# Carbon Utilization Efficiency in Marine Algae Biofuel Production Systems Through Loss Minimization and Carbonate Chemistry Modification


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Algae Platform Review

DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

This presentation does not contain any proprietary, confidential, or otherwise restricted information

WBS 1.3.2.440

# Project Overview

This team was spun out of the larger MAGIC consortium, and represents a smaller group with one new member who brings specialized experience

Our focus here is to build on substantial team experience associated with outdoor algae cultivation and TEA/LCA of algae biofuels to develop and test approaches to minimize $CO_2$ use and losses and to enhance overall algae productivity

(FOA: DE-FOA-0001908 *Efficient Carbon Utilization in Algal Systems)*

*Our goal:* ***Demonstrate enhanced algal growth with an overall reduced $CO_2$ requirement at an industrially relevant scale with a system that has improved economics and environmental impacts***

*Success means improved algae biofuel economics and reduced environmental impact*

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# 1 - Approach (Major Tasks)

Goal: *Demonstrate enhanced algal growth with an overall reduced $CO_2$ requirement at an industrially relevant scale with a system that has improved economics and environmental impacts*

- Task 1: Verification
- **Task 2: Strain assessment** (Cultivation) - $\Sigma CO_2$ threshold and $HCO_3$ enhancement→ **reduced $CO_2$ use & enhanced growth**
  - Risk / management: limited response / multiple strains & down selection
- **Task 3: $CO_2$ conversion** - $CO_2$ to $HCO_3$ using $CaCO_3$→ **reduced $CO_2$ use**
  - Risk / management: poor performance / design & iterate
- **Task 4: Demonstration** - integrated system, industrially relevant scale→ **translation to industry**
  - Risk / management: scale-up does not translate / multiple scales & strains
- **Task 5: TEA/LCA & System Modeling**→ **economics/sustainability**
  - Risk / management: limited risk

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# 1 - Approach (continued)

- Go/No-Go between BP2/BP3
  - Each task has quantifiable decision points to demonstrate feasibility prior to scaling up to ≥1000 L (e.g ID of strains, [$CO_2$] limits)
- Incorporation of past comments (Go/No-Go; Peer-Review)
  - Project design has been updated to included different biofuel relevant strains; additional outdoor testing; TEA modeling of additional carbonate reactor designs

"successful projects from Topic Area 1 in this FOA will include innovative, improved, and economical $CO_2$ utilization within algae cultivation systems resulting in increased productivities and reduced production costs of advanced algal biofuels and bioproducts without a reduction in overall biofuel yield."

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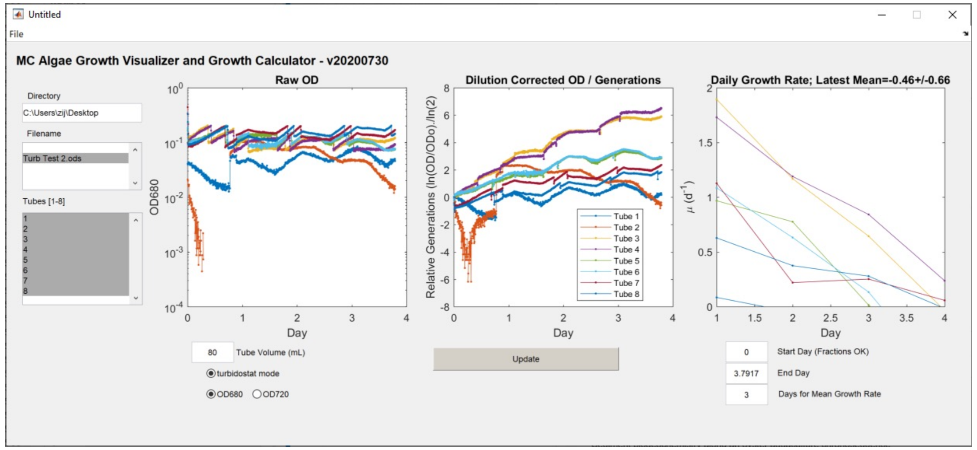
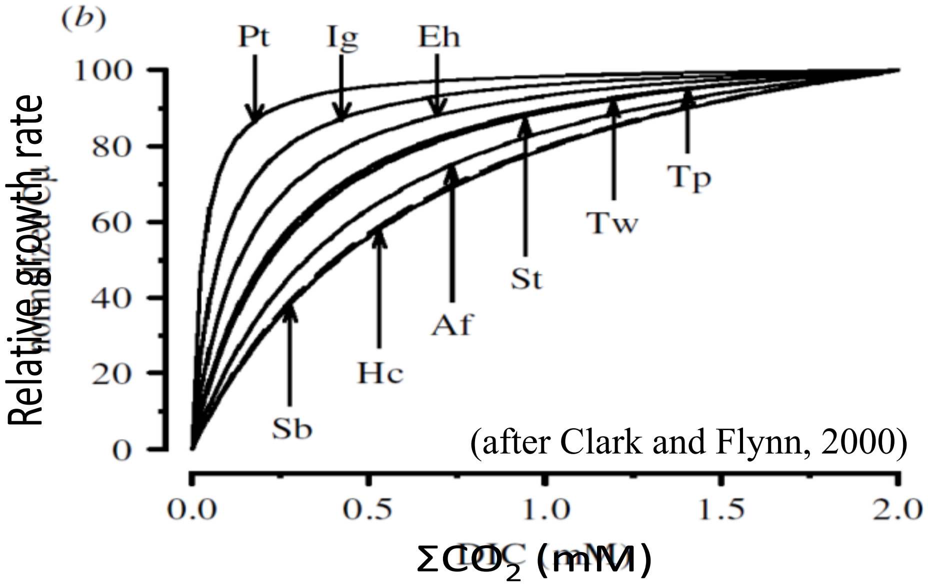
# 2 - Progress and Outcomes

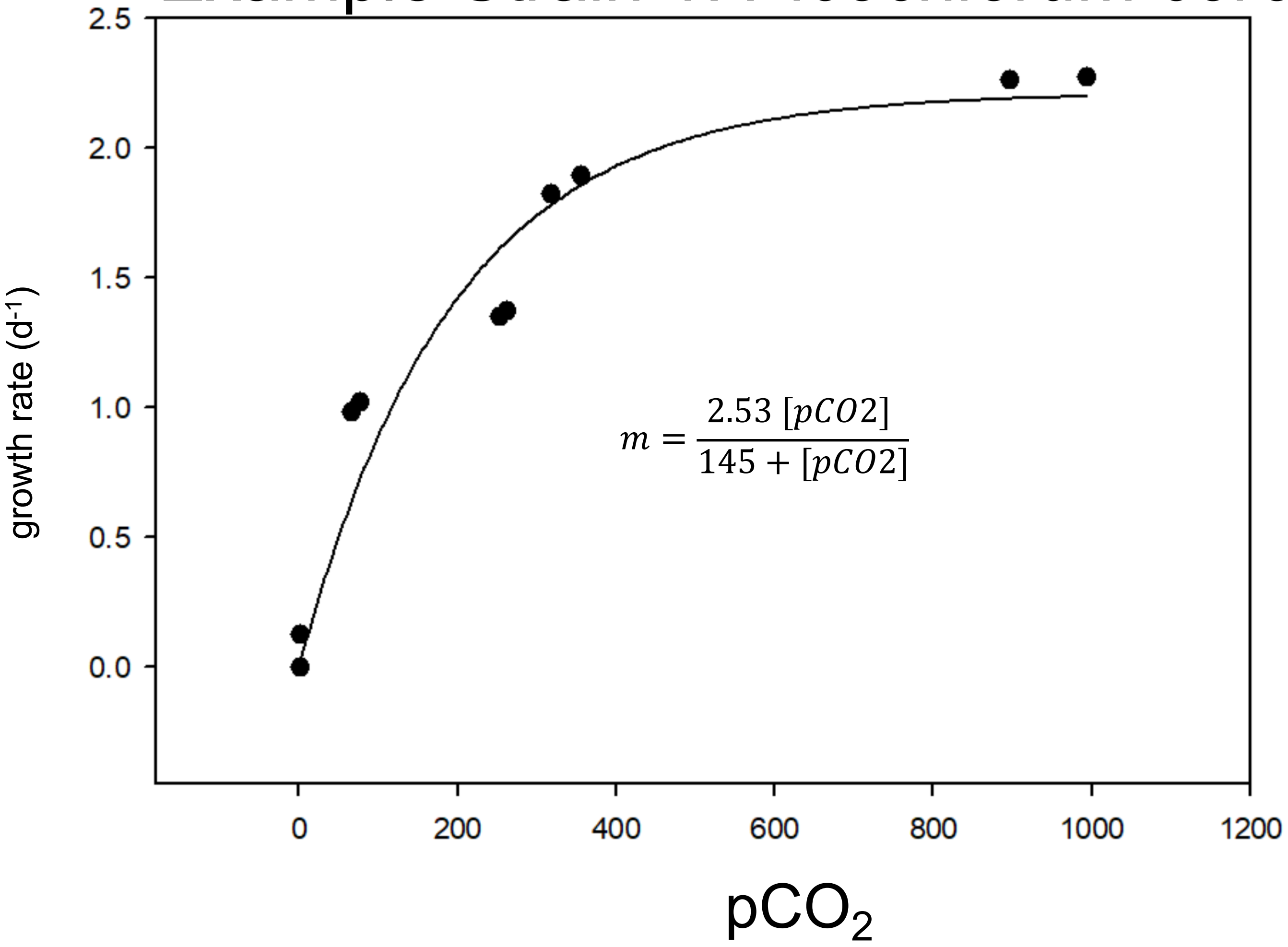
## Task 2: Strain assessment: *ID of strains with reduced $pCO_2$ threshold for growth*


Strains assessed for this project are all biofuel relevant (SOT, MAGIC, other)

# Example Strain 1: *Picochlorum cereli*

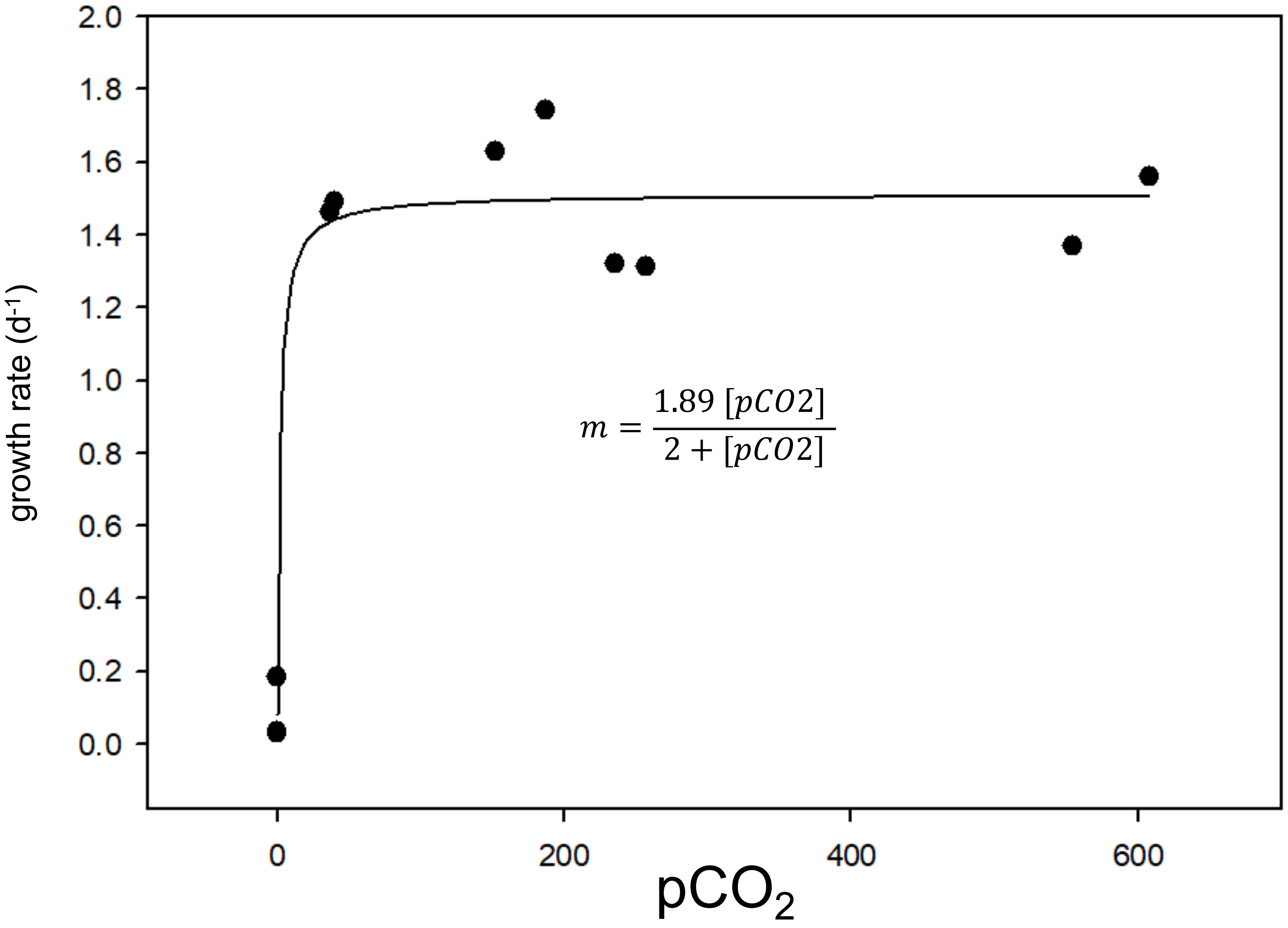



Km=145 µatm

2x half saturation (290 µatm) is < atmospheric pCO2 (~400 µatm).

**Thus, ponds of Pico do not need to be supersaturated with $CO_2$**

# Example Strain #2: *Oocystis sp.*




Km=2 µatm!

2× half saturation (4 µatm) is <<< atmospheric pCO2 (~400 µatm).

Thus, ponds of *Oocystis* may not need any $CO_2$ supply (and do not need to be supersaturated) → **reduced $CO_2$ usage**

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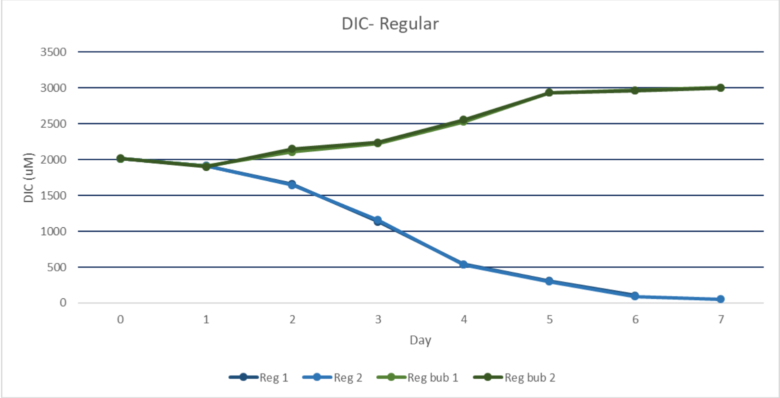
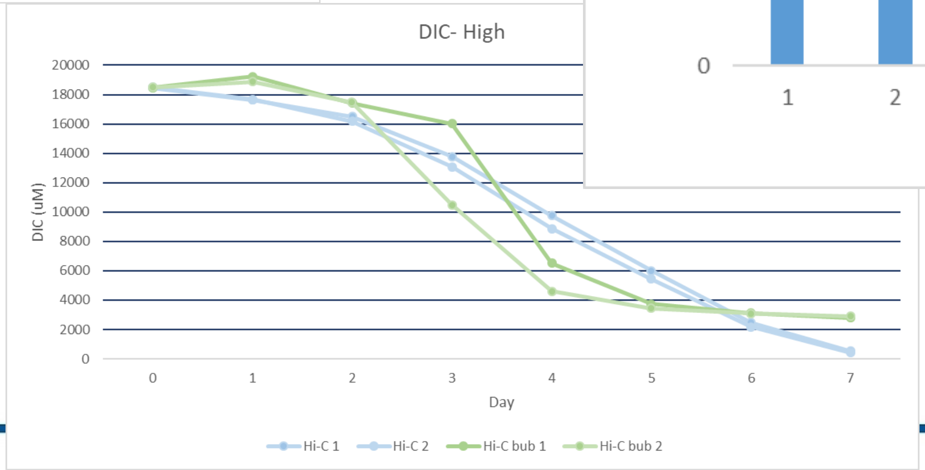
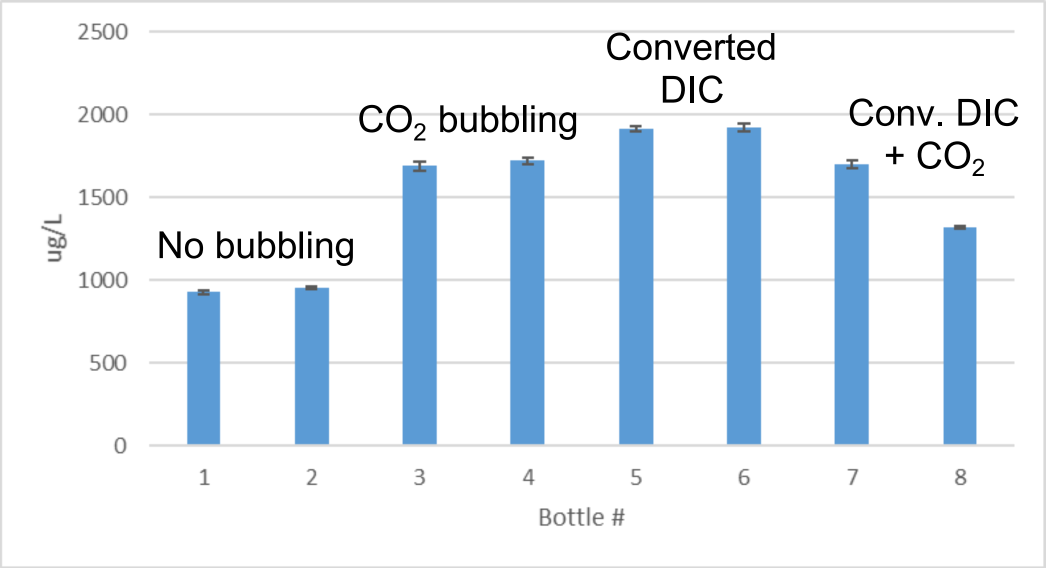
# Task 2: Strain assessment: *Growth (enhancement) on converted DIC waters*

Numerous strains assessed. Two strains (*Nannochloropsis & Chlorella*) identified that show a growth stimulation.

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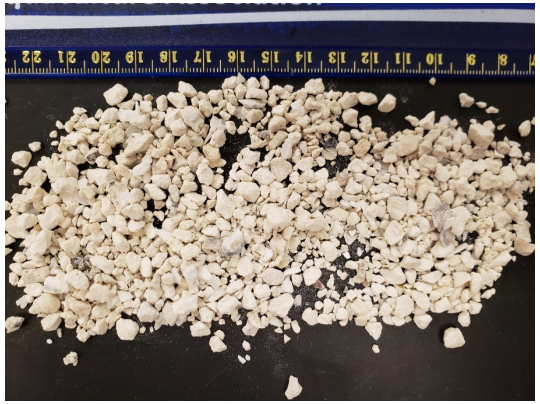
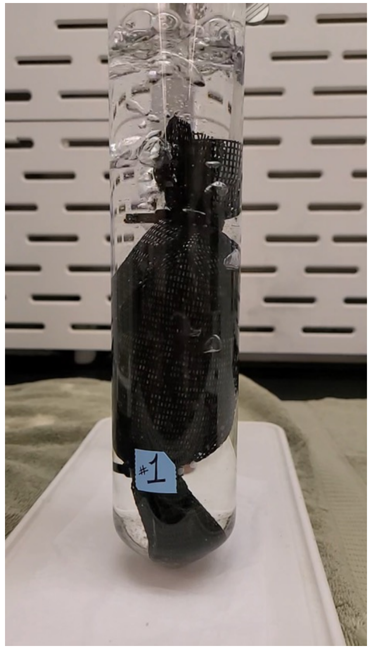
# *Task 3 – $CO_2$ Conversion*

Task Summary - The goal of this task is to demonstrate the "conversion" of $CO_2$ to $Ca^{2+}$ + $2HCO_3^-$ using $CaCO_3$ mineral as a source of DIC with the intent of increasing efficiency and lowering cost of algae culture. This task is based on an existing LLNL/DOE patent, but importantly has not yet been demonstrated for algae growth. In BP2, this task will involve construction of a pilot scale converter for testing with small scale (~100 L) raceway ponds.

Subtask 3.1: $CO_2$ conversion in lab/pilot (Q2-Q4)
A prototype $CO_2$ conversion system will be built in the laboratory and optimized to convert $CO_2$ to $HCO_3$ using $CaCO_3$. This system will be optimized (in absence of algae) and delivered for trials for subtask 4.1

**Milestone 3.1.1 $CO_2$ conversion in lab/pilot – start construction (m, Q3)**
**Milestone 3.1.2 $CO_2$ conversion in lab/pilot – working prototype (DP, Q4)**



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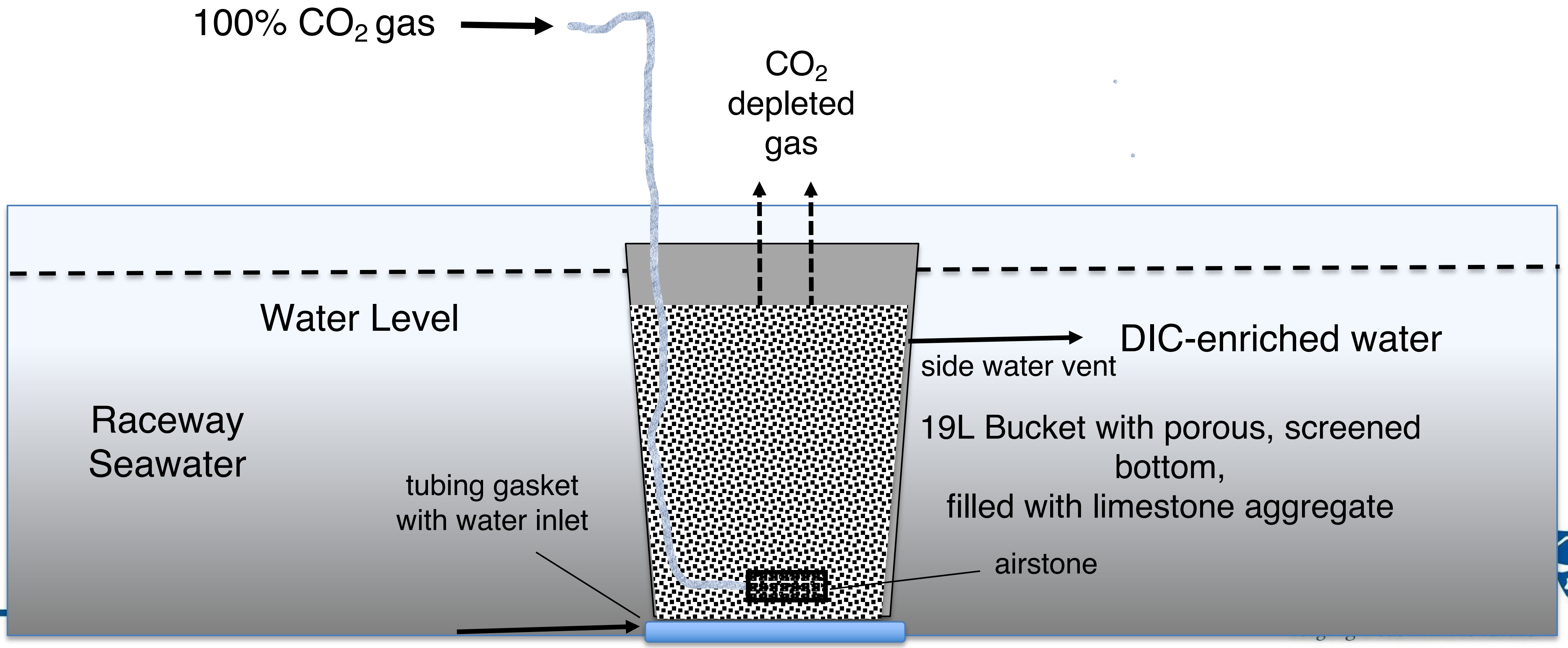
# *Task 3, BP 2: 1000L DIC Generator V2.0*

*refined from earlier trials with other designs and smaller scales*

**Employing this reaction:**

$CO_{2g} + H_2O_{sw} + CaCO_{3s} \rightarrow Ca^{++} + X(HCO_3^{-}) + Y(CO_3^{--}) + Z(CO_{2aq})$

rather than conventionally: $CO_{2g} + H_2O_{sw} \rightarrow H^{+} + HCO_3^{-} + CO_{2aq}$



# DIC Generator Testing:

Fabrication

Deployment in
1000L raceway

Testing and Measurement

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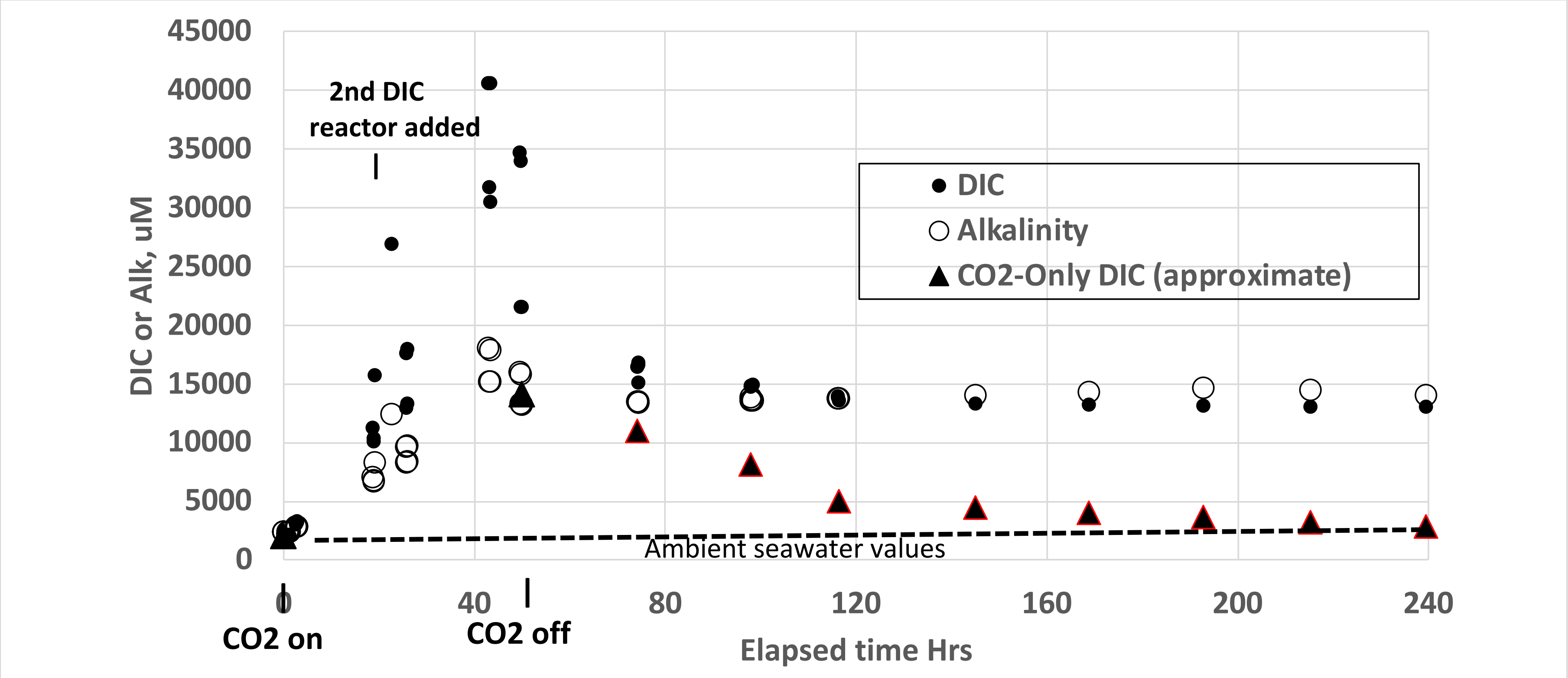
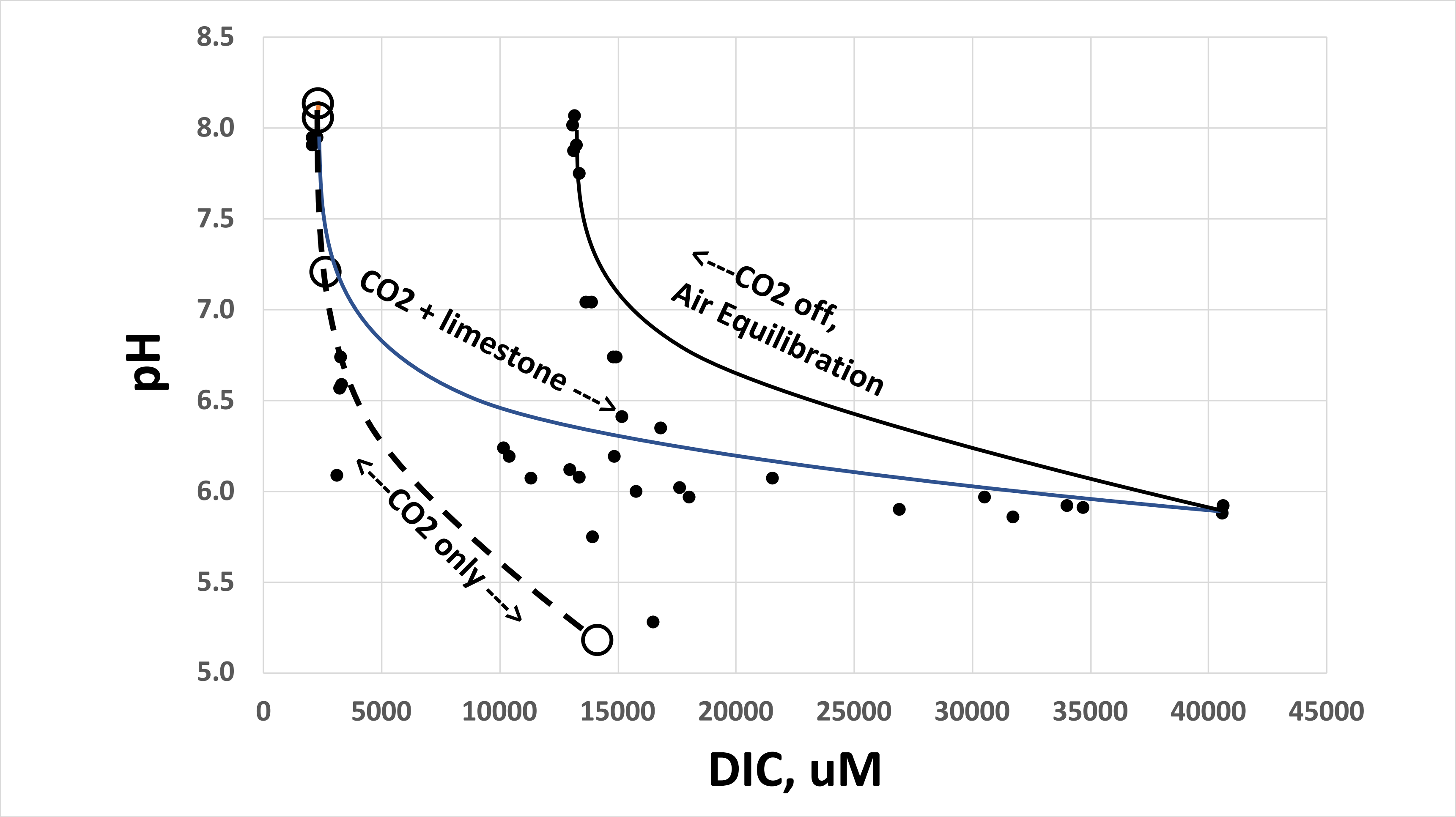
# DIC and Alkalinity Results




1) DIC increased by >12× relative to ambient
2) Much of the DIC is stable with air equilibration
   a. loss to air is limited, unlike $CO_2$-only DIC generation
   b. no evidence of DIC loss via $CaCO_3$ reprecipitation

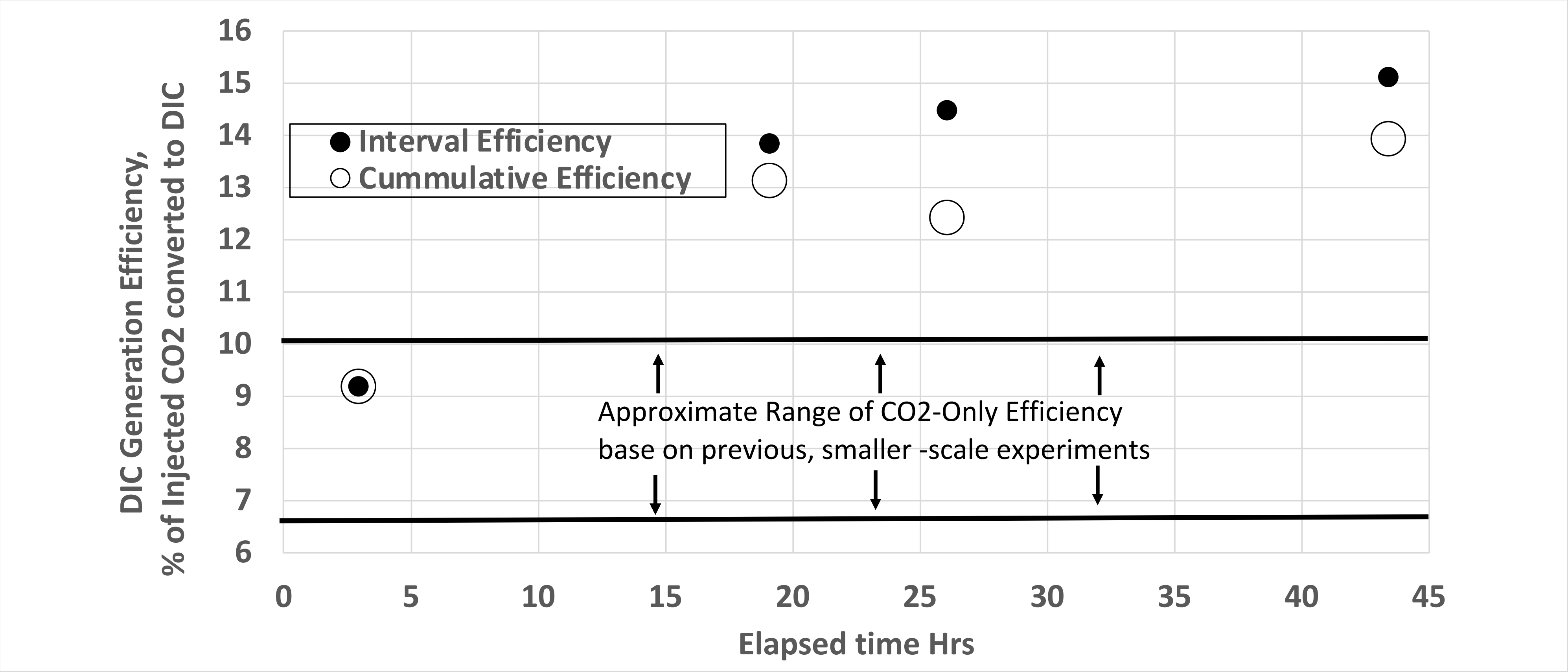
# Evolution of pH and DIC




1) pH depression with increasing DIC is less than in $CO_2$-only DIC generation.

2) Subsequent loss of $CO_2$ to air returns pH values to >= background SW while maintaining elevated DIC, unlike with $CO_2$-only generation.

# Efficiency of DIC Generation Relative to $CO_2$ Input




Efficiency of $CO_2$ → DIC generation is roughly 30% greater with limestone

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# Task 4: Demonstration: testing algae with High-C at ~100 L

Experiment:
Pond 1 = $CO_2$ controlled with pH set point
Pond 2 = Converted $CO_2$ water, no further bubbling/$CO_2$ additions

Hypothesis: high-C pond will grow faster and to higher yield

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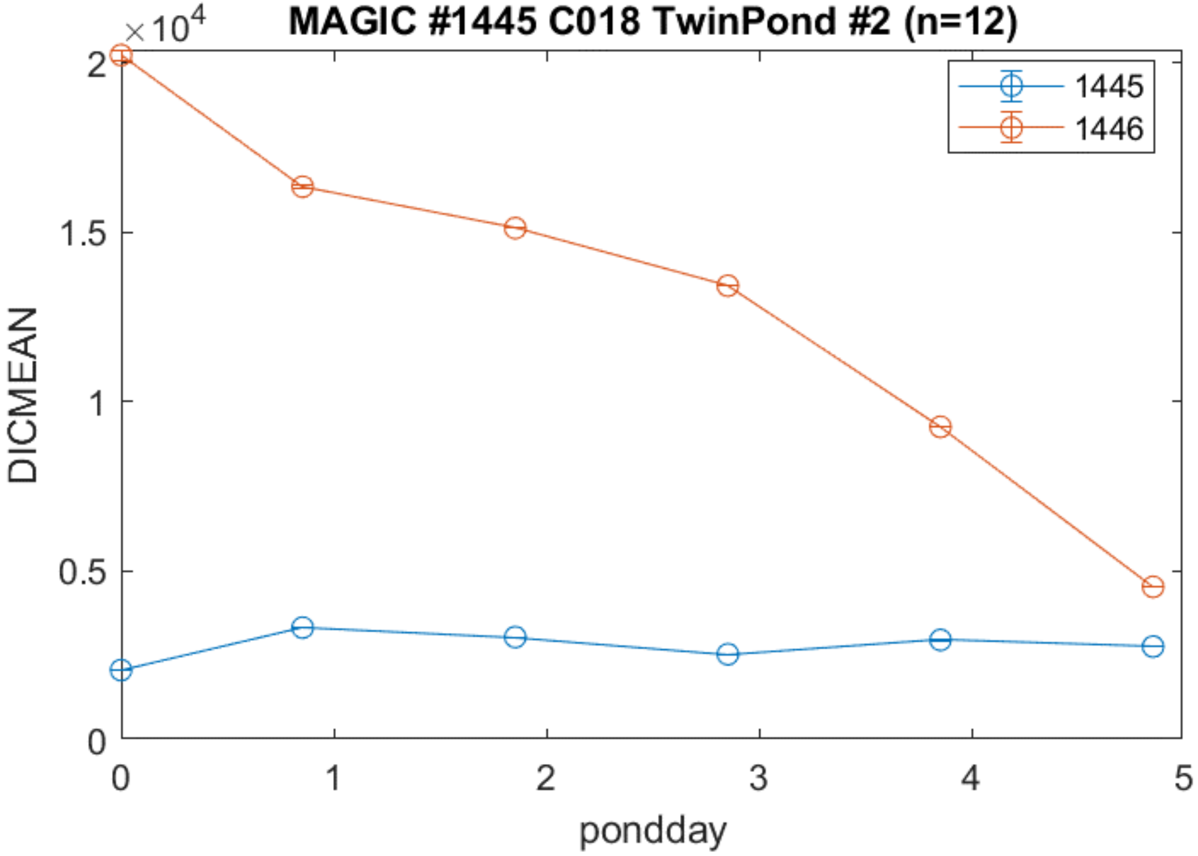
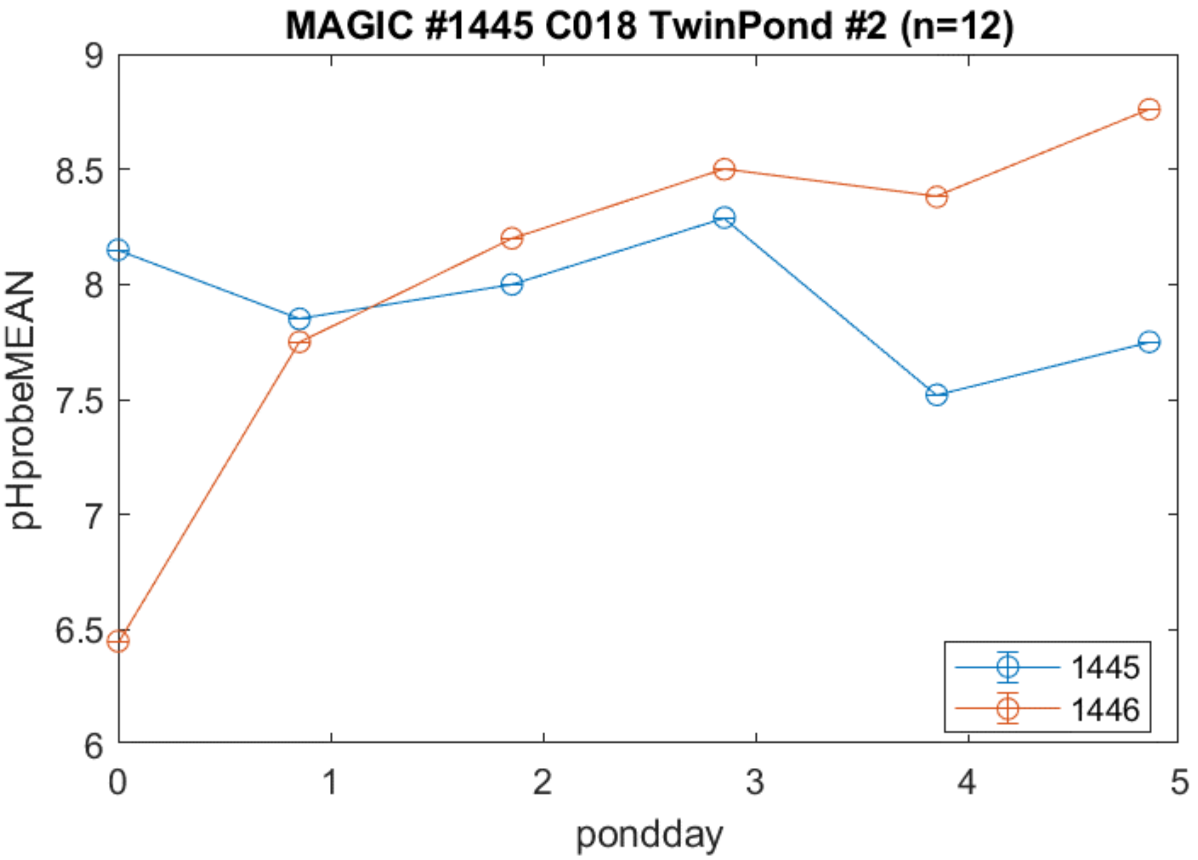
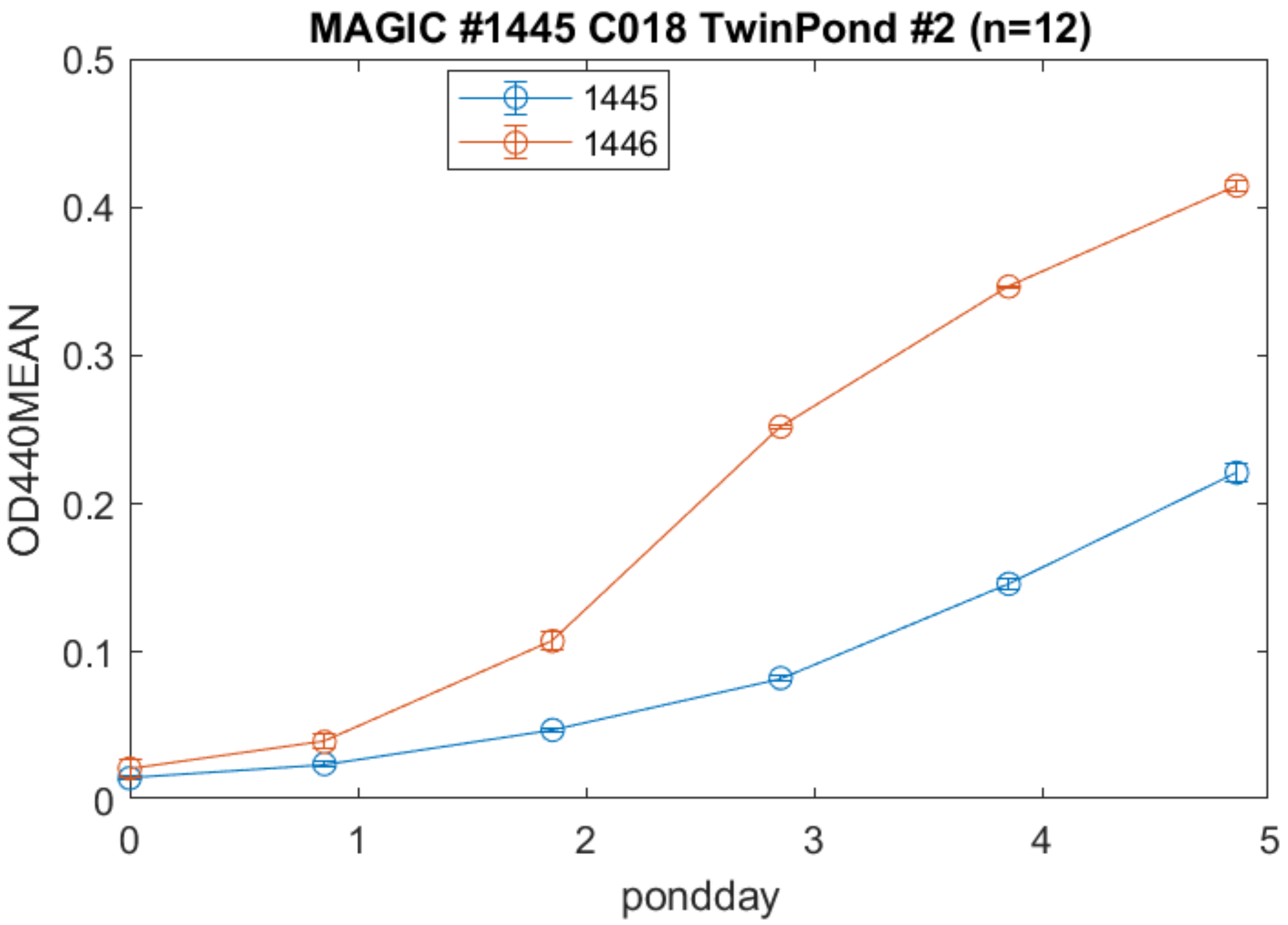
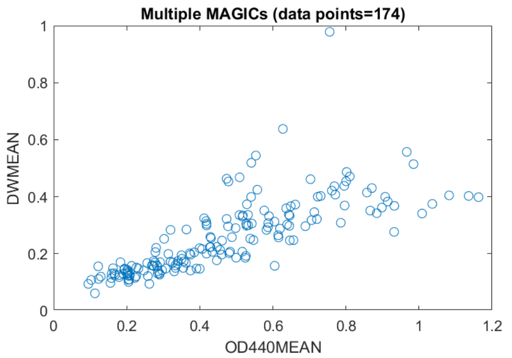



We did not 'equilibrate' high-C water prior to use…

Day 5 TAlk: 1445=2940 μM; 1446=5900 μM

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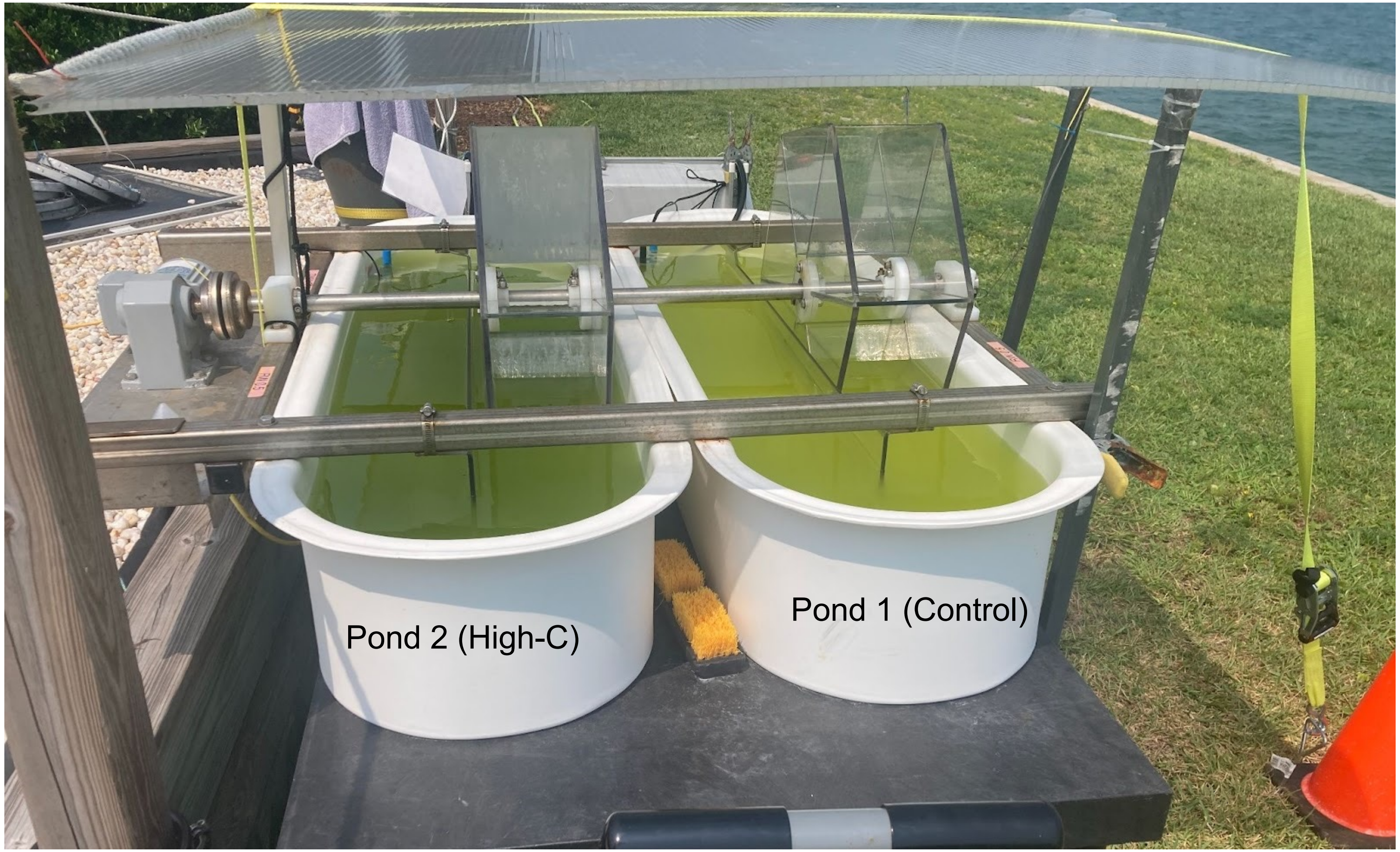
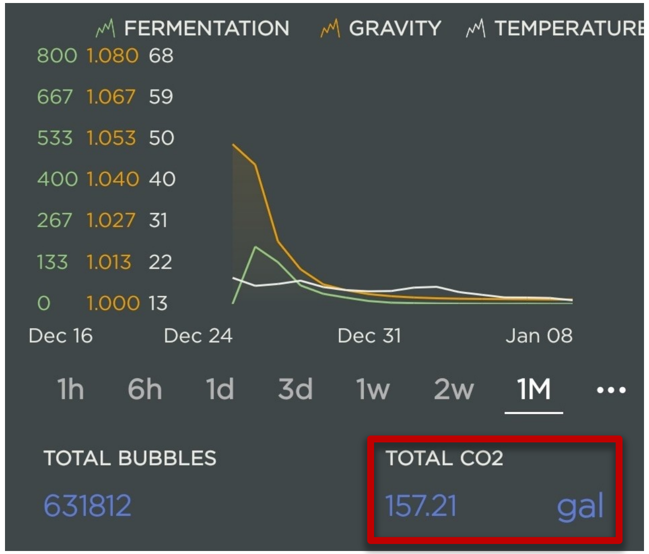



## High-C water improves the growth and yield of algae in the field!

Next step: scale up to ≥1000L

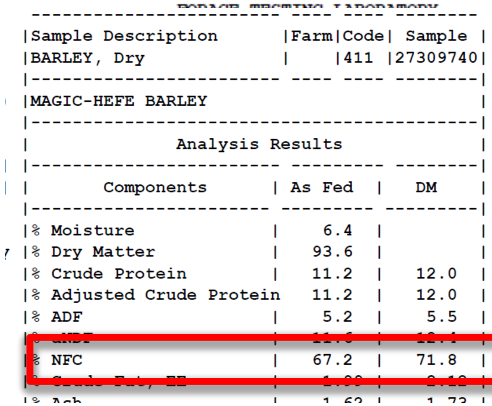
# Task 4: Integration with industry

*Collection of commercial brewery $CO_2$, converting to high DIC solution, growing algae*




~157 gallons $CO_2 \approx$ 0.5 kg C

## Raw grain



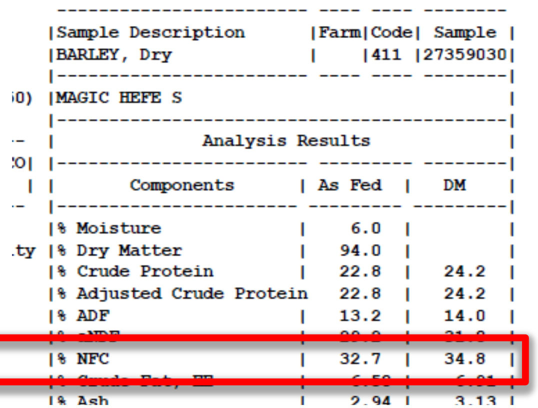
| Sample Description | Farm | Code | Sample |
|---|---|---|---|
| BARLEY, Dry | | 411 | 27309740 |

MAGIC-HEFE BARLEY

Analysis Results

| Components | As Fed | DM |
|---|---|---|
| % Moisture | 6.4 | |
| % Dry Matter | 93.6 | |
| % Crude Protein | 11.2 | 12.0 |
| % Adjusted Crude Protein | 11.2 | 12.0 |
| % ADF | 5.2 | 5.5 |
| % aNDF | [illegible] | [illegible] |
| % NFC | 67.2 | 71.8 |
| % Crude Fat, EE | [illegible] | [illegible] |
| % Ash | 1.62 | 1.73 |

## Spent grain



| Sample Description | Farm | Code | Sample |
|---|---|---|---|
| BARLEY, Dry | | 411 | 27359030 |

MAGIC HEFE S

Analysis Results

| Components | As Fed | DM |
|---|---|---|
| % Moisture | 6.0 | |
| % Dry Matter | 94.0 | |
| % Crude Protein | 22.8 | 24.2 |
| % Adjusted Crude Protein | 22.8 | 24.2 |
| % ADF | 13.2 | 14.0 |
| % aNDF | [illegible] | [illegible] |
| % NFC | 32.7 | 34.8 |
| % Crude Fat, EE | [illegible] | [illegible] |
| % Ash | 2.94 | 3.13 |

4 kg of grain lost ~35% of mass in sugars → ~0.5 kg C

Prototyped a "femtoscale brewery", quantified $CO_2$ release, achieved mass balance with inputs

Next steps: integration with commercial brewery

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# Task 5: ***Commercialization Analysis (TEA/LCA) - GOALS***

Task 5 – TEA/LCA (B&D and Bucknell)
The overall goal of this task is to ground experimental data in a larger commercialization and biofuel development framework to evaluate economic and environmental performance.

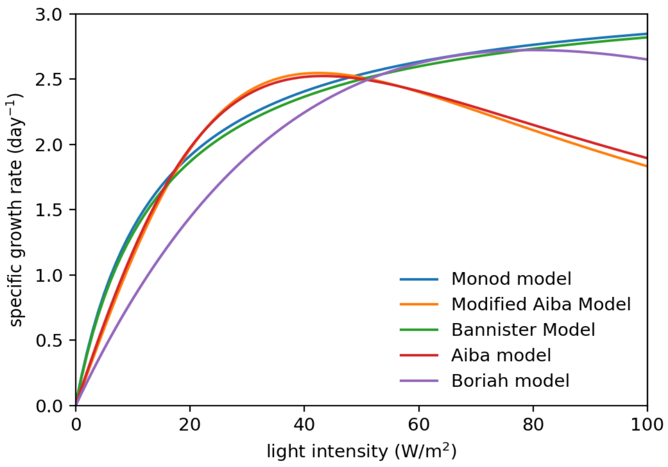
TEA/LCA efforts will focus on integrating $CO_2$ threshold reductions and $CO_2$ conversion results for algae grown at ~5000 L scale for end-to-end demonstration ($CO_2$ waste stream to algae growth).

Milestones: **Pending Final Results from Tasks 2 and 4**
**5.1.1 TEA/LCA integration of milestone 2.1.2 (strain assessment) data (DP, Q6)**
**5.2.1 TEA/LCA integration of milestone 4.1.1 data (DP, Q6)**
**5.3.1 TEA/LCA integration of milestone 4.2.2 data - end (MS, Q12)**
**5.4.1 TEA/LCA integration of milestone 4.3.1 data - end (MS, Q12)**

# Task 5: ***Commercialization Analysis (TEA/LCA) - RESULTS***

## Modeling carbonate chemistry & algal growth (Bucknell)

- Modeled algal growth with different kinetic models with similar results up to light intensities of 40 W/m$^2$
- Used Monod model in subsequent work

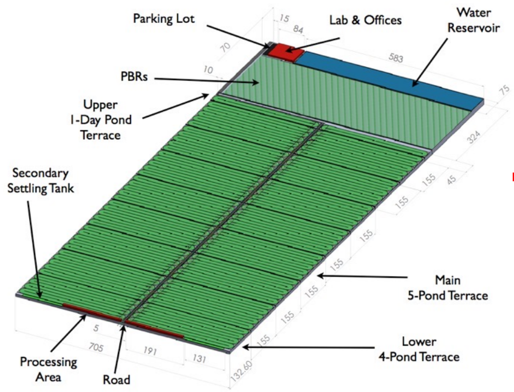


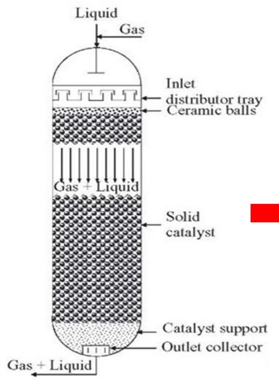

| Model | Equation |
|---|---|
| Monod | $\mu = \mu_{max}\left(\frac{I}{K_I + I}\right)$ |
| Bannister | $\mu = \mu_{max}\left(\frac{I}{(K_1{}^m + I^2)^{\frac{1}{m}}}\right)$ |
| Aiba | $\mu = \mu_{max}\left(\frac{I}{K_1 + I + K_I I^2}\right)$ |
| Modified Aiba | $\mu = \left(\frac{I}{K_1 + K_2 I^2}\right)$ |
| Boriah | $\mu = f(I)\, h(T)$<br>where: $f(I) = \left(\frac{I}{I_s}\, e^{\left(1-\frac{I}{I_s}\right)}\right),\ h(T) = e^{K(T-T_{opt})^2}$ |

## Process Modeling (B&D)

- Evaluated commercial-scale DIC generation through a Trickle-Bed Reactor Design
  - Design was CAPEX intensive (reactors)—leverage existing infrastructure in future solutions

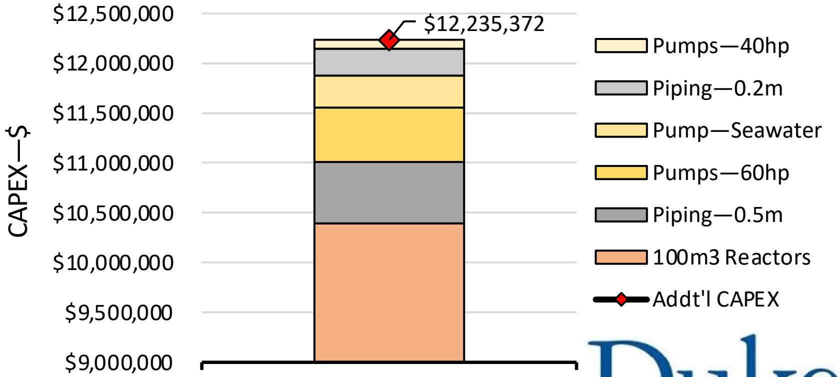
100-ha Algae Production Facility




Trickle-bed reactor (Co-current flow)

TBR–Rocks Design CAPEX Difference




(Additional CAPEX as compared to the baseline design case)

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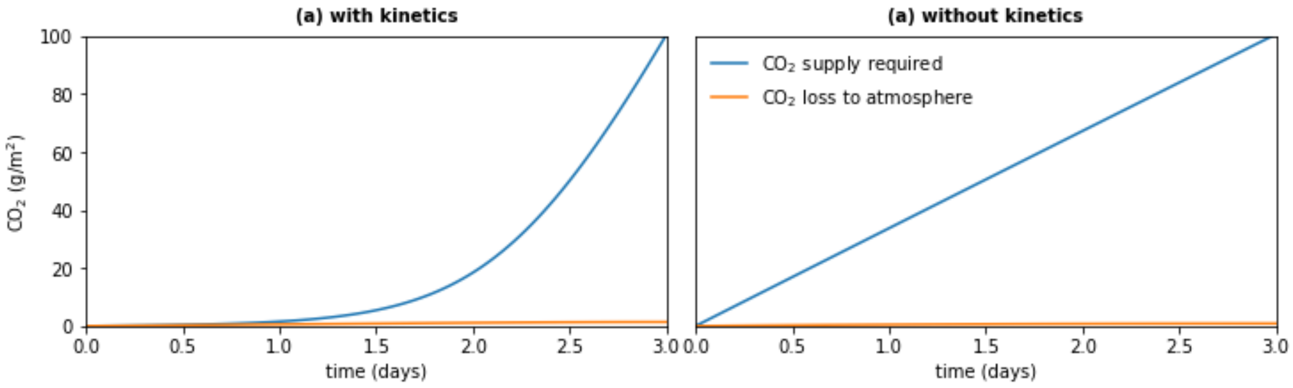
# Task 5: ***Commercialization Analysis (TEA/LCA) - RESULTS***

Modeling carbonate chemistry & algal growth (Bucknell)

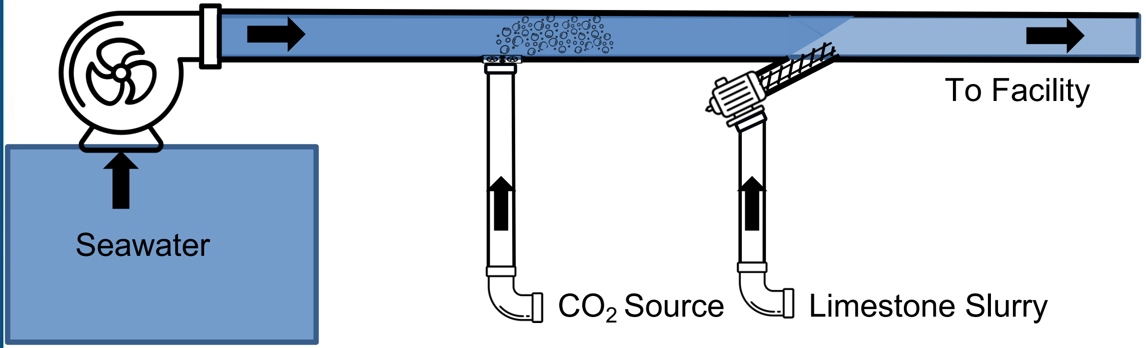
- Modeled carbon loss for models with and without kinetics.
- Assumed pH=8, growth rate= 20 $gm^{-2}day^{-1}$ (for no kinetics)
- $CO_2$ loss is minimized whether constant growth rate, or Monod kinetics used in model.



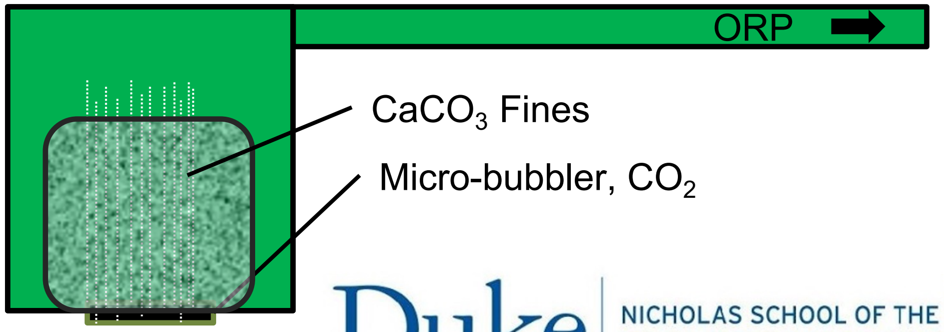

Process Modeling (B&D)

- Ongoing modeling of additional commercial-scale DIC Generation systems
  - Seawater Pipeline Residence Design; generate DIC for facility at supply
  - Sump Ponds Design; generate DIC for facility in ORPs with algae

PipeRes–Fines Design




Sump–Fines Design

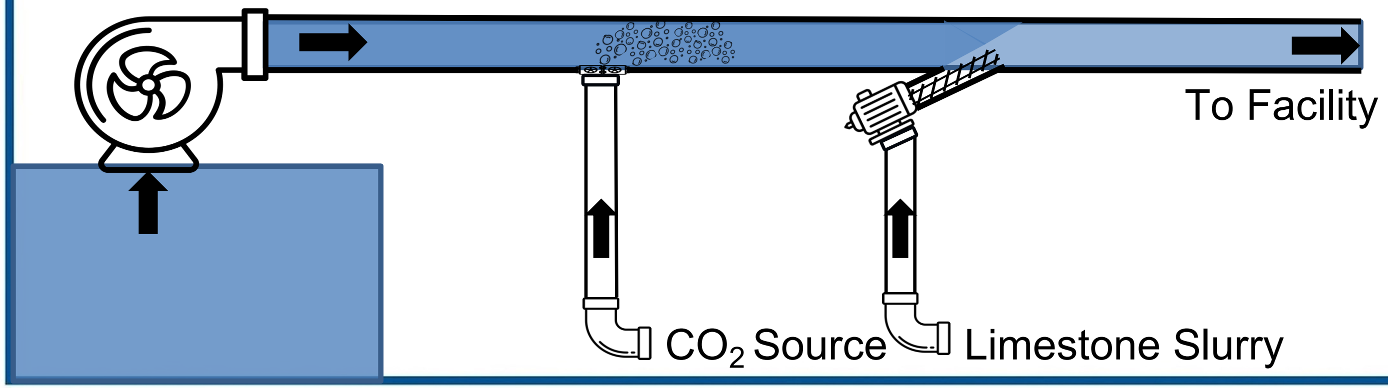


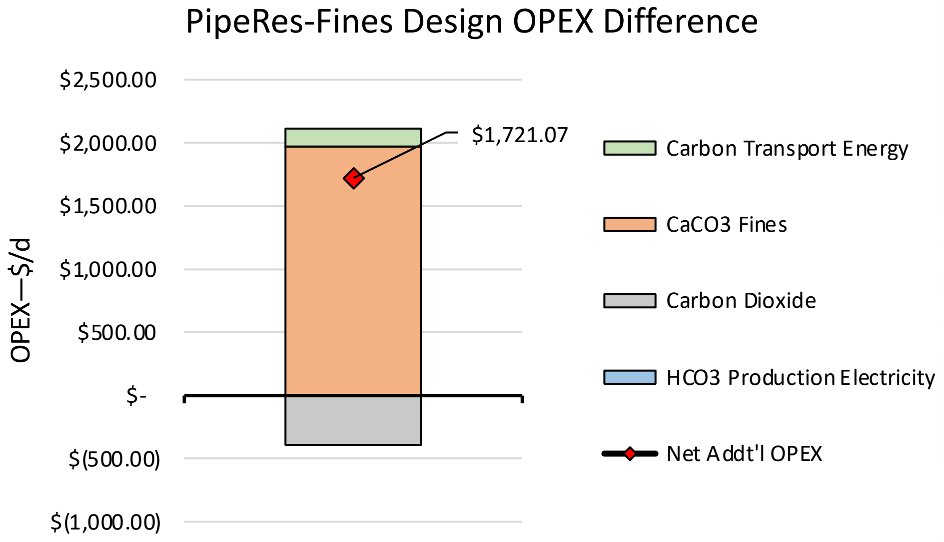
# Task 5: ***Commercialization Analysis (TEA/LCA) - ONGOING***

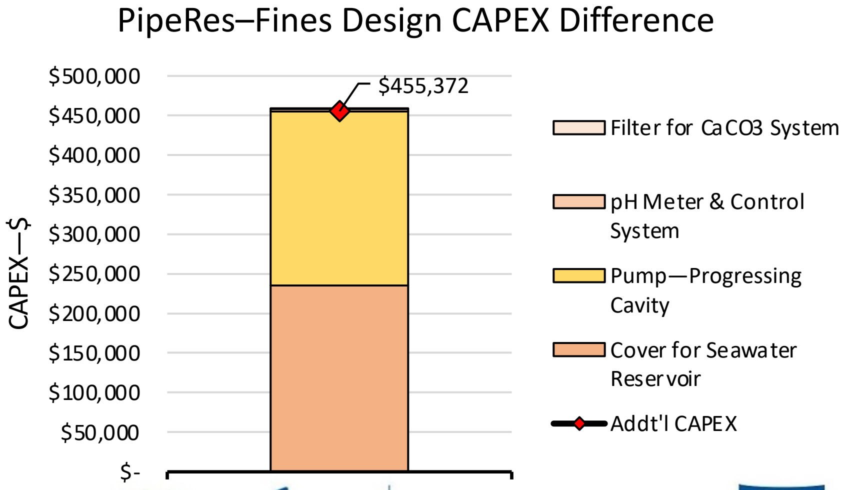
PipeRes–Fines Design

- Leverage seawater supply pipeline as reactor
- Progressing Cavity pump for $CaCO_3$ slurry

| Design Case ID | Modeling Status | CAPEX Total ($M) | Total OPEX ($/d) |
|---|---|---|---|
| Baseline Scenario | Completed | $ 55.41 | $ 8,119.03 |
| TBR-Terr-Rocks | Completed | $ 67.65 | $ 8,952.23 |
| STR-PipeRes-Fines | In Progress | $ 55.87 | $ 9,840.10 |
| SUMP-Pond-Fines | In Progress | $ 56.49 | $ 11,036.43 |
| STR-PipeRes-Rocks | In Progress | | |
| STR-Res-Rocks | In Progress | | |

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# Task 5: ***Commercialization Analysis (TEA/LCA) - ONGOING***

## Sump–Fines Design

- Generate DIC in Sumps on ORPs, with algae
- Question of fouling and growth behavior

| Design Case ID | Modeling Status | CAPEX Total ($M) | Total OPEX ($/d) |
|---|---|---|---|
| Baseline Scenario | Completed | $ 55.41 | $ 8,119.03 |
| TBR-Terr-Rocks | Completed | $ 67.65 | $ 8,952.23 |
| STR-PipeRes-Fines | In Progress | $ 55.87 | $ 9,840.10 |
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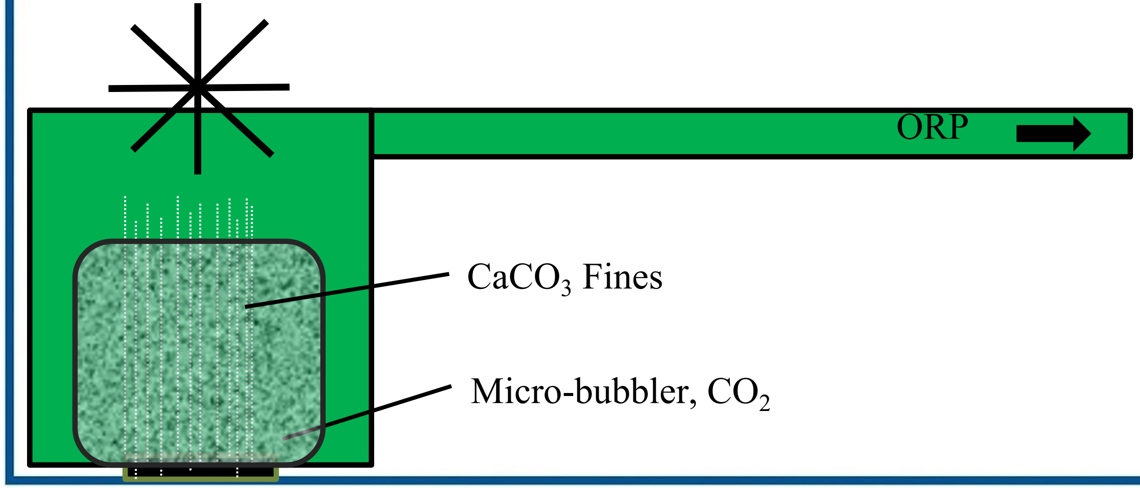


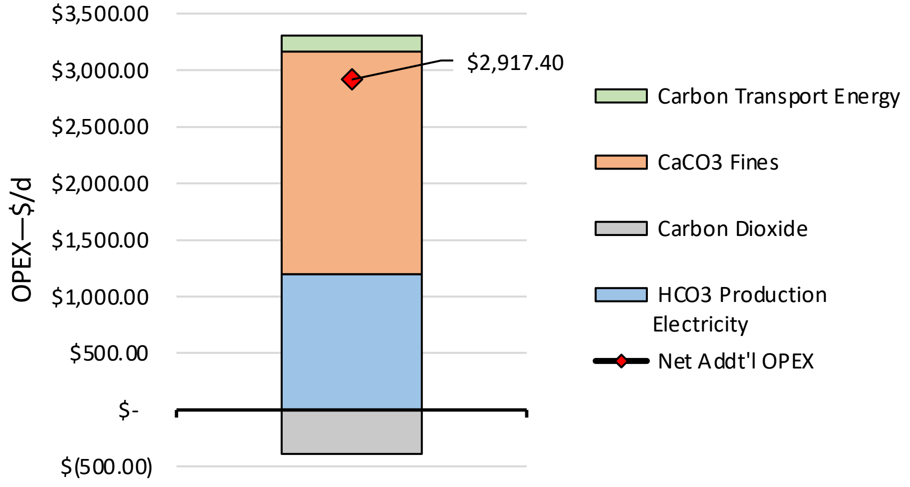


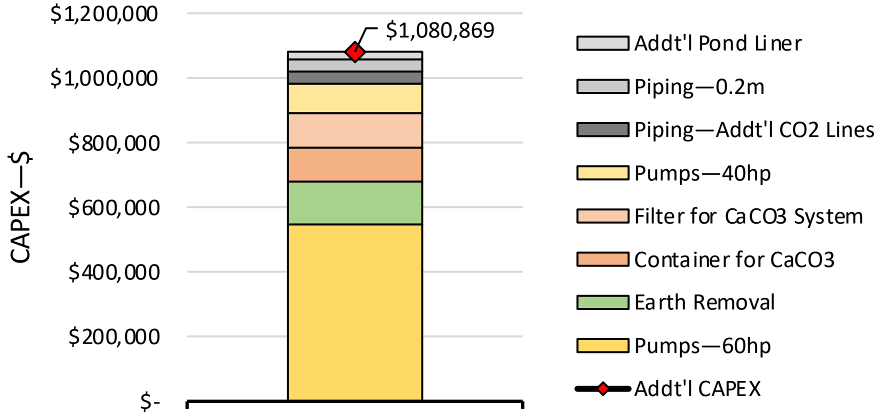


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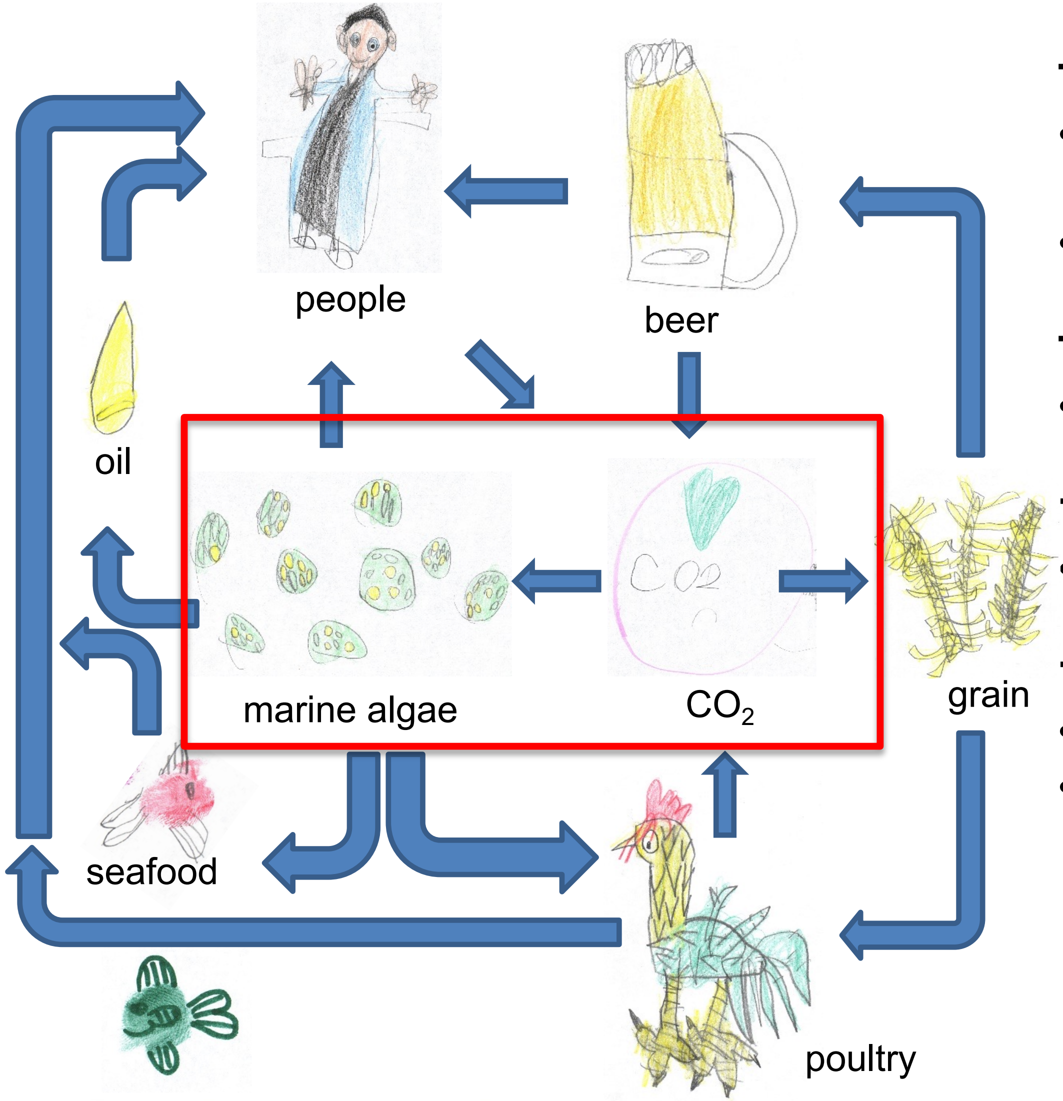
# 3 - Impacts

- **Productivity is the #1 driver of the economics of algae biofuels**
  - *demonstration of productivity enhancement would make algae-derived biofuels more economically feasible*
- **$CO_2$ limits siting of economically feasible algae biofuel production**
  - *Demonstration of conversion of $CO_2$ to $HCO_3$ would provide a $CO_2$ "integrator", expanding locations*
  - *Demonstration of uncoupling of $CO_2$ production and algae use would greatly expand locations*
  - *Identification of strains that have reduced [$\Sigma CO_2$] requirements could greatly reduce (or even eliminate) the requirement for $CO_2$, greatly expanding locations and lowering costs*
- **Results disseminated through peer-reviewed publications and other public presentations**

# MAGIC-C(ircular Carbon) Summary




**Task 2**

- Demonstrated algae strains that grow under reduced $\Sigma CO_2$ environments → **reduced $CO_2$ losses**
- Demonstration of algae uptake and growth on converted carbon → **reduced $CO_2$ losses, enhanced growth**

**Task 3**

- Demonstration of high DIC waters from $CO_2$ + limestone reactor → **reduced $CO_2$ losses, scalable**

**Task 4**

- Demonstration of biogenic $CO_2$ production and quantification (with mass balance) → **scaled, enhanced production**

**Task 5**

- Working model of carbonate chemistry with/without algae
- Process model of algae facility incorporating DIC generation

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# MAGIC-C (EE0008518) - Quad Chart Overview

## Timeline (approved period)

- October 1, 2018
- March 31, 2023

| | FY22 Costed | Total Award |
|---|---|---|
| **DOE Funding** | *$199,479* | $1,511,515 |
| **Project Cost Share** | *$144,185* | $416,780 (22%) |

TRL at Project Start: 3

TRL at Project End: 5

## Project Goals

**Strain assessment of key algae strains -** identify the $pCO_2$ threshold for growth, quantify the growth enhancement on high DIC medium, translate/verify these results in outdoor environment

**$CO_2$ conversion** – demonstration of conversion of $CO_2$ to bicarbonate at multiple scales

**Integrated system** – demonstration of coupled DIC generation (ultimately from industrial $CO_2$) + algae growth

**TEA/LCA** – translation of laboratory and field findings to nth plant design, TEA/LCA of findings to quantify impacts on environment and economics

## End of Project Milestone

Demonstrate enhanced algal growth on high DIC water at industrially relevant scale with a system that has improved environmental impact and economics

## Funding Mechanism

DE-FOA-0001908, Efficient Carbon Utilization in Algal Systems, 2018

## Project Partners

Bucknell

B&D Engineering

UCSC

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# Thank you

Zackary Johnson: zij@duke.edu
http://www.duke.edu/~zij
http://www.ml.duke.edu/webcam/algae/

We're a team!

B&D

Bucknell University

U.S. DEPARTMENT OF ENERGY
EERE #DE-EE0008518

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# Additional Slides

# Publications


Doo SS, Kealoha A, Andersson A, Cohen AL, Hicks TL, Johnson ZI, Long MH, McElhany P, Mollica N, Shamberger KEF, Silbiger NJ, Takeshita Y, Busch DS (2020). The challenges of detecting and attributing ocean acidification impacts on marine ecosystems. ICES Journal of Marine Science. DOI: https://doi.org/10.1093/icesjms/fsaa094

Loftus SE, Hunt DE, Johnson ZI (2020). Reused cultivation water from a self-inhibiting alga does not inhibit other algae but alters their microbiomes. Algal Research 51: 102067. DOI: https://doi.org/10.1016/j.algal.2020.102067

Hall ER, Wickes L, Burnett LE, Scott GI, Hernandez D, Yates KK, Barbero L, Reimer JJ, Baalousha M, Mintz J, Cai W-J, Craig JK, DeVoe MR, Fisher WS, Hathaway TK, Jewett EB, Johnson Z, Keener P, Mordecai RS, Noakes S, Phillips C, Sandifer PA, Schnetzer A, Styron J (2020). "Acidification in the U.S. Southeast: Causes, Potential Consequences and the Role of the Southeast Ocean and Coastal Acidification Network." Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00548

Marra JF, Barber RT, Barber E, Bidigare RR, Chamberlin WS, Goericke R, Hargreaves BR, Hiscock M, Iturriaga R, Johnson ZI, Kiefer DA, Kinkade C, Knudson C, Lance V, Langdon C, Lee Z-P, Perry MJ, Smith WO, Vaillancourt R, Zoffoli L (2020). A database of ocean primary productivity from the 14C method. Limnology and Oceanography Letters. https://doi.org/10.1002/lol2.10175

# Patents, Awards, and Commercialization

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

Algae Biomass Organization Mid-Career Award: PI - Zackary Johnson

**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.

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# Strains Assessed for $pCO_2$ threshold

| | Outdoor | ≥18g/m²/d |
|---|---|---|
| Ocy3 – MAGIC production strain (*Oocystis sp.*) | × | |
| S002 – MAGIC production strain (*Oocystis sp.*) | × | |
| **Pico – SOT strain (Exxon) (*Picochlorum cereli*)** | | x |
| C985 – MAGIC production strain (*Tetraselmis sp.*) | × | |
| C018 – MAGIC production strain (*Nannochloropsis sp.*) | × | x |
| H1117 – MAGIC production strain (*Chlorella sp.*) | × | |
| D046 – MAGIC production strain (*Desmodesmus sp.*) | × | |
| **C046 – Cellana / MAGIC production strain (*Desmodesmus*** | × | × |
| **UTEX646 – SOT Strain (*Phaeodactylum tricornutum*)** | | |
| **C417 – USDA Production strain (unidentified green)** | × | × |

A range of taxa, sources, biochemistries – all were originally targeted as 'biofuel' strains

# Peer Review 2021 Comments Received

**Reviewer Score/Comments:**
Comments: The need for collaboration with both B&D Engineering and Bucknell University in TEA and LCA task do not seem clear. The approach of splitting this work among institutions seems to present unmitigated risk of model discontinuity. The lack of commercial partnerships in the project seems to limit the work to an academic exercise. The use of limestone with high dissolved organic carbon in media seems to be an approach unique to this project. Even knowing that the team's LCA model validates this approach it is conceptually difficult to embrace the active volatilization of sequestered carbon proposed as a component of a carbon capture and utilization strategy. An independent third-party assessment of this technology compared to other state of the art design concepts may be especially useful in this case to help ameliorate this concern. Finding optimal partial pressure for CO2 uptake may have impact for bioreactor design and help pair strains with changeable reactor conditions. nth plant assumptions are typically less impactful than those developed with commercial production partners. TEA and LCA models developed in this project do not seem to directly integrate with models developed by the National Labs or be aligned with commercial partner expectations with any product specificity. Modeling based on existing facilities or with a specific product target add impact to these results. Baseline growth rates and CO2 utilization efficiencies were not reported as defined metrics for this review, so it is difficult to compare the impact of this work to other work done in the portfolio. The only results of this work appear to be models based on bench top experiments. Plans for construction of a pilot scale converter for use in a 100 L raceway pond seem unclear. It does not appear that there is any plan to work with algae in this system during the projects period of performance. End of project milestones seem to lack clear metrics but do not appear close to being met by Sep 30, 2021.

# Peer Review 2021
# Comments Received / Responses

# Comment #1

Comment #1: The goal of this project is to demonstrate enhanced algal growth with overall reduced CO2 requirement at an industrially relevant scale. If successful, the proposed work will have benefits to the algal industry and is well aligned with BETO mission and MYP goals. The team outlined a management plan with a defined task structure and leads leveraging team expertise and previous experiences. They identified risk and outlined mitigation strategies as well as established channels of communication and collaboration amongst team members. The team did not outline measurable goals. It's not clear if the proposed work will result in an increase in biomass productivity over baseline using their strategy since algal strains did not evolve in environments with high DIC levels. Their approach of assessing strains that require low CO2 for growth, growth enhancement on high DIC waters, and developing CO2 conversion process to DIC is reasonable. However, the team should consider providing clarity on how strains will be selected and if selected strains grown on low pCO2 will demonstrate similar or higher biomass productivity compared to current SOT. The team should address how they intend to promote CO2-limestone contact to increase dissolution kinetics at scale using brewery waste water and if this will be a standalone system or integrated with a pond. The team should also consider outdoor testing to validate the proposed integrated process. Overall, progress have been made towards the outlined goals, but there is still some work to do to meet the end of project milestone.

# Response #1

- Dr. Beal and Prof. Sills have been co-authors on 7 peer-reviewed manuscripts over the span of 6 years. While working across institutions can present challenges, overall this risk is managed.
- A private company is part of our team, and overall the project is an investigation of a commercially-promising system to grow algae.
- This project does not involve carbon capture. The use of $CaCO_3$ was proposed because it's cheaper than conventional $CO_2$. Every carbon source has different LCA implications. The fossil carbon contained in $CaCO_3$ that is used to grow algae and eventually released during combustion/metabolism is included in our LCA. We are currently working on a TEA/LCA analysis that will directly compare the impacts of a range of carbon sources (power plant flue gas, pure $CO_2$ flue gas, EOR pipeline $CO_2$, bottled chemical plant $CO_2$, limestone, etc.) and energy sources (grid, solar, wind, etc.) and intend to publish the results by 2022. (FYI – our proposal reports the GHG impact for this system to be 3.2kg $CO_2e$/kg algae, which is huge – about 10X more than soybeans. The fossil carbon from $CaCO_3$ was the largest source of these emissions. However, we also assumed brewery $CO_2$ with no LCA impact for half of the carbon and our baseline case assumed fossil carbon from a pipeline, which was even worse. Using flue gas or DAC C would be lower GHG.)
- The above referenced manuscript in preparation will address concerns about transparency and be reviewed by multiple "third parties" (i.e., reviewers) similar to our publications.
- The National Labs have developed numerous TEA/LCA models for algal biofuels, spanning a huge range of cultivation conditions, conversion methods, and upgrading processes to produce a range of fungible fuels in a variety of scenarios. However, several of the NREL algae models are actually partially based on our models, such as Clippinger and Davis, Techno-Economic Analysis for the Production of Algal Biomass via Closed Photobioreactors, NREL, 2019. or Davis et al., Process Design and Economics for the Production of Algal Biomass, NREL, 2016.
- Modeling a lab facility can be useful for informing commercial models, but yields results that are not representative of commercial production. The specific product that we are targeting is high-quality algal biomass for fuels and feeds.
- We are on track to meet our milestones by Sept 2021.

# Comment #2

Comments: The project presentation provides nice detail and supporting information that documents their achievements and progress towards project goals and end of project milestones. It is not clear if practical strains were tested in high DIC media. Additionally much of the experimentation was conducted using limestone as a generator for DIC without the practicality of using limestone for the same purpose at any relevant commercial scale. The implied outcome still requires some co-located industrial source for reliance of CO2 or CO2 conversion. The project clearly achieves many of its goals but additional work is likely needed to achieve the end of project milestone demonstrating enhanced algal growth on high DIC water at an industrially relevant scale.

# Response #2

Both (1) identification of strains that grow on low pCO2 and (2) enhancement of growth on high DIC waters were identified as goals in the presentation.  The presentation included preliminary results, and progress, on both milestones (slides 6 & 7). All strains tested were downselected from promising biofuel candidate strains identified by us and other groups (e.g. DISCOVR).

Thank you for the additional comments on CO2 conversion. We are actively pursuing approaches to optimize this system for integration with commercial scale CO2 sources (e.g. brewery).

# Comment #3

Comments: The aim of this project is to demonstrate enhanced algal growth with reduced $CO_2$ requirement at scale. The team and management approach described are appropriate for this project. The presentation did not provide a description of progress to be achieved through tasks, milestones and go/no go decision points, providing an inadequate assessment of progress for the project. The presentation would have benefited from a discussion of risks and mitigation strategies. The approach was described based on four major tasks for strain assessment in high alkalinity systems, $CO_2$ conversion to bicarbonate using a $CaCO_3$ starting bed, demonstration of the system, and TEA/LCA modeling. The use of a carbonate bed to enhance $CO_2$ dissolution into bicarbonate is innovative and unique. The presentation would have benefited from a more logical approach by discussing the water chemistry right away and how the carbonate bed catalyzes the dissolution of $CO_2$, and then discussing what is known of strain stability under these conditions. The impacts discussion was limited to justifying the work. This can be enhanced through a broader discussion of $CO_2$ sources envisioned and impacts on emissions, along with impacts to the BETO and DOE goals in productivity enhancements, etc. Progress for the project is underway and appropriate as it is at initial stages. The strain assessment is in process. The discussion would benefit from more specifics as to what strains are being looked at and extensiveness of the search. Water chemistry in a carbonate bed and a bicarbonate generation system are being developed, along with the collection of $CO_2$ from brewery systems. They are modeling expected losses of $CO_2$ in large scale farms.

# Response #3

We agree that the bulk of our experiments to-date have been at laboratory scale. This is by design - to develop and refine the process, then scale-up in the second half of the project to demonstrate the process at a commercially relevant scale. This approach was taken to minimize risk.

# Comment #4

Comments: Goals are clearly stated, and communications including data sharing and task assignment are well defined. It would have been helpful to see more about the project team's roles and responsibilities. The mass balance seems counter to the funding agency goals: instead of removing CO2 from the air, this project will result in adding more CO2 to the air. Even assuming some can be recaptured, the end process will be inefficient and result in releasing more CO2 that is currently sequestered underground. The goal of being able to cultivate algae in areas where there is no flue gas, brewery waste carbonic acid or other carbon capture technology in place is clearly tied to the research, but ideally this would done via direct air capture, as opposed to feeding mined materials. This needs at least a plan to trial outdoors in open ponds; the diagram seems to indicate a closed system, which has serious consequences for the TEA if it cannot be run in raceways or open ponds. Although the need for flue gas has been decoupled, the effort is still coupled to brewery activities at the moment.

# Response #4

As above, milestones were specifically articulated in the presentation. We agree that we did not go into the specifics of strains or water chemistry in the presentation - there simply was not enough time to detail the list of strains, each of their specifics, and so on. We look forward to discuss the details of this results at future meetings or in publications.

# Comments #5

Comments: Goals are clearly stated, and communications including data sharing and task assignment are well defined. It would have been helpful to see more about the project team's roles and responsibilities. The mass balance seems counter to the funding agency goals: instead of removing CO2 from the air, this project will result in adding more CO2 to the air. Even assuming some can be recaptured, the end process will be inefficient and result in releasing more CO2 that is currently sequestered underground. The goal of being able to cultivate algae in areas where there is no flue gas, brewery waste carbonic acid or other carbon capture technology in place is clearly tied to the research, but ideally this would done via direct air capture, as opposed to feeding mined materials. This needs at least a plan to trial outdoors in open ponds; the diagram seems to indicate a closed system, which has serious consequences for the TEA if it cannot be run in raceways or open ponds. Although the need for flue gas has been decoupled, the effort is still coupled to brewery activities at the moment.

# Response #5

Thank you for the comments - team member roles were described in slide 3 under management/structure.  The goal of this FOA was to utilize carbon more efficiently and grow algae with higher productivity. In this project, we are not using DAC or other approaches to minimize the carbon footprint. In another project, we are specifically addressing the use of DAC in combination with carbonate/bicarbonate conversion. Our initial results suggest that this will indeed reduce the overall use of fossil carbon.  Outdoor tests will be done using raceway style open ponds to ensure translation of results to large scale facilities.