Beneficial Reuse of CO_2 from Coal Fired Power Plants for Production of Animal Feeds

U.S. DOE, Office of Fossil Energy, NETL
Agreement DE-FE0031717, 2019–2021, Andy Aurelio, PM

MicroBio Engineering, Inc.
San Luis Obispo, California
Orlando, Florida

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Ruth Spierling, Sr. Engineer, Site Manager
Cooper Gibson, Mechanical Eng., TEA-LCA
Neal Adler, Sr. Engineer, Facility Design
John Benemann, PhD, CEO

* Also Civil & Environmental Engineering, Cal Poly State Univ.,

CO_2 Utilization Research Facility at the Stanton Energy Center, Orlando, Florida.



Raceways for production of filamentous algae feeds on flue gas CO_2.

Goal: Advance commercialization of animal feed produced through flue gas CO_2 utilization.

- Funding
  - DOE NETL: $1,442,854
  - Cost Share: $300,595 mostly OUC
- Project Performance
  - 1/1/2019 to 9/30/2021 w/ NCE
- Project Participants
  - MicroBio Engineering Inc. (MBE)
  - Orlando Utilities Commission (OUC)
  - Cal Poly State University (CP)
  - University of Central Florida (UCF)
  - Global Thermostat (GT)

General CO_2 Utilization Goals

Develop technologies/products that:

1. Allow industries to sell huge quantities of CO_2 as a feedstock, which offsets some cost of capture, utilization, and sequestration.
2. CO_2-derived commodities should have large markets and high value.
3. The commodities should reduce net GHG emissions by substituting "bioproducts" for fossil-derived products or conventional products with higher GHG emissions.

Microalgae Fit the Need.

1. High-value composition for feed or food is possible.
   - Algae can contain omega-3s, xanthophyll, protein, oils.
2. Assimilate CO_2 from flue gas directly.
3. Higher productivity (yield) than other crops.
4. Can use non-agricultural land (salinized, poor soil)
5. Can use non-agricultural water (saline, brackish)
6. Can treat nutrient-polluted waters.
7. 2018 Farm Bill made algae a US Dept. of Agriculture "Title Crop" qualifying it for crop insurance, etc.

Algae in feeds gives potentially better animal performance and better consumer products.

Claims include improved:

- Animal health and productivity
- Health benefits to consumers
- Appearance of the final product

Source: NBO3 website

Example: Algae containing the omega-3 fatty acid, EPA, are produced by Qualitas Health/IWi in New Mexico.

Paddle Wheel Mixed Raceway Ponds

The major commercial technology for microalgal biomass production and used in most TEA studies.

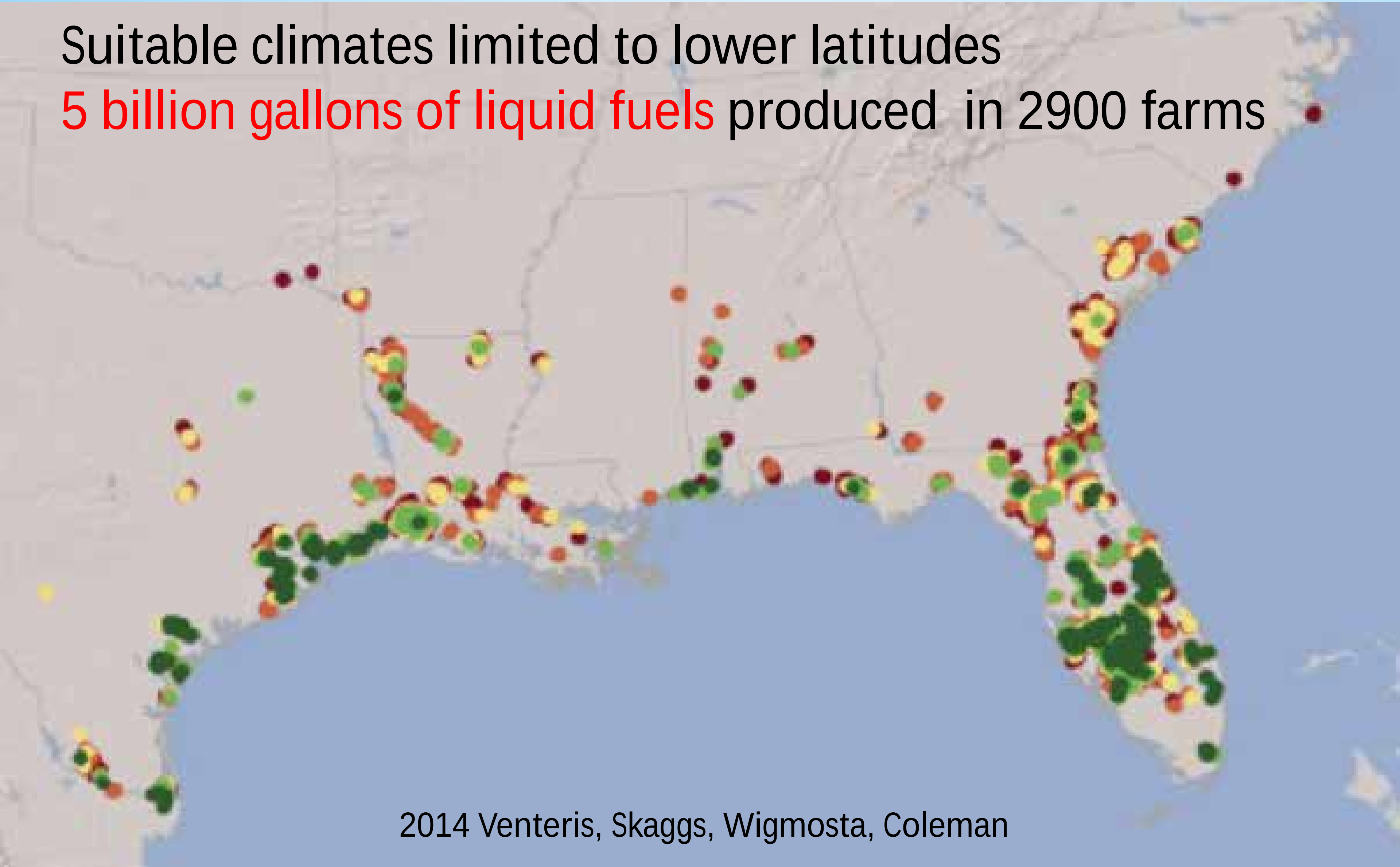
- ~ 1-ft (30 cm) deep
- Mixed at 20-25 cm/s
- CO_2 sparged in water
- pH control 7.5- 8.2
- Fertilize with N, P, K and micronutrients

Seambiotic pilot plant, Israel, first to use flue gas from a coal-fired power plant

The Gulf Coast and especially Florida are thought to be ideal locations for an algae industry.

Suitable climates limited to lower latitudes

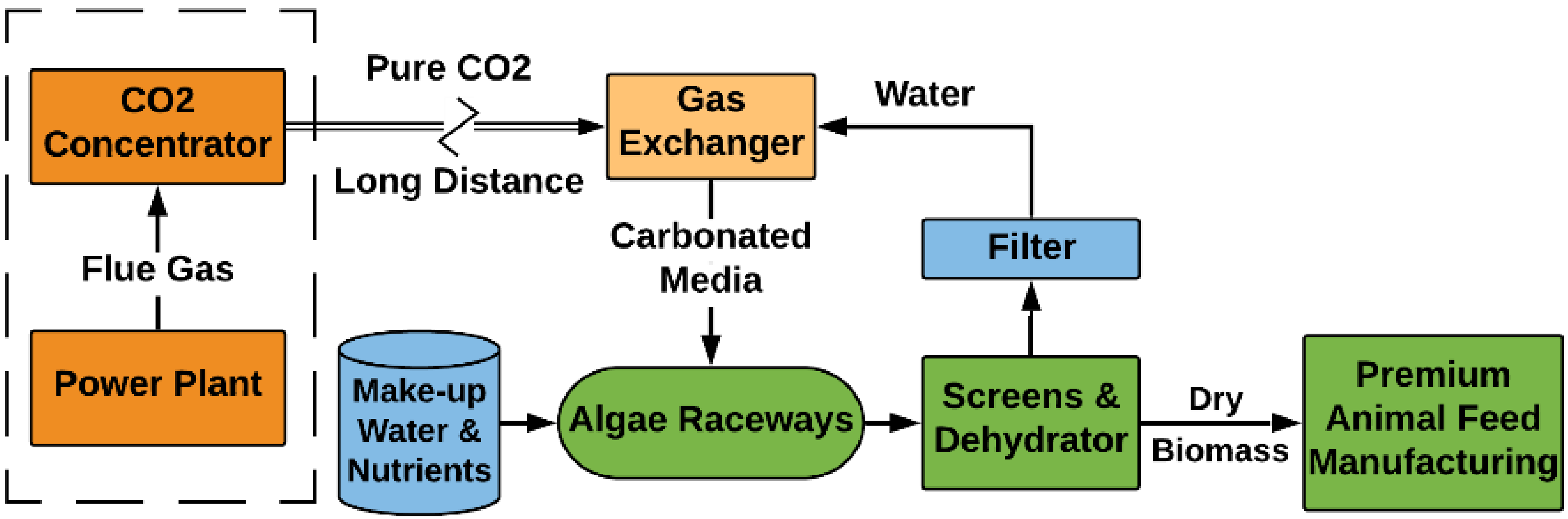
5 billion gallons of liquid fuels produced in 2900 farms



2014 Venteris, Skaggs, Wigmosta, Coleman

CO_2 delivery involves optimization of concentration in pipeline and gas-to-liquid exchange device.

CO_2 concentrator adds costs but pure CO_2 decreases transport cost and improves gas exchange rate.



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Project objectives and technical-economic challenges.

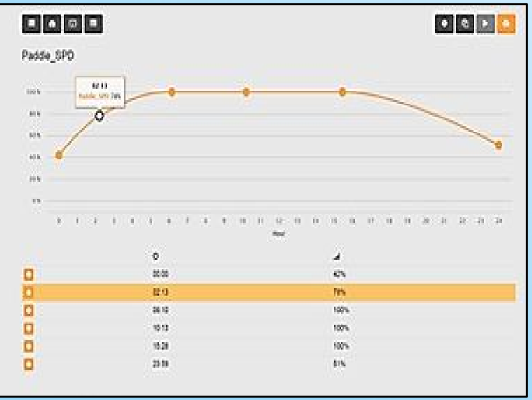
- How much net CO_2 mitigation can be achieved with premium algae feeds?
- How can productivity and composition be maximized to improve process economics and land use?
- What will the CO_2 offset cost after biofuels or commodity animal feeds revenues?
- Develop detailed site specific TEA and LCA for OUC SEC for CO_2 mitigation for premium animal feeds.

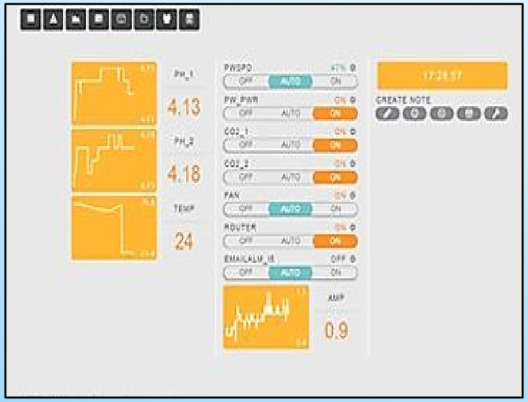
Task 3 Goal: Larger-scale production, harvesting, dewatering and drying, for feed production.

We start with Task 3 because it includes the facility setup needed for the other tasks.

- Task 3.0 Algae feed production using flue gas CO_2
  - Subtask 3.1: Design, Fabrication, Installation, Start-up of 43-m^2 ponds (MBE/OUC)
  - Subtask 3.2: Algae Cultivation CO_2 Utilization, Biomass Production (MBE/OUC)

150 m^2 of raceway ponds installed at SEC for cultivation experiments and biomass production.

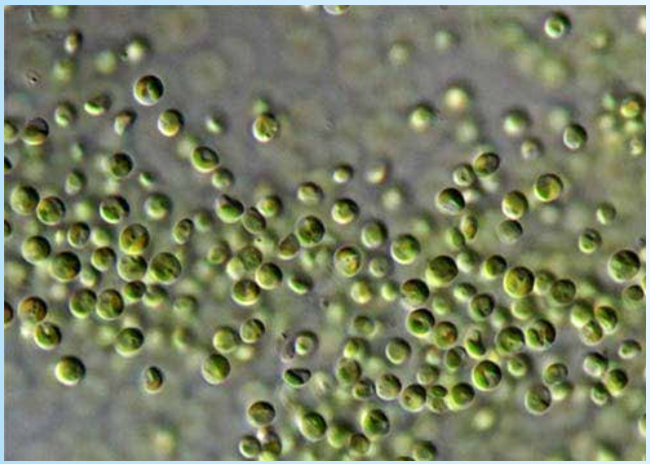


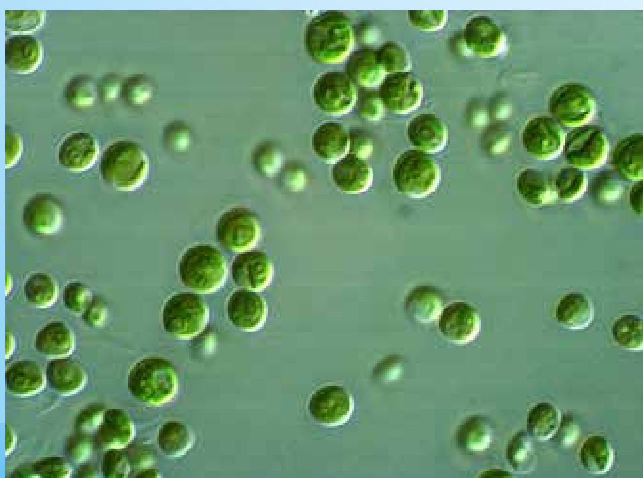


Continuous monitoring and control via internet-enabled instrumentation

MBE filaments are screen-harvested at lower cost/power vs. single cells common to the industry.

Nannochloropsis & *Chlorella*
à Centrifuge-harvested





Tribonema & Spirulina
à Screen-harvested

Filamentous algae are being harvested and dehydrated for shipment to Cal Poly, where additional poultry feeding trials will be conducted.

Harvesting units for filamentous algae are being evaluated. Both screening and settling work.

Pond effluent flows to either cone-bottom settling tanks or screening channels.

Task 2 Goal: Highly productive, stable strains in outdoor cultures for animal feeds.

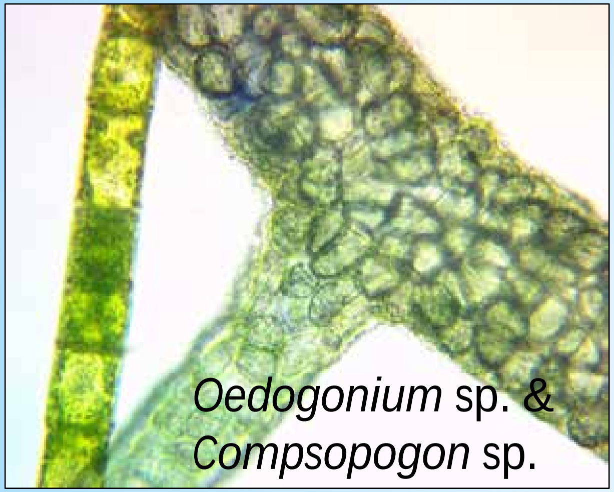
MBE California strains

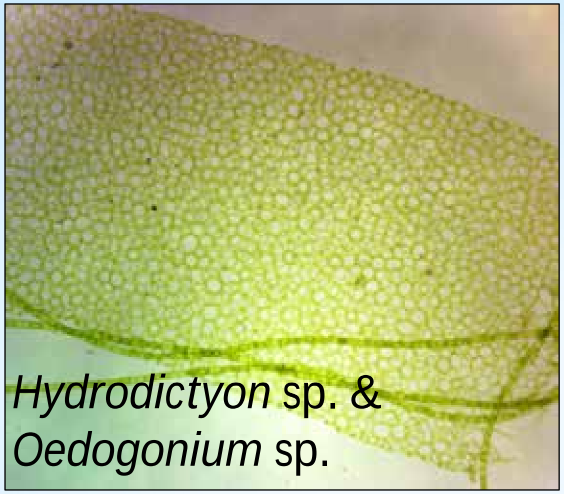
- Omega-3 fatty acid producing filaments from California: *Tribonema minus* & improved strain *T. minus* MBE501
- Spirulina, UTEX culture collection, media can store CO_2

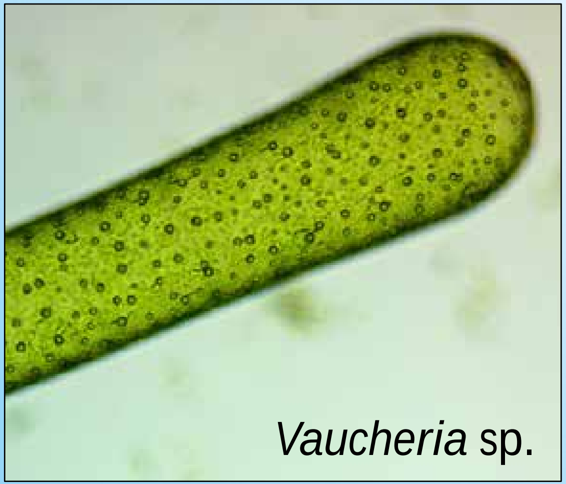
SEC local strains

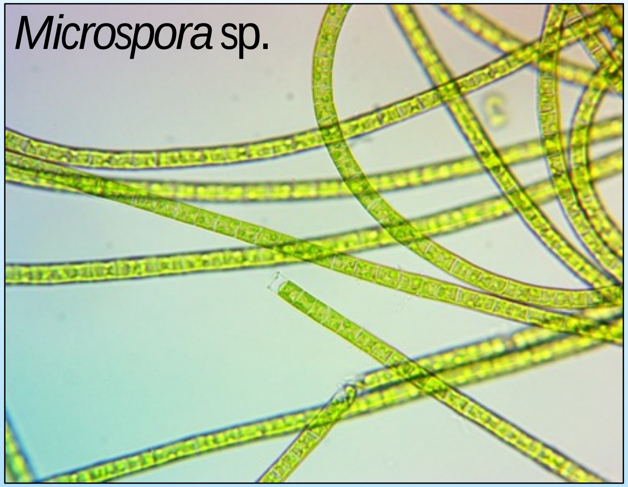
- Omega-3 fatty acid filament: *Vaucheria*
- High protein and pigment: *Oedogonium, Hydrodictyon, Microspora, Vaucheria, etc.*
- Local prospecting continues on OUC Stanton Energy Center (SEC) property.

Cultivatable strains prospected locally at SEC.







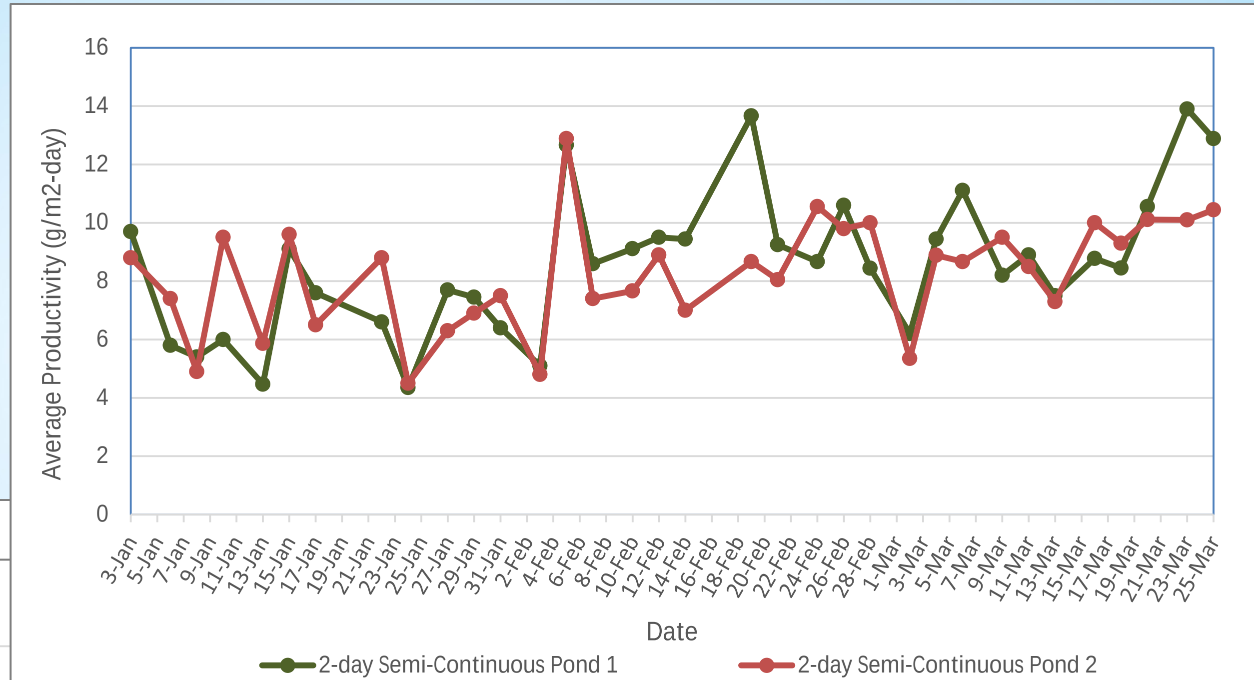


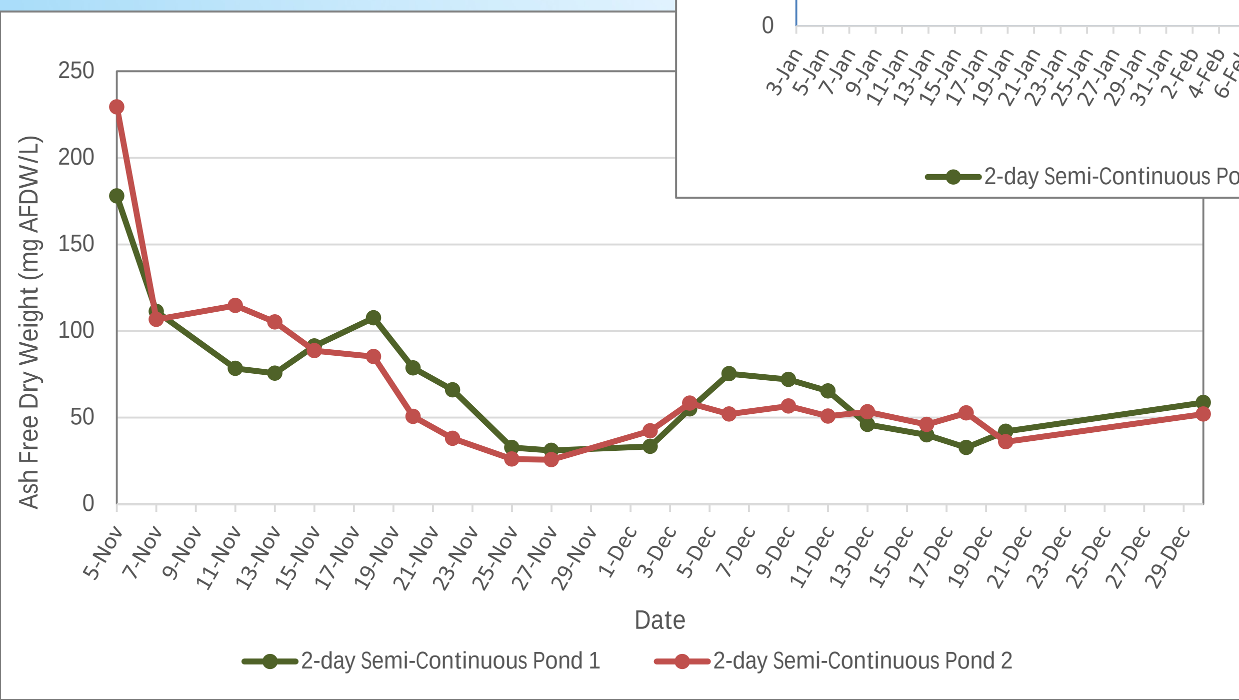
Task 2 Goal: Highly productive, stable strains in outdoor cultures for animal feeds.

- Cultures are scaled-up from test tube to bubble column to carboy to pond.

Task 2 Goal: Highly productive, stable strains in outdoor cultures for animal feeds.

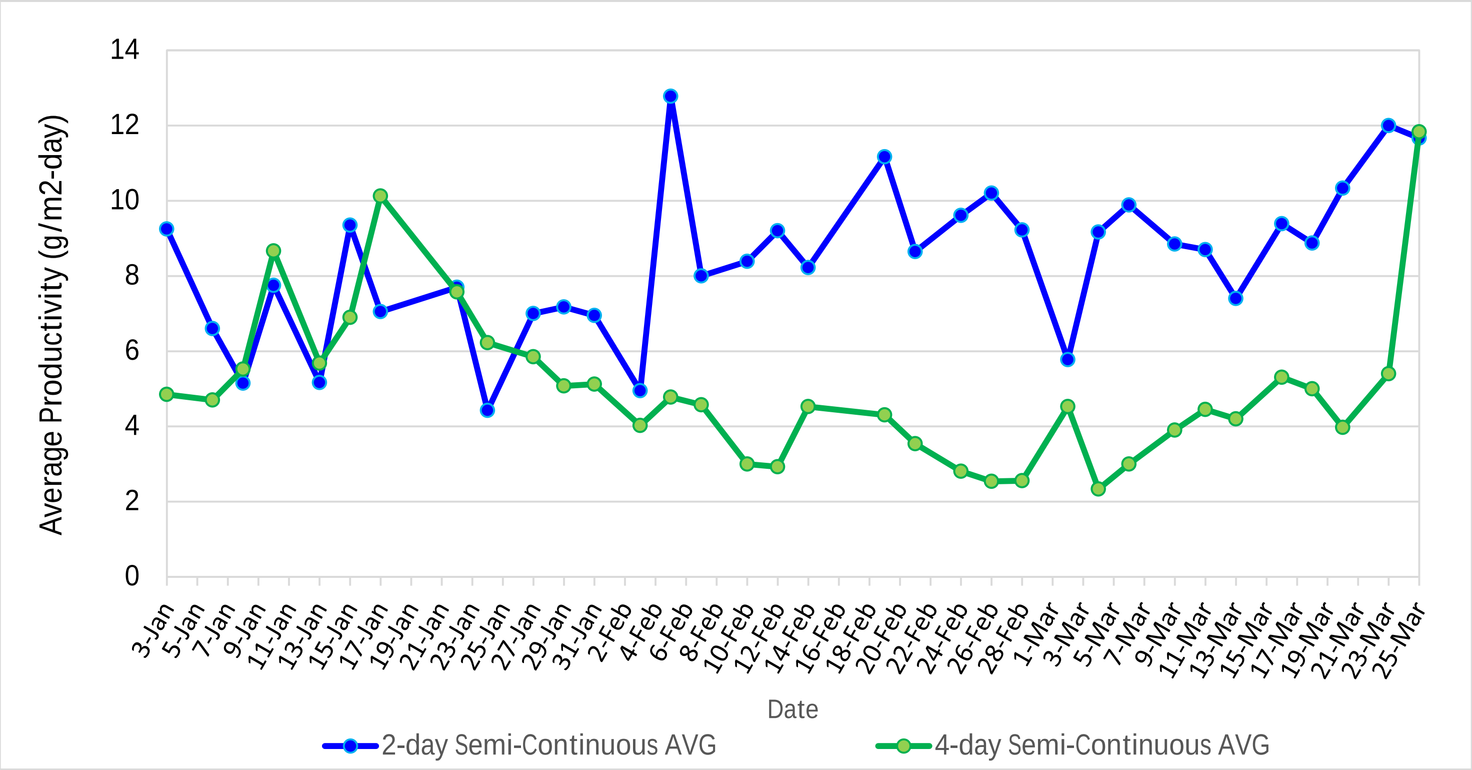
- Data from duplicate ponds is reproducible.
- Duplicates allow uncertainty to be quantified.





Pond operational methods are tested to achieve high productivity but also strain type stability.

- Hydraulic residence time and dilution frequency affect productivity and culture stability.
- Short HRT promotes high productivity, but long HRT promotes stability.

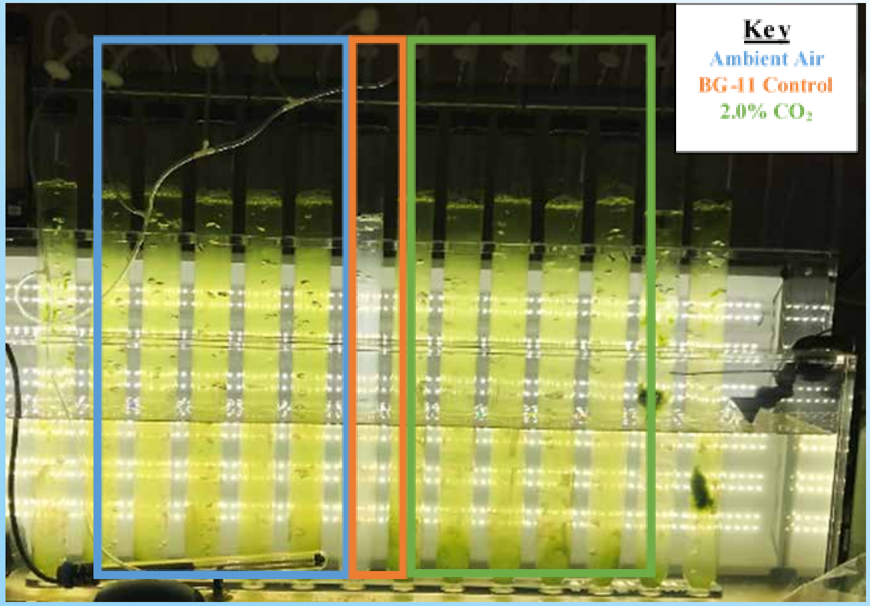


Average productivity for 2-day HRT and 4-day HRT semi-continuous Oedogonium sp. conditions.

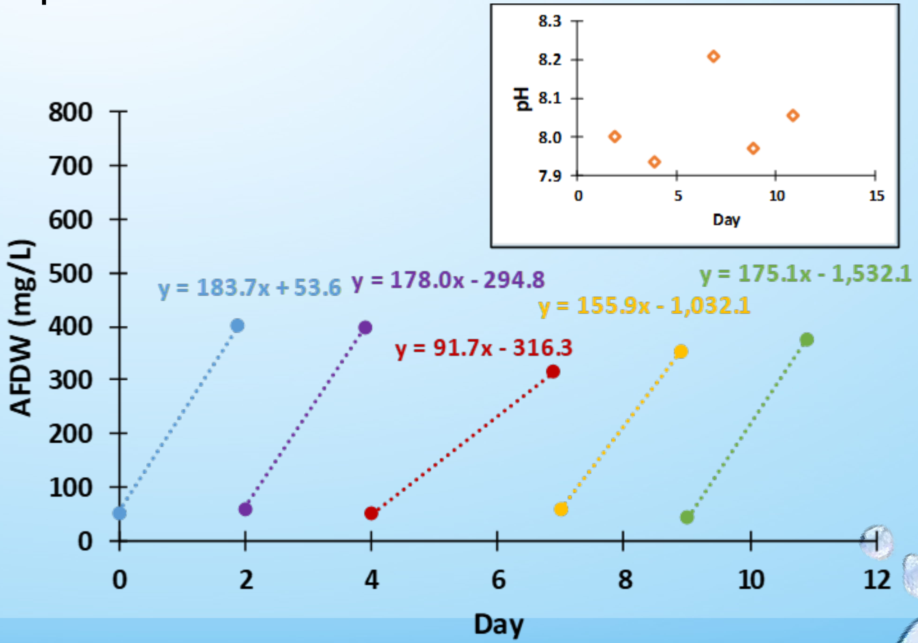
Task 4 Goal: Determine the carbon utilization efficiency.

- Task 4.0 Carbon Balances during Algal Flue Gas Utilization (UCF)

T. minus cultures sparged with ambient air and CO_2-enriched air to a pH of 7-7.4.



Growth rates of *T. minus* cultures sparged with CO_2-enriched air under a controlled pH range of 8.0-8.4 over a 14-day growth period.



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Task 5 Goal: Determine the potential of algae biomass as a value-added feed for chickens.

- Task 5.0 Poultry Feeding Trials with Algal Biomass (CP)
  - Subtask 5.1 – Feed Manufacturing and Analysis
  - Subtask 5.2 –Layer Feeding Trials
  - Subtask 5.3 – Broiler Feeding Trials

Some local strains have significant fatty acid content, even without specific efforts to increase.

ML-7:Demonstrate in algae produced at OUC equivalent omega-3 fatty acid productivity as baseline algae grown by MBE in California.

Strain	FAMEs % of AFDW	Omega-3 % of total FAMEs	Omega-6 of % total FAMEs	Omega-3 + -6 % of total FAMEs	Omega-3 % of total AFDW
Tribonema sp.	**7.87**	**32.34**	**11.73**	**44.07**	**2.55**
Hydrodictyon sp.	2.66	32.12	18.38	50.51	**3.33**
Oedogonium + Unknown	3.18	28.36	11.89	40.25	0.85
Vaucheria sp.	3.14	39.09	11.83	50.92	1.23
Oedogonium sp.	7.22	38.48	8.52	47.00	**2.78**
Hydrodictyon sp.	4.91	51.43	18.07	69.50	**2.52**

FAMES = a measure of triglycerides. AFDW = ash-free dry weight of biomass.

Layer feeding trial at Cal Poly State University

Diets

- Corn-soybean meal based
- Algae content (0-10%)

Production parameters

- Egg production
- Egg quality
    - Egg size, eggshell quality
    - Yolk fatty acid analysis
- Feed conversion
- Bone strength

Animal Scientists
Drs. Darin Bennett and Mark Edwards
Cal Poly State Univ.

Cal Poly Feeding Trials: Done the Right Way

<u>Step 1</u>: Determine algae biochemical composition.

<u>Step 2</u>: Conduct digestibility trials.

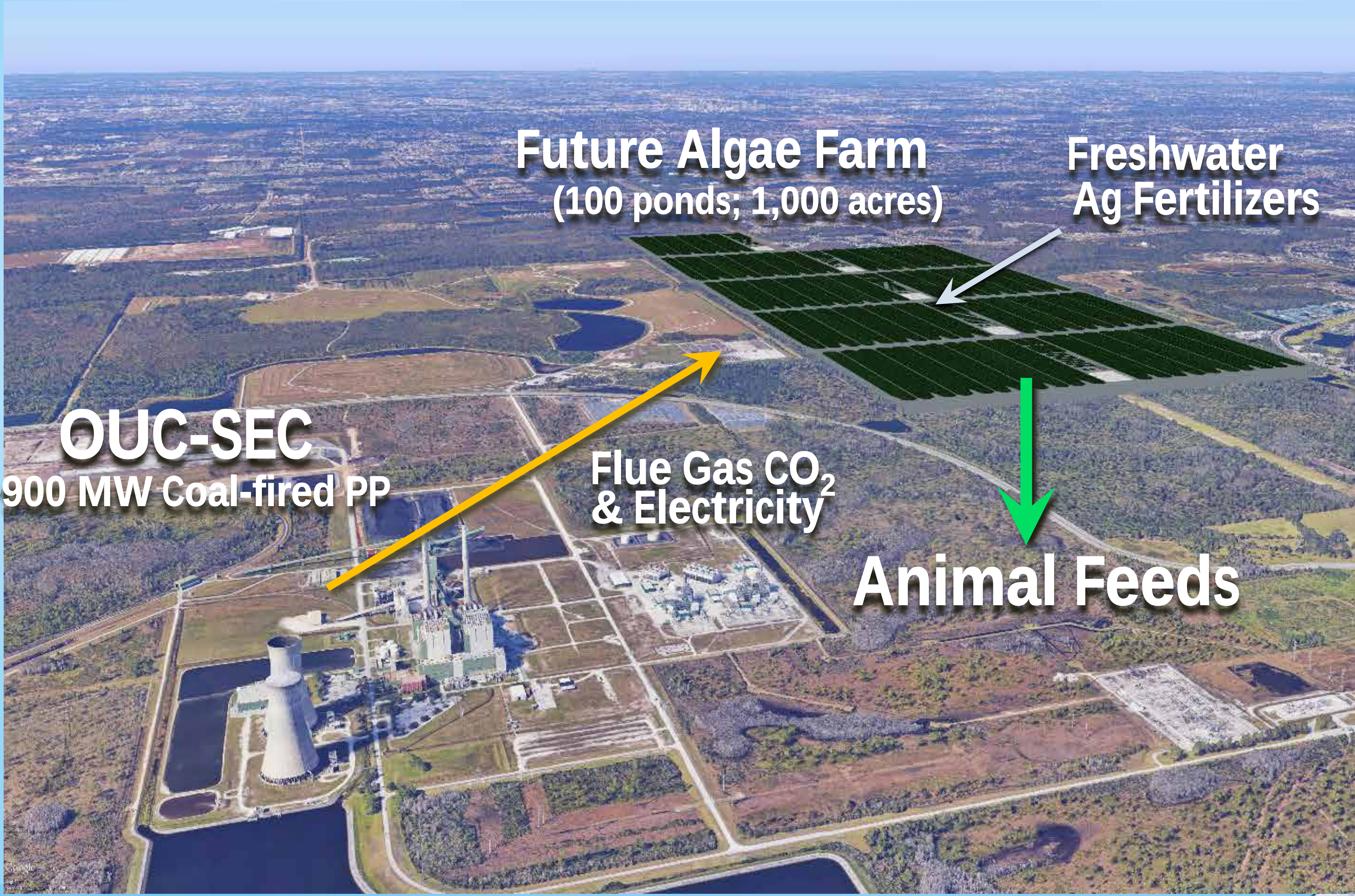
<u>Step 3</u>: Based on 1 & 2, formulate feed that can be fairly compared to conventional feeds.

Tribonema minus and Spirulina (*Arthrospira platensis)* were pond cultivated, harvested, solar dried, and used in poultry feed manufacturing. These feeds were used in digestibility studies. Final results are pending post-Covid lab access.

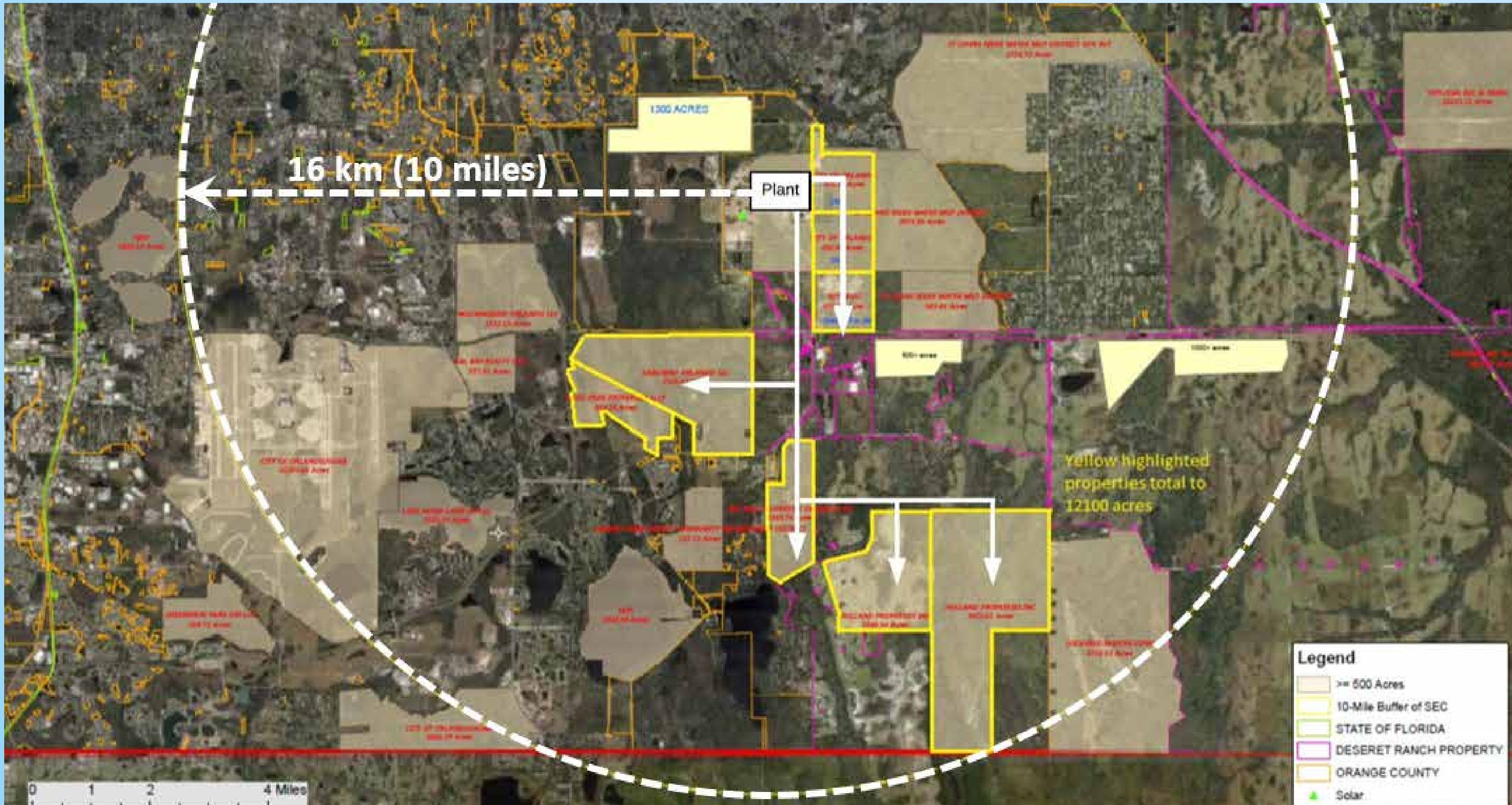
Task 6 Goal: Use project outcomes in TEA-LCA assessment studies.

- Task 6.0 Engineering and Technoeconomic Analyses and Life Cycle Assessment (MBE/OUC/GT)
  – Subtask 6.1 – Farm Engineering Design(MBE/OUC/GT)
  – Subtask 6.2 – Techno-economic Assessment (TEA) (MBE)
  – Subtask 6.3 – Life Cycle Assessment (LCA) (MBE)
  – Subtask 6.4 – Gap Analysis

400-ha (1000-acre) farm sited for Phase-1 project.



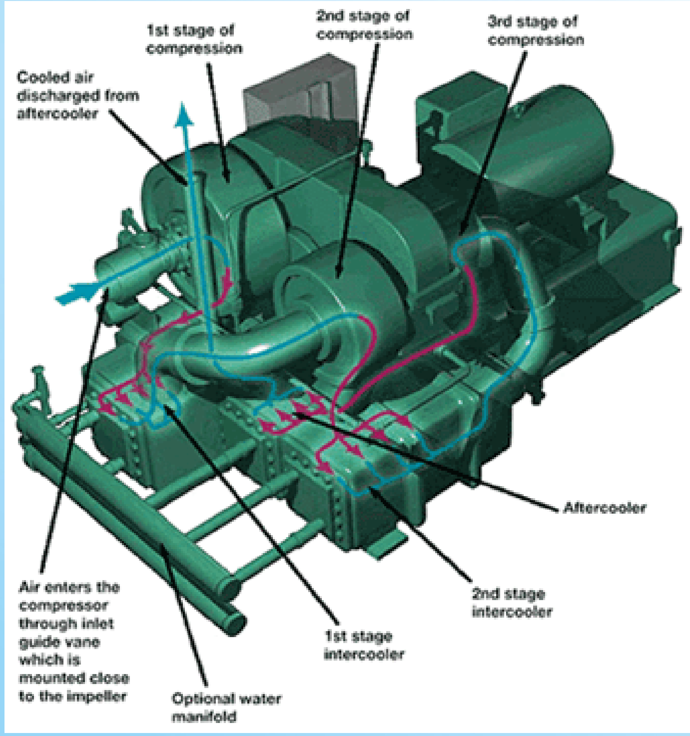
Map shows >10,000 acres on undeveloped land near SEC, with pipeline routing, for Phase-2.



Gas concentration and transport options

Compressor for flue gas, or MEA or Global Thermostat technologies for concentrating flue gas to ~100% CO_2.

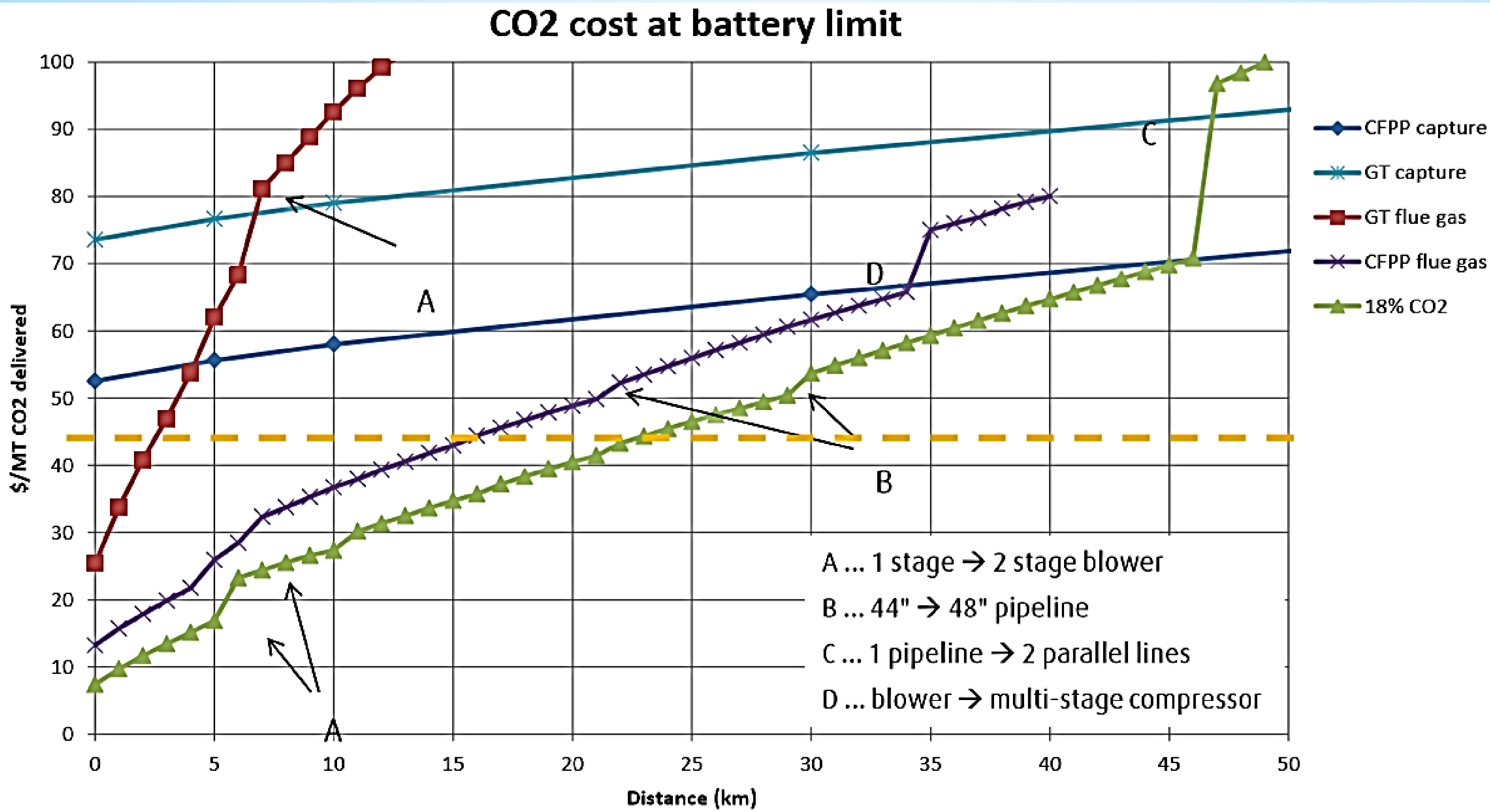
3-stage centrifugal compressor for flue gas transport



MEA absorbing and stripping towers – a 60 gallons per minute model

CO_2 Costs at Algae Facility Gate (Linde-Sapphire 2014)

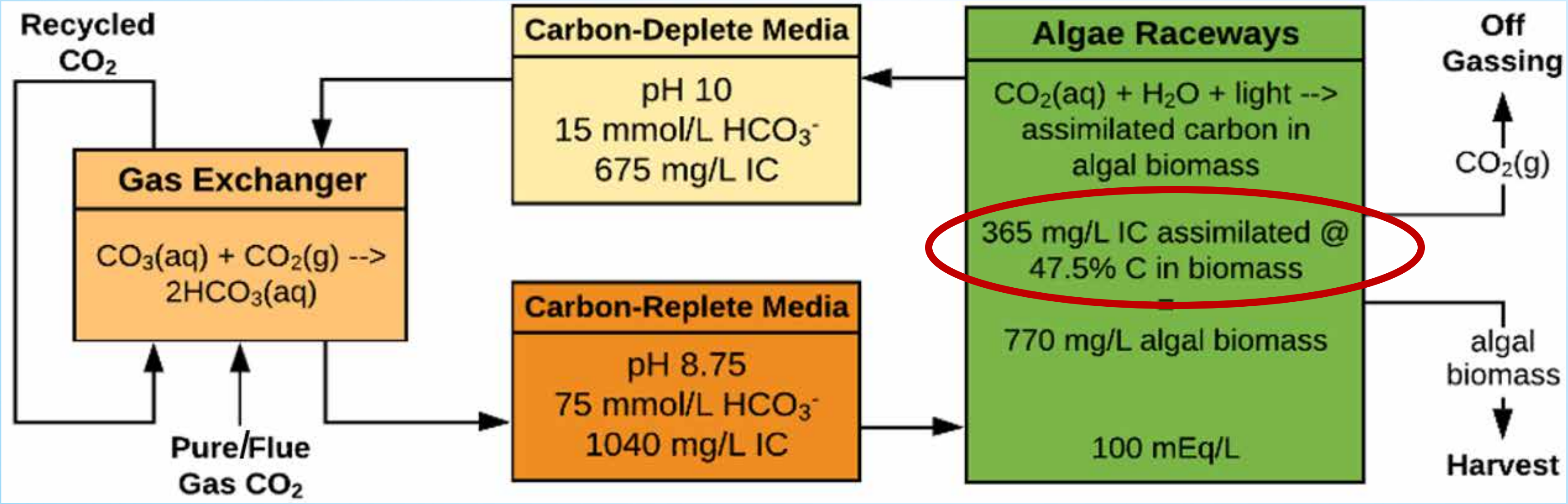
- “Capture” systems are post- combustion MEA.
- **Most economical delivery method within 16 km (10 miles) is low pressure** delivery of flue gas from a coal fired power plant (CFPP)



CFPP=Coal Fired Power Plant, GT= Natural Gas Turbine power plant

Example:
A potentially optimal alkalinity is 100 meq/L.

We can calculate CO_2 storage, estimate offgassing, and project biomass productivity.

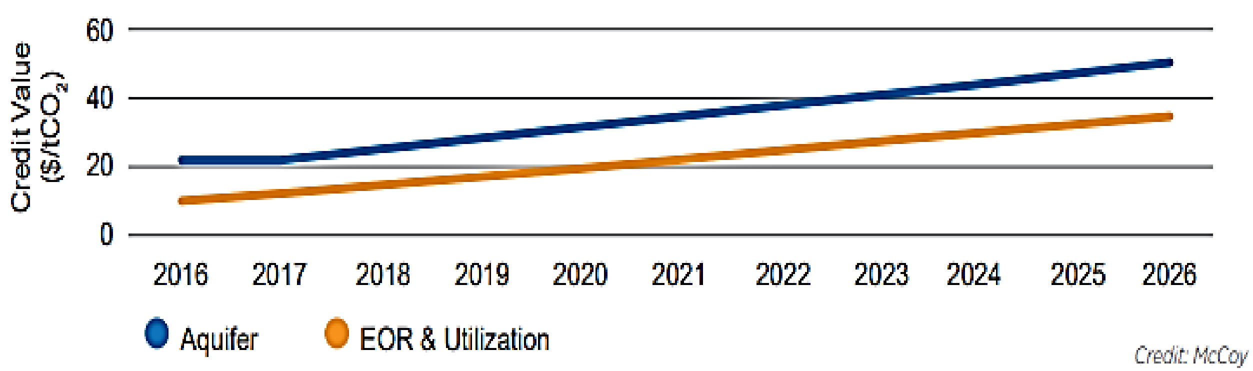


TEA General Methods

- Economics **aligned with NREL methodology** (2017 NREL "Algae Harmonization Study").
- 30-year cash flow analysis at **10% IRR** and "*n*th" plant cost assumptions.
- The wetted area of all the sub-facilities totals **~10,000 acres**.
- **Applied 45Q Tax Credit** to the cash flow analysis due to net negative GHG emissions for the proposed algae process. See table below.

45Q, Types of Sources and Credit Between 2018-2026

	Threshold by Facility Type (ktCO_2/y0			Credit in 2026 ($/t)
	Power Plant	Industrial Facility	Direct Air Capture	
Dedicated Storage	500	100	100	50
EOR	500	100	100	35
Utilization	25	25	25	35



Credit: McCoy

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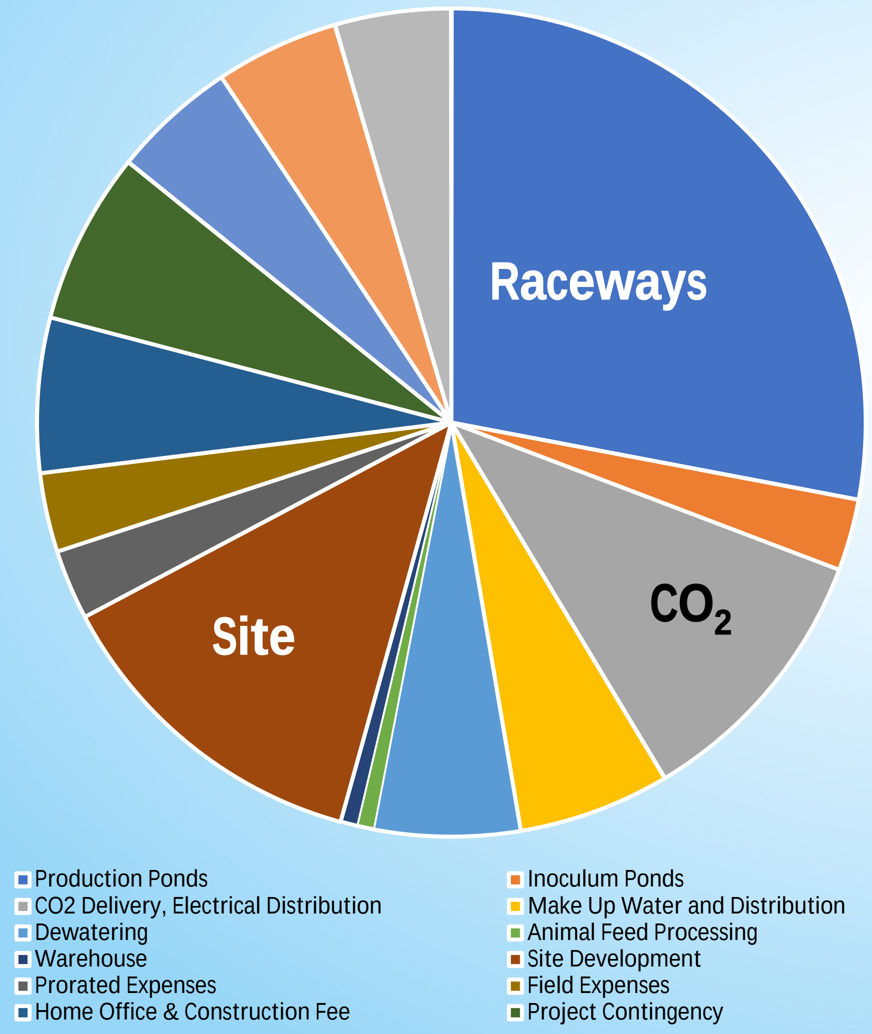
Production Facility CapEx (Preliminary)

Total Capital Investment: ~$1B



Assumptions

Production Ponds: 4-ha clay-bottom ponds with lined walls.

CO_2 Delivery: Low pressure flue gas delivery from co-located power plant.

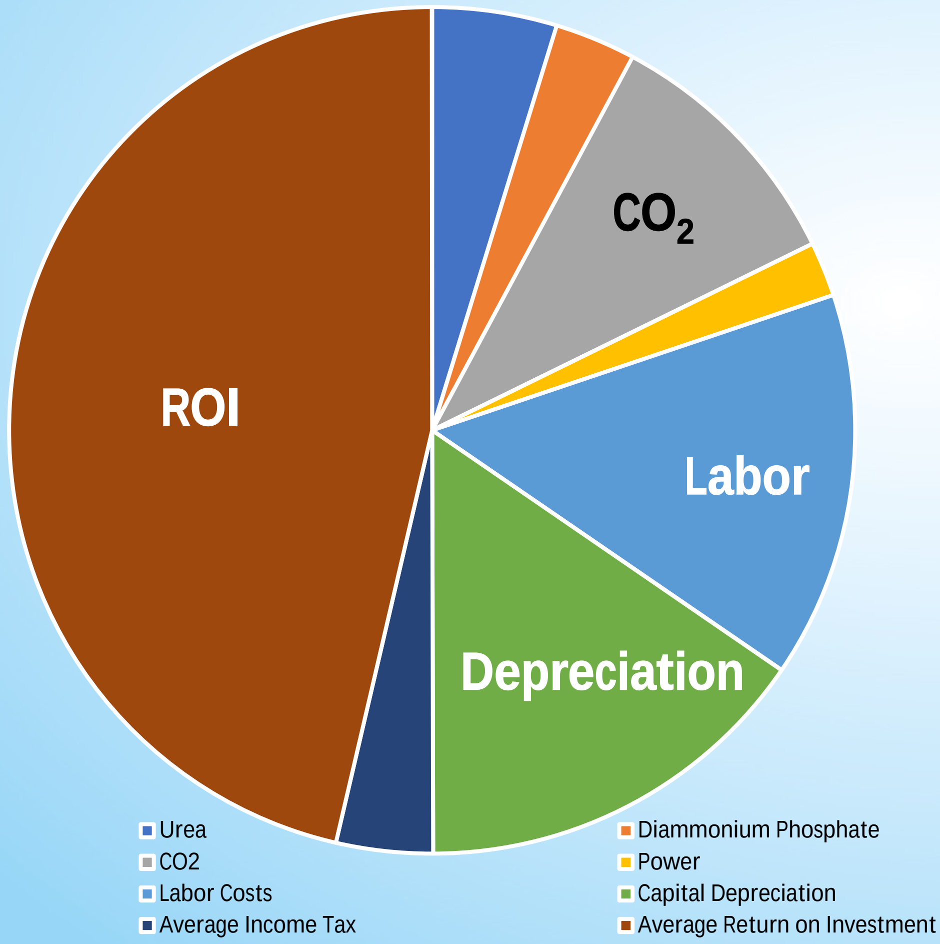
Dewatering: Canal screens for harvesting and screw presses to thicken biomass to ~20% solids.

Site Development: Includes topographical surveying, land preparation, grubbing, grading and infrastructure development (roads, fences, etc…)

Project Contingency: Assumed at 10% of total direct costs, per NREL Harmonization Report.

CapEx + OpEx Mean Feed Selling Price (Prelim.)

Minimum Feed Selling Price: $699/mt which is less than the projected feed value of $1000-$1200/mt.



Assumptions

CO_2 Costs: $18-$37/mt CO_2 delivered to facility gate for the four pipelines.

Labor Costs: Sourced from NREL 2017 Harmonization Report and adjusted based on sub-facility size.

Capital Depreciation: IRS Modified Accelerated Cost Recovery System (MACRS), assuming 7-year recovery period.

Average ROI: Assuming 40% equity financing at 10% after tax IRR.

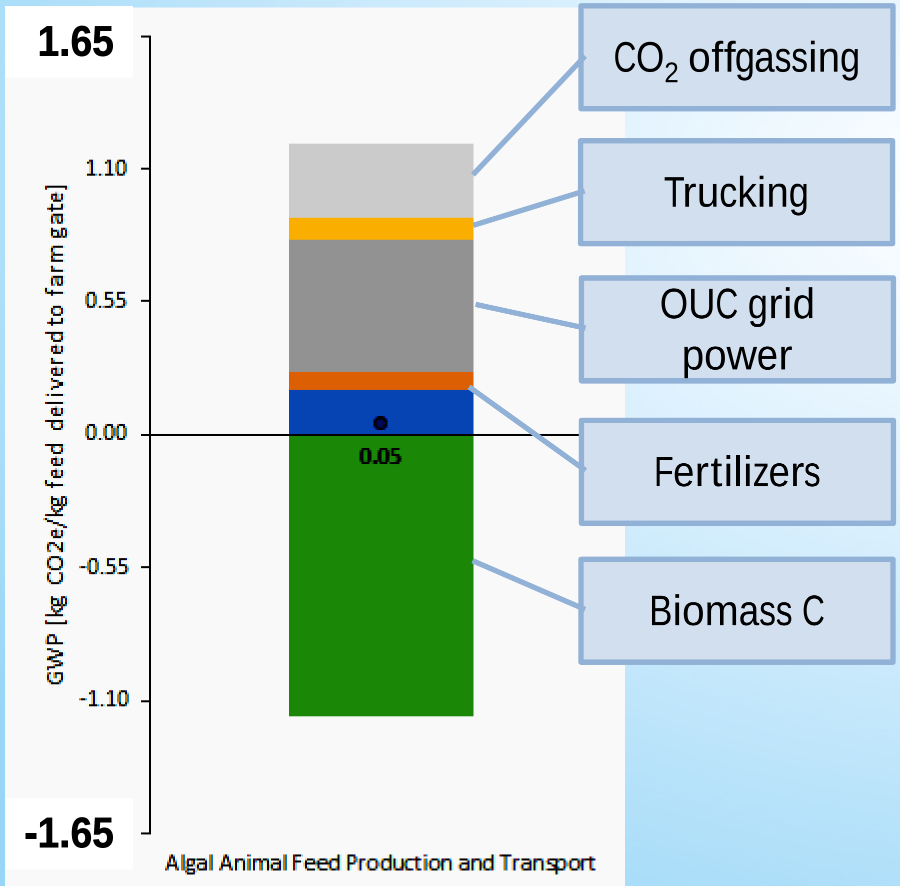
LCA methods used for both algae and soybeans

1. **NETL's OpenLCA CO2U Database and methods were used (T. Skone et al.)**
   - LCA Approach: "**Consequential**" - algal animal feed compared to whole soy beans.
   - Functional unit: **kg of animal feed trucked (diesel) 500 miles to animal production farms**
   - **Power plant "sized" for 100% flue gas delivered to 4,000 ha** (10,000 ac) of algae facilities (next slide)
   - **Same kWh generated** by both algae and soybean cases.
   - **TRACI 2.0** set of impacts (climate & other air pollutants, eutrophication, human health, etc.)
2. **Ecoinvent inventory implementation**
   - **Comparison product system (whole soybean)** included the steps:
     - Sow, till, fertilize, apply pesticides, and harvest.
     - Dry whole soybeans to 12% moisture w/ solar + natural gas finish.
   - Power plant, **without CO_2 concentration**, transported cradle-to-algae facility gate

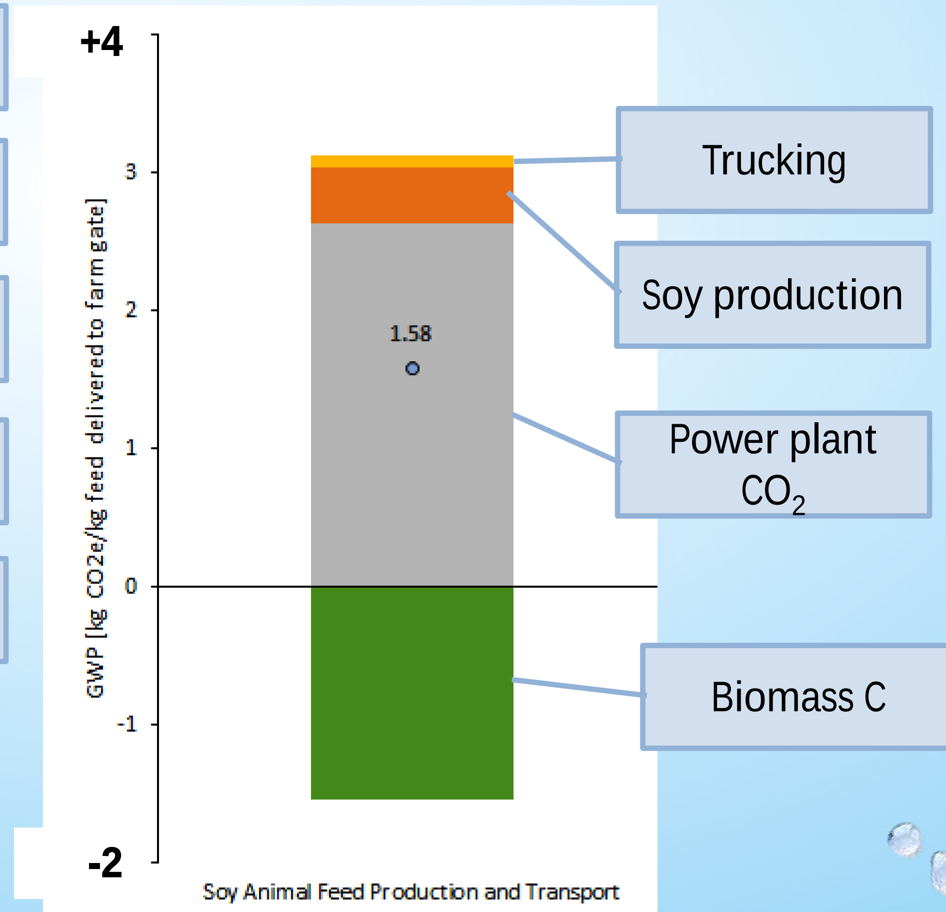
Algae had lower emissions than soybean feeds.

Electricity co-product set equal for both cases. Preliminary results.

Algae Animal Feed
Net +0.05 kg CO_{2e}/kg feed



Soy Animal Feed
Net +1.6 kg CO_{2e}/kg feed



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Key Take-Aways

- **Local algae appear more stable than non-native.**
- **Local strains with omega-3 and -6 were prospected and cultivated.**
- **Low cost screen harvesting and dewatering developed.**
- **Experience cultivating year-round in Florida.**
- **Confirmed that scrubbed flue gas gives same productivity and algae quality as pure CO_2.**
- **Algae cost <$1,000 per mt at 4,000-ha scale.**
- **Beneficial GHG impact vs. soybean feed.**

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Appendix

- These slides will not be discussed during the presentation, but are mandatory.

- **Team Description and Task Assignments**
- **Schedule of Milestones and Deliverables**

MBE Team Details, Covid Period

Ruth Spierling, MS, PhD candidate, MBE/UCF, Env. Eng., 9 years conducting and managing algae and fermentation projects.

Jesse Conklin, BS, Biology, trained in sterile technique, indoor/outdoor cultivation, analytical techniques.

Two additional student technicians

Cooper Gibson, BS, Mech. Eng., MBE, TEA-LCA, facility design

Neal Adler, MS, Civil Eng., MBE, facility design

Braden Crowe, BS, Chem. Eng., MBE, carbonate system expert

Tryg Lundquist, PI

John Benemann, CEO

OUC Team Details, Covid Period

Justin Kramer, PE, Mech. Eng., Supervisor of Emerging Technologies

Chanda Durnford, CEM, Project Manager, Emerging Technologies

Eric Costello, PE, Senior Engineer, Stanton Energy Center

Charles Linder, Managing Chemist, Water Lab, Stanton Energy Ctr.

Jim Shoemaker, Managing Chemist, Gardenia Laboratory

Linda Ferrone, Chief Customer Officer

Various tradesmen and EH&S personnel at Stanton.

All subcontracts originate directly from MBE.

Darin Bennett, PhD, Poultry Science Prof., Cal Poly State University

Mark Edwards, PhD, Animal Science Prof., Cal Poly State University

Woo-Hyoung Lee, PhD, Env. Eng. Professor, UCF, CO_2 tracking, cultivation

Jaehoon Hwang, PhD, Env. Eng. UCF, CO_2 tracking, cultivation

3 grad and undergrad UCF engineering students

Ron Chance, PhD, PE, Chemistry, Vice President R&D, Global Thermostat

Project Milestones, 1 of 2

- ML-1: Commission three 43-m^2 raceway ponds at SEC. Planned Date: March 30, 2019 (Q1) **Completed 9/2019**
- ML-2: Commence Tribonema cultivation in ponds at SEC. Planned Date: June 30, 2019 (Q2) **Completed 1/2020**
- ML-3: Shipment of dry algae to Cal Poly for the layer feed trial. Planned Date: August 30, 2019 (Q3). **Completed 9/2020**
- ML-4: Complete growth rate comparison of three filamentous strains including Tribonema. Planned Date: December 30, 2019 (Q4) **Completed 6/2020**

Project Milestones, 2 of 2

- ML-5: Demonstrate 90% harvesting of algae biomass and dewatering to 20% solids at pilot scale. Planned Date: March 30, 2020 (Q5) **Preliminary results reported 3/2020**
- ML-6: Shipment of dry algae to Cal Poly for the broiler feed trial. Planned Date: April 1, 2020 (Q6). **Expected 2/2021**
- ML-7: Demonstrate in algae produced at OUC equivalent omega-3 fatty acid productivity as baseline algae grown by MBE in California. Planned Date: September 30, 2020 (Q7). **Expected 11/2020**
- ML-8: Improve carbon uptake efficiency by 25% over baseline. Planned Date: December 31, 2020 (Q8) **Expected 2/2021**

Project Deliverable Status

Some tasks delayed by Covid labor restrictions

#	Task No.	Due date	Name	Status
D1	1	2-28-19	Project management plan	**Complete**
D2	1	6-30-19	Technology maturation plan	**Complete**
D3	2	9-30-19	Cultivation optimization interim report	**Complete**
D4	3	9-30-19	Productivity interim report	**Complete**
D5	6	1-31-20	Preliminary TEA results	**Complete**
D6	5	7-31-20	Feeding trial interim report	In progress
D7	4	7-31-20	Carbon utilization interim report	In progress
D8	6	7-31-20	Preliminary LCA results	**Complete**
D9	6	9-30-20	Preliminary gap analysis	In progress
D10	1	12-31-20	Final Report	In progress