The ecology of algal biodiesel production

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Sustainable energy production represents one of the most formidable problems of the 21st century, and plant-based biofuels offer significant promise. We summarize the potential advantages of using pond-grown microalgae as feedstocks relative to conventional terrestrial biofuel crop production. We show how pond-based algal biofuel production, which requires significantly less land area than agricultural crop-based biofuel systems, can offer additional ecological benefits by reducing anthropogenic pollutant releases to the environment and by requiring much lower water subsidies. We also demonstrate how key principles drawn from the science of ecology can be used to design efficient pond-based microalgal systems for the production of biodiesel fuels.

Algae-based biofuels hold great promise

Because of dramatic recent variations in oil prices and strong global concerns about climate change, biologically-produced fuels have increasingly been identified as potential alternative energy sources [1]. Biofuels are currently being promoted by many as one of the most promising pathways to reducing the world's dependence on fossil fuels, lowering CO_2 emissions, and in some cases, supporting local agriculture and developing economies [2]. In particular, the synthesis of biofuels from renewable biological resources is seen as a highly desirable means of meeting aviation and other worldwide transportation demands. Intense interest has focused on the biofuel promise of photosynthetic plants, which produce storage lipids in the form of triacyglycerols (TAGs) that can be used to synthesize biodiesel fuels via simple transesterification reactions [3,4]. Diesel fuel already holds a dominant position in the refined petroleum products market, and even in countries where gasoline is the primary liquid fuel, diesel vehicles have unique importance across a wide range of economic sectors [5]. The EU for example intends to replace 5.75% of all transportation fossil fuels with biofuels by 2010 and 10% by 2020, and major developed countries worldwide have similarly ambitious goals [6].

Trends in the global production of biodiesel reflect these goals: annual production rose from near zero levels in 1991 to almost 2 billion gallons in 2006, with a steeply exponential growth of 43% per year between 2001 and 2006 [7]. However, a major biodiesel dilemma already exists: even if it were advisable to turn this important food resource into fuel, the global annual production of TAGs from oilseed crops could not meet current the diesel demands of 44 billion gallons per year by the United States alone [8], and it has been estimated that the combined production of biofuels from traditional oil crops plus waste cooking oils and fats cannot offset the world's demand for transportation fuels [9].

Other biofuel feedstocks will thus be needed to meet the world's future energy demands, and biodiesel from microalgae could represent the only renewable source of oil that can meet global transportation fuel needs [10]. Microalgal biofuels are produced from the lipid content of the algal cells, which potentially can serve as the feedstocks for many high energy density transportation fuels, including biodiesel as well as green diesel, green jet fuel and green gasoline; the remaining algal biomass can also be converted to biofuels through either biochemical or thermochemical conversion routes [11].

Although the relative merits of cultivated terrestrial plant biomass versus microalgae as feedstocks for biofuel production are still a subject of debate [12–15], microalgae have numerous characteristics that favor their use as a biofuel source (Box 1). Conventional terrestrial plants are relatively inefficient in capturing light, converting less than 0.5% of the solar energy received at typical mid-latitudes into plant biomass; in contrast, the photosynthetic efficiency of microalgae potentially can exceed 10% [16]. In addition, microalgae require far less land, can be converted to liquid fuels using simpler technologies than needed to convert cellulose, and have secondary uses that fossil fuels do not provide [17]. Algal biodiesel can easily be used in unmodified diesel engines, and it has significant advantages over conventional diesel fuel because it is renewable, biodegradable and might produce lower emissions of sulfur oxides and particulates when burned [3]. In addition, microalgae are microscopic in size and can be grown continuously in well-mixed liquid cultures, potentially providing the benefits of controlled high-output productivity that are seen in industrial fermentation [18].

If microalgae are to be capable of meeting future global transportation fuel demands, sustainable and cost-effective systems for their large-scale cultivation must be put into place. Extensive research has focused on the selection and bioengineering of microalgal strains that can be grown in transparent photobiobioreactors (PBRs; e.g. [19])). However, we are unaware of any high-production PBR that is currently in sustainable operation for biofuel production, and conclude that the commercially viable use of PBRs is

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Box 1. Favorable characteristics of microalgae

A number of key features potentially make microalgae a superior feedstock for biofuel production, relative to terrestrial vascular plants (e.g. Refs. [75,76]). Microalgae can exhibit extremely rapid growth rates (1–3 doublings per day), and they can thrive in waters of widely varying salinities and chemical composition. Microalgal cells synthesize and accumulate large quantities of neutral lipids and oils, and they produce a wide range of other harvestable biochemical products that can be sold to help offset the costs of biofuel production. Microalgae also lack the large non-photosynthetic structures (roots, stems, fruits, etc.) that are produced by terrestrial crops, and they can be grown on marginal lands that might be unsuitable for agriculture and other uses. Moreover, the annual biomass productivity of microalgae per unit land area can greatly exceed that of terrestrial plants. Harvesting rates can be modified to keep microalgal biomass at optimal levels at all times, and the potential of microalgae for continuous, year-round production helps avoid the strong seasonality of terrestrial crop plant production.

Optimal nutrient supplies (e.g. CO_2, N, P, etc.) can be provided at all times of the year, and their growth can remove nutrients and other contaminants from a wide variety of wastewater sources, providing the additional environmental benefits and cost savings that accompany wastewater bioremediation. Microalgae also can potentially be used to sequester carbon dioxide gas produced by fossil fuel-fired power plants and other sources, thereby reducing greenhouse gas emissions. Control of microalgal biochemical composition is possible without decreasing their productivity, thus maximizing potential biofuel production rates as well as CO_2 sequestration capacity.

not likely at the present time. Whereas we acknowledge that debate about the relative advantages of PBRs versus pond bioreactors is likely to continue [4], we propose, as do others [19,20], that outdoor ponds are feasible for use as economically viable systems for sustained, high-volume, microalgae-based biofuel production. Outdoor pond bioreactors are a versatile and highly desirable alternative to PBRs, and they can simultaneously be used for high-throughput energy production, resource recovery and wastewater reclamation [21].

Because outdoor ponds are open to the environment, they contain diverse assemblages of natural algae and zooplankton; their behavior and operation is both subject to, and informed by, known ecological principles. Ecologists can therefore make critical intellectual contributions to the development of algal biofuels, particularly in conjunction with bioengineers, but to date there has been limited exchange of ideas between ecologists and bioengineers (however, see [22,23]). Here, we describe several ecological benefits of producing microalgae-based biofuels relative to crop-based feedstocks and we present several ecological principles that can help guide the successful mass production of microalgae.

We do not intend to present an exhaustive review of the challenges associated with land-based biofuel feedstock production, or to detail the technologies that will be required by biofuel production from crop or algal feedstocks. Rather, we highlight key issues of concern for land-based biofuel crops and several important ecological principles that should help to maximize the potential of algal-based biofuel production systems. First, we briefly describe the advantages of using microalgae as feedstocks relative to land-based, biofuel crop production. We then discuss how pond-based algal biofuel production, which generally requires significantly less space than land-based biofuel efforts, can offer additional ecological benefits by reducing pollutant releases to the environment and by requiring much lower water subsidies. Finally, we outline three key ecological principles that can inform the design and successful operation of pond-based microalgal systems for biofuel production.

Environmental advantages of algal biofuels

In order to be a viable alternative energy source, a biofuel should provide a net energy gain, have environmental benefits, be economically competitive and be producible in large quantities without reducing food supplies [24]. In the subsections below we illustrate how the use of microalgae as feedstocks for biodiesel production can provide significant environmental benefits by reducing the land, pollutant and water footprints of biofuel production.

Reductions in ecological impact and land footprint

The potential for biofuel feedstock production to create greater environmental damage than benefit is a critical challenge to establishing a successful advanced bioenergy industry [25]. The National Non-Food Crops Centre (NNFCC) of the UK has produced calculators that allow growers to assess whether it is economically feasible to produce their own fuel, invest in anaerobic digestion, or switch from cereals to non-food crops [26]. However, these calculators do not yet take into account the potential environmental costs that would be associated with such production decisions. We share the concerns of Johnston and Holloway [5] that until more efficient methods of biofuel production become commercialized, the growth of biodiesel will eventually have strong impacts both on global food supplies and on the long-term sustainability of agricultural production.

Quantifying the land use changes associated with intensive biofuel feedstock production relies upon many assumptions [27,28], but it is clear that the accelerated cultivation of terrestrial plant biomass for biofuels will have an exceptionally large land footprint. For example, the United States has the fourth largest absolute biodiesel potential of the 119 countries studied by Johnston and Holloway [5]. However, recent work has suggested that the projected year 2016 demand for corn ethanol alone would require 43% of all U.S. land used for corn production in 2004 [29]. A related study concluded that the annual corn production needed to satisfy one half of all U.S. transportation fuel needs would require an area equivalent to more than eight times the U.S. land area that is presently used for crop production [4]. Other land-based crops would require less cropland, based on their oil content: oil palm (24% of current cropland area), coconut (54%), jatropha (77%), canola (122%) and soybean (326%) [4]. Moreover, recent work indicates that the ability of countries to grow terrestrial crops explicitly for the production of biofuels such as ethanol and biodiesel is significantly overestimated [30], contributing to concerns that these biofuels are not feasible options for providing a significant fraction of global fuel demand.

The above studies take on added importance when we consider that cultivation of terrestrial biofuel crops can