ATP3 Algae Testbed Public-Private Partnership

# 2013 DOE Bioenergy Technologies Office Algae Platform Review

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Arizona State University

May 23, 2:00 pm

# Vision

The ATP$^3$ vision is to establish a **sustainable network of regional testbeds** that empowers **knowledge creation and dissemination** within the algal biofuels community, facilitates innovation, and **accelerates growth** of the nascent algal fuels industry.

# Goals

The ATP$^3$ goal is to create a **network of operating testbeds**, bringing together world-class scientists, engineers and business executives to lead the effort to increase **stakeholder access to high quality facilities** by making available an unparalleled array of outdoor cultivation, downstream process equipment, and laboratory facilities tightly managed by a multi-institutional and transdisciplinary team.

ATP$^3$ will utilize that same powerful combination of facilities, technical expertise, and management structure to **support DOE's techno-economic, sustainability, and resource modeling** and analysis activities, helping to close critical knowledge gaps and inform robust analyses of the state of technology for algal biofuels.

# Objectives

**Collaborative Open Testbeds (Function 1)**

- Provide access to a geographically diverse network of algal biomass production facilities.
- Through our infrastructure, enable the acceleration of applied algae research, development, investment, and commercial applications for biofuel feedstock.

**High Impact Data (Function 2)**

- Design and implement unified experimental programs across network of testbed sites.
- Harmonize requirements of computational models with practical, realistic & objective experimental design.
- Execute long term cultivation trials and publish data.

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# Quad Chart Overview

## Timeline

- **Project start date: 2/1/2013**
  - Pre-Award (at risk) 11/12-1/13
- **Project end date: 1/31/2018**
- **Percent complete: 5%**

## Budget

**Total project cost: $17.05M**
**DOE Commitment ($15M)**

- Function 1: $7.3M
  - **DOE share: $5.25M**
  - Contractor share: $2.05M
- Function 2: $9.75
  - **DOE share: $9.75M**
  - Contractor share: N/A

**Funding received in FY13: $4.6M**
**Funding for FY14: $4.3M**

## Barriers

- **Ft-B** Sustainable Production**:** Existing data on the productivity and environmental effects of biomass feedstock production systems…are not adequate
- **St-E** Best Practices for Sustainable Bioenergy Production
- **At-A/At-C** Lack of comparable, transparent and reproducible analysis and inaccessibility and unavailability of data

## Partners

ASU (AzCATI)
National Renewable Energy Laboratory
Sandia National Laboratories
Cellana
Cal-Poly
Touchstone Research Laboratory
Georgia Tech
UTEX
Commercial Algae Management
Valicor Renewables

# Project Approach: Project Timeline

**ATP$^3$ Phases:**

1. **<u>Months 1-12</u>**: Coordinate mobilization of partnership and initiate work to perform both functions – **Go/No Go for Phase 2.**

   **Major Milestones:**

   - ATP organization, systems and **processes established**
   - Methodologies **harmonized** across all partner sites
   - Initial cultivation trial and detailed **experimental planning completed**
   - Biomass stocks **generated**

2. **<u>Months 13-36</u>**: Long term cultivation trials implementation and building customer base as a user facility – **Go/No Go for Phase 3**

   **Major Milestones:**

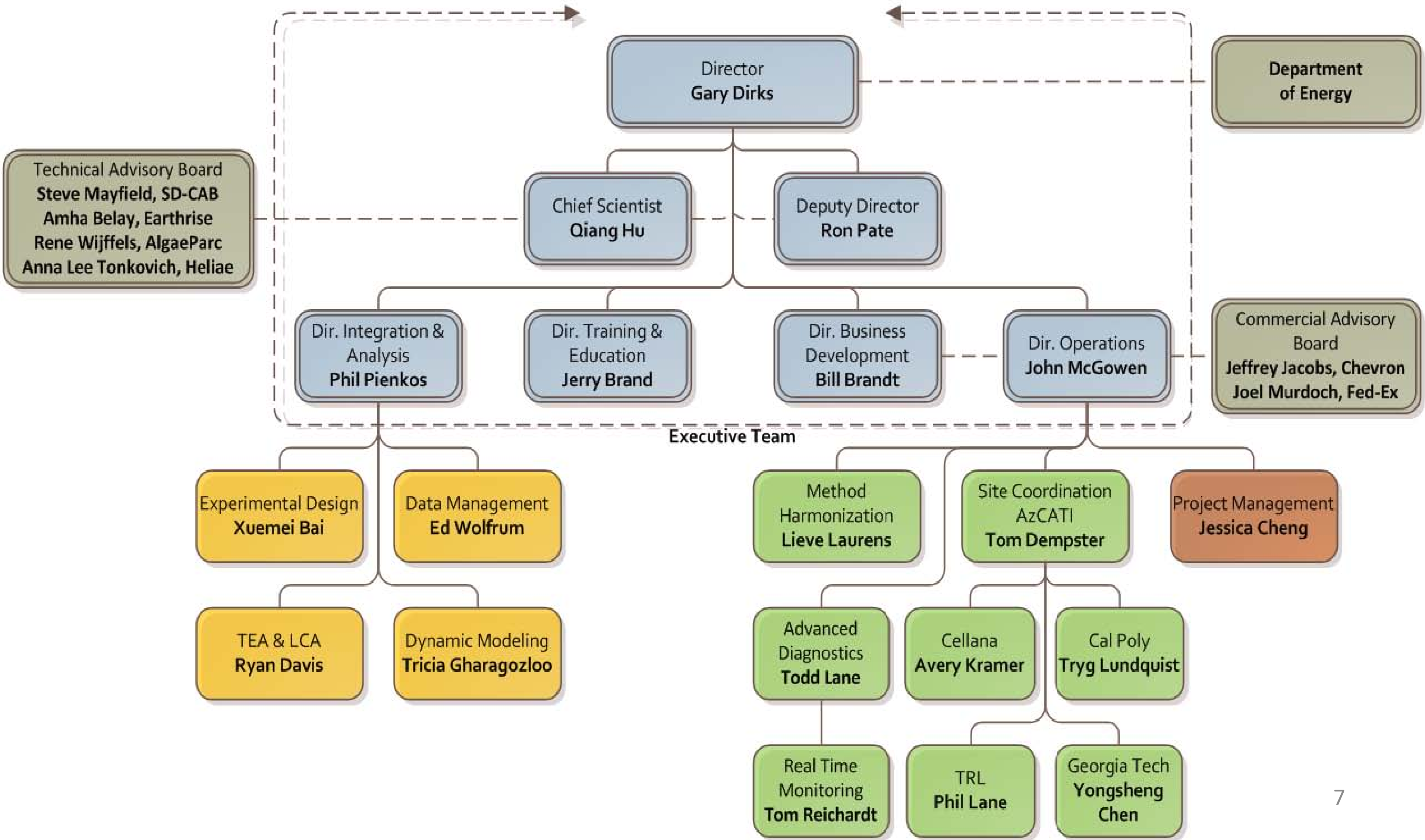
   - Cultivation trials executed, data distribution implemented and **state of algal biofuels technology design report** completed
   - Capability of testbed network to **serve stakeholder community** demonstrated

3. **<u>Months 37-60</u>**: Sustainable Testbed Operations.

   **Major Milestones:**

   - State of algal biofuels technology design report updated with customer data
   - Value network created and funding secured to **sustain network** in out years

# Project Approach: Organization



# Active Management: Director Processes

In order to ensure that ATP3 achieves its goals efficiently, the executive team under the Director will follow a core set of management processes. The processes are primarily aimed at internal coordination and performance management, but will include communication with key stakeholders.

**Core Processes**

- In alternate weeks the Director will lead an executive team call to review performance and set priorities.
- In alternate weeks the Director will lead a coordination call with the Directors of Integration and Analysis, Business Development and Operations to discuss coordination issues.
- Director will attend and when appropriate lead reviews with the CAB and TAB, DOE and all hands.
- Yearly All-Hands meeting

# ATP3 Kick-Off Meeting April 15-18th, 2013

**50+ attendees for 3 days of project planning and review**

- Met with members of both TAB and CAB and reviewed overall program
- Full team brought together for 2½ days of full technical review of all the major program elements
- Workshops held on method harmonization, mini pond (YSI) data acquisition, project communications (Sharepoint)
- Team building and networking

# Active Management: Coordination Teams

- Team Coordination Telecoms
  - Integration and Analysis and Operations
    - Alternating weekly telecom between the lead sub teams
      - Analytical Protocols and Data Management
      - Production Protocols and Data Management
  - Experimental Design
    - Bi-weekly calls led by Experimental Design Lead with modeling, and site leads
      - Phase 1 focus is on detailed planning for Phase 2
  - Business Development and Operations
    - Monthly calls led by Dir. Bus Dev., Dir. of Ops and Site Leads
      - Focus on opportunities, scheduling, ongoing activities for Function 1
      - Quarterly calls with boards as Scholarship/Innovators program comes on-line

# Technical Plans and Progress to Date

# Work Breakdown Structure: Function 1

| Table 1. Activities, schedule, and budget | | | Time (month) |
|---|---|---|---|
| 1.0 Collaborative Open Testbed ($7.3M) | 1.1 | **Operations** - Assemble a network of geographically diverse sites to carry out integrated testbed operations. | 12-60 |
| | | **Milestone:** Organized and operational set of testbed facilities (Go/No Go) | |
| | | **Deliverable**: Generate minimum of 500 kg of biomass plus 50 L of oil and residuals and make available to algae R&D stakeholder community | 12 |
| | 1.2 | **Business Development and Marketing of Testbed** – establish a sustainable network of regional testbeds | |
| | | **Deliverable:** IP management plan, tiered fee structure, user facility marketing plan established. | 12 |
| | | **Milestone:** Demonstration of TF's capability to serve customers (Go/No-Go) | 36 |
| | | **Deliverable:** Partner Participation Program fully active and funding continued operations | 48-60 |
| | 1.3 | **Training and Education** – Develop and deploy high quality training and education programs. | |
| | | **Deliverable:** Training workshops, and integrated ATP$^3$ website for dissemination of best practices/protocols. | 12-60 |

# Function 1: Key Elements for a Successful Collaborative Open Testbed

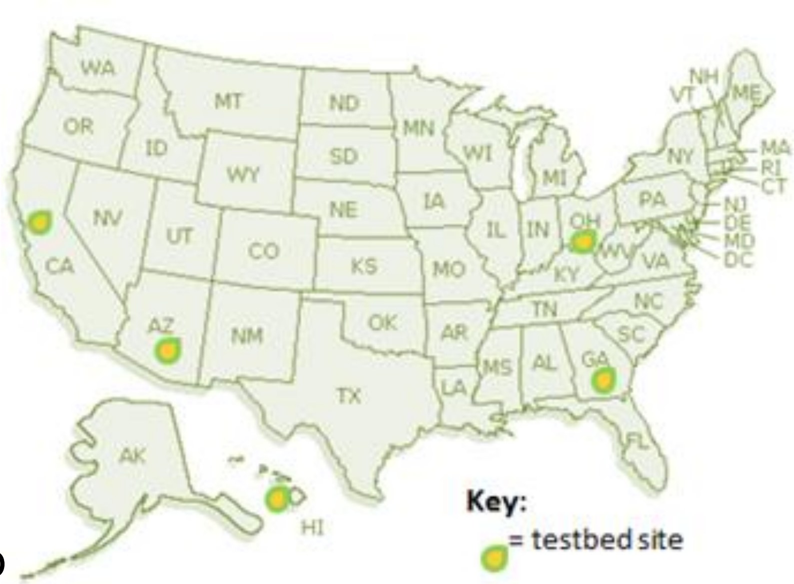
- Leverages **existing test bed facilities**, resources and expertise through an integrated partnership between academia, industry, national labs.
- **High volumetric capacity** and process flexibility in cultivation and **baseline downstream technologies** available and "**Plug and Play**" capability for additional/new technologies
- Internationally recognized team of **experts**
- **Robust** analytical capabilities
- Detailed **site access plan**: One stop shopping – single point of contact for customers for coordination of projects across the partnership
- **Experimental management** of outdoor cultivation trials and established **Scientific Data Management System**
- **Training and Education** capacity

# Function 1: Testbed Services & Data

**ATP³ offers a wide array of services:**

- strain identification, isolation & documentation
- analytical testing
- education & training
- equipment testing & validation
- biomass production and supply
- improved stakeholder access to facilities

**ATP³ functions as a multi-regional testbed to provide high quality data** for the algal research community supporting the operation of existing outdoor algae cultivation systems, allowing researchers to access to real-word conditions for algal biomass production for biofuel and performing long-term cultivation trails.




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

# Variety of Cultivation Systems, Types, and Scale

| ATP³ Partner Site | Cultivation Capacity Total (Liters) (unit scale range) | | Annual Production Capacity (AFDW) | Yr. Outdoor Operations Began |
|---|---|---|---|---|
| | Open Pond | Closed PBR | | |
| ASU (AzCATI) | 235,000 (200 - 125K ) | 21,000 (15 – 1500) | 1.5 –2.0 MT | 2006 |
| Cellana (KDF) | 750,000 (200 - 120K) | 300,000 (20 – 24K) | 12 – 15 MT | 2008 |
| Touchstone (TRL) | 450,000 (500-115K ) | 9000 (75 – 750) | 3 – 6 MT* | 2012 |
| Cal Poly | 100,000 (1000- 10K) | 1200 (200-1000) | 1.0- 1.5 MT | 2007 |
| Georgia Tech. (GT) | 6000 (500-1000) | 200 (indoor only) | < 0.1 MT* | N/A |
| **Total** | **1,540,000 L** | **330,000L** | **17.5 – 24.5 MT** | |

* Expected capacity





# Variety of independent and vertically integrated downstream harvesting unit ops

**I. Provide service to ATP³ customers**

a. Produce algal biomass in the form of slurry, paste and dry powers

b. Serve as baseline technologies for the improvement of future harvesting/dewatering and oil extraction processes

**II. Support DOE’s TEA, sustainability, and resource modeling**

a. Generate harvesting data for the current harmonized model

b. Provide more options to generate data on the selection of harvesting methods

c. Provide feedstock for lipid extraction and other downstream product applications


# Site Access and Customer Management

**ATP$^3$ will offer a 3-tier fee structure based on user requirements for data confidentiality and IP ownership.**

- Platinum: Full data confidentiality (fully burdened rate)
- Gold: Willing to share data generated at test bed (discounted)
  - level of discount site specific
- Subsidized Access (Scholarship and Innovators Awards)
  - Support proposals for use of the testbed and provide access to materials, equipment, personnel
  - Travel support may be made available
  - First call for proposals Fall 2013 with first projects early 2014.

**ATP$^3$ partners already have IP Management Plan in place (complete at time of proposal submission)**

- Standard IP, MTA, NDA, and facilities use agreement in progress for customers and builds off same language and principles already agreed to by partners.

**AzCATI has already been operating under this framework for multiple years.**

# Progress to Date

- Program Management
  - Notice of Award September 2012
  - Contract negotiations begun November 2012
  - Contract completed end of January 2013
  - Official start date February 1, 2013
  - All subcontracts executed
- Pre-award (at-risk) activities focused on:
  - Function 1 activities
    - Expanding detail for implementation of site access plan and facilities use agreement framework
    - Standard pricing fee established (AzCATI) as model for remainder of sites
    - Website (www.ATP3.org) live as of February 1st, 2013
    - Early exercising of this system through the ABY FOA (use of facilities priced out for 4 proposals, 3 submitted).
    - **First ATP$^3$ workshop held week of May 6th, 2013.**

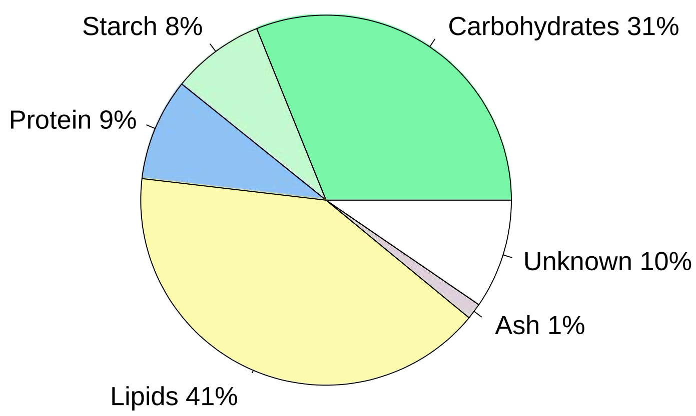
# Function 2: Work Breakdown Structure

| **Table 1.** Activities and Major Deliverables | | | **Time (month)** |
|---|---|---|---|
| 2.0 High Impact Data ($9.75M) | 2.1 | **Setting Standards** - Identify and implement current best practices across our partner sites with a strong focus on continuous improvement | |
| | *2.1.1* | Harmonized Methods for Analytical/Production Metrics - establish standards for analysis that streamline reporting on biomass production and composition and expected fuel yields from biomass<br>**Deliverable:** Harmonized methodologies and documented protocols for determination of biomass productivities and analysis of biomass and co-products (Go/No Go Deliverable) | 12 |
| | *2.1.2* | Data management - Establish web-based Scientific Data Management System (SDMS) with layered security to protect data<br>**Deliverable:** SDMS implemented and operational (Go/No Go Deliverable)<br>**Deliverable:** Demonstrated data collection/transmission among partners and customers | 12<br>24-48 |
| | *2.1.3* | Advanced diagnostics and real-time monitoring - microscopic visualization, real-time productivity monitoring and state-of-the-art metagenomic population analysis for production strains, contaminants, pathogens and predators in order to establish predator-prey relationships and impact assessment<br>**Deliverable:** Monitoring protocols established at all sites and real-time diagnostics tools deployed at minimum of one site (and at multiple sites) | 12 (24) |

# Harmonizing Productivity and Analytical Measurements for High Quality Data

## Composition of Biomass

- Yield calculations and process economics dependent on individual measurements
- Process and Biomass mass balance determine target metrics
- Establishment of common language for unambiguous biomass analysis




**Productivity metrics:**

- Volumetric Dry Weight
- Ash Free Dry Weight
- Lipids
- Carbohydrates
- Protein
- ➢ Integrated Mass Balance Analysis

# Productivity and Analytical Metrics

- 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…

# Productivity and Analytical Metrics

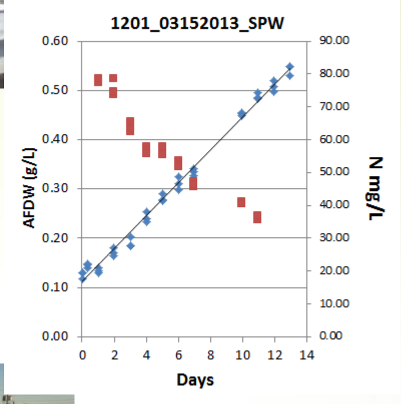
- ATP$^3$ will mitigate this variation via:
  - adoption of a uniform design of indoor seed cultivation and outdoor pond design
  - uniform (and automated) water quality monitoring on outdoor production units (YSI)
  - rigorous verification and validation of production methodologies for measuring biomass productivity and indoor and outdoor cultivation SOP's
  - standardized data reporting and analysis
- Harmonization in Phase 1 (i.e. yr 1) is primary focus of Function 2 activities.

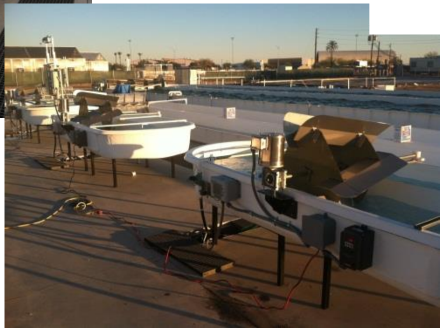
# Function 2: Progress to Date

- Pre-award (at-risk) activities focused on:
  - Function 2 Activities:
    - Early harmonization and alignment of sites
    - Baseline understanding of capabilities through detailed site visits
    - Design and implementation plans for systems (seed and mini-pond)
    - Detailed schedule for Phase 1 harmonization activities established and weekly coordination calls underway
    - Methods harmonization has begun: data modeling needs captured, data management structure established, methods harmonization framework designed and being exercised
    - Testbed site personnel attended workshop at AzCATI May 6-10, 2013
    - Experimental design planning for Phase 2 has begun

# Function 2: Progress to Date

## Pre-award thru Q1-Q2 acceleration activities for harmonization



# Function 2: Work Breakdown Structure (cont.)

| Table 1. Activities, schedule, and budget | | | Time (month) |
|---|---|---|---|
| 2.0 High Impact Data ($9.75M) | 2.2 | **Long Term Outdoor Cultivation Trials** | |
| | *2.2.1* | Design, validate and implement experimental framework for cultivation trials (UFS, AFS) | |
| | *2.2.2* | **Milestone:** Initial cultivation trials complete<br>**Deliverable:** Phase I Report and Detailed Plan for Phase II Long Term Cultivation Trials (Go/No-Go)<br>**Deliverable:** UFS and AFS complete and data made available (interim/final) | 12<br>24/36 |
| | *2.2.3* | TEA/LCA - update a benchmark case to represent today's state of technology, first based onATP$^3$'s own work and then updated with work done for customers<br>**Deliverable:** Design Report and State of Algal Biofuels Technology (initial report based on Phase I and early Phase II data/update based on completed UFS/AFS/final based on additional customer data | 24/36/48 |
| | *2.2.4* | Dynamic Modeling - implement and validate existing physics-based computational fluid dynamics model to enhance predictive capability for determining biomass productivity from different cultivation systems across a wide range of scales, environmental and operating conditions<br>**Deliverable:** Estimation of annual productivity at different geographic locations based on mini-pond systems (month 12) and then large raceways and other production systems (at one/multiple ATP$^3$ sites month 24/36) | 12/24/36 |

# Input Needs From the Modeling Community

**Summary of key modeling inputs captured for:**

- TEA (NREL Aspen models)
- LCA (ANL GREET models, input provided from Ed Frank)
- RA (PNNL BAT models, input provided from Mark Wigmosta)
- Strain productivity models (PNNL, input provided from Michael Huesemann)
- Physics-based modeling (Sandia, input provided from Tricia Gharagozloo)

# Modeling inputs: cultivation

| Metric | Units | Notes |
|---|---|---|
| Water evaporation rate from ponds | cm/day | Daily basis if available (modelers can aggregate as needed) |
| Precipitation | cm/day | Precipitation data, “as available” from weather events |
| Air temperature | °C | Hourly basis if available |
| Dew point temperature | °C | Hourly basis if available |
| Water (culture) temperature | °C | Hourly basis if available |
| Air pressure | mm Hg | Hourly basis if available |
| Wind speed | m/s | Hourly basis if available |
| Solar radiation/insolation | $w/m^2$ | Hourly basis if available |
| PAR (photosynthetically active radiation) | $umols/m^2$-sec | Hourly basis if available |
| Algal biomass productivity | $g/m^2/day$ (afdw basis) | Daily basis (modelers can aggregate into monthly or seasonal basis as needed) |
| Oil content | Dry wt% (afdw basis) | • Oil content associated with the point when algal biomass is harvested from ponds (continuous basis or end of batch cycle, etc)<br>• Total “FAME” measurement (total “fuel potential”) |
| Algal biomass elemental analysis | CHONSP (afdw basis) | • Most important are C,N,P; models also track H,O; S is helpful if available<br>• Most helpful for models is *average* elemental composition over the growth cycle |
| Algal biomass component analysis | Dry basis | • Protein, “oil” ( “total FAME” as per above), carbohydrate, ash, etc<br>• Helpful to have average composition over the duration of the growth/harvesting cycle, as well as at the point of harvesting (eg, associated with the same “oil” content as per above) |
| Algal biomass concentration | g/L | Daily basis; most important is concentration at harvest |
| Light absorption coefficient | ?? | Needed for strain productivity modeling (Huesemann model) |
| Light extinction coefficient | ?? | Needed for Sandia physics-based modeling |
| Water salinity | mg/L | Salinity of ponds (include note for freshwater vs saline strain), hourly basis |
| Water pH | pH | Hourly basis if available |
| Pond downtime (unplanned) | % of month | % of downtime due to unplanned events (pond crashes, emergency maintenance, etc) |
| Pond mixing energy | $KWh/day/m^3$ volume | Only relevant at large scale |

# Data collection/dissemination

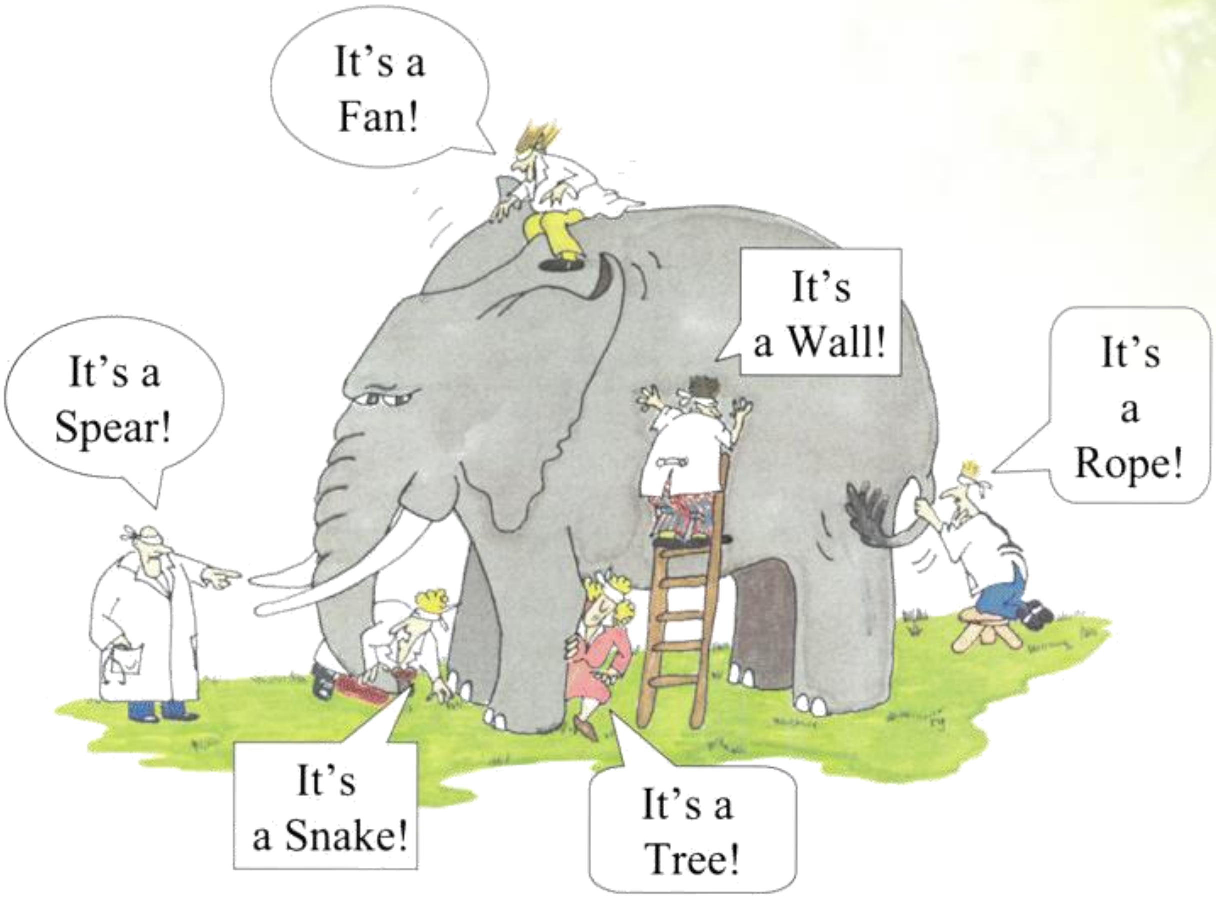
**Data collection: Viewpoint from the Modelers**

- How will data be made available in database?
- Frequency of data generation (e.g., weather data on hourly basis vs frequency of productivity data vs biomass composition)
- Most useful way to understand by modelers
  - Need units for each data metric
  - Need explanation for what each data metric is and how it was measured
  - Need explanation for the premise of each experiment/cultivation run (can be attached separately)
    - Strain, mode of operation (batch vs continuous), saline vs freshwater, etc

# ATP$^3$ data management in 1 slide…

- ATP$^3$ will use a web-based scientific data management system (SDMS) to store & retrieve data about samples
  - Existence & Location (what & where they are)
  - Composition (what they look like)
  - History (how were they produced)
- Standardizing how we collect and store these data across all ATP$^3$ sites is absolutely necessary for success
  - Each site will use standardized spreadsheets to collect defined primary data about samples & experiments
  - Local data champions at each site are responsible for getting data into the system
  - NREL will host & maintain the web-based system

# How We "See" Algal Cultivation



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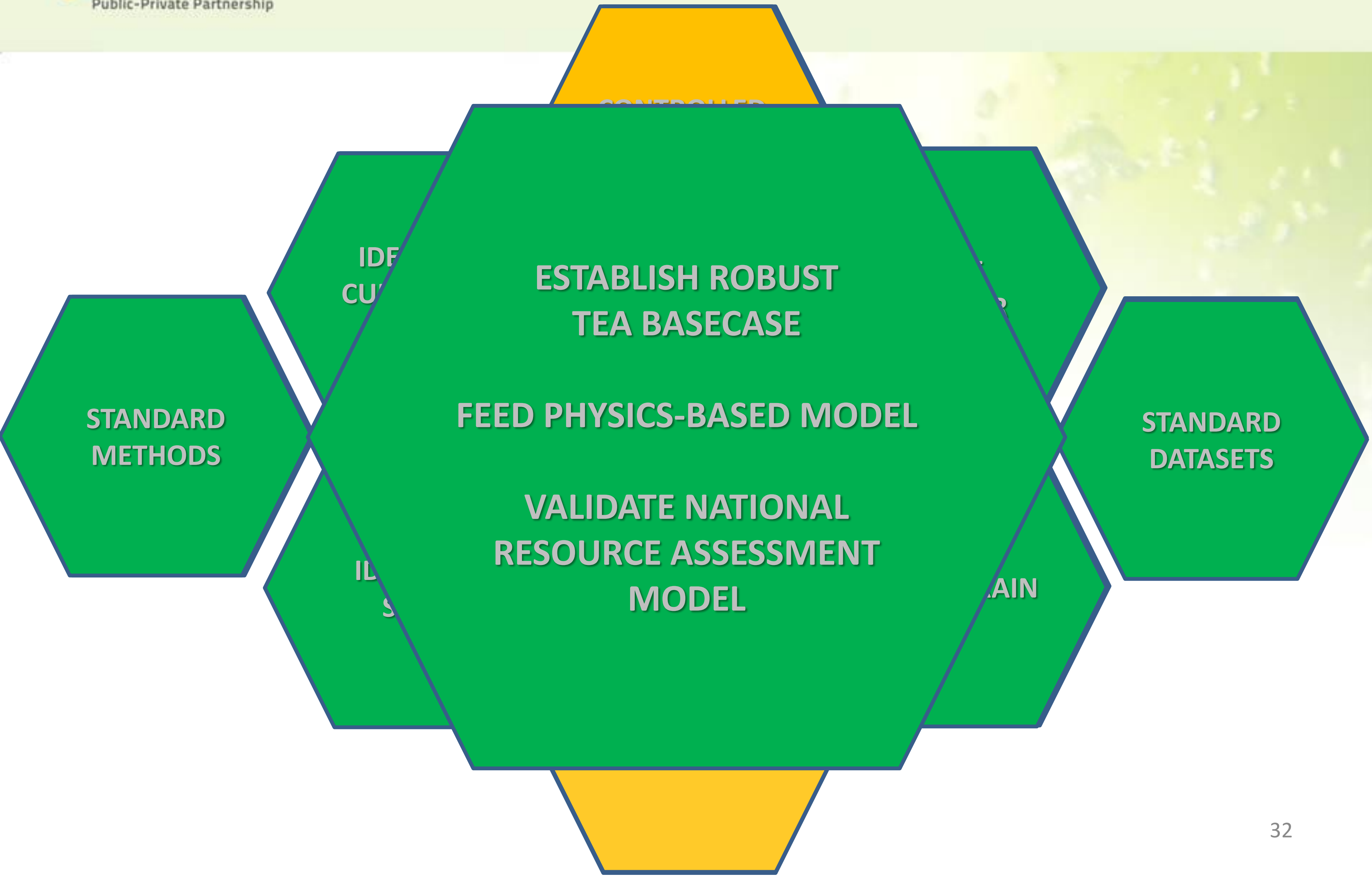
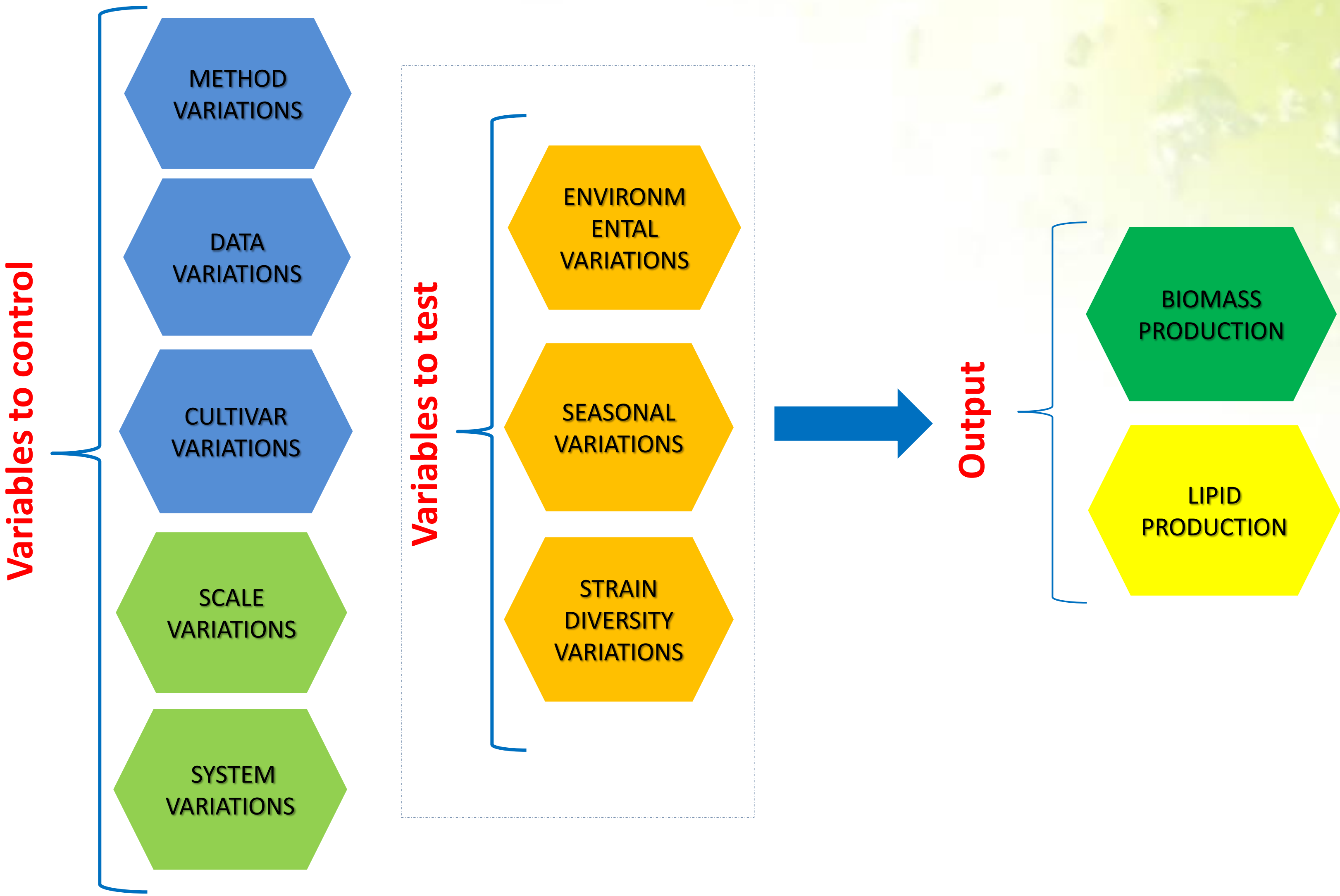
# How We "See" Algal Cultivation

# ATP³ Alignment



# To sort things out…



# Experiments: Unified Field Studies (UFS) and Advanced Field Studies (AFS)

Variables to test

ENVIRONMENTAL VARIATIONS

SEASONAL VARIATIONS

STRAIN DIVERSITY VARIATIONS

***UFS (all TF's)***

- ***Fixed Variables***
  - ✓ *Identical 1000L Mini Ponds implemented at all TF's*
  - ✓ *Environmental (water quality/media)*
  - ✓ *Cultivars*
- ***Factors***
  - ✓ *Seasonality*
  - ✓ *Geographic Region*
  - ✓ *Cultivation/Harvest Process*

***AFS (1 or more TF)***

- ***Factors***
  - ✓ *Seasonality*
  - ✓ *Geographic Region*
  - ✓ *Cultivars*
  - ✓ *Cultivation system and scale (utilize UFS mini-ponds as controls)*
  - ✓ *Cultivation/Harvest Process*
  - ✓ *Environmental (water quality e.g., media composition, wastewater, recycle volume)*

Output

BIOMASS PRODUCTION

LIPID PRODUCTION

# Example: Seasonal Experimental Plan A

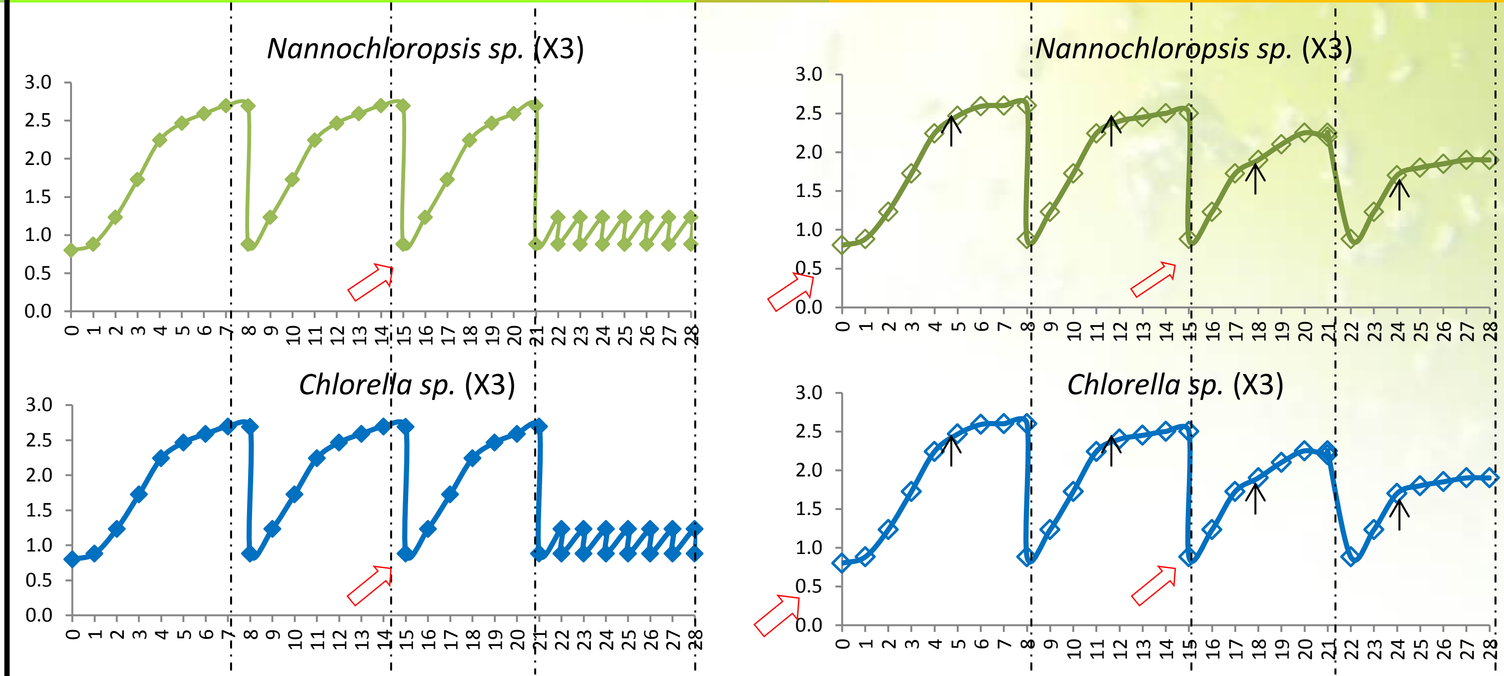
wk1 wk2 wk3 wk4 wk5 wk6 wk7 wk8 wk9 wk10 wk11 wk12

**Summary:**

1. Run 2 strains simultaneously in triplicate
2. Collect seasonal data for 3 weeks
3. Optimize Max. biomass pdty via semi-continuous harvesting
3. Optimize lipid by testing starvation time due to TN levels

↑ N depletion

Re-inoculation




**Week 1-3:**
1.Seeds production
2. Sensor calibration
3. Pond cleaning
4. Water treatment
5. Nuts. Prep
6. …

**Week 4-7:**
1. Two species in triplicates, Total Nitrogen (TN) =2500µM
2. First 3 weeks, full growth curve for growth rates, and biomass productivity vs. stock density
3. Re-inoculate every two weeks if needed, e.g. culture loss due to contamination or any other incidences
4. 4th week, semi-continuous dilution for maximum biomass productivity based on data collected during first 3 weeks

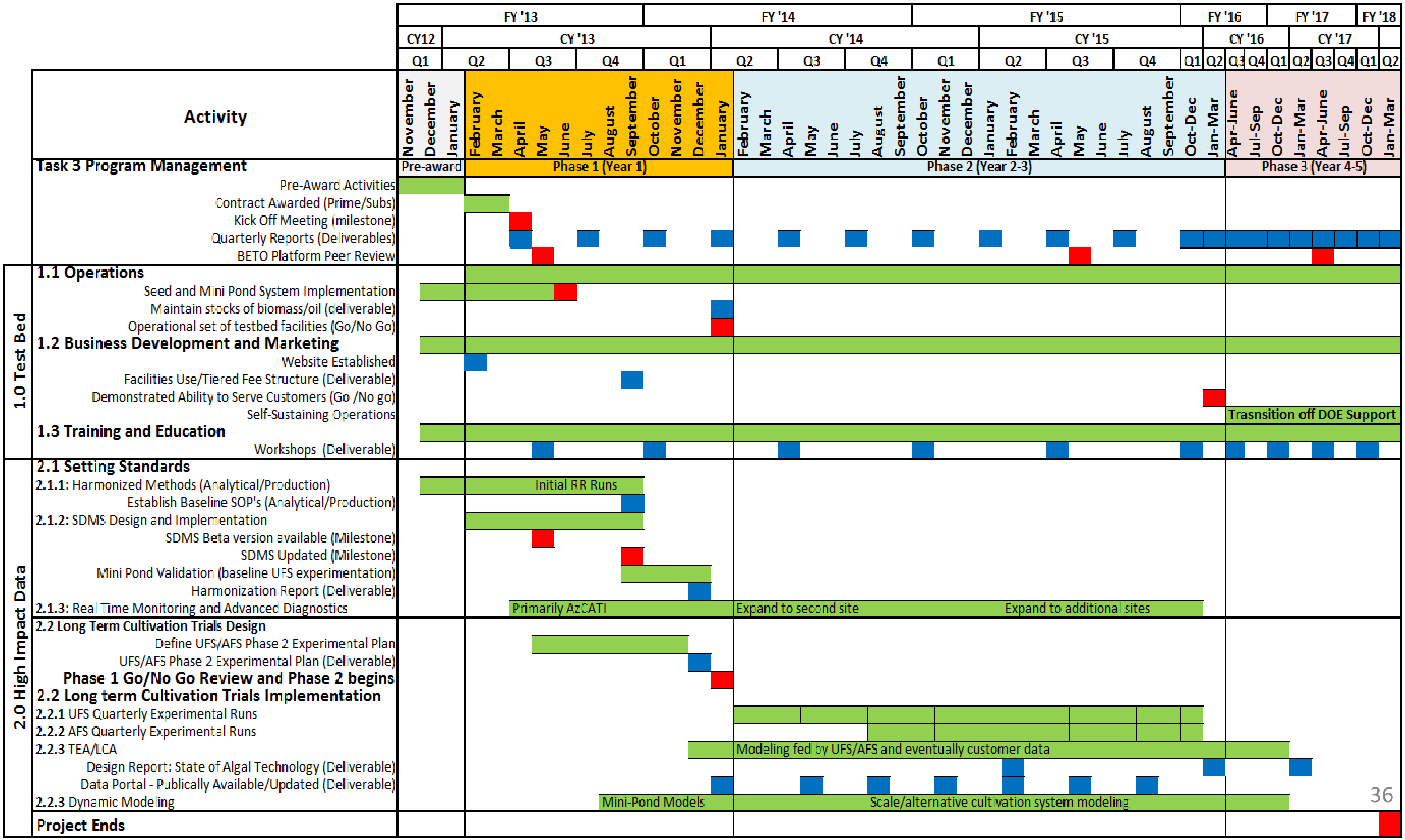
**Week 8:**
1. Re-evaluate plans
2. Re-inoculate ponds
3. Data analysis

**Week 9-12:**
1. Week 9: TN=2100µM
2. Week 10: TN=1800µM
3. Week 11: TN=1500µM
4. Week12: TN=1200µM

OR repeat week 4-7 if needed

**Week 11-14:**
1. Data analysis
2. Reports writing

# Overall Program Schedule



# Relevance

- "Existing data on the productivity and environmental effects of biomass feedstock production systems and residue collection are not adequate to support lifecycle analysis of biorefinery systems"
- "To fully understand the biomass-to-bioenergy supply chain and its economic, environmental, and other impacts requires complete and comparable data..."
- "The lack of standardized datasets, assumptions, and guidelines makes results difficult to compare and integrate with the results of other analyses."
- "Because bioenergy production is relatively new, few "best practices" are defined for all components of the bioenergy supply chain"

# Relevance

## ATP$^3$'s near term impact:

- Providing stakeholder access to quality testbeds in real-world outdoor settings, and expertise and related resources, is necessary to generate new tools, datasets and best practices
- Taking algal biofuels and co-products development from research to successful commercialization demands:
  - Solid and objective testing to provide **data**
  - **Integrated process equipment** needed to inform and guide research, systems and process improvements
  - Subsequent **analysis to support strategic** technical and investment decisions

# Critical Success Factors

- Phase 1
  - Harmonized systems and operational protocols verified and validated and all sites ready to perform both functions in Phase 2 and 3
  - Facilities use agreement boiler plate (MTA/NDA/IP) in place and stakeholder access to test bed network established
    - First call for Scholarship/Innovator complete and projects selected
    - Customers using 1 or more of the test bed sites
  - **Phase 1 Go/No Go stage gate passed**
- Phase 2
  - UFS and AFS execution successful, data generated and made available to the stakeholder community
  - Update state of technology for algal biofuels
  - Capability to operate as testbed and improve stakeholder access to facilities demonstrated
  - **Phase 2 Go/No Go sage gate passed**
- Phase 3
  - Ability to sustain operations after initial DOE funding ends

# Summary

- Phase 1 plans defined and execution well underway
  - Harmonization and alignment for performing both functions of the testbed primary focus
    - All sites operational with seed production  and mini-ponds by end of June, cultivation in mini ponds begins in July/Aug.
  - Detailed design for Phase 2 Cultivation Trials Underway
    - Iterative process that will inform and be informed by the Phase 1 harmonization activities
  - Aggressive marketing push underway
    - Website launched, phased updates planned (next one end mid June 2013)
    - First ATP$^3$ workshop held – sold out with wait list
- Actively exploring ways to expand impact
  - Additional sites
  - Specific technologies, cultivars, processes from other BETO programs

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# Partners

AzCATI
Arizona Center for Algae Technology and Innovation

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Sandia National Laboratories

cellana
algae-based products for a sustainable future

CAL POLY
SAN LUIS OBISPO

Georgia Tech

UTEX The Culture Collection of Algae
at The University of Texas at Austin

Valicor Renewables

TOUCHSTONE

Commercial Algae Management, Inc.

ASU LightWorks

ASU Arizona State University

U.S. DEPARTMENT OF ENERGY

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# SUPPLEMENTAL SLIDES

# Technical Advisory Board

The role of the Technical Advisory Board (TAB) is to provide feedback and guidance on the scientific validity and statistical defensibility of technical protocols and analytical methods.

- Led by Deputy Director and convened by Chief Scientist.
- A cross section of leading scientists and engineers from industry and academia were selected to participate in the TAB.
- Participants who have accepted this role (2-3 TBD):
    - Steve Mayfield, San Diego Center for Algae Biotechnology
    - Amha Belay, Earthrise Nutritionals
    - Rene Wijffels, AlgaePARC
    - Anna Lee Tonkovich, Heliae Development, LLC.

# Commercial Advisory Board

The role of the Commercial Advisory Board (CAB) is to provide feedback and guidance on the strategic direction, quality of ATP$^3$ programs, and effectiveness of outreach and marketing programs in meeting the needs of industry.

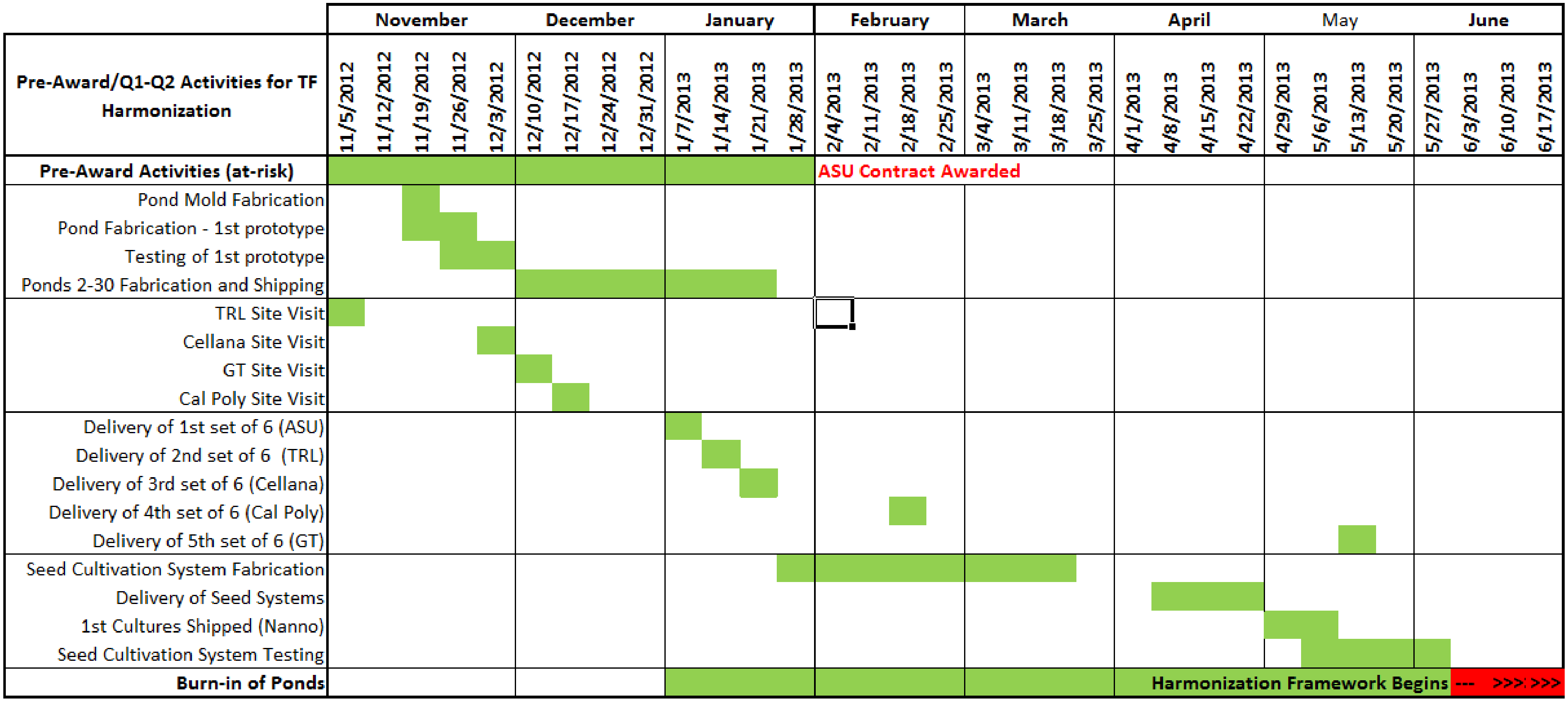
- Convened the Director of Business Development and the Director of Operations is a member.
- Jeffrey Jacobs, Chairman, Chevron Technology Ventures
- Joel Murdoch, Fed-Ex Express Strategic Projects
- 3-4 TBD

# Organisms Available to ATP³

| | Genus | Species | Source | Culture Code | Medium | Experience growing outdoors | Screened for growth and lipid content |
|---|---|---|---|---|---|---|---|
| UFS Available Strains | *Scenedesmus* | *sp.* | AzCATI | LRB-AS 0401 | BG-11 | Yes (>3 yr) | Yes |
| | *Chlorella* | *sp.* | UH/Cellana | C596 | f/2 | Yes | Yes |
| | *Chlorella* | *vulgaris* | AzCATI | LRB-UT 1211 | BG-11 | Yes | Yes |
| | *Nannochloropsis* | *granulata* | AzCATI | LRB-MP 0209 | f/2 | Yes (>2 yr) | Yes |
| | *Nannochloropsis* | *sp.* | Cellana | KA19 | f/2 | Yes | Yes |
| Additional strains available for Function 1 and AFS | *Chaetoceros* | *muelleri* | Cellana | CH60 | f/2 + Si | Yes | Yes |
| | *Chlorella* | *sp.* | AzCATI | LRB-AZ 1201 | BG-11 | Yes (>2yr) | Yes |
| | Desmochloris | halophila | Cellana | C046 | f/2 | Yes | Yes |
| | *Isochrysis* | *galbana* | AzCATI | LRB-CB 3100 | f/2 | Yes | Yes |
| | *Nannochloropsis* | *sp.* | AzCATI | multiple (13) | f/2 | No | Yes |
| | *Pseudochlorococcum* | *sp.* | AzCATI | LRB-AZ 0501 | BG-11 | Yes | Yes |
| | *Pseudochlorococcum* | *sp.* | AzCATI | LRB-AZ 0505 | BG-11 | No | Yes |
| | *Scenedesmus* | *dimorphus* | AzCATI | LRB-AZ 0411 | BG-11 | Yes | Yes |
| | *Scenedesmus* | *sp.* | AzCATI | LRB-AZ 0414 | BG-11 | Yes (>4 yr) | Yes |
| | *Staurosira* | *sp.* | Cellana | C323 | f/2 | Yes (>1.5 yr) | Yes |
| | *Tetraselmis* | *sp.* | AzCATI | LRB-CB 1501 | f/2 | No | Yes |
| | *Tetraselmis* | *sp.* | Cellana | C088 | f/2 | No | Yes |

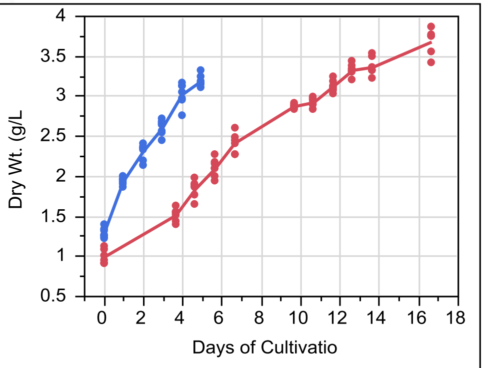
# Progress to Date

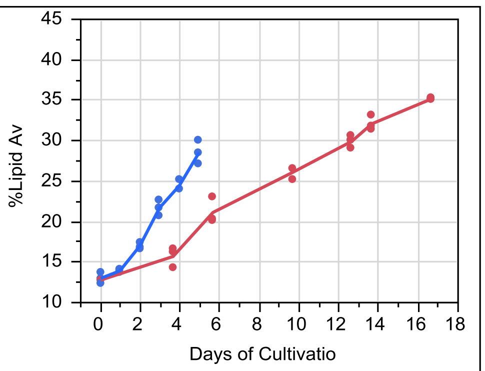
## Pre-award thru Q1-Q2 acceleration activities for harmonization

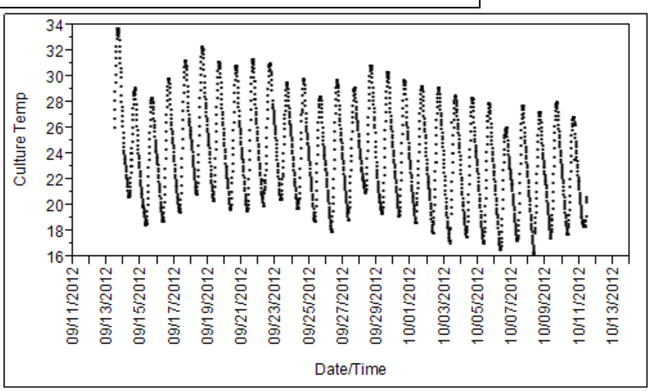



The significant upfront effort through the site assessments paid significant dividends.
All sites very engaged - even before awards in place!

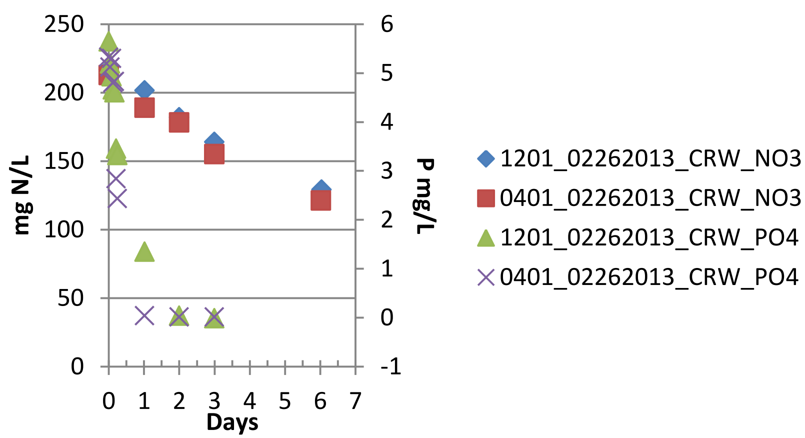
# Monitoring

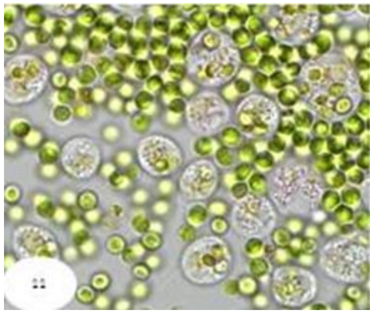


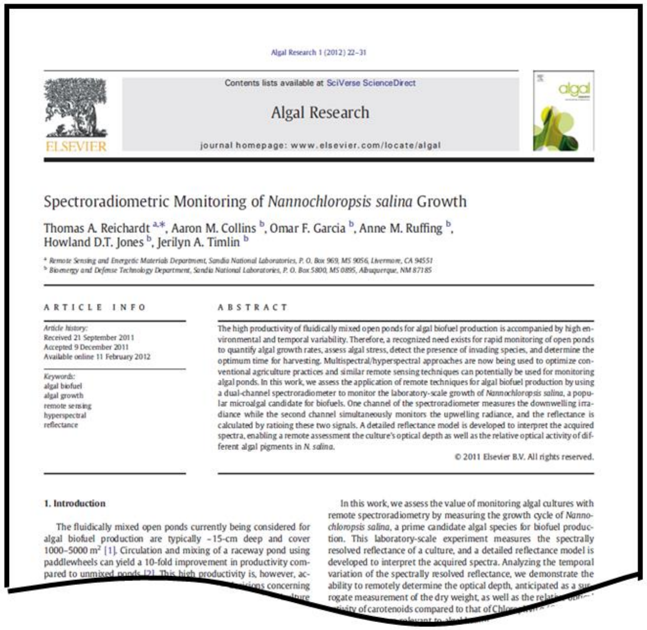




| | ASU | Cellana | Cal Poly | TRL | GT | SNL | NREL | SRS |
|---|---|---|---|---|---|---|---|---|
| ***Routine Monitoring*** | | | | | | | | |
| Temperature, pH, Irradiance and Evaporation | X | X | X | X | X | X | X | |
| Predator Identification & Monitoring | X | X | X | | X | X | X | |
| Nutrient Analysis | X | X | X | X | X | X | X | |
| Dry Weight/AFDW/Moisture Content | X | X | X | X | X | X | X | X |
| Total Lipid Analysis | X | X | X | | X | X | X | X |
| Total Protein Analysis | X | X | X | | X | X | X | X |
| Total Carbohydrate Analysis | X | X | | | X | X | X | X |



# Deployment of Real-Time Productivity Monitoring



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Spectroradiometric Monitoring of *Nannochloropsis salina* Growth

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ABSTRACT

The high productivity of fluidically mixed open ponds for algal biofuel production is accompanied by high environmental and temporal variability. Therefore, a recognized need exists for rapid monitoring of open ponds to quantify algal growth rates, assess algal stress, detect the presence of invading species, and determine the optimum time for harvesting. Multispectral/hyperspectral approaches are now being used to optimize conventional agriculture practices and similar remote sensing techniques can potentially be used for monitoring algal ponds. In this work, we assess the application of remote techniques for algal biofuel production by using a dual-channel spectroradiometer to monitor the laboratory-scale growth of *Nannochloropsis salina*, a popular microalgal candidate for biofuels. One channel of the spectroradiometer measures the downwelling irradiance while the second channel simultaneously monitors the upwelling radiance, and the reflectance is calculated by ratioing these two signals. A detailed reflectance model is developed to interpret the acquired spectra, enabling a remote assessment the culture's optical depth as well as the relative optical activity of different algal pigments in *N. salina*.

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1. Introduction

The fluidically mixed open ponds currently being considered for algal biofuel production are typically ~15-cm deep and cover 1000–5000 $m^2$ [1]. Circulation and mixing of a raceway pond using paddlewheels can yield a 10-fold improvement in productivity compared to unmixed ponds [2]. This high productivity is, however, ac-

In this work, we assess the value of monitoring algal cultures with remote spectroradiometry by measuring the growth cycle of *Nannochloropsis salina*, a prime candidate algal species for biofuel production. This laboratory-scale experiment measures the spectrally resolved reflectance of a culture, and a detailed reflectance model is developed to interpret the acquired spectra. Analyzing the temporal variation of the spectrally resolved reflectance, we demonstrate the ability to remotely determine the optical depth, anticipated as a surrogate measurement of the dry weight, as well as the relati

**Laboratory studies described in Algal Research 1, 22-31 (2012).**

- Demonstrated capability to measure biomass and pigment optical activity
- Non-contact method, uses COTS equipment
- Provisional patent also submitted

**Advantages over Current Sampling Methods**

**In-situ measurement of biomass and pigment optical activity**

Extremely rapid (~5-min) measurement times

**Real-time detection of predators, invading species, and algal flocculation**

All demonstrated

**Non-sampling**

No laboratory facility access required

**Integrates rigorous light transport physics into the data analysis**

No pre-calibration required

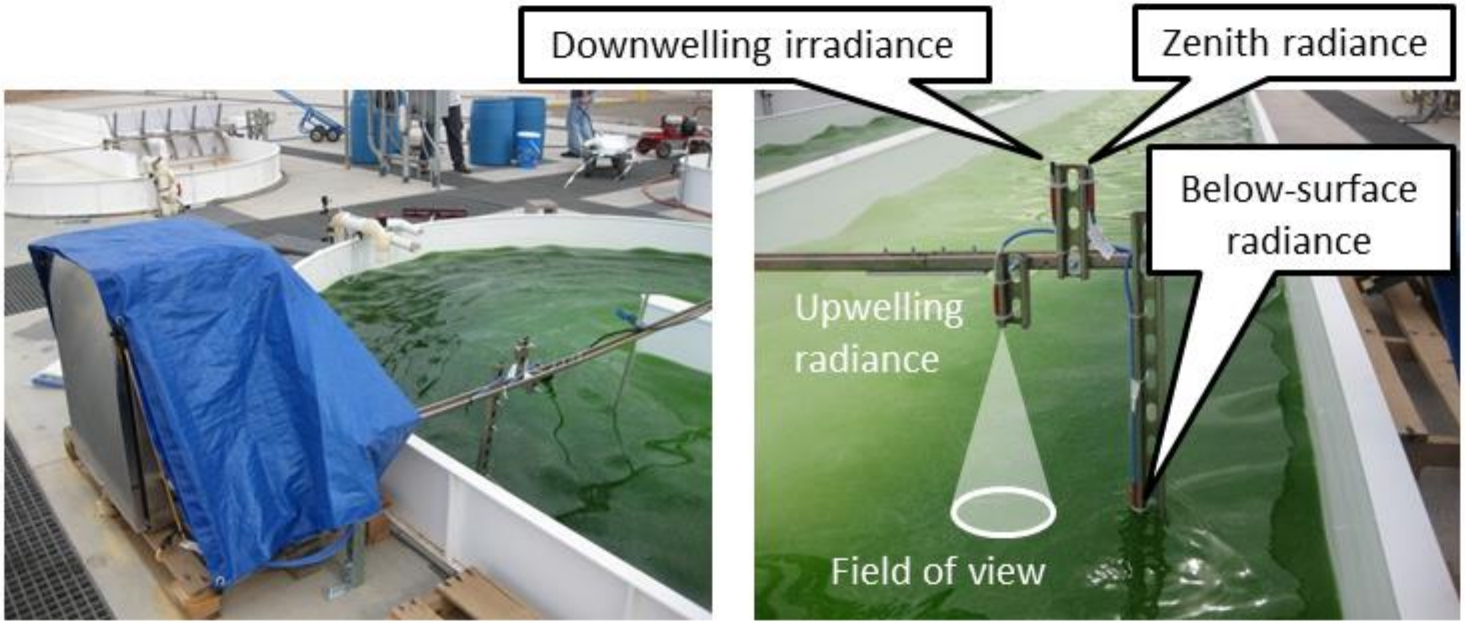
**Non-contact**

Avoids instrument fouling

**Fully autonomous operation**

Deployed over several months in the field

# AzCATI Field Deployment: Assessed culture of *Nannochloropsis Granulata*




*Photos by Aaron Collins, Sandia (2012)*

- Collected all four spectra at 5 minute intervals
  - 2-20 ms integration times, 1000 averages
- Converted counts to spectrally resolved intensity (W/cm$^2$-nm) via calibrated lamp measurements
- Stared at Spectralon target for calibration of reflectance

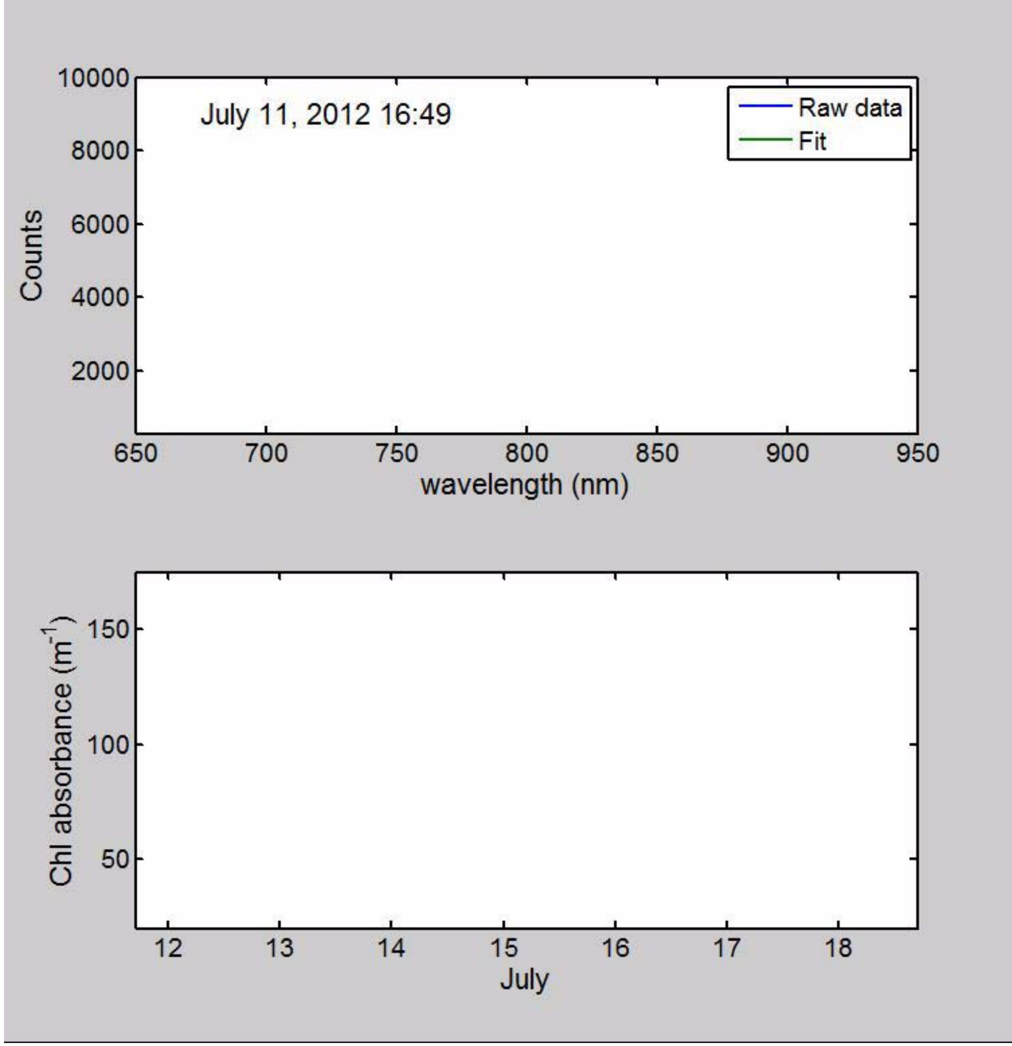
# Analysis of Reflectance Data and Implementation Plans for ATP$^3$

- Began with 7 variables: $C_1$-$C_6$ + $L_f$
- We have added 6 more variables: $C_7$-$C_{11}$ + $T$
- For now, we fit only 660-900 nm, eliminating need for $C_2$-$C_4$
- 10 total fit variables

**Implementation: Six mini-raceway ponds at AzCATI in Phase 1**

- Experiments at an intermediate scale
- Outdoor, real-world conditions
- 1×6, 2×3, 3×2 etc. experimental configuration

Controlled predation
Controlled stress experiments
Pigment development
Nutrient variation
Direct strain comparison
Seasonal variation
Multiple species/communities



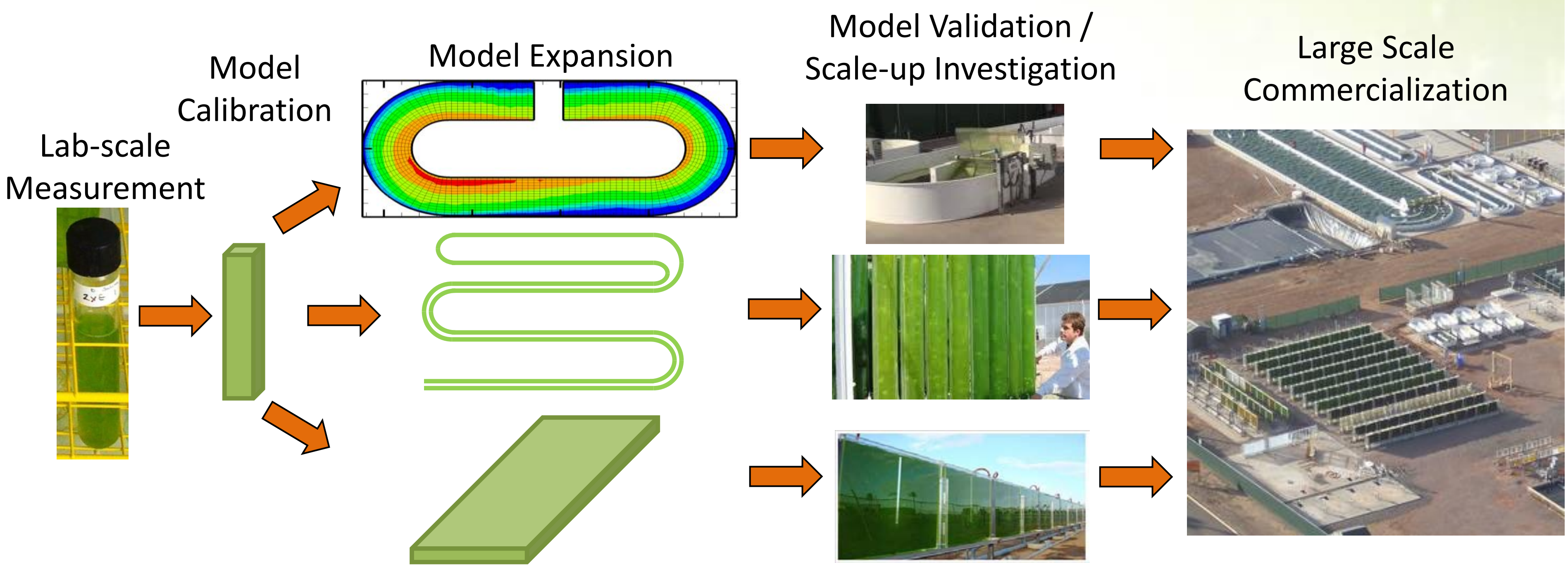
# Modeling Needs Summary

**Modeling provides important focus and direction for R&D, policy, quantification of goals, and a way to track progress towards these goals**

- BUT: models are only as good as the data that feeds them
- Many models show strong sensitivities to cultivation performance and seasonality variations
  - RA: Increased productivity beyond modeled predictions would lead to screening out the poorest sites
  - LCA/TEA: non-linear response to biomass/oil yields, tradeoffs in implications for seasonal operations
- Consensus of modeling community is a continued lack of publicly available data for algal processing
  - Need meaningful (large-scale), sustained (year-round) data to set realistic baseline and target values
- ATP$^3$ offers a prime opportunity to validate or improve models for resource assessment, LCA, TEA, strain-specific productivity prediction, and dynamic physics-based models

# Motivation (Need for Model)

- 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**
*Source: Patricia Gharagozloo at Sandia*

**Algae cultivation systems**
*Source: Photos taken from asu.edu*

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

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

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

$$0 \le f_i \le 1$$

# Modeling inputs: downstream processing

| Metric | Units | Notes |
|---|---|---|
| **Dewatering** | | |
| Inlet/outlet concentrations | g/L | Algal biomass concentrations across each operation |
| Biomass recovery | % | % recovery of algal biomass into concentrated phase |
| Power demand | KWh/$m^3$ inlet | Power demand for each operation, per total inlet feed |
| Chemical demand | g/$m^3$ inlet | Chemical usage and type (eg flocculent) for each operation |
| **Extraction/conversion** | | |
| Oil yield | wt% of cell dry mass | Yield of oil intermediate product via extraction or other conversion method; need associated algal biomass composition as defined in "cultivation" table |
| Oil composition (elemental) | CHONSP | Elemental composition of produced oil intermediate |
| Oil composition/speciation | wt% | Speciation of oil components (TAG, FFA, polar lipids, etc); as available |
| Solids content of processed biomass | wt% solids | Solids concentration processed through extraction/conversion step |
| Power demand | KWh/$m^3$ inlet | Power demand for each operation, per total inlet feed |
| Process conditions | °C, atm | Temperature/pressure utilized for operation |
| Chemical demand | Kg/kg dry algal biomass | Chemical usage and type (eg solvent) for each operation, per dry wt biomass |
| **Oil upgrading/refining** | | |
| Oil cleanup utilized prior to refining? | Y/N | If cleanup of intermediate oil is required (to remove polar lipids etc), need process conditions for cleanup step (T/P/chemical usage), yield of recovered oil (wt%), and composition of oil exiting cleanup (CHONSP or speciation) |
| Refining process conditions | °C, atm, $hr^{-1}$ | Temperature, pressure, $H_2$ partial pressure, LHSV, catalyst utilized for oil refining |
| Hydrogen consumption | wt% of feed | $H_2$ consumption for hydroprocessing operations |
| Product yield | wt% of feed | Fuel blendstock product yield |
| Product composition | wt% | Composition of products exiting reactor (off-gas, naphtha-range, diesel-range, $H_2O$, $CO_2$, etc) |