APEC Workshop on the Resource Potential of Algae
for Sustainable Production of Biofuels in the Asia Pacific Region
The Hyatt Regency Hotel, San Francisco 12th September, 2011

Keynote Presentation

Algal Biodiesel and Biofuels:

The State of the Science & Technology

John Benemann

Benemann Associates,

Walnut Creek, California, USA

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Algae blooms, salt evaporation ponds in San Francisco Bay

(I only discuss autotrophic, planktonic growth)

11 Division, 29 classes vs. 2/12 vascular plants

Each species (>100,000), <u>each strain is different</u>

Chaetoceros sp., diatom (Silicate cell wall, note spines, for protection against grazer; diatoms brown, main pigment fucoxanthin)

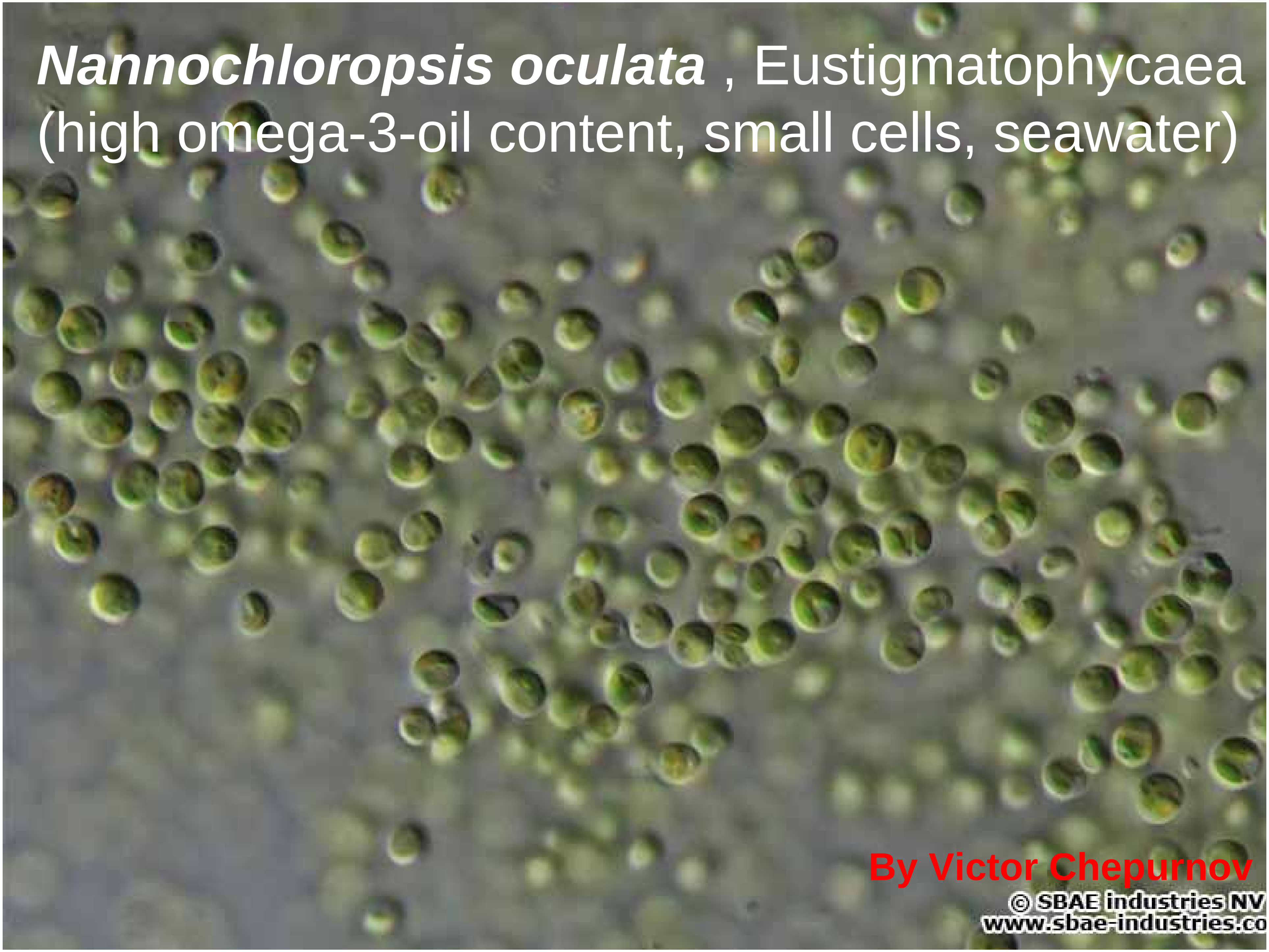
Thalassiosira weissflogii, diatom (whiskers?)

Phaeodactylum tricornutum, a diatom species that grows with less silicate nutrient

By Victor Chepurnov

***Scenedesmus* sp.,** a green alga
(main photosynthesis pigment is chlorophyll)

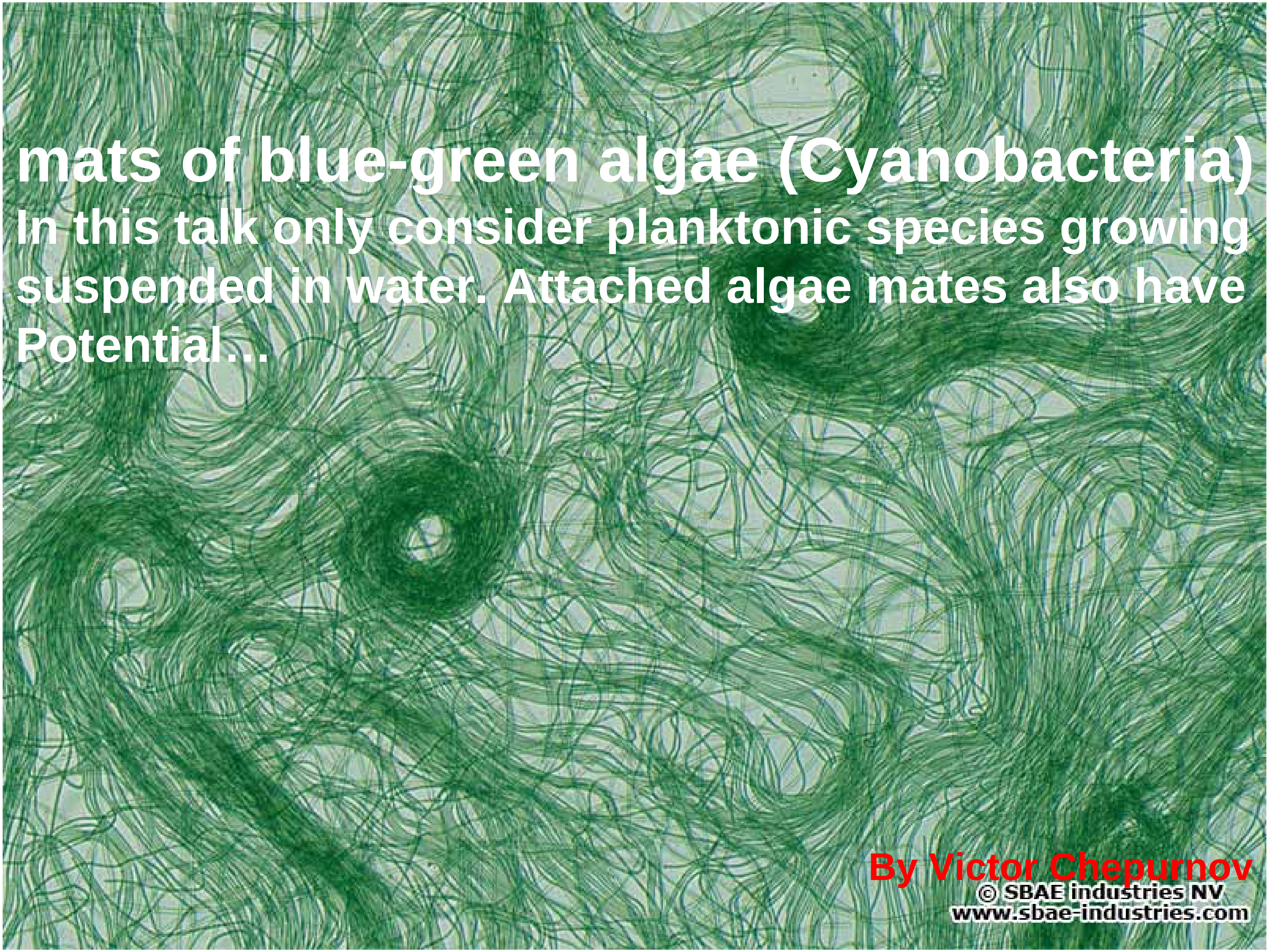
Nannochloropsis oculata , Eustigmatophycaea
(high omega-3-oil content, small cells, seawater)



By Victor Chepurnov

mats of blue-green algae (Cyanobacteria)

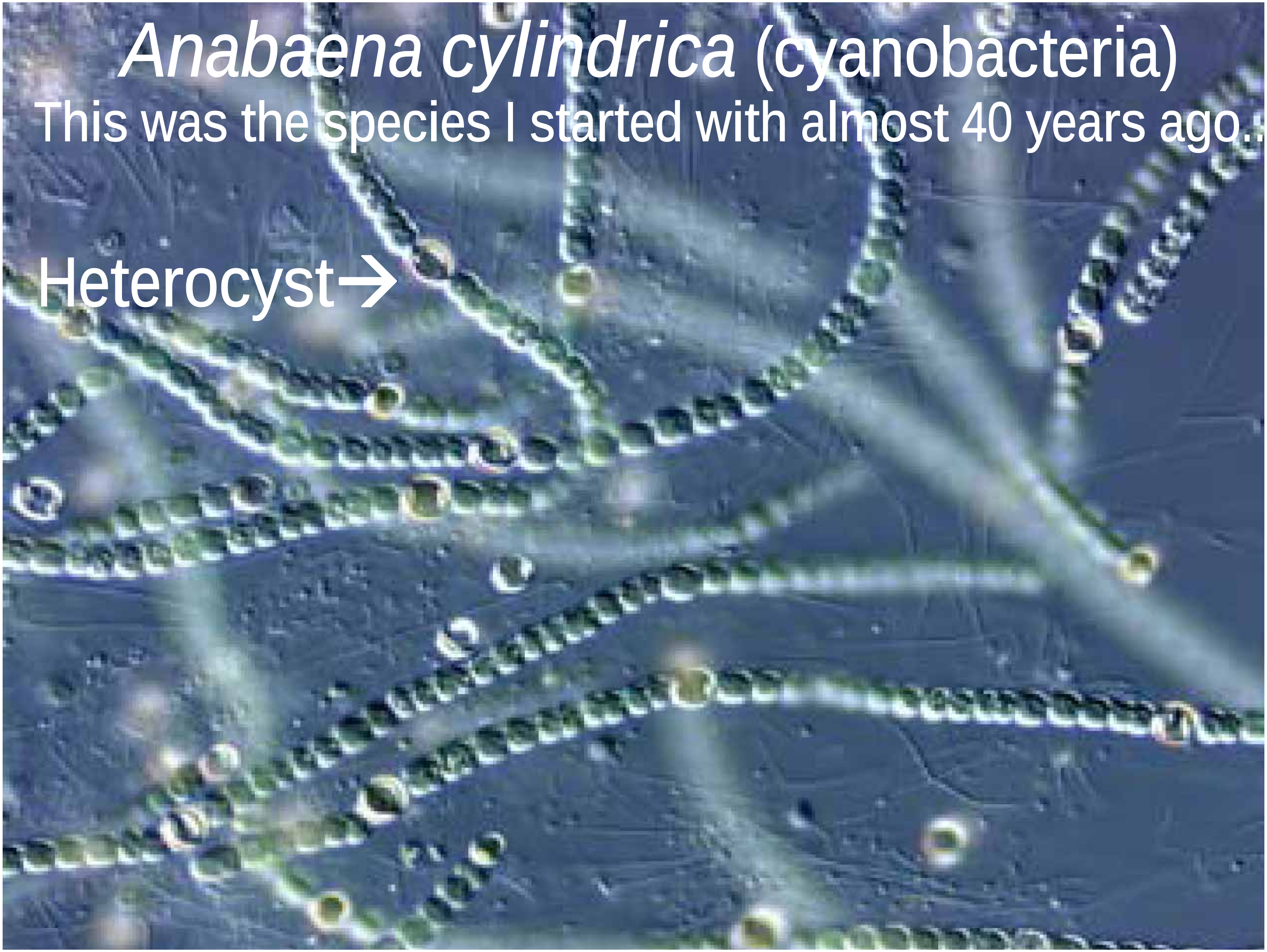
In this talk only consider planktonic species growing suspended in water. Attached algae mates also have Potential…



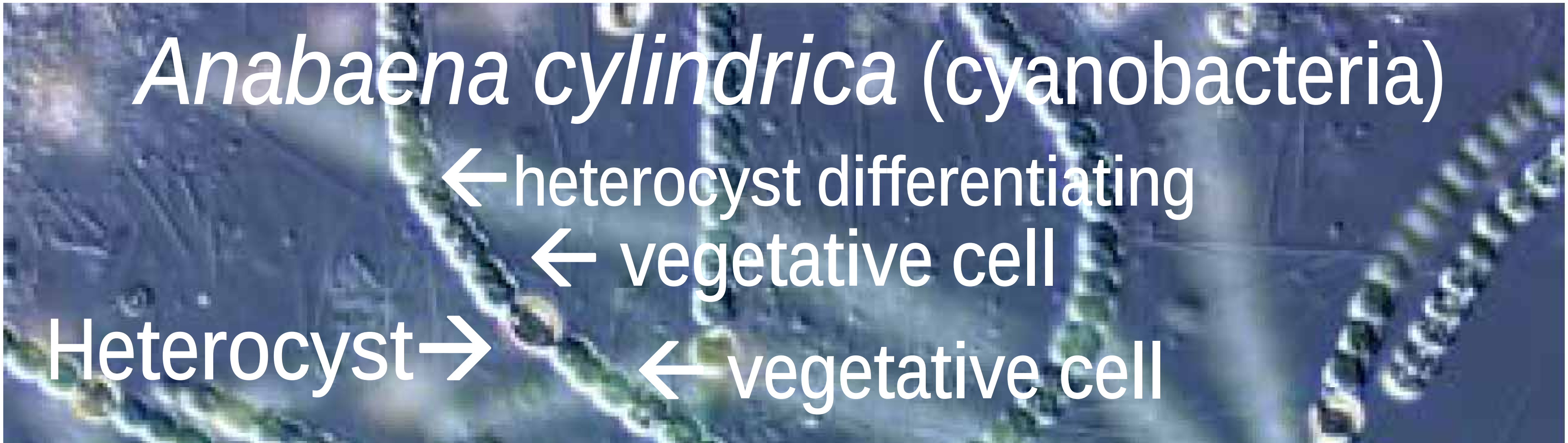
By Victor Chepurnov

Anabaena cylindrica (cyanobacteria)

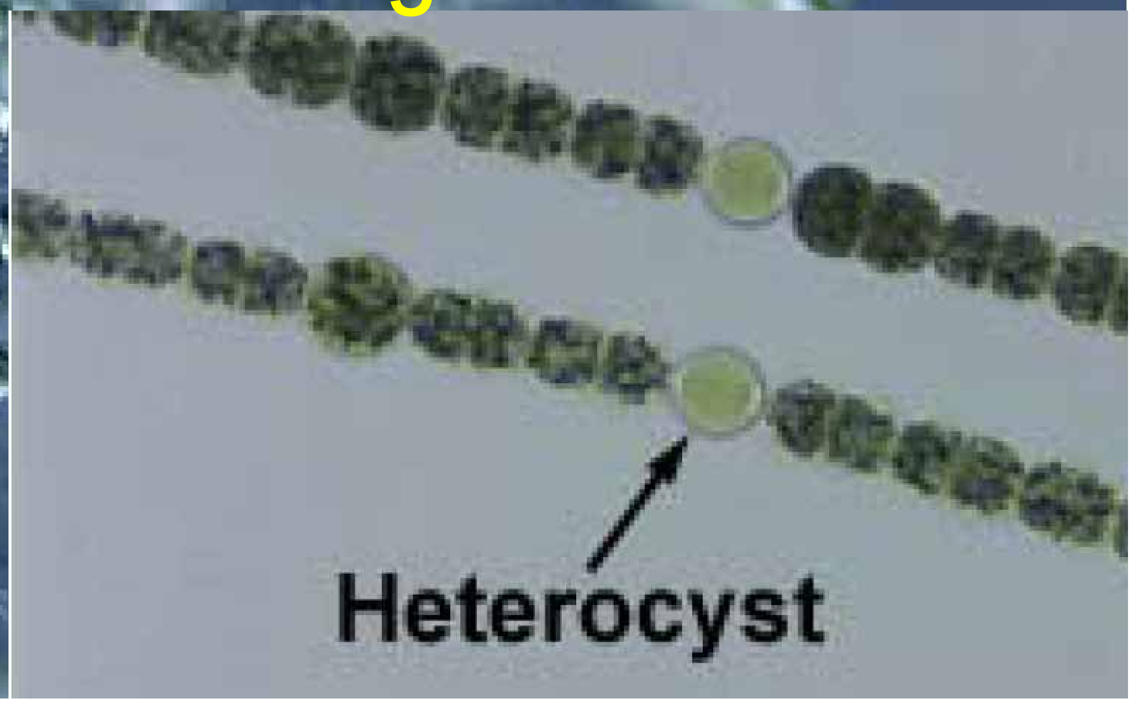
This was the species I started with almost 40 years ago…



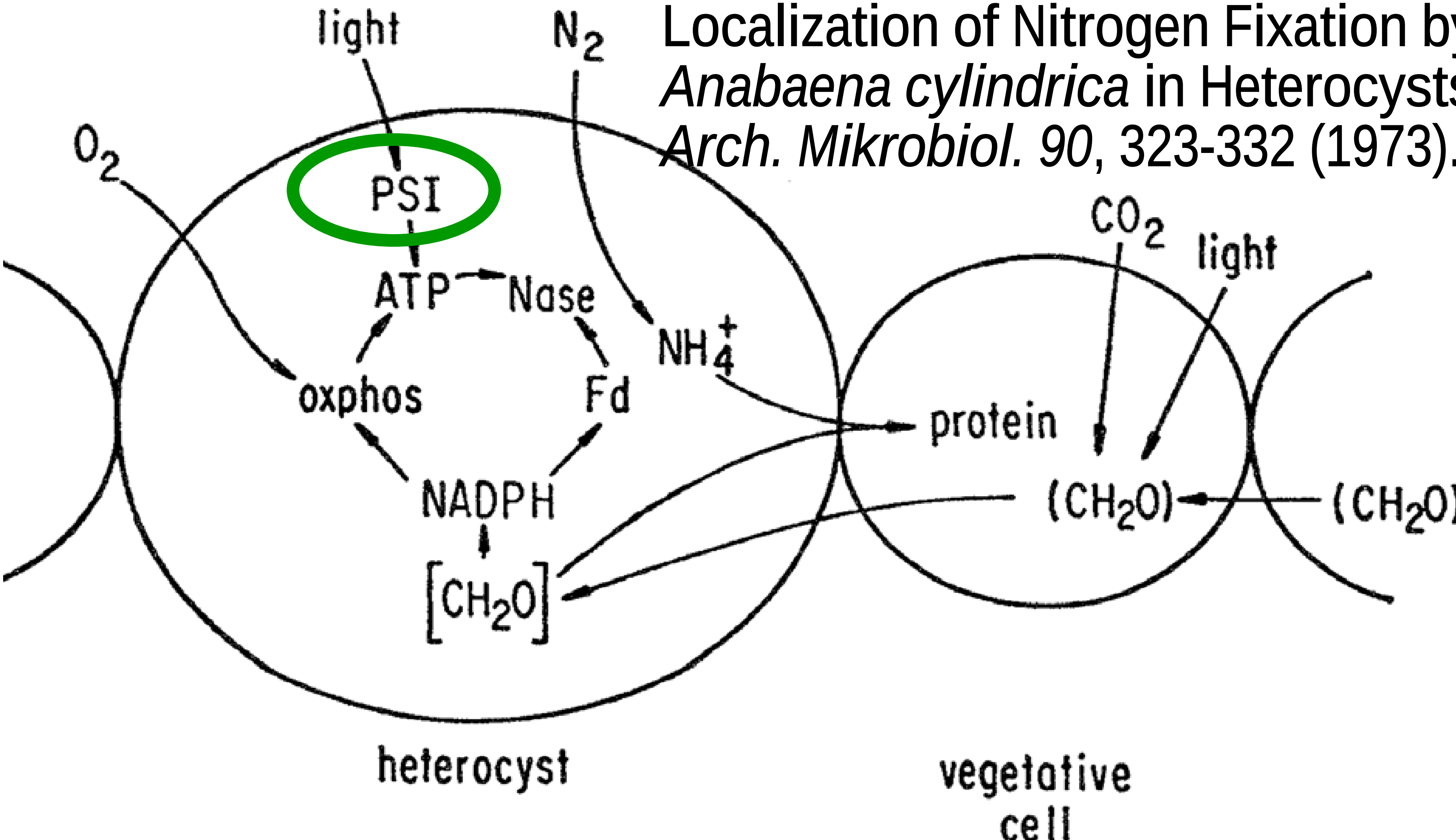
Anabaena cylindrica (cyanobacteria)

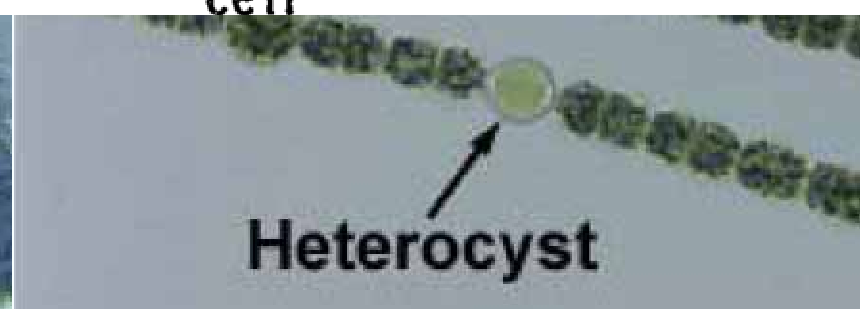


Heterocysts are cells that differentiated from the vegetative cells in the algae filaments and were thought to be the site of N2 fixation, and with a graduate we published the first model of this



Weare, N.M. and J.R. Benemann. Localization of Nitrogen Fixation by *Anabaena cylindrica* in Heterocysts. *Arch. Mikrobiol. 90*, 323-332 (1973).

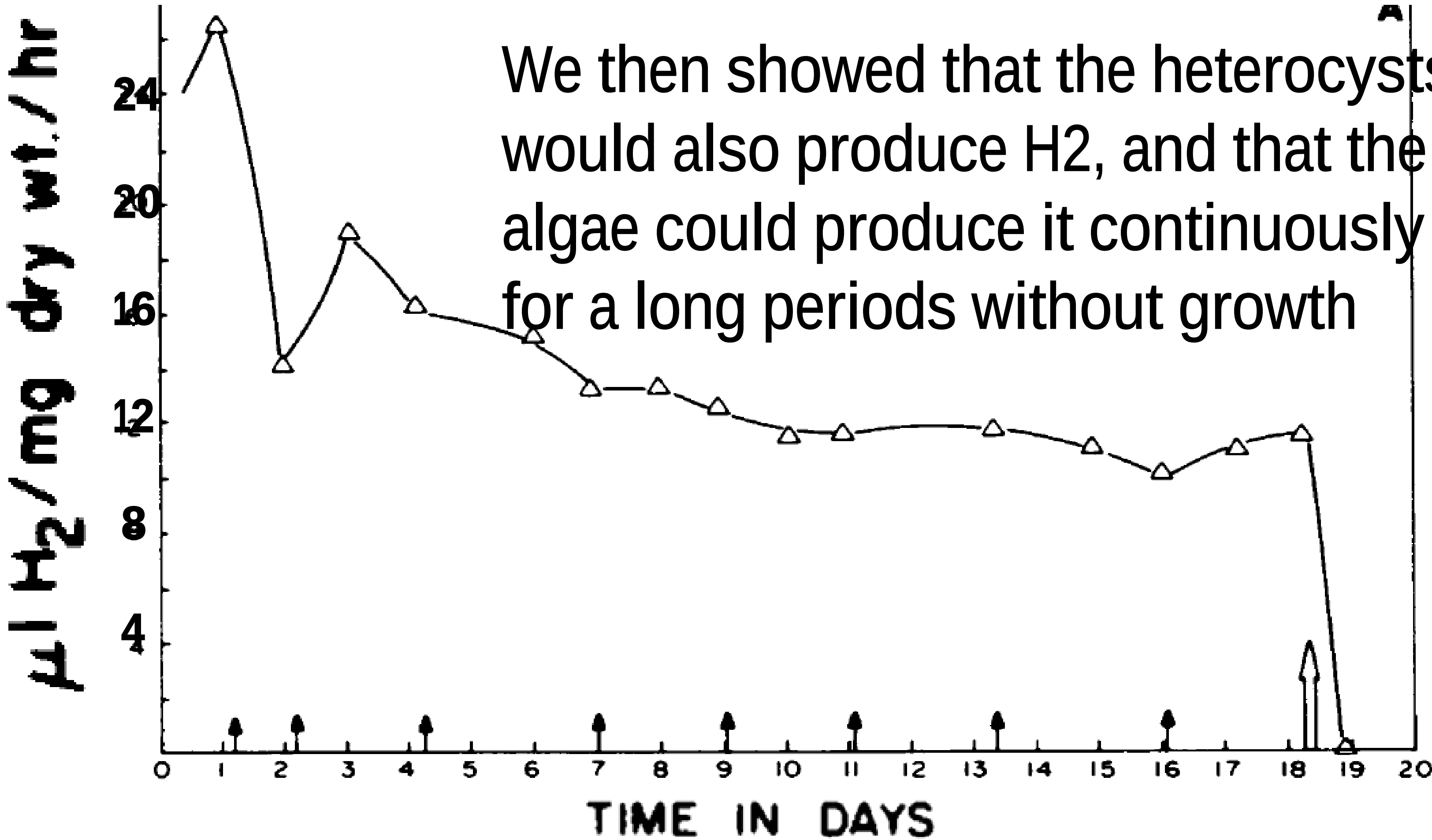




Applied and Environmental Microbiology, Jan. 1977, p. 123–131

Hydrogen Production by Nitrogen-Starved Cultures of *Anabaena cylindrica*

JOSEPH C. WEISSMAN[1] AND JOHN R. BENEMANN



We then showed that the heterocysts would also produce H2, and that the algae could produce it continuously for a long periods without growth

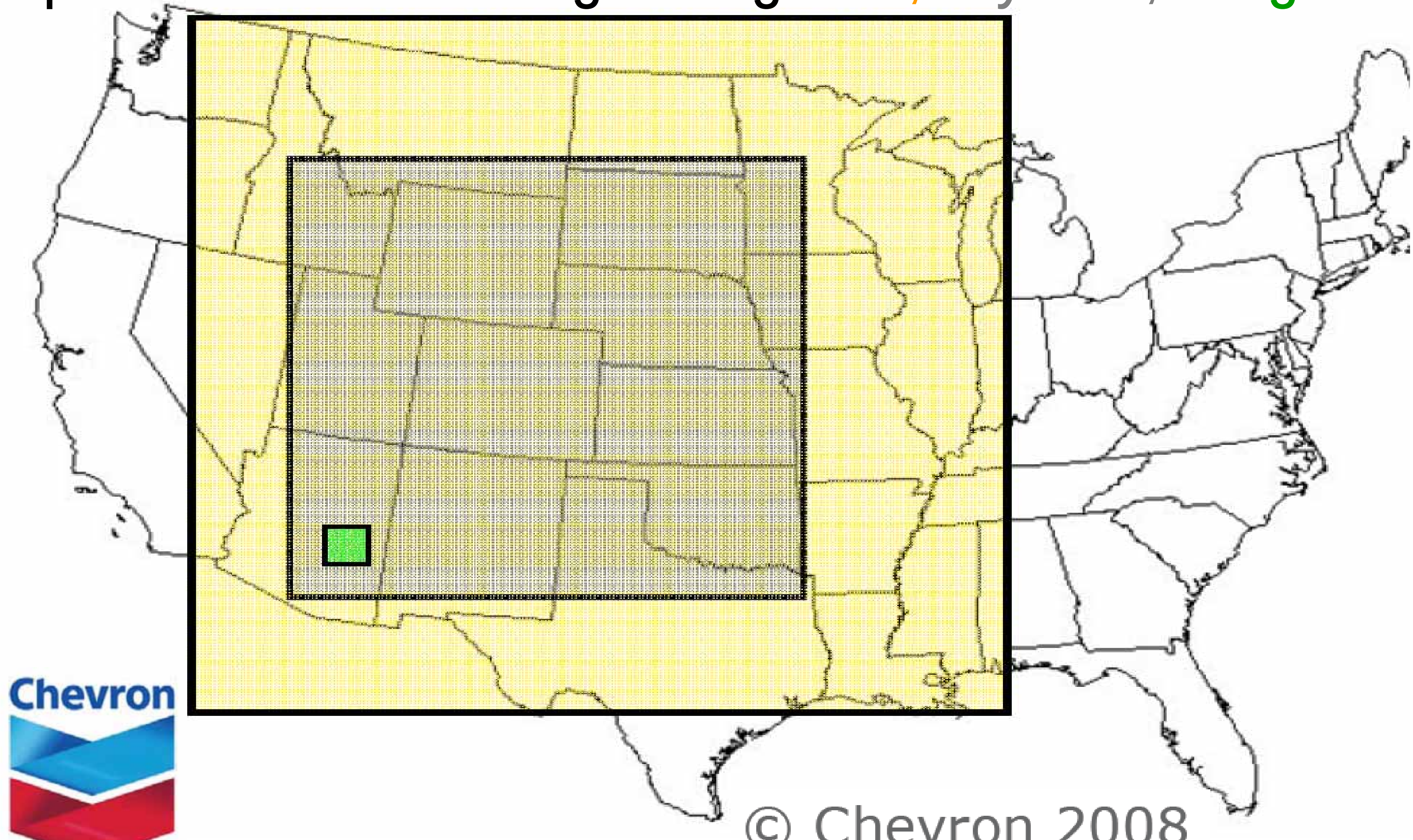
WHY MICROALGAE FOR BIODIESEL /BIOFUELS?

Some attributes of algae claimed by proponents

1. HIGHEST PRODUCTIVITY / FASTEST GROWTH RATE
2. VERY HIGH OIL CONTENT (>50% OF BIOMASS)
3. CAPTURE/ ABATE / SEQUESTER POWER PLANT CO2
4. DO NOT COMPETE WITH FOOD/FEED PRODUCTION
5. LITTLE WATER USE (WITH PHOTOBIOREACTORS)
6. CAN USE BRACKISH, SEAWATER, WASTEWATERS
7. CAN BE CULTIVATED ANYTIME, EVERYWHERE
8. ENORMOUS POTENTIAL RESOURCE WORLDWIDE
9. TECHNOLOGY IS NOW, READY TO COMMERCIALIZE
10. BIOFUELS LOW COST, HIGH VALUE CO-PRODUCTS

Example of projection (by Chevron) of algae vs. other biofuels:

Amount of land required to replace 50% of current USA petroleum- diesel usage using corn, soybean, & algae..



Range of projected yields for autotrophic microalgae vs. actual yields for oil crops

CROP	liters/ha-yr	barrels/acre-yr
Soybeans	400	1
Sunflower	800	2
Mustard	1,600	4
Jathropha (est.)	2,000	5
Palm Oil	6,000	15
Microalgae	20,000-150,000	50- 400

Note: to convert l/ha-yr to US units of gal/acre-yr divide by 9.5 (~10)

Commercial Production of Autotrophic Microalgae

Cultivation of microalgae for foods and biofuels first proposed about 60 years ago and ever since an active area of R&D.

First commercial microalgae production initiated 1960 with *Chlorella* cultivation in Japan, and then Taiwan, followed by *Spirulina* early 1970s in Mexico, then Thailand, USA, India, etc., *Dunaliella* for beta-carotene: Australia, USA, Israel during 1980s *Haematococcus* astaxanthin, USA, Israel, others starting 1990s

Essentially all (>99%) commercial microalgae production, world-wide 15-20,000 metric tons (~3/4th in China), uses open ponds. Almost all sold for human nutritional products (>$10,000/ton!). Only a few commercial closed photobioreactors (PBRs) built.

Wastewater treatment ponds are another practical application of microalgae, but in these algal species are not controlled, and the biomass harvested only at a few larger systems, using chemical flocculants; not used beneficially (e.g. for biofuels)

History and Developments in Microalgae Biofuels

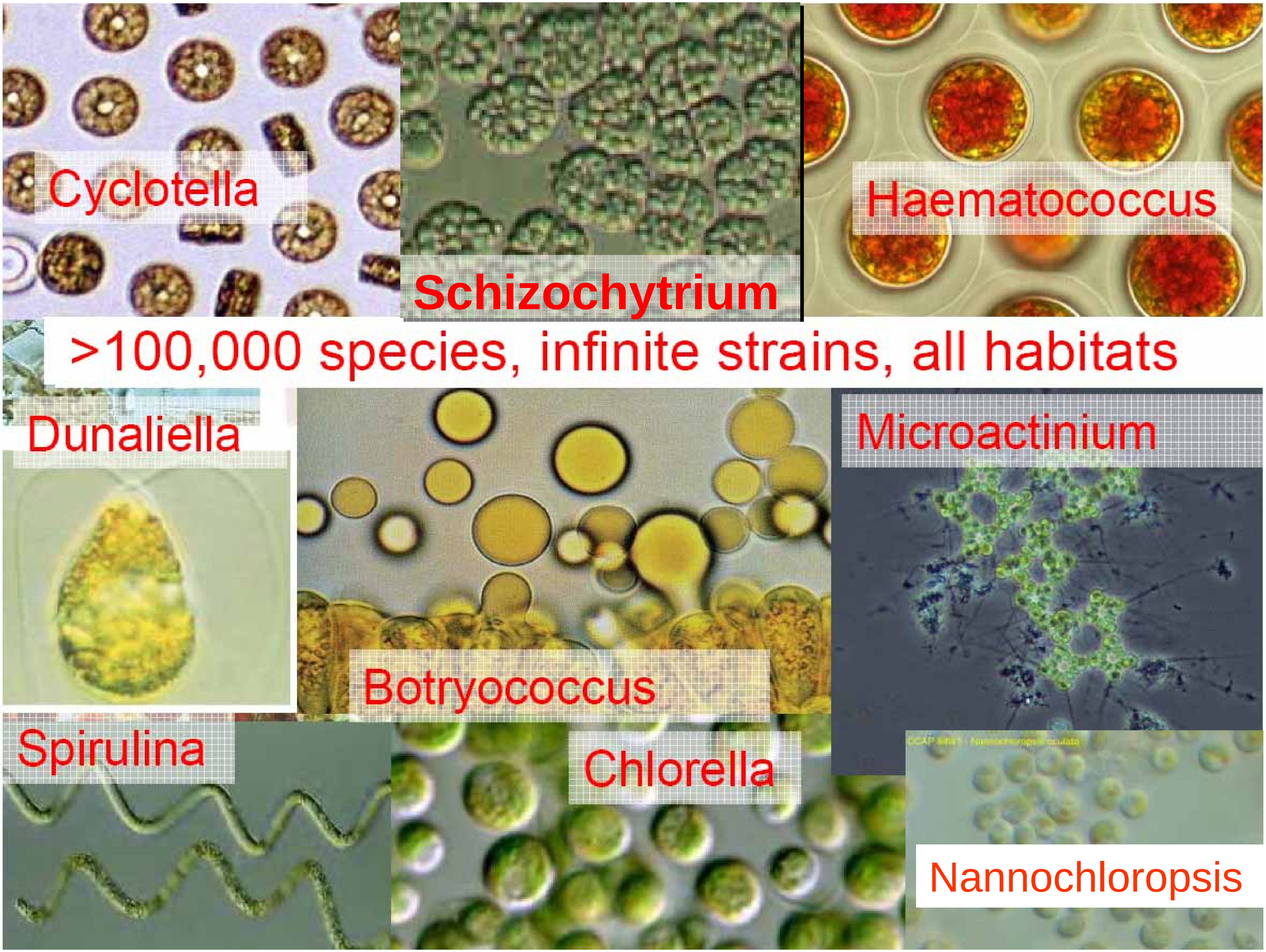
The concept of producing biofuels with microalgae was first proposed 60 years ago, and a subject of R&D programs in the US (1980s) Japan (1990s) including techno-economic studies.

In the last few years microalgae biofuels have become the focus of a world-wide, multi-billion $ R&D effort, with many major government & industry supported projects, >hundred small start-up companies and many university R&D projects.

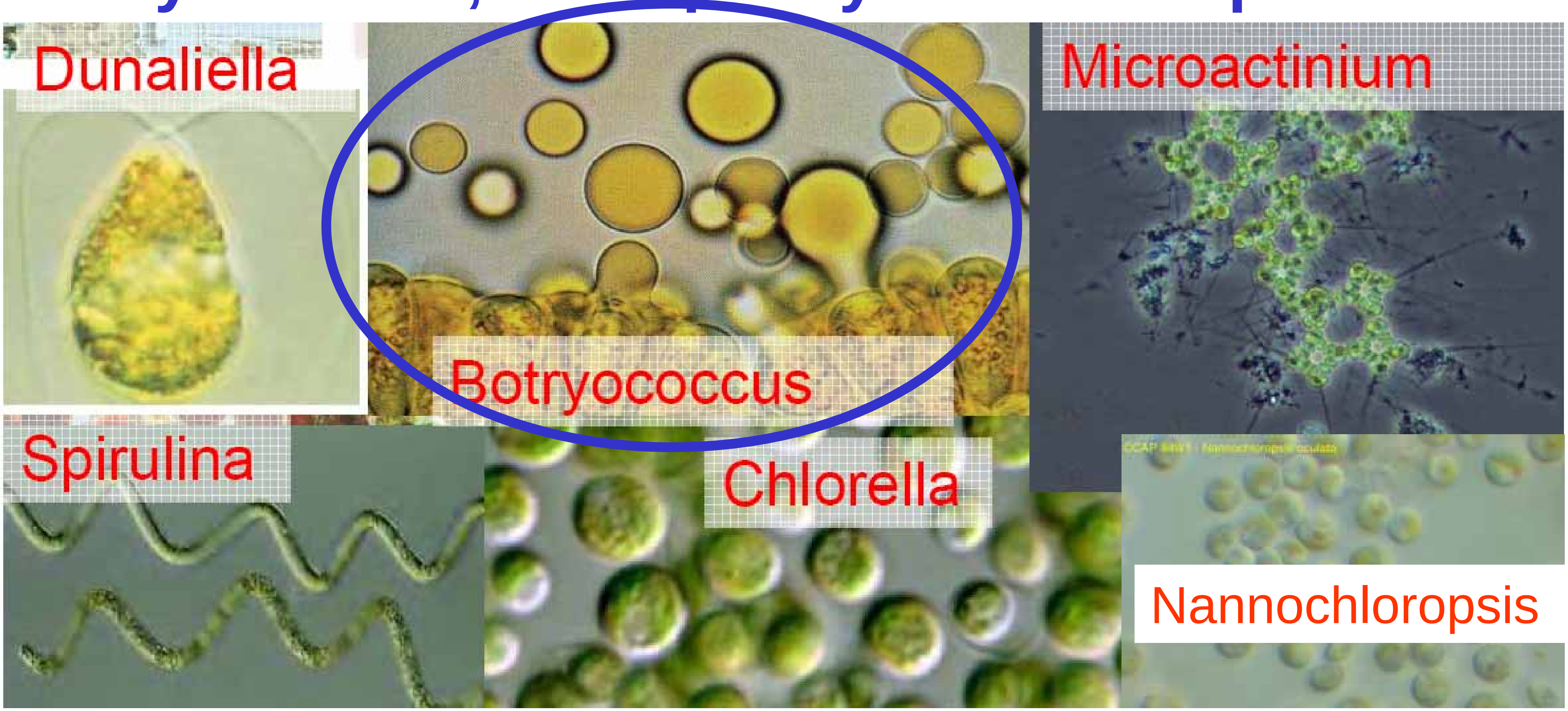
Many algal species and production technologies are being developed, ranging from laboratory studies, to announced near-term full-scale commercial projects in many countries.

Microalgae are also produced by dark fermentation of sugars (heterotrophic) for omega fatty acids (DHA for infant nutrition, Martek), and for other products & biofuels (Solazyme)

Note: in this presentation I discuss only autotrophic production

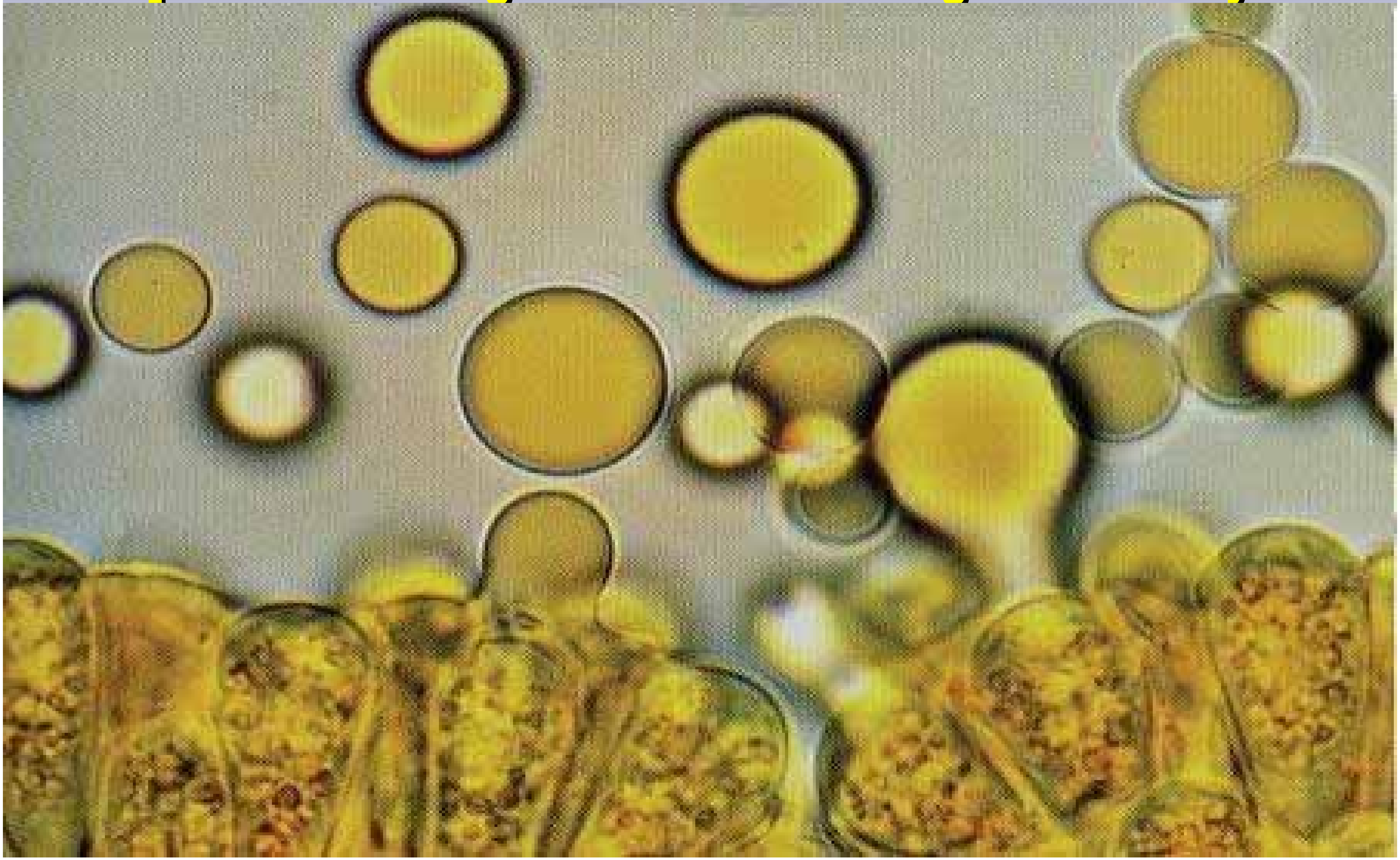

Cyclotella
Schizochytrium
Haematococcus
>100,000 species, infinite strains, all habitats
Dunaliella
Microactinium
Botryococcus
Spirulina
Chlorella
Nannochloropsis

Botryococcus, a unique hydrocarbon producer



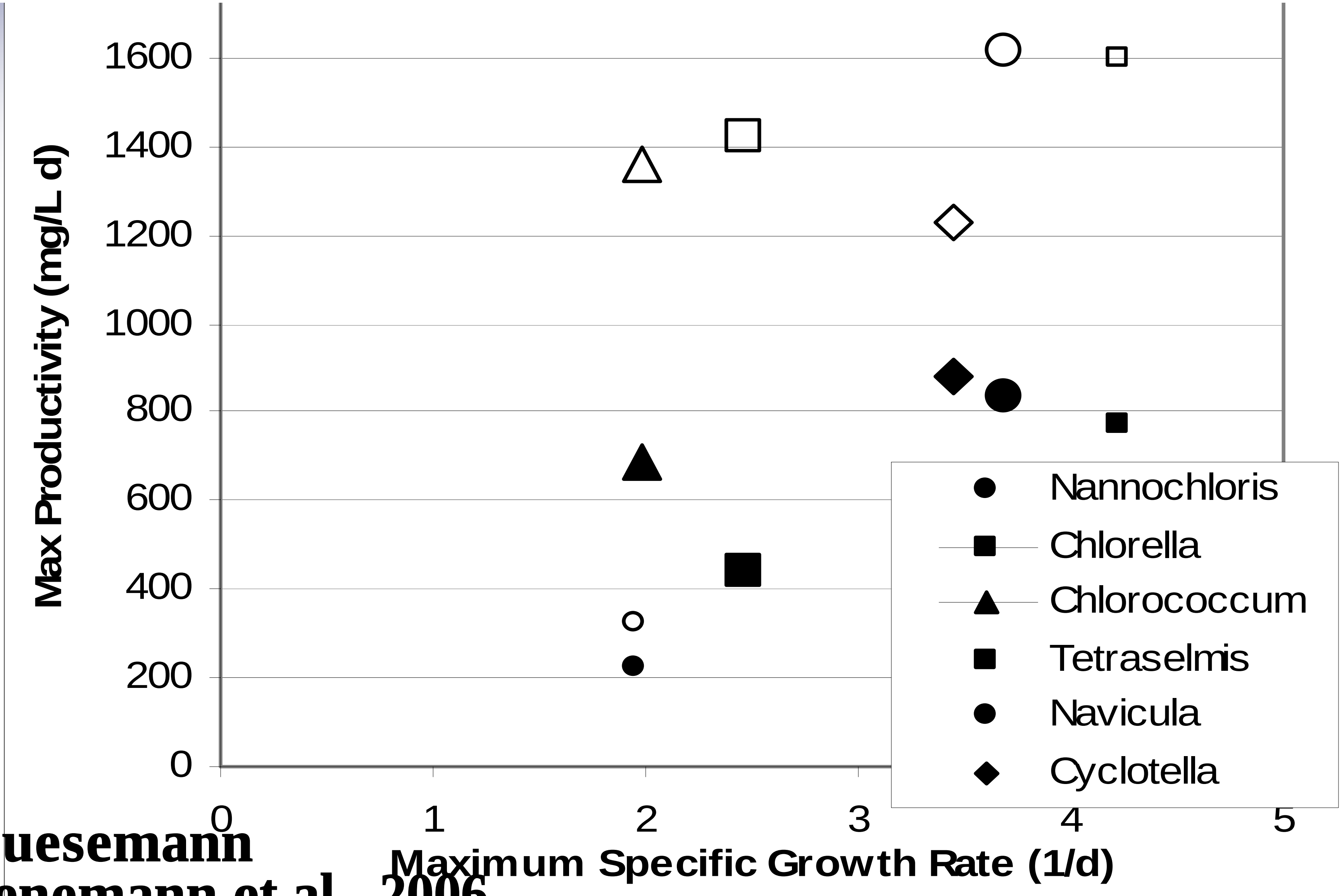
Botryococcus braunii, produces hydrocarbons!

Up to 50% of dry weight pure hydrocarbons (in some strains / races] under normal growth ... but normal growth is very slow!



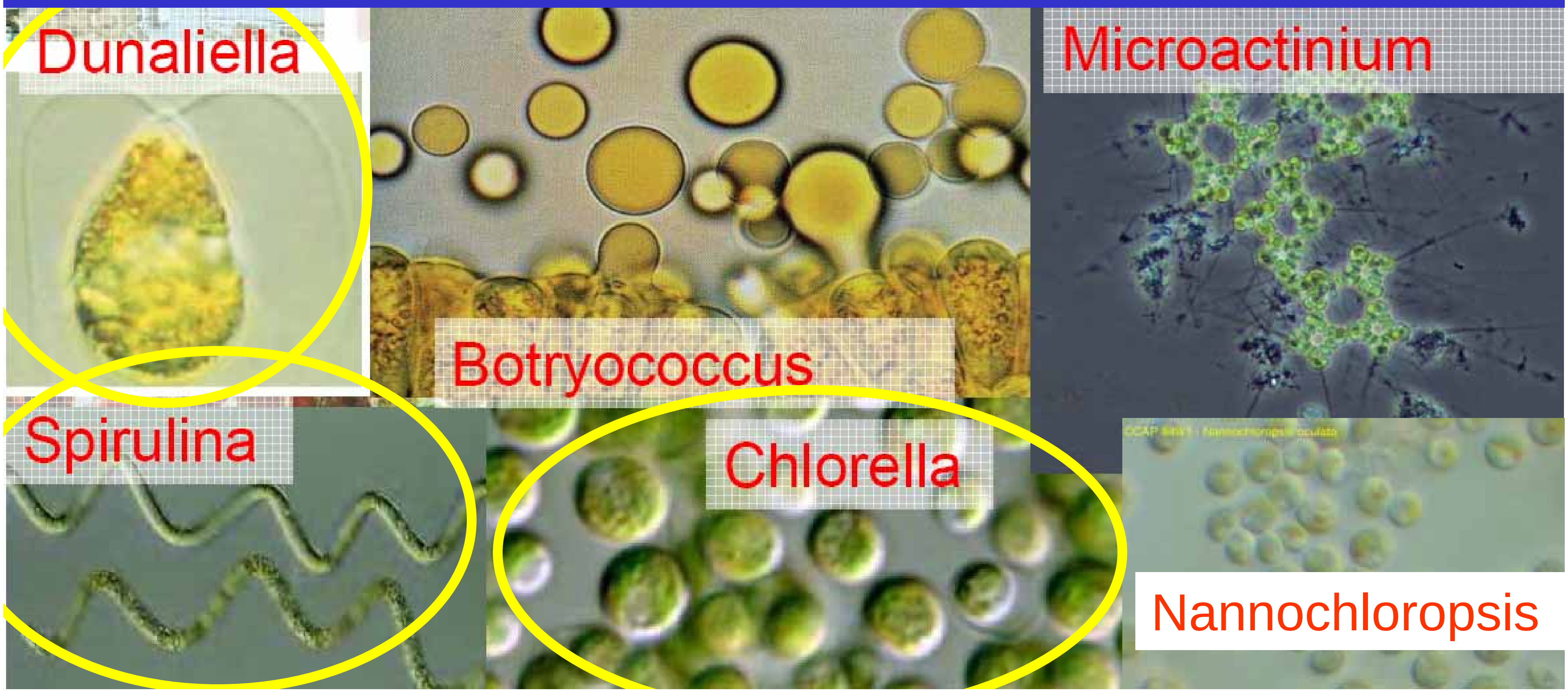
Fast growth rates not synonymous with high productivity

Laboratory experiments at high (open) and low (closed) light intensities for 6 species: max. P vs. max growth rate

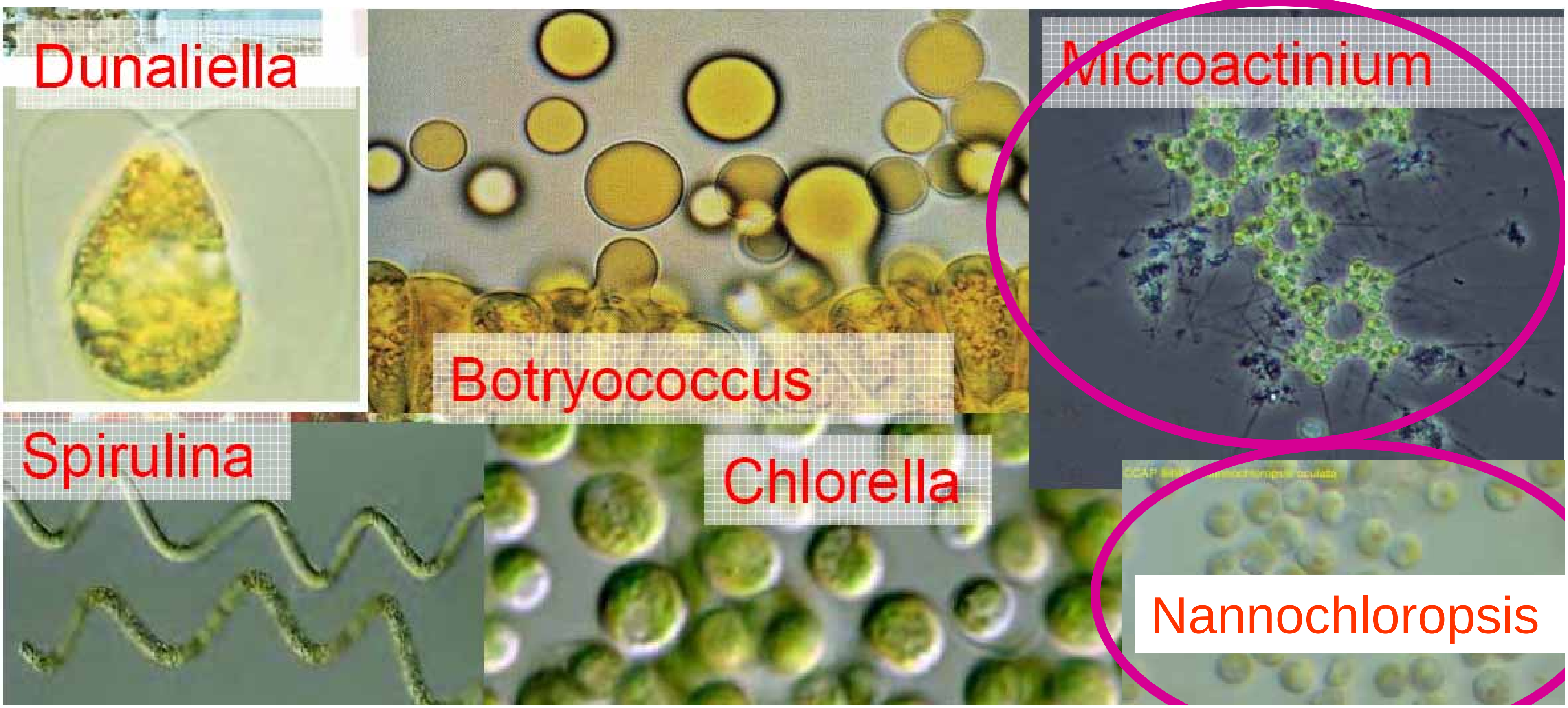


Huesemann
Benemann et al., 2006

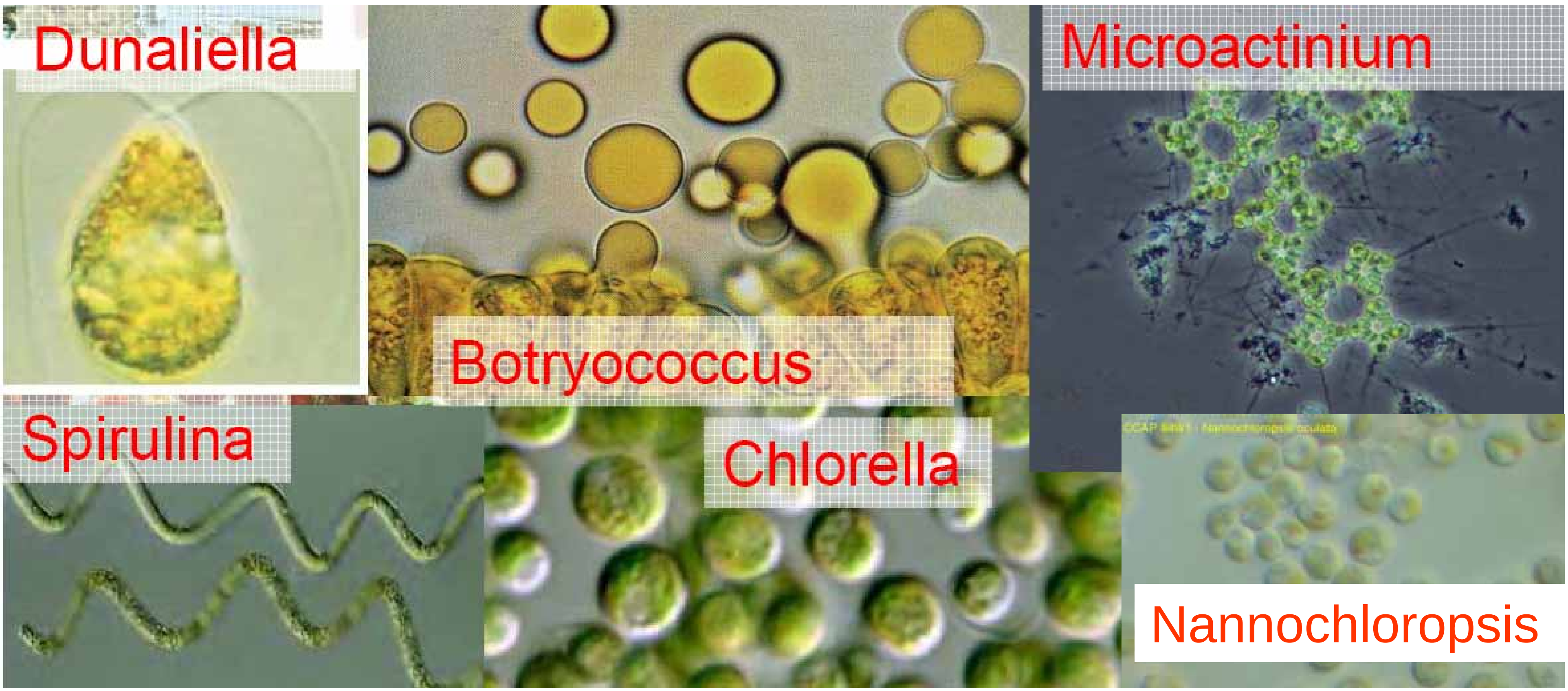
Commercially species grown autotrophically for nutritional products



A few more grown autotrophically in ponds, of interest for biodiesel



Produced heterotophically (on sugars in dark) for oil



The WHATs and WHENs Of Microalgae Biofuels

- What **processes**? auto-, mixo-, photohetero- heterotrophic?
- What **cultivation technologies**? ponds, PBRs, hybrids?
- What **harvesting/processing technologies?** At what cost?
- What **fuels?** biodiesel, green diesel, ethanol, methane, H_2?
- What **algae?** native, selected, mixed, genetically modified?
- What **productivity?** tons biomass or liters biofuel /ha-year?
- What **economics?** How much will microalgae biofuels cost?
- What **co-products?** - animal feeds, wastewater treatment?
- What **sustainability**? energy and GHG balances, LCAs?
- What **resources**? - climate, land, water, nutrients, CO_2?
- What potential? How much in USA, Asia-Pacific, world?
- When will microalgae biofuels be commercial viable?

For when?
we need a
crystal ball…


BLUE-GREEN ALGAE
“…algae will secrete
hydrocarbon fuels …”


BLUE-GREEN ALGAE
"…algae will secrete hydrocarbon fuels …"


BLUE-GREEN ALGAE
"…algae will secrete hydrocarbon fuels …"
ExxonMobil TV commercial, 2010

The New York Times TUESDAY, JULY 14, 2009

Exxon to Invest Millions to Make Fuel From Algae

On Tuesday, Exxon plans to announce an investment of $600 million in producing liquid transportation fuels from algae — organisms in water that range from pond scum to seaweed. The biofuel effort involves a partnership with **Synthetic Genomics**, a biotechnology company founded by the genomics pioneer J. Craig Venter.

NOTE: $600 million, over ~5 years + ~$100 million ad campaign

ExxonMobil TV commercial, 2010


ExxonMobil TV commercial, 2010 (30 seconds!

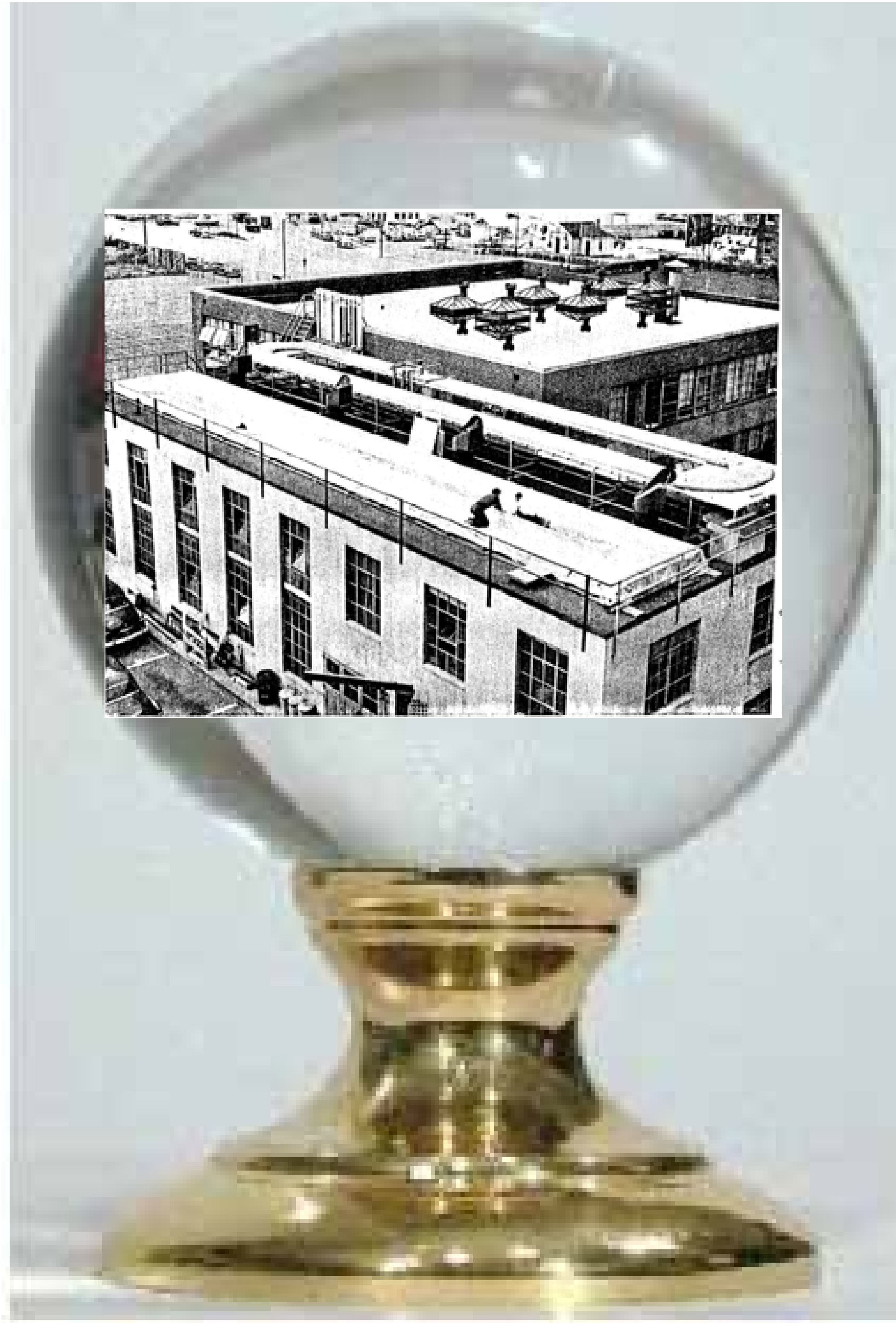
"The year was 1975, and my professor in Berkeley asked me if I wanted to change the world, and I said, sure, lets grow algae, that started it…"

ExxonMobil TV commercial, 2010

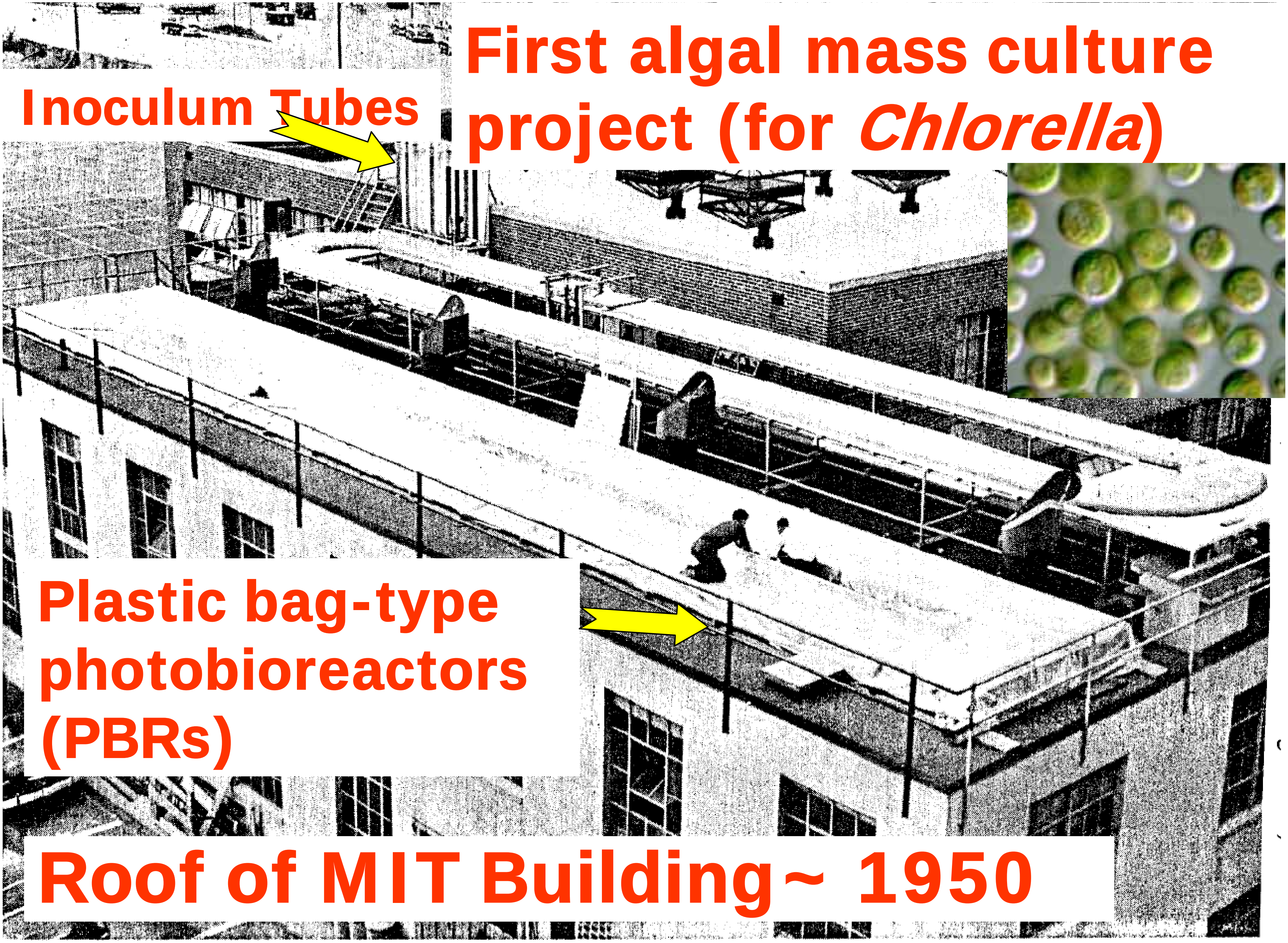
1975, algae ponds at the Univ. Calif. Berkeley

Actually, it started not in 1975, but in 1950: algae cultures were first grown on a rooftop at MIT, using bag-type photobioreactors (PBRs)

Seems that the crystal ball is predicting the past, not future…
I better stop now



First algal mass culture project (for *Chlorella*)



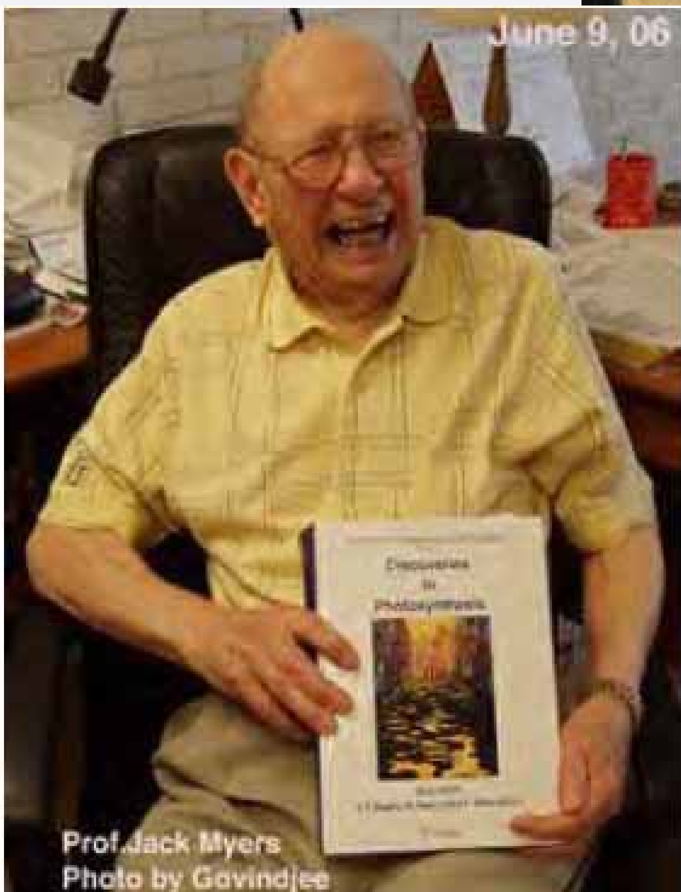
Roof of MIT Building~ 1950

Algae mass culture was first investigated over fifty years ago

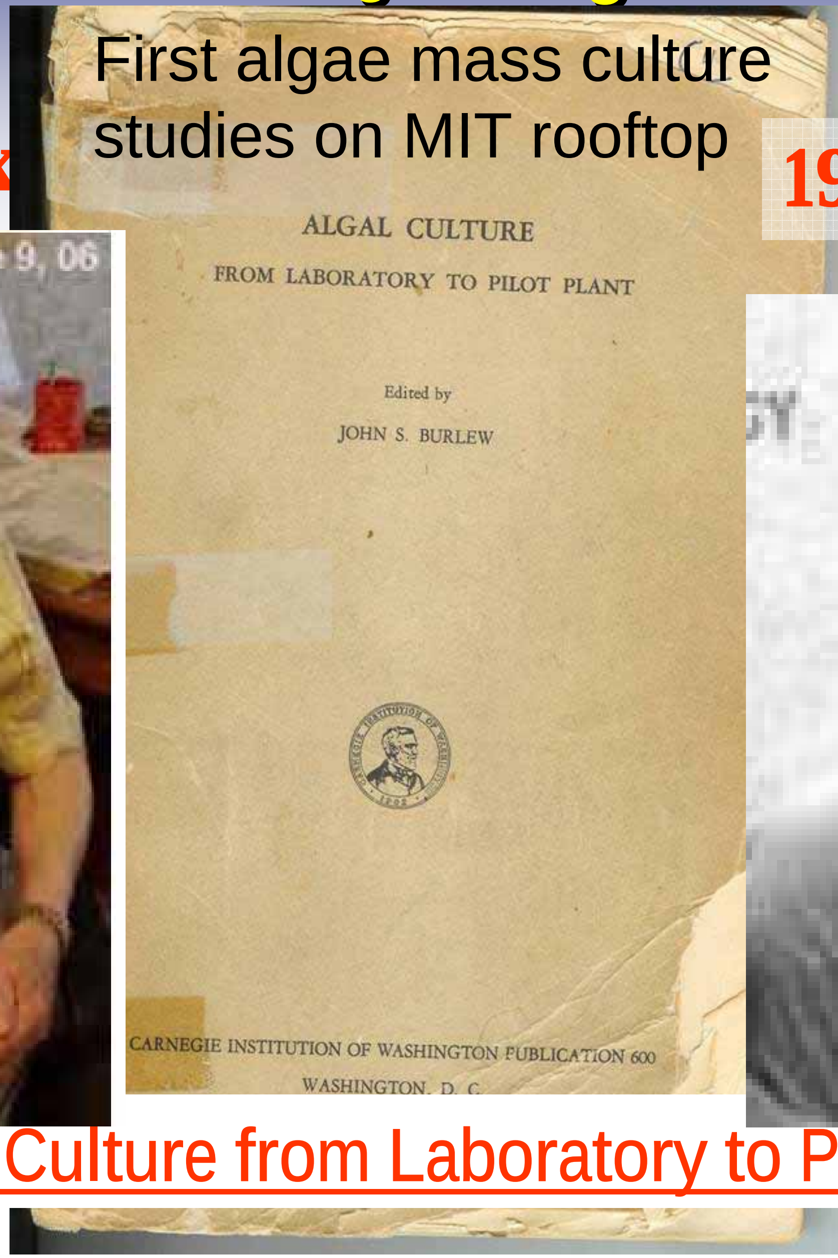
Carnegie Institute of Washington Algae for Food Project

Jack Myers

2006, Austin, Tx



First algae mass culture studies on MIT rooftop


ALGAL CULTURE

FROM LABORATORY TO PILOT PLANT

Edited by

JOHN S. BURLEW

CARNEGIE INSTITUTION OF WASHINGTON PUBLICATION 600

WASHINGTON, D. C.

Bessel Kok

1956, Stanford

Burlew (ed.) <u>Algae Culture from Laboratory to Pilot Plant,</u> 1953

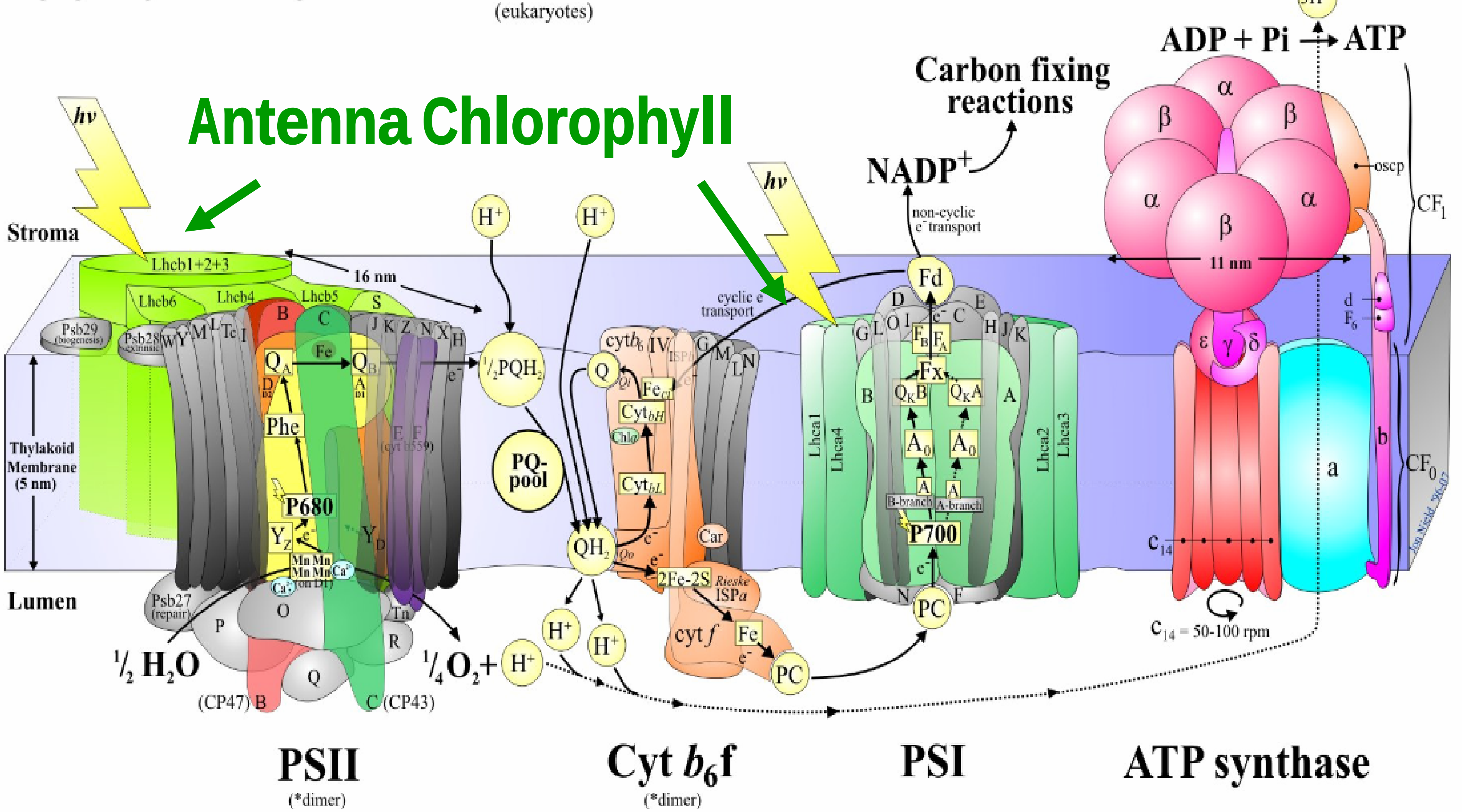
From Burlew, 1953: Productivity of Microalgae

"The maximum efficiency of light utilization is a controversial subject… the latest evidence is that algae and higher plants appear to be about equal in their inherent capacity to utilize the energy of visible light - at very low light intensity both algae and higher] plants can utilize as much as 20 % [convert to biomass] … but when they are growing at full sunlight the conversion in both cases [plants and algae] is reduced to 2 to 3 %"…

WHY? The light saturation effect – photosynthesis saturates at low light levels, ~10% of full sunlight

Schematic of Photosynthesis in green algae and plants

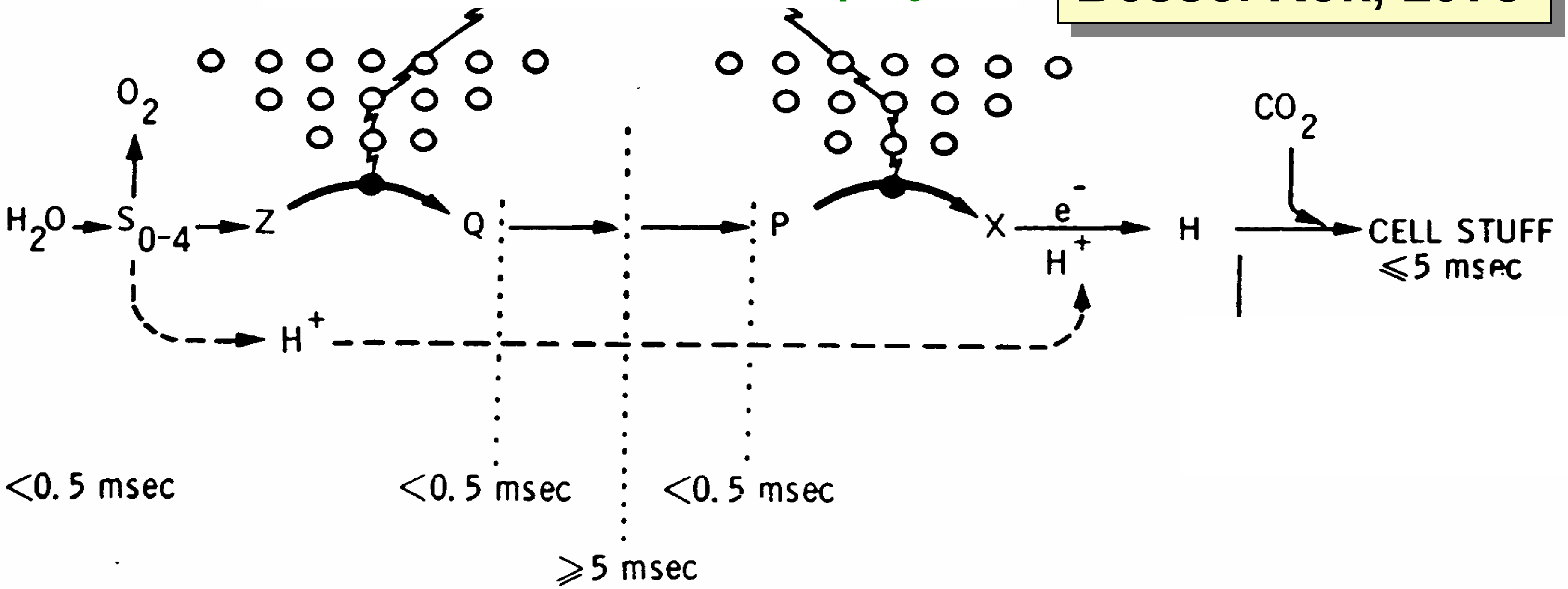
http://photosynthesis.sbcs.qmul.ac.uk/nield/downloads.html



BASIS FOR THE LIGHT SATURATION EFFECT

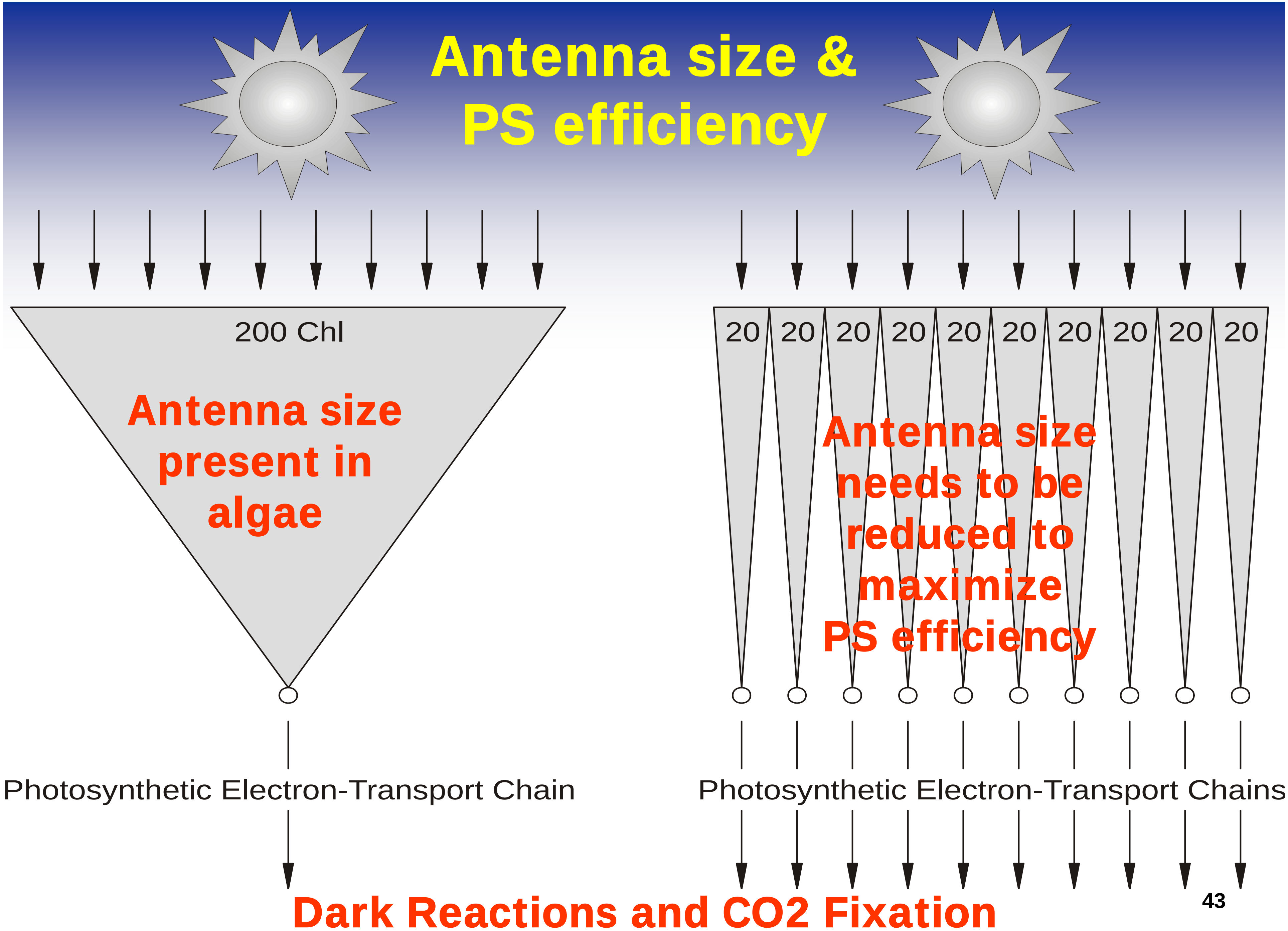
200 Antenna chlorophyll

Bessel Kok, 1973



At full sunlight One photon captured per chlorophyll every 0.1 sec x 200 chl. = 2000 photons/sec (0.5 msec/photon), BUT at 5 msec/ enzyme turnover use 200 onlyphotons/sec

Kok "Presently there is no rational approach for accelerating the dark reactions. The alternate approach seems easier: a search for a plant with a small number of antenna chlorophylls per trap"



Antenna size &
PS efficiency
200 Chl
Antenna size present in algae
20 20 20 20 20 20 20 20 20 20
Antenna size needs to be reduced to maximize PS efficiency
Photosynthetic Electron-Transport Chain
Photosynthetic Electron-Transport Chains
Dark Reactions and CO2 Fixation

Benemann, "The Future of Microalgal Biotechnology" 1989, Chapter in "Algal and Cyanobacterial Biotechnology"

"… we must search for genetic or adaptive characteristics which provide for maximum rates of photosynthesis per chlorophyll (pigment) unit at both high and low light intensities. … This is a high priority area for research. Both genetic and physiological approaches...can be considered."

"One major problem [is] the poor competitiveness of such strains: individual cells compete for sunlight … By each individual algal cell maximizing its own competitive advantage (e.g. antenna size) under the light limited conditions in algal mass culture ponds- the overall productivity of the system is reduced."

Journal of Applied Phycology 11: 195–201, 1999.

Improvement of microalgal photosynthetic productivity by reducing the content of light harvesting pigment

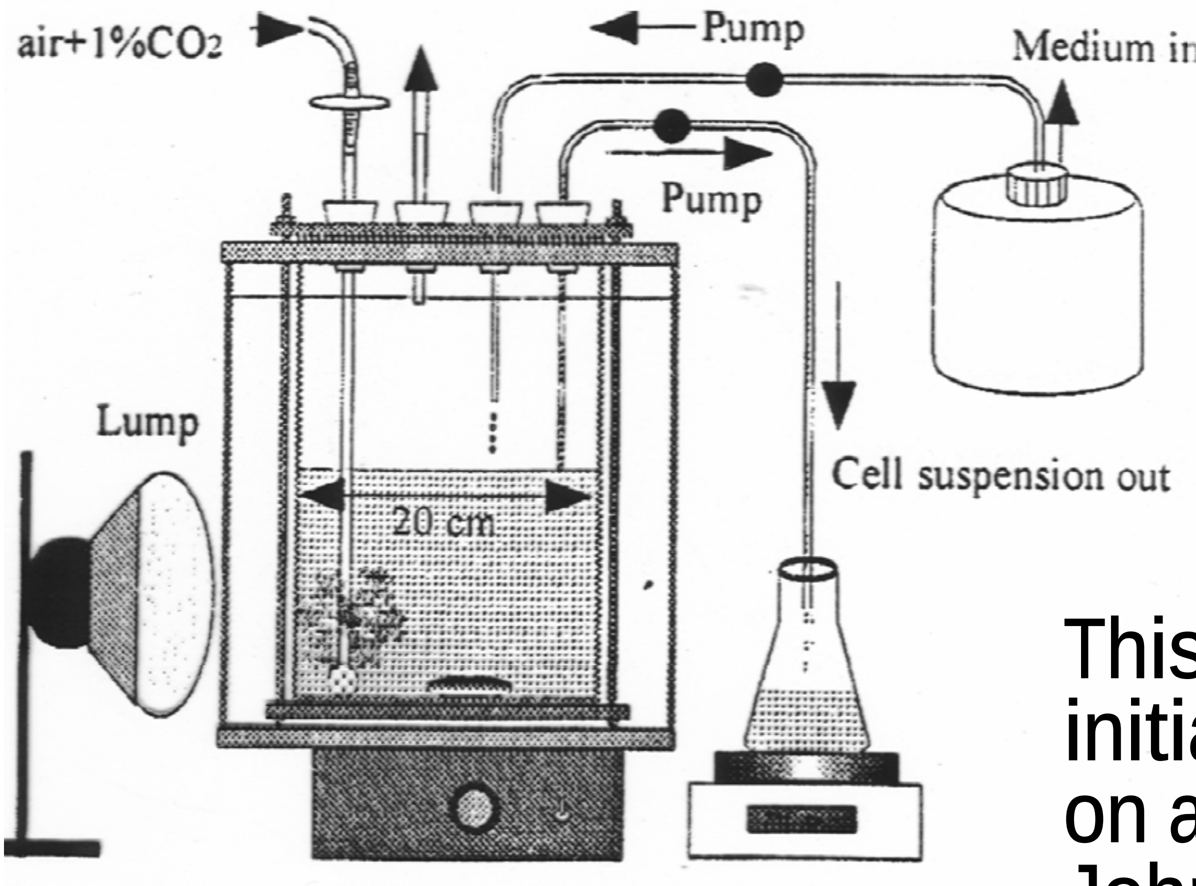


Figure 1. Continuous culture system.

Nakajima & Ueda

Mitsubishi Heavy Industries, Japan

This research was initiated by MHI based on a report prepared by John Benemann

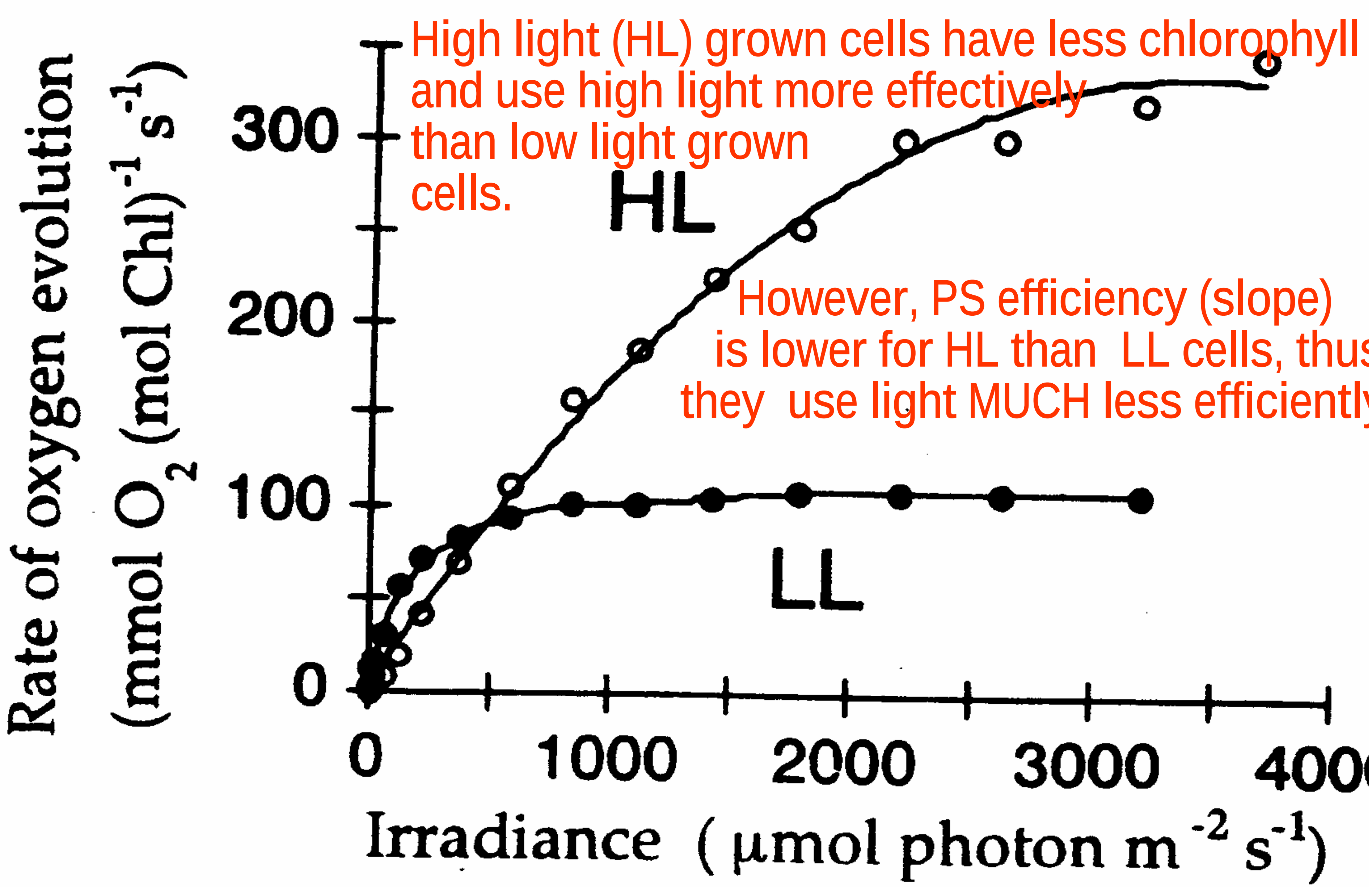


Figure 2. Light-saturation curves of photosynthesis

Neidhardt, Benemann, Melis, 1997, J. App. Phycology

Wild type and PAL Mutant Synechocystis 6803 Productivities at low and high intensity

Culture Productivities

$uE/m^2/s$	WT	PAL
130	15	5
1300	20	40

Note that mutant has higher productivity at higher light intensity but lower at lower light intensity than wild type

Weissman, Benemann et al. 2005

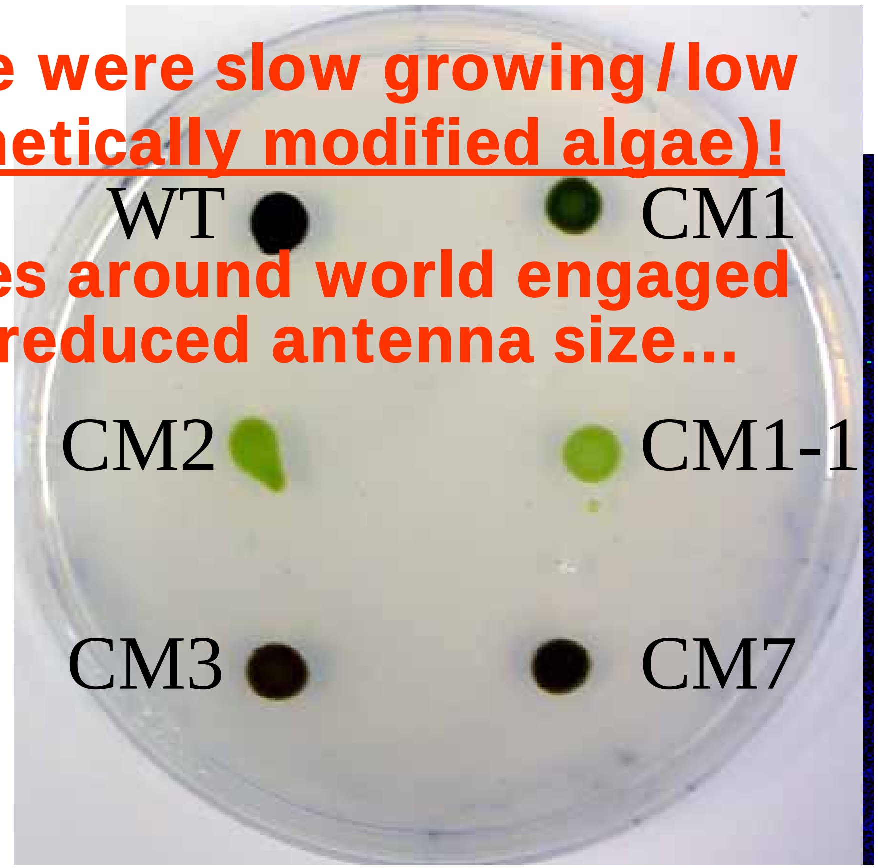
Appl Biochem Biotechnol (2009) 157:507–526

Biomass Productivities in Wild Type and Pigment Mutant of *Cyclotella*

Michael H. Huesemann · Tom S. Hausmann
Richard Bartha · M. Aksoy ·
Joseph C. Weissman · John R. Benemann

Mutants with small antenna size were slow growing / low productivity – NEED GMA <u>(genetically modified algae)</u>!

Now laboratories and companies around world engaged in developing GMA strains with reduced antenna size…



WHAT ABOUT OIL PRODUCTION IN MICROALGAE?

Can increase oil content by limiting cells for N

Cyclotella cryptica, Nile Red lipid fluorescence

N limitation results in PS shut down → low oil productivity

Projected yields for algae vs. actual for oil crops (assuming small antenna strains, no N limitation, etc.)

Biodiesel yields	liters/ha-yr	barrels/acre-yr
Soybeans	400	1
Sunflower	800	2
Mustard	1,600	4
Jathropha (est.)	2,000	5
Palm Oil	6,000	15
Microalgae	50,000*-150,000	120- 600

***maximum possible long-term yield**. Assumes highest possible oil productivity (small antenna strains, most photosynthesis into oil, etc.) Anything above is just fantasy. Near-term best is ~20,000 l/ha-yr Actual microalgae yields not yet available: nobody has produced any barrels of oils from an acre over a year, thus far, that I know of…

What does crystal ball predict about microalgae oil (biodiesel) productivity?

Joule Unlimited, Cambridge MA (pilot plant in Texas)
genetically modified cyanobacteria excrete oil
Claims 150,000 l/ha-yr (peer reviewed publication!)

Paul Falkowski – April 7, 2011 (DOE Review)

"…I have seen some really horrendous papers, one in Photosynthesis Research by Joule claiming 12% solar energy conversion efficiency. That is just nonsense, just nonsense! If we get 3% I will be very happy. But these kind of statements are confusing and deceitful frankly, and are creating a level of expectation that is not achievable…"

What about excretion of biofuels by algae?

Advantages: 1. no photons wasted in producing biomass,
2. no need to harvest the biomass,
3. no need to recycle nutrients… etc.

Disadvantages: 1. bacteria consume product
2. require closed PBRs (expensive)
3. must recover very dilute biofuel

The prognosis not good to solve even one of the problems, particularly not bacterial consumption of excreted biofuels!

CONCLUSION: excretion of biofuels by microalgae is a laboratory pass- time, without practical significance or application, unless all three above problems are solved.


"…algae will
NOT secret
biofuels …"

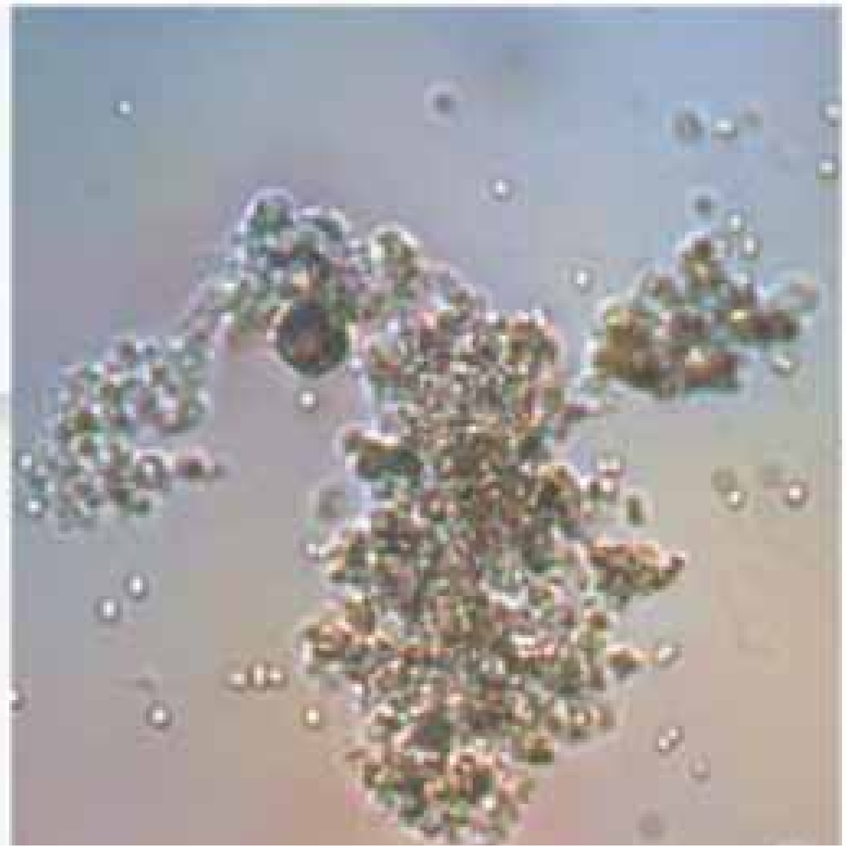
Fatty acid production in genetically modified cyanobacteria

PNAS

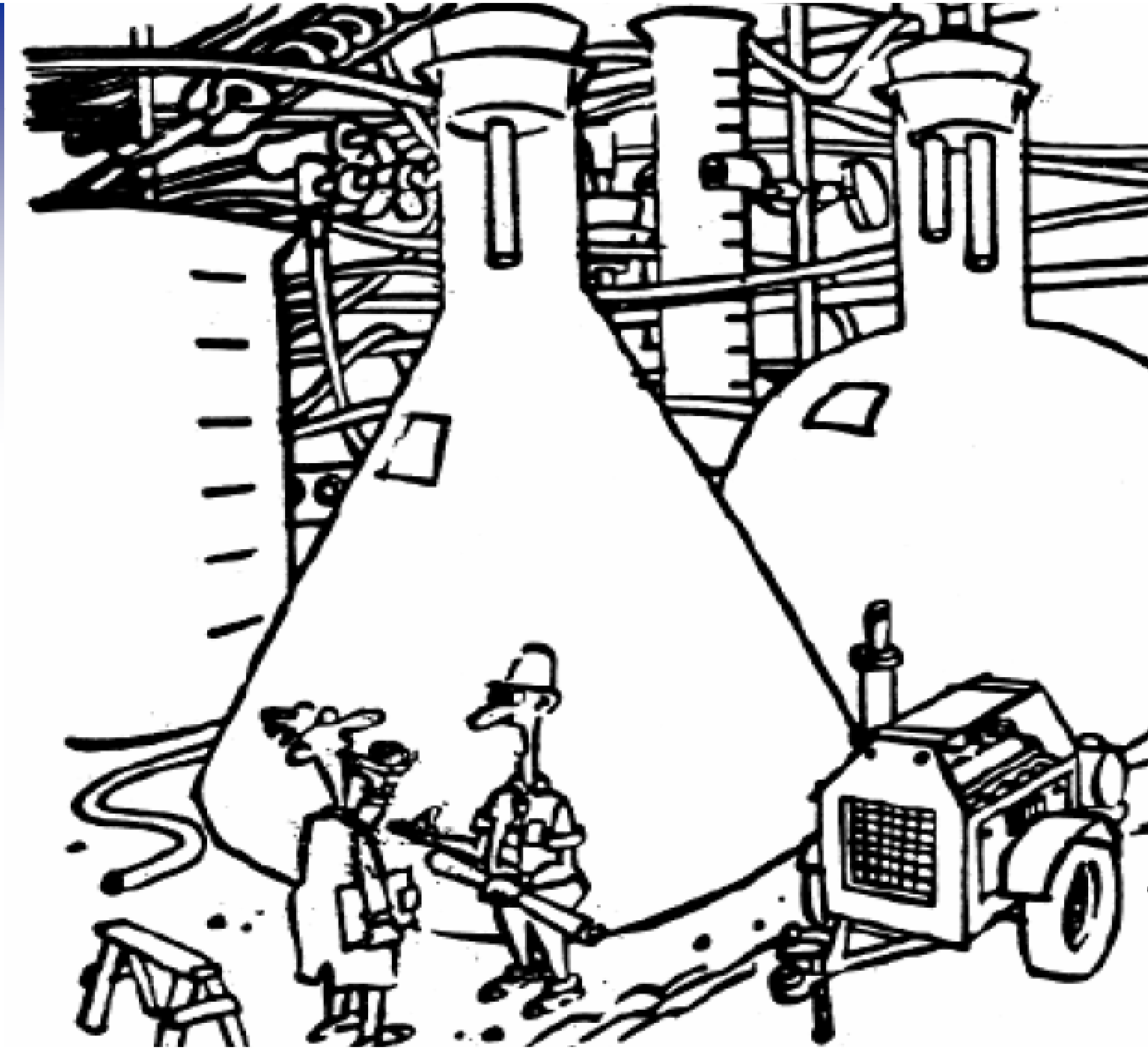
- **Liu, Sheng and Curtis (ASU)**

mutant strains overproduced fatty acids (C10 –C18) and secreted them into the medium

- **February 2011**



BUT: laboratory experiments, sterile cultures. In scale-up they will be unavoidably contaminated with bacteria that will consume the oil



We seem to have a few problems going from lab-scale to full-scale production

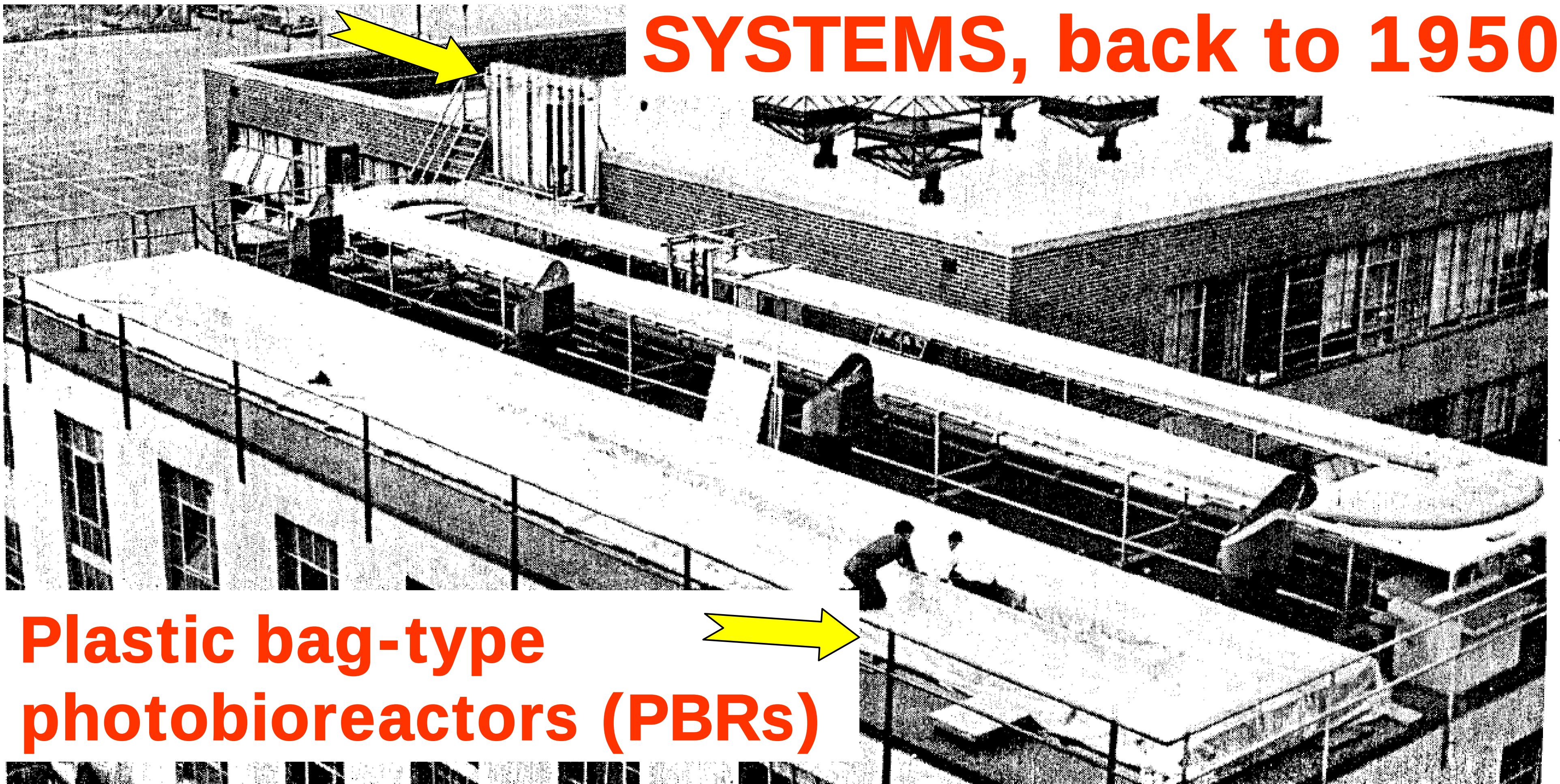
THE KEY PROBLEMS IN MICROALGAE CULTIVATION ALREADY KNOWN IN THE 1950s (but not the solutions)

- **Productivity (solar conversion efficiency) g/m2-day or tons biomass/hectare-yr**, must reduce antenna size
- **Cultivation Systems: Ponds, photobioreactors (PBRs)**
- **Oil production**: very high content after N or Si limitation BUT very low productivity – a still unresolved problem
- **CO2** source, supply (piping), transfer (A very dismal topic)
- **Mixing** – needed, but why, how much, what energy input?
- **Harvesting** – difficult, costly: < 500 ppm, <50 micron cells
- **Culture Stability** – selected strains, grazers, weed algae.
- **Processing** - wet or dry oil extraction, residues to biogas?

Next I address: **Cultivation Systems;** ponds and PBRs

NEXT: CULTIVATION SYSTEMS, back to 1950

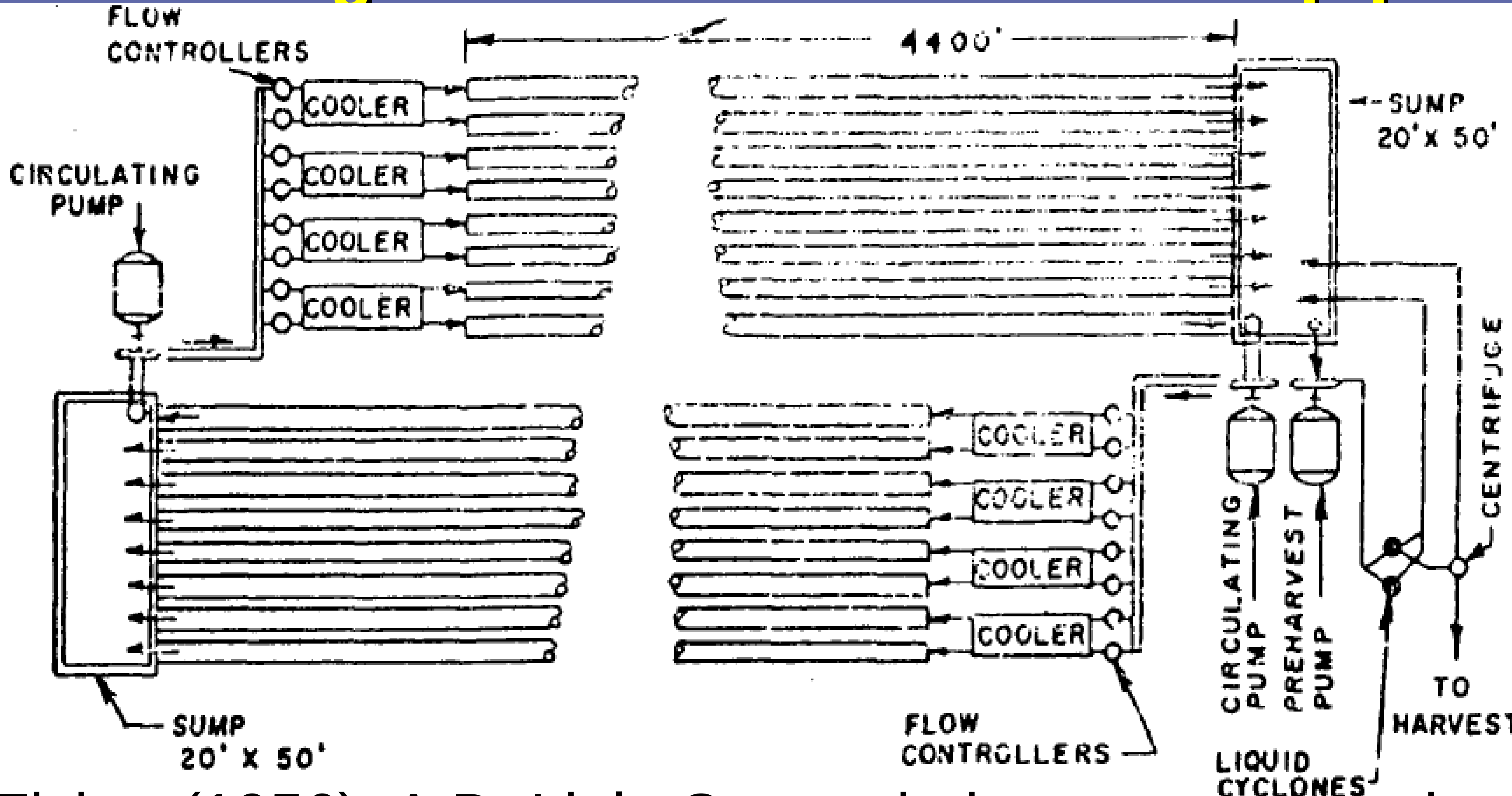
Inoculum Tubes



Plastic bag-type photobioreactors (PBRs)

Roof of MIT Building~ 1950 – First algae production scale-up. Problems? Many, most critical does not scale!

40 ha design based on 1950's MIT rooftop plant



Fisher (1956), A.D. Little Co. carried out an engineering design-cost estimate for a 40 hectare system of plastic tubes estimating (2008 $) capital cost **>$1.25 million/ha**
Still ~ what we estimate now for PBRs (best case)

Popular Science 2007: Solix Biofuels (photoshop) the iconic picture of algae biofuels!

Latest Example: Solix Pilot Plant, 2010, Colorado

Hanging bags in pool - many hoses, valves, connectors, etc.

Here is another problem: how to clean
E.on- Hamburg, Germany (Subitec PBR)

Biotechnology and Bioengineering, Vol. 31, Pp. 336–344 (1988)

Photobioreactor Design: Mixing, Carbon Utilization, and Oxygen Accumulation

Joseph C. Weissman* and Raymond P. Goebel
Microbial Products, Inc. 408A Union Ave., Fairfield, California 94533

John R. Benemann
Department of Applied Biology, Georgia Institute of Technology, Atlanta,

Photobioreactor design and operation are discussed in terms of mixing, carbon utilization, and the accumulation of photosynthetically produced oxygen. The open raceway pond is the primary type of reactor considered; however small diameter (1–5 cm) horizontal glass tubular reactors are compared to ponds in several respects.

This paper concluded that individual PBRs were limited in scale-up to at most few hundred square meters, but raceway ponds likely scale to hectares. PBRs are not suitable for large-scale algae cultivation

Claims for superiority of PBRs over ponds are spurious

A PREDICTION BY
THE CRYSTAL BALL:
PHOTOBIOREACTORS
WILL NOT BE USED TO
PRODUCE BIOFUELS.

RWE, Germany, hanging bags PBR to capture CO2 from a coal-fired power plant - would need 100 million such bags!

Potential of Algae for Coal Power Plant (CCP) CO2 Capture for Greenhouse Gas (GHG) Abatement

Capture of CO2 by microalgae is NOT GHG abatement NO difference with plants using CO2 from air. Only biofuels replacing fossil fuels can reduce GHGs. ALSO:

<10% of CCP in climatically favorable areas for algae

<10% of these have >10,000 ha + water for algae ponds

<10% of CO2 could be captured by algae systems (due to limits to flue gas transport, day/night & seasonal differences, transfer and outgasing losses, etc.)

Potential for algae to capture CO_2 from CPPs

$<0.1 \times <0.1 \times <0.1 = <<<0.001$

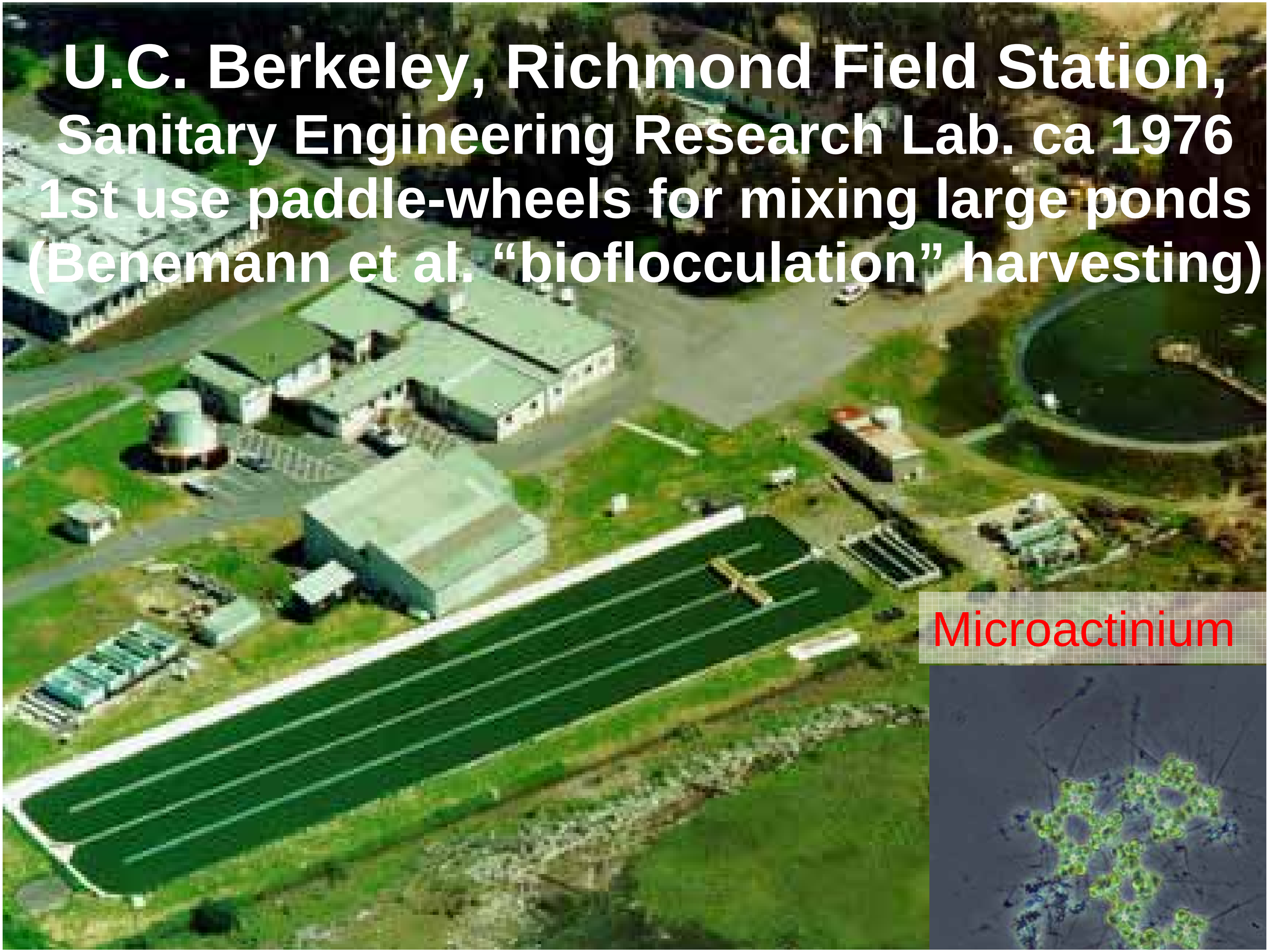
Conclusion re. abating coal power plant CO_2:

ABANDON ALL HOPE


ANOTHER PREDICTION
BY THE CRYSTAL BALL:
MICROALGAE WILL NOT
SIGNIFICANTLY REDUCE
FOSSIL POWER PLANT
CO2 EMISSIONS.


During the 1950s Prof. W.J. Oswald pioneered
“high rate ponds” (HRPs) for low-cost waste
water treatment and biofuels production :
shallow, raceway, slowly mixed ponds
(paddle wheel mixing intruduced in 1970s)

U.C. Berkeley, Richmond Field Station,
Sanitary Engineering Research Lab. ca 1976
1st use paddle-wheels for mixing large ponds
(Benemann et al. “bioflocculation” harvesting)



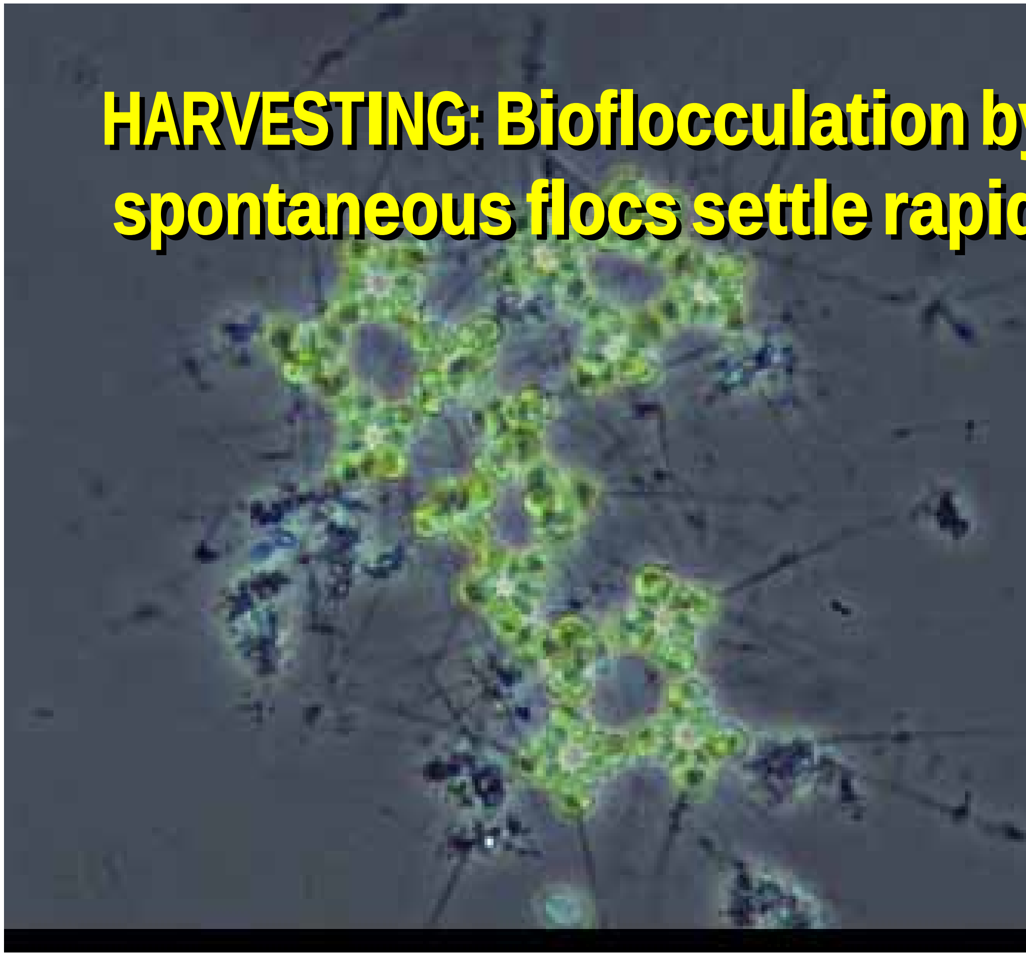
Algae Biomass **Elsevier, 1980, pp. 457 - 496**

G. Shelef and C.J. Soeder. Editors

DEVELOPMENT OF MICROALGAE HARVESTING AND HIGH-RATE POND TECHNOLOGIES IN CALIFORNIA

JOHN BENEMANN, BEN KOOPMAN, JOSEPH WEISSMAN, DON EISENBERG AND RAY GOEBEL

HARVESTING: Bioflocculation by *Microactinium* sp. these spontaneous flocs settle rapidly for low-cost harvesting



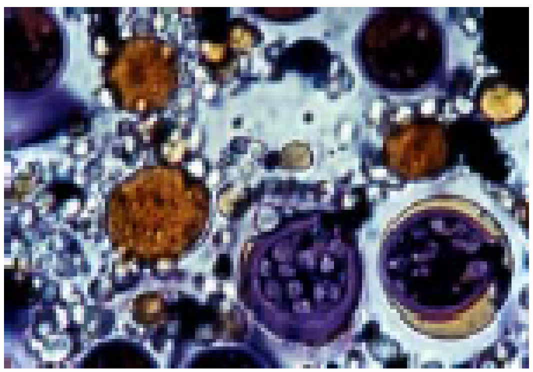
Grazers: THE MAJOR ISSUE in algal cultivation (along with fungi, bacteria, viruses] in algal cultivation; how control?

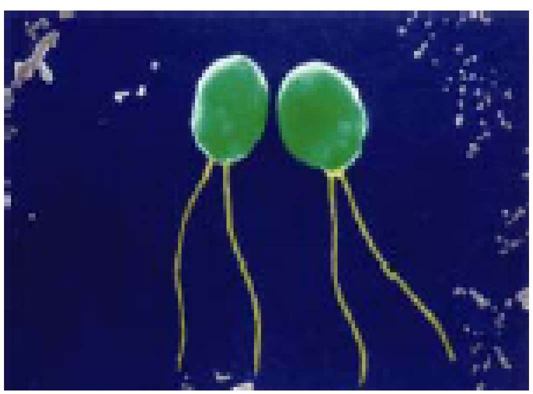
National Renewable Energy Laboratory

NREL/TP-580-24190

A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae

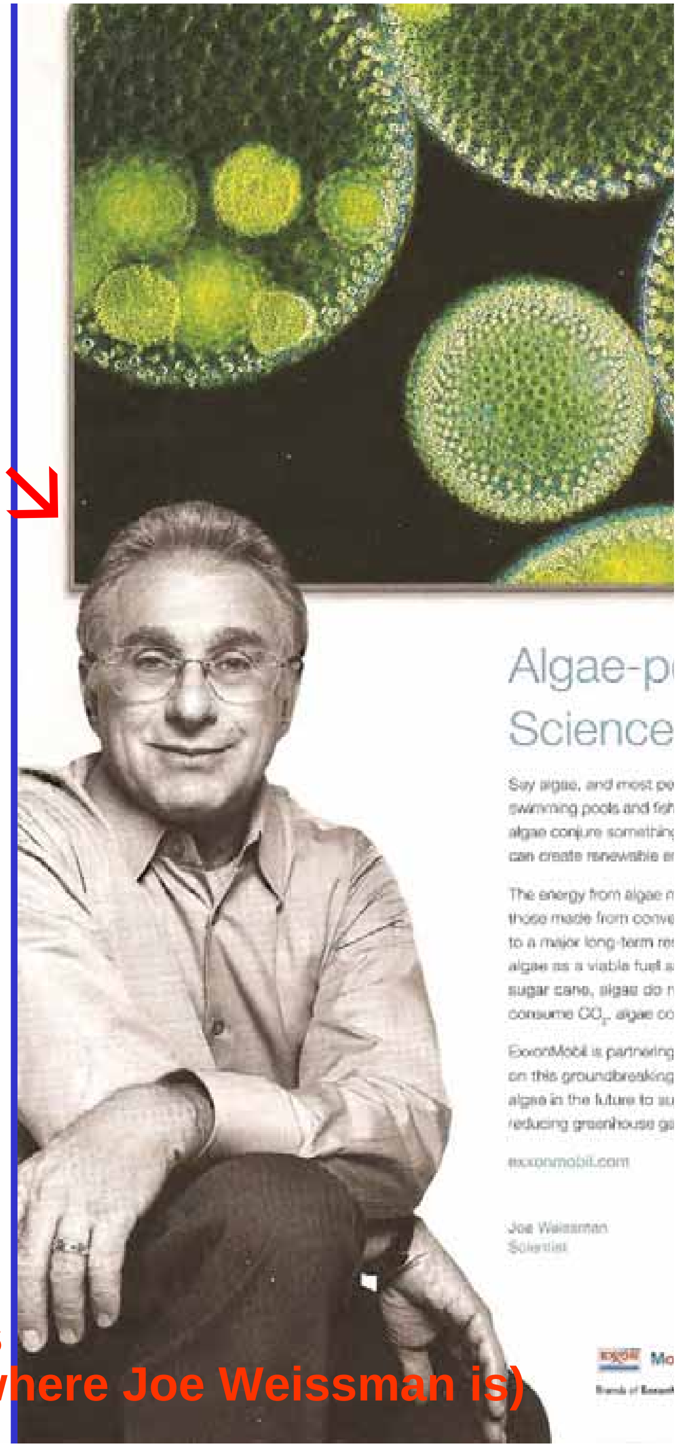
J. Sheehan,
P. Roessler,
T. Dunahay,
J. Weissman
J. Benemann
(Principal Investigator)





Close-Out Report

Paul Roessler now at Synthetic Genomics (funded by ExxonMobil where Joe Weissman is)




AQUATIC SPECIES PROGRAM : ROSWELL, NEW MEXICO 1990
←lined pond
←unlined pond
←CO2 injection
← Inoculum pond 50m²
Joseph Weissman., P.I.,
David Tillett, Ray Goebel
Microbial Products, Inc
Two 0.25 acre ponds, one lined and one unlined
Demonstrated key engineering and biological parameters in algal mass cultures, such as mixing gas transfer, CO₂ utilization/losses, liners vs. dirt, culture productivity & stability, strain selection….

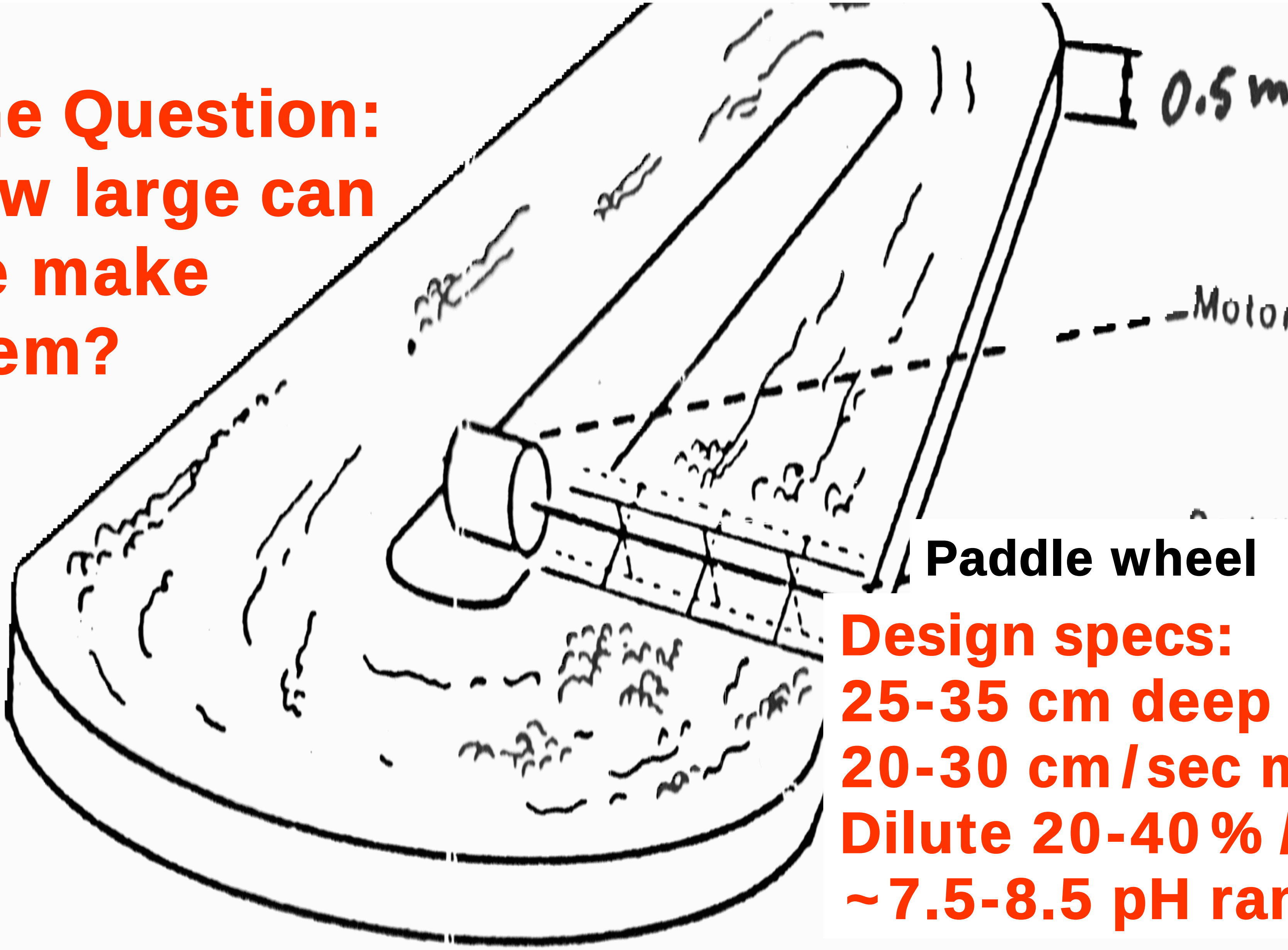
Production of Microalgae for Fuels

Aquatic Species Program, U.S. Dept. of Energy - National Renewable Energy Laboratory, 1980- 1994.

Note raceway ponds, and algae settling-harvesting ponds, Artist conception based on Benemann et al., 1982 Report

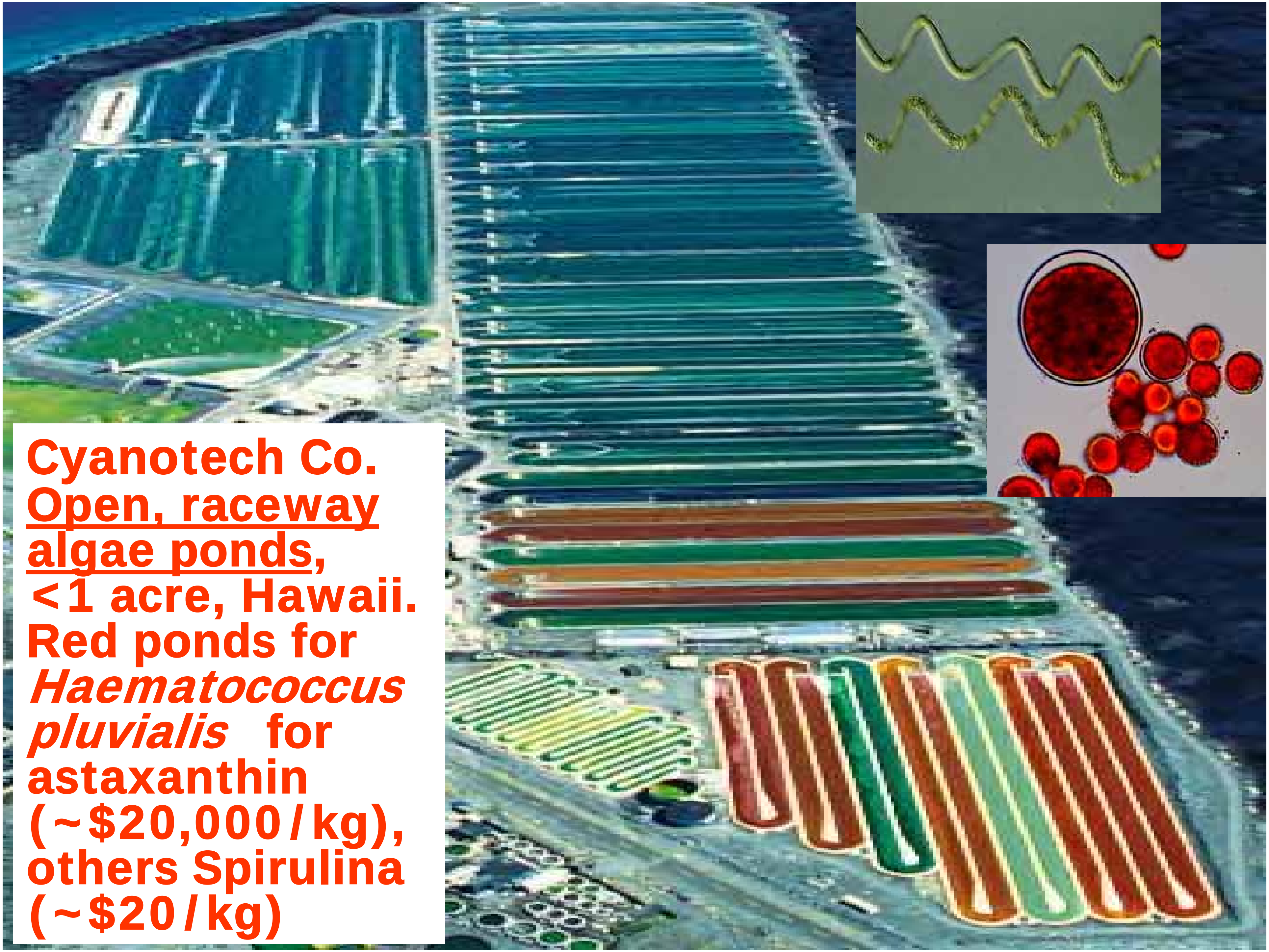
Open ponds <u>only option for algal biofuels production or wastewater treatment</u>.

One Question: how large can we make them?



Design specs:
25-35 cm deep
20-30 cm / sec mix
Dilute 20-40 % / d
~7.5-8.5 pH range

Raceway paddle wheel mixed high rate open ponds now the main (>99%) commercial production systems for microalgae



Cyanotech Co.
<u>Open, raceway algae ponds</u>, <1 acre, Hawaii.
Red ponds for *Haematococcus pluvialis* for astaxanthin (~$20,000/kg), others Spirulina (~$20/kg)


Lamellar settler harvesting →
Sump for CO2 transfer →
Paddle wheel →
Largest high rate ponds in world now
Christchurch NZ 5 hectares, 4 ponds
Investigator: Dr. Rupert Craggs at NIWA

CONCLUSIONS Re. ALGAE STRAIN DEVELOPMENT

- **Microalgae are not yet domesticated … still need to be!**
- Each species, <u>each strain,</u> requires specific development
- Time-space of algae is about a billionth that of crop plants
  e.g. 1 million times smaller, a thousand times faster!
  A small pond has more algae than trees in whole world!
- Small size and fast growth rates present enormous practical problems: very low standing biomass, frequent harvest, etc.
- Fast growth rates do not mean high productivity, but <u>allow fast domestication- major advantage of microalgae biofuels</u>.
- High productivity may be possible: <u>one goal (of very many) for domestication is strains with small antenna size.</u>
- <u>For domestication need traditional strain improvement **and** molecular ("genetically modified algae", GMA) technologies.</u>
- GMA and also "non-native" algae present regulatory issues.

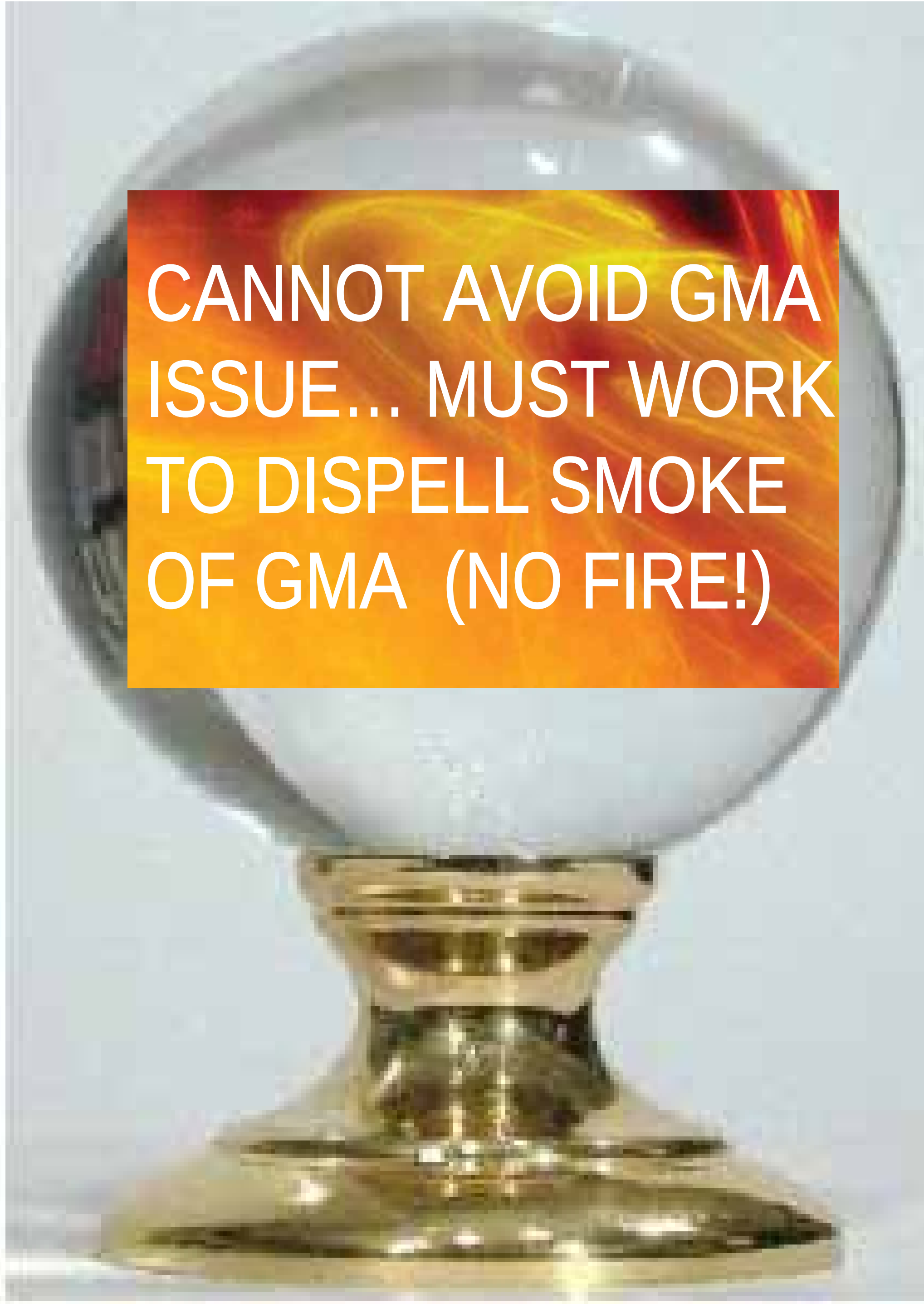
THE ISSUE OF GMA

(GENETICALLY MODIFIED ALGAE)

Could GMA escape and take over the planet?

NO! such strains are not competitive in nature. Why? A very different case compared to higher plants/animals. Space-time dimensions differ by factor of ~1 billion!)

HOWEVER: it must be phytoplankton ecology experts who say this, not those affiliated with commercial interests.

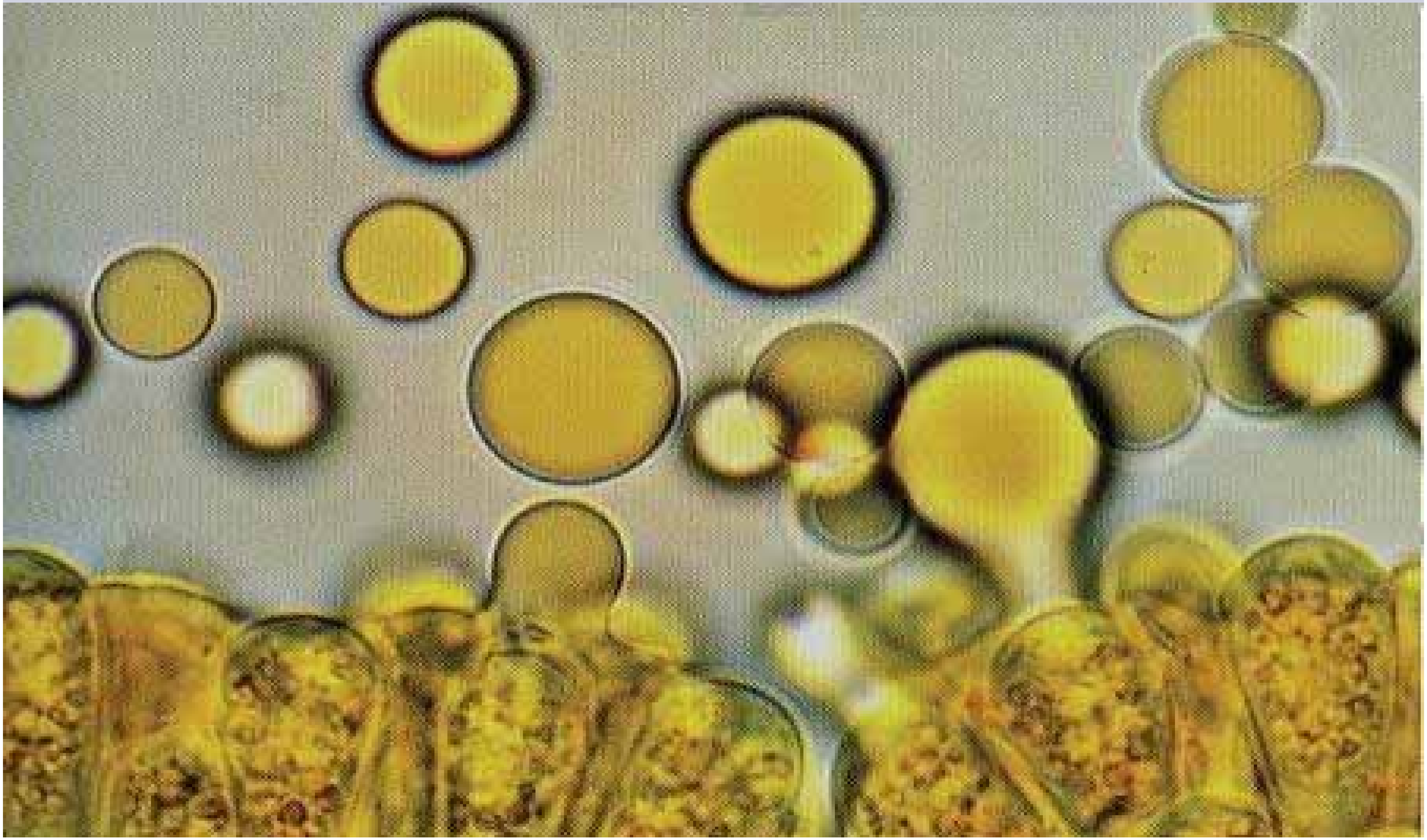


CANNOT AVOID GMA ISSUE… MUST WORK TO DISPELL SMOKE OF GMA (NO FIRE!)

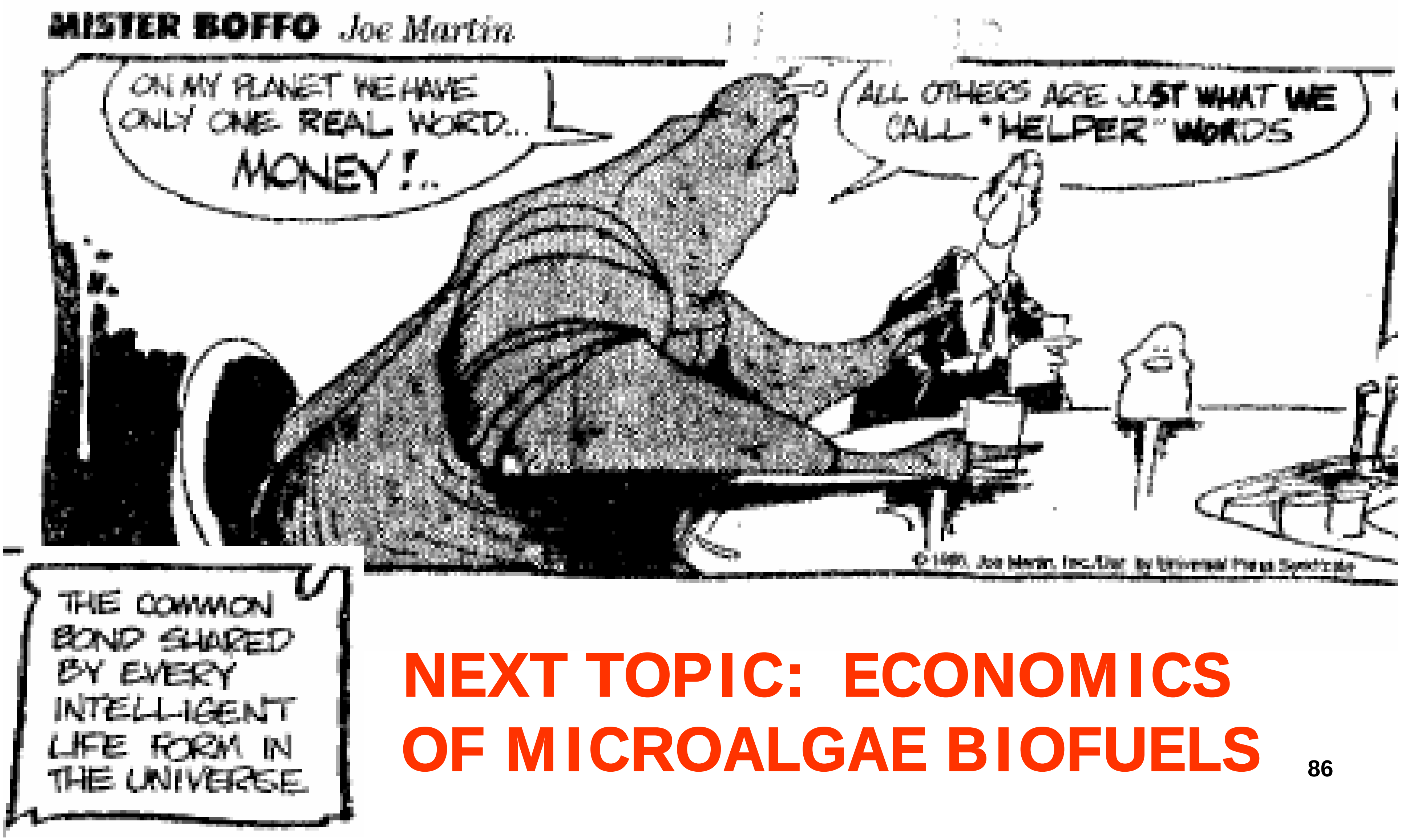
A REASON FOR OPTIMISM ABOUT ALGAE BIOFUELS:

“ We now have wonderful tools”
(Richard Sayre, St. Louis, July 20, 2011)

Nature already provides what we want to make using genetic modifications and synthetic biology: oil globs made by the alga *Botryococcus braunii*

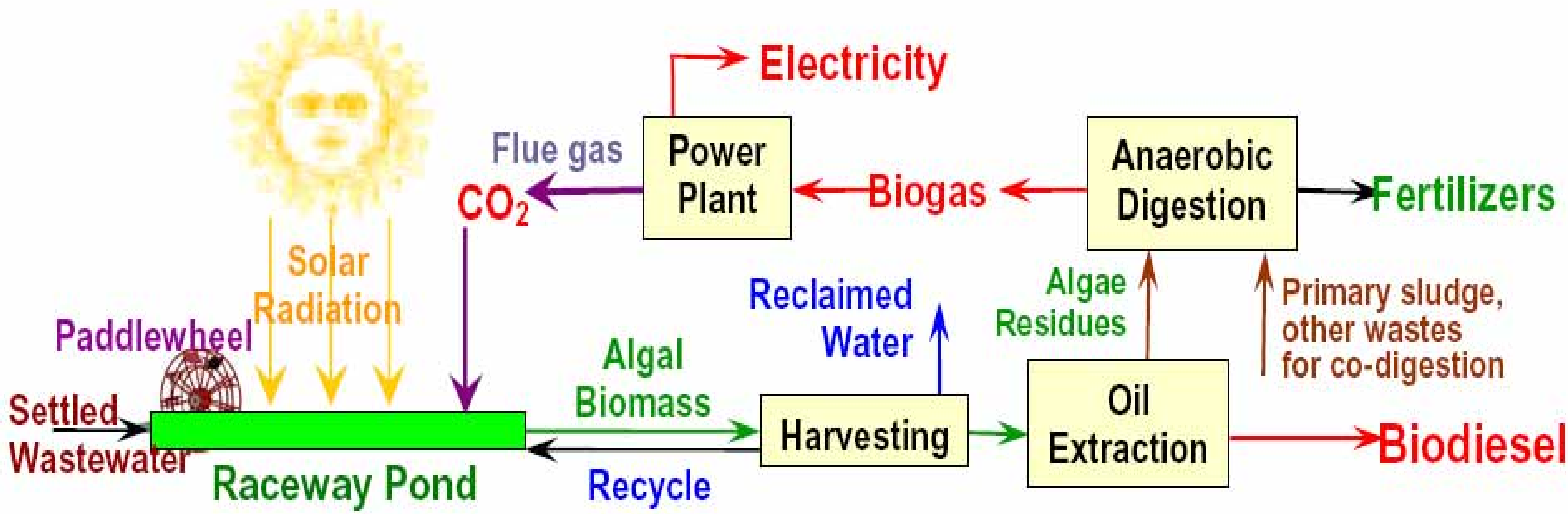


Final Topic: 'On my planet, we only have one real word: Money' (everything else are "helper words")



NEXT TOPIC: ECONOMICS OF MICROALGAE BIOFUELS

Basic Schematic of Algae Biofuels Production based on wastewater inputs for water/nutrients



Lundquist, T., I. Woertz, N. Quinn and J. Benemann, 2010 "A Realistic Technology and Engineering Assessment of Algae Biofuel Production", Energy Biosciences Inst., U.C. Berkeley

Prior techno-economic studies of open pond production also suggest low costs possible

Benemann, J.R. P. Pursoff, & W.J. Oswald, 1978. Engineering Design and Cost Analysis of a Large-Scale Microalgae Biomass System, Final Report US DOE. NTIS #H CP/T1605-01UC-61 (for methane only)

Benemann, J.R., R.P. Goebel, J.C. Weissman, & D.C. Augenstein 1982. Microalgae as a source of liquid fuels. Final Report U.S.DOE BER

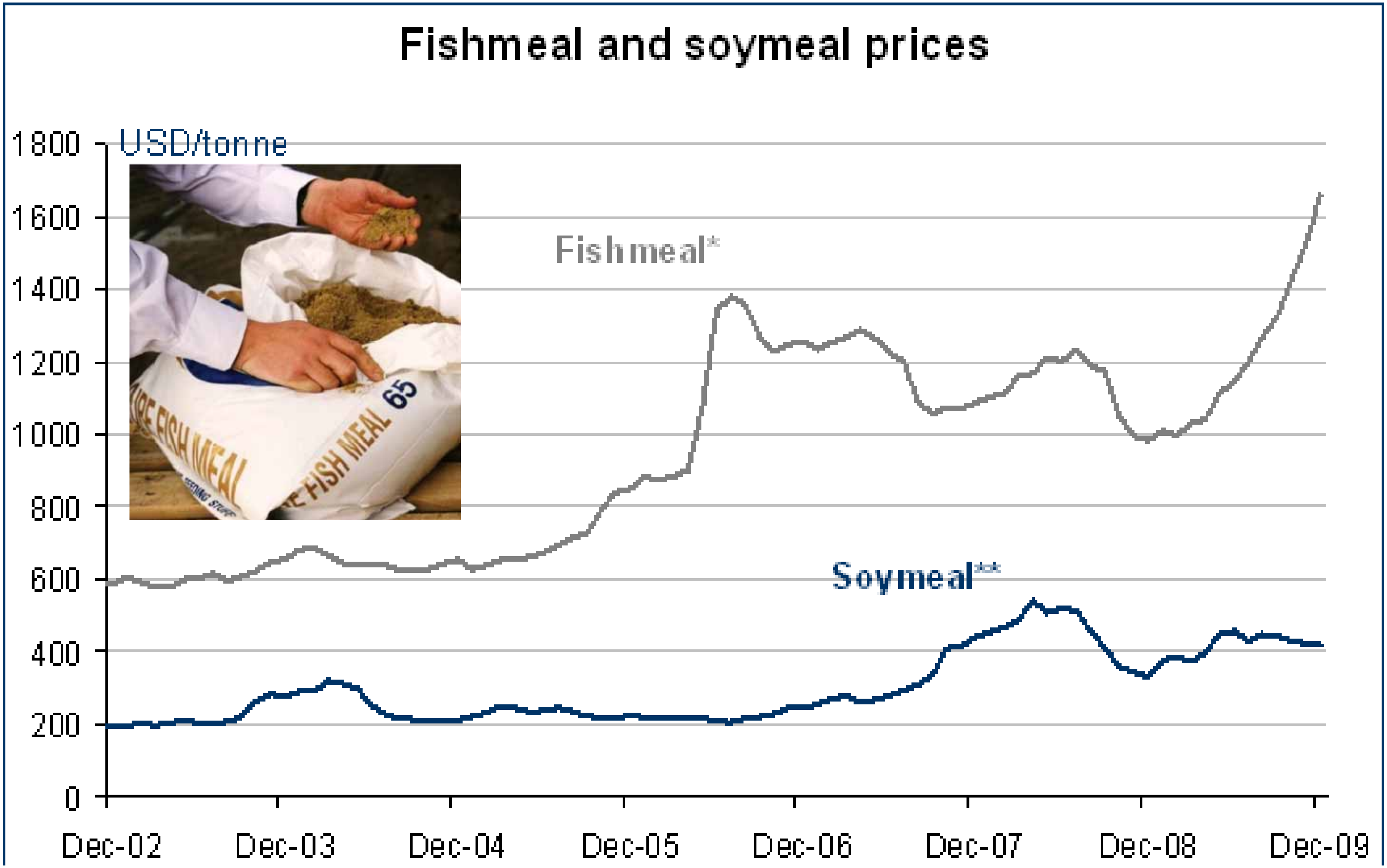
Weissman, J.C., & R.P. Goebel, 1987. Design and analysis of microalgal open pond systems for the purpose of producing fuels Report to US DOE- SERI (fo the Aquatic Species Program)

Benemann, J.R. & W.J., Oswald 1996, Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass. Report to US DOE-NETL (National Technology Energy Laboratory)

Lundquist, T., I. Woertz, N. Quinn and J. Benemann, 2010 (prior slide)

Conclusion: algae biofuels maybe possible BUT NEED VERY HIGH PRODUCTIVITIES, AND MANY OTHER FAVORABLE ASSUMPTIONS

Recent Developments in the APEC region: Cellana (Hawaii), initially supported by Shell Oil, but no longer but now emphasizing aquaculture feeds, not fuels

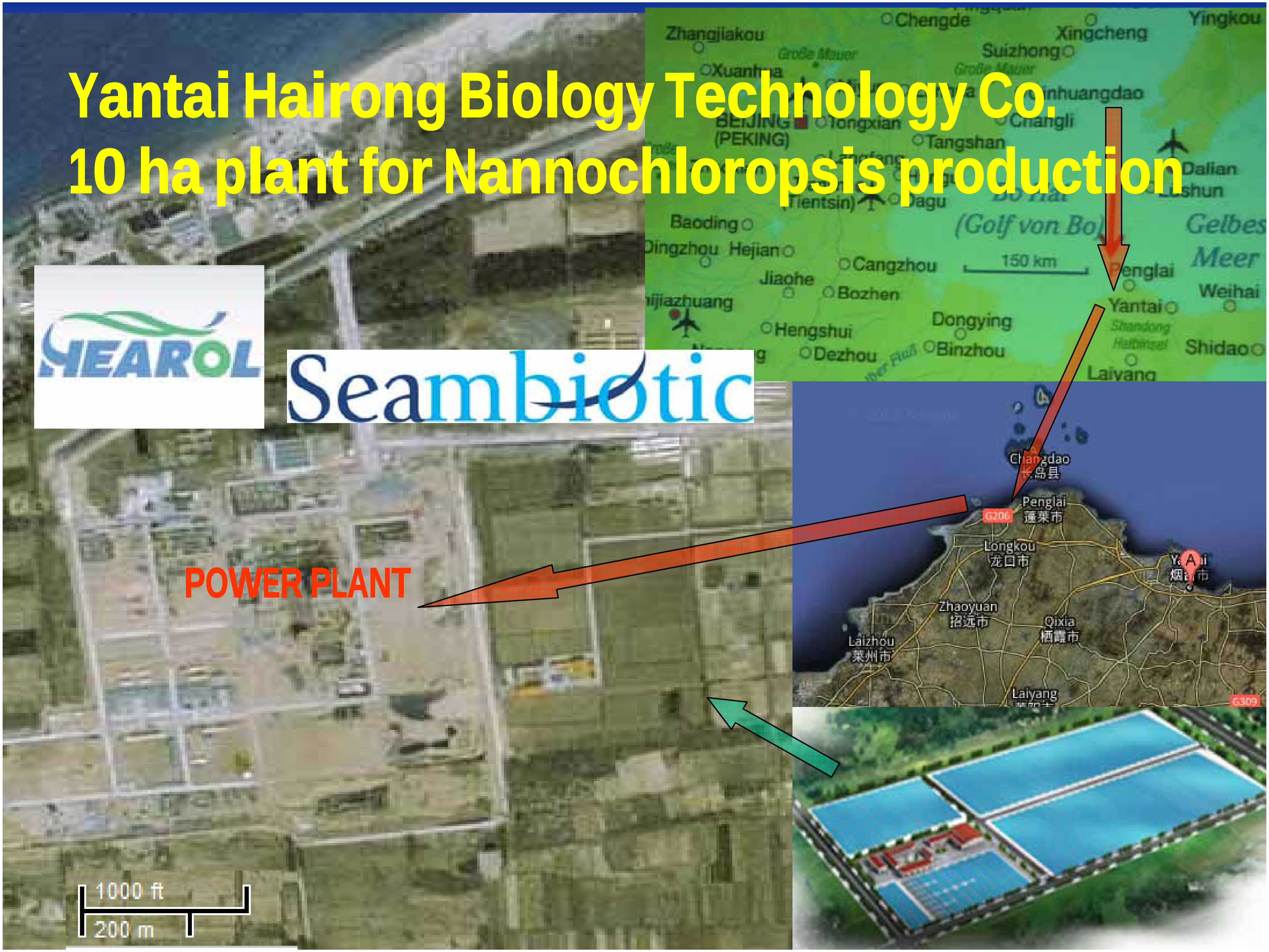


Less fishmeal in world market leads to record high fishmeal prices Total Peruvian landings were 7 million tonnes in 2009, a 6% decline from 2008.

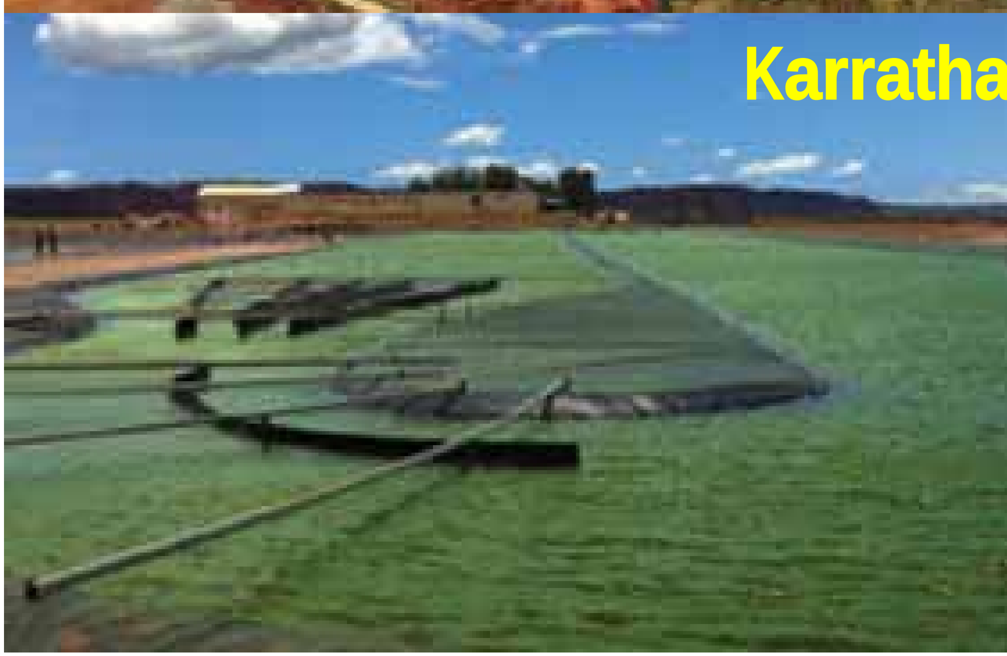
RECENT DEVELOPMENT: Sapphire Energy: 120 ha ~$100 million New Mexico demonstration plant, rice cultivation type pond design (sheet flow]

Production of algae oil and biogas/electricity

Yantai Hairong Biology Technology Co.
10 ha plant for Nannochloropsis production



Aurora algae's demonstration opens for business in Algstralia, by Jim Lane, *Biofuels Digest*, May 4, 2011



Karratha, W. Australia

My initial slide of why microalgae for biodiesel/ Biofuels: attributes of algae claimed by proponents

1. HIGHEST PRODUCTIVITY / FASTEST GROWTH RATE
2. VERY HIGH OIL CONTENT (>50% OF BIOMASS)
3. CAPTURE/ ABATE / SEQUESTER POWER PLANT CO2
4. DO NOT COMPETE WITH FOOD/FEED PRODUCTION
5. LITTLE WATER USE (WITH PHOTOBIOREACTORS)
6. CAN USE BRACKISH, SEAWATER, WASTEWATERS
7. CAN BE CULTIVATED ANYTIME, EVERYWHERE
8. ENORMOUS POTENTIAL RESOURCE WORLDWIDE
9. TECHNOLOGY IS NOW, READY TO COMMERCIALIZE
10. BIOFUELS LOW COST, HIGH VALUE CO-PRODUCTS

Better arguments for microalgae biodiesel and biofuels: Attributes of algae that justify further R&D

1. POTENTIALLY HIGH PRODUCTIVITY, 100MT/HA-YR
2. POTENTIALLY HIGH OIL CONTENT (30-40% AFDW)
3. POTENTIAL GHG REDUCTIONS > GEN1 BIOFUELS
4. CAN BE USED FOR FOOD AND FEED PRODUCTION
5. WATER USE EFFICIENCY HIGHER THAN CROPS
6. CAN USE SEAWATER, BRACKISH, WASTEWATERS
7. CLIMATE FAVORABLE IN MANY REGIONS - APEC
8. SIGNIFICANT POTENTIAL RESOURCE WORLDWIDE
9. R,D&D, DEPLOYMENT MIGHT BE RELATIVELY FAST
10. WASTEWATER TREAMENT IS LOW HANGING FRUIT

THE POTENTIAL AND PROMISE OF MICROALGAE
current US food/fuel crops vs. future algae production

U.S. CROP	Avg. Yield Mt/ha-yr	Protein/oil Mt/ha-yr	1,000s Ha Harvested	Protein – million Mt/yr	oil(equiv.) - bbl/yr
CORN GRAIN	7.0	0.77/starch	30,000	23,000	440,000*
SOYBEAN	1.5	0.9/0.30	30,000	27,000	60,000
ALGAE for feed	100	50/10	1,000	50,000	---
for fuel	100	30/40	1,000	30,000	250,000

NOTE: crop productivities are actual, algae are future projections
CONCLUSION: 1 million ha of algae farms could replace US protein feed production (~ 10% of world) or ~1% of world liquid fuels use). Assumes 40% actual oil yield (2.5 bbl/mt, 40,000 l/ha-yr) from algae

•All figures rounded/approx.: U.S. avg. corn yield avg. 8.2 mt/ha-yr adjusted for 15% moisture and yield of 0.5 l EtOH/kg dry corn x 0.67 for oil eq. and 160 l/bbl Average soy yield and content of protein 60%, oil 20% (2 bbl/ha biodiesel yield).

Biofuels Digest, Jim Lane, June 21, 2011, Paris Air Show

UK-NY in 1 hour: algae-powered rocket plane


THANK YOU!
ANY
QUESTIONS?