Algal Production and Harvest for Food, Feed and Biofuels

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Objectives;
High Rate Photosynthetic Systems

- Increasing Energy Independence
  - Limitations of biological productivity
  - Area requirements and costs
  - Water requirements
- Environmental Protection / Remediation
  - GHG reduction through carbon-neutral food, feed, fuel, replacement
  - Municipal wastewater treatment
  - Animal waste treatment

Why Algal Culture

Good

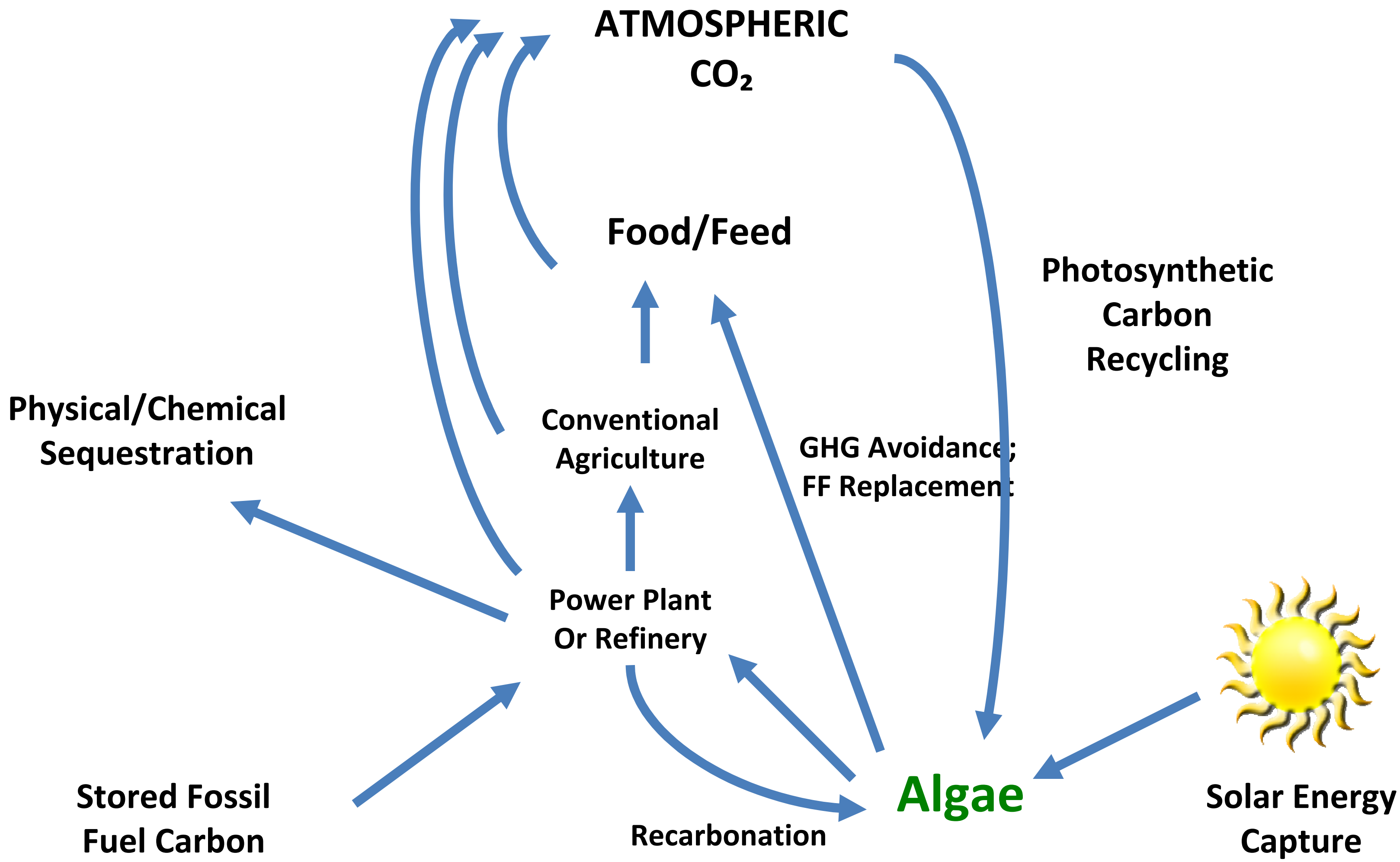
- 4-10 X productivity over conventional crops
- Growth in brackish and saline water
- Production on under-utilized lands
- Fluid transport and handling
- Production at low nutrient concentration
- Short algal cell generation time

Bad

- Costly to harvest, concentrate and process
- Under-developed technology
- Culture system capital investment high

GHG Reductions

- Carbon sequestration; physical- chemical storage
- Carbon avoidance; solar-based biological
- Carbon neutral; wind, water, nuclear, photovoltaic



Algae for Carbon Avoidance, NOT Sequestration
Must be ENERGY EFFICIENT

Clemson Approach; Low-Cost, Low Energy Input Using Biological Systems

- Earthen ponds, paddlewheel driven
- Tilapia stabilized algal cultures, zooplankton control, algal genera selection, young cell age
- Brine shrimp; harvest, concentrate and convert algae, easy to process animal protein and oils
- Anaerobic digestion of algae for methane production

Algal Harvest Techniques

Algae Harvest Method	Relative Cost	Algal Species	Previous Studies
Foam fractionation	Very High	*Scenedesmus, Chlorella*	Smith 1988
Ozone flocculation	Very High?		Sukenik et al. 1987
Centrifugation	Very high	*Scenedesmus, Chlorella*	Brunner and Hemfort 1990
Electrofloatation	High?		Shelef et al. 1984
Inorganic Chemical Flocculation	High	*Oxidation ponds*	Golueke and Oswald 1965
Polyelectrolyte Flocculation	High	*Dunaliella*	Barclay et al. 1987
Filtration	High	*Spirulina, Coelastrum*	Shelef et al. 1984
Microstrainers	High	*Spirulina*	Kormarik and Cravens 1979
Tube Settling	High?	*Micractinium*	Nurdogan and Oswald 1996
Discrete Sedimentation	Medium?	*Coelastrum*	Mohn 1980
Phototactic Autoconcentration	Unknown	*Euglena, Dunaliella*	Nakajima and Takahashi 1991
Autoflocculation	Low?	*Micractinium*	Moellmer 1970
Bioflocculation	Low?	*Micractinium*	Beneman et al. 1980
Tilapia-Enhanced Sedimentation	Very Low?	*Scenedesmus, Chlorella*	Schwartz et al. 2004

- Tilapia/sedimentation Clemson Technology

2-Ac Freshwater System for Aquaculture @ Clemson

Algal Genera Control within Clemson Controlled Eutrophication Process (CEP) Units with Tilapia filtering

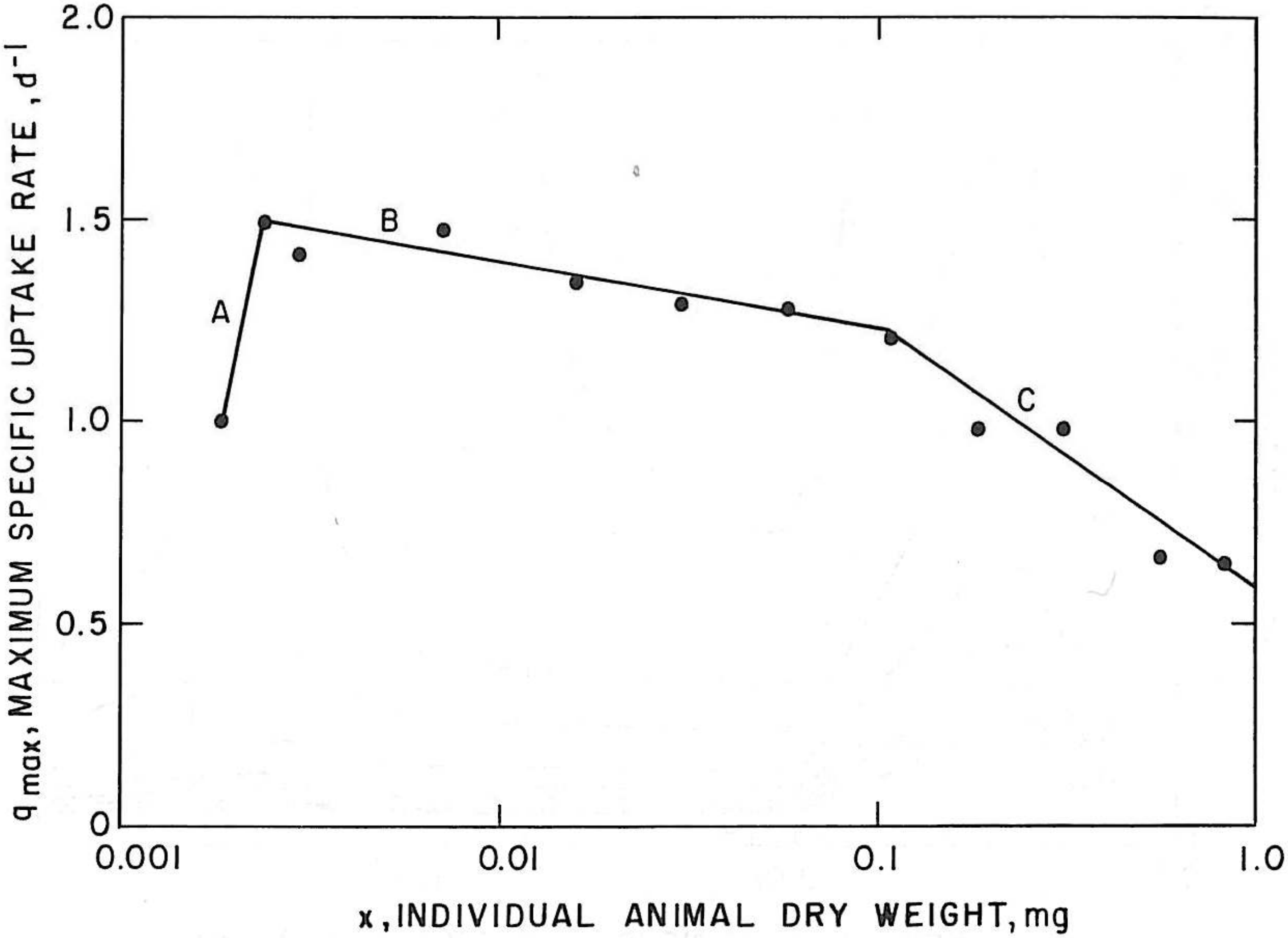
Brine Shrimp Harvest and Conversion

- 5,000 animals / liter in flowing bed reactor(1)
- Two stage culture based on uptake kinetics(2)
- Wet grind in two-phase solvent

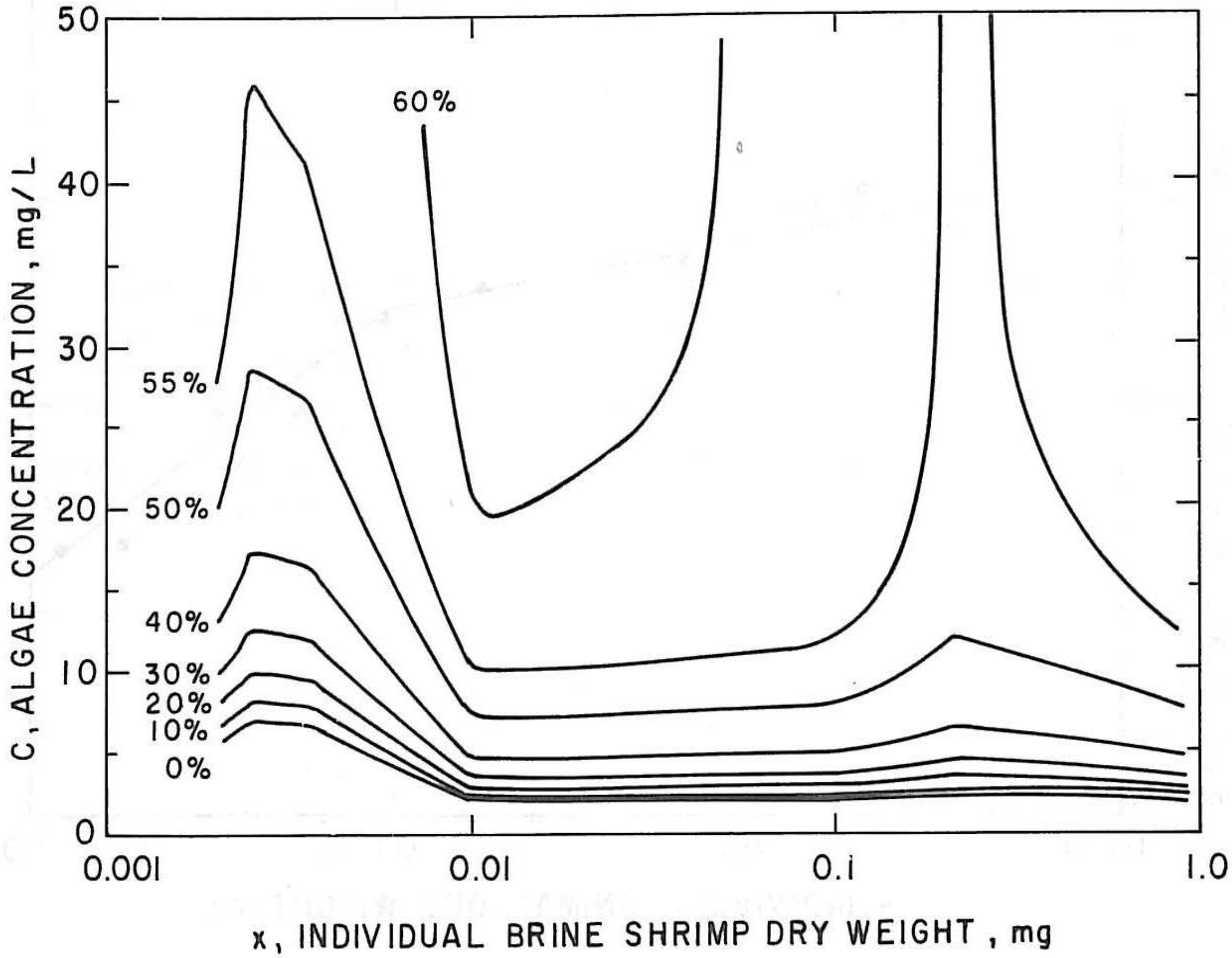
- 1)Brune, D. E., Design and Development of a Flowing Bed Reactor for Brine Shrimp Culture, Aquacultural Engineering, 1(1): 63-70, 1982
- 2)Brune, D. E. and Anderson, T. H., The Application of Process Kinetics for Predicting Optimum Performance of Continuous Brine Shrimp Culture, Journal of the World Mariculture Society, 15(1): 1985.
- 3)Brune, D.E., Flowing Bed Method and Apparatus for Culturing Aquatic Organisms, USA Patent No. 4,369,691


100
60
20

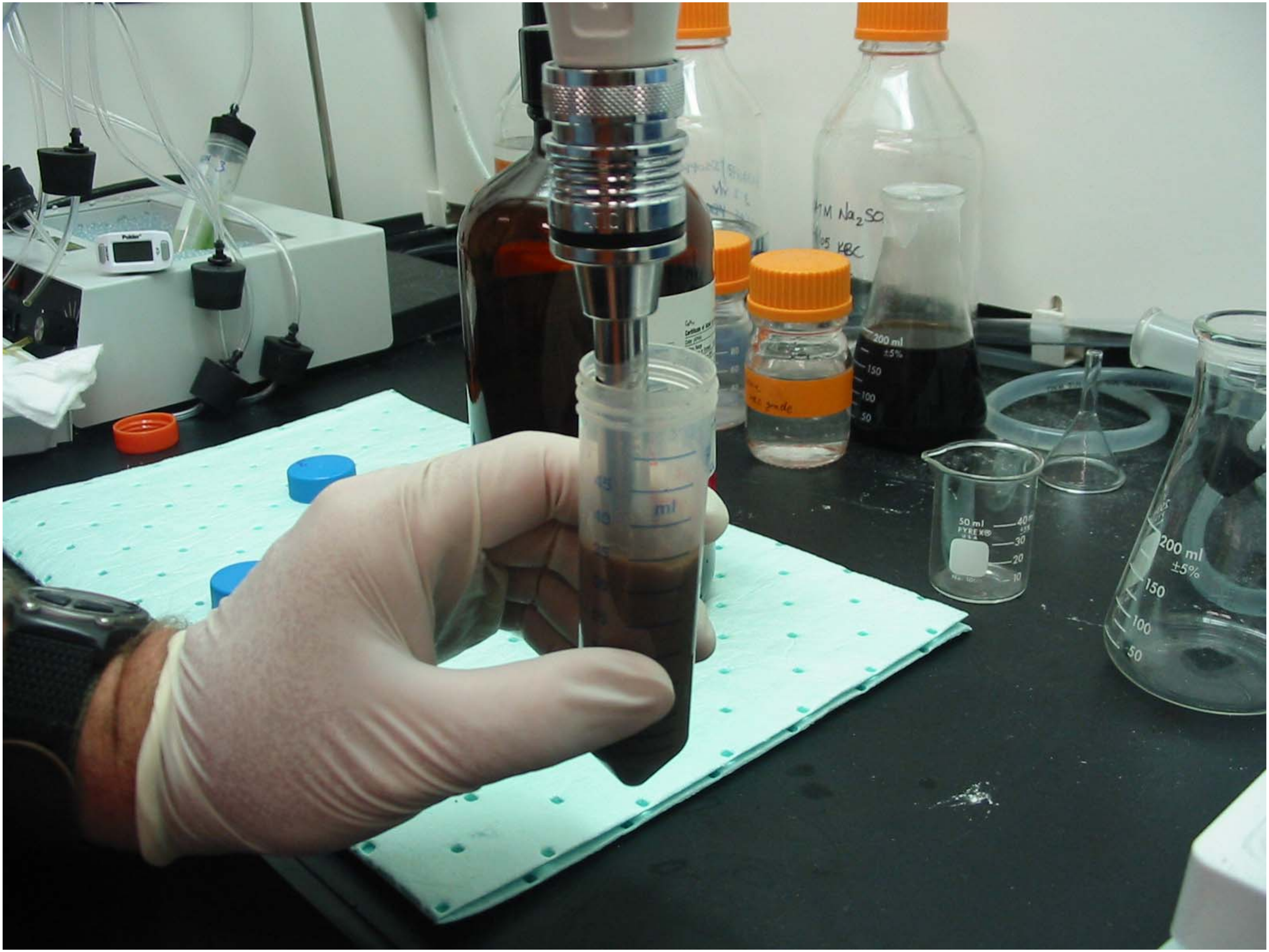
Green Algae 9% lipid,
Brine shrimp 22% lipid (50% conversion)



Brine Shrimp Specific Uptake Rate



Brine Shrimp % Conversion


ml
200 ml
±5%
150
100
50
50 ml
PYREX
40
30
20
10

US Land Availability

- Total US, 2,264 million acres
- Farmland, 938 million acres
- Cropland, 434 million acres
- Harvested Cropland, 303 million acres

Current Soybean Production and Costs

- 63 million acres (21% cropland), 2600 lbs/yr
- Cost = $0.075 -0.15/lb (dry wt)
- GHG emissions = 16.0 MMTCE (1% US total)

Algal Productivity

- Current sustained best case
  - Annual average 15 gm vs/m^2-d, 48,000 lb/acre-yr
  - Protein = + 50%, Oil = 10 to 20%

- Projected sustainable maximum
  - Annual average 25 gm vs/m^2-d, 80,000 lb/acre-yr
  - 5% solar efficiency (PAR)

Soy Replacement with Algae

- **48,000 lb/ac-yr algal biomass**
  - 4.5 million acres (7% of soy footprint)
  - 1.4 x soy protein,1.1 x soy oil
  - Cost = $0.18/lb (soy = $0.075 -0.15/lb)
  - Carbon offset = 16 MMTCE less algal production, harvesting, and processing energy costs

Energy Yield Comparison

- Soy biodiesel, 63 million acres, 50 gallons/acre = 0.3% of US energy
- Algal biodiesel, 600 - 1200 gallons/acre, on 4.5 million acres on using arid land using saline water
- Algal energy replacement = 1.3 %; 100% protein replacement
- Algal methane, replacing 20% of US fuel (natural gas) = 133 million acres, 44% of US harvested land.
- Corn on 63 million acres, @ 382 gallons ETOH/acre = 0 - 0.5% of US energy, at net yield of 0 to +25%

Energy Cost Comparison

- At 600 – 1200 gallons biodiesel/acre (60-100 million BTU/acre-yr), cost = $10-$15/gal, not counting co-product recovery
- Algal methane at 150 -200 million BTU / acre = 3-4X natural gas cost

Water Requirements

- Algae on 4.5 million acres of arid land using saline groundwater
- Evaporative replacement = **23,000 MGD** requiring 10% pumping energy
- Compare to western US water withdrawal of **68,000 MGD**
- Compare to Ogallala aquifier ~ 100+ years pumping capacity

Algal System
Costs vs. Production

Capital Cost		Velocity	Productivity
Type*	$/acre	fps	gm VS / m^2
u	30–50K	0.1 - 0.3	14 - 18
l	80–100 K	0.8 -1.0	20 - 25
p	350-1,000K	varies	25 – 40

*unlined pond, lined pond, closed photobioreactor

best case production increase = 2.9 X

best case cost increase = 7 X

CLOSED PHOTOBIOREACTORS: System Limitations

Integrating Environmental Remediation with By-Product Recovery

Clemson/Kent SeaTech

Salton Sea Restoration & Remediation

Large-Scale Microalgae Cultivation in Agricultural Wastewaters for Biofixation of CO_2 and Greenhouse Gas Abatement

State of Caliornia and U.S. Department of Energy Project

Principal Investigator: Michael J. Massingill, Vice President, Kent SeaTech
Cooperating Investigators: David E. Brune, Professor, Clemson University,


Salton Sea
Whitewater River
Pilot-scale CEP Systems

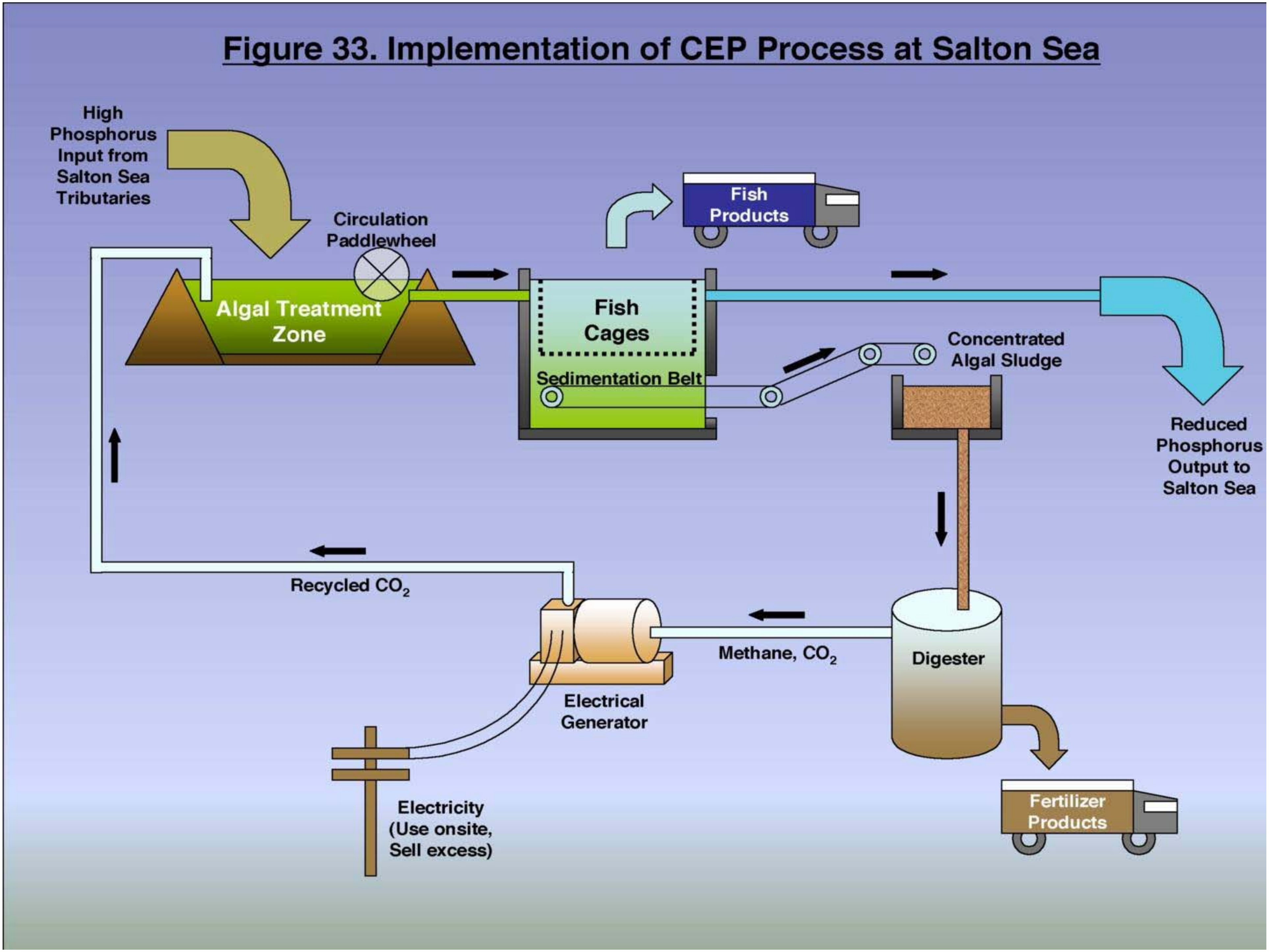
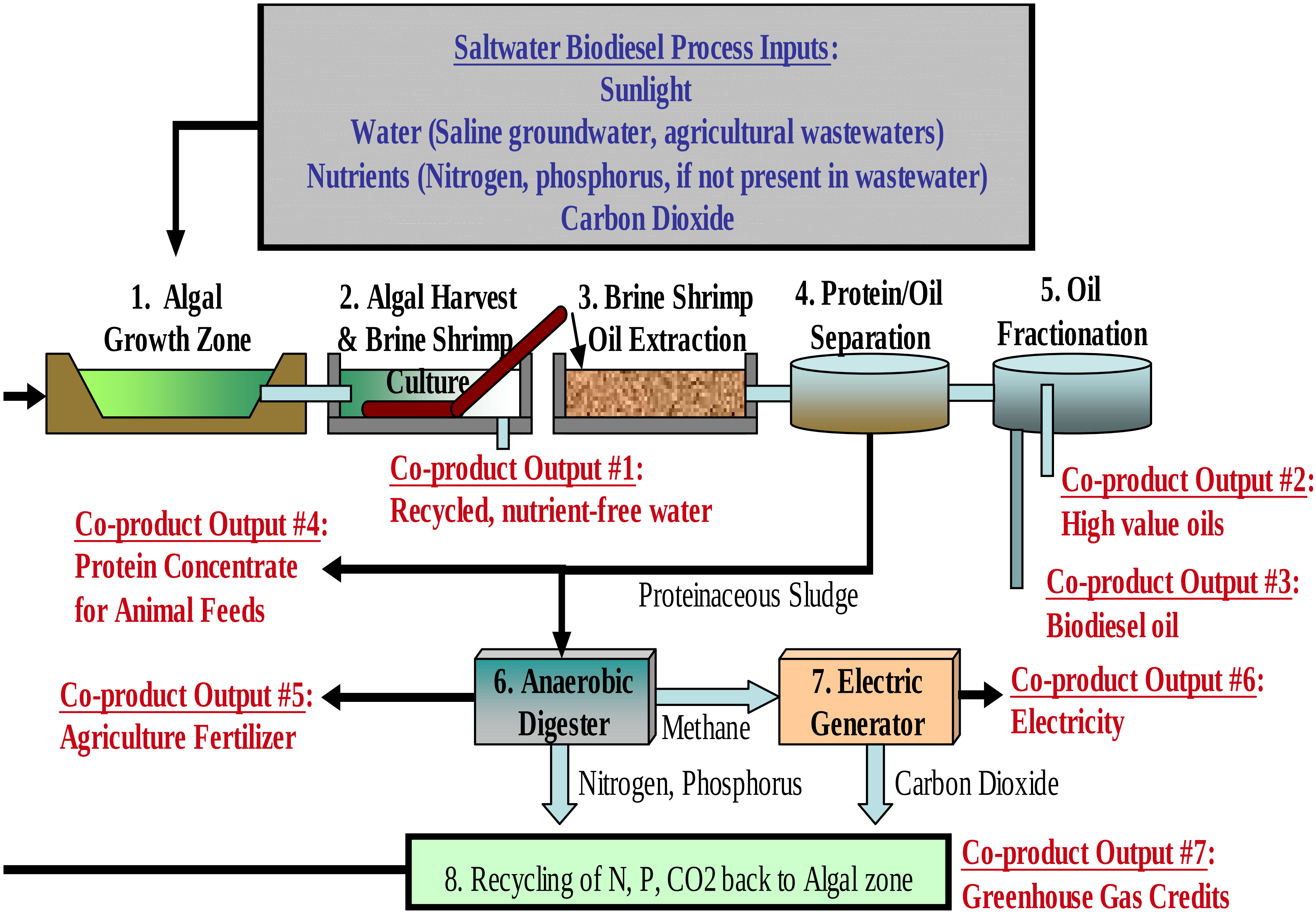


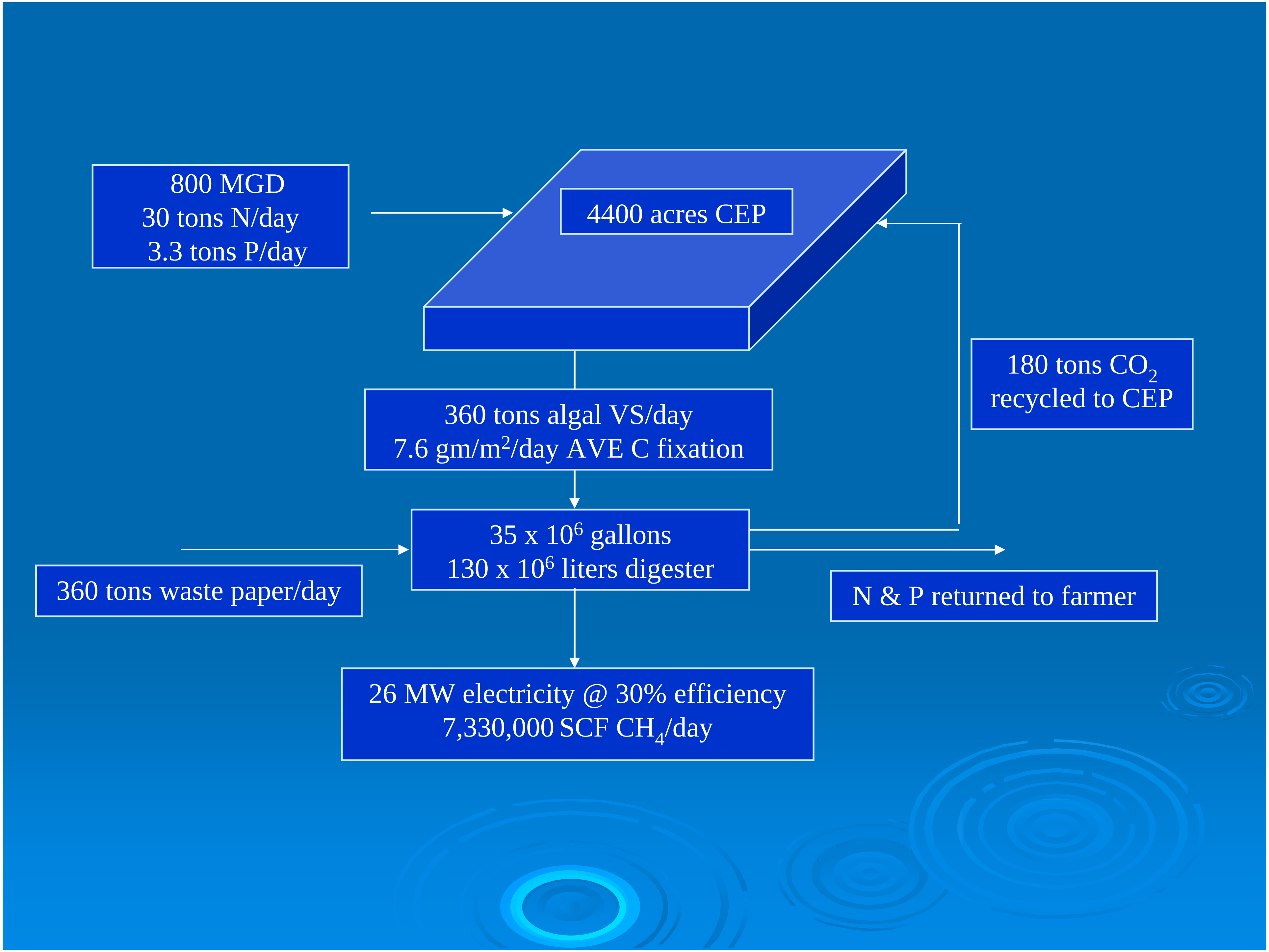
Figure 33. Implementation of CEP Process at Salton Sea
High Phosphorus Input from Salton Sea Tributaries
Circulation Paddlewheel
Algal Treatment Zone
Fish Cages
Fish Products
Sedimentation Belt
Concentrated Algal Sludge
Reduced Phosphorus Output to Salton Sea
Recycled CO2
Methane, CO2
Digester
Electrical Generator
Electricity (Use onsite, Sell excess)
Fertilizer Products

CEP Algal Sedimentation Belt at Kent SeaTech in California

Polishing Chamber

Belts harvest 3 d/wk, 12-16%; Solar drying on 400 ft^2/24 hr (1.2% of culture area) 98% solids,@45% VS, yielding 95 lb dry solids/acre-day


Saltwater Biodiesel Process Inputs:
Sunlight
Water (Saline groundwater, agricultural wastewaters)
Nutrients (Nitrogen, phosphorus, if not present in wastewater)
Carbon Dioxide
1. Algal Growth Zone
2. Algal Harvest & Brine Shrimp Culture
3. Brine Shrimp Oil Extraction
4. Protein/Oil Separation
5. Oil Fractionation
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
Proteinaceous Sludge
6. Anaerobic Digester
Methane
7. Electric Generator
Co-product Output #5:
Agriculture Fertilizer
Co-product Output #6:
Electricity
Nitrogen, Phosphorus
Carbon Dioxide
8. Recycling of N, P, CO2 back to Algal zone
Co-product Output #7:
Greenhouse Gas Credits


800 MGD
30 tons N/day
3.3 tons P/day
4400 acres CEP
360 tons algal VS/day
7.6 gm/m^2/day AVE C fixation
180 tons CO_2
recycled to CEP
35 x 10^6 gallons
130 x 10^6 liters digester
360 tons waste paper/day
N & P returned to farmer
26 MW electricity @ 30% efficiency
7,330,000 SCF CH_4/day

Income generation from by-product recovery

Product	Income $/yr
Fish meal (@ 15¢/lb)	$ 8,000,000
Energy $10/$10^6$ BTU, 10¢/Kw-hr)	$27,000,000
Nitrogen Fertilizer (@ 40¢/lb)	$ 4,350,000
TOTAL	$39,000,000

Capital Costs estimate ~ $300,000,0000

Algal Systems Applications

- Low-cost, open-air systems
- Biological control for harvest, processing
- Providing environmental services
- Integrated with food, feed, fuel co-production

Ecological Constraints

- Conventional crop biomass potential energy on 300 million acres = 25% of 100 quad, 11% to process.
- Food delivered to population ~ 1% of 100 quad
- Algal photosynthesis on ~10% of land would require ~ 100X yield increase for 25% energy replacement; Demonstrated algal potential = 10X over conventional
- GMO improvements ?
- Water, & nutrient flux, availability incompatible with biosphere process rates

Summary

- Open-pond algal production using aquatic animal harvesting with gravity settling, comparable to soybean production costs ~$0.18/lb. Closed reactor costs = 2-10X
- Maximum algal feed/food energy replacement 8%; GHG avoidance less depending on algal production efficiency
- Algal replacement of soy possible on arid land using saline water at 7% of ag land
- Evaporation replacement = 33% of western states water withdrawal

Summary

- Algal oil and protein replacement on 4.5 million acres = 1.3% of US energy
- Algal replacement of US natural gas (20% of energy) = 44% of US ag land
- Projected algal biodiesel or methane costs 3-4X current FF costs
- Algal systems for environmental remediation integrated with by-products recovery best match
- Algal genetic manipulation better to target high-value product enhancement