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Editorial

Weeds in the algae garden – A source of biomass for the algae-to-biofuels program

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ABSTRACT

Despite decades of effort, viable algal biofuels remain a distant vision. High-lipid microalgae for biodiesel is plagued by low productivity, poor biomass quality, and pond instability, so conversion of non-specific algal biomass into other fuels is now the favored approach. Nevertheless, with low productivity and high costs, microalgae cannot provide the annual tonnage of biomass needed for fuel production. An alternative source of easily produced algal biomass has been available for decades. Algal turf scrubbing (ATS) robustly cultivates indigenous algae in an open flume photobioreactor. It is a proven, cost-effective, point- and non point-source treatment method for recycling the aquatic nutrient pollution whose levels threaten to exceed sustainable earth system boundaries. Using ATS to reverse nutrient loading in eutrophic waters would produce copious algal biomass at essentially no cost, for biofuel production or for development into other bioproducts.

1. Introduction

For more than thirty years, the United States Department of Energy (DOE) has been developing the capacity to convert algal biomass into replacements for diesel and gasoline (Sheehan et al., 1998), which, if successful, would expand energy security and could begin stabilizing net greenhouse gas emissions (Darzins et al., 2010; U. S. DOE, 2010; IPCC, 2011; OECD/IEA, 2011).

The first element of DOE's algal biofuels strategy involved prospecting for phytoplankton strains having potentially desirable properties. Dubbed the Aquatic Species Program (ASP), this project was active from 1978 to 1996 (Sheehan et al., 1998), and collected approximately 3000 algal species, from a variety of ecosystems and geographical locations (Sheehan et al., 1998; Knoshaug et al., 2009). Most of the collected strains were ultimately rejected, and only about 10% of the original candidates are preserved (Knoshaug et al., 2009).

The second element of the ASP strategy was to develop the chosen strains into crops that grow rapidly in outdoor ponds. The consensus design for a microalgal growth pond is an oval raceway, with a volume ranging from tens of thousands to millions of liters, and a water depth of up to 200 cm (Nurdogan and Oswald, 1995). The pond is equipped with a paddlewheel that operates continuously to provide mixing (Darzins et al., 2010) and a source of concentrated CO_2 to overcome the limited exchange of this essential nutrient between the atmosphere and the culture medium. A production run starts with a test tube of pure culture that is serially expanded in 100× increments, first in the laboratory and then outdoors; the final 100× expansion is harvested. Initially it was considered possible to harvest half the contents of a mature pond, allow the remaining half to re-expand by 2×, and repeat this cycle indefinitely. Unfortunately, it has proven almost impossible to cultivate defined phytoplankton monocultures outdoors reliably for more than a single harvest, as they are inevitably out-competed by unwanted exogenous algae, consumed by grazers, or infested by non-photosynthetic microbes (Darzins et al., 2010; Lane and Carney, 2014; Schenk et al., 2008).

The third element of the strategy was to focus initially on what appeared to be the most promising drop-in fuel, biodiesel, as demonstrating economically sustainable production of this biofuel would encourage a smooth transition from lower-productivity agricultural biomass (e.g. corn for ethanol) to higher-productivity algal biomass as a feedstock, while exploiting existing distribution infrastructure. Because lipids can serve as biodiesel precursors, algal strains that accumulate easily extracted lipids in laboratory culture were chosen for initial development. Initial analyses, using assumptions then considered conservative suggested that microalgal biodiesel was potentially economically feasible if production improvements could be implemented (Chisti, 2007; Wijffels and Barbosa, 2010; Chisti, 2013; Dassey et al., 2014; Rogers et al., 2014).

1.1. Issues with microalgae production

Microalgal production protocols have matured since they were first introduced. Currently a series of closed photobioreactors (PBRs) is required to incrementally expand microalgal seed cultures prior to production outgrowth, and these systems are costly to build and operate (Darzins et al., 2010; Schenk et al., 2008;

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Stephens et al., 2010; Walker, 2009). Harvesting and dewatering are also prohibitively expensive (Darzins et al., 2010; Lundquist et al., 2010; Coons et al., 2014). Furthermore, continuous production of microalgae – that is, harvesting half the biomass then allowing it to double again before each subsequent harvest – has proven difficult. During the single interval of outgrowth and harvest possible under currently achievable production conditions, the chosen algal strains do not accumulate large proportions of lipids as they do in laboratory culture (Lundquist et al., 2010; Schenk et al., 2008; Griffiths and Harrison, 2009; Henley et al., 2013), nor has biomass productivity in the field been as high as in laboratory or pilot scale projects (Lundquist et al., 2010; Stephens et al., 2010; Walker, 2009; Weyer et al., 2010).

The need to use defined culture media to cultivate microalgae for biofuels requires large-scale production of sterile solutions of macro- and micronutrients and recycling of nutrients from fuel-production residue. To support rapid microalgal growth in raceway ponds, supplementation with concentrated CO_2 is necessary, requiring either co-location of production ponds with a source of this nutrient, which would require extensive reengineering of these installations, or transport via pipeline, which would compete with existing markets for this industrial gas (Gao et al., 2012). Most of the best solar resource for growing microalgae in the US is located in arid regions, making water supply challenging.

Achieving reliable year-round high productivity and lipid yield is thus likely to require further major effort, including ecological or genetic manipulation (Beer et al., 2009; Radakovits et al., 2010; Peralta-Yahya et al., 2012; Benemann, 2013; Shurin et al., 2013). Even with generous assumptions for annualized biomass productivity and lipid content, as yet undemonstrated, biodiesel production from microalgae is not likely to be cost effective (Lundquist et al., 2010; Richardson et al., 2014; Sikes et al., 2010). These obstacles to microalgal biofuel production are troubling, as the Energy Independence and Security Act of 2007 mandates that by 2022 – only seven years from now – the United States produce 21 billion gallons (80 billion liters) of non-corn-based biofuel annually (Energy Independence and Security Act of 2007). This target, 8.3% of the United States' 2013 gasoline consumption (U.S. Energy Information Administration, 2015), is unlikely to be achieved, either by exploiting microalgae grown in raceway ponds or by any source of non-algal biomass, and has been revised downward (Schnepf and Yacobucci, 2014).

1.2. DOE's new strategy

DOE is therefore now investigating alternative fuels produced via bio- and thermochemical conversion of non-specific algal biomass into fuels and fuel precursors (Biddy et al., 2013; Toor et al., 2011). These processes depend upon total organic content rather than the presence of one specific class of biochemicals, and thus the major relevant characteristic of the biomass is whether it can be produced reliably at a high rate. This decision relaxes some constraints by expanding the range of algal species worth considering. However, it imposes new hardships related to engineering the conversion processes, including more capital-intensive fermentation processes, the higher temperatures and pressures needed for thermochemical conversion, means for handling the high ash and salt content of the biomass, and the suitability of thermochemically produced biocrude as a refinery input.

2. Algal turf scrubbing

During the same three decades that DOE has been pursuing microalgal biofuels, a completely independent algal cultivation practice, conceived for purposes unrelated to biofuel production, has evolved from initial discovery to multi-hectare outdoor production. Algal turf scrubbing (ATS), as this practice is known, is used not for producing algal biomass per se, but rather to remove point and non point-source nitrogen or phosphorus pollution from contaminated waters (Adey et al., 2011; Stewart, 2004). ATS™ is a trademark, and Algal Turf Scrubber® a registered trademark, of Ecological Systems Inc., the primary RT&D entity for the technology; these are licensed to HydroMentia, Inc., the primary commercial entity that deploys and licenses it. Figs. 1 and 2 depict ATS units of various scales; Table 1 provides a list of past and current ATS installations. ATS mimics the algal turfs that colonize tropical coral reefs by providing a growth substratum readily colonized by algal cells present in the input water, along with a flow regime that supplies continuous adequate nutrition. The algal cells attached to the stationary substratum develop into an immobilized mass of interwoven filaments and trapped cells (the "turf") whose rapid growth extracts nutrients and other pollutants from the water as it flows through the system.

Table 1
Representative algal turf scrubber projects.

Location	Water source	Area (m^2)	References
Florida	Indian River	18,535	(Hydromentia, 2010; Indian River County, 2014)
Florida	Runoff	10,000	(Hydromentia, 2005)
California	City of Patterson	1021	(Craggs et al., 1996)
Maryland	Bridgetown	300	[a]
Florida	Ft. Pierce	281	(D'Aiuto et al., 2015)
Maryland	Baltimore Harbor	200	[a]
Queensland	Aquarium Exhibit	144	(Adey and Loveland, 2007)
Maryland	USDA	120	(Mulbry et al., 2008)
Florida	Runoff	111	(Hydromentia, 2010)
New York	Jamaica Bay	65	(Jamaica Bay Research Symposium, 2011)
Florida	Powell Cr. Bypass	47	(Hydromentia, 2008a)
Florida	Santa Fe R.	47	(Hydromentia, 2010)
Florida	Lake Lawne	37	(Hydromentia, 2008b)
Maryland	Living classrooms	28	(May et al., 2013)
Arkansas	Spring Cr.	27	(Sandefur et al., 2011)
Virginia	York R.	25	(Rothman et al., 2013)
Virginia	Great Wicomico R.	24	(Adey et al., 2013)
Florida	Runoff	22	(Adey et al., 1993)
Pennsylvania	Susquehanna R.	19	[a]
Pennsylvania	Susquehanna R.	9	(Laughinghouse, 2012)
Maryland	Choptank R.	3	(Ray, 2014)
New York	Lake Erie	3	(Blersch, 2013)
Maryland	Patuxent R.	1	(Mulbry et al., 2010)
Maryland	Patapsco R.	1	(Mulbry et al., 2010)
Maryland	Bush R.	1	(Mulbry et al., 2010)

[a] P. Kangas, personal communication.

2.1. Discovery and initial development of ATS

Studies leading to development of ATS occurred in the 1970s and 80s, when one of us (Adey), sampling coral reefs in the Caribbean for the Smithsonian Institution's Marine Systems Laboratory, discovered that despite residing in what are essentially nutrient deserts, beds of benthic filamentous algae exhibited surprisingly high growth rates. This phenomenon was ultimately traced to efficient delivery of nutrients by wind-driven pulses of water (Adey and Steneck, 1985). The algal turfs were capable of rapid growth, up to 12 g of dry biomass per square meter of reef surface per day (ash included); because the reef surface undulates, this value can be extrapolated to 30 g per square meter per day, and this is demonstrated by measurements of oxygen concentration in the overflowing water (Adey and Steneck, 1985). In still waters, rapid algal growth would quickly deplete already low nutrient concentrations to their growth-halting lower limits, but in waters with an external supply of extremely dilute nutrients, un-depleted water