DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Marine AlGae Industrialization Consortium (MAGIC)

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Algae Platform Review

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Goal Statement

- **BETO MYPP Goals (2)**

  Demonstrate

1. Model the sustainable supply of 1 million metric tonnes ash free dry weight (AFDW) cultivated algal biomass (2017)
2. Demonstrate valuable co-products produced along with biofuel intermediates to increase value of algal biomass by 30% (2019)

- **DOE Project Goal**

  Demonstrate and validate high-value co-products

- **Relevance**

  Project goals are all top-level DOE MYPP goals

- **Outcome**

  A clear pathway to economically competitive, sustainable biofuels

Quad Chart Overview

Timeline

Project Start Date:	10/2015
Validation submitted:	11/2015
Validation approved:	03/2016
Rev Plan submitted:	03/2016
DOE issues funds:	**02/2017**
Project End Date:	09/2018
Percent Complete:	5%

Budget Summary

	FY 12-14 Costs	FY 15 Costs	FY 16 Costs	Total Planned (FY 17-End)
DOE Funded	-	-	$267K	$4.9M
Project Cost Share (Comp.)*	-	-	$33K	$1.3M

Barriers / Targets

- **Aft-B. Sustainable Algae Production:** Demonstrate sustainable biorefinery systems via TEA and LCA
- **Aft-E. Algal Biomass Char-acterization, Quality, and Monitoring:** Quantify efficacy of biofuel intermediates and co-products for up to 10 strains produced at 20-kg scale
- **Aft-H. Overall Integration & Scale-up:** Show that integrated unit operations at scale deliver sustainable production

Partners

FY 15-16 Percentages
Duke (24%), UHH (76%)

All Consortium FY17-END
ADM (5%), Bentley (2%), Bucknell (1%), Cornell (8%), Nord (8%), UTEX (8%), Shell (2%), UHH (23%), UHM (7%), USM (2%), Valicor (8%), Duke (26%)

(See next page for Consortium partners details)

Quad Chart Overview – Budget Detail

	FY 16 DOE Costs	FY 16 Cost Share	Total Planned Funding DOE (FY 17 - END)	Total Planned Funding Cost Share (FY 17-END)
Duke	$17K	$17K	$1.5M	$173K
ADM	-	-	-	$286K
Bentley	-	-	$54K	$54K
Bucknell	-	-	$48K	$10K
Cornell	-	-	$410K	$103K
Nord	-	-	$402K	$101K
UTEX	-	-	$383K	$100K
Shell	-	-	-	$120K
UH Hilo	$217K	$16K	$1.5M	$101K
UH Manoa	-	-	$347K	$102K
USM	-	-	$100K	$25K
Valicor	-	-	$388K	$100K

Note: dollar amounts are rounded for clarity

1 - Project Overview

- The Consortium began in 2008, funded by Shell, built a 6-acre demonstration facility, and funded 4 years of commercial R&D for $100 million, ended 2012 – developed platform technology
- With $20 million from DOE & USDA (2010-2015) we demonstrated production of commercially viable, sustainable biofuels and animal feed co-products from marine algae
  - Exceeded 2014 BETO MYPP productivity goal by 250%
  - Exceeded 2018 BETO MYPP productivity goal by 50%
  - Published comprehensive techno-economic analysis (TEA) and life cycle assessment (LCA) for commercial production
- Current objectives are aligned with DOE MYPP goals
- Primary objective now: demonstrate a combined product value of >$1,000/MT that yields a biofuel intermediate that exceeds the RFS for advanced biofuels, EROI>3, and sells for <$5/gge

2 – Approach (Technical)

Integrated Process

1) ***Strain development*** will deliver 10 new strains to meet product specifications for biofuel and animal feed applications
2) ***Mass culture*** uses an innovative hybrid system of PBRs and open ponds to produce 30-50 kg quantities of 10 strains for
3) ***Recovery and conversion*** of algal feedstock to refined biofuels and food and feed ingredients – by two pathways - to be used in
4) ***Product demonstrations*** to assess product efficacy and value, and
5) ***Commercialization analysis*** of commercial scale facilities based on demonstrated results using a reiterative TEA/LCA process

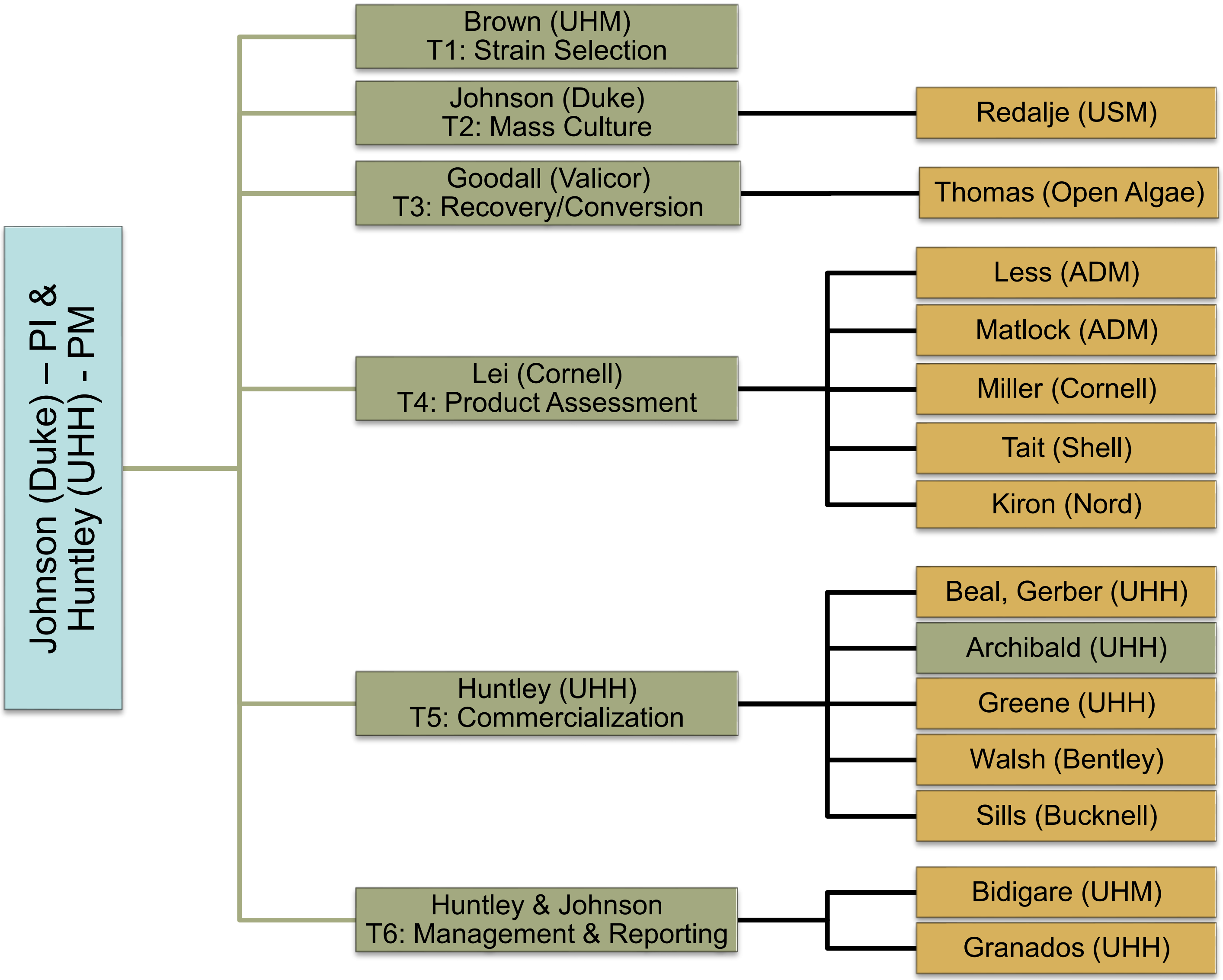
Unique features*:* marine algae, PBR technology, co-products

Top challenges*:* co-product value, LCA, EROI*

Critical success factors*:* production, processing, product viability

**Energy Return On Investment*

2 – Approach (Management)



3 – Technical Accomplishments/Results

DOE Validation Process (Task 0)

- Completed in 2 months (Nov 2015)
- Approved by DOE in 6 months (Mar 2016)

DOE Funding

- Issued 16 months after award (~Feb 2017)

Strain development
Mass culture
Recovery and Conversion
Product Demonstrations

} No funding to date

Commercialization Analysis — Limited funding to date

- Peer-reviewed publications
  - 6 published
  - 6 in press/in review
- Presentations
  - 17 delivered

3 – Published Results*

Key Publications

Production of fatty acids and protein by Nannochloropsis in flat-plate photobioreactors. (2017) *PLoS ONE* 12(1): e0170440. [Hulatt, CJ, RH Wijffels, S Bolla, V Kiron] https://doi.org/10.1371/journal.pone.0170440

Marine Microalgae: Climate, Energy, and Food Security from the Sea. (2016) *Oceanography* 29(4):10–15. [Greene, CH, ME Huntley, I Archibald, LN Gerber, DL Sills, J Granados, JW Tester, CM Beal, MJ Walsh, RR Bidigare, SL Brown, WP Cochlan, ZI Johnson, XG Lei, SC Machesky, DG Redalje, RE Richardson, V Kiron, V Corless] https://doi.org/10.5670/oceanog.2016.91

Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. (2016) *Environ. Res. Lett.* 11 114006. [Walsh, MJ, LN Gerber Van Doren, DL Sills, I Archibald, CM Beal, XG Lei, ME Huntley, ZI Johnson, CH Greene] https://doi.org/10.1088/1748-9326/11/11/114006

**14 peer-reviewed publications: 6 published, 6 in press/in review, 2 in preparation*

3 – Published Results*

Key Publications

Target Cultivation and Financing Parameters for Sustainable Production of Fuel and Feed from Microalgae. (2016) *Environ. Sci. Technol*., 50 (7), pp 3333–3341. [Gerber, LN, JW Tester, CM Beal, ME Huntley, and DL Sills] https://doi.org/10.1021/acs.est.5b05381

Defatted Biomass of the Microalga, Desmodesmus sp., Can Replace Fishmeal in the Feeds for Atlantic salmon. (2016) *Frontiers in Marine Science*, Vol. 3, pp 67. [Kiron, V, M Sørensen, M Huntley, GK Vasanth, Y Gong, D Dahle, and AM Palihawadana] https://doi.org/10.3389/fmars.2016.00067

Creating ω-3 Fatty-Acid-Enriched Chicken Using Defatted Green Microalgal Biomass. (2015) *J. Agric. Food Chem.,* 63 (42), pp 9315-9322. [Gatrell, SK, J Kim, TJ Derksen, EV O'Neil, and XG Lei] https://doi.org/10.1021/acs.jafc.5b03137

** 14 peer-reviewed publications: 6 published, 6 in press/in review, 2 in preparation*

3 – Published Results*

Key Publications

Screening for lipids from marine microalgae using Nile Red (in press) *Handbook of Hydrocarbon and Lipid Microbiology Series. Consequences of Microbial Interactions with Hydrocarbons, Oils and Lipids: Production of Fuels and Chemicals* Springer [Johnson, ZI, RR Bidigare, SK Blinebry, SL Brown, JJ Cullen, SE Loftus, DG Redalje, C Swink, BAS Van Mooy]

Cross-study analysis of factors affecting algae cultivation in recycled medium for biofuel production (in press) *Algae Research* [Loftus, S and ZI Johnson]

Digestibility of the defatted microalgae *Nannochloropsis* sp. and *Desmodesmus* sp. when fed to Atlantic salmon, *Salmo salar.* (in press) *Aquaculture Nutrition* [Gong, Y, HADS Guterres, M Huntley, M Sørensen, V Kiron]

Geoengineering, Marine Microalgae, and Climate Stabilization in the 21st Century – (in review) *Earth's Future* [Greene, CH, ME Huntley, I Archibald, LN Gerber, DL Sills, J Granados, CM Beal, MJ Walsh]

**14 peer-reviewed publications: 6 published, 6 in press/in review, 2 in preparation*

3 – Published Results*

Key Publications

Financial tradeoffs of energy and food uses of algal biomass under stochastic conditions (in review) *Appl. Energy* [Walsh, MJ, L Gerber Van Doren, N Shete, A Prakash, U Salim]

Defatted microalga meal of Nannochloropsis sp. as a modest fishmeal replacer in Atlantic salmon feeds (in review) *PLoS ONE* [Sørensen, M, Y Gong, F Bjarnason, GK Vasanth, D Dahle, M Huntley, V Kiron]

Marine microalgae: a sustainable and commercially viable replacement for global fishmeal and fish oil production (in preparation) [Beal, CM, S Thongrod, W Phromkhunthong, K Viswanath, B Goodall, L Gerber, J Granados, CH Greene, I Archibald, and M Huntley]

Use of Marine Microalgae for Biofuels Production: Reduction in Ash Content for Potential Improvements in Downstream Processing (in preparation) [Redalje, DG and SL Brown]

**14 peer-reviewed publications: 6 published, 6 in press/in review, 2 in preparation*

4 – Relevance

- **To the BETO MYPP**
  - *Project Goals directly address major BETO MYPP Goals* –
    (i) sustainable supply of 1 million MT AFDW algal biomass and
    (ii) production of valuable co-products that increase value of algal biomass by 30%
- **Impacts on science and the bioenergy industry**
  - High value *food and animal feed co-products* improve revenues
  - *Costs* are reduced; *EROI* is increased
  - *Sustainability* is demonstrated
- **Global impacts of large-scale production**
  - No impact on *freshwater resources –* near-zero waste of *N and P*
  - Simultaneous supply of *fuel and feed* – global scales match
  - *Reduced atmospheric CO_2 and a reversal of ocean acidification* are achieved at global scale
  - *Enormous land-use change impacts* result from intensified cultivation of fuel and feed products replacing corn, soy, palm, and sugarcane

5 – Future Work

This project will benefit from actual funding. Future work consists primarily of executing the proposed workplan, which was approved and formally validated by DOE 16 months ago.

Publish, publish, publish. The Consortium's ~10 peer-reviewed publications to date demonstrate how much we can accomplish with only a trickle of funds. Imagine what can be achieved now that the Consortium is actually funded.

Maintain public access to Consortium results. The Consortium continues to maintain and build upon its website (*https://www.AlgaeConsortium.com*) providing both internal and public access to the most recent results. News articles are published monthly. *Please visit the website – comments welcome!!*

Summary

Overview This Consortium has demonstrated a fully integrated process for the production of biofuels and high-value bioproducts at pre-commercial scale

Approach Demonstrate and evaluate high-value co-products that substantially increase biorefinery revenues. Apply reiterative TEA/LCA to improve design and performance.

Technical Accomplishments/Progress/Results

- DOE validation process completed 1 year ago
- DOE funding approved 1 month ago (Feb 2017)
- 10 Peer-reviewed publications since project approval

Relevance Results address central BETO MYPP goals for 2017 *and* 2019. Rigorous demonstration of co-product value, based on an integrated production process and efficacy trials are expected to increase revenues. Global impacts are significant.

Future work Fund the project. **Do the workplan.** A total of 10 peer-reviewed publications – even without funding - demonstrate the potential of MAGIC.

Thank you

Additional Slides

Publications

In Review / In Press – *with Abstract*

Screening for lipids from marine microalgae using Nile Red. (in press) *Handbook of Hydrocarbon and Lipid Microbiology Series. Consequences of Microbial Interactions with Hydrocarbons, Oils and Lipids: Production of Fuels and Chemicals* [Johnson, ZI, RR Bidigare, SK Blinebry, SL Brown, JJ Cullen, SE Loftus, DG Redalje, C Swink, BAS Van Mooy]

The fluorescent stain Nile Red has been used extensively for the quantification of lipids in phytoplankton, including microalgae, because it preferentially stains neutral lipids and it is economical and sensitive to use for screening purposes. Although its basic application has not changed for several decades, recent improvements have been made to improve its utility across applications. Here we describe additional refinements in its application and interpretation as a high-throughput method for the rapid quantification of neutral lipids in liquid cultures of marine phytoplankton. Specifically we address (1) inter-species comparisons, (2) fluorescence excitation and emission wavelengths and (3) the time-course of the Nile Red signal in the context of using bulk or cell-specific fluorescence to quantify neutral lipids of live or preserved cells. We show that with proper caution in its interpretation across species and physiological states that the quantity of lipid in hundreds of small volume samples can be reliably assessed daily using a refined Nile Red protocol.

Publications

In Review / In Press – *with Abstract*

Cross-study analysis of factors affecting algae cultivation in recycled medium for biofuel production. (in press) *Algae Research* [Loftus, S and ZI, Johnson]

Current high costs of commercial-scale algal biofuel production prevent its widespread use as a renewable fuel source. One cost-saving approach is to reuse algae cultivation water after biomass harvesting, thereby reducing water pumping and treatment costs. However, dissolved compounds, cell debris, and microorganisms remaining in the water could affect subsequent algae generations. Previous studies demonstrate a wide variety of effects of recycled medium on algae growth, yet their results have not been collectively analyzed. Here we integrate data across 86 studies to present the first meta-analysis that determines the relative importance of different factors influencing algae growth in recycled medium. We found that algae taxa can have the greatest influence, while the culture age and harvesting method are less influential on growth outcomes. This cross-study analysis identifies favorable taxa and thus provides a tool for algae cultivation decision-making when medium reuse is an important driver. Results can also aid in estimating relative algae yield and growth rates for technoeconomic assessments that incorporate water recycling.

Publications

In Review / In Press – *with Abstract*

Geoengineering, Marine Microalgae, and Climate Stabilization in the 21st Century. (in review) *Earth's Future* [Greene, CH, ME Huntley, I Archibald, LN Gerber, DL Sills, J Granados, CM Beal, MJ Walsh]

Society has set ambitious targets for stabilizing mean global temperature. To attain these targets, it will have to reduce CO_2 emissions to near zero by mid-century and subsequently remove CO_2 from the atmosphere during the latter half of the century. There is a recognized need to develop technologies for carbon dioxide removal; however, attempts to develop direct air capture systems have faced both energetic and financial constraints. Recently, BioEnergy with Carbon Capture and Storage (BECCS) has emerged as a leading candidate for removing CO_2 from the atmosphere. However, BECCS can have negative consequences on land, nutrient, and water use as well as biodiversity and food production. Here, we describe an alternative approach based on the large-scale industrial production of marine microalgae. When cultivated with proper attention to power, carbon, and nutrient sources, microalgae can be processed to produce a variety of *biopetroleum* products, including carbon neutral biofuels for the transportation sector and long-lived, potentially carbon-negative construction materials for the built environment. In addition to these direct roles in mitigating and potentially reversing the effects of fossil CO_2 emissions, microalgae can also play an important indirect role. Because microalgae exhibit much higher primary production rates than terrestrial plants, they require much less land area to produce an equivalent amount of bioenergy and/or food. On a global scale, the avoided emissions resulting from displacement of conventional agriculture may exceed the benefits of microalgae biofuels in achieving climate stabilization goals.

Publications

In Review / In Press – *with Abstract*

Digestibility of the defatted microalgae Nannochloropsis sp. and Desmodesmus sp. when fed to Atlantic salmon, Salmo salar. (in press) *Aquaculture Nutrition* [Gong, Y, HADS Guterres, M Huntley, M Sørensen, V Kiron]

The aim of the study was to investigate the apparent digestibility coefficient (ADC) of defatted biomass derived from microalgae Nannochloropsis sp. and Desmodesmus sp. when fed to Atlantic salmon postsmolts in seawater. Two experiments, one employing cold-pelleted and the other employing extruded pellets, were carried out to determine the ADC of dry matter (DM), protein, ash and energy. The test feeds consisted of a fishmeal-based reference feed and the algal biomass, at a ratio of 70:30, and yttrium oxide as the inert marker. The ADC of DM and protein in fish fed microalgae-incorporated cold-pelleted feeds were significantly higher for Nannochloropsis sp. compared with Desmodesmus sp. The Nannochloropsis sp. inclusion in extruded feeds led to higher ADCs of DM and energy compared with Desmodesmus sp. The extrusion processing significantly increasedthe ADC of ash in both defatted microalgae biomass, as well as ADCs of DM in Nannochloropsis and protein in Desmodesmus sp. In conclusion, the microalga Nannochloropsis sp. was more digestible than Desmodesmus sp., and extrusion processing can be used as a means to improve digestibility of certain nutrients.

Publications

In Review / In Press – *with Abstract*

Financial tradeoffs of energy and food uses of algal biomass under stochastic conditions. (in review) *Appl. Energy* [Walsh, MJ, L Gerber Van Doren, N Shete, A Prakash, U Salim]

The industrial cultivation of microalgae can produce oil and protein rich biomass at yields that greatly exceed those of conventional agriculture. Given that algae has been demonstrated as both a potential biofuel and a food product it is important to consider the environmental and economic tradeoffs associated with each of these uses. Here we evaluate the financial value of capital options for three processing strategies that produce feed and fuel from marine algae. We show, in stochastic price regimes for production inputs and outputs, that the greatest returns are achieved when algal biomass is valorized as a high value fishmeal replacement. A co-production technology strategy that valorizes extracted oils as fuel and residual biomass as fishmeal replacement can enable the economic production of a renewable biofuel. Consistent with other studies, fuel-only production remains uneconomical. Capital options that include flexible combinations of these technologies improve increase product output in economically challenging time-periods, but have lower returns than single-product options due to larger upfront capital investment. The application of a carbon tax places a penalty on food production, but improves returns when combined renewable electricity is utilized in production. This analysis demonstrates an approach for evaluating financial tradeoffs at the food-energy nexus under uncertain market conditions.

Publications

In Review / In Press –

Defatted microalga meal of Nannochloropsis sp. as a modest fishmeal replacer in Atlantic salmon feeds (in review) *PLoS ONE* [Sørensen, M, Y Gong, F Bjarnason, GK Vasanth, D Dahle, M Huntley, V Kiron]

Publications

In Preparation – *with Abstract*

Use of Marine Microalgae for Biofuels Production: Reduction in Ash Content for Potential Improvements in Downstream Processing. (in preparation) [Redalje, DG and SL Brown]

Many species of microalgae have shown potential as feedstocks for production of algal biofuels. Freshwater species have been chosen because of they have demonstrated relatively greater neutral lipid biosynthesis in mass culture. Freshwater has become relatively scarce and there are competing uses making freshwater species less attractive for biofuels applications. Marine microalgae do not require freshwater and can be grown in mass culture on land that is less suitable for other uses. It is also more favorable to isolate local marine species for any mass culture endeavor due to possible accidental release to the environment. Two groups of marine microalgae, diatoms and chlorophytes, have shown great potential for biofuels production. Diatoms often have greater rates of synthesis of biofuel lipids. However, the silica content of diatom frustules can be problematic for downstream processing and lipid extraction. For these reasons, as part of a U.S. Department of Energy Algal Biofuels Consortium, we conducted a study that included pre-screening of 35 strains for biofuel suitability and further testing at a demonstration scale facility in Hawaii. Cultures were grown in f/2 medium with treatments of 100, 75, 50 and 25% of f/2 Si. Some species showed greater biomass with decreased Si. Some species demonstrated enhanced lipid content with lower Si. The best performing 18 species of diatoms and 6 species of chlorophytes were grown at reduced Si content in the medium (for diatoms) or reduced trace metals in the medium (for chlorophytes). Treatments were 100, 50, 25, 12.5 and 0% f/2 Si or f/20 trace metal mix. Five of the diatoms were from culture collections with the others isolated from coastal Hawaiian waters. All of the chlorophytes were isolated from Hawaiian waters. The results showed that ash content of the diatoms was generally <5-10% of DW for diatoms, but that there was no reduction in ash content with reduced trace metals for chlorophytes.

Publications

In Preparation –

Marine microalgae: a sustainable and commercially viable replacement for global fishmeal and fish oil production. (In preparation) [Beal, CM, S Thongrod, W Phromkhunthong, K Viswanath, B Goodall, L Gerber, J Granados, CH Greene, I Archibald, and M Huntley]

Presentations

2016

"Co-products are key to economic success," Algae Biomass Summit, Phoenix, Arizona. [Gerber, LN, MJ Walsh, JW Tester, CM Beal, ME Huntley, DL Sills] – October

"Substitution of fishmeal with defatted microalgae (Nannochloropsis sp.) from biorefinery in diets for European seabass (Dicentrarchus labrax)" Aquaculture Europe 2016, Edinburgh, Scotland. [Custódio, M, H Fernandes, S Batista , V Kiron , LMP Valente] – October

"Molecular insights into the hidden majority of the ocean's biological engine" [ZI Johnson] – September

"Natural Products from Microalgae," Annual Meeting of the Phycological Society of America, John Caroll University, Cleveland, Ohio. [Manning, SR] – July

"Large Scale Algae Production: The Basis for a Sustainable Shrimp Aquaculture Industry in Thailand," Prince of Songkla University, Hat Yai, Thailand [M Huntley] (July)

"From Test Tubes to Tonnes: Updates on Lab Trials to Commercial Scale Relevance (and some paths forward)" San Diego, California. [ZI Johnson] – May

"Microalgae: the good, the bad, and the ugly," Plant Biology Seminar, University of Texas, Austin, Texas. [Manning, SR] – May

"Current State of Technology in Algae Cultivation: Hybrid Cultivation Systems," World Congress on Industrial Biotechnology, San Diego [M Huntley] - April

"Climate, Energy, and Water Security from the Sea," Computer Assisted Process Engineering (CAPE) Forum, Swiss Polytechnic Institute (EPFL), Valais, Sion, Switzerland. [Sills, DS, Walsh, MJ, Gerber Van Doren, L, Greene, CH] – March

Presentations

2016 (Continued)

"*Prymnesium parvum*: Killer Algae in the Southwest," American Society of Microbiology, Texas Tech University, Lubbock, Texas. [Manning, SR] – March

"Use of Marine Microalgae for Biofuels Production: Reduction in Ash Content for Potential Improvements in Downstream Processing," Poster for Ocean Sciences Meeting, New Orleans, Louisiana. [Redalje, D, S Brown] – February

2015

"Green crude or brown crud?: Economic and environmental assessment of algal biofuel," Mechanical and Environmental Engineering Seminar, Tel-Aviv University, Israel. [Sills, DS, MJ Walsh, L Gerber Van Doren, CH Greene] – December

"From Test Tubes to Tonnes: Scaling up Lab Trials to Commercial Scale Relevance," Washington DC. [Johnson, ZI] – September

"The Potential (and Progress) of Marine Algae for Feed and Fuel," Stewards of the Future, Beaufort, North Carolina. [Johnson, ZI] – June

"Marine microalgae: climate, energy, and food security from the sea," Friday Harbor Laboratories Seminar Series, University of Washington, Friday Harbor, Washington. [Greene, CH] – June

"Fossil fuel junkies, climate change, and better living through algae," Climate Change Resiliency Network, Friday Harbor, Washington. [Greene, CH] – June

"Marine microalgae: climate, energy, and food security from the sea," School of Aquatic and Fisheries Science Aquaculture Lecture, University of Washington, Seattle, Washington. [Greene, CH] – May

Publications & Presentations

SUMMARY

14 peer-reviewed Publications

17 Presentations

Patents, Awards, and Commercialization

No patents have been applied for based on the work supported by DOE.

No special awards have been received.

All primary results from this project are being published in the open, peer-reviewed literature. The publications from this project – cited above – provide a comprehensive and detailed analysis of commercialization potential. This information will be available to anyone with access to the open literature.