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Nannochloropsis sp. algae for use as biofuel: Analyzing a translog production function using data from multiple sites in the southwestern United States

Steven Archambault [a,*], Cara Meghan Starbuck Downes [b,c], Wayne Van Voorhies [c], Christopher A. Erickson [b], Peter Lammers [c]

[a] Agricultural Economics and Agricultural Business, New Mexico State University, MSC 3169 NMSU, P.O. Box 30003, Las Cruces, NM 88003-8003, United States
[b] Economics, Applied Statistics, and International Business, New Mexico State University, MSC 3CQ, PO Box 30001, Las Cruces, NM 88003-8001, United States
[c] Algal Bioenergy Program, New Mexico State University Laboratory, Box 30001, MSC 3RES, Las Cruces, NM 88003-8001, United States

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ABSTRACT

This paper investigates the production of *Nannochloropsis* sp. algae at five different sites located in the southwestern region of the United States. Studies of the economic viability of algae production typically calculate the Capital and Operating Expenses of stylized algal production firms with minimal understanding of the linkages between production and input variables that drive the costs being estimated. These results work towards filling this gap by estimating several production functions using real world data. Our dataset includes 10,316 days of algae growth, from which we generate 495 growth period observations. Particularly, the study analyzes the relationship between variation in input factors over a growth period and the resulting algae production measured by ash free dry weight. We carry out several multivariate econometric regression analyses. The variables photosynthetically active radiation (PAR), length of growth periods, and the growth of *Nannochloropsis salina* result in increased algae production. Algae production at the Texas AgriLife at Texas A&M University in Pecos, Texas, and Flour Bluff, Texas, resulted in higher algae production than the three sites in New Mexico. Increases in the initial algae inoculation levels and average precipitation consistently indicated a negative relationship with algae production in our model. These results should be useful for further studies aiming to connect real world algae production decisions with measures of costs and profitability.

1. Introduction

1.1. Microalgae suitability for bioenergy

Considerable interest has been expressed in policy circles regarding the potential of microalgae biofuels as an alternative source of clean energy [1]. Microalgae are diverse unicellular microorganisms that can convert sunlight and CO_2 into carbohydrates, protein, and natural oils, using photosynthesis [2]. As much as 75% of body weight in some species is made up of natural oils [1,3,4]. These oils can be processed into numerous products through transesterification [5], hydrothermal liquefaction [6,7], or gasification [8]. Microalgae lipids have been upgraded to jet fuel, diesel fuel, gasoline, green diesel, or biodiesel through many of the same processes used to convert petroleum crude into finished fuel products [9,10]. These products have the advantage, in contrast to ethanol, of being energy dense fuels that are compatible with existing energy infrastructure [11]. Algal based biofuels have the potential to be produced with a smaller carbon footprint than traditional fuels and can be produced with water, land, and nutrient inputs that do not compete with food production, unlike other feedstocks, such as corn, sorghum, and sugarcane [12]. Algae also have a much faster rate of growth and smaller land footprint due to the increased photosynthetic efficiency relative to land crops [13].

The first generation of biofuel production focused on *Nannochloropsis salina*, which are a coldwater marine species [14,15] shown to be tolerant of brackish water [16] and suitable for CO_2 fixation [16]. *Nannochloropsis* are also high in triglycerides and have a relatively high growth rate. Thus, this species was thought to be a good candidate for use as a biofuel species. While continued research has found additional species that are more viable for production scale, much has been learned from the initial cultivation experience with *Nannochloropsis* [11]. It has been used as the base organism in many of the Life Cycle Assessments and first generation techno-economic models, and many of the growth and nutrient predictions for greenhouse gas and land use change calculations have been done using *Nannochloropsis* [2,13,17–21]. Many algae cultivation studies have used techno-economic assessment (TEA) to analyze the potential economic viability of algae production and to calculate the Capital and

* Corresponding author.
E-mail addresses: sarchamb@nmsu.edu (S. Archambault), cdownes@nmsu.edu (C.M. Starbuck Downes), wavanvoo@nmsu.edu (W. Van Voorhies), chrerick@nmsu.edu (C.A. Erickson), plammers@nmsu.edu (P. Lammers).

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Operating Expenses (CAPEX and OPEX) of stylized algal production firms [11,22–28], with minimal understanding of the linkages between production and input variables that drive the costs being estimated. This research works towards bridging this gap with an applied algae production analysis that estimates the relationships between a selection of critical environmental and control variables and the impact on biomass production using 10,316 days of outdoor *Nannochloropsis* production data from five sites in the southwestern United States. Using econometric analysis, production functions are estimated, allowing for the examination of the role of various environmental and control inputs in the production of algae. Both Cobb–Douglas and translog functional forms of production are estimated. The research provides a systematic analysis of the relationship between biomass productivity and the explanatory variables of temperature, PAR, production cycle length, and initial inoculation, using real world data. The methodology can identify inputs that are over- and under-utilized. The results allow simulation of the impact from changes to the quantity of algae production input variables, and provide a comprehensive analysis of microalgae production data. The results should be useful for the development of additional models concerned with financial and environmental viability of algal fuel production.

1.2. Production and economic efficiency

Understanding the relationship between inputs and outputs is a critical step in accurately determining economic feasibility, and more importantly, can be used to direct research and development toward reducing costs and increasing output in order to increase economic viability of the use of algae as a biofuel [29]. Any given production process can be represented by a production function:

$$Y = f(X). \tag{1}$$

Eq. (1) gives the combination of inputs (X) and outputs (Y) that are technologically feasible at a specified point in time, and allows the flow of inputs and outputs for a given time period to be tracked through a production system or process (see, e.g., [30–32]). An applied production analysis focuses on defining the elements and relationships in $Y = f(X)$ such that profit can be estimated and sensitivity analyses for the various production inputs can be investigated [33, pp. 54–75].

To further understand $Y = f(X)$, it is useful to divide this input vector into three categories. First are elements of X that are under the operational control of management and can be varied in the short-run. The second category includes capital inputs that are under the control of management, but can only be varied in the long run, between growing cycles or when longer-term management strategies are being considered. Third are environmental factors that are important for the production process but are not under the direct control of management. These environmental variables are stochastic in nature. While management does not directly control these environmental variables, many of the Capital and Operating Expenses incurred will be related to mitigating the adverse impact of these environmental stochastic variables on production. Thus, stochastic non-control variables enter into the choice set of the firm through decisions regarding the use of capital and operating systems and processes. Thus, the production function can be represented as follows:

$$Y = f(\mathrm{o}, \kappa, \varepsilon) \tag{2}$$

where o is a vector of inputs under operational control that can be varied in the short run, κ is a vector of capital inputs that are fixed in the short run, and ε contains stochastic environmental variables not under the direct control of management. Eq. (2) captures the basic elements of algae lipid production, which can be used to derive the revenues, costs, and profit or loss of the firm. More directly, the stylized production function captures the production based variables and their interdependencies.

The conceptual framework defined by Eq. (2) needs to be translated into a functional analysis. Typically TEAs do this by using mathematical equations to populate a spreadsheet with the economic and financial metrics of interest. Parameters for these equations are typically derived using lab bench experiments or other prototypes. Often, idealized operation is assumed. An alternative procedure, which is pursued in this paper, is to estimate a production function from actual data generated from experiments. In particular, a production function for *Nannochloropsis* sp. is estimated using a panel data set created by pooling data from five experimental production facilities [34].

2. Material and methods

2.1. Description of data

The authors use 10,316 days of algae growth from five sites located in the southwestern United States collected from 2009–2012. From this sample, 495 growth period observations were generated. Data was collected from the following sites and partners: (1) Sapphire Energy in Las Cruces, NM (SAP); (2) New Mexico State University Energy Research Laboratory, in Las Cruces, NM (NMS); (3) Center for Excellence in Hazardous Materials Management in Atoka, NM (CHM); (4) Texas A&M AgriLife Extension in Pecos, Texas (PEC); and (5) Texas A&M AgriLife Extension in Flour Bluff, Texas, near Corpus Christi, Texas (COR). The cultivation data was collected over a four year period in outdoor reactors similar to traditional Oswald raceways. Cultivation volume was from 1000 l to 100,000 l and more than 50% of the observations are drawn from cultivation volumes in excess of 25,000 l.

Table 1 provides descriptive statistics for the variables included in our study. AFDW is a uniform measure of organic content that eliminates the variability that may arise from samples with differing water content or ash content [35]. In many instances, including the measuring of initial values that were non-zero, AFDW was extrapolated from a recorded value of AFDW density (g/l). For other cases, optical density at 750 nm (OD750) was used to determine AFDW [35]. For the latter case, an observed relationship between OD750 and AFDW was determined via an ordinary least squares regression analysis for each site. From this analysis, the AFDW values are determined.

The growth periods were a number of days of growth, which began with an initial measurement of AFDW, and ended with a final measurement of AFDW. The final measurement of AFDW was recorded from a measurement of harvested biomass, a final reading of AFDW density in the pond, or from a combination of the two. In some growth periods, for example with the PEC site, biomass was not harvested, yet the batch was moved to a different pond, diluted, and a new growth period began. In the case of CHM, and in some of the SAP growth periods, biomass was partially harvested, then growth was allowed to continue. The day of harvesting, or the last day of consecutive days of harvesting if harvest occurs over multiple days, is considered the final day of a growth period. For each growth period in which biomass was harvested throughout the growth period, the harvested quantity was added to the final growth quantity. The following equation summarizes the AFDW calculation:

$$\mathrm{AFDW} = \text{ending biomass-initial biomass} + \text{harvested biomass}. \tag{3}$$

The average daily-integrated photosynthetically active radiation (PAR) over the growth period is taken from data collected in three-minute intervals by Colorado State University (CSU) [36]. Several sites did collect PAR onsite, but the CSU data set provides a uniform methodology to collect PAR. The CSU PAR sensors closest to the production site were used [27,37,38].[1] The use of CSU PAR sites introduces measurement

[1] The NMS site was 38 km from the PAR sensor, located at the Jornada long-term agricultural research site near Las Cruces, New Mexico. This sensor also provided data for SAP (43 km distance) and CHM (221 km distance). The PAR sensor in Seguin, Texas, provided the COR PAR data (227 km distance). The PEC PAR observations were taken from the PAR sensor in Big Bend, Texas (253 km distance).