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Applying ecological principles of crop cultivation in large-scale algal biomass production

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ABSTRACT

Successful algal biomass cultivation at scale is a key limiting step for the production of algal biofuels and other high-value products, and crop protection against undesirable biomass losses will be a critically important component of commercialization efforts. If algal biomass production occurs in large, open, outdoor ponds, then it can be expected that invasions of these production facilities by multiple species of algae, invertebrate herbivores, and pathogens will only be a matter of time. This review identifies and discusses key aspects of community and ecosystem ecology that have direct relevance to the successful cultivation of algal biomass. We use experiences and examples from commercial agriculture to illustrate core ecological principles of crop cultivation that we believe can successfully be transferred to large-scale algal biomass production. We then discuss the degree to which herbivores and disease can significantly reduce potential yields, and the concepts of biological control. We also discuss the effects of crop species diversity and composition on algal biomass production, and explore the potential benefits of algal polycultures in large-scale algal biomass cultivation systems.

1. Introduction

Algae have great promise as a feedstock for the production of transportation biofuels that can help meet the world's energy needs [1–3]. Algae-based biofuels in principle can achieve cost efficiencies close to those needed to compete with petroleum-based fuels, along with reduced environmental impacts, but their viability at a sufficiently large scale is just beginning to be tested [3]. Based upon their high photosynthetic efficiency and rapid growth rate, the production of almost 200 barrels of algal oil per hectare of land area per year may potentially be achievable, a value that is a hundred-fold greater than for soybeans, a terrestrial crop used for biodiesel production in the United States [4]. Chisti and Yan [5] have noted that more than a dozen startup companies worldwide are currently attempting to commercialize algal biofuels. However, although significant progress is being made at essentially every step in the production chain, algal biofuels technology must overcome very significant challenges and hurdles before it can compete successfully and sustainably in the marketplace, and become adopted globally as an energy alternative [6].

One of the key hurdles to algal biofuels sustainability is achieving a high degree of crop protection [6]. As is true of terrestrial plants that are cultivated for domestic agriculture, large-scale algal growth facilities will be susceptible to invasions by a diverse array of highly undesirable competitors, plant-consuming pests, and pathogens that can dramatically reduce achievable yields [6–9]. A recent technical report [10] identified low algal biomass yields as a major driver of the high cost of algal biodiesel because of the high projected capital investments necessary to achieve commercial-scale production levels. Similarly, a report by the U.S. National Academy of Sciences [11] has concluded that improving the efficiency, reliability, and stability of the algal biomass cultivation process will be an important component of future R&D needed to realize the full potential of algal biofuels. Whether the goal is to produce algal oils for downstream transesterification to biodiesel; to produce total algal biomass for hydrothermal liquefaction to green crude oils; or to produce other biofuel products such as ethanol or hydrogen, achieving a satisfactory cost–benefit balance for the entire production chain will require the maximization of harvestable bioenergy feedstocks. Maximization of algal production will similarly be required if the harvested biomass is intended for use in alternative or additional markets, such as the food, feed, fertilizer, and chemical industries.

Algal cultivation is thus a key limiting step for the entire commercial enterprise, and successful crop protection against undesirable biomass losses will be a critically important component of these cultivation efforts. Several major factors that might be expected to cause significant crop losses in algal cultivation systems are summarized in Fig. 1. Crop losses may be expressed either in absolute terms (kg per hectare, or financial loss per hectare), or in relative terms (loss in percent). Crop loss rate is typically expressed as the proportion of attainable yield (the preferred method of calculation in agriculture), but sometimes the lost proportion of the actual yield may be calculated [12]. As in the agricultural context [12], algal crop losses may be quantitative and/or

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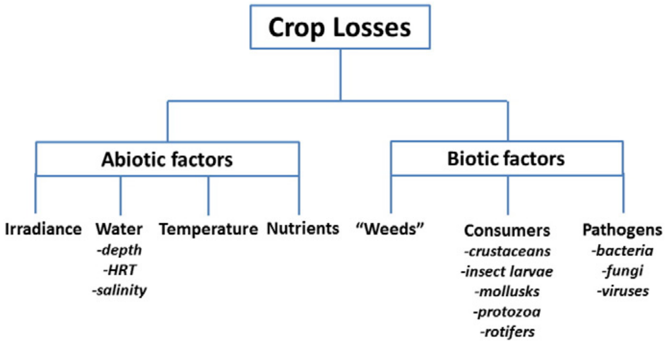

Fig. 1. Abiotic and biotic factors causing crop losses in algal biofuels production (modified for algae from the agricultural review of Oerke [12]). Only the roles of nutrients and biotic factors are discussed in this review.

qualitative. Quantitative losses result from reduced rates of production, leading to smaller yields per unit area. Qualitative losses from pests may result from reduced content of biofuel precursors and/or co-products, reduced storage characteristics, contamination of the harvested product with toxic products of the pests (e.g. toxins), or reduced efficiency downstream processing to marketable algal biofuels.

Because carefully documented experience in the mass culture of microalgae is far more limited than in agriculture, we believe that a comprehensive meta-analysis similar to that of Oerke [12] cannot yet be performed for microalgae. Although Stephens et al. [13] have suggested that there is evidence that open ponds can be operated using a wide range of microalgae without significant contamination for more than six months, we have a more pessimistic view. For multiple reasons that will detail in the sections below, we believe that invasions of large, open, outdoor cultivation facilities by multiple species of microalgae, invertebrate herbivores, and pathogens will only be a matter of time. These invading organisms in turn can potentially have very major implications for algal biomass production.

Our goal in this review will be to identify and discuss key aspects of community and ecosystem ecology that we believe have direct relevance to the successful, large-scale development of algal biofuels. We will focus here upon the biotic controls of algal biomass; the potential limiting roles of abiotic factors will be discussed in a separate paper. Wherever possible, we will draw from the literature in domestic agriculture to illustrate core principles of crop cultivation that we believe can successfully be transferred to algal biofuels production. Our review will initially draw from agricultural history in order to highlight the pivotal role of nutrients in determining potential primary productivity, and we will then demonstrate the degree to which herbivores and disease can act to reduce this potential. Finally, the effects of crop species composition will be discussed in relation to the existing agricultural practice of polyculture, and we will explore the potential benefits of high species diversity for algal crop production. Although our primary focus here will be upon the ecological behavior of open outdoor ponds, the core principles presented here can be expected to apply to closed photobioreactors as well.

2. Spatial scale influences biological structure: algal cultivation facility size matters

Algal biomass production will be very strongly influenced by the biological structure of the algal cultivation system [15,16]. We argue here that even if monocultures are intended, biotic contamination of open ponds will be almost certain, because algal cultures grown in these ponds will be susceptible to invasions by microflora and microfauna that inhabit other aquatic ecosystems located in the local and regional landscape. For example, both resting stages and live individuals from taxonomically diverse groups of cyanobacteria and eukaryotic microalgae will be deposited continuously onto the pond surface during system operation, either via the direct deposition of atmospheric particulates, or in association with rain and snowfall [17–19]. From the point of view of the system operators, these algal invaders will most likely be considered "weeds".

Similarly, open ponds also will be invaded constantly by a diverse community of aquatic consumers, including crustacean zooplankton, insect larvae, protozoa, and rotifers. These organisms can be transmitted primarily via insects, migratory waterfowl, and other regionally-mobile animals that may visit open ponds [20–22], but some herbivorous species can also be transmitted by wind and rainfall [23]. Similarly, microbial pathogens can be expected to invade open pond systems via direct atmospheric deposition (e.g., disease-causing bacteria: see [24]). Both the taxonomic identities and the diversity of algal and invertebrate species that are available to invade microalgal cultivation ponds will depend upon the size and composition of regional species pools [25,26].

How many biotic invasions actually occur, as well as how many of the invading species will subsequently survive to become stable residents, will depend strongly upon the physical size of the pond cultivation system. One of the oldest and best established laws in ecology is the consistent observation that the number of resident plants and animal species scales positively with their habitat size [27,28]. These Species–Area Relationships (SARs) have reported between the species diversity of weeds and crop area [29,30], and also between the species diversity of agricultural insect pests and total crop area [31].

Most importantly for this review, SARs also have been reported for phytoplankton, protozoa, and zooplankton in aquatic ecosystems worldwide [32–34]. As a result, the total number of species (the *species richness*) of algae, microzooplankton, and macrozooplankton that become established in algal production systems will tend to covary positively with the water surface area of its open cultivation ponds. Thus, as the total surface area of algal cultivation ponds increases with production scale-up, it certain that these facilities will need to cope with an ever-increasing diversity of potential pests and weed species.

The biodiversity implications of algal cultivation system size are illustrated in Fig. 2, which illustrates that microalgal species richness increases logarithmically with water surface area in natural freshwater ecosystems worldwide. The dotted box designates the ranges of microalgal species richness and water surface area (circa 0.5–100 ha) that might be expected to be resident within an individual algal biomass production pond, as well as within the total pond surface area that might potentially be employed by an entire algal cultivation facility. Thus, a minimum of 10 coexisting species of microalgae might be

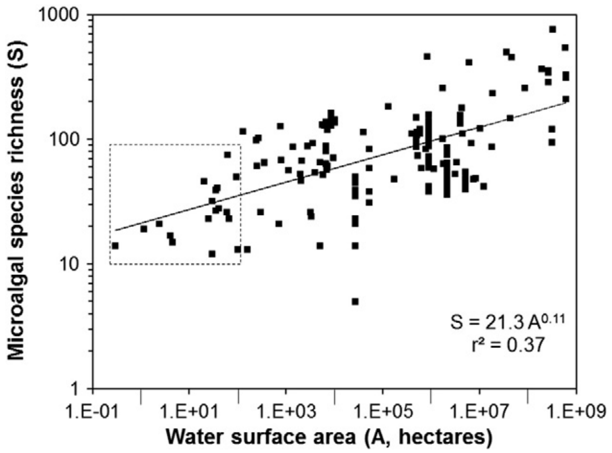

Fig. 2. The number of resident microalgal species (species richness) increases with water surface area in natural freshwater lakes worldwide (data from Smith et al. [34]). The dotted box designates the ranges of microalgal species richness and water surface area (ca. 0.5 – 100 hectares) that might be expected to be observed within a *single* algal cultivation pond, as well as within the *total* pond surface area that might potentially be employed within an entire algal biomass production facility.

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