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"Modeling and Harvesting Optimization of Nannochloropsis oceanica Growth in Seasonal Algae Testbed Unified Field Studies"

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ATP³ Algae Testbed Public-Private Partnership

Strain Identification & Isolation › Analytical Services › Biomass Production & Supply › Equipment Testing › Education & Training

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ATP^3's Two Main Objectives

Collaborative Open Testbeds

- Establish **network** of facilities for algal researchers and **increase access** to real-world conditions for algal biomass production.
- **Accelerate** applied algae research, development, investment, and commercial applications.

High Impact Data from Long Term Algal Cultivation Trials

- Design and implement a unified experimental program across **regional, seasonal, environmental and operational conditions** comparing promising production strains at meaningful scales.
- **Data made widely available** to the TEA/LCA and overall research community.

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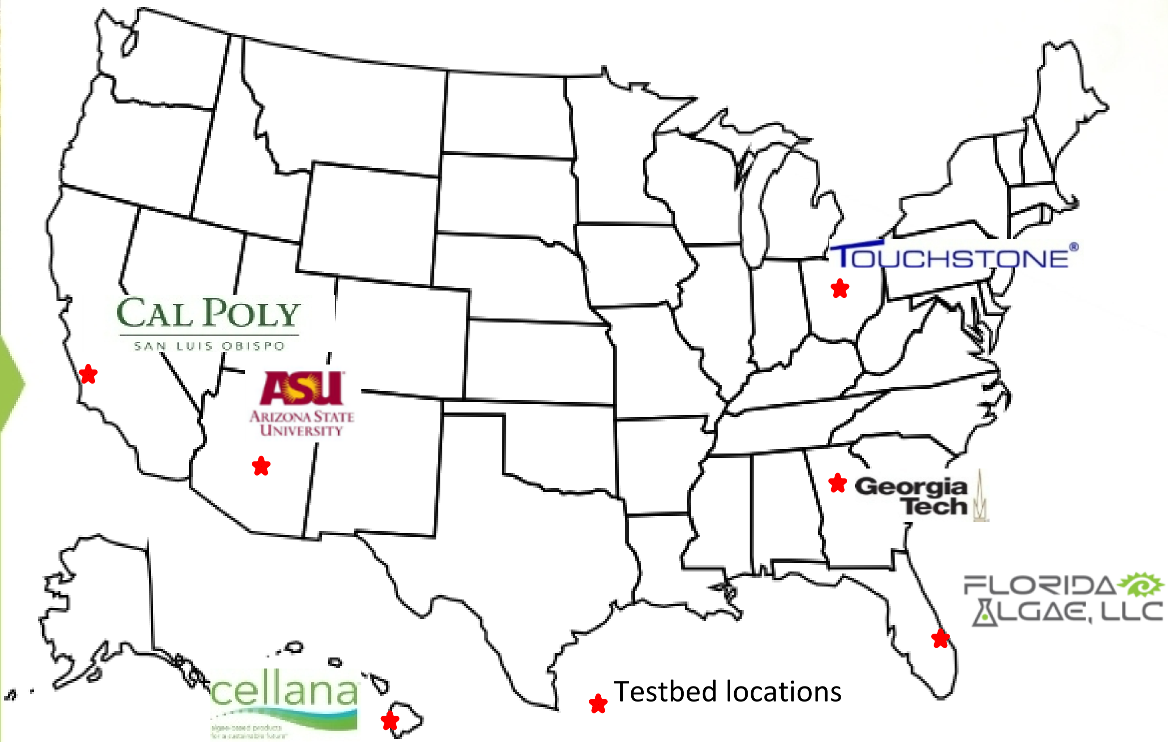
Collaborative Open Testbeds

Year 1: Establish standard processes, harmonize methodologies, and conduct initial cultivation trial.

Year 2-3: Implement long term cultivation trials.

Year 4-5: Sustainable testbed operations.



Regional testbed facilities for the partnership are physically located in **Arizona, Hawaii, California**, **Ohio, Georgia, and Florida.**

High Impact Data:
Long Term Algal Cultivation Trials

Set standards and conduct harmonized, rigorous, and objective long term cultivation trials to provide a realistic assessment of the state of technology for algal based biofuels and bioproducts.

- Unified Field Studies (UFS) at 6 testbed sites and Advanced Field Studies (AFS) enable comparison of promising production strains at meaningful scale across variable conditions
- Scientific Data Management System and validated, harmonized SOP's for analytical and production processes ensure data integrity across all sites
- Our data from the UFS and AFS will be made publicly available and provide a critical resource to TEA and LCA analysis yielding **high impact, validated data**





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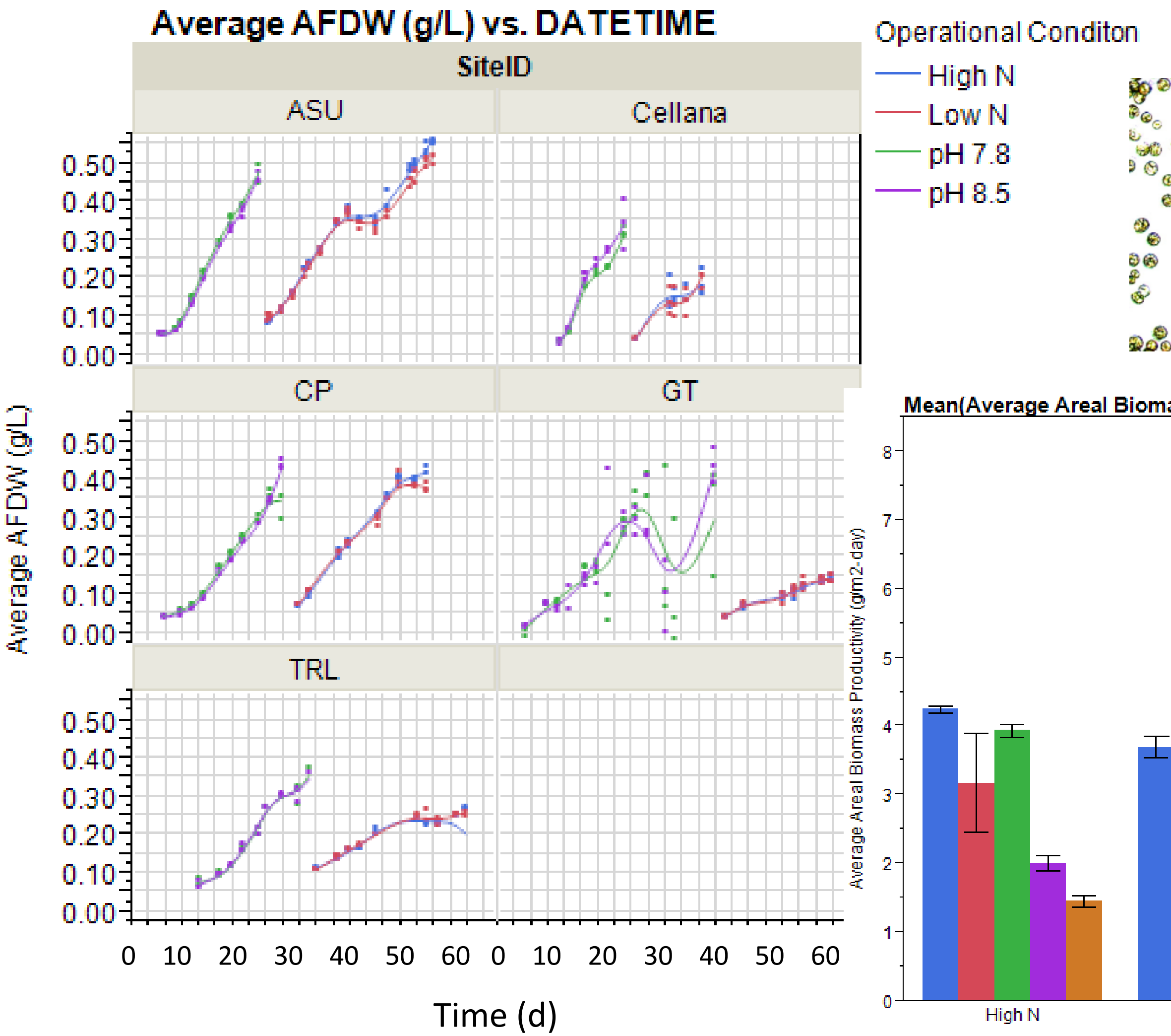
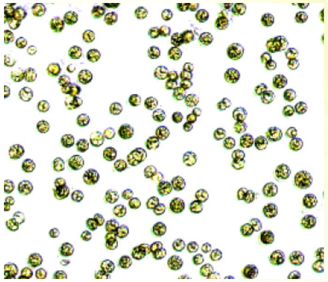
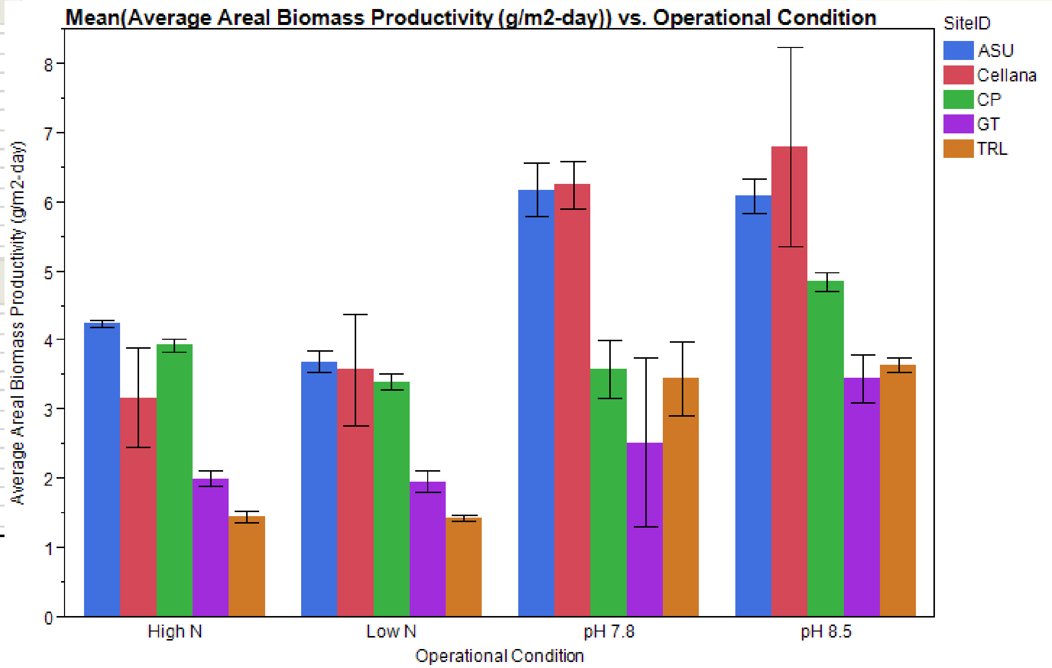
Production Harmonization Progress:

Initial Baseline Verification of Mini-Ponds – Productivity



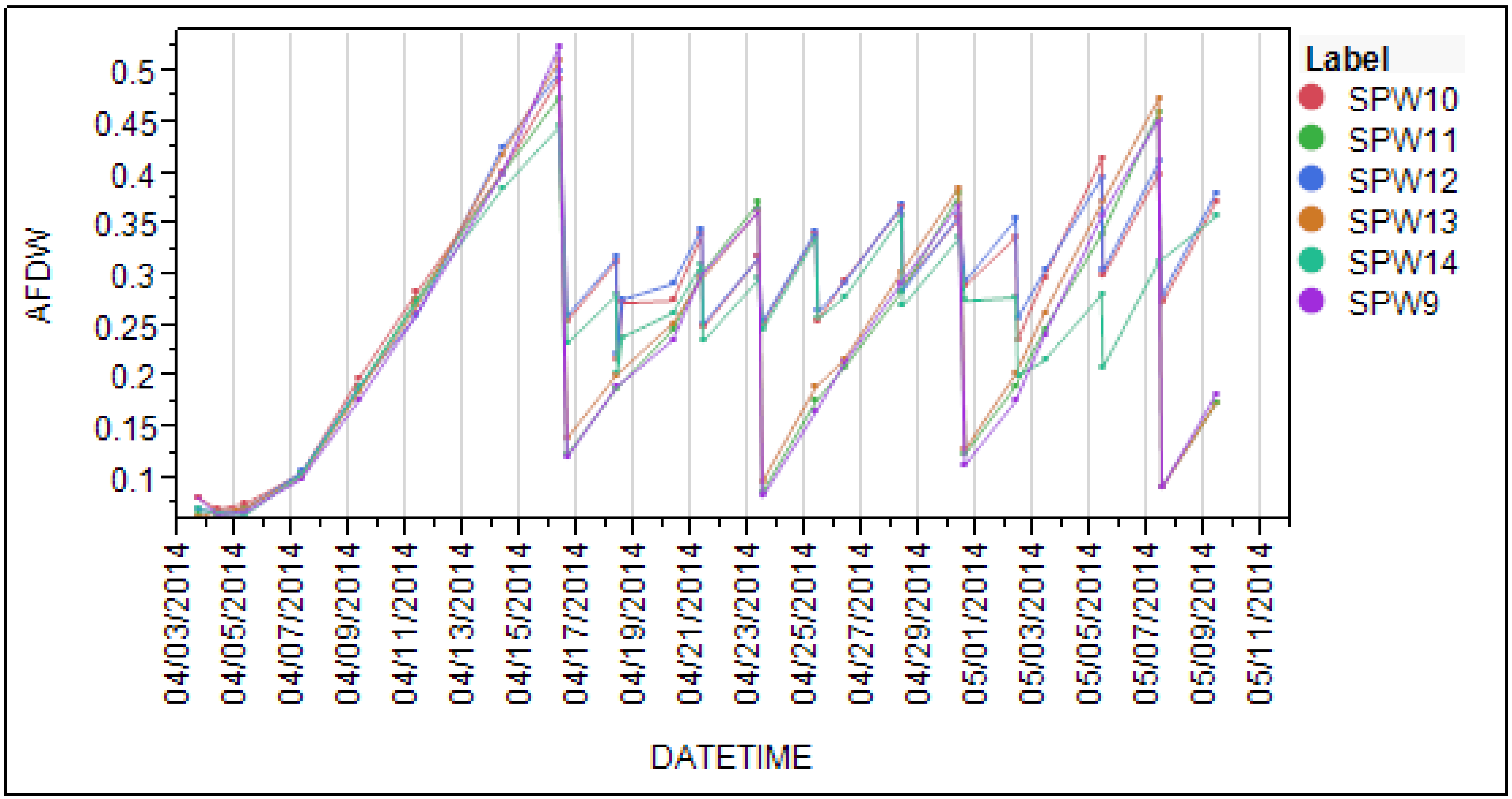


Nannochloropsis Oceanica (KA32 – Cellana)



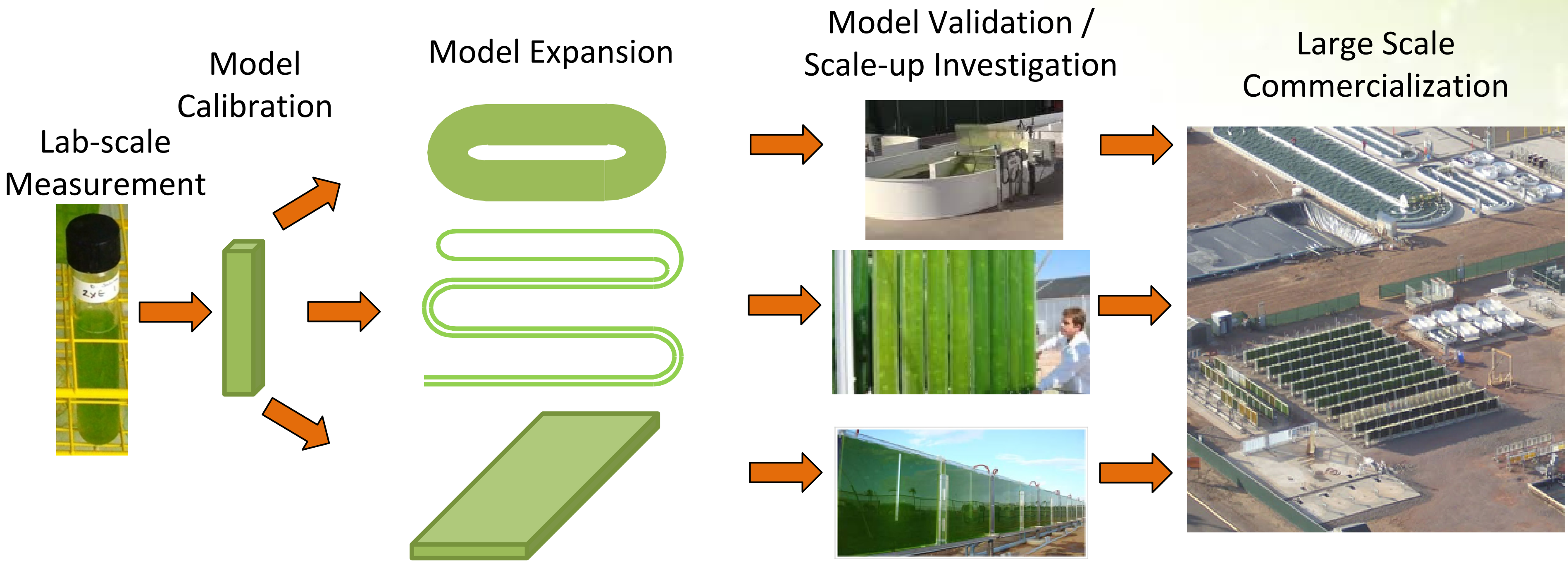
Spring 2014 UFS: Batch vs Semi-continuous Cultivation

Spring 2014 UFS: Batch vs Semi-continuous Cultivation



We Need Models!

- We need to be able to optimize algae growth and lipid production in large commercial scale systems
- It is too time consuming and expensive to test various solutions on a commercial scale
- A computational model facilitates faster and cheaper optimization



Lab-scale measurement and model images

Algae cultivation systems

Algae Growth Model Overview

Predict algae production based on:

- Algae strain
- Light intensity (depth dependent)
- Temperature
- Nutrient concentration (N, P, and CO_2)
- pH
- Salinity
- Respiration

Governing Equation:

- Biomass concentration, B
- Production rate, P
- Basal metabolic rate, B_M
- Predation rate, P_R
- Biomass source or sink, B_L
- Maximum instantaneous production rate, P_{max}
- Productivity Limitation functions, $f_{1\text{-}5}$

$$\frac{\partial}{\partial t}B(\mathbf{x},t) = (P - B_M - P_R)B(\mathbf{x},t) + \frac{B_L}{V}$$

$$P = P_{\max} \cdot \left[f_1(v) f_2(I) f_3(T) f_4(S) f_5(pH)\right]$$

$$f_3(T) = \begin{cases} \mathrm{e}^{-k_{T1}(T - T_{opt,1})^2} & T \le T_{opt,1} \\ 1 & T_{opt,1} < T \le T_{opt,2} \\ \mathrm{e}^{-k_{T2}(T - T_{opt,2})^2} & T > T_{opt,2} \end{cases}$$

$$f_2(I) = \frac{e}{Kess \cdot \Delta z}\left(e^{-\alpha_B} - e^{-\alpha_T}\right)$$

$$\alpha_B = \frac{I}{I_{opt}} e^{-Kess(H_T + \Delta z)}, \quad \alpha_T = \frac{I}{I_{opt}} e^{-Kess \cdot H_T}$$

$$Kess = K_{e,b} + K_{e,B} B$$

Gharagozloo, et al, J. Appl. Phycol. 2014

$$B_M(T) = B_M(T_0)\exp(K_{TB}(T - T_0))$$

Model Has Multiple Fidelities

CFD handled by ANSYS-FLUENT

Levels of Model Fidelity

- Simple single cell fully mixed for light and temperature
- 1D light and/or temperature with depth
- 2D conditions varying with depth and along raceway including flow.
- 3D with flow, varying conditions

Considerations

- Evaporation
- Heat transfer/Radiation
- Fluid dynamics
- Boundary and initial conditions
- Wind
- Settling
- Nutrient and dissolved gas transport

Model Validated – *Nannochloropsis salina* Lab/Greenhouse/Raceway

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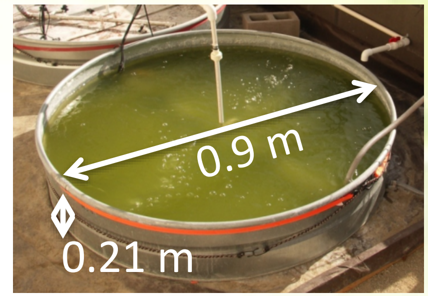
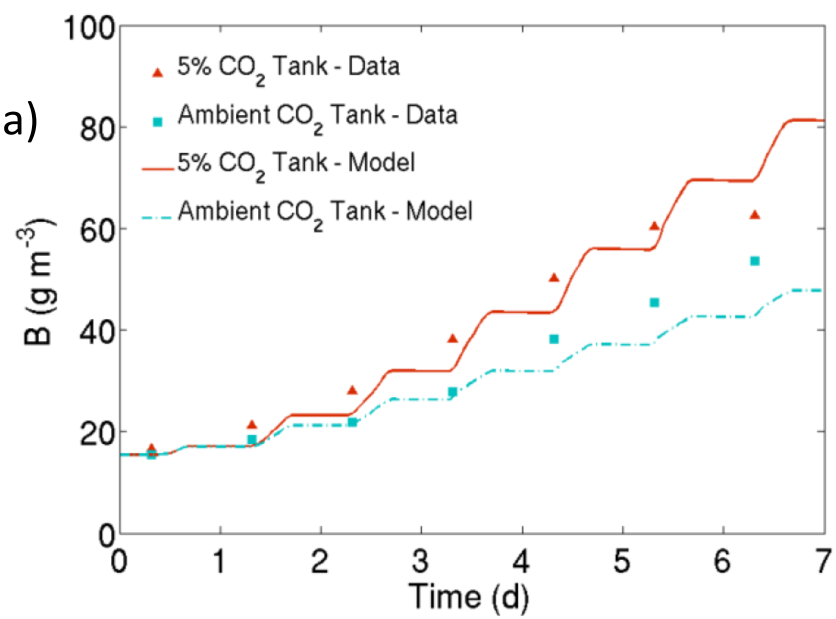
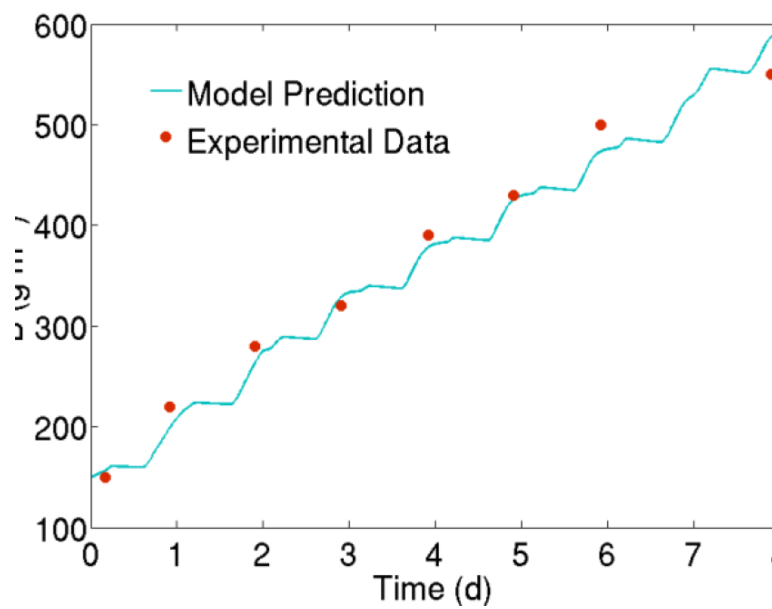
- Model calibrated in the laboratory.
- Validated by comparison to greenhouse tank and outdoor raceway.



(a) Greenhouse tank – simple model with CO_2 limitation
(b) Outdoor raceway – 1D light and temperature model

(a)





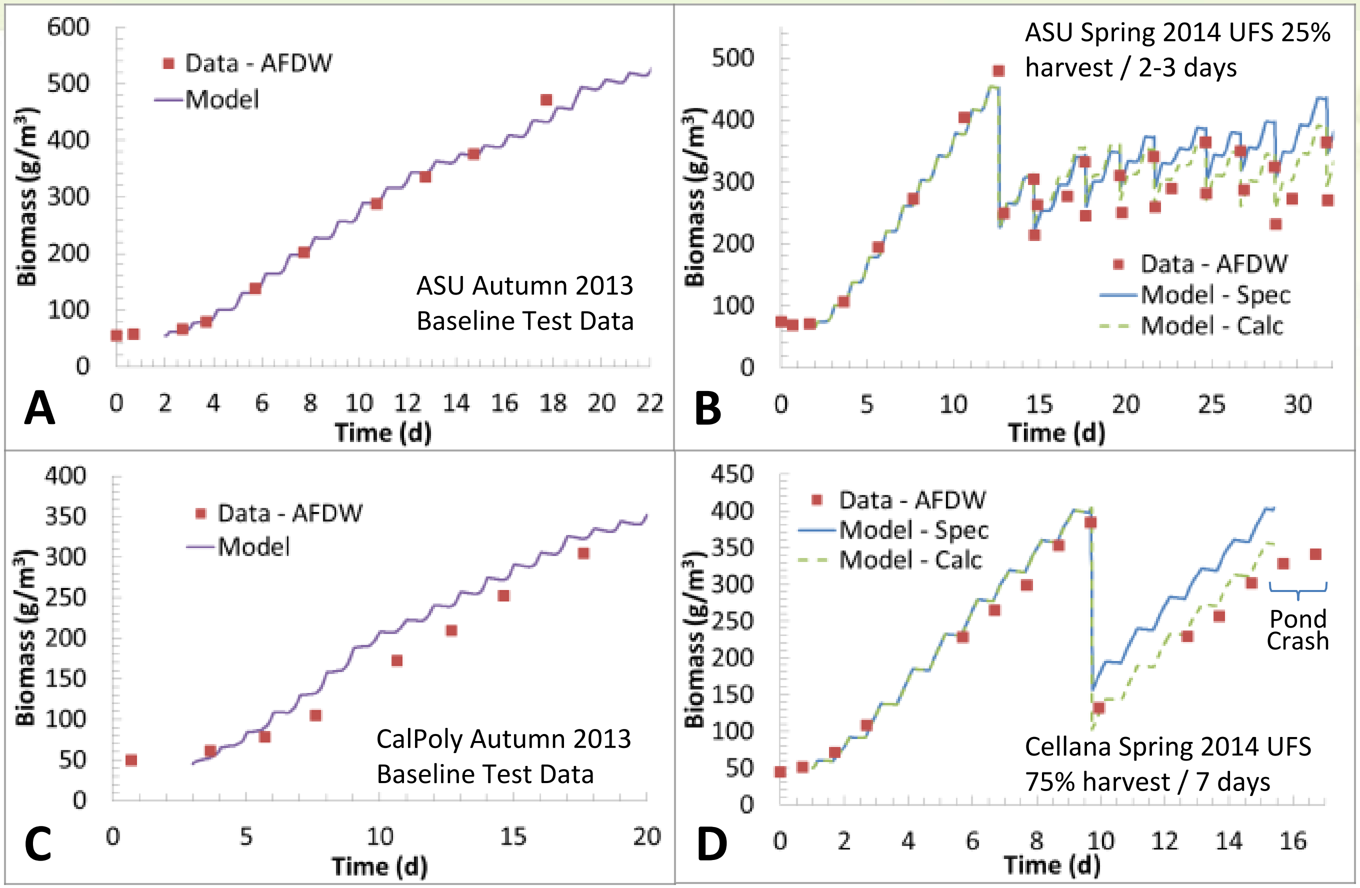
(b)

Gharagozloo, et al, J. Appl. Phycol. 2014

Initial Field Study Model Calibration – *Nannochloropsis oceanica*

Parameter	Value
Light extinction coefficient, $K_{e,B}$	0.216 m^2/g-Biomass
Minimum optimum PAR adjusted solar radiation, I_{opt}	20 W/m^2 (100 μmol photons/m^2/s)
Lower optimal temperature, T_{opt}	25 °C
Temperature effect coefficient, k_T	0.009 $°C^{-2}$
Maximum instantaneous productivity, P_{max}	2.2 1/d
Basal metabolic rate, B_M	0.02 1/d

Model Validated for Multiple Locations and Seasons



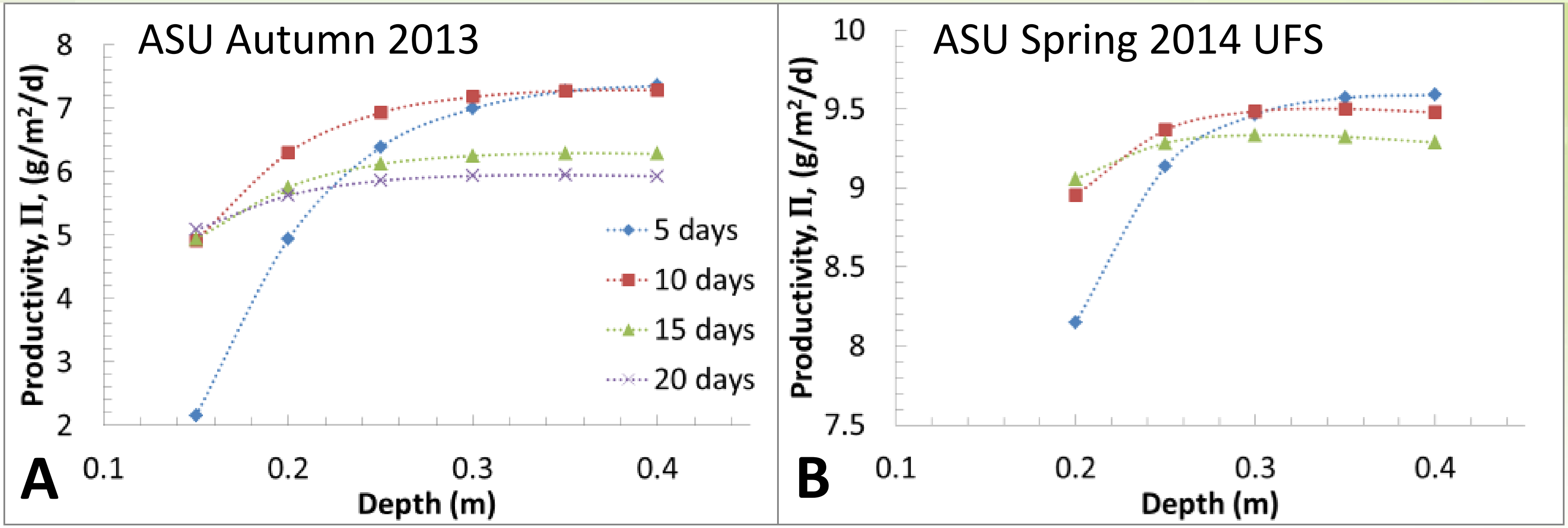
Comparisons of model results and measured data are plotted to show breadth of locations and seasons:

A) Data used for calibration from ASU in autumn 2013,
B) ASU spring 2014 with harvesting,
C) CalPoly in autumn 2013,
D) Cellana in spring 2014 with harvesting.

Harvesting is modeled by either specifying the biomass removed based on data or calculating based on the planned frequency and dilution rate.

- Used 1D model for light with uniform temperature based on data.
- Max growth rate and limitation functions are calibrated using data from ASU autumn 2013 baseline study.
- Same calibration applied to all cases
- Calculated harvest fits better
- Model showed good agreement over different locations and seasons.

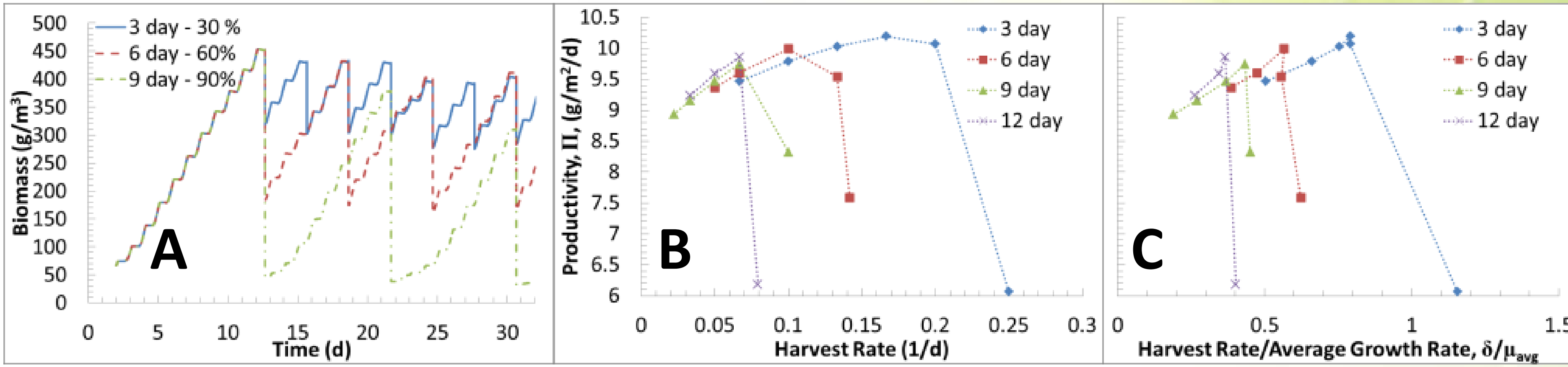
Pond Depth Effects (Light)



Modeled pond productivity as a function of pond depth for ASU location in: A) autumn 2013, and B) spring 2014.

- Depth of the modeled pond is varied for two seasons at the ASU location for given temperature cycles.
- The productivity is calculated after lag time with: $$\Pi = \frac{(Biomass\ Growth)}{(Volume)(Time)} \times depth$$
- The calculated productivity is plotted versus depth for various harvesting frequencies.
- Depth has a greater impact with faster harvesting.
- Little improvement was seen for ponds deeper than 25 cm at all harvesting frequencies.

Harvesting Rate Effects



A) Modeled algae concentration over time for a harvest rate of 0.1/d at various harvest periods. B) Modeled productivity versus harvest rate for various harvest periods. C) Modeled productivity versus ratio of harvest rate to average growth rate for various harvest periods.

- Harvesting rate is varied by adjusting both the dilution and frequency of harvests.
- Productivity is compared to the harvesting rate and the ratio of harvesting rate to growth rate.
- The ideal harvesting rate depends on the harvesting frequency.
- When the concentration goes too low, the productivity is reduced due to the low population numbers.
- When the concentration is allowed to increase, the productivity slowly reduces due to self shading effects.

Summary

- Our algae growth model has been validated for use over multiple seasons and locations.
- A minimum optimal depth of 25 cm for the cases studied has been identified.
- More frequent harvesting allowed for a greater overall harvesting rate and productivity.
- This study identifies a potential 26% increase in productivity with improved cultivation and harvesting strategies.
- Validated model suggests potential productivity improvements from 13.2 to 16-17 $g/m^2/d$.
- This model can be utilized for pond design and harvesting process optimization, strain selection, and process optimization for improved algal yields and productivities.

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