Aquaculture, Algae and Biofuels; Three Decades of Microalgae Lessons

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Where?

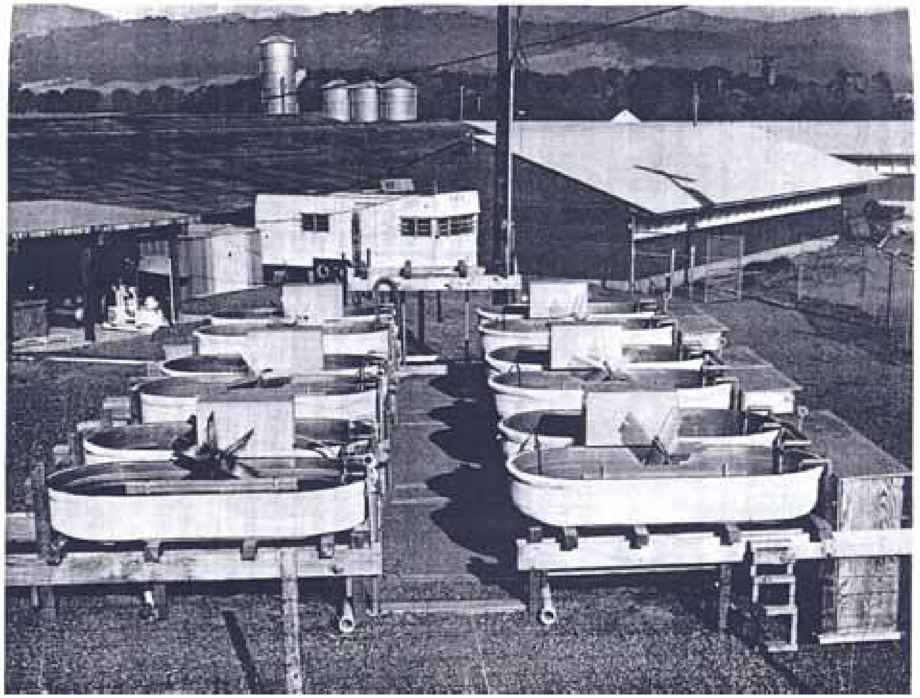
- Oregon State University, 1975
  - Research assistant
- University of Missouri, 1975-1978
  - PhD Student
- University of California-Davis, 1978-1982
  - Assistant Professor
- Pennsylvania State University, 1982-1987
  - Associate Professor
- Clemson University, 1987-2009
  - Professor and Endowed Chair
- University of Missouri, 2009-Present
  - Professor

Oregon State; 1975

Protein and Energy from Swine Manure

Lessons

- algal harvesting costly
- culture stability issues
- bacterial competition from organic loading



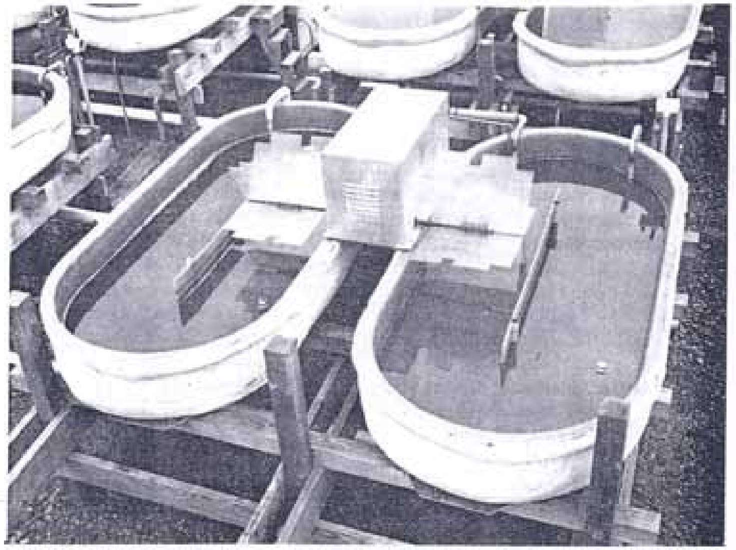


Figure 24. Appearance of swine waste medium under conditions favorable to bacterial growth

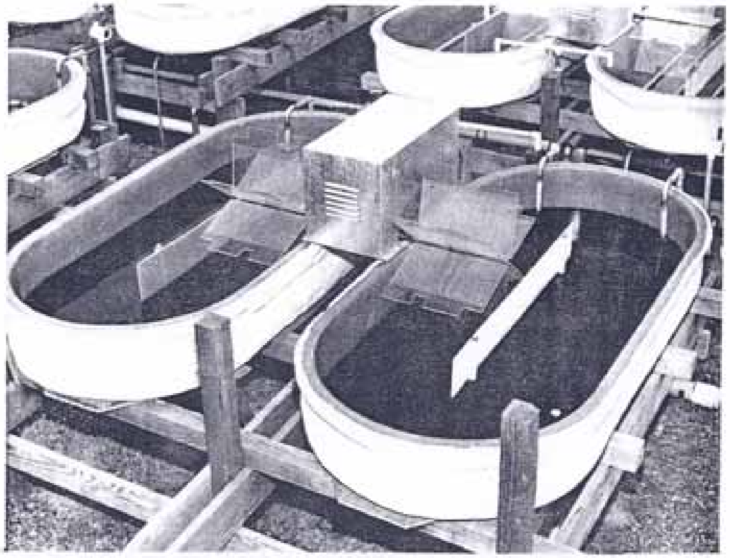


Figure 25. Appearance of swine waste medium under conditions favorable to algal growth.

University of Missouri; 1975-1978
The Growth Kinetics of Freshwater Algae

Lessons

- lab-data time consuming
- complex interactions
- plasticity of algal growth
- limited field applicability

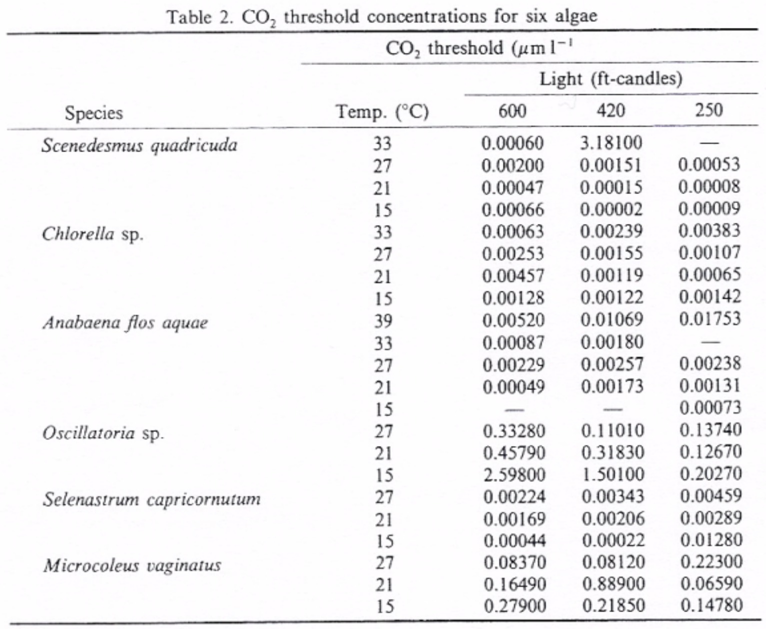


Table 2. CO_2 threshold concentrations for six algae

Species	Temp. (°C)	CO_2 threshold ($\mu m\, l^{-1}$) Light (ft-candles) 600	420	250
Scenedesmus quadricuda	33	0.00060	3.18100	—
	27	0.00200	0.00151	0.00053
	21	0.00047	0.00015	0.00008
	15	0.00066	0.00002	0.00009
Chlorella sp.	33	0.00063	0.00239	0.00383
	27	0.00253	0.00155	0.00107
	21	0.00457	0.00119	0.00065
	15	0.00128	0.00122	0.00142
Anabaena flos aquae	39	0.00520	0.01069	0.01753
	33	0.00087	0.00180	—
	27	0.00229	0.00257	0.00238
	21	0.00049	0.00173	0.00131
	15	—	—	0.00073
Oscillatoria sp.	27	0.33280	0.11010	0.13740
	21	0.45790	0.31830	0.12670
	15	2.59800	1.50100	0.20270
Selenastrum capricornutum	27	0.00224	0.00343	0.00459
	21	0.00169	0.00206	0.00289
	15	0.00044	0.00022	0.01280
Microcoleus vaginatus	27	0.08370	0.08120	0.22300
	21	0.16490	0.88900	0.06590
	15	0.27900	0.21850	0.14780

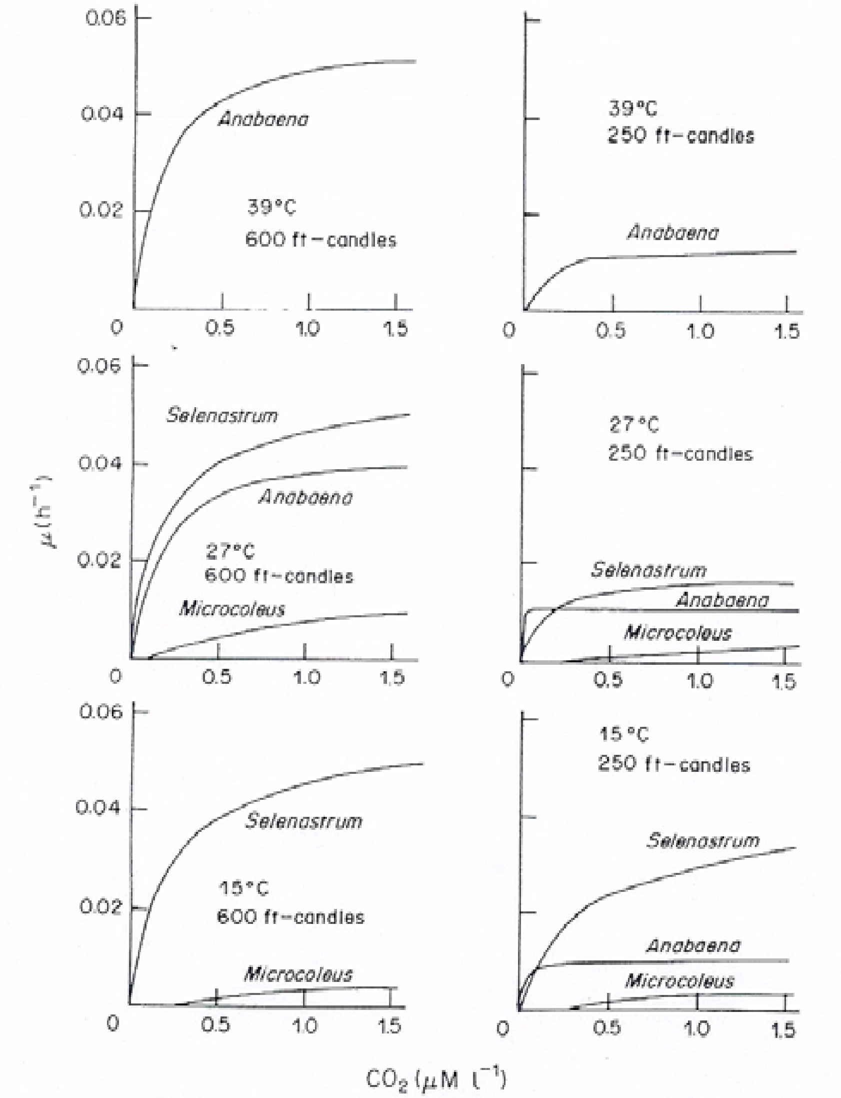


Fig. 13. Specific growth rates of three algae at varying light and temperature.

University of California-Berkley, W.J. Oswald,1979

Paddle-wheel Mixed High-rate Ponds for Wastewater Treatment

Lessons

- 4-5X algal productivity in high-rate ponds
- algal harvesting costly; discharge land applied
- culture stability issues

University of California-Davis, 1980
Benard Colvin; ***The Puerto Penasco Shrimp Culture Project***

Lessons

- 10-20,000 lb/acre shrimp production in raceway systems
- water discharge to lagoon with sand-well filtration and dilution to bay not sustainable

University of California-Davis, 1981
Brine Shrimp Algal Harvest and Conversion

Lessons

- aquatic-animal algal-harvest cost effective and energy efficient
- biological vs. mechanical harvest not widely accepted

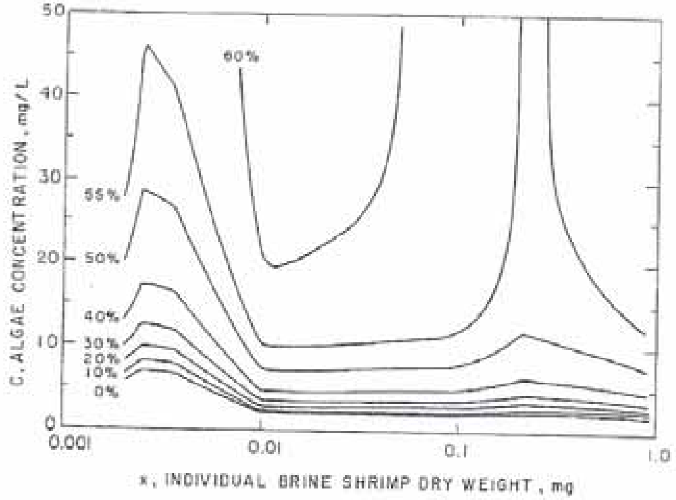
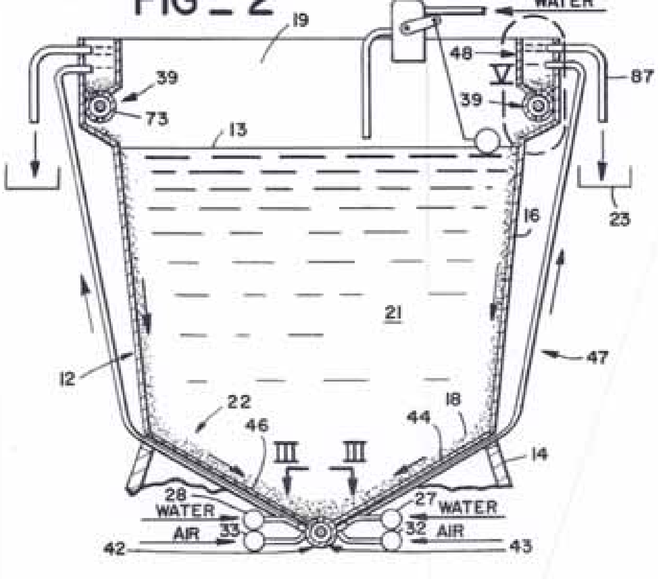


Figure 3. Lines of constant percent conversion at varying algal concentration and animal weight.

FIG_2



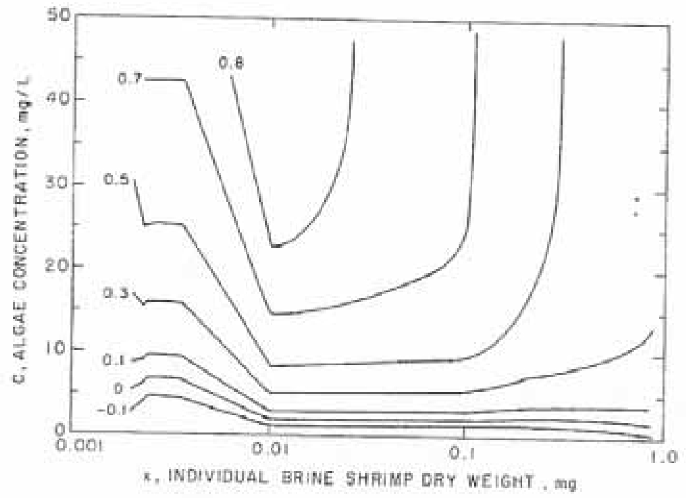


Figure 4. Lines of constant specific uptake rate at varying algal con-

University of California-Davis, 1981

Inland Saltwater for Algal Biomass Production

<u>Lessons</u>

- high-rate algal production from inland saltwater possible
- inland saltwater highly variable
- evaporation limiting factor

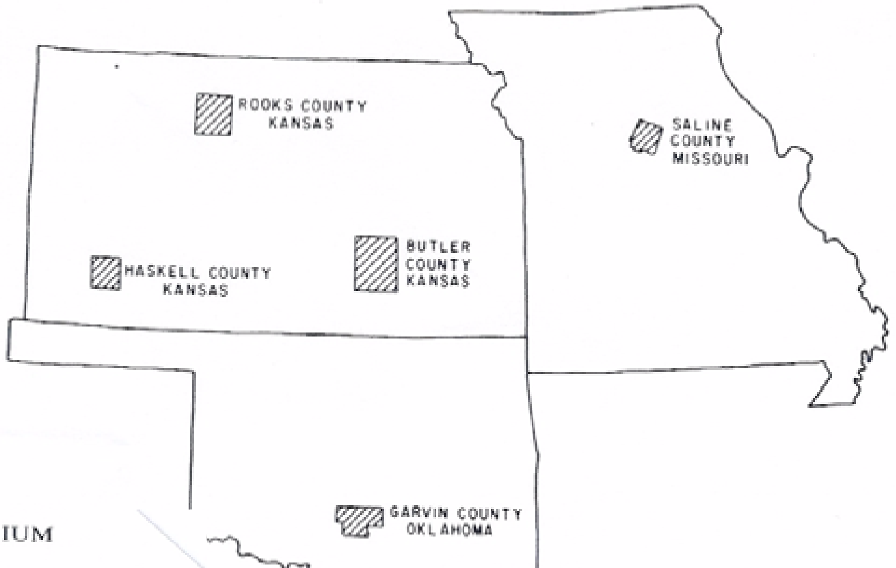


Fig. 2. Locations of inland saltwater samples.

SALTWATER AS A BIOMASS PRODUCTION MEDIUM

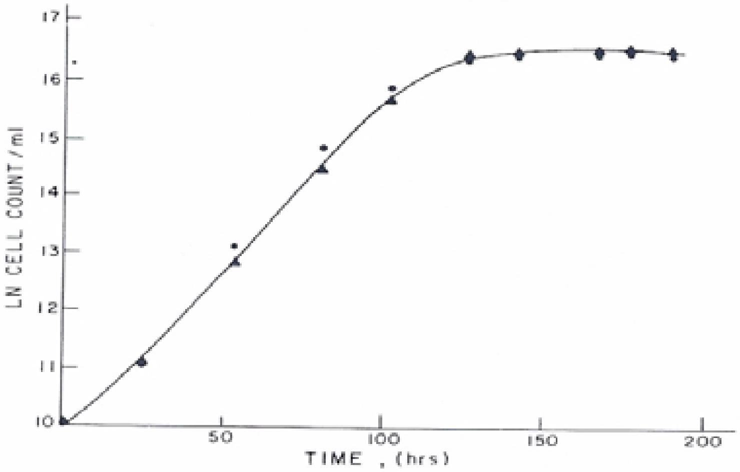
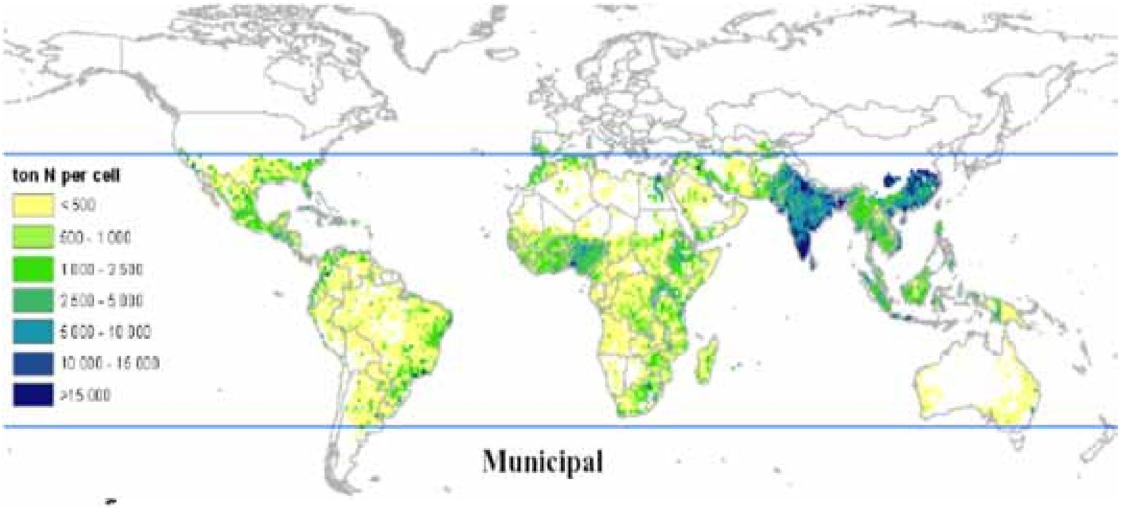


Fig. 6. Log plots of algal (*Phaeodactylum*) growth in both saline groundwater and control. (▲) Synthetic seawater (control 2); (●) Saline County plus secondary effluent.

Penn State University, 1984
Recirculating Trout Culture using Nitrifying RBC

Lessons

- RBC aquaculture not cost effective
- PA climate not suitable for algae



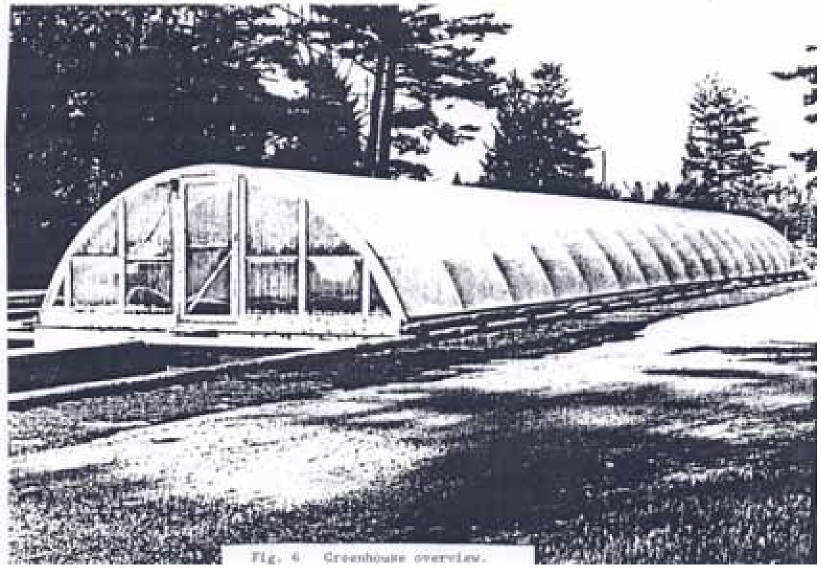
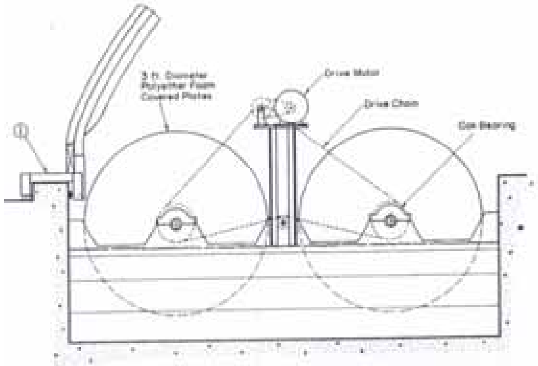
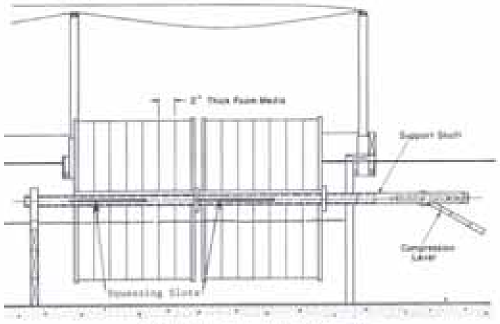


Fig. 6 Greenhouse overview.



CROSS-SECTION, RBS UNITS IN RACEWAY

Fig. 10 Retained biomass surface disk installation.



SIDE VIEW, RBS UNITS IN RACEWAY

Fig. 11 Retained biomass surface disk installation side view.

Texas A&M, 1985

Stillwater Shrimp Culture Ponds; The King Ranch Experience

Lessons

- pond algae populations unstable and unpredictable
- mixing and aeration of large ponds inefficient
- management of animals in large ponds ineffective
- harvesting of animals labor intensive

Transport limitation of oxygen in shrimp culture ponds

Albert Garcia and David E. Brune

Agricultural Engineering Department, Texas A&M University, College Station, Texas 77843, USA

Agricultural & Biological Engineering Department, Clemson University, Clemson, South Carolina 29634, USA

Clemson University, 1989-2001
Partitioned Aquaculture Systems (PAS)

Lessons

- 15-20,000 lb/ac fish production
- tilapia stabilizes algal density and composition, eliminates zooplankton blooms
- algal harvest maximizes system performance

Clemson University, 2000
Zero-Discharge PAS Marine Shrimp Culture

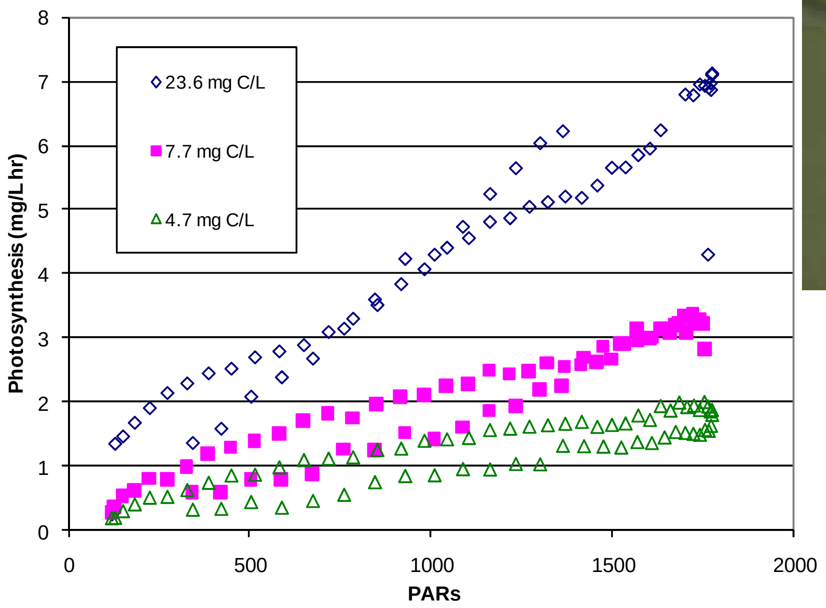
Lessons

- 35,000 lbs/acre routine in "designed ecosystems"
- weather sensitivity of algal systems
- energy and cost sensitivity of bacterial systems

Clemson University, 2001
In-Situ Determination of Algal Growth Kinetics

Lessons

- algal density and water velocity/depth interaction
- field production 50 - 80% of lab-data projections

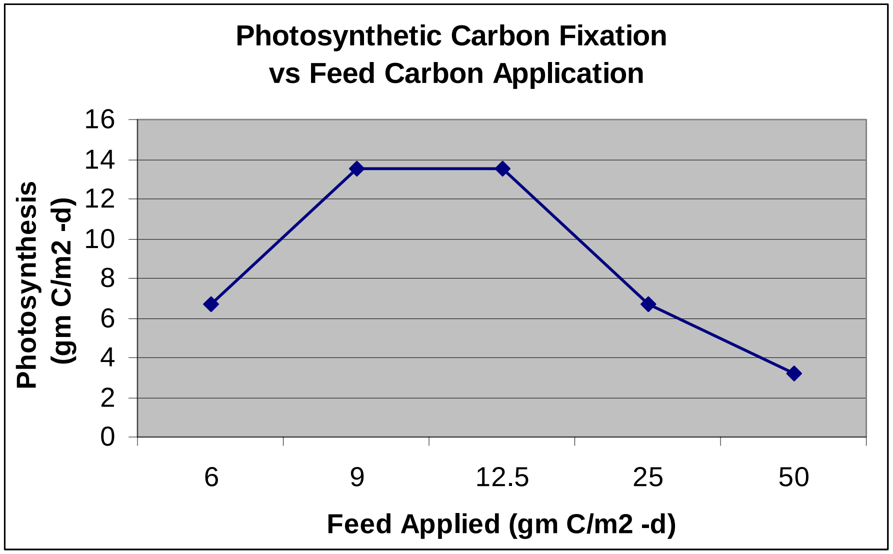


Clemson University, 2002
The Controlled Eutrophication Process

Lessons

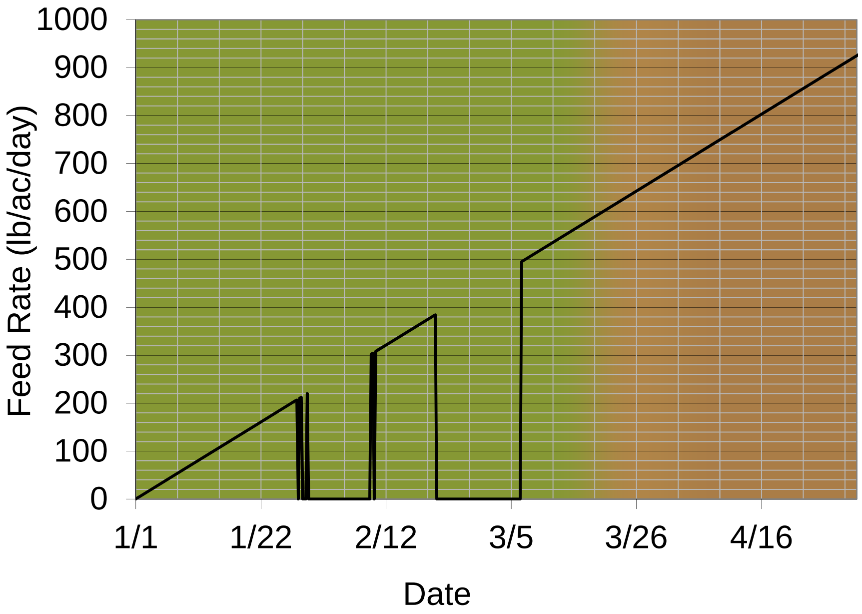
- tilapia-driven algal harvest
- high inert solids in algae harvested from earthen ponds
- multiple products needed to off-set systems cost

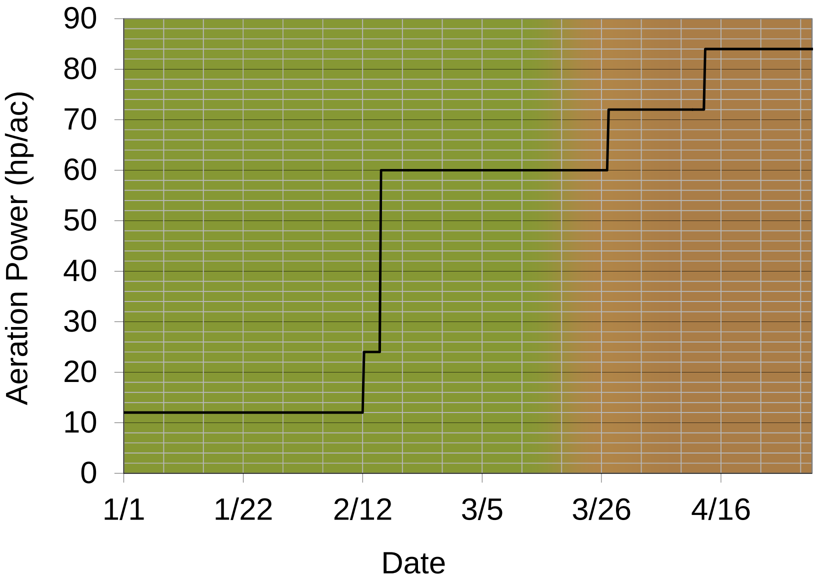
Clemson University, 1989 - 2011
Modeling Algal/Bacterial Interactions



Lessons

- photosynthesis max, 20 g-vs/m^2-d
- aeration requirement dependent on algal/bacterial interaction
- 20,000 lb/acre shrimp in algal
- 35,000 lb/acre shrimp in bacterial

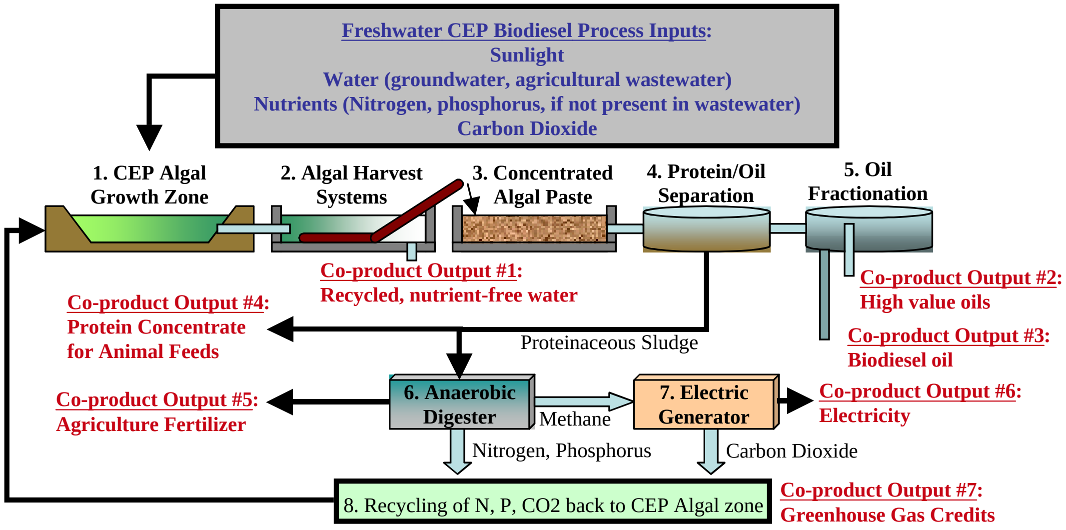




Clemson University, 2007
Aquacultural Processes for Biodiesel Production

Lessons

- high-lipid algae not needed
- low-cost extraction of animal lipids possible
- integrated systems needed



Freshwater CEP Biodiesel Process Inputs:
Sunlight
Water (groundwater, agricultural wastewater)
Nutrients (Nitrogen, phosphorus, if not present in wastewater)
Carbon Dioxide

1. CEP Algal Growth Zone
2. Algal Harvest Systems
3. Concentrated Algal Paste
4. Protein/Oil Separation
5. Oil Fractionation
6. Anaerobic Digester
7. Electric Generator
8. Recycling of N, P, CO2 back to CEP Algal zone

Co-product Output #1: Recycled, nutrient-free water

Co-product Output #2: High value oils

Co-product Output #3: Biodiesel oil

Co-product Output #4: Protein Concentrate for Animal Feeds

Co-product Output #5: Agriculture Fertilizer

Co-product Output #6: Electricity

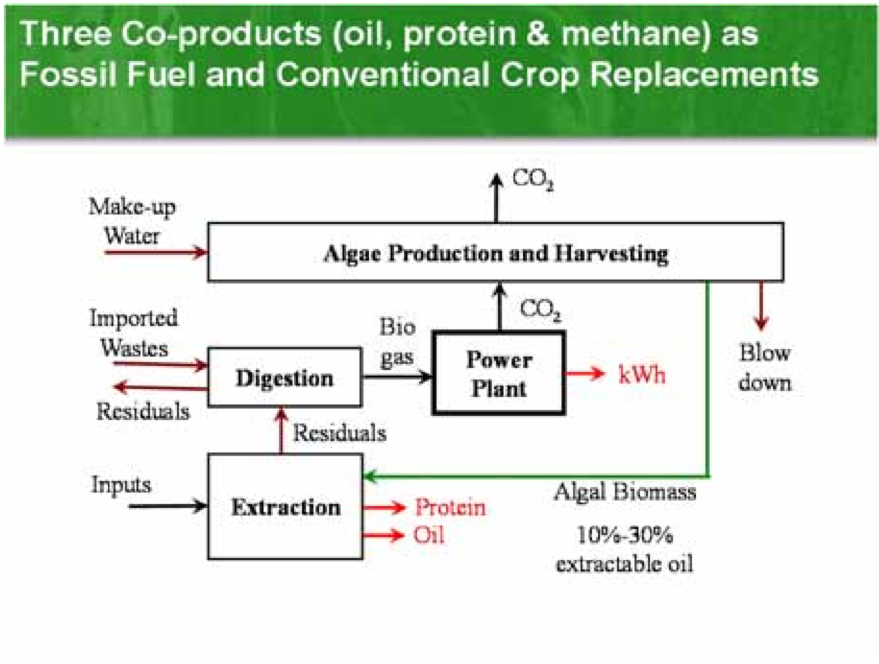
Co-product Output #7: Greenhouse Gas Credits

Gravity separation; oil, water and biomass fractions

University of Missouri, 2009
Algal Production and Harvest for Food, Feed and Biofuels

Lessons

- 50 MW power-plant needs 2,000 acres of algae
- 30% of algal energy needed to grow and process algae
- 25% reduction in natural gas usage possible



Projected power-plant GHG avoidance

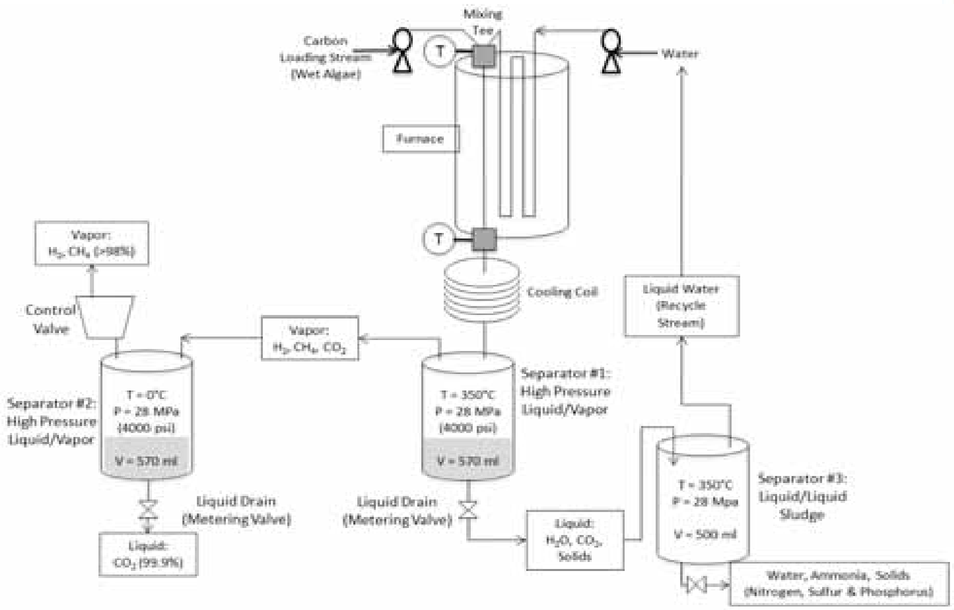
	Gross GHG Avoidance (%)	Parasitic Loss (%)	Net GHG Avoidance (%)
CO2 Utilization (%)	*70%*		*60% 70% 80%*
Algal Product			
Biogas methane[1]	26.0	7	13.7 – 16.0 – 18.3
Soybean Feed Replacement[2]	17.0	7	8.6 – 10.0 - 11.4
Biodiesel[3]	20.0	10	8.6 – 10.0 -11.4
Combination			
Methane	7.8		
Soybean Protein	8.5		
Biodiesel	20.0		
Total (@ 70%)	36.3	10	22.3 – 26.3 – 29.7

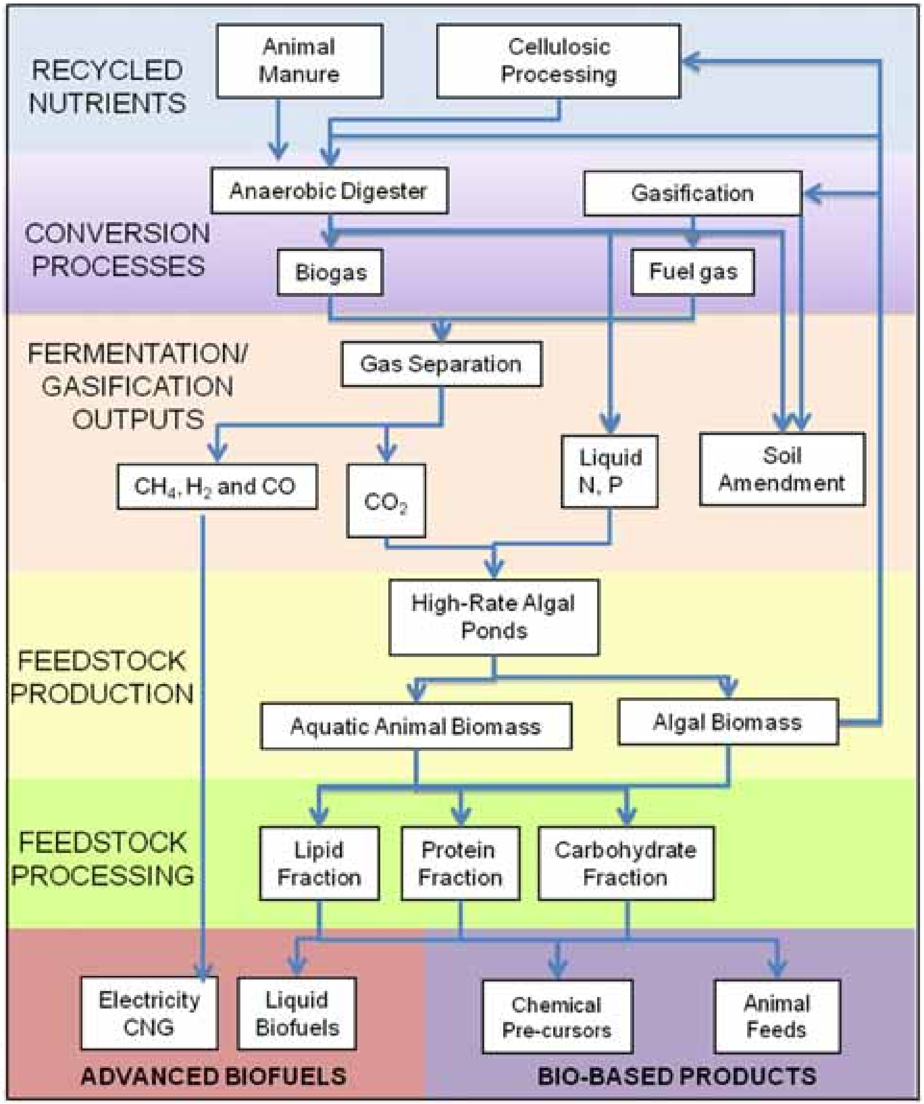
University of Missouri, 2012

Integrating Physiochemical and Controlled Eutrophication Processes

Questions?

- 2.2/1 energy yield from direct gasification of 5% algal solids
- cost-effective?





University of Missouri 2012

Sustainable Seafood and Bioenergy Co-production

Biomass driven electricity generation with waste-heat utilization supporting marine shrimp production

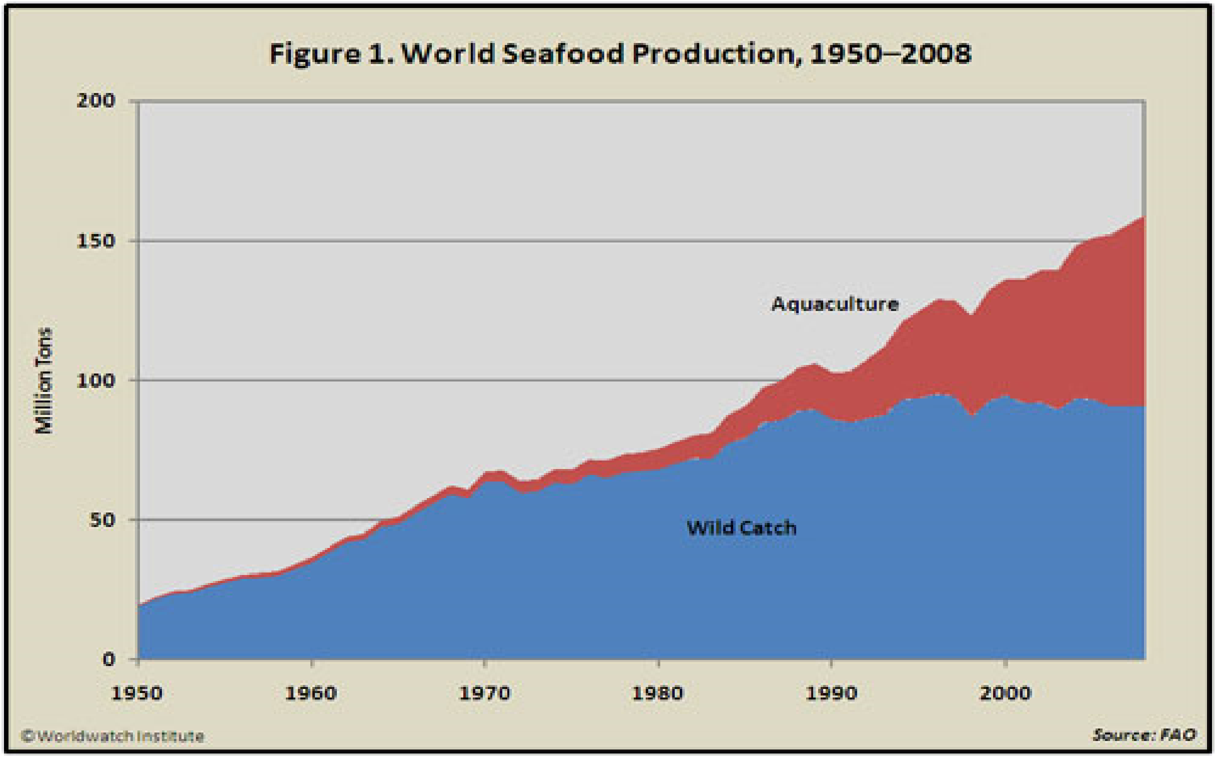
Aquaculture/Bioenergy Co–Production; Cash–Flow Potential

- High-rate algal production maintaining water quality in zero-discharge aquaculture yielding 25,000 lb/acre-yr fish or shrimp
- Algal biomass of 40,000 lb/acre-yr yielding 10 tons/yr fish-meal replacement
- 10 kW/acre of stationary power (as syngas and/or biogas) with 1,000 gallons of liquid fuel/yr
- 60% of the cash-flow provided by fish and shrimp, 30% from animal feeds, and 10% from bioenergy co-production

- QUESTIONS: To what degree can “green-energy” prices support profitable year-round temperate-climate aquaculture production? Bacterial or algal systems?

Potential of Microalgae?

- Aquaculture must expand
- Sustainable aquaculture best application of algal technology
- Animal feeds and bioenergy as co-products



Algae applications could;

- Increase aquaculture production 3 to 4-fold
- Reduce fish production costs $0.05-0.10/lb
- Reduce N, P discharge from agriculture and municipal waste streams
- Provide higher-value industrial chemicals, nutraceuticals, pharmaceuticals
- Algae on ~ 5 million acres of desert yielding protein and oil equal to 60 million acres of soybeans
- Avoid 20-30% of GHG from gas-fired power-plant

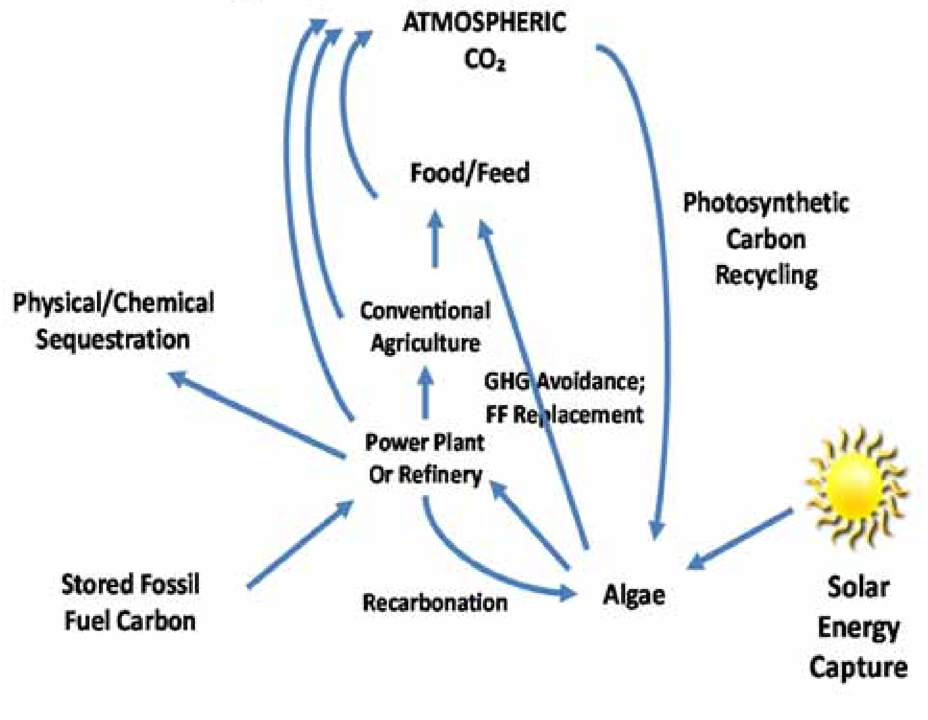
Algae not likely;

- Algae NOT carbon sequestration; carbon avoidance only
- GHG reduction potential NOT significant for base-load coal-fired power-plant
- Algal liquid-fuel likely not cost effective primary application

Algae PP-CO_2 capture potential *

- <10% favorable location
- <10% have 10,000 ha for algae
- ~10% of CO_2 could be captured
- Cumulative CO_2 capture < 0.1%

** (Benemann 2011)*



Algae for Carbon Avoidance, NOT Sequestration

Research and Extension

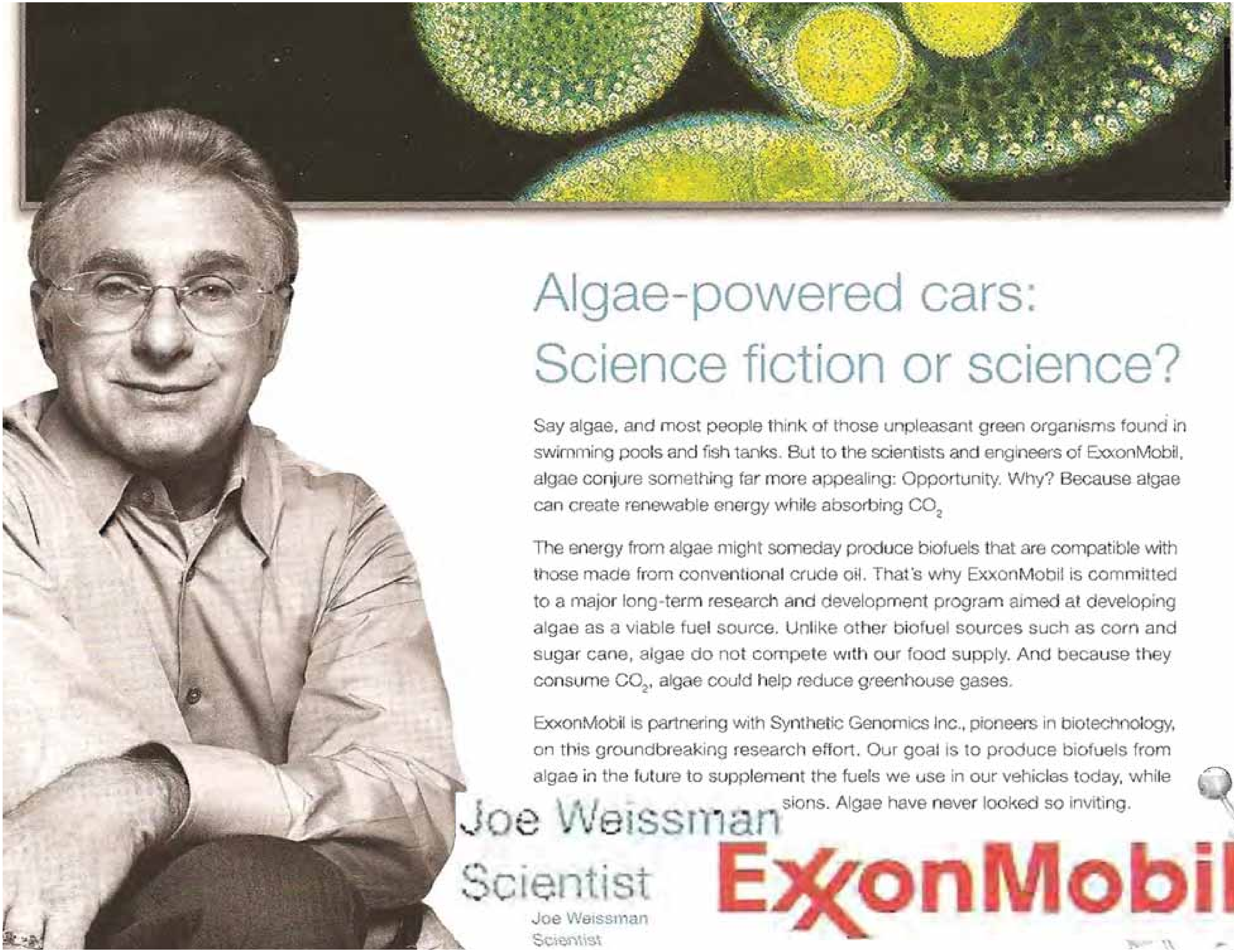
We’ll likely **NOT** be successful promoting system designs focused primarily on production of biofuels, bioenergy, or sustainability

….. given current economic constraints

PROPOSED APPROACH;
Developing a Transitional Agriculture

We must cultivate knowledge and techniques supporting capability and capacity to:

- Integrated systems providing nutrient recycle
- Maximize resource use and energy efficiency
- Target environmental remediation and recovery
- Cost effective within current FF economy
- With potential to transition to solar-based production



Algae-powered cars: Science fiction or science?

Say algae, and most people think of those unpleasant green organisms found in swimming pools and fish tanks. But to the scientists and engineers of ExxonMobil, algae conjure something far more appealing: Opportunity. Why? Because algae can create renewable energy while absorbing CO_2

The energy from algae might someday produce biofuels that are compatible with those made from conventional crude oil. That's why ExxonMobil is committed to a major long-term research and development program aimed at developing algae as a viable fuel source. Unlike other biofuel sources such as corn and sugar cane, algae do not compete with our food supply. And because they consume CO_2, algae could help reduce greenhouse gases.

ExxonMobil is partnering with Synthetic Genomics Inc., pioneers in biotechnology, on this groundbreaking research effort. Our goal is to produce biofuels from algae in the future to supplement the fuels we use in our vehicles today, while

sions. Algae have never looked so inviting.

Joe Weissman

Scientist

Joe Weissman
Scientist

ExxonMobil