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Review

Better management practices for environmentally sustainable production of microalgae and algal biofuels

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ABSTRACT

The commercialization of biofuels produced from microalgae is in its infancy; therefore, many resource-management practices and production processes are still flexible. The purpose of this paper is to guide development of supply chains toward more environmentally sustainable practices. We review current and projected technologies and practices for autotrophic microalgae cultivation that promote environmental sustainability. We develop a framework that leverages these studies to propose better management practices (BMPs) for water quality and quantity, biodiversity, or greenhouse gas emissions in concert with productivity and profitability considerations. Some proposed BMPs are linked to numerical environmental targets, such as percent reductions in nutrient loadings to streams, whereas others seek to avoid thresholds leading to adverse health or ecological effects. Still others involve using the best available technologies, developed iteratively through life-cycle and techno-economic analyses. Proposed BMPs for microalgae cultivation focus on water quality and quantity, as well as improving greenhouse gas (GHG) emissions to obtain advanced biofuel designation. BMPs must allow producers to meet productivity and profitability targets, as well as environmental targets. These example BMPs characterize the state of science and engineering; thus, they will change over time.

Contents

1. Introduction

Microalgae are promising feedstocks for biofuels and bioproducts, with a high growth rate and high lipid, carbohydrate, and nutrient content (Singh and Gu 2010). Microalgal biofuels and

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bioproducts are expected to be environmentally sustainable (e.g., to achieve specified greenhouse gas emissions or water consumption objectives), as well as profitable, in the future. Guidance on resource management or industrial process options to improve environmental indicators can help the algal biomass and biofuel industry meet environmental targets. Although the commercialization of algal biofuels is in its infancy, early planning can ensure that the supply chain is as sustainable as possible.

Best management practices are typically defined as approaches, processes, activities, permitting conditions, or even incentives or rewards that are associated with a favorable outcome. Best practices related to environmental sustainability, sometimes termed "conservation practices," are common in forestry and in agriculture. Best management practices have been described as 'useful,' 'cost-effective,' 'proven,' and 'generally accepted' (Texas State Soil and Water Conservation Board 2005). These practices are most useful when the objective of interest is explicit, e.g., improving nitrate loading to a stream compared to a baseline (Ice 2004; Schilling 2009).

Some practices are more likely to meet a sustainability objective than others, although the *best* practice under a given circumstance may change with technology innovation (Measham et al., 2007). The Food and Agriculture Organization of the United Nations (Rossi 2012) and others (Dale et al., 2015; McDowell et al., 2016; Yang et al., 2007) use the term "good practices" or "good management practices" or "beneficial management practices" because of the uncertainty regarding what is "best." We adopt Clay's (2008) assertion that the familiar acronym BMP is useful if it refers to *better* management practice, i.e., better than alternative practices with respect to meeting an environmental sustainability target. "Better" BMPs are appropriate for sustainability and for algal biofuel development, because the goal of gradual improvement in productivity, profitability, and environmental sustainability implies BMPs are dynamic. Declaring a best practice for an industry in the pilot stage would be presumptuous, but describing practices that achieve greater (better) environmental benefits as we develop the industry is useful. Our analysis is consistent with Measham et al.'s (2007) idea that the conceptualization and development of BMPs involves continual improvement and adaptive learning.

Large-scale algae production could affect water quality and quantity, greenhouse gas emissions, and biodiversity (Efroymson et al., 2017). Water-related challenges or risks for some algae production systems could include high water consumption, salinization of freshwater aquifers from drilling, and releases of nonnative taxa during extreme events (NRC 2012; Gerbens-Leenes et al., 2014; ANL, NREL, and PNNL 2018). Carbon-related issues can include CO_2 sourcing and energy for transporting the gas to algae, inefficient CO_2 utilization by algae, high emissions of CO_2 from power sources used during dewatering and drying processes (Davis et al., 2016), and high emissions from pond-liner manufacture (Canter et al., 2014).

Practices and processes that improve environmental sustainability have been proposed for algae facility siting, cultivation, harvesting, and conversion options and throughout algal biofuel supply chains. However, these BMPs for environmental sustainability of algae and algal biofuel production have not been established, compiled, or reviewed elsewhere. DuPont (2013) summarized "big-picture concerns" and broad environmental objectives that he termed best practices for the sustainable production of algae-based biofuel in China. Tu et al. (2016) described water conservation technologies, i.e., BMPs for water availability, for an algal biodiesel production pathway. The Algae Biomass Organization's Technical Standards Committee has as part of its mission "developing and advocating algal industry standards and best practices" (ABO 2017), but most of the practices that have been developed relate to measurement methods. Studies that compare environmental effects of a several algal biofuel production pathways (Mu et al., 2014) are more common than BMP recommendations. At present, academic scientists and industry practitioners must attend numerous conferences and read a large number of papers to develop a broad understanding of algae production and biofuel supply chain practices that can improve or reach targets for water quality and quantity, greenhouse gas (GHG) emissions, and other environmental indicators. This paper synthesizes information on practices that can address environmental indicators while improving productivity and lowering costs of algae and algal biofuels.

We present a framework within which BMPs can be developed for microalgae and algal biofuel production. The framework relies on techno-economic analysis (TEA) (combined engineering design, process modeling, and economic evaluation), life-cycle analysis (LCA) (evaluation of environmental effects of all stages of the life of a product), and resource analysis (determination of quantity and location of resources needed to produce product), in addition to experimental studies. We review current technologies and resource management practices, as well as anticipated future innovations, related to autotrophic microalgae cultivation, harvesting, and conversion to fuel, highlighting management practices that have the potential to improve water quality, water consumption, GHG emissions, or biodiversity. We propose several BMPs originally developed for other industries. Proposed BMPs that also increase productivity and profitability are highlighted.

2. Background on algae and algal biofuels production

Algae are cultivated for food, especially nutraceuticals; feed; fertilizers; chemicals; wastewater treatment; and biofuel (Benemann et al., 2018; Deviram et al., 2020). Most commercial experience with algae is in food and feed; however, interest in algal biofuels has been growing. Algal biofuels include biodiesel, renewable diesel, ethanol, or other liquid fuels. General steps in the algal biofuels supply chain are depicted in Fig. 1; cultivation, harvesting, lipid extraction (or hydrothermal liquefaction, HTL), conversion/refining, and disposal/reuse; and include technologies and practices that may influence environmental indicators. Unlike fuel produced from corn and soy, most algal biofuel companies are involved in the entire pathway. BMPs can also be recommended for siting, which is conducted prior to cultivation.

Algae cultivation may occur in open ponds and raceways, either lined or unlined, or in sealed photobioreactors (PBRs). Fresh water, saline or brackish water, and wastewater can be used. Carbon dioxide is a required input. Crop-protection methods may be required to reduce likelihood or frequency of pond crashes (McBride et al., 2014). Dewatering is a major harvesting technology, and drying is necessary if the lipid extraction pathway to biofuel is selected. The choice of coproducts, compared to alternative products or waste disposal options, influences the environmental effects attributable to biofuel. Coproducts that may be produced with biofuel include nutraceuticals, livestock feed, aquaculture food, biochar for fertilizer, polyunsaturated fatty acids, and recombinant protein extracts (e.g., astaxanthin) (Brennan and Owende, 2010; Kiron et al., 2012; Austic et al., 2013). Water and nutrient cycling affect environmental indicators. Biofuel producers seek processes that save energy for both economic and environmental reasons.

3. Framework for developing BMPs

BMPs are practices designed to improve environmental indicators, including water quality and quantity, GHG emissions, air quality, soil quality, biodiversity, and ecosystem productivity

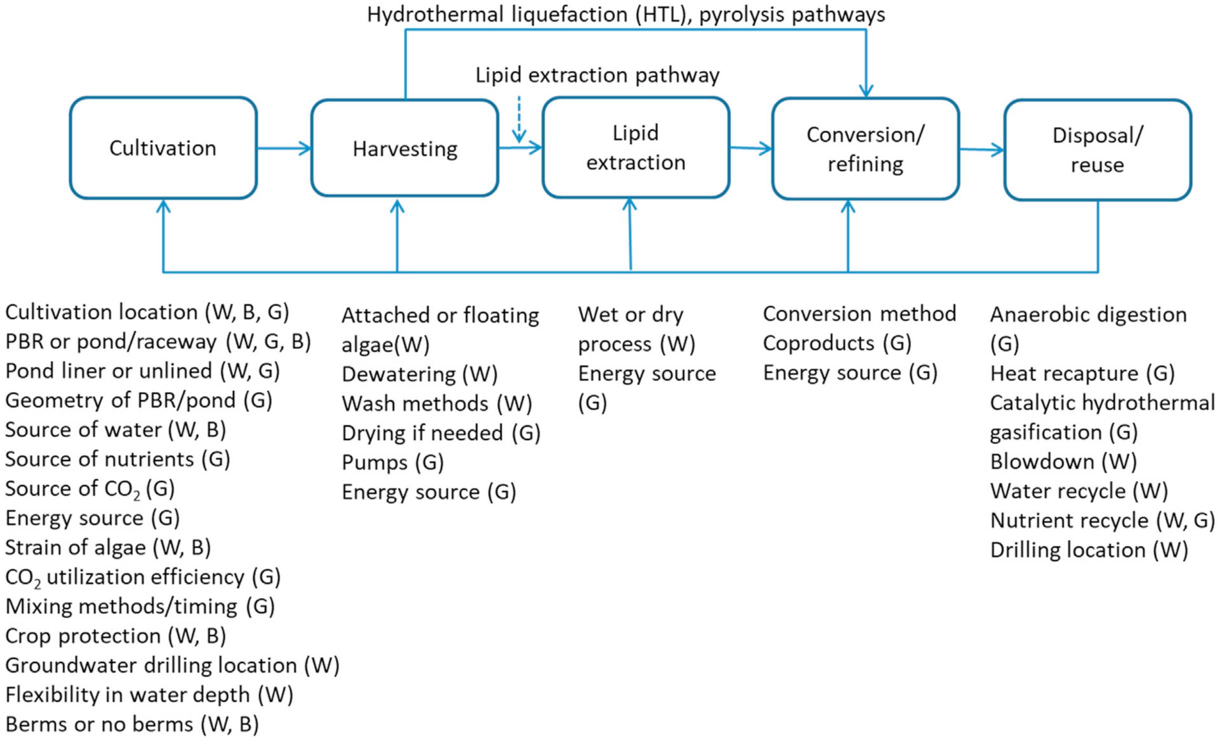

Fig. 1. Algae cultivation and downstream process steps in the algal biofuel supply chain. The text indicates choices that relate to BMPs. Parentheses indicate whether the process or practice relates to water quality or quantity (W), greenhouse gas emissions (G), or biodiversity (B).

(McBride et al., 2011). Environmental indicators for sustainable algal biofuel production are described in Efroymson and Dale (2015) and were adopted by the Algae Biomass Organization's Technical Standards Committee (ABO 2017). BMPs are sometimes used as substitutes for measuring performance under the assumption that if a specific practice is employed, there is a high likelihood that a target for an environmental indicator is met, but BMPs are an "inexact shortcut" (Clay 2008). Better practices can be developed through an assessment approach that includes a set of well-defined environmental indicators with baseline and target values (i.e., desired numerical values for each indicator) and periodic revaluation of progress toward targets (Dale et al., 2019).

A proposed framework for developing BMPs for microalgae cultivation and biofuel production is provided in Fig. 2. Generating better practices begins with a sustainability objective, such as to minimize GHG emissions or to eliminate eutrophication or protect human health. Many types of targets for environmental indicators (Fig. 2) reflect the objectives, and a simple categorization is depicted in Table 1. Furthermore, many pathways can lead from the development of targets to BMPs and to refinement of targets (Fig. 2). One cannot evaluate the effectiveness of better practices unless they relate to specific sustainability targets (Shepard 2006; Ice 2011).

The first broad type of target is an absolute value, i.e., specified without reference to a baseline value (Table 1). This may be a regulatory standard, a company target, a certification requirement, a scientifically determined environmental threshold, or an absolute target based on best (or better) available technology. The European Union, for example, sets sustainability targets and requires sustainability certification for liquid fuels (Laurens et al., 2015).

Absolute-value targets (sometimes termed criteria) may be allocated to point sources within a region. Target nutrient loadings to water, for example, Total Maximum Daily Loads (TMDLs) for impaired surface water bodies in the US, may be allocated among many point sources that have effluents moving into the same water body; thus, the arrow from regulations to targets in Fig. 2 may involve a process of allocation. In the U.S. most industries are governed by the National Pollution Discharge Elimination System; therefore, permitted loadings of nutrients for algae and algal biofuels facilities would need to be developed (Menetrez 2012).

A second type of target is a relative target, i.e., an improvement in an indicator compared to a well-defined baseline (Table 1). Often the rate or extent of improvement is not specified, but the target is simply continual improvement. The management practices that can lead to general improvement in an indicator comprise broader options than those that can meet a minimum change. Sometimes the percentage improvement required compared to a baseline is specified by policy (Table 1) or a group of stakeholders. Sustainability targets of this type include regulatory standards, such as the US Renewable Fuel Standard's 50% GHG emissions reduction goal for advanced biofuels, relative to emissions for the average 2005 petroleum diesel baseline. The baseline value selected for the indicator depends on the product and sustainability objectives. Environmental indicator baselines typically represent values prior to the time period of algal biomass or biofuel development. Baselines for GHG emissions assessments are typically business-as-usual, fossil-fuel cases that may be specified by regulations. For this type of target, system boundaries should also be described. For example, LCAs for greenhouse gases emitted during algae production typically include the manufacture of infrastructure, such as plastic pond liners, as part of the system (Canter et al., 2014).

An algae facility might allocate a relative target to multiple steps in a supply chain. For example, a water consumption reduction target could be allocated 70% to algae production and 30% to conversion. Facility operators might know from experience that they cannot reduce water consumption from one process and that the reductions must come from another. Understanding these targets and constraints leads to an achievable BMP.

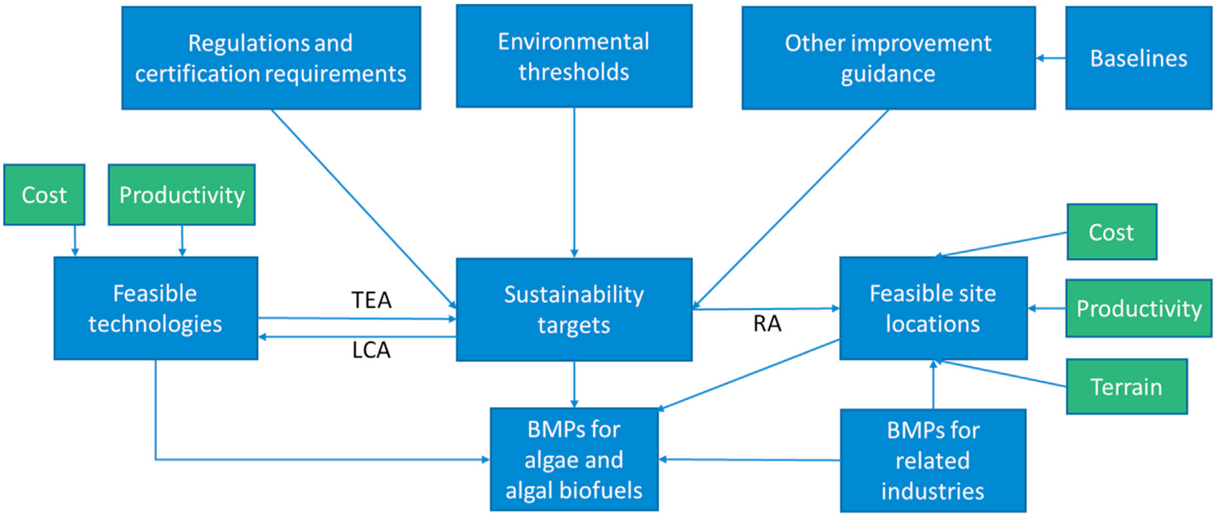

Fig. 2. Framework showing pathways to environmental sustainability targets and BMPs for microalgae and algal biofuels production. TEA is techno-economic analysis, LCA is life-cycle analysis, and RA is resource analysis. Green boxes are factors that are not directly related to environmental targets or BMPs but that influence the pathways in the framework. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Simple matrix classifying types of targets for environmental indicators, which BMPs are designed to meet. Two key dichotomies are a) whether the target is numerical or qualitative and b) whether it is defined relative to a baseline or as an absolute value. Examples are included in the matrix.

Target type	Absolute value	Relative value
Quantitative target	Ecological threshold; water quality regulatory criterion (e.g., a specific chemical concentration)	Specified percentage nutrient use reduction from recycling harvest water, based on use of a particular technology; specified GHG emissions reduction for advanced biofuel production
Qualitative target	Not applicable	Improvement compared to baseline, e.g., nitrate loading lower than a 10-year mean baseline

Established BMPs can be adopted from industries with non-algae-specific technologies or processes that are also used in algae or algal biofuel production (Fig. 2). Examples are BMPs for industrial water users (Texas Water Development Board 2013) or for aquaculture (Tucker and Hargreaves 2008).

Some BMPs are developed based on a combination of assessments of technological feasibility of practices employed to reduce costs or to improve productivity, as well as to meet environmental targets. Thus, the BMP emerges from experimentation in TEA and LCA modeling environments (Rickman et al., 2013) (Fig. 2), where assumptions are harmonized (Laurens et al., 2015; ANL, NREL and PNNL 2018). In the U.S., the volume requirements for renewable fuel and advanced biofuel provide an incentivized market. Technoeconomic analysts, who simulate minimum fuel selling prices from candidate technologies, often iterate with life-cycle analysts to ensure that the full biofuel pathway reduces GHG emissions sufficiently to meet advanced biofuel requirements and price goals (ANL, NREL and PNNL 2018). BMPs for GHG emissions typically address elements of the life cycle of materials (e.g., pond liners, fertilizer, CO_2 pipelines) in addition to land management and fuel production processes. In contrast, water-related BMPs do not generally emerge from TEA-LCA iterations, because targets for water consumption are spatially explicit.

Some research and related TEAs for algal biofuels focus on future technologies that could achieve productivity, cost, and sustainability goals; BMPs and sustainability targets generated by those studies may not yet be achievable (Davis et al., 2016; ANL, NREL and PNNL 2018). An example is sourcing high-purity CO_2 for algae cultivation by advanced flue-gas carbon-capture technologies at supercritical pressures (rather than the more expensive and energy-intensive, standard monoethanolamine scrubbing method) (ANL, NREL, and PNNL 2018).

Supplementing federal and state regulations, local permitting processes for algae facilities may have discharge limits or require BMPs for water quality or quantity, such as the use of plastic pond liners for open pond systems. However, if algae biomass cultivation were defined as agriculture, state and federal requirements would likely change. In US states, agricultural facilities are typically encouraged to employ voluntary BMPs (Borisova and Wade, 2017), and algae cultivation for biofuels and bioproducts has many characteristics of agriculture that have been affirmed in US Farm Bill policy (ABO 2018). Algae cultivation has the potential to be classified as agriculture in additional future policies (Trentacoste et al., 2015).

Some BMPs below could be termed “better siting practices.” Most reflect inputs or outputs of resource analysis (Fig. 2). Essentially, the practices consist of avoiding land areas where algae cultivation is unable to meet environmental targets (e.g., water or waste nutrient availability). Siting-related BMPs can be designed to promote biodiversity or a favorable net carbon emissions balance, as well as water quality and quantity objectives.

BMPs can be custom-made to reflect context-specific objectives (see Efroymson et al., 2013), such as local environmental concerns. Custom BMPs are based on optimization or tradeoff analysis of multiple types of sustainability targets or multiple spatially explicit targets by the user (e.g., Gramig et al., 2013).

4. Example BMPs

Various practices for algae and algal biofuel production could be considered BMPs, based on an intent to improve environmental indicators, compared to other options. Here we organize BMPs by the pertinent environmental indicator and provide background on the objectives that the BMPs address. We also indicate the type of target related to each BMP from the simple taxonomy in Table 1. Many company-specific BMPs, such as those related to energy usage, are closely tied to profit and are therefore confidential.

Multiple environmental indicators are sometimes treated by a single BMP. For example, many BMPs intended to conserve water help meet water quality targets because of dilution effects. Similarly, BMPs that address water quantity and quality issues are usually beneficial for aquatic biodiversity. These BMPs are pertinent to algae cultivation for all uses, and some are pertinent to specific downstream steps in the algal biofuel supply chain. The simplified, general diagram of the algal biofuel supply chain (Fig. 1) summarizes processes and practices that relate to water quality or quantity (W), greenhouse gas emissions (G), or biodiversity (B), as described below.

4.1. Water quantity

Competition over water resources could be a concern if algal biofuel production were developed at commercial scale (Gerbens-Leenes et al., 2014). BMPs for water quantity may be designed to address facility targets for water consumed in cultivation or later steps in the supply chain. Alternatively, BMPs can address water scarcity targets or associated water temperature targets for ecosystems, with the algal biofuel industry acting in concert with other water-withdrawing facilities. However, until now, water saved through conservation practices typically has not been measured (Tu et al., 2016), so most BMPs are intended to conserve as much water as possible, rather than meeting a more-specific target. BMPs related to water quantity are summarized in Table 2.

Water consumption by algal facilities replaces evaporated water (the largest loss for ponds or raceways, up to 10 L $m^{-2}d^{-1}$, NRC (2012)) and, in some cases, discharge, to control pond salinity (blowdown) or leakage from ponds (Pate et al., 2011; NRC 2012; Frank et al., 2016; Tu et al., 2016). If PBRs are used to cultivate algae, cooling water inputs can be the main consumptive use of water (Tu et al., 2016).

Consumption of fresh water for algal fuel production can be minimized through the choice of infrastructure; use of non-potable water, which may involve salinity-tolerant species; and recycling of water (Table 2). Freshwater PBRs save substantial volumes of water compared to open ponds (25–72 L water per L biodiesel for PBRs, compared to 216–2000 L water per L biodiesel for open ponds in Tu et al. (2016)). PBRs minimize evaporation compared to an open pond or raceway, and, therefore, the use of closed cultivation systems is a BMP for water quantity. Pond liners or compacted soil can reduce water loss below ponds. If non-potable water (saline and brackish water and wastewater) is used, freshwater may only be required to make up evaporation losses.

Evaporation and discharge of harvest wastewater constitute consumptive water uses. To minimize consumptive use, culture water can be recycled by pumping back to the cultivation system. Water can also be recycled following the dewatering process. However, the quantity of water used in cultivation, drying, extraction, or esterification does not change if the harvest water recycling rate increases (Yang et al., 2011).

Water consumption during harvesting and dewatering in preparation for biodiesel transesterification depends on the efficiency of separation of algae from water. A two-step separation process is commonly employed to harvest microalgal biomass. The primary dewatering step, such as flocculation, creates an algal slurry with about two to seven percent suspended solids. To increase the concentration of solids to 15 to 25 percent, a secondary dewatering step, such as centrifugation or filtration, is used (Barros et al., 2015). Finally, after harvesting, the thickened slurry is usually dried to improve the downstream processing of algal biomass. The commercial facility of Sapphire Energy, Inc., in Columbus, NM, USA, achieved no more than 20% solids in algal slurry using a combined Dissolved Air Flotation system (as in a wastewater treatment plant) and a secondary, scroll decanter procedure (White and Ryan 2015). Water losses were minimized by optimizing dewatering steps to increase solid concentration before drying.

One way to ensure more efficient harvesting and reduce water consumption is to use a biofilm (attached algae) such as an algal turf scrubber (Adey et al. 2011, 2013), rather than floating algae. Water conservation practices during algal diesel production will likely include those used by biodiesel manufacturers, namely, wash-water reuse and dry wash methods such as the use of absorbents (Tu et al., 2016).

HTL, heating wet biomass under pressure, has been increasingly used to produce biocrude from algal biomass without lipid extraction. Because HTL does not require dried biomass, this process avoids water losses due to drying and evaporation. Furthermore, the aqueous phase remaining after conversion contains both water and minerals from algal feedstocks, which can be recycled for further biomass production. Thus, the HTL process can affect both water quality and water quantity indicators.

Consumptive water loss, as well as regional water scarcity, are influenced by the locations where facilities are sited. Thus, siting practices that minimize consumptive use of freshwater constitute BMPs. Siting BMPs can also be developed for stream or lake temperature targets, which are influenced by water withdrawals (Jager et al., 2019). Although evaporative cooling maintains favorable temperature for growing algae in arid regions (Rogers et al., 2014), minimizing evaporation through siting or cultivation infrastructure is important. Location-specific factors that affect evaporative water losses include water and air temperature, wind velocity, humidity, and atmospheric pressure (Boyd and Gross 2000). Wigmosta et al. (2011) recommend selecting lands for development based on estimated water use per L of biofuel. Siting PBRs in regions where cooling water is not needed also reduces water consumption for microalgae production, and we propose this as a BMP. According to some analyses, water footprints of algal biomass production per liter of biofuel can be lower than terrestrial biofuel feedstock crops (Wu et al., 2014).

4.2. Water quality

Algal biofuel production can influence water quality in downstream receiving waters through discharge and withdrawal of water. Releases of nitrogen, phosphorus, salt and pesticides can be minimized. In the US, individual facilities may be responsible for meeting nutrient loading limits or TMDLs established by the USEPA through a point-discharge permitting process. Nutrient concentration targets may be met jointly by multiple point-source facilities.

Example water quality BMPs include integrating biomass production with algal wastewater treatment systems, recycling wastewater, using biological crop protection methods, and using pond liners or compacting soil in unlined ponds to reduce leaching (Table 2). Recycling wastewater provides a water purification service that improves downstream water quality compared to a baseline in which wastewaters (or those with primary settling only) are released to streams or the sea (Zhou et al., 2014). Harvesting algae from high-rate algal ponds used to treat wastewater is currently a niche market opportunity (Park et al., 2011; Kern et al., 2019), which may improve profitability of biomass production.

If managed improperly, water from algal production ponds could leach nutrients to groundwater. Nitrate in groundwater is a

Table 2
Better management practices (BMPs) for algae biomass and biofuel production to meet water quantity and water quality targets.

Sustainability indicator	Production step	System type	Objective	Target	BMP	Type of target	Reference
Water quantity	Siting	All cultivation systems	Minimize water use	Reduce freshwater requirement (by 90% in Yang et al. example)	Use seawater, wastewater, or saline groundwater, as well as algae strains that tolerate those waters, especially in semi-arid regions	Relative	Yang et al. (2011), DuPont (2013), Tu et al. (2016), Mayer et al. (2020)
	Siting	Open pond	Minimize water consumption	Improve water consumption	"Preferentially select available land with the lowest water use per liter of biofuel produced"	Relative	Wigmosta et al. (2011)
	Siting	PBR	Minimize water consumption	Improve water consumption	Avoid siting where cooling of PBRs is needed	Relative	NA
	Cultivation	All cultivation systems	Minimize competitive water use	Improve water consumption	Use only water not required for farming, domestic usage, or industrial uses	Relative	DuPont (2013)
	Cultivation	PBR	Minimize freshwater consumption	Zero freshwater consumption	Use desalination for makeup freshwater	Absolute	R. Chance, Algenol Biofuels, March 2014
	Cultivation	Open pond	Minimize water consumption	Improve water storage	Allow water depth in pond to fluctuate over limited range during periods when precipitation exceeds evaporation so pond can store water for later use	Relative	Wigmosta et al. (2011)
	Life cycle, CAP	Ponds and PBRs	Minimize water consumption	Reduce water consumption (in these examples by 84%, 76%, and 90%)	Recycle harvest water	Relative	Yang et al. (2011), Nogueira et al. (2018), Branco-Vieira et al. (2020)
	Harvest and cultivation	Open pond	Minimize water consumption	Reduce water consumption (up to 40%)	Recycle harvest water	Relative	White and Ryan (2015)
	Cultivation and harvest	Algae turf scrubber	Minimize water consumption	Reduce water loss during harvest	Use algae turf scrubber	Relative	Adey et al. (2011), Adey et al. (2013)
	Cultivation	Open pond	Minimize water use and nutrient discharge	Use 100% precipitation water and reduce nutrient discharge compared to baseline (60% in Mississippi catfish example)	Use drop-fill management in conjunction with harvest	Absolute, relative	Tucker et al. (2008), Tucker et al. (2017)
	Cultivation	PBR	Minimize water use	Reduce evaporation	Use closed system	Relative	ABO (2017), Tu et al. (2016)
	Logistics-dewatering	Centrifuge	Minimize water consumption	Improve water consumption	Water recovery	Relative	Baliga and Powers (2010)
	Conversion	HTL	Minimize water consumption	Improve water consumption	Recycle water	Relative	ANL, NREL, and PNNL (2018)
	Conversion	Two conversion systems	Minimize water consumption	Reduce water use (e.g., freshwater by 42.8%, saline water by 84.4%	Use HTL, rather than combined algal processing	Relative	ANL, NREL, and PNNL (2018); Venteris et al. (2014a)
Water quality	Siting, waste disposal	Freshwater ponds and PBRs	Avoid saltwater intrusion	Maintain salinity of freshwater sources with chloride below 150 mg/L, specific conductivity >1000 US/cm, and total dissolved solids >700 mg/L	Avoid drilling adjacent to coast, e.g., within 50 m. Avoid drilling deep within areas close to coast. Use known methods to estimate depth of transition zone and monitor conductivity	Absolute	British Columbia (2016)
	Water consumption and waste disposal	PBRs or ponds	Avoid saltwater intrusion	Maintain salinity and various contaminant levels in drinking water	Drill deeper than municipal water sources	Absolute	DOE (2010)
	Cultivation	PBRs or ponds	Avoid saltwater intrusion	No increase in salinity or nutrient concentrations in fresh groundwater	Drill wells for water withdrawal and waste injection well below drinking water sources	Absolute	DOE (2010)
	Life cycle	Biodiesel production	Minimize release of nutrients in harvest water	Reduce nutrient usage (by 55% for this technology)	Recycle harvest water	Relative	Yang et al. (2011), Savage et al. (2020)
	Cultivation	Algae turf scrubber	Remove nutrients from wastewaters	Reduce nutrient concentrations compared to land-use baseline	Use algae turf scrubber	Relative	Adey et al. (2011), Adey et al. (2013)
	Cultivation	Pond/raceway	Avoid overtopping, release of nutrients to streams	Reduce overtopping probability to negligible value	Employ freeboard distance based on pond size and extreme event frequency (ranges from 0.3 to 0.6 m)	Relative	USDA (1982), USEPA (2011)
	Cultivation	Ponds or PBRs	Mitigate effects of hurricanes	Retain all water onsite	Use berms to catch water	Relative	Pat Ahlm, Algenol Biofuels, pers. Comm, March 2014

Table 2 (*continued*)

Sustainability indicator	Production step	System type	Objective	Target	BMP	Type of target	Reference
Water quality and quantity	Cultivation	Ponds or PBRs	Reduce release of nutrients from municipal wastewater	Maintain or improve NO_3^- and P loadings to water, compared to land-use baseline, and minimize freshwater use	Use municipal wastewater as nutrient and water source for algae	Relative	Park et al. (2011), Fortier and Sturm (2012), Zhou et al. (2014), Barlow et al. (2016)
	Cultivation	Pond/ raceway	Avoid seepage below ponds	Reduce soil hydraulic conductivity below 10^{-7} cm/s (value used for municipal, industrial, and hazardous waste landfills)	Compact soil liners to prescribed conductivity	Absolute	Daniel and Benson (1990), Benson and Trast (1995)
	Cultivation	Pond/ raceway	Avoid seepage below ponds	Reduce soil hydraulic conductivity below 10^{-7} cm/s (requirement for some municipal, industrial, and hazardous waste landfills in US)	Select soils that self-seal	Absolute	Daniel and Benson (1990), Benson and Trast (1995)
	Cultivation	Pond/ raceway	Minimize water losses below ponds	Modeled compacted soil K_{sat} below 0.0145 mm/h	Maximize liner area or select soils for self-sealing or compaction	Absolute	Venteris et al. (2014b)
	Cultivation	Pond/ raceway	Avoid seepage below ponds	Reduce soil hydraulic conductivity below 10^{-6} cm/s (requirement in some states for ponds containing liquid waste)	Apply swine or dairy waste or other waste with similar solids content to seal ponds	Absolute	Cihan et al. (2006)
	Cultivation	Pond	Avoid seepage below ponds	Achieve soil hydraulic conductivity of $<10^{-12}$ cm/s	Use plastic liners such as high-density polyethylene	Absolute	Ng (2008)
	Construction and siting	Unlined pond/ raceway	Avoid seepage below ponds	No measurable seepage	Site where fine-textured and silty clays extend below pond depth; avoid removing surface soil during construction, or pervious material may be exposed	Absolute	USDA (1982)

PBR = photobioreactor, HTL = hydrothermal liquefaction.
CAP = combined algal processing pathway where biofuels are produced from both carbohydrates (after acid pretreatment and fermentation to ethanol) and lipids.

concern for infants in the Midwest US who drink well water, because of the risk of methemoglobinemia (Greer and Shannon 2005). High nitrate concentrations are found in many aquifers across the US, especially where aquifers are shallow and soils are well-drained (Burow et al., 2010).

Groundwater can be protected from potential leaching of nutrients in cultivation water. Lining ponds or raceways with plastic liners is one option (Venteris et al., 2014b). Another is to locate unlined ponds on clayey soils (Venteris et al., 2014b) or soils that biologically self-seal (Pattullo et al., 2019; Efroymson et al., 2020). Liners are protective of groundwater, meeting saturated soil hydraulic conductivity targets of less than 10^{-12} cm/s (Ng 2008), indicative of extremely low leaching rates. However, liners (flexible membrane, clay, or composite) fail in about 12 percent of industrial, lined impoundments over their lifetimes (USEPA 2001), and algae pond liners could fail as well.

Less-stringent targets for leaching could allow self-sealing, unlined ponds to be proposed as BMPs for algae cultivation. Saturated soil hydraulic conductivity below 10^{-7} cm/s represents a target for negligible seepage according to permitting requirements in some US states (Daniel and Benson 1990; Benson and Trast 1995; USDA 2008). However, many states require a less conservative saturated soil conductivity ($<10^{-6}$ cm/s) for ponds containing liquid waste (Cihan et al., 2006; USDA 2008). Allowable leakage rates for various types of liquid impoundments and wastewater ponds are reviewed by Koerner and Koerner (2009). These rates are options for environmental targets. A BMP for self-sealing soils has not been established, but knowledge of factors that influence soil hydraulic conductivity is increasing (Pattullo et al., 2019; Efroymson et al., 2020). ANL, NREL, and PNNL (2018) recommend site-screening criteria tied to soil texture, but other literature suggests that sealing of unlined pond bottoms may be independent of soil texture (Efroymson et al., 2020). Furthermore, lining the 'turns' of otherwise unlined ponds or raceways to prevent erosion (Davis et al., 2016) can provide groundwater protection.

BMPs are needed to reduce the likelihood of nutrient-containing cultivation water reaching natural waters as a result of overtopping events. About 20 percent of surface impoundments with fishable waterbodies within 150 m experienced overtopping in one extensive but older US study (USEPA 2001). Therefore, the management of freeboard (distance from operating maximum water-holding depth to overtopping elevation) based on extreme events is a recommended BMP. Freeboard distances for farm or municipal wastewater ponds based on pond or raceway length range from about 0.3 to 0.6 m (USDA 1982; USEPA 2011). Freeboard BMPs could be designed based on extreme-event statistics and pond geometry. Seasonal or pre-storm drawdown may be a strategic, temporal BMP. One model assumes that pond depth varies month to month, based on meteorological conditions, among other factors (ANL, NREL, and PNNL 2018). Installing berms around a site could catch overtopping water, preventing it from entering natural waters.

Avoiding saltwater intrusion into groundwater used for drinking or irrigation is an important water-quality objective in coastal areas and areas where saltwater and freshwater aquifers are at risk of mixing. Models can be used to optimize the magnitude and timing of water withdrawals while limiting saltwater intrusion, as well as to design temporal strategies for managing aquifer recharge (White and Kaplan 2017). For example, distance-based drilling BMPs can be developed by implementing three-dimensional groundwater models. Groundwater quality can be protected by drilling wells for water withdrawal and injection (blowdown) deeper than drinking water sources (DOE 2010). In general, drilling saltwater sources should be avoided at depths near freshwater aquifers (British Columbia 2016). Avoiding areas near coastal seawater is a BMP that applies to drilling freshwater sources for any use. Site-specific BMPs were developed to optimize locations for groundwater withdrawals in coastal aquifers, considering cost and water demand while considering likelihood of saltwater intrusion and risk tolerance of decision makers (Ferreira da Silva and Haie, 2007).

Algal crops are susceptible to grazing from zooplankton and pathogens, but pesticide amendments can adversely affect surface or ground water quality if culture water is released to natural waters. Biological and chemical BMPs are proposed to avoid direct application of pesticides to algal ponds. For example, cultivation of multispecies assemblages of algae (polyculture) can be an effective pest-control strategy. Polycultures not only protect algal crops from pathogens and grazers, but they can also increase overall biomass productivity, increase nutrient use efficiency, and enhance crop stability (Newby et al., 2016; Mandal et al., 2018). Biological control using food web manipulation (e.g. introducing aquatic predators of algal grazers) can be effective at maintaining a stable and productive algal crop without the addition of chemical pesticides (e.g., Smith and Crews. 2014). Physical (e.g. cavitation or filtration) and chemical (e.g. added CO_2) methods also may control zooplankton and can be preferable over commercially available pesticides (Montemezzani et al., 2017).

As with water quantity, siting BMPs can maintain or improve water quality. Algae can be cultivated for the joint purpose of treating wastewater and producing biomass.

4.3. Biodiversity

The primary biodiversity concern associated with freshwater algal biofuel production (excluding diversity within the culture) is disturbance of habitat for terrestrial and aquatic organisms. Therefore, BMPs for biodiversity focus on avoiding adverse impacts to rare or valued species, communities or habitats. Algae-facility-induced water scarcity or temperature changes in streams could adversely affect biota, so avoiding siting in areas of water scarcity is a BMP not only for water quantity but also for biodiversity (Jager et al., 2019). Similarly, sensitive areas such as mangrove wetlands should be avoided (Subhadra and George, 2011). Development of algae facilities on designated critical or other important habitat for terrestrial or aquatic rare species should also be avoided. Excluding these land areas is typical in national-scale resource analyses for algal biomass (Wigmosta et al., 2011; Efroymson et al., 2016). However, few studies have been conducted to assess risks to biodiversity from algae production or to propose BMPs to mitigate them.

Invasion by toxin-producing or bloom-forming cultures, or strains that have the potential to outcompete or exchange genetic material with native algae, pose a risk to algal cultures (NRC 2012; USEPA 2016). Therefore, BMPs would avoid use of algae that produce toxins or that form blooms. Moreover, the use of berms to reduce the probability of overtopped algae culture fluid entering neighboring streams is a BMP that helps to protect biodiversity. A BMP for the use of nonindigenous or genetically modified algae is to select strains that have a survivorship disadvantage in the ecosystem adjacent to cultivation systems in which they are deployed. The first US Environmental Protection Agency (USEPA) approval of growing genetically modified algae in the field showed that percent fatty acids increased in *Acutodesmus dimorphus* without a negative impact on phytoplankton communities in local lake water (Szyjka et al., 2017).

4.4. Greenhouse gas emissions

The primary environmental indicator used to estimate global warming potential is CO_2-equivalent (CO_2e) emissions, which include CO_2, methane, and nitrogen dioxide. GHG emissions reduction targets apply to the entire algal biofuel or bioproduct supply chain, both because of the integrated nature of algal biofuel systems and because policies relate to the full life cycle. For example, the U.S. Renewable Fuel Standard's 50% GHG emissions reduction goal for advanced biofuels such as algal biofuels is defined relative to that of petroleum diesel. To reach this target, analysts can apportion the needed carbon emissions reduction among processes and materials in an algal bioproduct supply chain through LCA. Cyclic linkages among supply chain steps, such as recycling of water and CO_2, must be considered when GHG reductions are estimated. BMP development for GHG reduction typically involves iteration between TEA and LCA so that costly technology options are eliminated (Fig. 2).

GHG emissions from algae cultivation and dewatering are driven primarily by processes to capture and potentially purify and transport CO_2; use of electricity, nitrogen, and phosphorus; and the manufacture of pond liners and other infrastructure (Davis et al., 2016; Frank et al., 2016; Efroymson et al., 2016) (Fig. 1), which is part of the life cycle of algae biomass and biofuel production. These are process steps for which GHG-emissions BMPs have been proposed (Table 3). Additional BMPs relate to land-cover transitions during pond construction, CO_2 utilization efficiency, and the development of coproducts (non-fuel products produced with fuel) whose emissions would not be attributed to biofuel.

Limiting siting to low-carbon land-cover categories reduces net GHG emissions, compared to developing algae facilities on forest or grassland. Arita et al. (2016) recommend siting algal facilities on barren land, which is a GHG-related BMP for this reason. Potential indirect land-use-change impacts of algae cultivation and algal biofuel production should be of lower magnitude than what is sometimes estimated for terrestrial biomass crops and biofuels (Arima et al., 2011; De Sá et al., 2013), because algae can be cultivated on marginal, unproductive land (Liu et al., 2013).

Sourcing CO_2 from a concentrated source such as an ethanol or ammonia plant at short distances is a BMP that decreases GHG emissions (Rickman et al., 2013; Efroymson et al., 2016; Schoenung et al., 2019). Cost-effective transport distances for CO_2 in flue gases are proposed in Schoenung et al. (2019), and GHG-related BMPs might include siting in such locations, as the parameters of resource analysis models (e.g., CO_2 utilization rates) become more certain. Clearly, practices that increase CO_2 utilization efficiency would improve GHG balance, and research is ongoing to improve this value. For example, the use of a bubble column increases the area of contact for gas exchange and in one study increased carbon utilization efficiency to 83% from 37% (Putt et al., 2011). Rickman et al. (2013) recommend improvements in CO_2 delivery methods, such as absorbing CO_2 into liquid media rather than pumping flue gas directly.

If cultivation is in ponds or raceways, a BMP with respect to life-cycle GHG emissions might be to use unlined or minimally lined ponds sufficient for erosion control. As Canter et al. (2014) note, "the first step to reducing infrastructure-cycle emissions would be to reduce or eliminate pond liners if soil conditions and environmental regulations permit."

Practices that affect energy balance also affect GHG emissions and are reviewed in Efroymson et al. (2017). Shutting down pond paddlewheels or other water circulation infrastructure at night improves energy and GHG emissions balances. Optimizing pond design with respect to channel velocities, sump locations (both based on algal growth rates and CO_2 uptake demands), optimal pH, and alkalinity are also recommended. Solar drying is preferred to energy-requiring drying processes. Companies are developing proprietary harvesting processes that have lower energy requirements than centrifugation. Sourcing nutrients from wastewater treatment plants or livestock waste should increase energy return on investment (EROI), depending on the transport distance and consistency and contaminants in the waste (Sturm and Lamer 2011).

The primary source of CH_4 and N_2O emissions from the algal biofuel supply chain is the anaerobic digestion process, which is

Table 3
Better management practices (BMPs) for algae biomass and biofuel production to meet GHG emissions targets.

Production step	System type	Objective	Target	BMP	Type of target	Reference
Siting	Open pond	Minimize GHG emissions from direct land-use change (LUC)	Maintain positive GHG benefit of algae systems (avoid 5% life-cycle GHG emissions over 10 years from LUC)	Use barren land preferentially	Absolute	Arita et al. (2016)
Cultivation	Open pond	Minimize GHG emissions	Meet RFS 50% GHG reduction goal, relative to petroleum diesel	Shut down pond circulation/ paddlewheels at night	Relative	ANL, NREL, and PNNL 2018
Cultivation	Open pond	Minimize GHG emissions	Meet RFS 50% GHG reduction goal, relative to petroleum diesel	Minimize liner area sufficient for erosion control and no more	Relative	Craggs et al. (2015); Davis et al. (2016)
Cultivation	Open pond	Minimize GHG emissions	39% decrease in GHG emissions compared to baseline high-density polyethylene pond liner	Use unlined ponds where leaching is negligible	Relative	Canter et al. (2014)
Cultivation	Ponds and PBRs	Minimize GHG emissions	Meet Renewable Fuel Standard (RFS) 50% GHG reduction goal, relative to petroleum diesel	Source CO_2 from facility with concentrated CO_2 in flue gas (e.g., ethanol plant)	Relative	Kadam (2001), Baliga and Powers (2010), Rickman et al. (2013)
Cultivation and CO_2 transport	Open pond	Minimize GHG emissions	Contribute less than 20 g $CO_{2\text{-}eq}$ MJ^{-1} to the overall system	Use uncompressed, pure sources of gaseous CO_2 with pipeline distance of 40 km or less or compressed supercritical CO_2 with pipeline distance up to 100 km	Absolute	Somers and Quinn (2019)
Cultivation and CO_2 transport	Ponds and PBRs	Minimize GHG emissions	Meet RFS 50% GHG reduction goal, relative to petroleum diesel	Absorb CO_2 in liquid sodium carbonate/bicarbonate solution, rather than pump flue gas directly	Relative	Rickman et al. (2013)
Cultivation	Open pond/raceway	Minimize GHG emissions	Improve CO_2 retention efficiencies in pond culture (achieve 75–90% efficiency)	Optimize pond design with respect to channel velocities, sump locations (both based on algal growth rates and CO_2 uptake demands), optimal pH and alkalinity	Relative	ANL, NREL, and PNNL (2018), de Godos et al. (2014)
Cultivation	Open pond/raceway	Minimize GHG emissions	Improve CO_2 retention efficiencies in pond (in this case achieve 83% transfer efficiency)	Use bubble column to increase interfacial area of contact available for gas exchange	Relative	Putt et al. (2011)
Cultivation	PBR	Minimize GHG emissions	Improve CO_2 capture efficiencies in PBR	Reduce the length of sparge time (in this case 5 s on, 55 s off)	Relative	Wilson et al. (2016)
Cultivation	PBR	Minimize energy use and GHG emissions	Reduce energy requirement (to 8% of the alternative PBR design in this study at given flowrate)	Use cyclic flow PBR rather than continuously circulating PBR	Relative	Wilson et al. (2016)
Cultivation	Pond or PBR	Minimize energy use and GHG emissions	Reduce GHG emissions compared to baseline (with purchased nutrients added)	Use wastewater as nutrient source	Relative	Sturm and Lamer (2011)
Life cycle	Pond	Minimize GHG emissions	Meet RFS 50% GHG reduction goal, relative to petroleum diesel	Adhere to specific “Original 2022 Target” scenario or “Revised 2022 Target scenario,” which includes CO_2 supplied by short-distance flue-gas pipeline	Relative	Frank et al. (2016)
Storage	All systems	Minimize energy consumption and GHG emissions	Reduce high GHG emissions from seasonal natural gas drying	Store biomass wet in covered pits	Relative	Wendt and Wahlen (2017), Discussed in ANL, NREL, PNNL (2018)
Coproduct production	Life cycle	Minimize GHG emissions and increase profitability	Reduce GHG emissions, compared to baseline	Displace products produced from petroleum with biogenic coproducts (e.g., polyurethane, succinic acid) that do not saturate markets	Relative	ANL, NREL, PNNL (2018)
Nutrient recycle credit	Ponds and PBRs	Minimize GHG emissions	Reduce GHG emissions, compared to baseline	Recycle nutrients from conversion back to cultivation	Relative	ANL, NREL, and PNNL (2018)

(*continued on next page*)

Table 3 (*continued*)

Production step	System type	Objective	Target	BMP	Type of target	Reference
CO_2 recycle credit	Ponds and PBRs	Minimize GHG emissions	Reduce GHG emissions, compared to baseline	Recycle nutrients from conversion back to cultivation	Relative	ANL, NREL, and PNNL (2018)
Cultivation and harvest	All systems	Minimize energy consumption	Reduce GHG emissions, compared to baseline	Minimize pumping from cultivation to harvest	Relative	Beal et al. (2012)
Harvest and conversion	PBR (ethanol secretion)	Minimize energy consumption and GHG emissions	Reduce GHG emissions, compared to baseline	Use solar thermal energy for some process heat	Relative	ABO (2017)
Refining	PBR	Minimize energy consumption and GHG emissions	Reduce GHG emissions, compared to baseline	Use high efficiency heat exchangers in ethanol purification	Relative	ABO (2017)
Cultivation	PBR	Minimize energy consumption and GHG emissions	Reduce energy consumption compared to baseline with no waste heat usage	Use waste heat	Relative	Baliga and Powers (2010), BioProcess Algae in Trentacoste et al. (2015)
Life cycle	Waste product handling	Maximize net energy ratio and Minimize global warming potential	maximum net energy ratio of 1.9 and minimum GWP of 1.0 kg CO_2e L-oil^{-1} in this reference	Employ gasification of aqueous waste products for onsite energy recovery	Optimization	Orfield et al. (2014)
Life cycle	All systems	Minimize energy consumption and GHG emissions	Improve net GHG emissions	Use waste heat	Relative	Liu et al. (2013)

PBR = photobioreactor

sometimes used to generate power from lipid-extracted algae or other process waste (Frank et al., 2012). Anaerobic digestion is often assumed in GHG LCA analyses because of water quality and GHG emissions benefits of nutrient recycling and combined heat and power production (ANL, NREL, and PNNL 2018). The relative GHG emissions benefits of conversion processes depend on the exact components of the processes. Hydrothermal liquefaction is a BMP if compared to pyrolysis with drying, for example (Bennion et al., 2015). In an LCA, HTL-derived algae fuels from the pilot-scale facility of Sapphire Energy had lower greenhouse gas (GHG) emissions than lipid-based biodiesel, petroleum fuels, and corn ethanol (Liu et al., 2013).

Some coproducts and production processes have better performance than conventional products with respect to GHG emissions. For example, many coproducts reviewed in Laurens et al. (2017), as well as the polyurethane coproduct evaluated in ANL, NREL, and PNNL (2018), have lower GHG emissions attributed to the bioproduct than the conventional production processes and lower regulated emissions when produced biogenically, leading to a large displacement credit for a fossil-derived equivalent product. Bioproducts such as polyurethane can sequester biogenic carbon (ANL, NREL, and PNNL 2018). For two conversion processes in ANL, NREL, and PNNL (2018) (hydrothermal liquefaction and the combined algal processing pathway with carbohydrate hydrolysis, lipid extraction of wet biomass and no energy-intensive drying), some scenarios with a polyurethane coproduct met the advanced biofuel GHG emissions target. Yet, the energy associated with production (and displacement) of many coproducts, as well as the sequestration of carbon fixed by photosynthesis into the bioplastics, has not been quantified, so a BMP related to the selection of coproducts has not been proposed. Energy and GHG emissions could increase if amino acids, peptides, and proteins from algae are converted into biopolymers and recycling of nutrients is thus reduced (Laurens et al., 2017). Estimating GHG emissions reductions in LCAs for integrated biorefineries that produce biofuels and other biochemicals depends on how the emissions are allocated with respect to products (e.g., masses or market values) or processes (Cai et al., 2018). Thus, BMPs are dependent on the choice of allocation method.

4.5. *Multiple indicators*

For most algae and algal biofuel producers, the most attractive BMPs reflect multiple sustainability targets. BMPs can be based on water quality and quantity, biodiversity, and GHG emissions targets discussed above, as well as productivity and profitability targets, and energy security, food security, or other social well-being targets.

Resource analysis can incorporate multiple environmental and productivity targets into better siting practices (Fig. 2). Venteris et al. (2014b) progressively applied site-selection criteria to the conterminous US, beginning with productivity, fresh and brackish water availability, soil properties (to promote sealing of unlined ponds), and proximity to infrastructure, including rail, natural gas lines, and electricity. The study identified regions that would be "ideal" for algae cultivation. Efroymson et al. (2016) constrained siting recommendations further by incorporating additional BMPs. These included implementing cost-effective distances to sources of CO_2 to reduce cost and GHG emissions and avoiding wilderness areas and wetlands to avoid negative effects on biodiversity. Water supply and aquatic habitat were considered in siting analyses by ANL, NREL, and PNNL (2018) and Jager et al. (2019). These studies demonstrated that over 1 Mt algae are available at a national scale without risk to water quantity or associated risks to water quality under defined environmental targets. Xu et al. (2020) combined water-use efficiency and a water scarcity footprint estimate, along with potential algae productivity, to site freshwater algae for energy and feed while minimizing freshwater demand.

Both complementarities and tradeoffs can occur among targets recommended for different dimensions of sustainability as BMPs are developed. BMPs that protect water quantity are often the same as those that protect water quality. Adequately lined ponds (or suitable siting for unlined or minimally lined ponds) prevent leaching and water and nutrient loss to groundwater. Recycling nutrients promotes water quality, profitability, and GHG balance. BMPs intended to reduce EROI typically reduce net GHG emissions and often reduce water use. Preventing leakage of nutrients from algal ponds and forgoing pesticide use protect biodiversity.

A few studies have optimized water quantity or quality variables while also considering productivity. Béchet et al. (2016) simulated algal productivity and water demand in five climatic regions and maximized productivity and minimized water demand by seasonally adjusting pond depth and hydraulic retention time. Xu et al. (2019) identified sites in the US where productivity and water availability would meet targets and where CO_2 sources were available for co-located production. Kern et al. (2019) developed a framework that optimizes the siting of algal biofuel production facilities with municipal wastewater treatment plants in a nutrient trading environment. Nutrient trading would affect targets for water quality and profitability.

Tradeoffs among environmental targets can result in compromise BMPs, especially where management goals compete (White and Kaplan 2017). Technologies that minimize water consumption, such as the use of PBRs, can have higher GHG emissions than open ponds (Resurreccion et al., 2012), especially those without liners (Canter et al., 2014). When environmental and economic indicators are considered together, regions of maximum potential productivity are not always preferred for siting (Venteris et al., 2014b). Venteris et al. (2014a) noted that the use of saline water sources, which benefits freshwater supply, is typically expensive because of the long transport distances from deep wells.

Excessive water withdrawals for algae production could result in flows that are too low for rare species and that elevate stream temperatures (Jager et al., 2019). Jager et al. proposed siting BMPs that combine biodiversity and water quantity considerations by limiting the number of facilities in watersheds where seasonal low flows or seasonal high temperature criteria are at risk of being violated. The study used representative reaches with long-term historical data monitored by a US Geological Survey gauge to evaluate the potential for harm. The paucity of gauges measuring water temperature limited the ability to address risk to thermal targets as a siting criterion, but the tradeoffs between total production and durations of low-flow events in representative streams were evaluated (Fig. 3).

In TEA and LCA, multiple economic and environmental indicators may be modeled and compared to targets, and alternative technologies or management practices can be evaluated as candidate BMPs (Fig. 2). An example is the evaluation of energy use, GHG emissions and water consumption in a few US Department of Energy scenarios and two algae-to-biofuel conversion pathways (Frank et al., 2016). Another recent study attempted to achieve simultaneous cost, productivity, and GHG emissions targets for the future using harmonized model assumptions (ANL, NREL, and PNNL 2018).

5. Discussion and conclusion

We propose a simple framework for identifying better management practices (BMPs) for algae and algal biofuel production. Examples of BMPs that are used or could be used by algae and algal biofuel producers are presented. These BMPs represent processes and practices that could meet specified targets for environmental indicators, sometimes along with productivity or profitability targets. Some BMPs come from algae-specific TEA and LCA, others are developed to meet regulations, some are imported from fields such as aquaculture and coastal drilling, and still others are modeled based on custom facility or regional goals. Many BMPs should be custom-made to address multiple targets, and they cannot be imported from other contexts. Algae and algal biofuel producers continue to develop more-sustainable practices in part because algal biofuel production offers examples of alignment among environmental and economic objectives. For example, recycling water and nutrients benefits water quality, water quantity, and profitability.

Clearly, environmental targets and BMPs depend on the context (Bretschneider et al., 2005; Efroymson et al., 2013). Targets for water conservation or GHG improvements can be specific numbers, or they can simply be an indication of progress toward a more sustainable state. Comparisons among technologies using LCA can be highly dependent on the scope of analysis (ABO 2017). Choosing an appropriate target and BMP depends on the scale, time frame, region, objective (Measham et al., 2007), resources (capital, labor and land), and current management practices (Clay 2008). The environmental targets in the examples above may not match the needs of all users of this framework, so we view these BMPs as examples that will be modified by specific users. Integrating microalgae with specific industries, e.g., sugarcane processing factories (Zewdie and Ali 2020), for example, would have very specific constraints, targets, and BMPs. Furthermore, regulatory criteria, such as TMDLs, vary depending on the quality of water in downstream water bodies and the number of other point-source discharges that affect them. A BMP for an algae producer to help achieve a downstream environmental target would not be the same as that for a wastewater treatment plant. Moreover, the feasibility of meeting many environmental targets, especially those that relate to industrial processes, depends on system parameters or assumptions; thus, for example, every system cannot recycle the same percentage of harvest water.

BMPs are not meant to be requirements. The selection of BMPs is moving away from regulatory prescription and toward producer-based approaches (Clay 2008; Tucker and Hargreaves 2008; Texas Water Development Board 2013; ABO 2017). BMPs are useful to algal facility managers if simple modifications allow them to be used in different contexts; research is needed to develop such tailoring guidelines for algal BMPs. As LCA is process-specific, it is helpful if published case studies classify processes that are similar, making it clear how their results can be generalized and more-broadly applied (Rickman et al., 2013).

Example BMPs presented in this paper are works in progress because commodity-scale algae production, especially for energy applications, is in the early stage of development. Thus, descriptors of recommended management practices for agriculture, such as ‘proven,’ and ‘generally accepted’ and ‘cost-effective’ (Texas State Soil and Water Conservation Board) cannot yet be applied to these proposed BMPs. Testing the efficacy of a broad list of BMPs in meeting environmental targets will help industry and researchers modify the list.

Over time, new scientific information and technologies necessitate different management practices to improve sustainability. As Beal et al. (2012) note with respect to their study of EROI, there is no “representative surrogate for future commercial processes.” Even for a single commercial facility at this time, there is little agreement about which technology or practice can meet an environmental target (Measham et al., 2007), and testing may be required. Some algae producers are advocating for an agricultural designation in

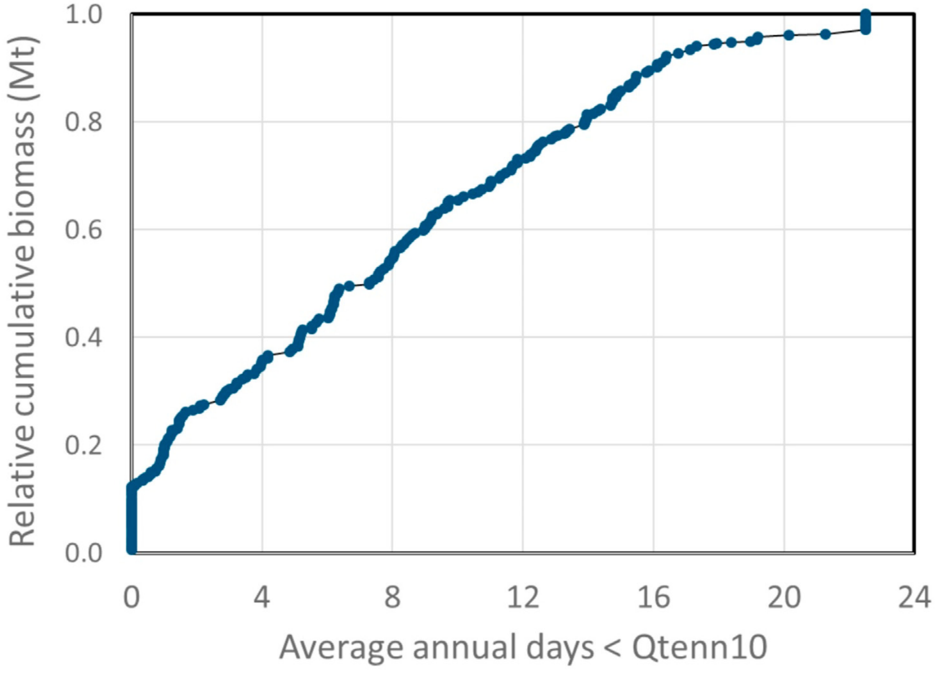

Fig. 3. Increase in the simulated availability of sustainable algal biomass as the target duration of instream flows below 10% of the annual average (Qtenn10) is relaxed.

the US (Trentacoste et al., 2015), and this classification as a nonpoint source of nutrients could affect whether BMPs are voluntarily implemented, required, or amenable to water quality credit trading in some US states (Borisova and Wade, 2017).

BMPs are important for algae and algal biofuel production because renewable energy must meet multiple environmental and economic targets. Social acceptability, social well-being (such as income and safety), and other social and economic indicators should be considered as BMPs for algae and algal biofuels are developed. Multiple objectives for BMPs will necessitate tradeoffs among objectives. Ultimately, decision-makers in industry and government, along with key stakeholders, will determine which objectives are most important, and industry will adopt BMPs accordingly. We hope that this framework and review will aid the algae biomass and biofuel industry in the process of adopting BMPs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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