2019 DOE BETO Algae Platform Review
Project # 1.3.5.100

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One little cell,
a world of
possibilities.

ATP3
Algae Testbed
Public-Private Partnership

U.S. DEPARTMENT OF ENERGY

ATP3 Algae Testbed Public-Private Partnership

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ATP³ partners

AzCATI
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FLORIDA ALGAE, LLC

COMMERCIAL ALGAE PROFESSIONALS
From Concept to Commercialization

HARMON CONSULTING

Litree立升

EVODOS
DYNAMIC SETTLERS

ASU LightWorks

ASU IRA A. FULTON SCHOOLS OF engineering
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U.S. DEPARTMENT OF ENERGY

Goal Statement

Establish a **sustainable network of regional testbeds** that empowers **knowledge creation** and **dissemination** within the algal R&D community, **facilitate innovation**, and **accelerate growth** of the nascent algal biofuels and bioproducts industry.

Outcomes:

- **Increased stakeholder access** to high quality, outdoor cultivation and laboratory facilities
  - Over 50 different testbed clients and >80 completed projects in 5+yrs.
  - Mix of national lab, academic and industrial stakeholders
  - 15 education/training workshops held at 3 ATP^3 sites and 2 additional sites
- **Support DOE**'s techno-economic, sustainability, and resource modeling activities and **close critical knowledge gaps** and inform robust analyses of the **state of technology** for producing algal biofuels and bioproducts
  - ATP^3 cultivation data **the prime source** for 2015-2018 BETO SOT
  - ATP^3 has set high data quality standards with 5+ yrs of cultivation data that is curated and available to the public
  - Data already seeing use beyond ATP^3 team and BETO SOT
  - The SOT cultivation framework established by ATP^3 has been extended and now continues under DISCOVR

Quad Chart Overview

Timeline

- **Project start date: 2/1/2013**
  - Pre-Award (at risk) 11/12-1/13
- **Project end date: 3/31/2019**
  - **Original 1/31/2018 - 14 mo extension)**
- **Percent complete: 100%**

Total project cost: $17.65M

- **Function 1: $7.05M**
  - **DOE share: $5.2M**
  - Contractor share: $2.05M
- **Function 2: $10.65M**
  - **DOE share: $10.65M**
  - Contractor share: N/A

(DOE Commitment $15.65M)

	FY 12-16 Costs	FY 17-18 Costs	Total Planned Funding (FY 19-Project End Date
DOE Funded	$11M	$4.6M	$0.1M
Project Cost Share	$2M	$0.05M	$0.0 M

Barriers

- **AFt-B** Sustainable Algal Production**: Existing data** on the productivity and environmental effects of biomass feedstock production systems… **are not adequate**
- **AFt-E** Algal Biomass Characterization, Quality, and Monitoring**:** Physical, chemical, biological, and post-harvest physiological variations in harvested algae are not well researched or understood
- **AFt-A** Biomass Availability and Cost: Lack of credible data on potential price, location, seasonality quality, quantity… needed to reduce financial, technical and operational risk.

Partners

ASU (AzCATI) (43%)
National Renewable Energy Laboratory (10%)
Sandia National Laboratories (10%)
Cellana (12%)
Cal-Poly (6%)
Georgia Tech (6%)
Touchstone Research Laboratory (4%)*
UTEX (5%)
Florida Algae (2%)
Commercial Algae Management (2%)

* No longer part of ATP^3 as of 8/14/2015

Project Overview

The formation of the Algae Testbed Public-Private Partnership **leveraged** the existing resources at AzCATI and our partner sites. The network represented a **collaboration** of industry, laboratory, and educational facilities across the nation. ATP^3 **convened** algae stakeholders to facilitate opportunities to progress algae technologies more rapidly towards commercialization.

ATP3 Algae Testbed Public-Private Partnership

ATP³ Primary Objectives

Strain Identification & Isolation

Biomass Production & Supply

Analytical Services

Education & Training

Equipment Testing

ATP³ offers access to a wide array of services, capabilities and facilities:

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

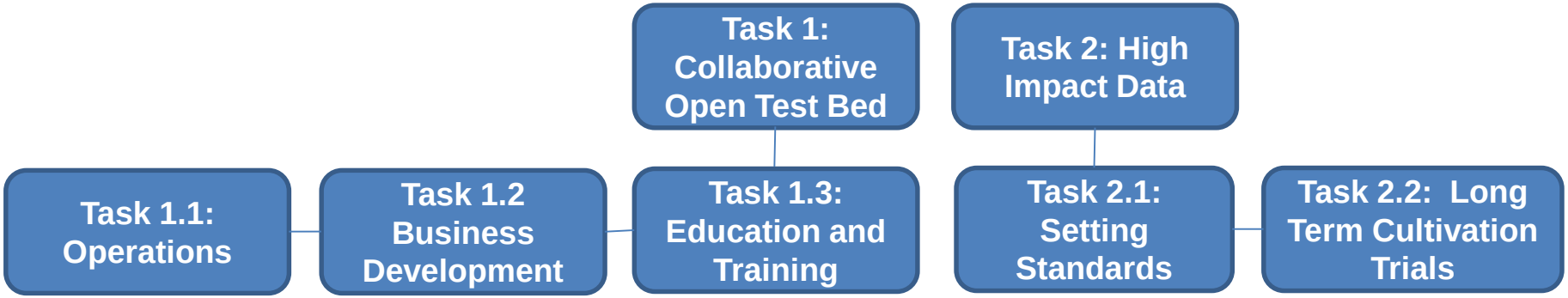
Collaborative Open Testbeds

- Form a national network of testbeds
- Provide increased access to stakeholders
- Share knowledge, learning
- Accelerate R&D outcomes
- Reduce technology and business risk

Collect and Distribute High Impact Data

- Unified research programs
- Pipeline for collection of **high-quality cultivation data** to support algae computational **modeling** including biomass productivity, techno-economic, and life cycle assessment.
- Make data available publicly
- Inform State of Technology (SOT)

Approach: Project Management and WBS



- ***Bi-weekly Exec Team telecoms (Exec Team: ASU, NREL, Sandia, UTEX)***
- ***Weekly full team site calls (cultivation trial progress)***:
- ***Monthly technical presentation webinars***
- ***Quarterly reports/Milestone reports***
- ***Annual all-hands face to face meeting***
- ***Multiple site visits to partner sites by operations lead***
- ***Annual advisory board meetings (Technical and Commercial advisors through CY17 – select members of TAB/CAB will be used for final technical report review)***
- ***Ad hoc data review/sharing with UA RAFT/DISCOVR and other stakeholders (at least every 6 months)***

Approach: Project Timeline

Phase 1 M1-12

Major Milestones

- ATP organization, **systems and processes established**
- Methodologies **harmonized**
- Initial cultivation trial and **detailed experimental planning completed**

Critical Success Factor:
Network established and experimental framework validated demonstrating readiness to proceed with the long term cultivation trails

Successful Go/No Go February 2014

Phase 2 M13-36

Major Milestones

- Cultivation trials **complete**
- Data made **widely available**
- **State of algal biofuels technology design report** completed (2015)

Critical Success Factor:
Capability of testbed network to **serve stakeholder community** demonstrated

Successful Go/No Go March 2016 (with scope change to extend multisite cultivation trials into Phase 3)

Phase 3 M37-72

Major Milestones

- State of algal biofuels technology **design report updated (2016 - 2018)**

Critical Success Factor:

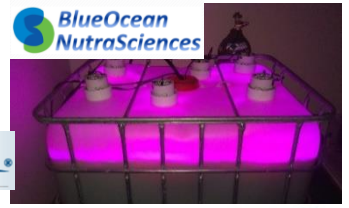
- Value proposition validated and funding secured to **sustain network** in out years
- Requires a r**obust algal industry seeking access** to user facilities and expertise – we continue to demonstrate the capability to effectively serve the stakeholder community

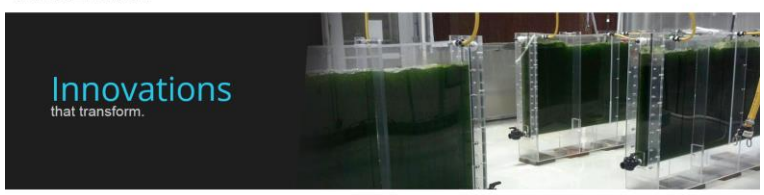
Technical Accomplishments, Progress and Results

ATP3 Algae Testbed Public-Private Partnership

ATP³: Open for Business

- ***Project Activities***:
  - ✓ biomass supply (1-100's kg)
  - ✓ equipment testing
  - ✓ analytical testing
  - ✓ culture maintenance and scale up
  - ✓ genetically engineered algae field trials
  - ✓ Education and Training Workshops
- ***Project Benefits***: access to facilities drive technology R&D, de-risk and validate technological innovations
- ***>50 individual clients to date***
- ***>80 completed projects***
- ***>$1M in additional TB revenue***





Education and Training

Education & Training

Demographics of Participants

By Discipline	Count
Academic	74
Industry	68
Government/Labs	18

By Geography	Count
Local	15
US national	82
International	63

Approximately 50% of the participants were students and educators - the majority of these have engineering backgrounds

Less than 30% of participants had exposure to basic lab techniques

- ATP3 hosted 15 educational workshops (~3/yr)
- Over 160 participants (80 different entities)
  - add'l 200 engaged through mini-workshops at PSA
- Week-long workshops
  - Over 30 lecture modules
  - Over 15 hands-on field site and laboratory activities
- Demonstrated ability to go **"on the road"**
  - Multiple ATP3 sites (AzCATI/UTEX/NREL) as well as other collaborator sites (LANL/SFCC) utilized
- Custom workshop development and delivery with industrial clients
- ATP3 workshop content adapted and made available to ATEC

ATEC ALGAE TECHNOLOGY EDUCATIONAL CONSORTIUM

thealgaefoundation

Open Collaborative Testbed Summary

Major Milestones/Critical Success Factor: Capability of testbed network to **serve stakeholder community** demonstrated

- Simple facilities use/service agreement boilerplate established
- >1000 kg of biomass harvested from AFS and customer (toll) projects
  - 160 kg supplied to Canadian collaborator (for large scale AD studies)
  - ~500 kg supplied into other DOE projects and for researchers
    - Combo of sponsored, direct purchase, toll, and subsidized from 100 g to 60 kg aliquots
- 7 "support projects" which all included direct access to testbeds/equipment/M&S/Personnel
- 15 E&T 1 week workshops with 160 participants – **established core strategy for supporting workforce development in algae based technology (e.g., in collaboration with ATEC)**
- Key resource for technology benchmarking and validation and thus technology and business risk reduction
- 80 fee-for service projects through CY '18 – including critical projects with national labs for model lab to field pre-pilot validations (e.g., LANL, NREL, PNNL, INL)
- Additional program income of ~$1M in 6 years - key for supplementing operational expenses of the testbed

High Impact Data:
Long Term Algal Cultivation Trials

ATP3 set standards and conducted harmonized, rigorous, and objective **long term cultivation trials** to provide a realistic assessment of the **state of technology** for algal based biofuels and bioproducts.

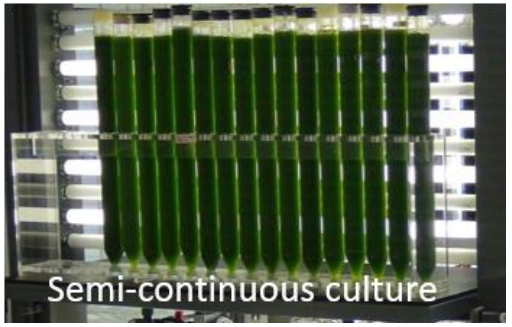
- Our Unified Field Studies (UFS) at the testbed sites along with our Advanced Field Studies (AFS) enabled **comparisons of promising production strains at meaningful scale** across variable conditions
- Our **Scientific Data Management** System and validated, harmonized SOP's for analytical and production processes ensured **data integrity** across all sites
- Our protocols and data from the UFS and AFS are publicly available and provide a critical resource to TEA and LCA analysis yielding **high impact, validated data** **http://en.openei.org/wiki/ATP3**

Laurens, L., et al. https://doi.org/10.1016/j.algal.2017.03.029.
McGowen, J., et al, https://doi.org/10.1016/j.algal.2017.05.017
Knoushaug, E., et al, Https://DOI.org/10.1038/sdata.2018.267

Setting Standards – Method Harmonization: Production and Analytical

Challenges to multi-site comparisons…

- Analytical method variation (method, operator skill, etc), can make evaluation of proximate composition across sites challenging.
  - This has a real impact on TEA, LCA and resource assessments uncertainties
- System and scale variation has the potential to induce unwanted, non-geographical related variability between testbeds as a function of:
  - system design
  - scale of operation
  - source water/nutrients
  - sampling protocols
  - productivity measurement protocols
  - operator skill/training/experience/consistency
  - Other…



Mitigation of Site-to-Site Variance

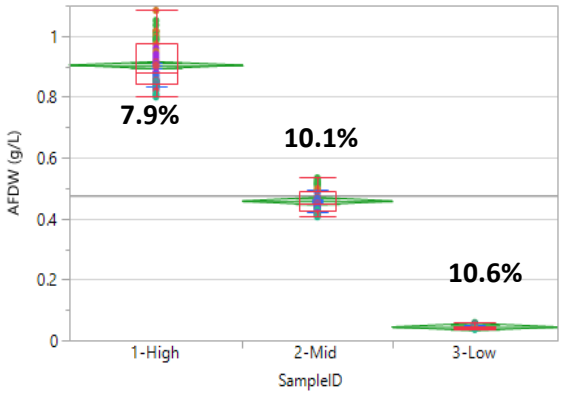
Harmonized Systems via

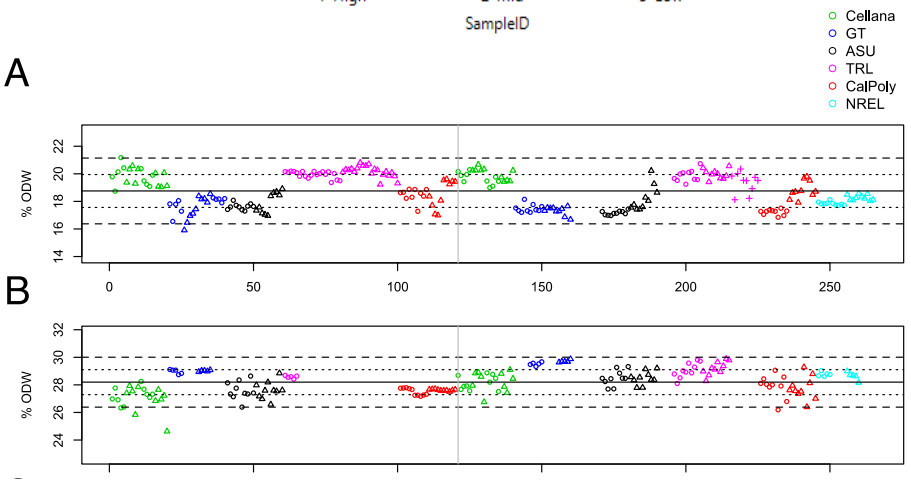
- Uniform design of indoor seed cultivation
- Uniform design of mini-pond system
- Uniform (and automated) water quality monitoring on production units (YSI)
- Uniform light intensity measurements through adoption of same - LiCor LI190 PAR Quantum Sensor (integrated into YSI units)

Harmonized Processes via

- Rigorous verification and validation of analytical and production methodologies
  - Biomass productivity - AFDW, OD, N:P, etc
  - Biomass composition – Ash, Total FAME, Total Protein, Total Carbohydrate
  - Rigorous verification and validation (round robin) framework implemented
- Indoor and outdoor cultivation SOP's (pond cleaning, inoculation, sampling protocols, nutrient adds, transfers/splits),
- Detailed analytical SOP's
- Standardized data reporting in version controlled and locked down spreadsheets with a Scientific Data Management System

Inter-site variance for AFDW

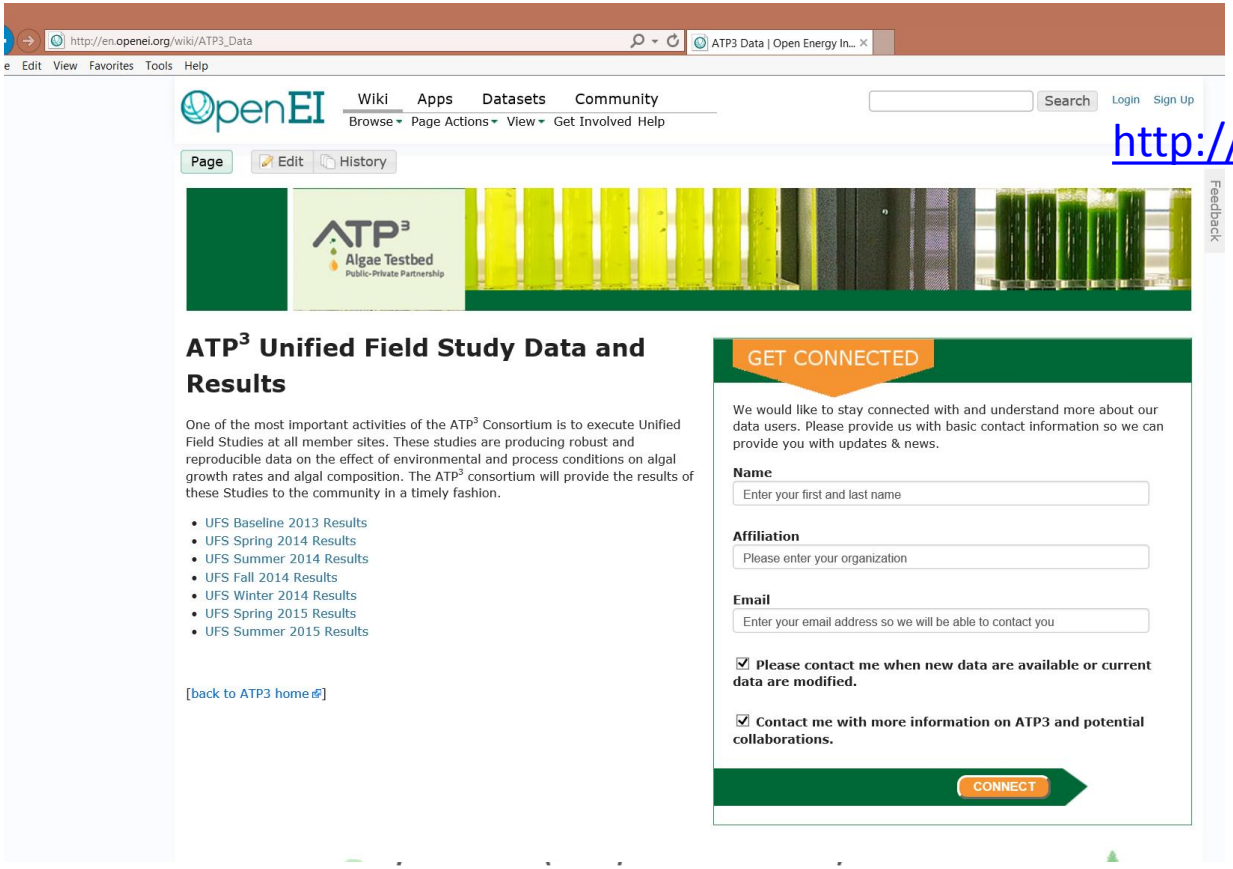




	mean	sd	RSD	*N*
Ash	**18.8**	**1.2**	**6.4**	*237*
Protein	**28.2**	**0.8**	**2.7**	*153*
FAME Lipids	**11.6**	**1.2**	**10.6**	*191*
Carbohydrates	**7.7**	**1**	**12.5**	*198*

The ATP³ Framework: systems, protocols, tools, data, models and projections

ATP³ used a harmonized, experimental framework to implement our Unified Field Studies that enabled comparison of promising strains at a standard system scale across multiple sites. ATP³ developed and implemented a pipeline for the collection and distribution of high-quality cultivation data to support algae computational modeling including biomass productivity, techno-economic, and life cycle assessment and made this data publically available.



http://en.openei.org/wiki/ATP3_Data

Cultivation Study Definitions

- Unified = All testbed sites performing the same experiment in the same systems with the same protocols and strains simultaneously

Standardization of processes and systems was key to executing meaningful multi-site cultivation trials

- Advanced = Sites with various capabilities testing additional production methods and variables to provide data to further enrich the model inputs

Cellana Large Scale Ponds

UFS Strains

UFS Strains (freshwater and marine)

- *Nannochloropsis oceanica* (KA32), supplied by Cellana (marine)
  - Distributed to all sites fall, 2013. Utilized in *"UFSBaseline"* validation for P1 Go/No Go
  - Known to NOT be high productivity but stable and robust cultivar especially for inland sites
  - Critical for initial validation of experimental framework and methods and establishing baseline seasonal/regional performance
- *Chlorella vulgaris, (LRB-AZ-1201) supplied by ASU (freshwater)*
  - Distributed to sites June, 2014, deployed to field Summer 2014
  - Known to be less robust (open pond), but available and importable to HI, high performer in PBR's
- *Desmodesmus* sp. (C046) supplied by Cellana (freshwater and marine)
  - Basis of Huntley et al 2015 publication
  - Good settling characteristics
  - Range of salinity possible
- Representative cultivars for fuel and high value production (feed, omega-3's)
  - Substantial historical data for both strains (faster project startup)
  - Unencumbered with little restrictions on biomass distribution to third parties (under MTA)
- For the UFS, main operational variables explored included dilution rate/harvest frequency (semi continuous production) and nitrogen source
- Marine strains were all more stable (lower frequency of pond crashes) across the network relative to freshwater strains

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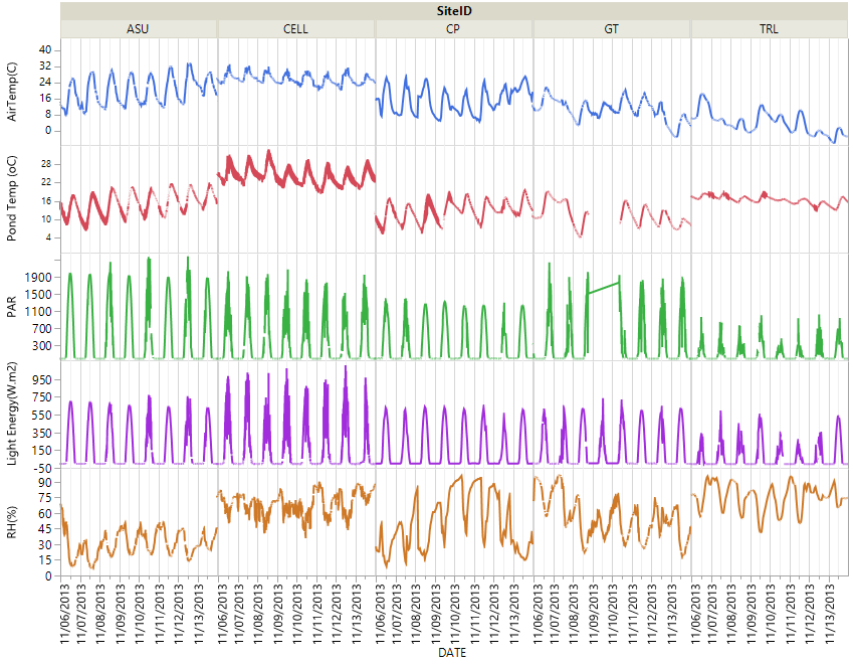
UFS Data Sets

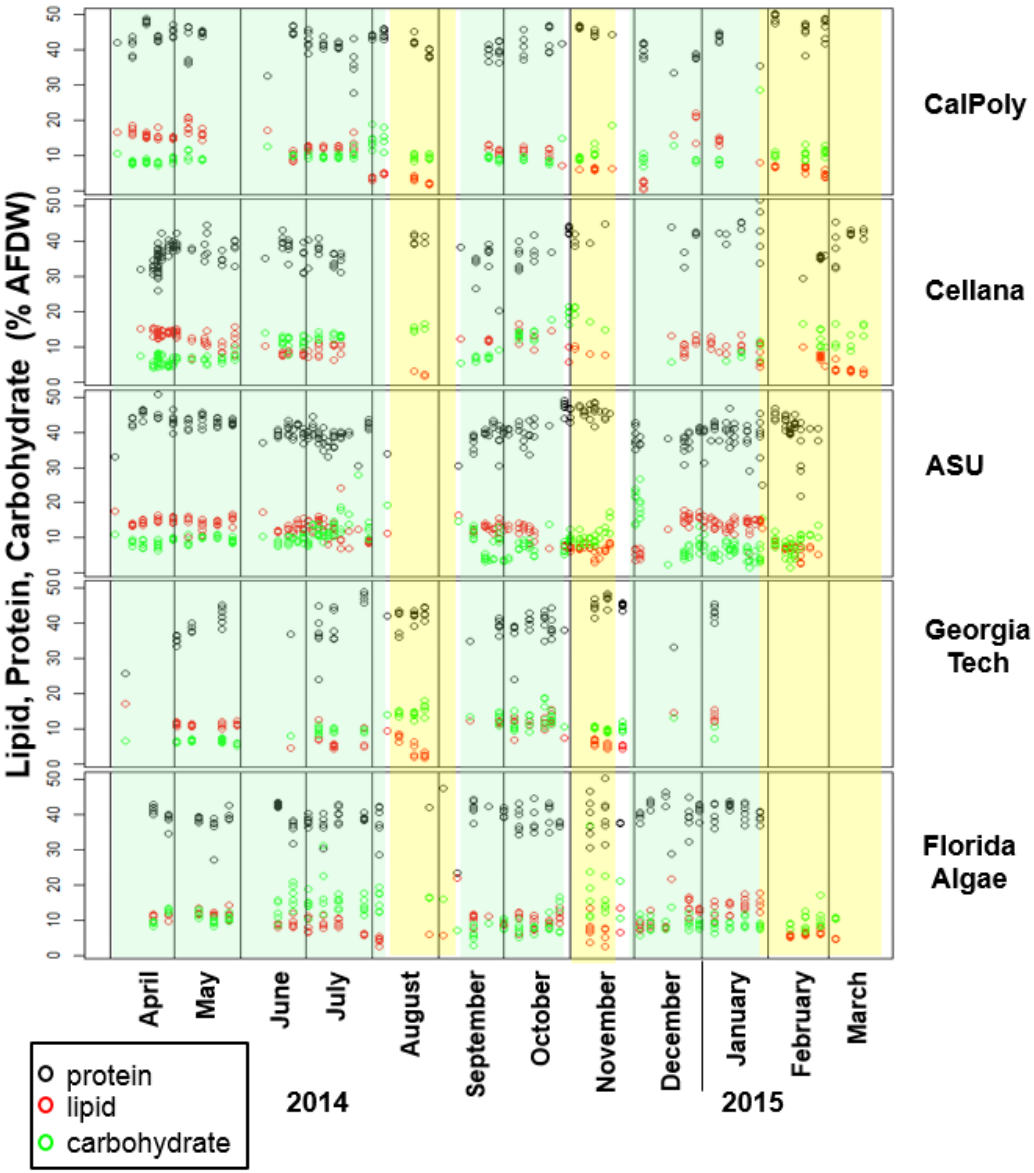
54 coordinated experiments across 7 seasor

strain	site	2013 Fall	2014 Spring	2014 Summer	2014 Fall	2014 Winter	2015 Spring	2015 Summer
N. oceanica KA32	ASU	48.7	55.3	39.8	40.3	42.7	40.7	
	CP	48.7	53.8	39.7	40.8	37.7	39.9	
	CELL	25.7	43.7	35.7	35.7	40.9	32.9	
	FA		48.8	36.7	47.7	41.7	37.8	
	GT	54.8	51.7	34.0	37.7	18.7	34.7	
	TRL	47.7						
C. vulgaris LRB-AZ-1201	ASU			25.8	41.7	25.6	49.7	
	CP			34.9	37.7	29.8	55.9	
	CELL			26.6	28.7	27.9		
	FA			45.7	47.6	29.7	46.7	
	GT			17.0	26.7	32.0	52.8	
Desmodesmus C046	ASU							39.9
	CP							39
	CELL							37.9
	FA							39.8
	GT							37.9

Weather and water quality data collected for all run

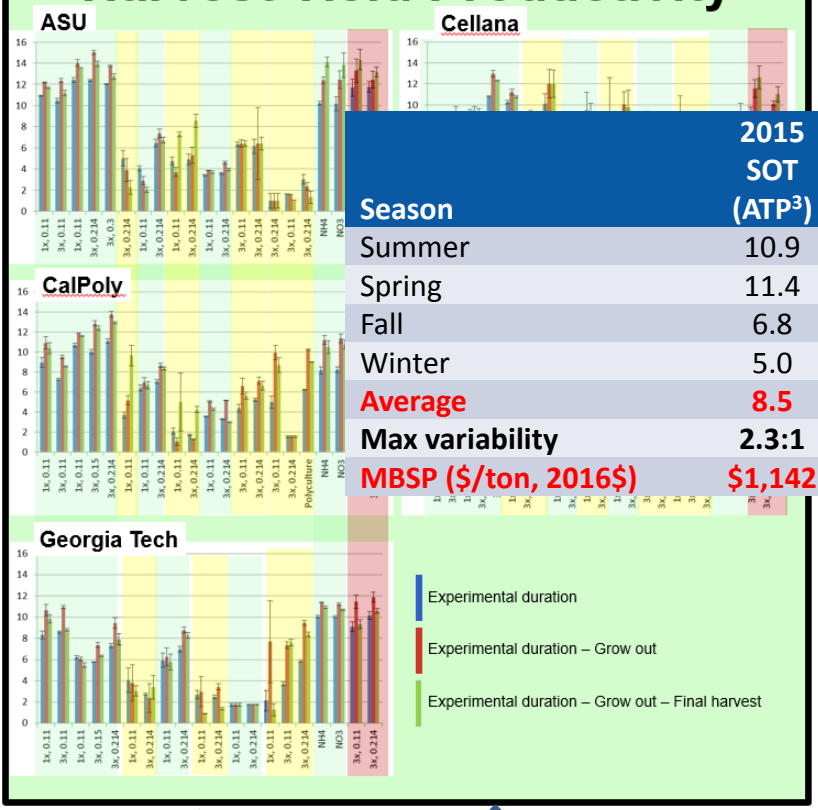


Algal Proximate Composition



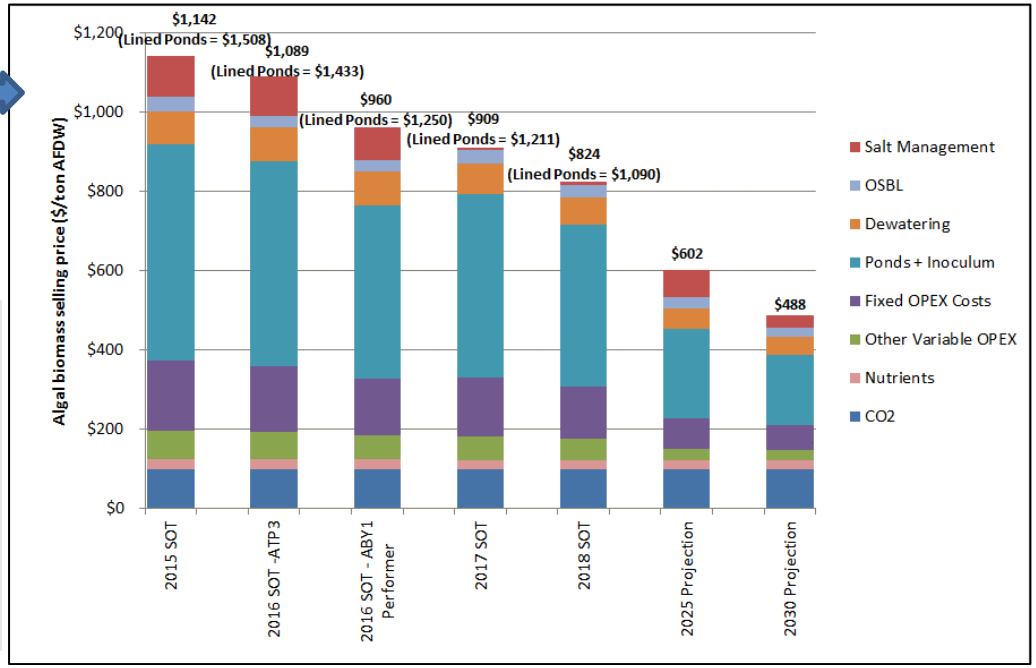
Unified Field Study Productivity: SOT Support

Harvest Yield Productivity

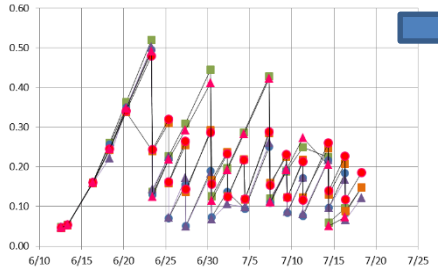


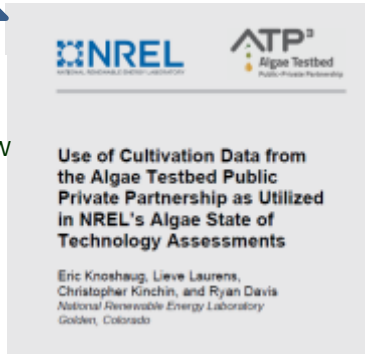
ATP3 cultivation data and methods available at:
http://www.nrel.gov/docs/fy17osti/67289.pdf

Season	2015 SOT (ATP³)	2016 SOT (ATP³)	2016 SOT (ABY1 Performer)	2017 SOT (ATP³)	2018 SOT (ATP³/ DISCOVR/ RACER)	2025 Projection	2030 Projection
Summer	10.9	13.3	17.5	14.1	15.4	27.7	35.0
Spring	11.4	11.1	13.0	13.2	15.2	24.0	28.5
Fall	6.8	7.0	7.8	8.5	8.5	18.4	24.9
Winter	5.0	5.0	4.8	5.5	7.7	10.0	11.7
Average	**8.5**	**9.1**	**10.7**	**10.3**	**11.7**	**20**	**25**
Max variability	**2.3:1**	**2.7:1**	**3.6:1**	**2.6:1**	**2.0:1**	**2.8:1**	**3.0:1**
MBSP ($/ton, 2016$)	**$1,142**	**$1,089**	**$960**	**$909**	**$824**	**$602**	**$488**

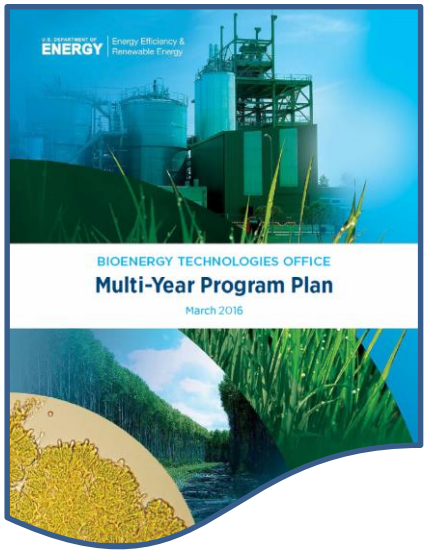


exp dur – grow out





High Impact Data: Informing Current State of Technology

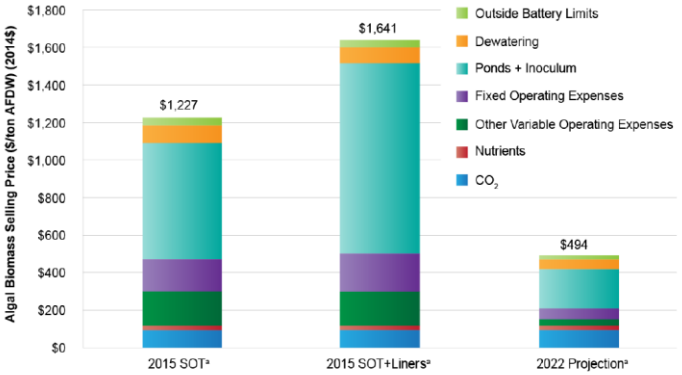


http://www.energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf

Table A-2: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Algae Farm[d]

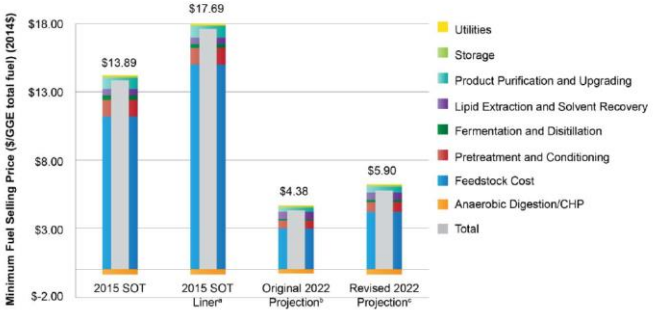
Processing Area Cost Contributions & Key Technical Parameters	Metric	2015 SOT [a]	2015 SOT (Fully Lined) [a]	2022 Projection
Biomass Selling Price	$/ton AFDW	$1227	$1641	$494
Production Cost	$/ton AFDW	$1069	$1483	$409
Harvest/Dewatering Cost	$/ton AFDW	$116	$116	$64
Other Cost (Facility Circulation, Storage)	$/ton AFDW	$42	$42	$21
Gross Biomass Production Yield	ton AFDW/acre-year	12.4	12.4	37.5
Total Farm Power Demand	KWh/ton AFDW	860	860	407
Production				
Total Cost Contribution	$/ton AFDW	$1069	$1483	$409
Capital Cost Contribution	$/ton AFDW	$629	$1015	$213
Operating Cost Contribution	$/ton AFDW	$440	$468	$196
Cultivation Productivity (Annual Average)	g/m^2/day AFDW	8.5	8.5	25
Max Seasonal Production Variability	max:min productivity	2.3:1	2.3:1	3:1
Lipid Content	dry wt% as FAME	27.4%	27.4%	27.4%
N Content	AFDW wt%	1.8%	1.8%	1.8%
CO_2 Utilization Efficiency	% utilized for biomass	90%	90%	90%
Gross CO_2 + Nutrient Cost Contributions[b]	$/ton AFDW	$124	$124	$120
Operating Days Per Year	days/year	330	330	330
Biomass Concentration at Harvest	g/L AFDW	0.27	0.27	0.5
Dewatering				
Total Cost Contribution	$/ton AFDW	$116	$116	$64
Capital Cost Contribution	$/ton AFDW	$93	$93	$52
Operating Cost Contribution	$/ton AFDW	$23	$23	$12
Gross Dewatering Efficiency [c]	%	87%	87%	87%
Net Dewatering Efficiency [c]	%	99%	99%	99%
Final Concentration of Dewatered Biomass	g/L AFDW	200	200	200
Dewatering CAPEX	$/MGD from cultivation	$18	$18	$6
Dewatering OPEX	$/MM gal from cultivation	$4	$4	$1
Balance of Plant				
Total Cost Contribution	$/ton AFDW	$42	$42	$21
Capital Cost Contribution	$/ton AFDW	$31	$31	$15
Operating Cost Contribution	$/ton AFDW	$11	$11	$6

[a] Base case assumes nth-plant facility utilizing low-cost unlined ponds; alternative SOT scenario considers fully lined ponds
[b] Included as part of "operating cost contribution"; gross cost does not account for CO_2/nutrient recycling from conversion



[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium with 2015 Algae Farm design report assumptions.

Figure 2-16: Cost contribution for algal biomass selling price by process area



[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium with 2015 Algae Farm design report and 2014 ALU design case assumptions.
[b] Original 2022 projection based on 2014 ALU design report (assumed biomass feedstock)[48]
[c] Revised 2022 projection based on modified ALU design case (modeled biomass feedstock)[49]

Figure 2-17: Cost contribution by process area for CAP Pathway

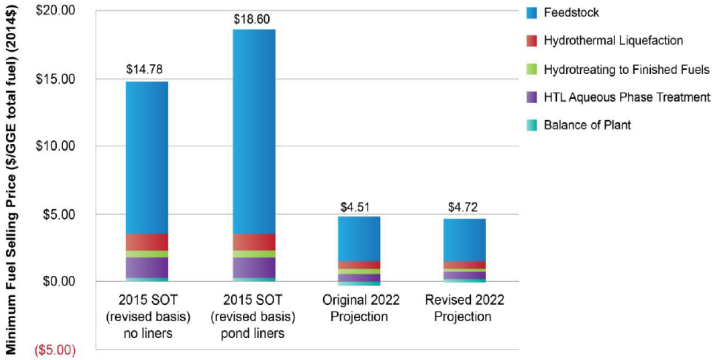


Figure 2-18: Cost contribution by feedstock and conversion process area for HTL Pathway

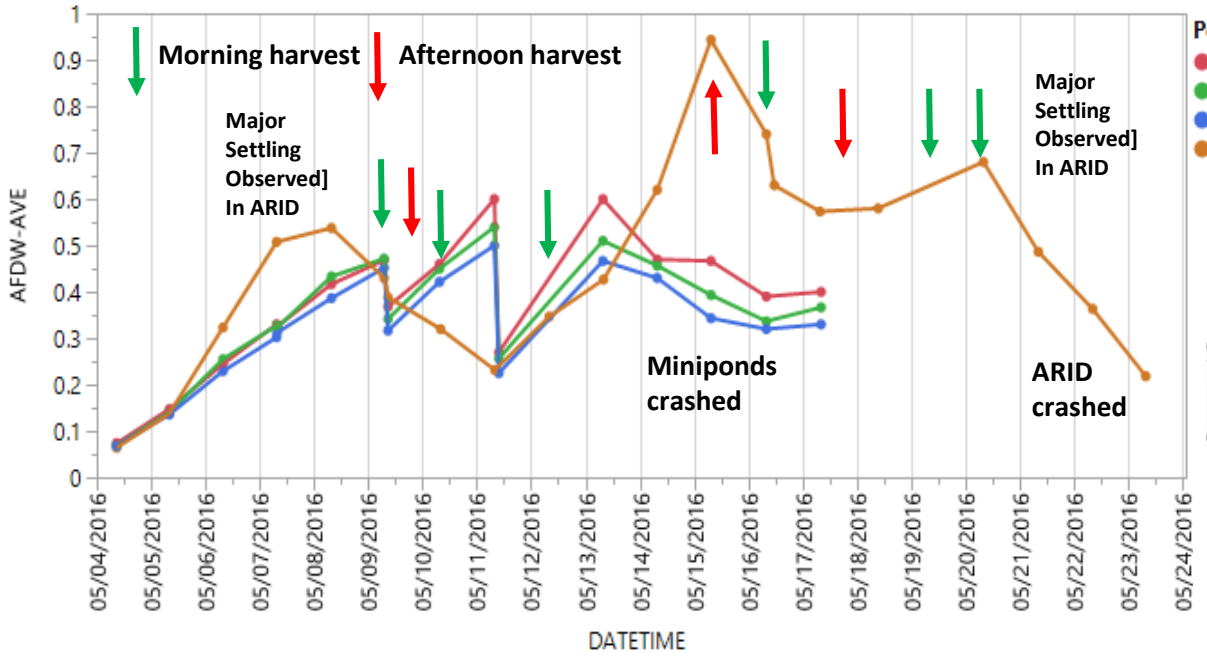
[44] ATP^3 Algae Testbed Public-Private Partnership, http://en.openei.org/wiki/ATP3.
[45] R. Davis, et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772, http://www.nrel.gov/docs/fy16osti/64772.pdf.

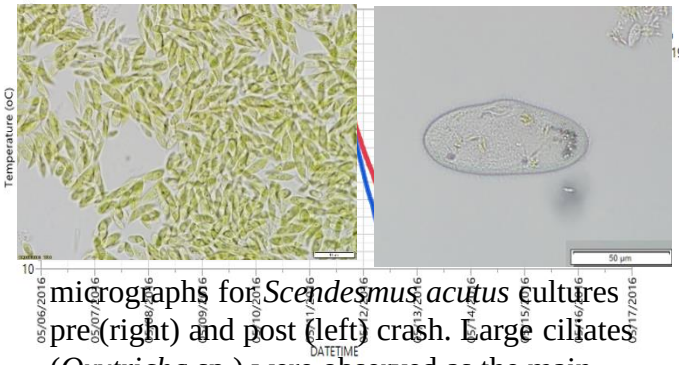
[50] Jones et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*, Pacific Northwest National Laboratory, PNNL- 23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf

Advanced Field Studies (AFS)

- Advanced field Studies began late in year 2 of the cultivation trials and continued thru Spring 2018
- AFS were meant to expand the experimental space and leverage unique assets of the individual sites
- Additional strains deployed **as planned** in years 2-6 of the cultivation trials – targeting known high performers and expanding into more site specific cultivation trials
  - Polycultures/wastewater, mixing energy (Cal Poly)
  - New marine strains shown to outperform *N. salina* (NREL supplied)
  - *Additional freshwater strains: Scenedesmus* sp., *Monoraphidium* sp. (ASU),
  - *C. sorokiniana* (DOE1230, DOE1228, DOE1412)
  - PBRs/larger scale cultivation
    - Flat panel PBR cultivation (AzCATI)
    - ARID (400 m2) vs ORP's (harvesting, nutrient source) (AZCATI)
    - Mid scale vs. large scale comparisons/2 stage PBR-Pond Batch vs. semi-continuous operation (Cellana and AzCATI)
    - HTL aqueous recycling
    - All the above include integrated harvesting at pilot scale
- >40 additional experimental data sets that directly support the SOT, some of which ran >90 days.

Advanced Field Studies: ARID™ example





micrographs for *Scendesmus acutus* cultures pre (right) and post (left) crash. Large ciliates (*Oxytricha* sp.) were observed as the main grazer leading to crash in all systems.

Harvest Datetime	Harvest ID	AFDW @ Harvest	Volume Harvested (gallons)	Calculated Biomass Removed (g)	Paste Yield (g)	Solids Content (DW)	Harvest Yield (g)	Harvest Effeciency (%)	Harvest Method	Total Ash (%DW)	Total FAME (% AFDW)
5/9/2016 7:00	204	0.43	2400	3906	13309	21.0%	2796	72%	Evodos	6.1	7.9
5/9/2016 16:00	205	0.8	2200	6662	23453	20.8%	4889	73%	Evodos	9.0	7.9
5/10/2016 8:00	206	0.32	2400	2907	43093	15.0%	6464	222%	Evodos	11.0	6.7
5/10/2016 8:00	207	0.32	800	969	40740	17.0%	6926	715%	Evodos	16.0	7.1
5/12/2016 8:00	208	0.35	2200	2914	14681	15.6%	2290	79%	Evodos	9.9	5.9
5/15/2016 16:30	210	0.94	2800	9963	38422	20.7%	7953	80%	Evodos	4.8	8.9
5/16/2016 8:00	211	0.74	2800	7843	29950	22.5%	6739	86%	Evodos	4.8	8.1
5/17/2016 16:30	212	0.8	2400	7267	30477	20.3%	6187	85%	Evodos	4.2	9.2
5/19/2016 8:00	213	0.63	2400	5723	26030	17.3%	4503	79%	Evodos	4.6	8.1
5/20/2016 8:00	N/A	0.68	2500	6435	28000	18.9%	5292	82%	Evodos	19.7	12.0
		Sum	23000	54591	288155		54038				
					avg g/day		4913				
					avg g/m2-day		14.0				

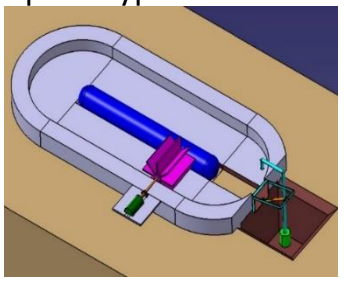
>17 g/m^2-day if harvest efficiency was consistently >90%

Advanced Field Studies: PW-ARID™

2018 Winter Season SOT Campaign at AzCATI

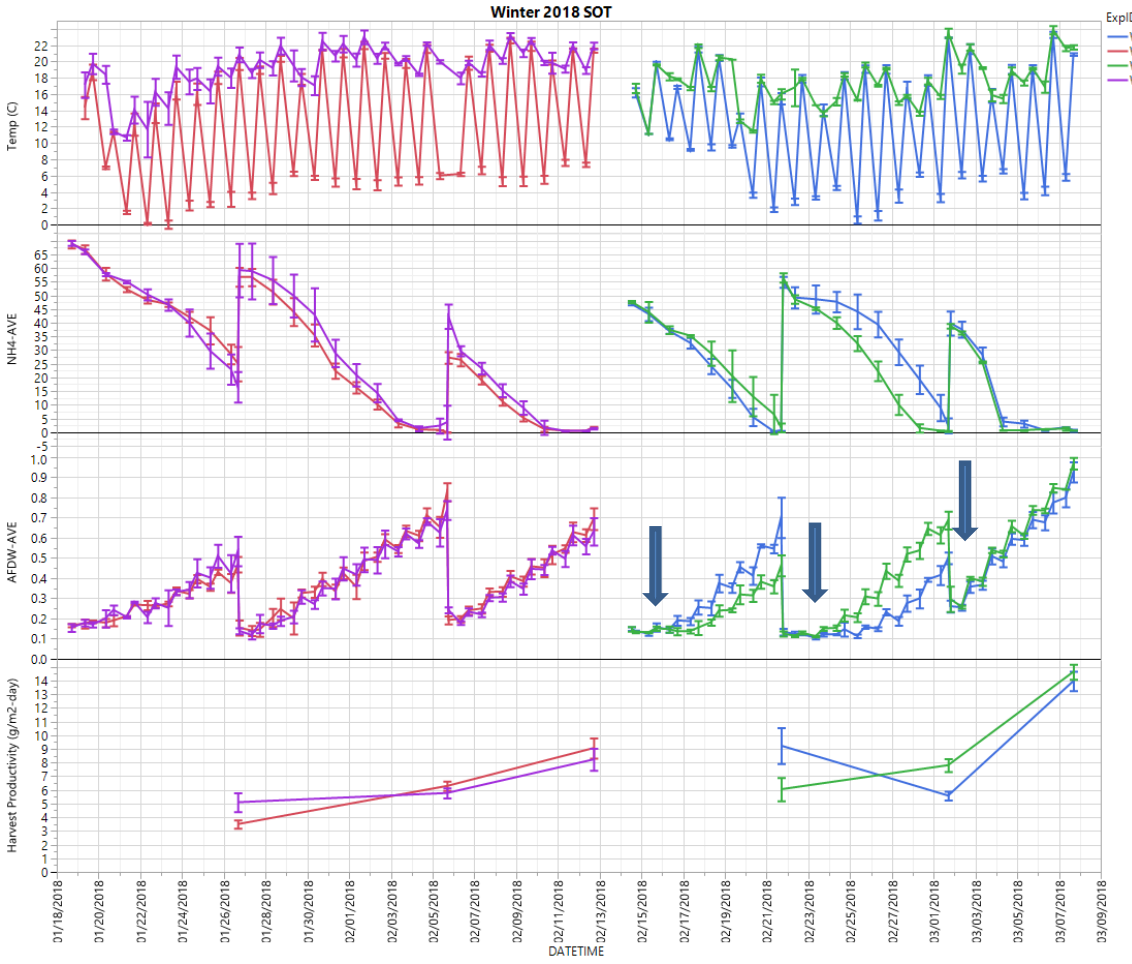
- Hypothesis: Thermal management through the novel ARID-PW (UA-Weller) design will improve productivity by increasing overall temperature of the culture relative to standard PW pond design
- Experimental conditions:
  - Two (2) strains tested in series:
    - *Scenedesmus acutus* (LRB-AP-0401) from Jan 18-Feb 12 and
    - *Monoraphidium minutum* (26B-AM) from Feb 14 – Mar 7.
    - Sampled am/pm throughout entire cultivation trial
  - Triplicate ponds for each condition. Ponds run at 10 cm depth.
- Steady increase in productivity from Jan-Mar.
- 26BAM>0401 but 0401 run early part of winter (colder/less light) so not a direct comparison between strains for the winter season.
- **NO SIGNIFICANT DIFFERENCE IN PRODUCTIVITY BASED ON THERMAL MANAGEMENT SCHEME**
- But – we did observe an overall ~47% increase in productivity for 2018 relative to 2017 (7.7 vs 5.5 g/m2-day)
  - We are still exploring why the large difference year over year with PNNL – weather/media/operation?
- 26BAM strain was continued into the spring 2018 run without the ARID-PW
  - Previously cultivated at AzCATI only until early March
  - Spring run focused mainly on semi-continuous production
  - Layered in strain (0401 vs 26BAM) and depth comparisons (10 vs 20cm)
  - 26BA > 0401 and was less susceptible to contamination

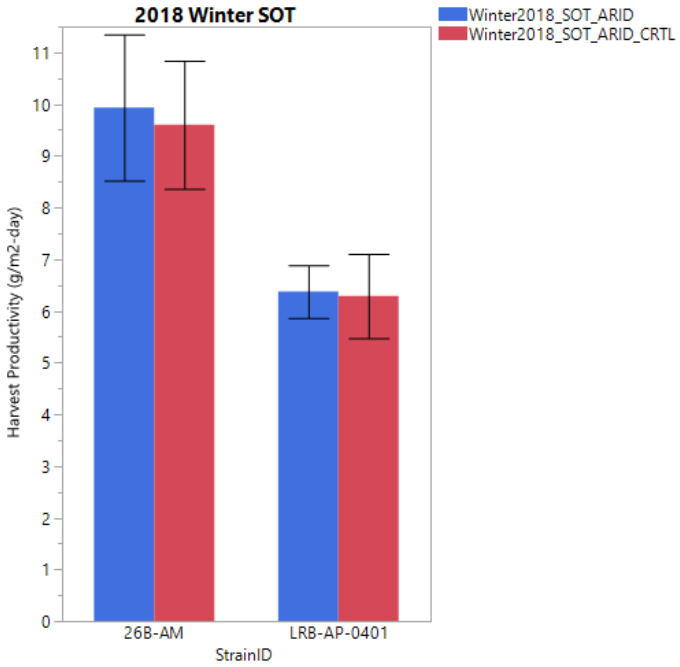
Univ. of Ariz. PW-ARID prototype in Tucson



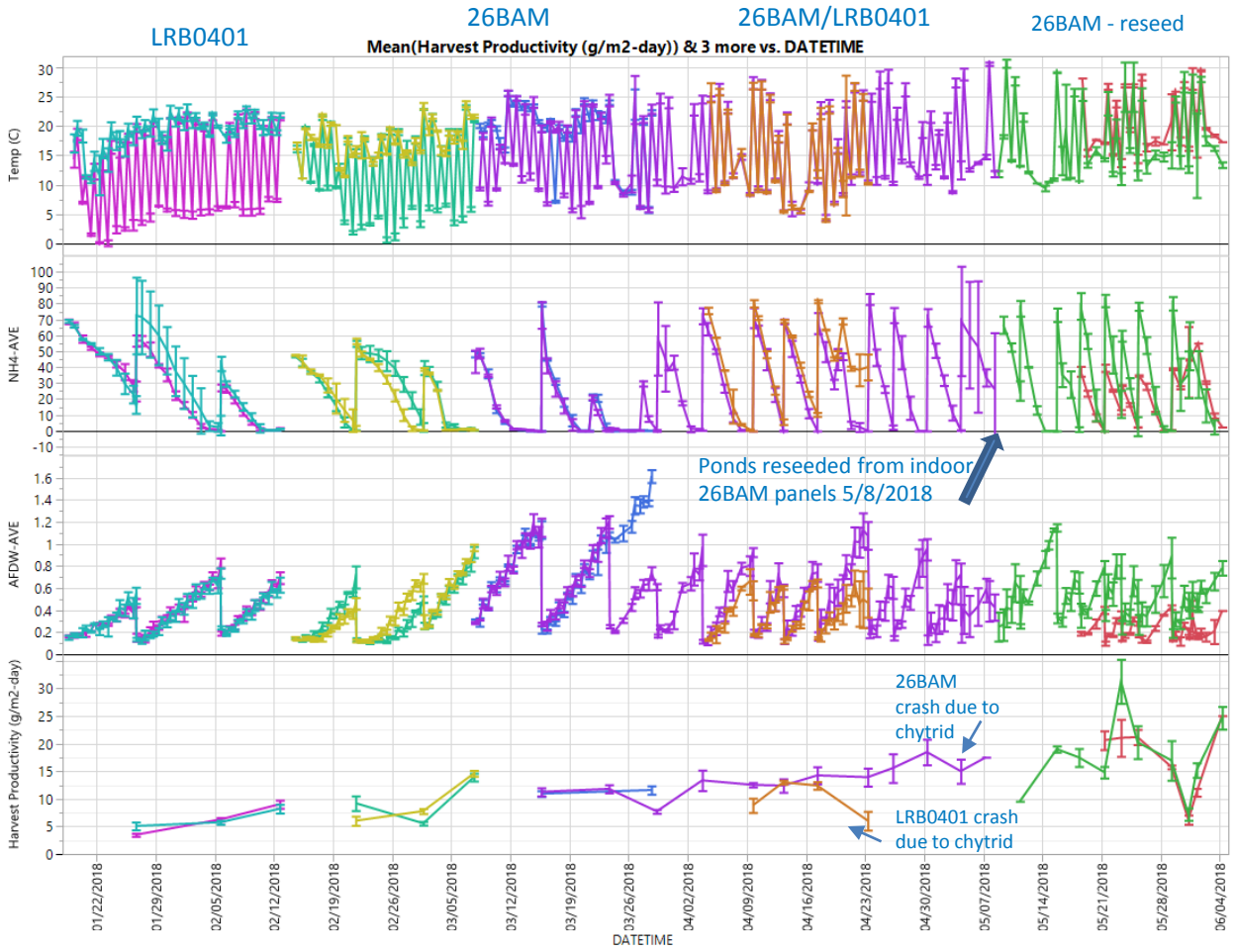
Advanced Field Studies: PW-ARID™

2018 Winter Season SOT Campaign at AzCATI





Winter and Spring 2018 SOT Summary



6 months of continuous cultivation across two seasons. Winter season focused on a novel thermal management approach that was predicted to lead to better productivities – it didn't…

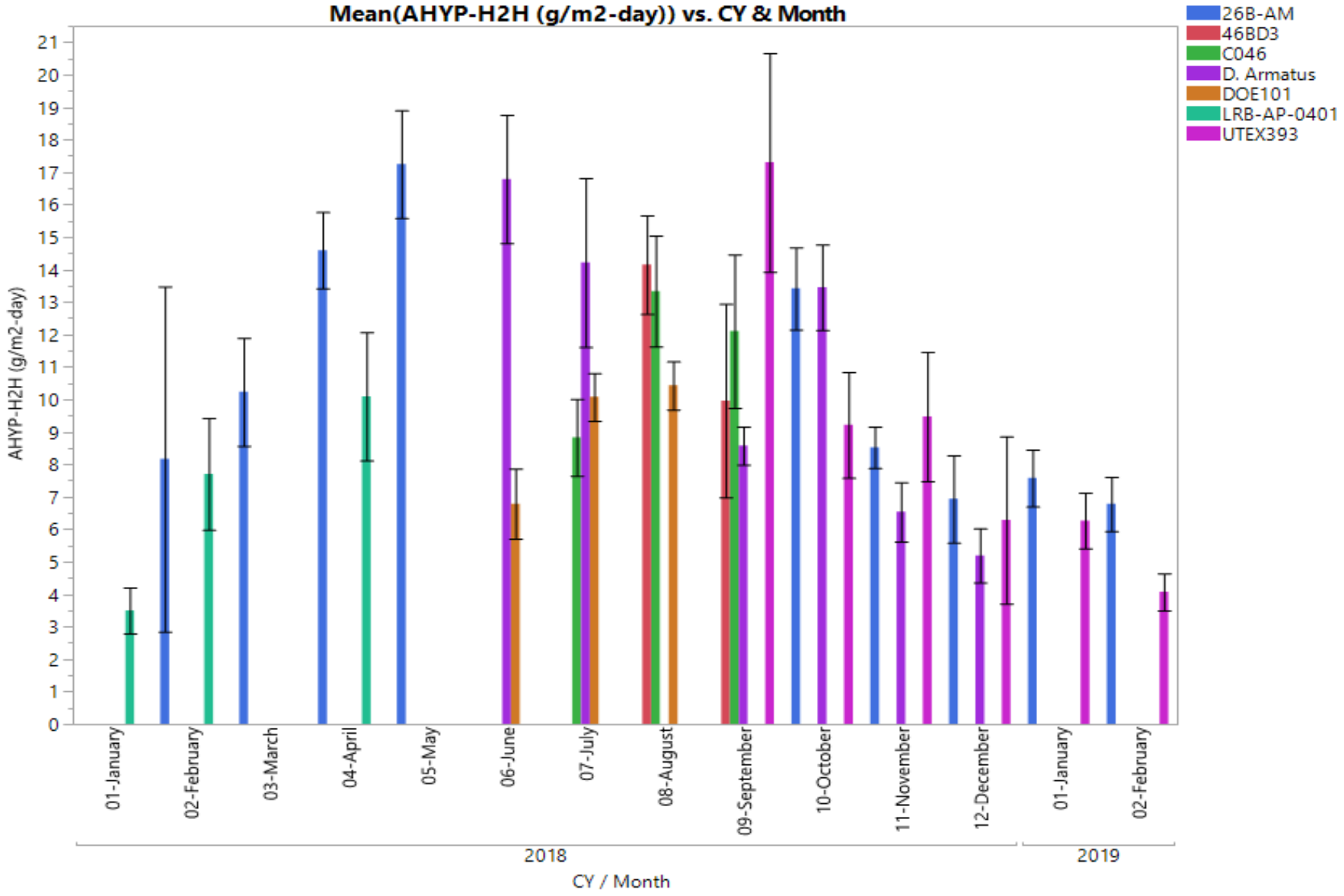
Different cultivars compared along with operational scenarios (nutrient loading, batch vs semi-continuous cultivation, thermal management)

Steady increase in biomass productivity as season progressed with year over year improvement demonstrated for 2018

*Monoraphidium minutum (*26BAM) shown to be more robust to chytrid contamination than *Scenedesmus acutus (*LRB0401)

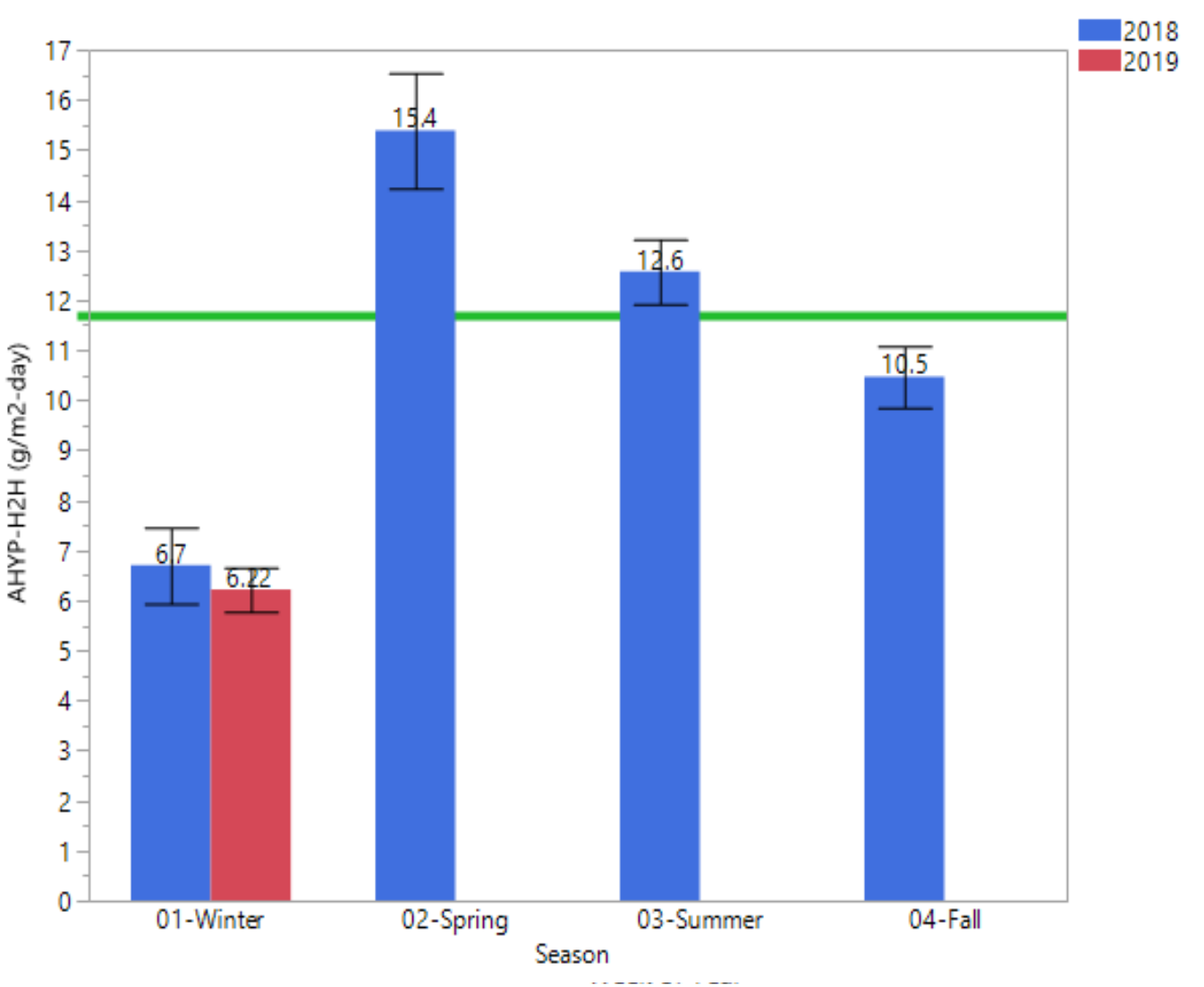
Advanced Field Studies:

2018 SOT Campaigns at AzCATI



Advanced Field Studies:

2018 SOT Campaigns at AzCATI



- Areal Productivity (harvest to harvest) for ALL cultivation trials conducted in calendar year 2018 (and into 2019) at AzCATI in Mesa, AZ – includes 7 strains

- N>700 discrete harvest events covering over 280 total days of cultivation in 2018

- The ATP^3 SOT framework successfully transitioned to DISCOVR

- Major efforts continue to improve towards the 2025 cultivation goals for BETO with additional focus on translating promising crop protection strategies from within the DISCOVR team and across the portfolio

Advanced Field Studies:

2018 SOT Campaigns at AzCATI

- *ATP3 SOT framework **successfully transitioned** and **implemented** in DISCOVR.*
- *Summer, Fall, and Winter cultivation trials successfully executed under DISCOVR*
- *Summer cultivation trial included three different cultivars: Scenedesmus sp.* (46BD3), *Desmodesmus sp. (*C046) and *Picochlorum soloecismus* (DOE101)
- *Fall and Winter trials included two different cultivars: Scenedesmus obliquus* (UTEX393) *and Monoraphidium minutum* (26BAM)
- *Six strains total tested in 2018 under DISCOVR SOT at AzCATI*
- *Data output will continue to be in standardized formats and made publically available*
- **FY18 SOT results yielded 13.6% improvement over FY17 SOT** (Target is ≥ 10% per year)

Strain	Experiment	Areal Prod. (g/m2-day)		AFDW at Harvest (g/L)	Total Days	Harvest Frequency	Operational Scenario
		Average	STDEV				
Nanochloropsis sp.	Fall 2016	8.5	0.44	0.3	42	1x/week	Batch (25cm)
Scendesmus acutus/ Monoraphidium sp.	Winter 2018	7.7	1.7	0.69	46	Every 10-13 days	Batch (10 cm)
Monoraphidium sp.	Spring 2018	15.2	1.8	0.7	80	1-3x/week	Semi-continuous (10 cm)
Desmodesmus sp.	Summer 2018*	15.4	1.8	0.35	51	3x/week	Semi-continuous (20 cm)
	Annual Average	**11.7**			219		
	% increase over 2017 (10.3)	13.60%					

* first season under DISCOVR

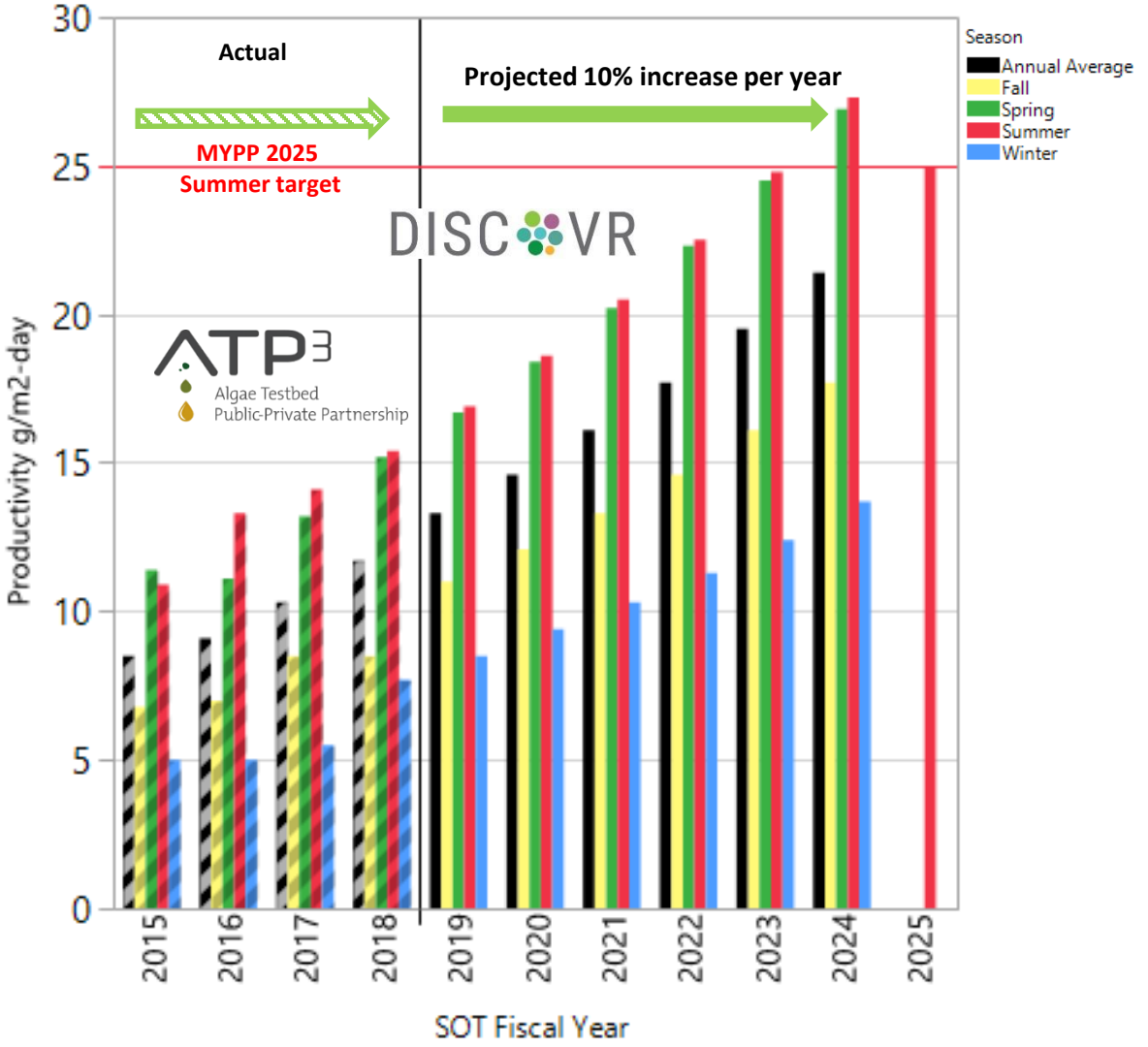
DISCOVR

Advanced Field Studies:

Future SOT Campaigns at AzCATI

- ATP3 demonstrated an overall **improvement of 38% in annual average productivity** from FY15 (baseline of 8.5 g/m2-day) to FY18 (11.7 g/m2-day) for Mesa, AZ location

- If target of ≥ 10% year over year improvement continues, the DISCOVR SOT program will hit the current BETO FY2025 target of 25 g/m2-day (summer) by 2024.



ATP3 Relevance

Major Milestones/Critical Success Factors:

- Completed UFS/AFS Cultivation Trials
- Data disseminated to the R&D community
- **State of algal biofuels technology (SOT) supported (and continues through DISCOVR)**
- Capability of testbed network to **serve stakeholder community** demonstrated AND value proposition validated/funding secured to sustain

ATP3 has established a validated framework for implementing rigorous, long-term multi-site cultivation trials (including GM) and operate as an open collaborative testbed user facility

- At the lead for promoting standards in the industry (Aft-E)
- Allowed determination of the effects of regional, seasonal, environmental variation that is to be expected for a national (international) deployment of algae cultivation (Aft-A, B, E)
- Critical validation data source for biomass productivity modeling, TEA, LCA and RA community - allows continued refinement of the current state of technology (SOT) assessments utilized by DOE and the broader industry/investment community (Aft-A,B,E)
- Enabling core AOP projects, competitively funded projects, and industry partners that need access to a validated experimental framework for conducting objective, outdoor cultivation trials with capability for **integrated** pilot-scale operations under real-world environmental conditions (Aft-D,F,G,H,I,J)
- **Integral resource to BETO algae portfolio – actively leading or engaged with >16 of the projects reviewed this peer review and core to SOT data generation**
- **Established core strategy for supporting workforce development in algae based technology – demonstrated through recent training activity for major nutraceutical company including new toolkit development for data driven decision making**

ATP^3 Summary

- From September 2013 through December 2018, over 95 individual experiments conducted across the network with an average duration of at least 50 days
- Major outcomes:
  - Standardized, validated methods with an emphasis on continuous improvement
  - 15 strains utilized in outdoor cultivation experiments with the majority of multi-season data coming from 6 strains with average run time of >40 days
  - Data and experimental protocols for the UFS and AFS (Fall 2013 through Summer of 2018) curated and posted on ATP^3's OpenEI.org web portal. http://openei.org/wiki/atp3
  - ATP^3 generated productivity data **continues to be the primary data sets** supplied to the DOE sponsored SOT reports for 2015, 2016, 2017, 2018 and under DISCOVR for 2019 and beyond
  - Data is being used by outside groups and pointed to as a key risk mitigation demonstration for commercial entities.
  - Strong E&T program that is well recognized as a key resource to the stakeholder community and major contributor to the DOE sponsored ATEC workforce development program
- Novel platforms for pond ecology monitoring and real-time monitoring of culture density and health, demonstrating ATP^3's capability for deploying new technology into an active R&D pilot facility (continues in AOP and DISCOVR)
- Novel methodology developed to quantify pond reliability metrics - a nascent idea in the research community but key to long term deployment and viability
- While overall customer base remains challenging for sustainably supporting a test bed network **without** ongoing federal support – ATP^3 has demonstrated the ability to work collaboratively across the algal value chain generating an addition $1M is testbed revenue.

Supplemental Slides

Publications and Presentations

Publications

1. Gharagozloo, P. E., Drewry, J. L., Collins, A. M., Dempster, T. A., Chris V. Choi, C. V., and S. C. James. Analysis and modeling of *Nannochloropsis* growth in lab, pond, and raceway experiments. 2104. *J. Appl. Phyc*. Online edition © Springer Science+Business Media Dordrecht February 2014 DOI 10.1007/s10811-014-0257-y. 12 pp
2. Park, S., Van Ginkel, S.W., Pradeep, P, Igou, T., Yi, C., Snell, T., Chen, Yongsheng. (2014) "The selective use of hypochlorite to prevent pond crashes for algae-biofuel production". *Water Environment Federation*. Accepted.
3. Igou, T., Van Ginkel, S.W., Penalver-Argueso, P., Fu, H., Doi, S., Narode, A., Cheruvu, S., Zhang, Q., Hassan, F., Woodruff, F., Chen, Y. S., (2014), "Effect of Centrifugation on Water Recycling and Algal Growth to Enable Algae Biodiesel Production", Water Environment Research, 86 (12): 2334-2338
4. Wang, J., Rosov, T., Wensel, P., McGowen, J., Curtiss, W. "A preliminary implementation of metabolic-based pH control to reduce CO2 usage in outdoor flat-panel photobioreactor cultivation of *Nannochloropsis oceanica* microalgae." Algal Research, 18: 288-295. DOI:10.1016/j.algal.2016.07.001
5. Knoshaug, E.P., Wolfrum, E., Laurens,L., Pienkos, P., Dempster, T., McGowen, J. "Open Pond Algal Cultivation Datasets of the Algae Testbed Public-Private Partnership (ATP3): Unified Field Studies" submitted (2017)
6. Laurens, L., Van Wychen, S., Pienkos, P., Harmon, V., and McGowen, J. "Harmonization of Experimental Approach and Data Collection to Streamline Analysis of Biomass Composition from Algae in an Inter-Laboratory Setting" submitted to Algal Research submitted to Algal Research (2017)
7. McGowen, J., Knoshaug, E., Laurens, L., Dempster, T., Pienkos, P., Wolfrum, E., Harmon, V. "The Algae Testbed Public-Private Partnership (ATP3) Framework; Establishment of a National Network of Testbed Sites to Support Sustainable Algae Production" submitted to Algal Research (2017)

Presentations:

1. "An Overview of a Successful Algae Testbed Model: Arizona Center for Algae Technology and Innovation (AzCATI) and the Algae Testbed Public-Private Partnership (ATP^3) at Arizona State University". Thomas A. Dempster, Consortium de Recherches et Innovations en Bioprocedes Industriels au Quebec (CRIBIQ), Sherbrooke, Quebec, October 2012.
2. ATP^3 BETO Project Peer Review, Washington DC, May 2013.
3. "Validated Algae Growth Model and Optimization Study." **Patricia Gharagozloo** and Jessica Drewry. 3rd International Algal Biomass, Biofuels and Bioproducts Conference June 2013.
4. "Pulsed Electric Field (PEF) Processing of Microalgae and Related Activities at Arizona Center for Algae Technology and Innovation (AzCATI) at ASU", Thomas A. Dempster, Bioelectrics Symposium 2013; Karlsruhe, Germany; September 2013.
5. "The Algae Testbed Public Private Partnership -ATP^3" Ron Pate. Algae Biomass Organization, Algae Biomass Summit, Orlando, FL, October 2013.
6. "Composition of Algal Biomass for Biofuels and Bioproducts: High Impact Data and Method Harmonization" **L. Laurens**, E. J. Wolfrum, T. Dempster, J. McGowen, P.T. Pienkos, Algae Biomass Organization, Algae Biomass Summit, Orlando, FL, October 2013.
7. "An Experimental Framework for Performing Long Term Cultivation Trials Across Different Regional, Seasonal, Environmental, and Operational Conditions" John A. McGowen, Bio Pacific Rim Summit, San Diego (December 11th, 2013).

Publications and Presentations

9. "Method Harmonization Efforts for Microalgae Production and Biomass Analyses at Arizona State University's Arizona Center for Algae Technology and Innovation (AzCATI) and the Algae Testbed Public-Private Partnership (ATP^3)" Thomas A. Dempster, 28th Congress of the Phycological Society of Southern Africa, Melkbosstrand, South Africa, January 2014.
10. "Algae Testbed Public Private Partnership (ATP^3): Multi-Region, Long-Term Algae Biomass Cultivation Trials" John A. McGowen, Bio World Congress on Industrial Biotechnology, May 2014.
11. "Overview of Innovative Algae Cultivation Modeling, Diagnostics, and Standardized Analytics Available Through DOE's National Algae Testbed Project – ATP^3" **Philip T. Pienkos,** Ron Pate, John McGowen, Todd Lane, Tricia Gharagozloo, Tom Reichardt, and Lieve Laurens, Symposium of Biotechnology for Fuels and Chemicals, Orlando, FL, May 2014.
12. "Modeling of *Nannochloropsis* sp. Growth in Algae Testbed Unified Field Studies" Patricia Gharagozloo, 5th Congress of the International Society for Applied Phycology, Sydney, Australia, June 25, 2014.
13. "Long term cultivation studies a the Algae Testbed Public-Private Partnership: Preliminary data from the Unified Field Studies" **Philp T. Pienkos**, Valerie Harmon, John McGowen, 4th International Conference on Algal Biofuels, Biomass and Bioproducts (ABBB), Sante Fe, NM, June 2014.
14. "Spectroradiometric monitoring for biomass measurement and predator detection in *Nannochloropsis* sp. cultures." **T. A. Reichardt**, A. M. Collins, J. A Timlin, T. A. Dempster, and J. A. McGowen, 4th International Conference on Algal Biofuels, Biomass and Bioproducts (ABBB), Sante Fe, NM, June 2014.
15. "Driving towards a common language for characterization of algal biomass for biofuels and bioproducts: High impact data and method harmonization," **L. Laurens**, J. McGowen, T. Dempster, P.T. Pienkos, 4th International Conference on Algal Biofuels, Biomass and Bioproducts (ABBB), Sante Fe, NM, June 2014.
16. "Driving towards a Common Language for Algal Biomass for Biofuels and Bioproducts: High Impact of Data and Method Harmonization **L. Laurens**, J. McGowen, T. Dempster, P.T. Pienkos, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
17. "Algae Testbed Public Private Partnership (ATP3): Education and Training Workshops Offer Extensive Hands-On Learning Opportunities" T. Dempster, M. Sommerfeld, S. Manning, Jerry Brand, Poster Presentation, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
18. "Performance Evaluation of the Helix™ Tubular Glass Photobioreactor for High Quality Inoculum Production" **J. A. McGowen**, T. A. Dempster, T. Rosov, and D. Cardello, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
19. "Long Term Cultivation Studies at the Algae Testbed Public Private Partnership: Spring and Summer Season Data Update from the Unified Field Studies" J. McGowen, T. Dempster, P. Pienkos, V. Harmon, Poster Presentation, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
20. "Algae Testbed Public Private Partnership (ATP3): Opportunities to Engage in Open Collaborative Testbed Network Activities" **T. Dempster**, J. McGowen, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
21. "Progress and Perspectives of Large Scale Algae Biomass Harvesting: A Case Study at the ATP3 Testbed" **X. Zhang**, J. McGowen, Q. Hu, M. Sommerfeld, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
22. "Modeling and Optimization of Nannochloropsis oceanica Growth in Seasonal Algae Testbed Unified Field Studies" P.E. Gharagozloo, J. L. Drewry, and T.A. Dempster, Poster Presentation, Algae Biomass Organization, Algae Biomass Summit, San Diego, CA October 2014.
23. "Long Term Cultivation Studies at the Algae Testbed Public Private Partnership (ATP^3): Spring and Summer Season Data Update from the Unified Field Studies". **J. McGowen**, T. Dempster, P. Pienkos, V. Harmon, 3rd Asia-Oceania Algae Innovation Summit, Daejeon, Korea, November 2014.

Publications and Presentations

24. "Enabling Algal Technology development at the Algae Testbed Public Private Partnership (ATP^3): J. McGowen, T. Dempster, **P. Pienkos**, L. Laurens, 3rd Asia-Oceania Algae Innovation Summit, Daejeon, Korea, November 2014. (Invited Talk)
25. "Algae Testbed Public Private Partnership (ATP^3): Enabling Algal Technology Research and Development." **J. McGowen**, BIO Pacific Rim Conference, San Diego, CA, December 2014.
26. P. Pienkos chaired a session at the Pacific Rim BIO Conference in December entitled, "Algae Testbeds: Models for Accelerating Commercialization." The panel included representatives of four algae testbeds: AlgaeParc in The Netherlands, the Algae Testbed Public-Private Partnership (ATP^3) and the Regional Algal Feedstock Testbed (RAFT) in the US, and the Algae Industry Incubation Consortium (AIIC) in Japan.
27. BETO Algae Platform Peer Review, March 25, 2015, Washington DC.
28. "Pond Crashes: Evaluation of ATP^3 Unified Field Study Results to Identify the Primary Factors Affecting Pond Reliability" V. Harmon, **J. McGowen**, T. Lane, E. Knoshaug, T. Dempster, B. Crowe, T. Igou, C. Withstandley, P. Pienkos, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 10th, 2015., San Diego, CA.
29. "Harmonized algal cultivation experiments in the Unified Field Studies: The first year of yield and productivity data from the ATP^3 testbed consortium." **E. Knoshaug**, L. Laurens, V. Harmon, T. Dempster, P. Pienkos, and J. McGowen, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 10th, 2015, San Diego, CA.
30. "Large-Scale Cultivation of Nannochloropsis sp. microalgae on Recycled Water and Harvesting with Centrifugation and Membrane Filtration." **P. Wensel**, J. McGowen, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 9th, 2015, Sand Diego, CA.
31. "Dynamic composition of Nannochloropsis sp. biomass with an emphasis on high-value omega-3 fatty acids." **L. Laurens,** E. Knoshaug, V. Harmon, E. Wolfrum, P. Pienkos, J. McGowen, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 9th, 2015, Sand Diego, CA.
32. "Harvesting Optimization Study for *Nannochloropsis oceanica* for Multiple Seasons and Locations" P. Gharagozloo, Poster Presentation, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 9th, 2015, Sand Diego, CA.
33. "Genetic Evaluation of Pond Crashes During ATP^3 Unified Filed Studies" T. Lane, K. Poorey, D. Curtiss, H. Geng, Poster Presentation, 5th International Conference on Algal Biomass, Biofuels, and Bioproducts, June 9th, 2015, Sand Diego, CA.
34. "ATP^3: A Collaborative Network for Algae Technology Commercial Development" **J. McGowen,** TechConnect World Innovation Conference and Expo, June 15th, 2015, Washington DC.
35. "Algae Testbed Public Private Partnership (ATP^3): Opportunities to Engage in Open Collaborative Testbed Network Activities" **T. A. Dempster** and J. McGowen, 29th Congress of the Phycology Society of Southern Africa, June 23rd, 2015, St. Lucia, South Africa.
36. "MALDI-TOF MS as a Tool for Taxonomic Discrimination and Identification of Economically Significant Microalgae Strains" **T. A. Dempster**, H. Gerken, D.L. Barbano, R. Diaz, L. Zhang, and T.R. Sandrin. 29th Congress of the Phycology Society of Southern Africa, June 23rd, 2015.
37. "ATP^3: A Collaborative Network for Algae Technology Commercial Development" **J. McGowen**, Bioenergy 2015, June 24th,, 2015, Washington DC.
38. "How ATP^3 is Addressing the Challenges of Scale-up in Algae Technology R&D" **J. McGowen**, Bioenergy 2015, June 24th,, 2015, Washington DC.
39. "Genetic Evaluation of Pond Crashes During the ATP3 Unified Field Study", **Poorey, Kunal**, Deanna J. Curtis, Haifeng Geng, Kelly P. Williams, and Todd W. Lane. ABO Summit, Sep 30 - Oct 2, 2015 Washington, DC.
40. "Genetic Evaluation of Pond Crashes During the ATP3 Unified Field Study", **Poorey, Kunal**, Deanna J. Curtis, Haifeng Geng, Kelly P. Williams, and Todd W. Lane. ABO Summit, Sep 30 - Oct 2, 2015 Washington, DC.
41. "Large-Scale and Long-Term Cultivation and Harvesting of *Nannochloropsis* sp. and *Scenedesmus acutus* Microalgae", **P. Wensel**, J. McGowen, T. Dempster, Poster Presentation ABO Summit, Sep 30 - Oct 2, 2015 Washington, DC.

Publications and Presentations

42. "ATP^3 Unified Field Studies: Primary Factors Driving Pond Crashes and Management Strategies in Open Ponds" **V. Harmon**, J. McGowen, P. Pienkos, T. Lane, E. Knoshaug, T. Dempster, B. Crowe, T. Igou, C. Withstandley, M. Saracco, ABO Summit, Sep 30 - Oct 2, 2015 Washington, DC.
43. "Long Term Cultivation Studies at the Algae Testbed Public Private Partnership (ATP^3): Results over one year of Unified Field Studies (UFS)" **B. Crowe**, V. Harmon, J. McGowen, P. Pienkos, T. Lane, E. Knoshaug, T. Dempster, T. Igou, C. Withstandley, M. Saracco, ABO Summit, Sep 30 - Oct 2, 2015 Washington, DC.
44. "The Arizona Center for Algae Technology and Innovation (AzCATI) and the DOE funded Algae Testbed Public Private Partnership (ATP^3)" **J. McGowen.** Invited talk, International Symposium on Algae Biomass (ISAB 2015), University of Tsukuba Algae Biomass Energy System R&D Center (ABES), Tokyo, Japan. November 16-17th, 2015.
45. "Algae Technology Development Progress: Algae Testbed Public Private Partnership Progress and Research Results" Panel Discussion on ATP^3 progress to date. Moderated by **J. McGowen**, with presentations from **T. Dempster, V. Harmon, L. Laurens, K. Poorey.** Bio World Congress on Industrial Biotechnology, San Diego, CA, April 17th-20th, 2016.
46. "Algae Testbed Public Private Partnership: Two Years of Unified Field Study Results to Identify Current State of Technology for Algal Biomass Production." **J. McGowen** TechConnect World Innovation Conference and Expo, Washington, DC. May 22nd-25th, 2016.
47. "The Algae Testbed Public Private Partnership (ATP3): A Platform for Engagement and Access to Industry, National Lab, and Academic Expertise, and World-class Algal R&D Facilities" **J. McGowen.** Invited talk, Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
48. "Seasonal and geospatial variation in algal biomass productivity; measured values from the field" **Hutton, M.** Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
49. "Capturing pond crash signature of atp^3 unified field study using machine learning on 16s amplicon sequencing" **Poorey, K.** Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
50. "Spectroradiometric monitoring for early warning detection of pond crash conditions" **Reichardt, T.A.** Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
51. "Settled algae return to promote reliable bioflocculation in wastewater grown algae" **Swain, C.L.** Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
52. "Large-scale cultivation and de-watering of microalgae using novel vacuum airlift (VAL) system, membrane filtration, and centrifugation **Wensel, P.** Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.
53. "Dynamic composition of the alga Nannochloropsis sp. at five geographical location sites over the course of a full year outdoor production" **Laurens, L.** *Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.*
54. "Identification, characterization, and development of deployable halotolerant algal strains." **Guarnieri, M.T.** *Algal Biomass, Biofuels and Bioproducts 6th International Conference, San Diego, CA, June 26th-29th, 2016.*
55. "The Algae Testbed Public Private Partnership (ATP3): The challenges and rewards of integrated lab to pilot-scale cultivation and downstream processing as demonstrated through ATP^3" **McGowen, J.** *AOAIS 2016, Wuhan China, September 18-20th, 2016.*

ATP3 Algae Testbed Public-Private Partnership

Previous Reviewer Comments

"The Algae Testbed Public-Private Partnership (ATP^3) stood out as **an outstanding resource for the entire community.** The team has served many stakeholders and provided high-quality, multi-regional, long-term growth data to establish the BETO state of technology (SOT). Methods development, standardization, and harmonization have been critical. **ATP^3 is one of several foundational projects that support the program**, including the National Renewable Energy Laboratory's (NREL's) Algal Biofuels Techno-Economic Analysis and Algal Biomass Valorization and Pacific Northwest National Laboratory's (PNNL's) Microalgae Analysis projects."

"Though the project **needs to find a viable path to support itself should DOE funding run out,** so far it appears to be a success. The long-term cultivation trials are also **providing a community service** by working to standardize protocols and provide robust realistic data sets to the field to assist R&D and modeling efforts…."

"ATP^3 **represents the backbone** of the DOE portfolio and represents a singular achievement in standardizing the metrics and methods with which to measure progress."

"ATP^3 is **serving a vital role in supporting the stakeholder community**. Its record of high productivity and the feedback from stakeholders speak to the fundamental value of this project. It would be a serious loss to the community if this function were no longer available, and it seems too early in the evolution of the industry to expect this work to be self-supporting."

"Overall, the ATP3 testbed has provided a valuable resource to the algal production industry. The ATP^3 team has **helped move the industry forward and provide a valuable service to companies** needed to test and prove technologies."

"Overall, this approach offers unique testing **capabilities to early stage projects and provides expertise and technical assistance for enhancing project outcomes**…Success of this project will benefit the state of technology and improve the viability of commercial bioenergy applications throughout many regions and climates."

"Throughout its mandate, the activities of the ATP^3 program have been closely followed by the international algae community on account of the valuable, comprehensive and high quality data it has generated. The ATP^3 leadership and research partners are to be commended for their service to fundamental and applied algal research through their success in gathering, curating, and widely disseminating information that matters. The National Research Council of Canada's Algal Carbon Conversion Flagship Program benefitted directly through discourse and knowledge exchange with the ATP^3 team, as well as through the supply of a significant quantity of algal biomass from the AzCATI site that enabled us to conduct key anaerobic digestion experiments at the pilot scale for biofuels applications. Moving forward, AzCATI has been identified as an important strategic partner for a Canadian algae research and technology network currently in development." (Dr. Stephen O'Leary, Director – NRC Canada's Algal Carbon Conversion Flagship Program).

New Impressions of ATP^3 from current stakeholders

"AzCATI's expertise, facilities, analysis capabilities, and ability to provide algae biomass across a breadth of strains, have been absolutely critical to our success."
- Diversified Technologies

"There are many claims that one technology or innovation is better than another or that one strain outperforms another. We have found that often these claims have a degree of internal bias that is skewed by those trying to sell or develop the technology, strain, method, etc. The ATP^3 test site at ASU/AzCATI gives us the actual side by side parameters that have helped determine what actually works and what is hype." – Commercial Algae Professionals

"ATP^3, through its commitment to high quality data has championed the work of the ABV to establish robust, reproducible, and accurate analytical methodologies. Through its incorporation of these methodologies into its standard practices, ATP3 has helped to set the bar for all other research groups in the BETO portfolio." - NREL Collaborator

"ASU/AzCATI has been able to thrive providing algae cultivation testing service to the industry with remarkable testing facility. This facility offers one of the only unbiased independent locations with adequate technology, personnel and know how to sort thru the multitude of claims and hype prevalent in the industry and drill down to actual quantifiable data that can be benchmarked. All this happened because the funding of DoE through ATP^3 program" -- --Morgan Hill Bioenergy

New Impressions of ATP³ from current stakeholders

Workshop Testimonials

I've returned with a great feeling in my heart. What a fantastic learning/growing experience. (University Professor, Alberta, Canada)

I highly recommend this workshop for anyone at any level involved in algae projects. The instructors focused their presentations toward the appropriate level of the participant's technical knowledge to provide the highest value of learning. The flow of this workshop was excellent and the logistics were perfectly coordinated. This was the best and most valuable workshop that I have ever attended on behalf of my lab. (National Lab Employee, Colorado, USA)

Many thanks for an excellent workshop experience. It was absolutely clear that a great deal of pre-planning and coordination were required to make the workshop run so smoothly at both of the New Mexico locations. The participation of SFCC and LANL was outstanding and every tour, lecture, lab experience and networking event provided a tremendous opportunity for learning and promoting algae. I really appreciate your attention to detail, your organization, and your attitude. (Industry Executive, Hawaii, USA)

Highly instructive and interesting workshop. I especially enjoyed your bioproducts module. Thanks for your intellectual, yet light and fun approach to teaching. (National Lab Employee, New Mexico, USA)

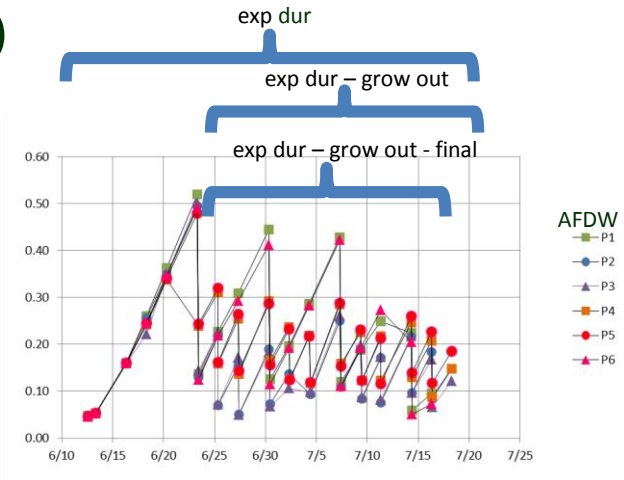
Spring 2016 workshop was superb! Thank you. I literally didn't have a chance to waste even a minute between the time I got off the plane on Monday and until I got back on the plane on Friday. The schedule was well planned out, instructors were extremely knowledgeable and open to answer all the questions I had. I wish all the training workshops that I've attended were organized in the same fashion. This kind of workshop is very important for the algae industry for people and companies that are just starting out and for those that have a ton of experience in the industry. (Industry Representative, California, USA)

I was blown away by how open and willing to help were the instructors. They definitely were not just going by the script; their passion for what they do was evident during every session. I learned a lot. (Industry Representative, California, USA)

I was very impressed with the comprehensive information I received, the valuable networking opportunities, and the overall organization of the event. I appreciate your willingness to share your knowledge, expertise, and resources with others - it is such a valuable quality and will allow for huge gains within the field. Additionally, I loved the fact that the workshop participants included a diverse array of individuals from industry, research, and education. This greatly added to the richness and collective knowledge of the group and allowed for the formation of important connections and novel ideas. I'm excited to use the knowledge and expertise I've gained to establish a thriving algae lab on my campus to introduce students to algae research and the exciting potential of algae to solve many of our current and future world challenges. The workshop greatly exceeded my expectations.
(Community College Instructor, California, USA)

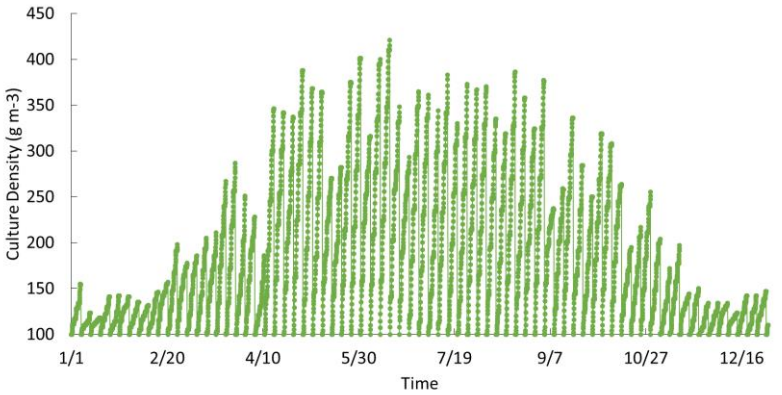
Unified Field Study Productivity

- **Calculation**
  - Harvested yield productivity (harvested biomass (g)/ 4.2 (m^2)/ elapsed time (days)
  - Different from daily changes in AFDW (biological) productivity
- **Calculated over three time ranges**
  - Entire experimental duration (exp dur)
    - Day of inoculation to day of final harvest
  - Without initial grow out (exp dur – growout)
    - Grow out to 0.5 g/L AFDW (1-2 weeks)
  - Without initial grow out and final harvest (exp dur – growout – final)
    - During semi-continuous operation
- **Data fed to TEA/LCA for DOE SOT assessments**

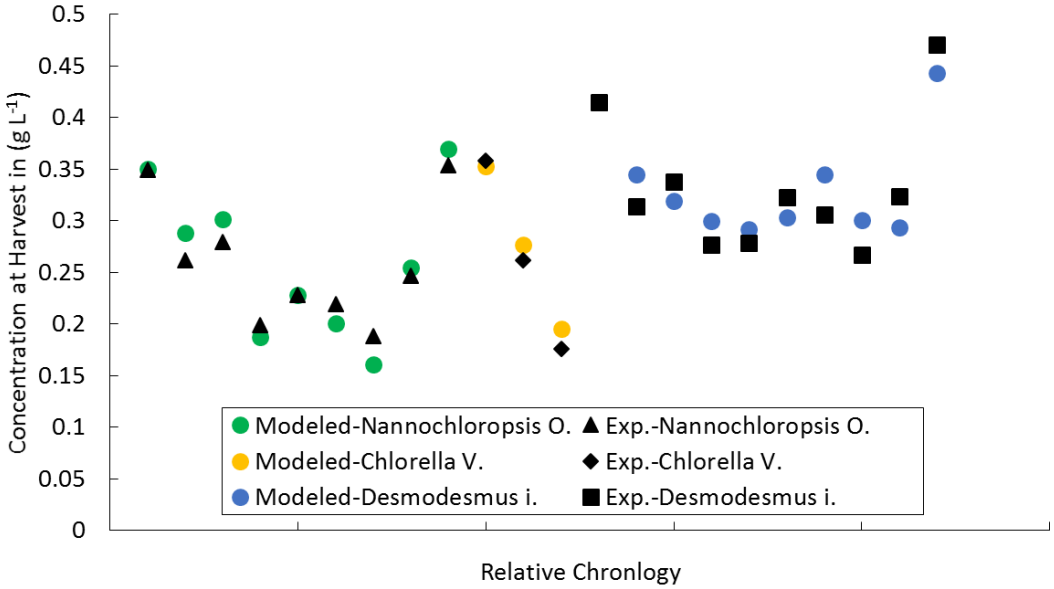


CSU Growth Modeling Validation: Example of external stakeholder using ATP3 Data

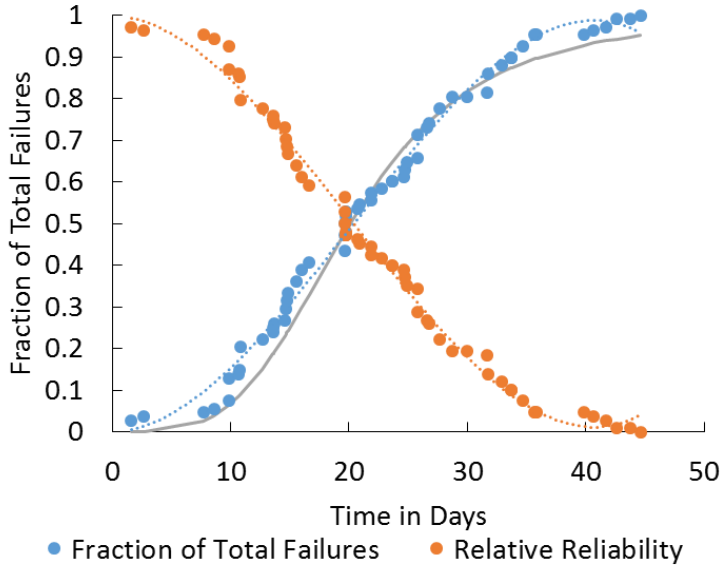
- Validation of a growth model approach for PBRs to ORPs
- Approach successfully applied to *Galdieria s.Nannochloropsis oceanica, Desmodesmus I, and Chlorella V.*
- Stochastic model of culture crashes fit to full ATP3 dataset



ORP Productivity- 1 year



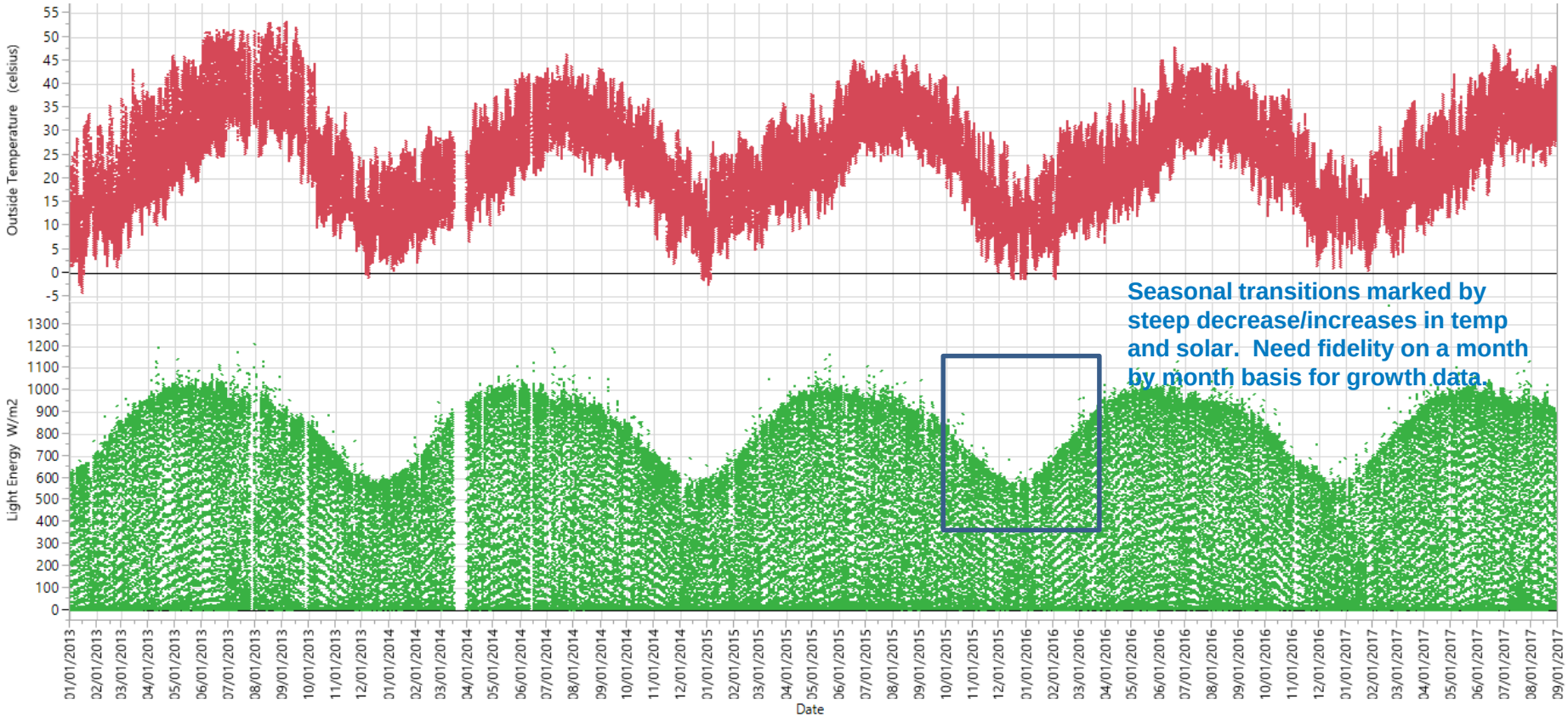
Validation Plot for 2 different species



Culture Failure Modeling

Jason.Quinn@colostate.edu

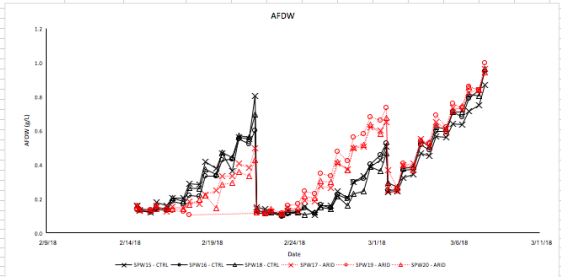
Light and Temp – its what matters (mostly):

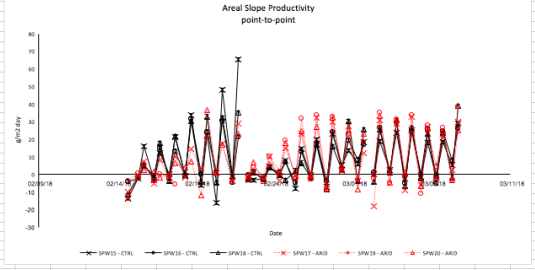


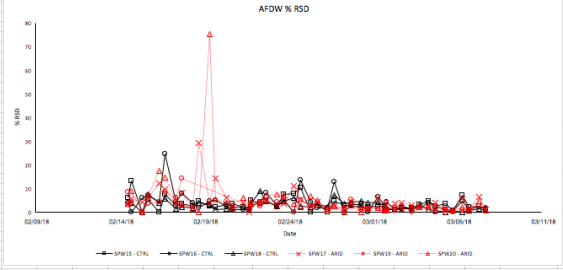
Standard Analytical Spreadsheet for Data Collection

	A	B	C	D	E	F	G	H	I	J
1								Graph Attributes		
2	SiteID		ExperimentID	PondID	StrainID	TreatmentID	Pond Classification	color	symbol	line
3	ASU		Winter2018SOT_26BAM	SPW15	26BAM	CTRL	control	black	x	solid
4	Pond surface area	(m^2)	start month/day/year	SPW16	26BAM	CTRL	control	black	circle	solid
5	including paddlewheel:	4.2	Dates	SPW18	26BAM	CTRL	control	black	triangle	solid
6	lighted only:	3.675	2/14/2018-3/7/2018	SPW17	26BAM	ARID	experimental	red	x	dotted
7	percent shaded:	12.5	Weeks of the year	SPW19	26BAM	ARID	experimental	red	circle	dotted
8	Pond volume	(L)	7-10	SPW20	26BAM	ARID	experimental	red	triangle	dotted
9		400								
10	at depth (cm):	10								

volume filtered remains constant throughout the experiment. If filtering a very small sample volume, it may be helpful to dilute the sample with DI water so that it is spread evenly across the filter. The filter is then stored in an oven overnight at 105°C and weighed the next day to obtain the dry weight. It is then placed in a muffle furnace at 540°C for 2 hours and weighed again to obtain the ash free dry weight.







ASU 26BAM Winter 2018

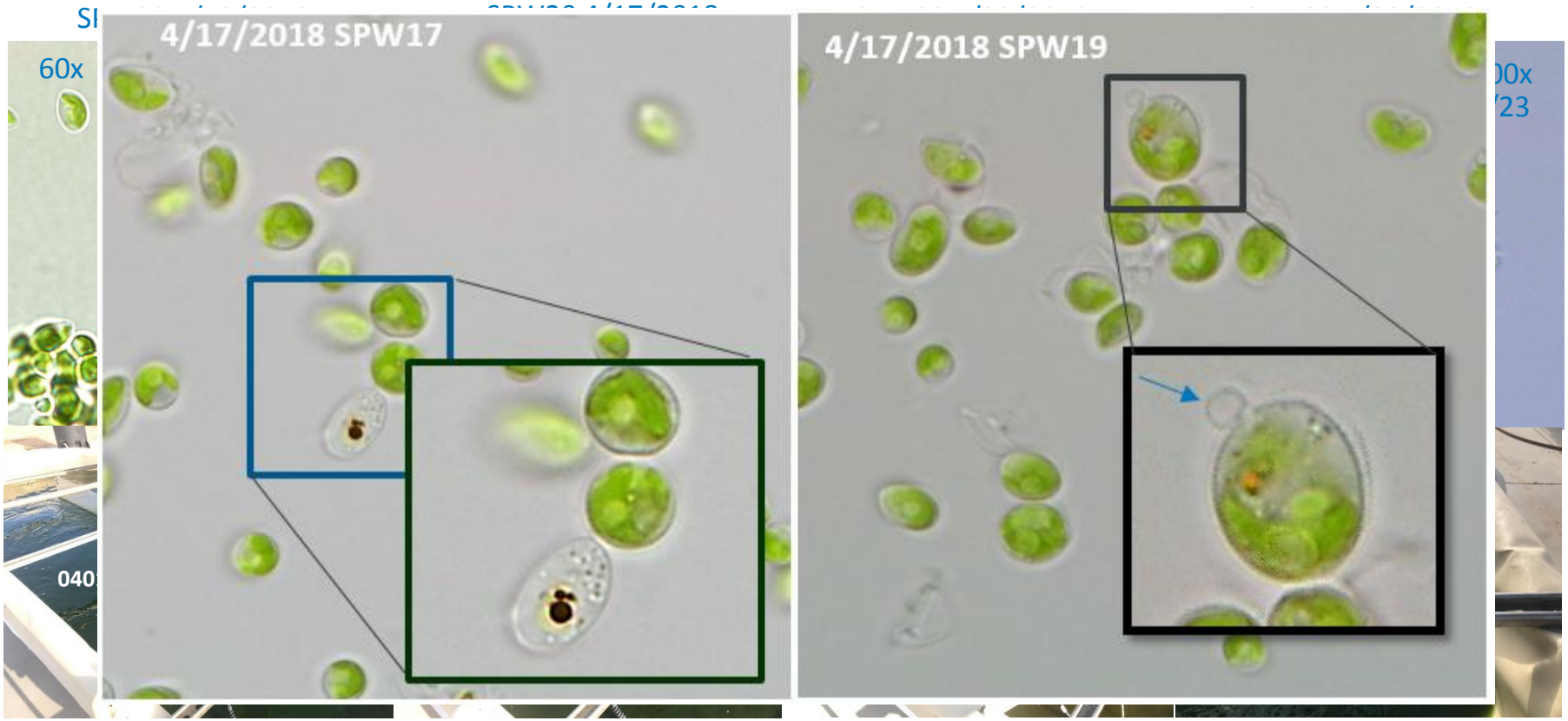
	filter ID			Volume Filtered (mL)			Mass of Filter after ignition at 550C (g)			Mass of Filter + Biomass after baking at 105C (g)			Mass of Filter + Ash after ignition at 550C (g)			Biomass (g)			Ash (g)			DW (g/L)						AFDW (g/L)						%ASH				
StrainID	TrackingID	DateTime	Experiment Duration (Days)	TreatmentID	PondID	filter ID Rep1	filter ID Rep2	filter ID Rep3	vol filter Rep1	vol filter Rep2	vol filter Rep3	mass filter Rep1	mass filter Rep2	mass filter Rep3	filter +bio Rep1	filter +bio Rep2	filter +bio Rep3	filter +ash Rep1	filter +ash Rep2	filter +ash Rep3	biomass-Rep1	biomass-Rep2	biomass-Rep3	Ash-Rep1	Ash-Rep2	Ash-Rep3	DW-Rep1	DW-Rep2	DW-Rep3	DW-AVE	DW-STDEV	DW-%RSD	AFDW-Rep1	AFDW-Rep2	AFDW-Rep3	AFDW-AVE	AFDW-STDEV	AFDW-%RSD	%ASH-Rep1	%ASH-Rep2	%ASH-Rep3	%ASH-AVE	AFDW-initials
26BAM		2/14/18 8:00 AM	0.00	CTRL	inoc																																				
26BAM		2/14/18 8:00 AM	0.00	ARID	inoc																																				
26BAM		2/14/18 12:30 PM	0.00	CTRL	SPW15	536	537	538	10	10	10	0.1037	0.1051	0.1049	0.1053	0.1067	0.1065	0.1037	0.1052	0.1048	0.0016	0.0016	0.0016	0	0.0001	-1E-04	0.160	0.160	0.160	0.160	0.000	-	0.16	0.15	0.17	0.16	0.010	6.25	0.00	6.25	-6.25	0.00	
26BAM		2/14/18 12:30 PM	0.00	CTRL	SPW16	203	204	205	10	10	10	0.1105	0.1106	0.1104	0.1118	0.1121	0.1119	0.1104	0.1106	0.1105	0.0013	0.0015	0.0015	-0.0001	0	0.0001	0.130	0.150	0.150	0.143	0.012	8.06	0.14	0.15	0.14	0.14	0.006	4.03	-7.69	0.00	6.67	-0.34	
26BAM		2/14/18 12:30 PM	0.00	CTRL	SPW18	543	544	545	10	10	10	0.1046	0.1050	0.1036	0.1061	0.1066	0.1051	0.1045	0.1049	0.1035	0.0015	0.0016	0.0015	-0.0001	-0.0001	-0.0001	0.150	0.160	0.150	0.153	0.006	3.77	0.16	0.17	0.16	0.16	0.006	3.53	-6.67	-6.25	-6.67	-6.53	
26BAM		2/14/18 12:30 PM	0.00	ARID	SPW17	539	540	542	10	10	10	0.1031	0.1044	0.1058	0.1046	0.1060	0.1072	0.1031	0.1044	0.1056	0.0015	0.0016	0.0014	0	0	-0.0002	0.150	0.160	0.140	0.150	0.010	6.67	0.15	0.16	0.16	0.16	0.006	3.69	0.00	0.00	-14.29	-4.76	
26BAM		2/14/18 12:30 PM	0.00	ARID	SPW19	206	207	208	10	10	10	0.1107	0.1123	0.1118	0.1121	0.1138	0.1123	0.1108	0.1123	0.1119	0.0014	0.0015	0.0014	1E-04	0	0.0001	0.140	0.150	0.140	0.143	0.006	4.03	0.13	0.15	0.13	0.14	0.012	8.45	7.14	0.00	7.14	4.76	
26BAM		2/14/18 12:30 PM	0.00	ARID	SPW20	546	547	548	10	10	10	0.1027	0.1046	0.1052	0.1043	0.1062	0.1068	0.1026	0.1046	0.1052	0.0016	0.0016	0.0016	-0.0001	0	0	0.160	0.160	0.160	0.160	0.000	-	0.17	0.16	0.16	0.16	0.006	3.53	-6.25	0.00	0.00	-2.08	
26BAM		2/14/18 5:00 PM	0.19	CTRL	SPW15	14	15	16	20	20	20	0.1095	0.1115	0.1105	0.1125	0.1146	0.1136	0.1102	0.1119	0.1106	0.003	0.0031	0.0031	0.0007	0.0004	0.0001	0.150	0.155	0.155	0.153	0.003	1.88	0.12	0.14	0.15	0.13	0.018	13.17	23.33	12.90	3.23	13.15	
26BAM		2/14/18 5:00 PM	0.19	CTRL	SPW16	17	18	19	20	20	20	0.1103	0.1114	0.1104	0.1132	0.1144	0.1133	0.1105	0.1117	0.1106	0.0029	0.003	0.0029	0.0002	0.0003	0.0002	0.145	0.150	0.145	0.147	0.003	1.97	0.14	0.14	0.14	0.14	0.000	0.00	6.90	10.00	6.90	7.93	
26BAM		2/14/18 5:00 PM	0.19	CTRL	SPW18	28	29	30	20	20	20	0.1099	0.1103	0.1102	0.1130	0.1134	0.1134	0.1103	0.1105	0.1105	0.0031	0.0031	0.0032	0.0004	0.0002	0.0003	0.155	0.155	0.160	0.157	0.003	1.84	0.14	0.15	0.15	0.14	0.006	4.08	12.90	6.45	9.37	9.58	
26BAM		2/14/18 5:00 PM	0.19	ARID	SPW17	20	26	27	20	20	20	0.1115	0.1113	0.1112	0.1145	0.1142	0.1143	0.1116	0.1116	0.1116	0.003	0.0029	0.0031	0.0001	0.0003	0.0004	0.150	0.145	0.155	0.150	0.005	3.33	0.15	0.13	0.14	0.14	0.008	5.59	3.33	10.34	12.90	8.86	
26BAM		2/14/18 5:00 PM	0.19	ARID	SPW19	31	32	33	20	20	20	0.1101	0.1105	0.1109	0.1132	0.1137	0.1135	0.1107	0.1110	0.1109	0.0031	0.0032	0.0026	0.0006	0.0005	0	0.155	0.160	0.130	0.148	0.016	10.84	0.12	0.14	0.13	0.13	0.005	3.85	19.35	15.63	0.00	11.66	
26BAM		2/14/18 5:00 PM	0.19	ARID	SPW20	34	35	36	20	20	20	0.1107	0.1119	0.1106	0.1137	0.1149	0.1136	0.1107	0.1124	0.1108	0.003	0.003	0.003	0	0.0005	0.0002	0.150	0.150	0.150	0.150	0.000	0.00	0.15	0.13	0.14	0.14	0.013	9.10	0.00	16.67	6.67	7.78	
26BAM		2/15/18 8:00 AM	0.81	CTRL	SPW15	91	92	93	20	20	20	0.1113	0.1108	0.1099	0.1142	0.1139	0.1127	0.1118	0.1105	0.1103	0.003	0.0029	0.0028	0.0006	0.0005	0.0004	0.150	0.145	0.140	0.145	0.005	3.45	0.12	0.12	0.12	0.12	0.000	0.00	20.00	17.24	14.29	17.18	
26BAM		2/15/18 8:00 AM	0.81	CTRL	SPW16	94	95	96	20	20	20	0.1116	0.1097	0.1095	0.1144	0.1125	0.1123	0.1120	0.1099	0.1100	0.0028	0.0028	0.0028	0.0004	0.0002	0.0005	0.140	0.140	0.140	0.140	0.000	-	0.12	0.13	0.12	0.12	0.008	6.28	14.29	7.14	17.86	13.10	
26BAM		2/15/18 8:00 AM	0.81	CTRL	SPW18	103	104	105	20	20	20	0.1098	0.1108	0.1097	0.1128	0.1138	0.1125	0.1101	0.1111	0.1098	0.003	0.003	0.0028	0.0003	0.0003	1E-04	0.150	0.150	0.140	0.147	0.006	3.94	0.14	0.14	0.14	0.14	0.000	0.00	10.00	10.00	3.57	7.86	
26BAM		2/15/18 8:00 AM	0.81	ARID	SPW17	100	101	102	20	20	20	0.1111	0.1104	0.1109	0.1140	0.1133	0.1138	0.1114	0.1107	0.1110	0.0029	0.0029	0.0029	0.0003	0.0003	0.0001	0.145	0.145	0.145	0.145	0.000	-	0.13	0.13	0.14	0.13	0.006	4.33	10.34	10.34	3.45	8.05	
26BAM		2/15/18 8:00 AM	0.81	ARID	SPW19	1	2	3	20	20	20	0.1106	0.1091	0.1097	0.1133	0.1122	0.1127	0.1106	0.1095	0.1100	0.0027	0.0031	0.003	0	0.0004	0.0003	0.135	0.155	0.150	0.147	0.010	7.10	0.14	0.14	0.14	0.14	0.000	-	0.00	12.90	10.00	7.63	
26BAM		2/15/18 8:00 AM	0.81	ARID	SPW20	4	5	6	20	20	20	0.1097	0.1098	0.1098	0.1126	0.1126	0.1126	0.1100	0.1100	0.1100	0.0029	0.0028	0.0028	0.0003	0.0002	0.0002	0.145	0.140	0.140	0.142	0.003	2.04	0.13	0.13	0.13	0.13	0.000	-	10.34	7.14	7.14	8.21	
26BAM		2/15/18 5:00 PM	1.19	CTRL	SPW15	385	386	387	10	10	10	0.1106	0.1105	0.1128	0.1124	0.1126	0.1147	0.1106	0.1107	0.1130	0.0018	0.0021	0.0019	0	0.0002	0.0002	0.180	0.210	0.190	0.193	0.015	7.90	0.18	0.19	0.17	0.18	0.010	5.56	0.00	9.52	10.53	6.68	
26BAM		2/15/18 5:00 PM	1.19	CTRL	SPW16	388	389	390	10	10	10	0.1109	0.1107	0.1129	0.1125	0.1124	0.1145	0.1112	0.1110	0.1130	0.0016	0.0017	0.0016	0.0003	0.0003	0.0001	0.160	0.170	0.160	0.163	0.006	3.53	0.13	0.14	0.15	0.14	0.010	7.14	18.75	17.65	6.25	14.22	
26BAM		2/15/18 5:00 PM	1.19	ARID	SPW18	394	395	396	10	10	10	0.1100	0.1114	0.1117	0.1146	0.1131	0.1135	0.1100	0.1117	0.1119	0.0016	0.0017	0.0018	0	0.0003	0.0002	0.160	0.170	0.180	0.170	0.010	5.88	0.16	0.14	0.16	0.15	0.012	7.53	0.00	17.65	11.11	9.59	
26BAM		2/15/18 5:00 PM	1.19	ARID	SPW17	391	392	393	10	10	10	0.1117	0.1102	0.1092	0.1133	0.1118	0.1110	0.1117	0.1103	0.1093	0.0015	0.0017	0.0018	0	1E-04	1E-04	0.150	0.170	0.180	0.167	0.015	9.17	0.15	0.16	0.17	0.16	0.010	6.25	0.00	5.88	5.56	3.81	

DateTime	SPW15	SPW16	SPW18	SI
2/14/18	0.16			
2/14/18		0.14		
2/14/18			0.16	
2/14/18				
2/14/18	0.13			
2/14/18		0.14		
2/14/18			0.14	
2/14/18				
2/14/18	0.12			
2/14/18		0.12		
2/14/18			0.14	
2/14/18				
2/15/18	0.18			
2/15/18		0.14		
2/15/18			0.15	
2/15/18				

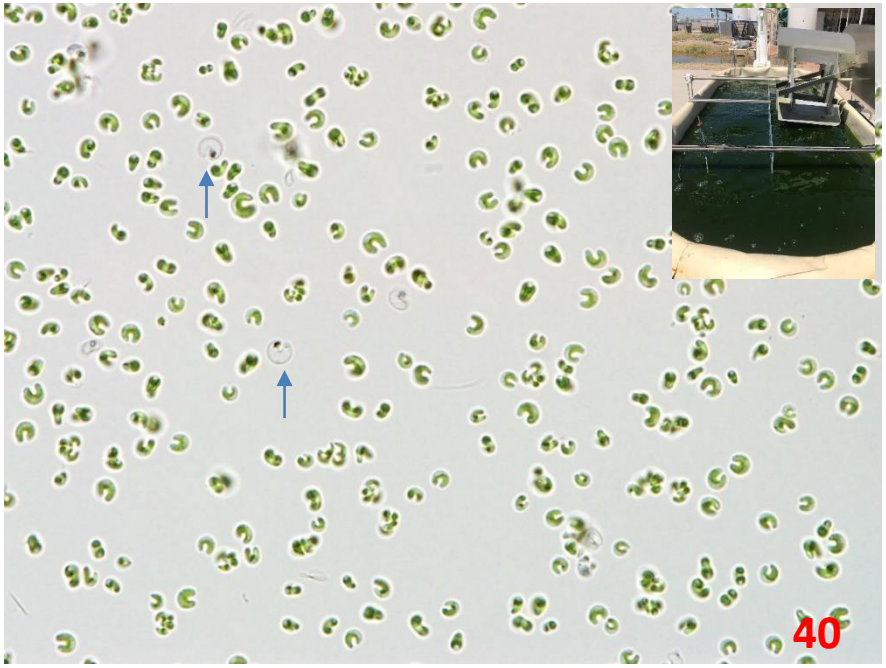
Experiment Description | Daily-Nutrient-Depth-Temp | OD | AFDW | Harvest Ops | activity log | OD-AFDW correlation | YSIDataContinuous | YSI plots | WeatherDataContinuous | contamination check | Individual Pond Graphs | +

Tabs for data capture and automated analysis/graphing

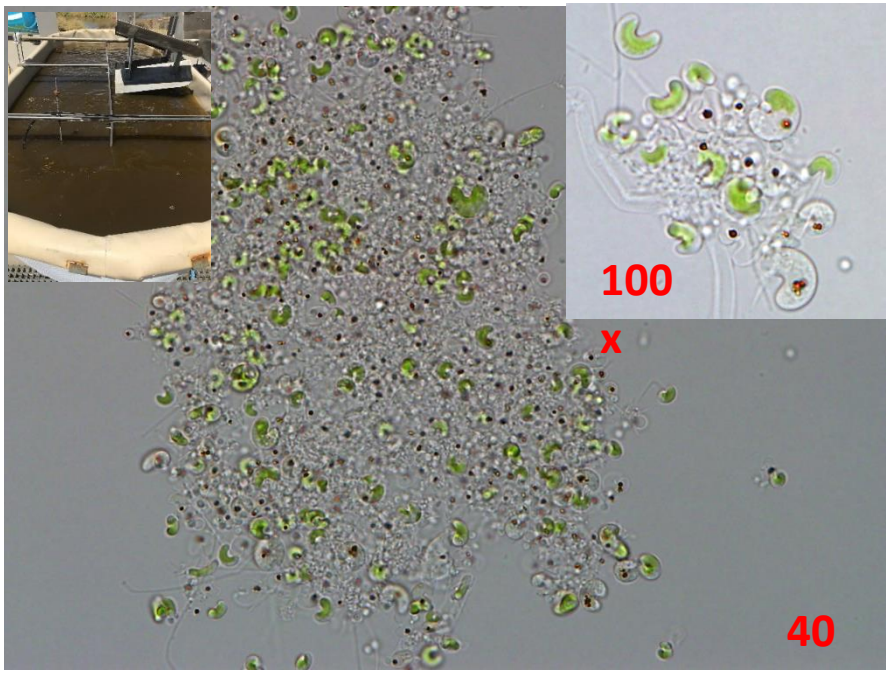
Main contamination issue for AzCATI Spring/Summer 2018



Main contamination issue for AzCATI Spring/Summer 2018



Chytrid infection easy to spot – a few ghost cells with brown spot, but early on not a lot of color change in culture, and no clumping/settling. For 26BAM – this level of infection can be stable for >3-4 weeks before progressing to culture collapse. For 0401, will show up and progress to culture collapse in <1-2 weeks.



As infection progresses, clumping/settling increases and macro change in color of culture from green to brown (in 1-2 days). 26BAM much more robust to chytrid than 0401…

ATP3 Algae Testbed Public-Private Partnership

ATP³ Workshop Participant Affiliations

> 80

AAAS
Algasol
Algenuity
AlgEternal
Algoma Algal Biotechnology LLC
Arizona State University
ARPA (Italy)
ASCONIT Consultants
Auburn University
Baker Hughes
BIOMEX
Bio-Rad
Boom Algae LLC
Bowie State University
Catalonia Department of Agriculture
Cawthron Institute
CDM I & E, Inc.
Clemson University
Continuum Energy Technologies
Department of Energy
Drexel University
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Essential Formulas
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Fluid Imaging Technologies
Grande Prairie Regional College
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Heliae
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