warning indicators of collapse (Lane, 2013). A suitable surrogate for pathogens or their genomes is the density of algae or chlorophyll and, ultimately, the rate of change of that value through time. The frequency of reversion of genetically modified algae will also affect yield, but, when commercial-scale applications are deployed, this potential issue should be resolved.

For the ecosystem outside of the algae culture, aboveground net primary productivity is an appropriate sustainability indicator. GBEP (2011) proposed a somewhat different but related indicator, productive capacity of the land and ecosystems. Both indicators would be applicable to terrestrial productivity of algae production locations after the cessation of production.

We propose that current and past productivity of an algal biofuel system be measured as yield of carbon per land area (Table 4), but we acknowledge that the yield of fuel from these fairly isolated feedstock systems represents economic sustainability more than environmental sustainability. Because of the potential for crashes of algae cultures in open ponds, pathogen densities are important measures of future productivity in these systems, but which pathogens are most important to measure in specific locations is still uncertain (Table 5). Aboveground net primary productivity is an important indicator for neighboring or displaced ecosystems.

### *4.8. Indicators of $CO_2$ resource requirements*

Resource inputs are an important aspect of sustainability if the resource is finite and is in decline, if the resource is being used at a different rate from replenishment, or if resource availability limits the potential locations of proposed facilities. We have discussed water quantity indicators in the context of regional supply. And we previously considered the depletion of non-renewable energy resources to be an indicator of socioeconomic sustainability effects, rather than an environmental indicator (Dale et al., 2013b). However, no sustainability indicator scheme for bioenergy, in general, has proposed $CO_2$ availability as a sustainability indicator, because it is pertinent only to algae. The NRC (2012) proposed mass of $CO_2$ required per liter of fuel produced and mass of $CO_2$ required per tonne dry biomass of algae as sustainability indicators, based on the units of nutrient requirements recommended by GBEP (2011).

Algae can fix $CO_2$ to produce biomass with greater efficiency and speed than terrestrial plants (Pienkos and Darzins, 2009). They require about 2 g of $CO_2$ per g biomass produced (Pienkos and Darzins, 2009) or 3.7 to 5.5 kg $CO_2$ per liter of algal oil (Pate et al., 2011). Supplemental $CO_2$ may be needed to reach productivities that are economically competitive (NRC, 2012), and $CO_2$ may be the most limiting nutrient for algae. One potential source of $CO_2$ is power plant flue gas (Kadam, 1997; Orfield et al., 2014). Another is natural repositories in the earth (Liu et al., 2013). Still another could be sodium bicarbonate (Pate et al., 2011).

$CO_2$ requirement is only a useful sustainability indicator if it varies with the biofuel supply chain and can be reduced with specific management practices. The solubility of carbon dioxide in water varies with temperature and pH, and the rate of $CO_2$ exchange between air and water depends on the surface area and turbulence of the water. Different systems will be more or less efficient in their use of $CO_2$, within a small range. An alternative sustainability indicator would be supplemental, non-recycled $CO_2$ required/L of fuel produced, suggesting that the use of $CO_2$ produced by a power plant is more sustainable than purchased bicarbonate. An additional qualitative indicator might be the presence or absence of flue gas within a certain distance of an algal biofuel facility.

However, these components of sustainability could be captured either in GHG emissions indicators or in profitability, a socioeconomic sustainability indicator category (Dale et al., 2013b). Aside from cost, $CO_2$ is not a regionally limiting nutrient. And we do not believe that the efficiency of $CO_2$ use can be controlled much by management practices. Therefore, we do not propose an environmental sustainability indicator related to $CO_2$ use.

## 5. Discussion and conclusions

We have proposed a practical, scientifically-based set of 16 environmental sustainability indicators for algal biofuels. The indicators may be used in concert with models and frameworks for comparing algae scenarios with each other, comparing them with other transportation fuel systems (Frank et al., 2012), and using them for other sustainability purposes. Eventually, these indicators may be used to set sustainability targets and to develop recommended management practices for algal biofuel systems.

Indicators were selected to be practical, widely applicable, predictable in response, anticipatory of future changes, independent of scale (where possible), and responsive to management. Clearly, there are compromises among selection criteria (Niemi and McDonald, 2004). Tradeoffs commonly relate to the usefulness versus the cost of information, the quality of the information versus the ease of measurement, and the specificity versus the generality of the indicator (Cairns et al., 1993; Catford et al., 2012).

The set of sustainability indicators for algal biofuels is very similar to the generic set proposed for bioenergy by McBride et al. (2011), with indicators proposed in each of six categories: soil quality, water quantity and quality, air quality, biodiversity, GHG emissions, and productivity. Many indicators, such as $CO_2$-equivalent emissions, are important to measure for all fuel production systems, whereas others, such as salinity, are only important for some algal biofuel systems. Although photobioreactor systems are different in structure and environmental connectivity from open-pond systems, the sustainability indicators are generally the same, though they may be prioritized differently for particular assessments. An examination of some of the main criteria for selecting algal strains suggests that few of those characteristics influence whether a sustainability indicator is chosen; instead they have more influence on the importance of the indicator. Concerns about genetically modified organisms differ in intensity from those of unmodified organisms, but it is not clear that effects will differ in kind.

The similarity of this set of sustainability indicators to a generic set of indicators for bioenergy means that most of the factors that need to be measured are not dependent on the obvious differences between algae and vascular plants or between the dominant supply chain steps or on the algal traits that are selected. For this reason, most of these indicators should not change as technologies narrow to a set that is commercially viable.

Nonetheless, there are a few differences between these indicators and those that have previously been recommended for bioenergy (McBride et al., 2011). Regular monitoring of soil nutrients, suspended sediment in streams, and herbicide loadings to streams are not usually necessary for algae production; water quality indicators should include salinity if saline water is used; and aquatic biodiversity indicators should include species richness for streams and abundance of potentially invasive algae.

Because of the nascent technology development for algal biofuel systems, research is needed on other environmental factors before some candidate indicators can be proposed or eliminated. These include toxins, metals, flocculants, and crop protection chemicals in water as indicators of water quality; volatile organic compounds as an indicator of air quality; and pathogen densities as an indicator of productivity.

It is challenging to propose generic sustainability indicators for algal biofuels because assessment purposes are not generic (Efroymson et al., 2013), and it is uncertain which technologies will prevail in the future. Most current algal biofuel systems, especially those using strains with high oil content, produce feedstock in open ponds (Menetrez, 2012), but it is unclear whether open-pond systems or photobioreactors will become dominant. Hence indicators for open-pond and photobioreactor systems and for saline and freshwater systems are included in the proposed set. However, components of the biofuel pathway (e.g., drying biomass, anaerobic digestion and disposition of waste) will influence the sustainability indicators that are selected for particular assessments.

In contrast, some aspects of the biofuel system will not influence sustainability indicator selection. Conversion processes will probably not affect the selection or measurement of sustainability indicators, unless they alter other steps of the supply chain (e.g., hydrothermal liquefaction not requiring a drying step or air quality indicators for that step).

The purpose for sustainability assessment typically determines the system boundaries for conducting the analysis. Measurements related to algal productivity would focus on the biofuel system itself, but biodiversity is usually measured in streams or terrestrial ecosystems.

There is significant overlap between environmental and socioeconomic sustainability indicators (Dale et al., 2013b). The overlap relates to relationships between productivity and profitability, water and air quality and human health (part of social well-being), and resource use and conservation. We have focused on environmental sustainability indicators but have sometimes discussed them in the context of socioeconomic effects. Including socioeconomic indicators in a proposed minimum set would provide a more comprehensive picture of sustainability of algal biofuels as deployed in particular contexts.

The proposed set of environmental sustainability indicators is a starting point for assessing sustainability of algal biofuels systems. The set of indicators will need to be modified for particular situations, and measurement protocols and interpretations of indicators must be specific to the context of the assessment (Efroymson et al., 2013). To use these indicators, sustainability goals and targets need to be defined in relation to stakeholder values and concerns for a particular algal biofuel system. Some indicators may be constrained by data availability. The next step is to use these indicators to develop appropriate management practices for algal biofuel systems.

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## Appendix 1

Appendix 1. Expected and actual air emissions from algal biofuel production and use and evidence. NA is not applicable.

| Stage of biofuel production | VOCs | Aerosols | Sulfate | $NH_3$ | PM2.5 | PM10 | NO*x* | CO | Acetaldehyde |
|---|---|---|---|---|---|---|---|---|---|
| Open pond cultivation | Expected based on Gschwend et al. (1985), Zuo et al. (2012), Shaw et al. (2010); 45 VOCs identified (Zimba, 2012; NRC, 2012) | Expected to include algae, nutrients, products of reactions of $SO_2$, $NO_x$, $NH_3$, VOCs (NRC, 2012) | NA | NA | NA | NA | NA | NA | NA |
| Drying | NA | NA | NA | NA | May include fine particulates (NRC, 2012) | May include coarse particulates (NRC, 2012) | NA | NA | NA |
| Extraction | Expected, such as hexane or other extractants (Demirbas, 2011; Lardon et al., 2009; Gong and Jiang, 2011) | NA | NA | NA | NA | NA | NA | NA | NA |
| Pyrolysis | NA | NA | NA | NA | Possible but not characterized (NRC, 2012) | Possible but not characterized (NRC, 2012) | Possible but not characterized (NRC, 2012) | Possible but not characterized (NRC, 2012) | NA |
| Anaerobic digestion | NA | NA | NA | Possible, but likely recycled | NA | NA | NA | NA | NA |
| Use of bioethanol | Reduced production for E85 (EPA, 2002a) | NA | Reduced production for bioethanol (EPA, 2002a) | NA | Reduced production for bioethanol (EPA, 2002a) | Reduced production for bioethanol (EPA, 2002a) | Reduced production for bioethanol (EPA, 2002a) | Reduced production for E85 (EPA, 2002a) | Higher emissions from bioethanol (EPA, 2002a) |
| Use of biodiesel | NA | | | NA | | | | | NA |

(*Continued*)

| Stage of biofuel production | VOCs | Aerosols | Sulfate | $NH_3$ | PM2.5 | PM10 | NO*x* | CO | Acetaldehyde |
|---|---|---|---|---|---|---|---|---|---|
| | | Reduced production for non-algae biodiesel (EPA, 2002b) | Reduced production for non-algae biodiesel (EPA, 2002b) | | Reduced production from blend in marine vessel (Khan et al., 2012) | Reduced emission from non-algae biodiesel (EPA, 2002b) | Reduced production from blend in marine vessel (Khan et al., 2012) | Reduced production from blend in marine vessel (Khan et al., 2012) | |

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