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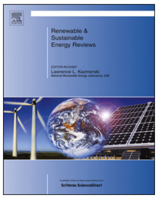

Modeling maximum lipid productivity of microalgae: Review and next step

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ABSTRACT

Microalgae are fast growing organisms and have the ability to accumulate lipid, which can be converted to biofuels. Here, we review specific growth rate, population productivity, and lipid productivity based on 192 publications of the marine microalgae *Nannochloropsis*. Specific growth rate was reported by thirty publications often using exponential growth equations, and fourteen publications stated biomass productivity. However, direct comparison among productivity estimates is impossible due to differences in calculations or omission of equations. Less than 5% of the publications directly reported lipid productivity, the key parameter for biofuels. We extracted growth data from 30 publications using Plot Digitizer software and tested best fit with exponential and logistic equations. The logistic equation often represents growth data better than the exponential one. Furthermore, we argue that maximum sustainable yield (MSY) is a more useful measure for harvest rates than specific growth rates. Interestingly, MSY displayed closer linear relationships with carrying capacity measures ($r^2 = 0.780$, $p < 0.001$ and $r^2 = 0.552$, $p < 0.001$ for algae density and biomass, respectively) than growth rate ($r^2 = 0.297$, $p < 0.001$ and $r^2 = 0.095$, $p = 0.090$). We propose to apply concepts of logistic growth, carrying capacity and MSY calculations to estimates of maximum lipid productivity, similar to commonly used density and biomass calculations.

Contents

1. Introduction

It is increasingly recognized that global power supplies will have to face a substantial change; away from fossil fuels toward regenerative energy sources. This is due to heightened energy demand, limited supply of fossil fuels and serious environmental challenges caused by anthropogenic greenhouse gas emissions [1]. Electricity generation techniques such as river damming have been over-developed, and all over the world there are over 45,000 large dams with severe impacts on natural river ecosystems [2]. Currently, renewable electricity supplies account only for a minor fraction of global energy demand, and even in future it will probably be impossible to displace fossil fuels entirely [3]. One alternative renewable energy source is biologically produced fuels, which are transportable and thus being touted as the most potential pathways to reduce the dependence on fossil fuels and the emissions of greenhouse gas [4]. Terrestrial plant-derived

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biofuels are controversial due to inefficient land use and food security [5]. Even combining biofuels from traditional crops, waste cooking oil and animal fats would unlikely be able to satisfy the demand for transportation fuels [6].

In this context, biofuels from microalgae have recently re-emerged as a potential to solve future challenges of energy supply and global climate change, and has re-attracted considerable attention from scientific, industrial and governmental sectors [7]. Microalgae are expected to have significant advantages over conventional energy crops [8]. Many species of algae exhibit much higher growth rate, and can accumulate over 50% lipids of dry weight biomass [9]. They are able to double their biomass within 24 h, and have even been claimed to be up to 20 times more productive compared to cultivated terrestrial plant [10]. One of the compelling reasons for using microalgae as biofuel feedstock is to greatly reduce the competition for arable land with crops for human foods, because microalgae can be cultured on non-agricultural area such as arid land, desert, ocean and lakes [11]. The environmental benefits of algal derived biofuels are that their cultivations cannot only absorb pollutants of nutrient-rich wastewater and capture anthropogenic carbon dioxide, but also do not require herbicides or pesticides [12,13].

While numerous studies have extensively reviewed the potential and advantage of using microalgae as biofuel feedstock, there are still many challenges in the development of algal derived biofuels including algal strain selection, biomass cultivation, harvest management and oil extraction [14]. Most of these processes remain in early stages [15], and all efforts to develop algal biofuels need to maximize lipid productivity and reduce production costs as well as energy requirements [16]. Maximizing lipid productivity is of fundamental importance to the success of any algal biotechnology for biofuel production, and one of the biggest challenges is the scaling up from laboratory scale to commercial scale while maintaining high lipid productivity [17]. However, to date there is little consensus on best practices of how to maximize lipid productivity from small-scale studies on algal cultivation [18], and it seems to limit effective scaling up of algae cultivation. Lipid productivity is an apparently easy concept, but it can give rise to misinterpretations if the theoretical bases of this concept are disregarded. Thus, thorough reviews and explanations from the scientific community are critical in order to make commercial algae lipid production viable [7].

The marine microalgae *Nannochloropsis* is known to have relatively high lipid content and interest has increased exponentially in the past 30 years as shown by increasing number of studies on *Nannochloropsis* (Fig. 1). Since any single study is worth little if not compared and related to others [19], comparisons of a set of studies are at the heart of science and are urgently needed in the development of microalgae biofuels. It is essential that the calculation and report of research data are uniform or can be converted to the same unit among a set of studies to allow quantitative comparisons, such as meta-analysis, which synthesize research findings. Furthermore, it is beneficial when methodology of data collection is consistent and calculations are well established. Originating from pioneering studies in fisheries management in the 1930s, the concept of maximum sustainable yield (MSY) has been well defined by Schaefer (1954), who developed surplus production models for one isolated logistic population under proportional harvesting effort [20]. MSY has been emphasized as the primary goal for sustained harvest management in the fields of fish, wildlife and forestry by almost of international and national plans such as the Implementation Plan (IP, South Africa) [21], Marine Life Management Act (MLMA, USA) [22], Implementing Sustainability in European Union Fisheries (ISEUF, Belgium) [23], Fisheries Management Act (FMA, Australia) [24] and Food and Agriculture Organization of the United Nations (FAOUN) [25]. Like other organisms, microalgae also follow logistic dynamics and experience growth phases including lag, exponential and stationary phase. MSY should be applied to estimate maximum productivity of populations in algal cultivation and sustained harvest management. Here, we took publications of the genus *Nannochloropsis* as a case to present research reviews on specific growth rate, biomass productivity and lipid productivity. In order to calculate maximum productivity of *Nannochloropsis* population based on the concept of MSY, both exponential and logistic equations were employed to test growth curve data (density or biomass over time) which were extracted from these publications. Finally, we propose a concept of "lipid mass population" which is similar to biomass population, and apply the theory of MSY to develop models for maximum lipid productivity.

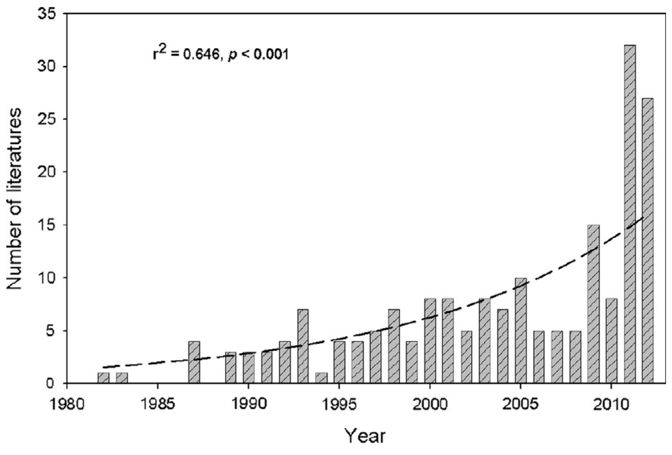

Fig. 1. Publications on the genus *Nannochloropsis* in each year (1982–2012) (Web of knowledge). A total of 192 publications were found.

2. Maximum sustainable yield theory

The review and detailed information of the MSY theory are available in many text books and published literatures. In the following, we only provide a brief introduction of the well known theory as a reference point for the application of the MSY concept to maximum productivity estimations of algal populations. In cases with density-dependent factors, an isolated population generally exhibit logistic growth which can be represented by the two equations:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \tag{1}$$

and

$$N(t) = \frac{K}{1 + (K - N(0)/N(0))\exp(-rt)} \tag{2}$$

In Eqs. (1) and (2), r is the growth rate of population under ideal conditions (d^{-1}), and K is the population size (density or biomass) when population remains stable and no longer increases and it is called the carrying capacity of the population. In Eq. (1), dN/dt is the rate of change in population size at time t and N is population size at time t; In Eq. (2), $N(t)$ is also population size at time t, and $N(0)$ is the initial population size at the time $t_0 = 0$. When an isolated logistic population is subject to proportional harvesting, we can obtain Schaefer's model [20]:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - eN \tag{3}$$