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, 2019–2022, Andy Aurelio, PM

MicroBio Engineering, Inc.

San Luis Obispo, California

Orlando, Florida

- Tryg Lundquist, PhD, PE, PI*, presenting
- Ruth Spierling, Sr. Engineer, Site Manager
- Cooper Gibson, Mechanical Eng., TEA-LCA
- John Benemann, PhD

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

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 3/31/2022 extended
- 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 large quantities of CO_2 as a feedstock, which offsets some cost of capture, utilization, and sequestration.
2. CO_2-derived commodities need 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

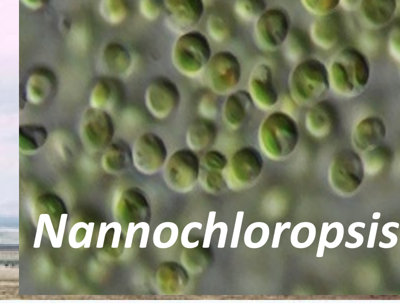
Paddle Wheel Mixed Raceway Ponds

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

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

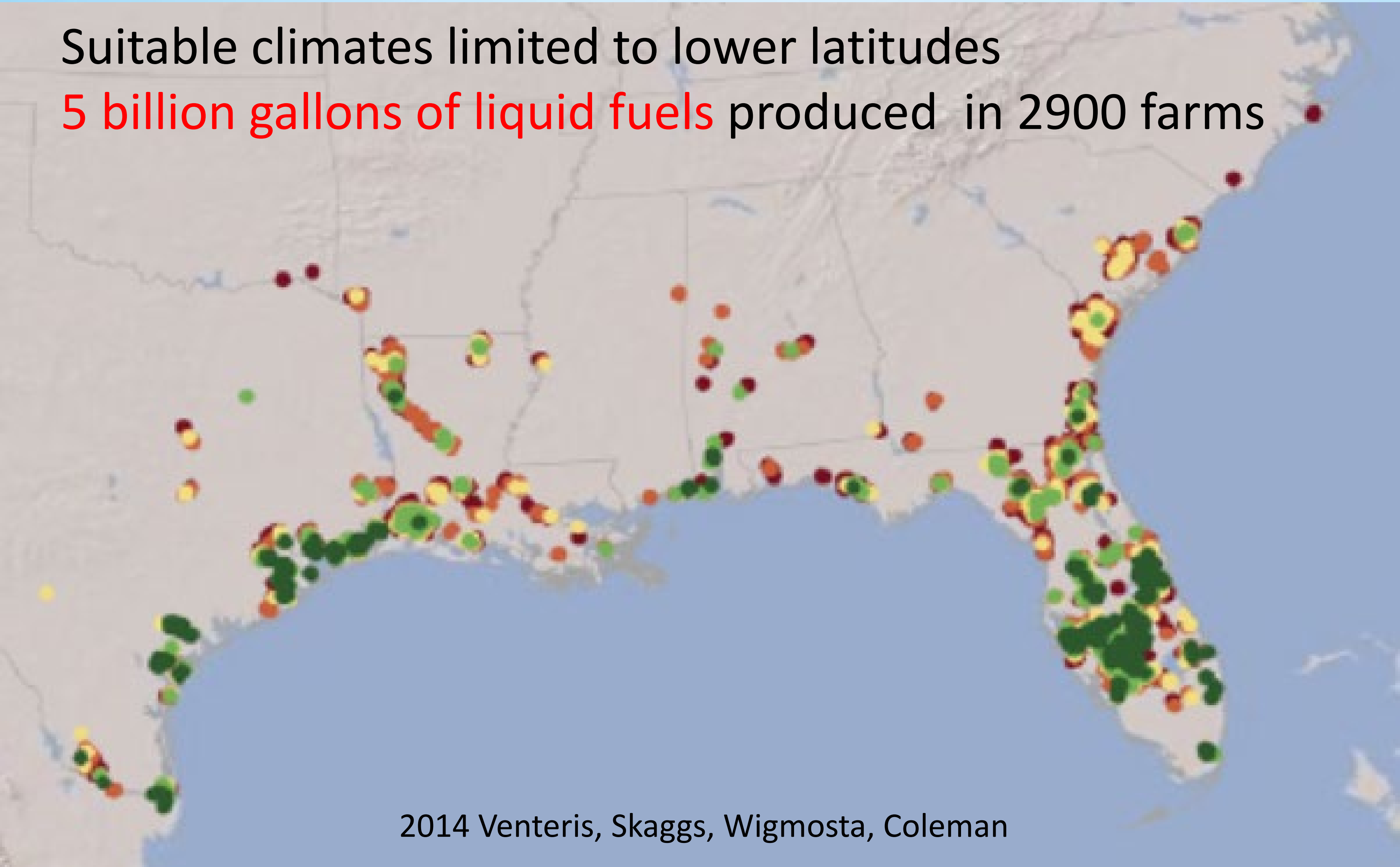


Columbus, New Mexico

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

Suitable climates limited to lower latitudes

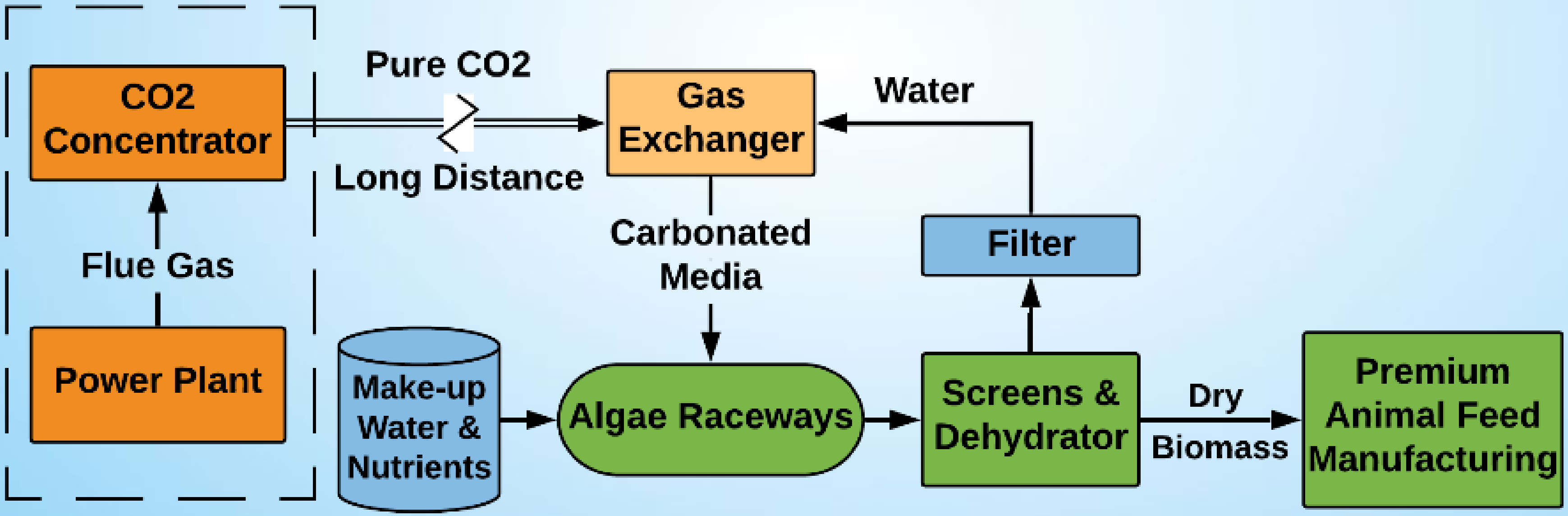
5 billion gallons of liquid fuels produced in 2900 farms



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.



Project objectives and technical-economic challenges.

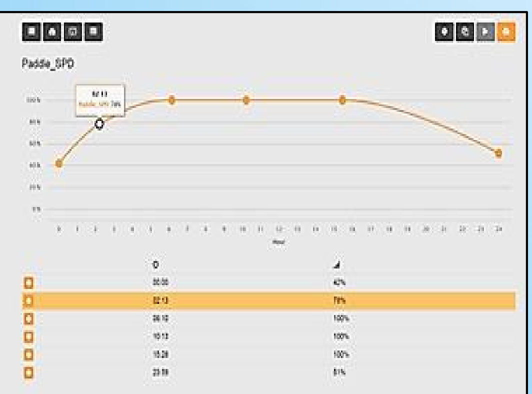
- How much net CO_2 mitigation can be achieved with premium algae feeds?
- How can productivity and composition be maximized to improve process economics and land use?
- What will the CO_2 offset cost after commodity animal feed revenues?
- Develop detailed site specific TEA and LCA for OUC SEC for CO_2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

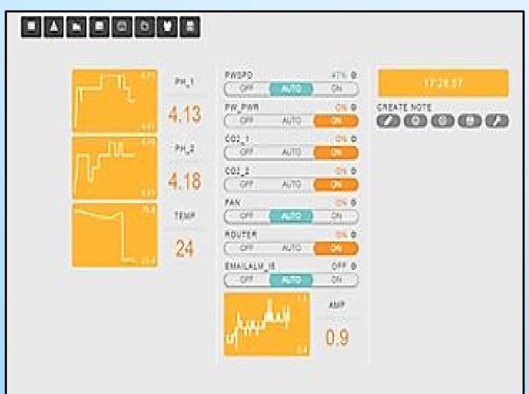
Task 3 Goal: Larger-scale production, harvesting, dewatering and drying, for feed production.

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

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

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

MBE California strains

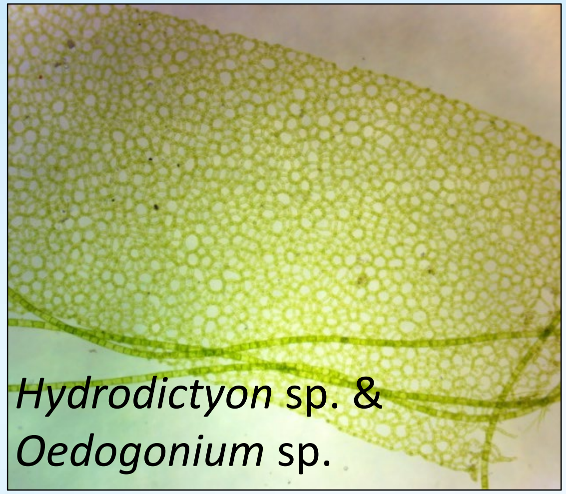
- Omega-3 fatty acid producing filaments from California: *Tribonema minus*
- Spirulina, UTEX culture collection, media can store CO_2

SEC local strains

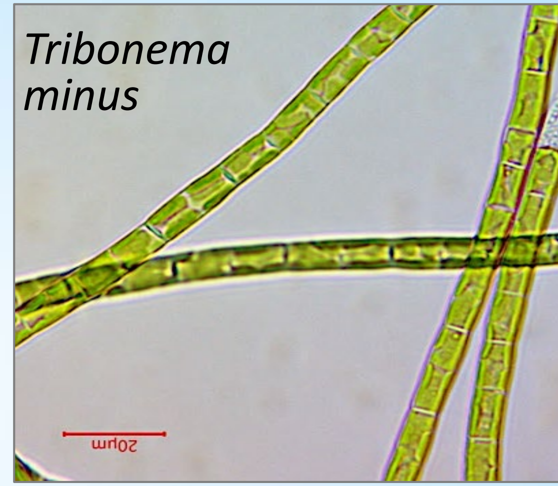
- Omega-3 fatty acid filament: *Uronema* sp. isolated on site. Identified using 16S RNA
- High protein and pigment: *Oedogonium, Hydrodictyon, Uronema, Vaucheria, etc.*

Cultivatable strains prospected locally at SEC.

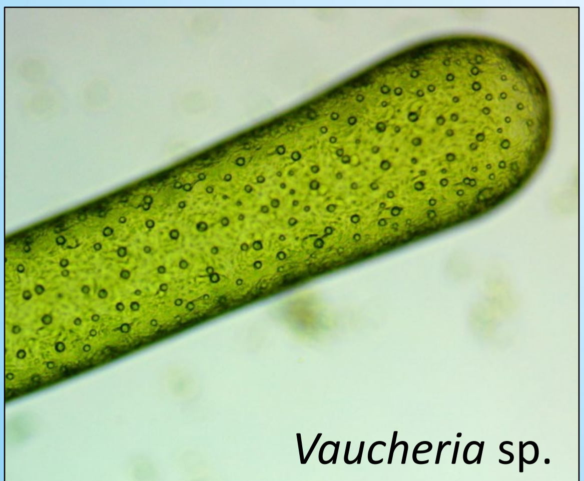
Oedogonium sp. & *Compsopogon* sp.



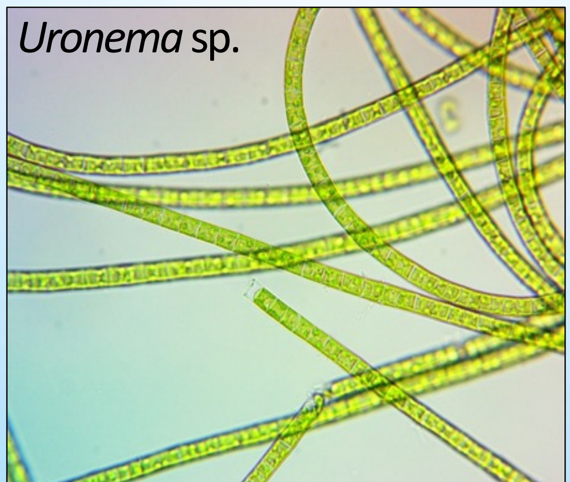
Hydrodictyon sp. & *Oedogonium* sp.



Tribonema minus



Vaucheria sp.



Uronema sp.

Spirogyra sp. & *Uronema* sp.

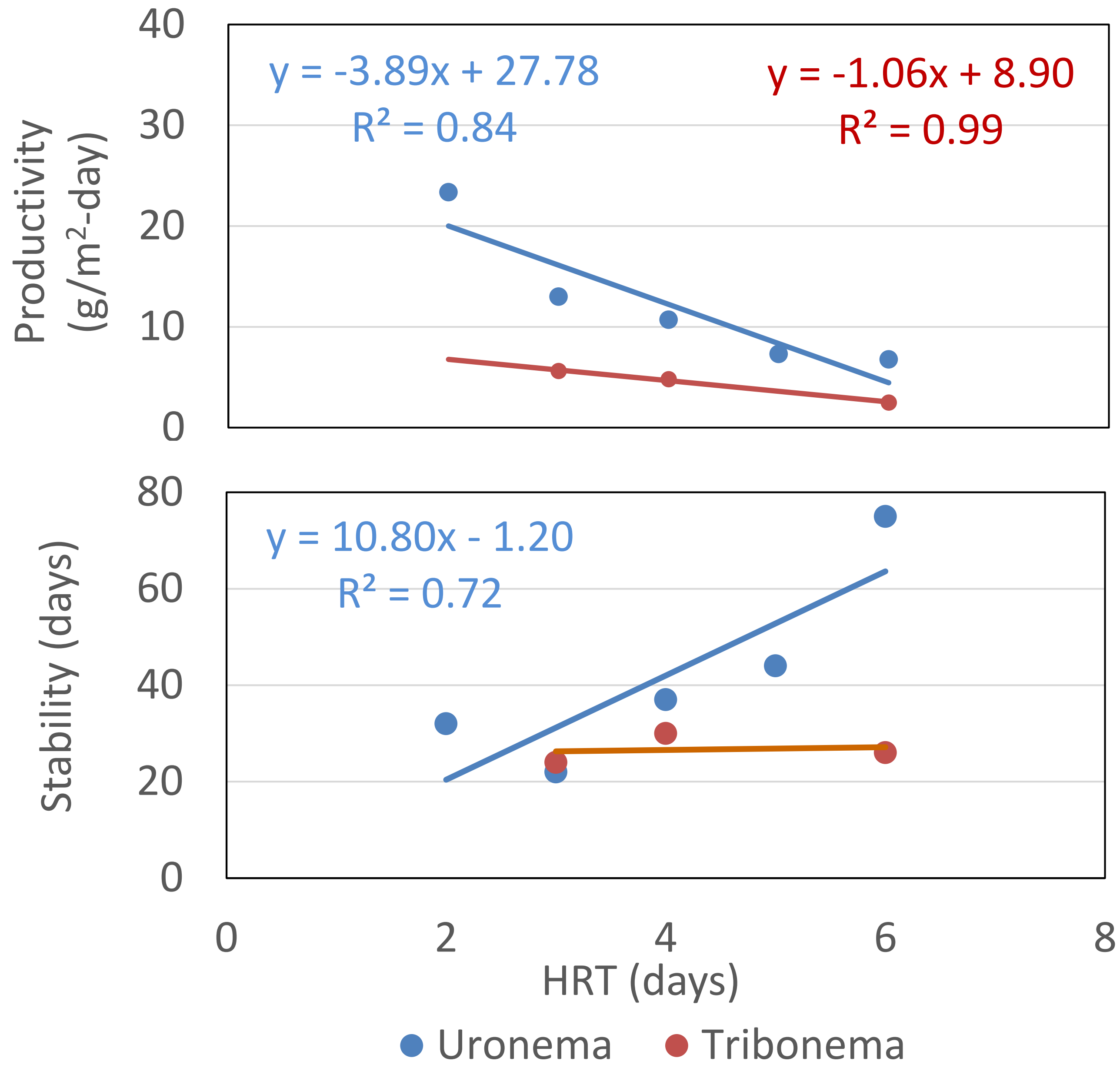
Cultures are scaled-up from test tube to bubble column to carboy to pond.

Pond operational methods were tested to achieve high productivity but also culture stability.

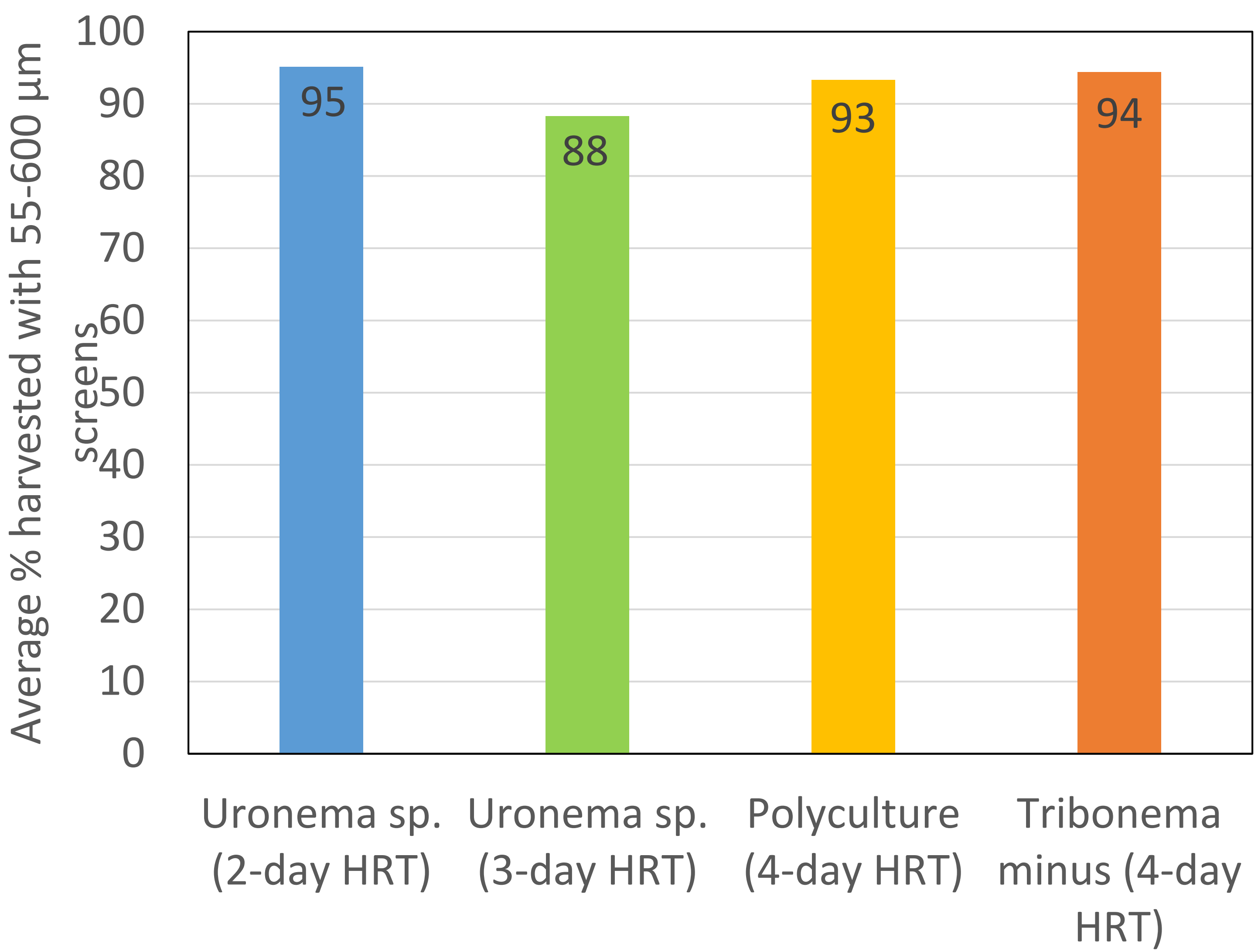
Hydraulic residence time, concentration and water dilution frequency affect productivity and culture stability.

Short HRT promotes high productivity, but long HRT can promote culture stability.

Uronema is most stable and productive at 9.8 g/m^2-d ann. avg.



Screen harvesting was greater than 90% effective for 55-600 µm screens and gravity settling.



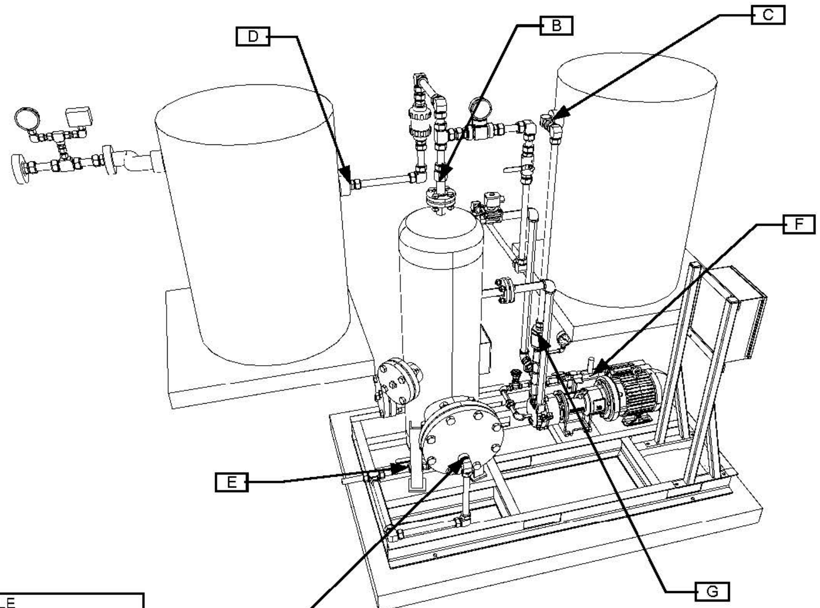
3-day HRT

2-day HRT

>20% solids after dewatering. 5 hr for dehydration.

Task 4: Determine the CO_2 utilization efficiency

- Task 4.0 Carbon Mass Balances during flue gas utilization
- Sized and designed a flue gas blower to meet algal demands



NOZZLE SCHEDULE		
IDENTIFIER	CONNECTION	SIZE
A	SEPARATOR OVERFLOW	1" FNPT
B	SYSTEM DISCHARGE	1" MNPT
C	KNCKOUT TANK 1 OUTLET	1" FNPT
D	KNCKOUT TANK 2 INLET	1" FNPT
E	SEPARATOR DRAIN	1" FNPT
F	SEAL FLUID INLET	1/2" FNPT
G	COMPRESSOR INLET	2" FNPT

NOTES:
1. OUC TO INSTALL MBE-SPECIFIED FLOW SWITCH ON THE SEAL FLUID INLET LINE [F] TO PROTECT EQUIPMENT AGAINST INTERRUPTIONS IN WATER SUPPLY. A 1/2" NPT PIPE NIPPLE WILL NEED TO BE INSTALLED TO CONNECT THE FLOW SWITCH TO THE INLET WATER LINE [F].
2. FIELD WILL SUPPLY SUGGESTED ROUTING OF SOURCE WATER LINE PER E. COSTELLO

Stanton Energy Center Algae Pond Pipeline	μBIO MicroBio Engineering P.O Box 15821 San Luis Obispo, California, USA 93406	Compressor Piping Layout	Drawn by: CEG Reviewed by: NCA Date:11/9/2020 DRAFT	01 C

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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
    - Nearly 100 kg of dried biomass delivered to Cal Poly
  - Subtask 5.2 –Layer Feeding Trials
  - Subtask 5.3 – Broiler Feeding Trials

Poultry feeding trials 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
- Meat quality
- Skin color

Animal Scientists: Drs. Darin Bennett and Mark Edwards

Layers and broilers were fed four filamentous algae diets: 3 isolated at OUC and 1 from California.

Feeding Formulation

Step 1: Determine algae biochemical composition.

Step 2: Measure digestibility of nutrients by mass/energy balances.

Step 3: Based on 1 & 2, formulate feed that can be properly compared to conventional feeds.

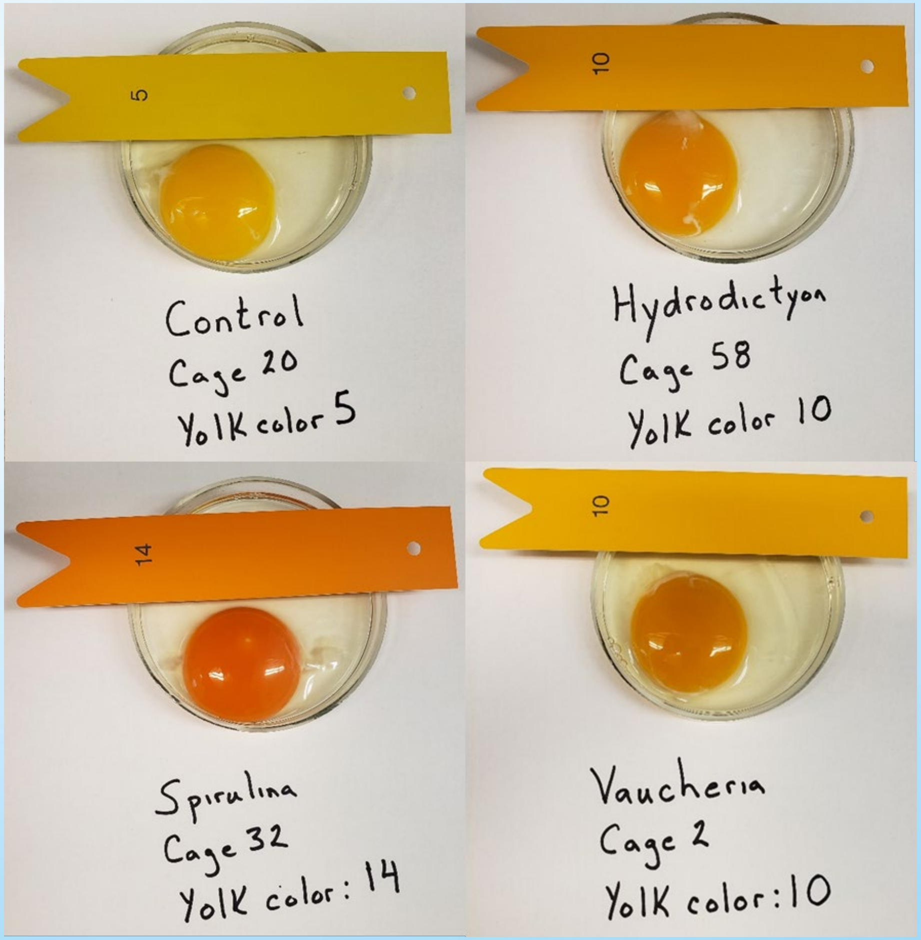
Hydrodictyon, Uronem

Digestibility trials completed. Production trials are in progress with OUC strains vs. conventional feed.

All 10 essential amino acids for poultry were digestible in algae, with Spirulina have the greatest quantities.

The algae ingredient had 30% greater energy content than conventional feed.

Algae pigments improve yolk color.



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

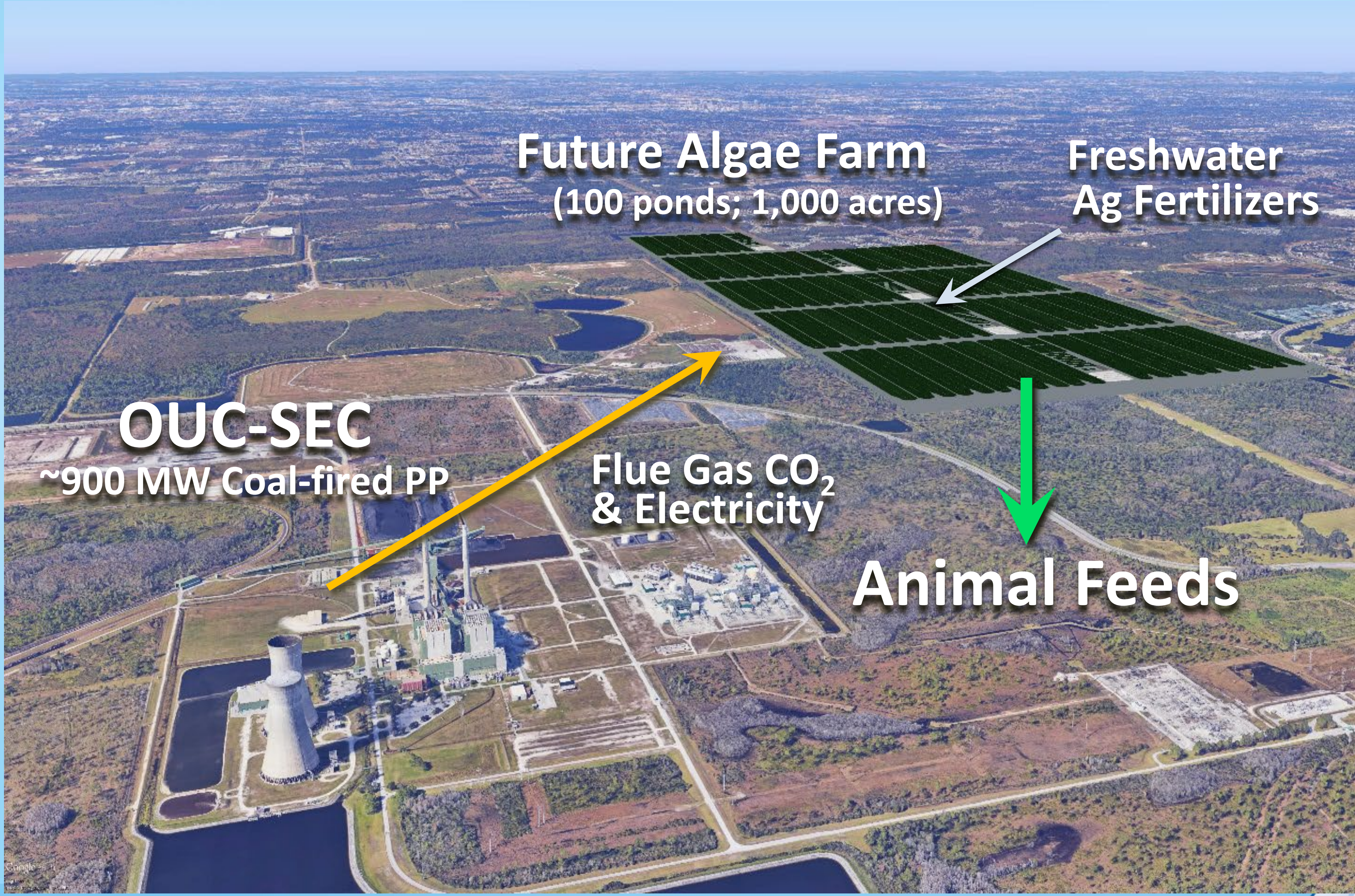
Task 6.0 Engineering and Technoeconomic Analyses and Life Cycle Assessment (MBE/OUC/GT)

- 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 (MBE)

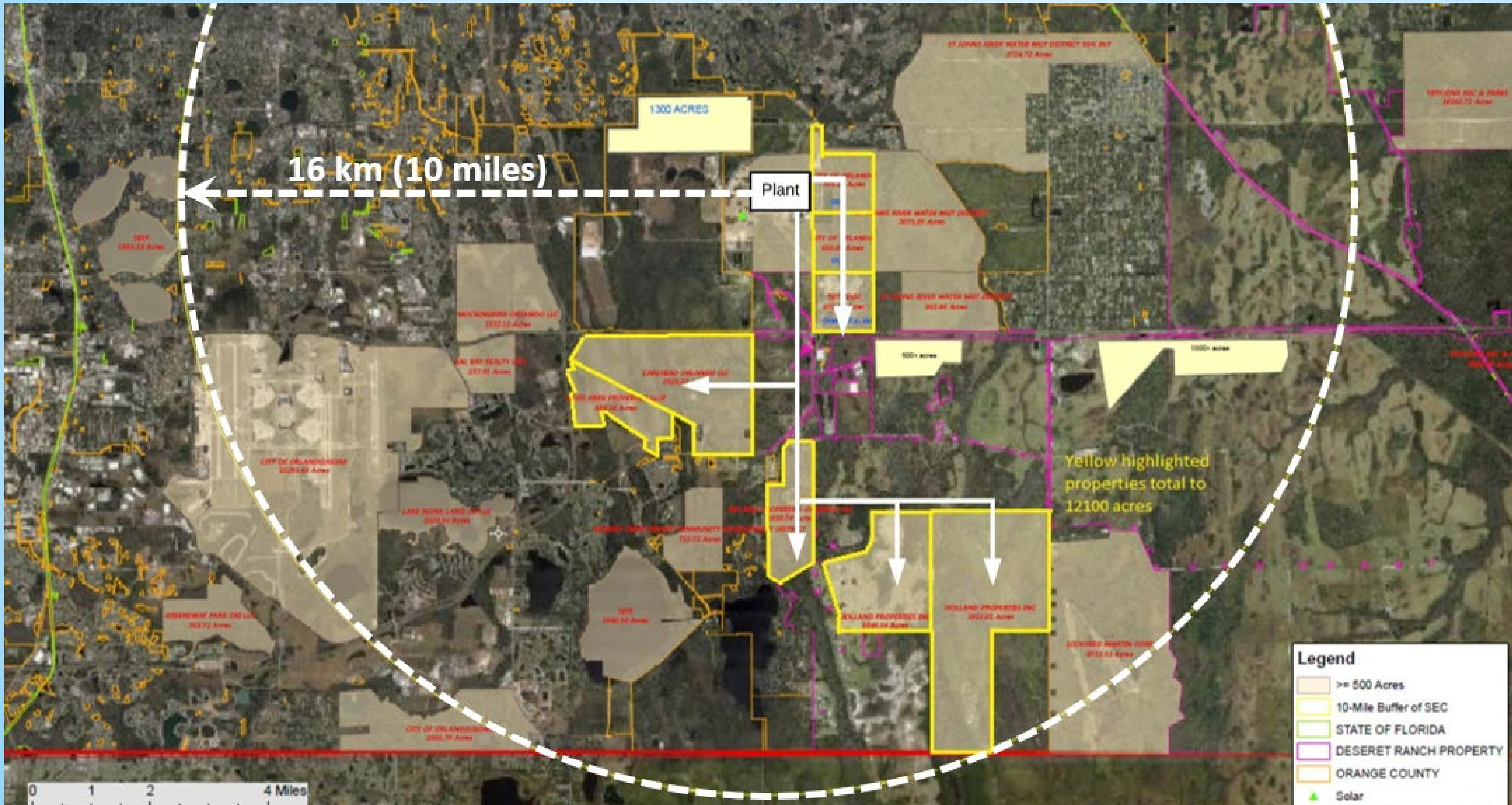
Key inputs to the TEA-LCA from Experimental Work

- Low-cost, low energy harvesting with canal screens or parabolic harvesters possible.
- Low-cost, low energy dewatering reaches 20% solids
- Low temperature 35-70°C dehydration is able to effectively dry biomass with no degredation of the organic material
- Abundant waste heat ~43 °C is available on-site

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

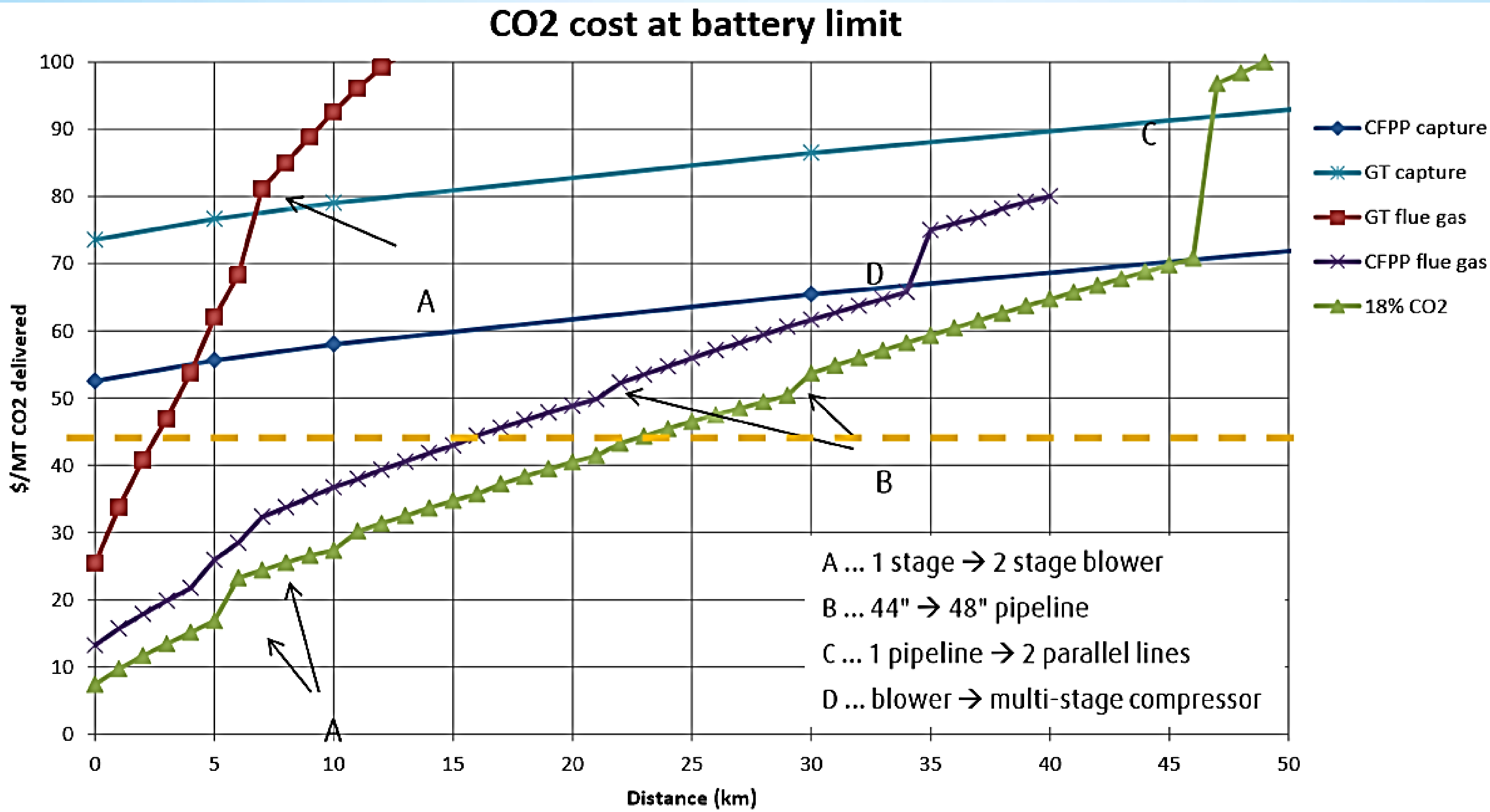


Map shows >10,000 acres on undeveloped land near SEC, with pipeline routing, for Phase-2.



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)



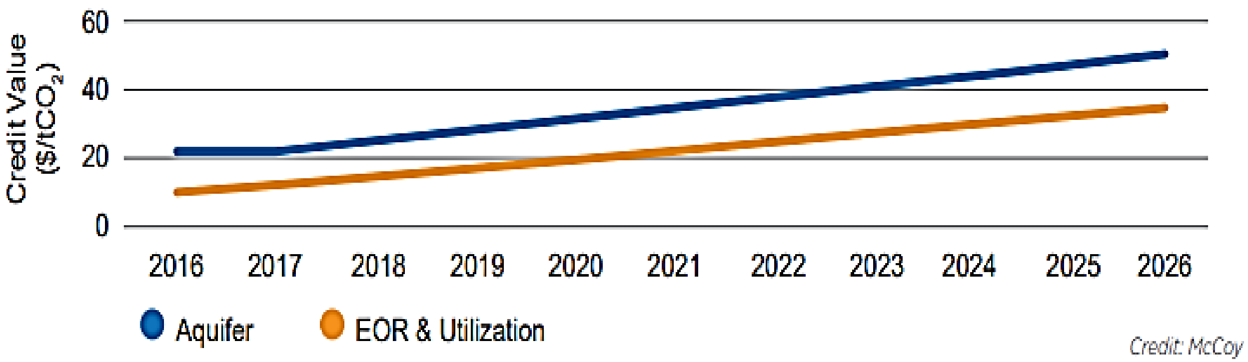
CFPP=Coal Fired Power Plant, GT= Natural Gas Turbine power plant

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.

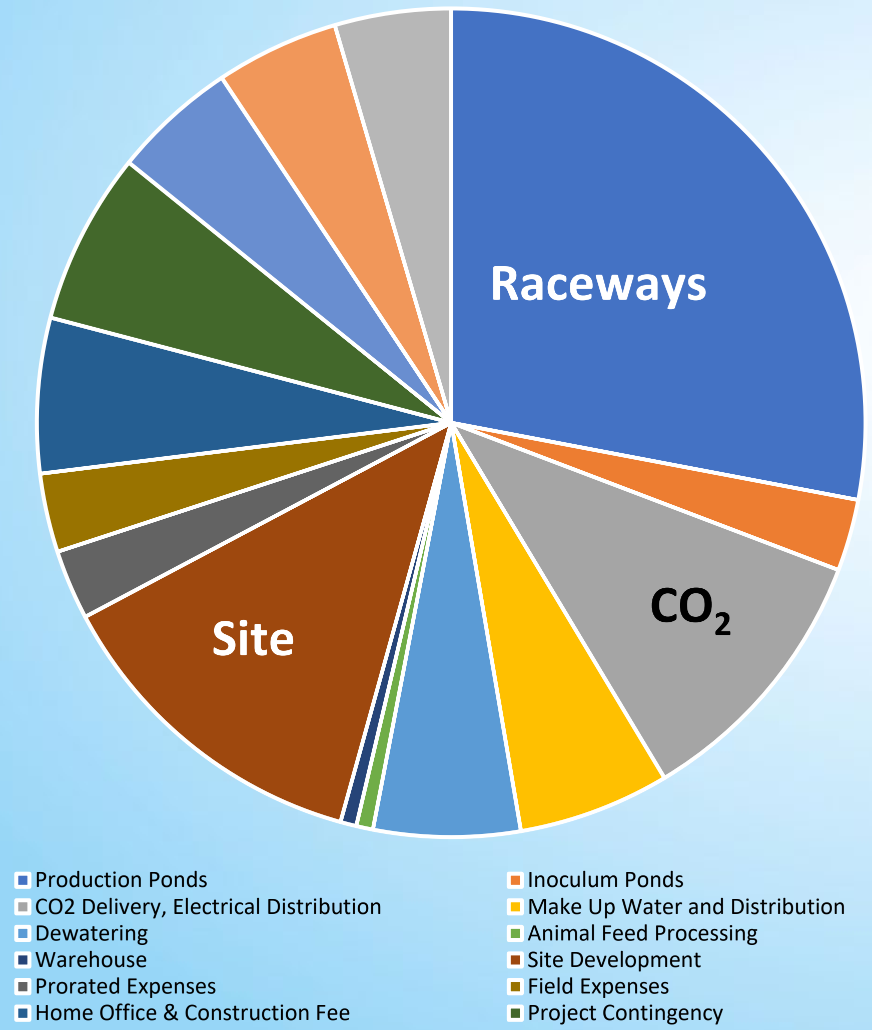
45Q, Types of Sources and Credit Between 2018-2026

	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



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.

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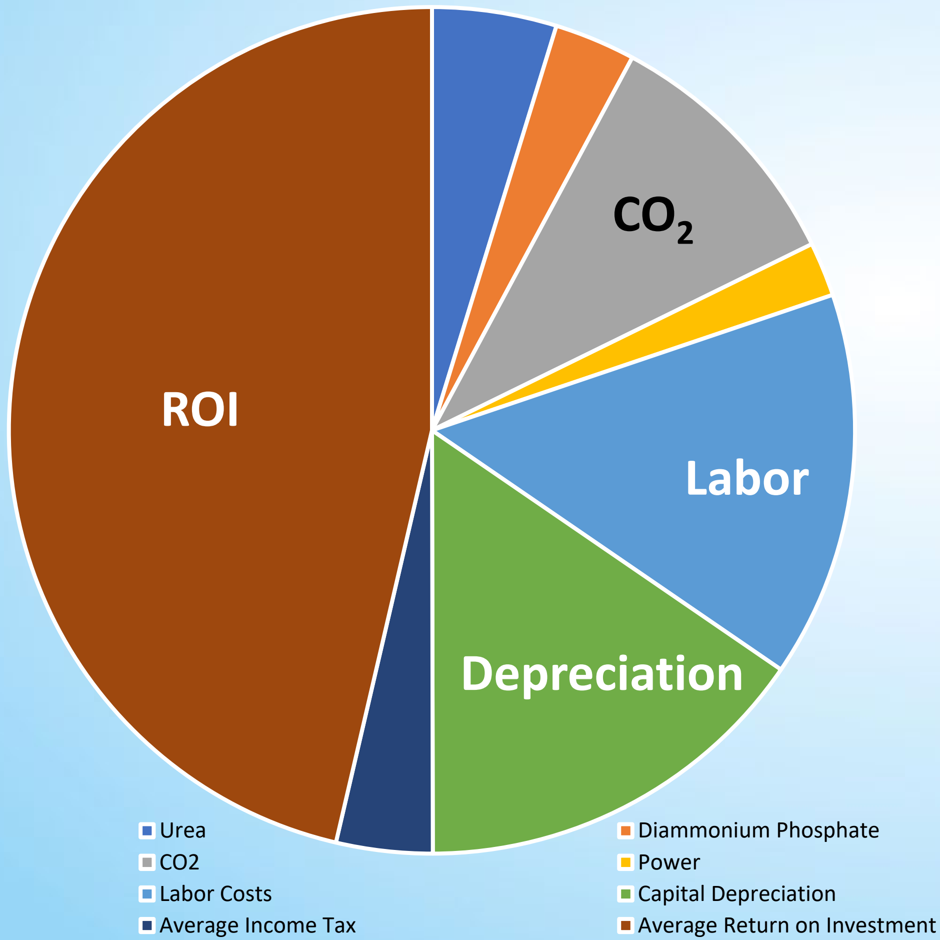
CapEx + OpEx Mean Feed Selling Price (Prelim.)

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

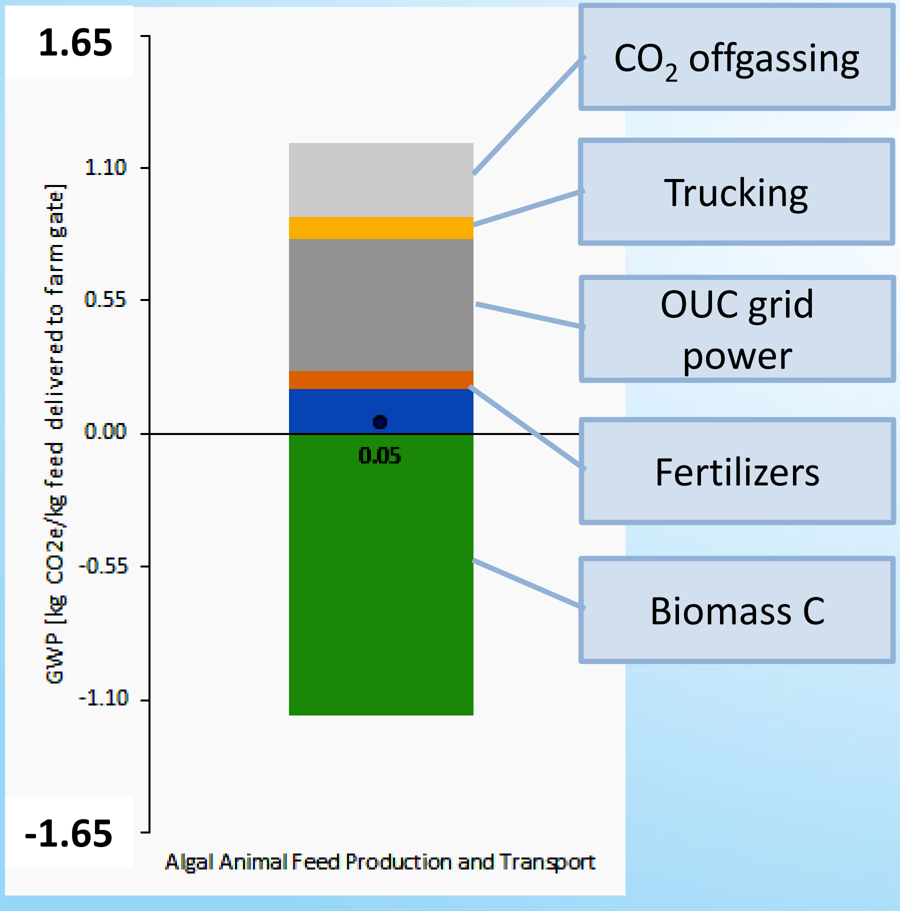
1. **NETL's OpenLCA CO2U Database and methods were used (T. Skone et al.)**
   - LCA Approach: "**Consequential**" - algal animal feed compared to whole soy beans.
   - Functional unit: **kg of animal feed trucked (diesel) 500 miles to animal production farms**
   - **Power plant "sized" for 100% flue 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.

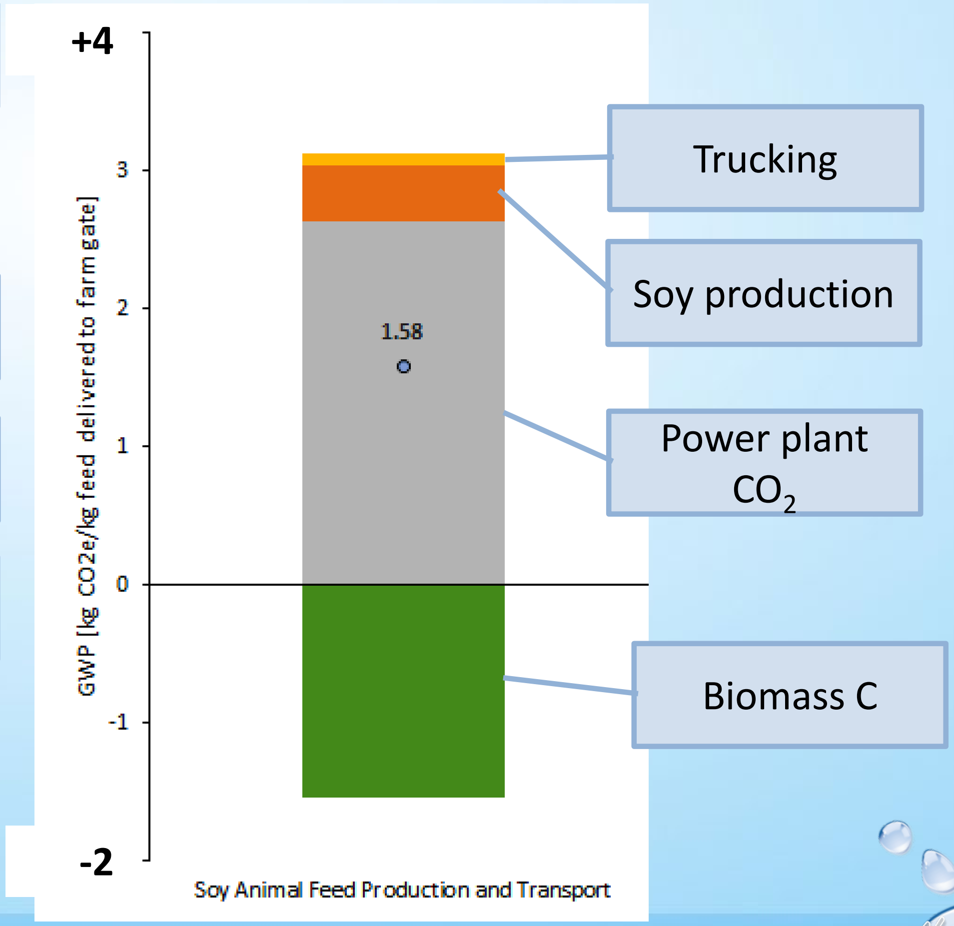
Algae Animal Feed

Net +0.05 kg CO_{2e}/kg feed



Soy Animal Feed

Net +1.6 kg CO_{2e}/kg feed



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Take-Aways So Far

- **Local strains with omega-3 and -6 were prospected, isolated and cultivated.**
- **Local algae have been more stable than non-native.**
- **Low-cost screen harvesting, dewatering and drying developed.**
- **Cultivated year-round.**
- **Improved yolk color with algae feeds**
- **Scrubbed flue gas gives same productivity and algae quality as pure CO_2.**
- **Algae cost \$300-\$500 per mt less than the projected value of the feed (4,000-ha scale).**
- **4,000 ha would fix 10% of OUC-SEC CO_2.**
- **Beneficial GHG impact vs. soybean feed.**

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TrygLundquist@MicroBioEngineering.com

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

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

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

Rubin York, Project Manager, Emerging Technologies

Nathan Parker, Engineer, Stanton Energy Center

Jim Shoemaker, Managing Chemist, Gardenia Laboratory

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.
  Completed 9/2019
- ML-2: Commence Tribonema cultivation in ponds at SEC.
  Completed 1/2020
- ML-3: Shipment of dry algae to Cal Poly for the layer feed trial.
  Completed 9/2020
- ML-4: Complete growth rate comparison of three filamentous strains including Tribonema.
  Completed 6/2020

Project Milestones, 2 of 2

- ML-5: Demonstrate 90% harvesting of algae biomass and dewatering to 20% solids at pilot scale.
  Completed 6/2021
- ML-6: Shipment of dry algae to Cal Poly for the broiler feed trial.
  68 kg produced, 4 kg remaining.
  Expected 9/2021
- ML-7: Demonstrate in algae produced at OUC equivalent omega-3 fatty acid productivity as baseline algae grown by MBE in California.
  Completed 11/2020
- ML-8: Improve carbon uptake efficiency by 25% over baseline.
  Expected 2/2022

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	2-28-22	Feeding trial interim report	In progress
D7	4	12-31-21	Carbon utilization interim report	In progress
D8	6	7-31-20	Preliminary LCA results	**Complete**
D9	6	9-30-20	Preliminary gap analysis	**Complete**
D10	1	3-31-22	Final Report	In progress